Design and Implementation of a Hybrid Solar-Grid-Powered Electric Bicycle

Fhumulani Mphephu, *Idowu Adetona* Ayoade, and *Omowunmi Mary* Longe*

Department of Electrical and Electronic Engineering Science, University of Johannesburg, Johannesburg 2006, South Africa

Abstract. The transition to electromobility in Sub-Saharan Africa has been slow due to many factors, among which is the uncertainty of the electric grid's ability to accommodate the additional electrical load from electric vehicles, including electric bicycles. This paper presents the design and implementation of a hybrid solar-grid-powered electric bicycle as an eco-friendly and sustainable transportation solution. The system integrates photovoltaic panels with an electric bicycle to enable off-grid charging from a direct current (DC) source and reduce reliance on the traditional power grid. A Maximum Power Point Tracking (MPPT) charge controller optimises solar energy harvesting and ensures efficient battery charging. A DC-DC boost converter was designed to regulate voltage levels, enhancing power transfer efficiency from solar panels to the battery. The research encompasses subsystem integration, experimental validation, and performance analysis, with test results presented through graphical evaluations of energy generation and consumption, voltage regulation, and overall system performance. Structural stability, battery endurance, and real-world usability are assessed under various conditions. Findings highlight key performance metrics, challenges, and future improvements, reinforcing the potential of solar-assisted electric bicycles in advancing renewable energy adoption in the transportation industry.

Keywords. Hybrid solar-grid electric bicycle, DC-DC Converter, electromobility, Maximum Power Point Tracking (MPPT), solar photovoltaic (PV) panels.

1 Introduction

Urbanisation is rapidly reshaping cities across Sub-Saharan Africa, particularly in South Africa, where population growth and economic activities are increasingly concentrated in urban areas [1]. One of the pressing challenges associated with this rapid urbanisation is urban mobility [2], which directly impacts economic productivity [3], environmental sustainability [4], and overall quality of life [5]. The growing reliance on fossil fuel-powered transportation or internal combustion engine vehicles exacerbates traffic congestion, fuel

* Corresponding author: omowunmil@uj.ac.za

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

consumption, air pollution, and carbon emissions [6]. Given the urgency of addressing these challenges, there is a heightened global focus on promoting sustainable mobility solutions that reduce dependence on conventional motorised transport. In recent years, electromobility initiatives have gained traction, with non-motorised modes of transport, such as cycling, emerging as viable alternatives for short-distance urban trips [7]. Cycling presents numerous benefits, including affordability, reduced environmental impact, and congestion mitigation. In South Africa, where public transportation infrastructure is often inadequate, electric bicycles can be a crucial link between commuters and transit networks, fostering greater accessibility and green mobility [8]. Integrating electric bicycles (e-bikes) with renewable energy sources, such as solar power, represents a promising step toward achieving eco-friendly urban transport solutions [9].

The evolution of bike-sharing programs worldwide has demonstrated the growing acceptance of cycling as a practical mode of transport [10]. Fourth-generation bike-sharing systems now incorporate electric bicycles powered by clean energy sources [11], reducing reliance on fossil fuels and addressing some of the limitations of conventional bicycles, such as rider fatigue and accessibility over longer distances [12]. Given South Africa's abundant solar energy resources, developing a hybrid solar-grid-powered electric bicycle system can enhance sustainable mobility while leveraging the region's renewable energy resources. E-bikes provide a cost-effective, eco-friendly solution, but adoption depends on infrastructure and public perception. Health-related mobility issues, particularly for individuals requiring frequent healthcare access, highlight the need for improved transport options. E-bikes can enhance connectivity while fostering social inclusion [11].

This research focuses on designing and implementing a hybrid solar-grid-powered e-bike, addressing the critical need for an efficient, clean, cost-effective urban mobility solution. The proposed system ensures reliable battery charging for extended usability by integrating solar energy harvesting with grid support. The findings of this research aim to contribute to the advancement of sustainable transportation solutions and inform policies promoting affordable and sustainable green mobility initiatives across the region. By overcoming the limitations of previous designs, this research contributes to developing more efficient and practical hybrid solar-grid e-bikes, supporting sustainable mobility in Africa.

To address the current challenges in sustainable mobility, this research presents a hybrid solar-grid-powered e-bike that optimises energy efficiency and reliability. The key contributions of this study are outlined as follows:

i. Developing a hybrid solar-grid powered e-bike that seamlessly integrates solar energy harvesting with grid-based charging, ensuring continuous, sustainable, affordable, and reliable power supply to the e-bike. The e-bike is equipped with adjustable frames for the solar panels to offer ease of parking and adaptation.

ii. Designing and implementing an optimised Maximum Power Point Tracking (MPPT) charge controller circuit to charge the electric motor's battery efficiently.

iii. Increased range as the e-bike is enabled to travel for a more extended period through the continuous charging of the batteries from the solar panels as the rider rides the e-bike around or even parks it in an open space during the day. Lower operation costs and charging bills are needed as the e-bike would only charge its battery from the grid if the weather were not satisfactory for charging during the day.

The rest of the paper is organised as follows: theoretical background, system architecture and design, results and discussion, and conclusion in Sections 2, 3, 4, and 5, respectively.

2 Theoretical Background

Urban transportation significantly contributes to air pollution, impacting human health, ecosystems, and the environment. Addressing emission-free mobility is crucial. Electric bicycles have emerged as a sustainable alternative, combining the benefits of conventional bicycles with enhanced comfort and longer trips.

However, there are a few factors and challenges to consider while constructing a solar-grid-powered e-bike. The engineers must optimise weight distribution for stability and balanced handling because solar panels would add weight to the e-bike. Furthermore, despite space limitations, optimising panel efficiency is hampered by the small surface area available on the e-bike for solar panels. It is also critical to balance usefulness and aesthetics because the design must appear streamlined, securely hold solar panels, and integrate them into the frame without sacrificing structural integrity or aesthetic appeal. The e-bike has three significant places where solar PV panels can be installed: on the front wheel, on the back of the wheel, and above the rider. The three locations were studied and analysed. However, the option of the top of the front and back wheels was explored for this solution to maximise the advantages of both locations for optimal voltage and energy generation from the solar panels. This study aims to increase the effectiveness of the e-bike while lowering its need for external charging sources, which will eventually help with environmentally friendly transportation options. The South African grid has an energy mix with about 75% coming from unclean energy sources such as coal; hence, charging the e-bike from a renewable energy resource would reduce the life cycle carbon emissions for every 1 kWh of energy it consumes.

3 System architecture and design

The design considered for the solar e-bike is for solar panels to be placed on the front and back wheels, as shown in Fig. 1. The frame was designed to hold the solar panels while allowing for easy and secure removal, should the need arise. The front frame is placed on top of the front wheel for a streamlined appearance, while the rear frame sits above the back wheel, distributing weight across the bike and maintaining stability. Quick-release fasteners were incorporated to allow users to detach the panels swiftly without needing tools. This modular approach also minimises the risk of damage to the panels by making them easy to remove for transportation or rough terrains. This design also provides the opportunity to generate more electrical energy from the sun since there is an increased area to place the solar panels. Therefore, the modelled solar e-bike in Fig. 1 has more surface area to place the solar panels that can supply the required energy to power the 76 cm high e-bike. Also, the solar panel was slightly tilted at an angle of about 20°. The study comprises key subsystems, each contributing to energy efficiency and structural stability. Collectively, these subsystems reduce dependency on grid electricity and enhance cost-effectiveness. Table 1 highlights the parameters of the developed e-bike and its battery specifics, while Table 2 details the solar panel parameters and its charge controller specifications.

Table 1: Battery and bike parameters

Parameters	Values
Battery nominal voltage	36 V
Battery nominal capacity	8 Ah
Battery maximum voltage	42 V
Maximum permitted load	120 kg

Table 2: Solar panel and MPPT parameters

Parameters	Values
Solar panel's weight (each)	2.1 kg
Solar panel dimensions	56*35*2.5 cm^3
Solar panel peak power (each)	30 W
Solar panel Current	1.71 A
Solar panel voltage	17.6 V
MPPT weight	1.1 kg
MPPT maximum input voltage	100 V
MPPT maximum current output	2.0 A
Front Frame weight	11.9 kg
Back frame weight	6.9 kg

Fig. 1. Modelled hybrid solar-grid e-bike.

3.1 Solar panel integration subsystem

The solar panel subsystem allows on-the-go solar charging, converting sunlight into stored electrical energy. The PV panels, rated at 30W each, are connected in series to achieve 90W total power for the 36 V, 8 Ah battery. The frame securely mounts solar panels while enabling easy detachment for transport and maintenance. Designed for stability, it distributes panel weight efficiently to prevent imbalance. The frame structure ensures stability and durability while minimising additional weight. Steel metal maintains robustness, while cable ties and adjustable slots allow flexible attachment. The frame is aerodynamically optimised to reduce drag, ensuring seamless integration with the bike's design. The front frame follows the wheel's contour, while the rear frame sits above the back wheel, ensuring streamlined performance as shown in Fig. 2. Quick-release fasteners facilitate rapid attachment and removal. Figure 3 displays the subsystem of the final solar panel integration. Monocrystalline solar PV panels were used in the design due to their lighter weight and higher efficiency than polycrystalline solar PV panels.

Fig. 2. Front Frame Subsystem.

Fig. 3. Solar panel integration.

3.2 MPPT integration subsystem

Three 30 W solar panels connected in series provide 52.8 V at 1.71 A and feed into the MPPT controller. The Victron MPPT mobile application enables real-time performance monitoring and configuration. The MPPT optimises power transfer using a Perturb and Observe algorithm, adjusting load dynamically to maximise efficiency. This system design is represented by Fig. 4 to illustrate the flow from solar panels to the MPPT controller, then to the battery and motor. The MPPT controller dynamically adjusts voltage and current to optimise charging under varying sunlight conditions. The system minimises power loss and prevents overcharging. The circuit in Fig. 5 presents the DC-DC boost converter circuit diagram, a switch-mode power supply, which is integral to the power management system of an e-bike. The designed converter regulates and ensures optimal charging and power supply to the e-bike battery pack. The transformer (TR1) uses a flyback/boost conversion topology, facilitating voltage step-up and electrical isolation between input and output stages.

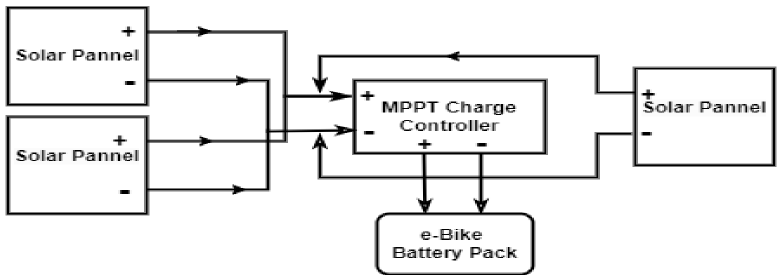


Fig. 4. Solar-powered e-bike wiring connection schematic.

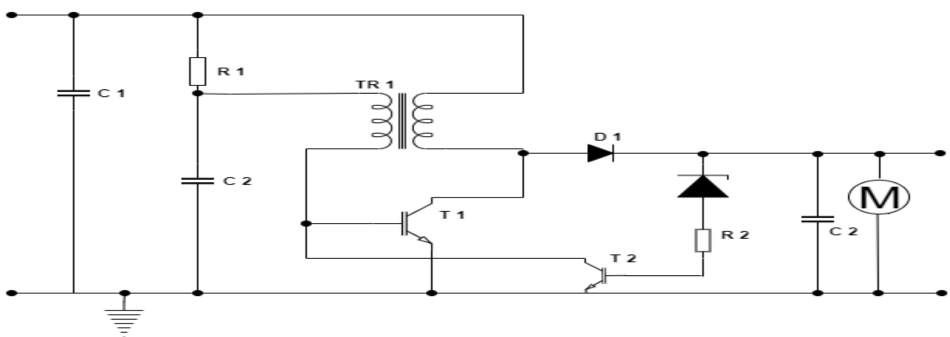


Fig. 5. DC-DC boost converter for hybrid solar-grid powered e-bike battery charging system.

The switching transistor (T1) operates as the central control element, regulating power flow through the transformer. This approach optimises energy transfer and minimises power losses. Capacitors (C1 and C2) act as filters, smoothing the rectified voltage and reducing ripple to ensure stable power delivery. Figure 5 circuitry plays a critical role in solar energy and grid-based power conversion, ensuring a stable and regulated power supply for battery charging and accommodating variable inputs from solar panels and grid sources. This study explores the comparative performance of the MPPT charge controller to improve the charging efficiency of the hybrid solar-grid e-bike system for extension in the range of travel.

3.3 The battery management system

A solar-powered electric bike's dependability and performance depend on its energy storage system. Lithium-ion batteries are widely utilised because of their excellent energy density, extended lifespan, and lightweight design. The Battery Management System (BMS) is needed to ensure battery longevity and optimal performance. The BMS monitors and optimises the battery's charging and discharging cycles. An algorithm was created for intelligent charging that considers the availability of solar energy, the battery's state of charge, and consumption trends of the e-bike for intelligent decisions to be taken on the energy source to charge the battery per time.

4 Results and discussion

The hybrid solar-grid e-bike provides a renewable alternative that minimises reliance on fossil fuels and mitigates climate impact. The project emphasises optimal photovoltaic panel placement, weight distribution, and motor efficiency, ensuring balance and safety. Results demonstrate the system's potential for daily commuting, business applications, and enhanced energy independence. The hybrid solar-grid e-bike was parked in the sun for charging on a partly cloudy day, shown in Fig. 6. Experiments confirmed the system's ability to charge the 36 V battery from 5% to 100% in approximately 8 hours under optimal sunlight. MPPT efficiency reached 90%, adapting dynamically to sunlight variations. Performance remained stable in partly cloudy conditions, with charging current ranging from 0.6 A to 1.4 A. The readings when the battery was between 0%-36% increased gradually, with approximately 20 minutes between every 5% increase in charge. The readings from 10:58 hrs and 12:38 hrs were approximately constant at 36% because the cloud cover delayed the charging process. Fig. 7 shows the charge directly at the output of the battery terminals compared with the charge displayed by the battery management system (BMS). The integrated BMS also shows the battery's state as the charging progresses, as shown in Fig. 8.

Further tests confirmed that the frame securely held the panels without excessive vibration or shifting. Ride tests on varied terrains showed minimal structural impact, with slight vibrations on rough surfaces but no detachment issues. The power consumption was derived from the voltage values at constant current when evaluating the efficiency of the hybrid solar-grid-powered e-bike, as represented in Fig. 9. The trend demonstrates how energy consumption varies with voltage, with AC power consistently higher due to its higher voltage values. The research was successful as the hybrid solar-grid e-bike became functional, offering students green and convenient mobility, as shown in Fig. 6. This work would indeed contribute towards increased adoption of electric bicycles on South African roads with extension to other African countries as motivated by [13], [14].

Fig. 6: Bike Charging in Partly cloudy conditions.

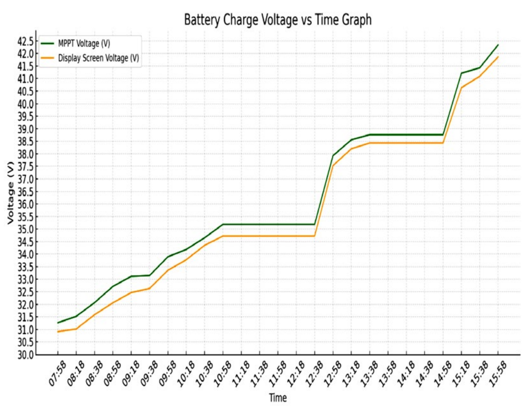
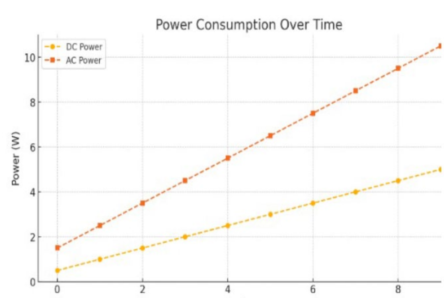


Fig. 7. Comparison of battery charge voltage from the MPPT and BMS display screen.

Fig. 8. Battery fully charged (100%) at 41.4 V.



Time (hours)

Fig. 9. E-bike power consumption.

5 Conclusion

The solar-powered e-bike project has successfully demonstrated the viability of sustainable transportation by harnessing solar energy for off-grid charging. The bike efficiently captures and stores energy by integrating the MPPT charge controller, solar panels, and a custom-built frame, allowing it to operate independently of conventional power sources. Testing has shown that the charge controller subsystem effectively manages energy flow, ensuring optimal battery charging and performance under various sunlight conditions. The system proved stable, with the frame supporting the panels securely without compromising the bike's flexibility. Overall, the project has met its objectives, offering a reliable and eco-friendly solution for areas with frequent power outages, and represents a practical step forward in renewable energy transportation solutions.

Several areas for improvement have been identified in this subsystem. Firstly, a boost converter could increase the current from 1.7 A to a maximum of 2 A, enhancing the system's charging speed and overall efficiency. This would allow for faster energy delivery to the battery, improving the bike's usability in low-sunlight conditions. Additionally, flexible solar panels with a higher voltage rating could be explored to upgrade the current setup. These panels would not only reduce the weight and bulk of the design but also provide greater output, potentially increasing the overall power generation capability of the system. This future development plan will help optimise the e-bike's energy efficiency and performance.

References

1. T.R. Gambe, I. Turok, J. Visagie, The trajectories of urbanisation in Southern Africa: A comparative analysis, Habitat Int., vol. 132, p. 102747, (2023).
2. M. Miskolczi, D. Földes, A. Munkácsy, M. Jászberényi, Urban mobility scenarios until the 2030s, Sustain. Cities Soc., vol. 72, p. 103029, (2021).
3. A. Ceder, Urban mobility and public transport: future perspectives and review, Int. J. Urban Sci., vol. 25, no. 4, pp. 455–479, (2021).
4. Z. Allam, A. Sharifi, Research structure and trends of smart urban mobility, Smart Cities, vol. 5, no. 2, pp. 539–561, (2022).
5. P. Bastida-Molina, D. Ribó-Pérez, T. Gómez-Navarro, E. Hurtado-Pérez, What is the problem? The obstacles to the electrification of urban mobility in Mediterranean cities. Case study of Valencia, Spain, Renew. Sustain. Energy Rev., vol. 166, p. 112649, (2022).
6. P. Zhang, Toward Net-Zero Carbon Emissions in Network AI for 6G and Beyond, IEEE Commun. Mag., vol. 62, no. 4, pp. 58–64, (2024).
7. G.K. Ayetor, J. Mashele, I. Mbonigaba, The progress toward the transition to electromobility in Africa, Renew. Sustain. Energy Rev., vol. 183, p. 113533, (2023).
8. A. Asrori, F. Rohman, E. Faizal, M. Karis, The Design and Performance Investigation of Solar E-Bike using Flexible Solar Panel by Different Battery Charging Controller, Int. J. Mech. Prod. Eng. Res. Dev., vol. 10, no. 3, pp. 14431–14442, (2020).
9. S. Adhisuwignjo, I. Siradjuddin, M. Rifa'I, R.I. Putri, Development of a solar-powered electric bicycle in bike sharing transportation system, IOP Conf. Ser. Earth Environ. Sci., vol. 70, no. 1, (2017).
10. R. Julio, A. Monzon, Long term assessment of a successful e-bike-sharing system. Key drivers and impact on travel behaviour, Case Stud. Transp. policy, vol. 10, no. 2, pp. 1299–1313, (2022).

11. Y. Zhou, Z. Lin, R. Guan, J.-B. Sheu, Dynamic battery swapping and rebalancing strategies for e-bike sharing systems, Transp. Res. Part B Methodol., vol. 177, p. 102820, (2023).
12. N. Ahmad, A. Harun, Reasons for tourist intention to use e-bike sharing services; an application behavioral reasoning theory (BRT), Tour. Rev., vol. 79, no. 9, pp. 1542–1559, (2024).
13. O. M. Longe, An Expository Comparison of Electric Vehicles and Internal Combustion Engine Vehicles in Africa - Motivations, Challenges and Adoption Strategies, in Proc. IEEE 2022 PES/IAS PowerAfrica Conference (PAC), Kigali, Rwanda, Aug. 22-26, pp. 1-5, (2022).
14. I.A. Ayoade and O.M. Longe, A comprehensive review on smart electromobility charging infrastructure, World Electric Vehicle Journal, vol. 15, no. 7, 286, (2024).