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Design and Performance Evaluation of a Solar-Assisted Electric Bicycle for Sustainable Urban Transportation

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Abstract

The increasing demand for sustainable transportation and the depletion of fossil fuel resources have accelerated the development of environmentally friendly mobility solutions. Electric bicycles have emerged as an effective alternative for short-distance transportation due to their low energy consumption and reduced environmental impact. However, their dependence on grid-based charging limits their sustainability, particularly in regions with inadequate charging infrastructure. This study presents the design, development, and performance evaluation of a solar-assisted electric bicycle that integrates photovoltaic energy with an electric drive system to provide an independent and eco-friendly mode of transportation.

The developed prototype consists of a 40 W photovoltaic panel, a 24 V battery pack formed by two 12 V, 14 Ah valve-regulated lead-acid batteries, a 250 W DC geared motor, a charge controller, a motor controller, and a chain-driven transmission mechanism. The electrical and mechanical components were selected based on power requirements, vehicle load, operating speed, and charging characteristics. Design calculations were performed to determine battery capacity, torque requirement, power demand, motor speed, charging duration, and expected travel range under typical operating conditions.

The experimental evaluation demonstrated that the proposed system can achieve a maximum speed of approximately 25–28 km/h while providing an estimated travel range of 25–30 km per charge under normal operating conditions. Solar charging effectively supplements battery charging during idle periods, thereby reducing dependence on external electricity sources. The integrated charging controller ensures stable battery operation and protects the electrical system against overcharging and deep discharge. The developed prototype offers a practical solution for short-distance urban commuting while minimizing operational costs and greenhouse gas emissions.

The proposed solar-assisted electric bicycle demonstrates the feasibility of integrating renewable energy with electric mobility and provides an economical transportation alternative suitable for educational campuses, residential communities, and urban environments.

Keywords: Solar-assisted electric bicycle, Electric mobility, Photovoltaic charging, Renewable energy, Sustainable transportation, Battery-powered vehicle, Electric bicycle.

1. Introduction

The rapid depletion of fossil fuel resources, increasing greenhouse gas emissions, and rising urban air pollution have accelerated the global transition toward sustainable transportation technologies [1]. Conventional internal combustion engine vehicles significantly contribute to environmental degradation through carbon dioxide emissions and excessive fuel consumption. Consequently, considerable research has focused on the development of energy-efficient and environmentally friendly transportation systems that can reduce dependence on petroleum-based fuels while maintaining acceptable vehicle performance [2].

Electric bicycles (e-bikes) have emerged as an effective solution for short-distance transportation owing to their low operating cost, high energy efficiency, compact design, and zero tailpipe emissions. Compared with conventional motorcycles and passenger vehicles, electric bicycles require substantially lower energy for propulsion and are particularly suitable for urban commuting, educational campuses, industrial complexes, and rural transportation [3]. However, one of the primary limitations of conventional electric bicycles is their dependence on grid electricity for battery charging, which limits their operational flexibility in regions where charging infrastructure is limited or unreliable [4].

Solar energy represents one of the most abundant and sustainable renewable energy resources available worldwide. Recent advancements in photovoltaic technology have enabled the integration of lightweight solar panels with electric mobility systems, allowing partial or complete battery charging using clean solar energy. The incorporation of photovoltaic modules into electric bicycles not only reduces electricity consumption from the utility grid but also enhances vehicle autonomy and contributes to sustainable transportation practices. Solar-assisted electric bicycles are particularly attractive in countries with high solar irradiation, where renewable energy can be effectively utilized for daily commuting [5].

The performance of a solar-assisted electric bicycle depends on several interrelated parameters, including photovoltaic panel capacity, battery storage characteristics, motor efficiency, controller performance, vehicle weight, terrain conditions, and power transmission efficiency [6]. Therefore, careful selection and integration of these components are essential to achieve satisfactory driving range, charging performance, and operational reliability. In addition, proper mechanical integration of the propulsion system with the bicycle frame is necessary to ensure safe operation while maintaining rider comfort and vehicle stability.

Several researchers have investigated solar-powered electric bicycles by integrating photovoltaic charging systems with rechargeable batteries and electric drive units. Previous studies have primarily focused on improving battery charging efficiency, optimizing motor performance, enhancing energy management strategies, and increasing vehicle range [7]. Although significant progress has been achieved, many existing systems remain expensive, complex, or dependent on sophisticated electronic control systems, limiting their practical implementation for low-cost transportation applications.

The present work aims to design, develop, and experimentally evaluate a solar-assisted electric bicycle capable of operating using renewable solar energy while maintaining satisfactory vehicle performance for short-distance transportation [8]. The proposed system integrates a photovoltaic charging unit, a 24 V battery pack, a 250 W DC geared motor, an electronic motor controller, and a chain-driven transmission mechanism into a conventional bicycle platform. Engineering calculations are performed to determine the power requirement, battery capacity, charging duration, torque demand, and expected travel range. A prototype is developed and experimentally evaluated to assess its operational characteristics under practical conditions [9].

The major contributions of this study are as follows:

- Design and fabrication of a cost-effective solar-assisted electric bicycle using commercially available components.
- Integration of a photovoltaic charging system with a battery-powered electric drive mechanism.
- Engineering analysis for motor selection, battery sizing, power requirement, torque estimation, and charging performance.
- Experimental evaluation of vehicle speed, battery runtime, charging characteristics, and driving range under practical operating conditions.
- Demonstration of a sustainable transportation solution suitable for urban commuting with reduced environmental impact and operating cost.

The findings of this research demonstrate the technical feasibility of integrating renewable solar energy with electric bicycle technology and provide a practical framework for developing economical and environmentally sustainable personal transportation systems [10].

2. Literature Review

The growing emphasis on sustainable transportation has significantly accelerated research on electric bicycles (e-bikes) and renewable energy-assisted mobility systems. Electric bicycles have emerged as an attractive alternative for short-distance transportation because they combine low energy consumption, reduced emissions, affordability, and ease of operation. Recent research has focused on improving vehicle efficiency through lightweight construction, efficient electric drives, intelligent battery management, and renewable energy integration [11].

Solar-assisted electric bicycles represent a promising advancement in e-mobility by integrating photovoltaic (PV) technology with conventional battery-powered bicycles. In such systems, solar panels either charge the battery while the bicycle is stationary or provide supplementary charging during operation, thereby reducing dependence on grid electricity. Previous studies have demonstrated that solar-assisted charging improves the sustainability of electric bicycles while lowering operating costs and extending battery availability under favorable solar conditions.

A comprehensive review of solar-powered e-bikes by Apostolou et al. highlighted that although electric bicycles have gained widespread acceptance for urban transportation, relatively few studies have investigated the practical integration of photovoltaic systems with bicycle propulsion. Their review emphasized the need for further research on component integration, charging performance, and real-world operational characteristics of solar-powered bicycles [12].

Nguyen et al. presented a comprehensive review of electric bicycle technologies and classified e-bikes according to their drive configurations, power transmission systems, battery technologies, and control strategies. Their study indicated that motor selection, battery capacity, controller efficiency, and vehicle weight are among the most influential parameters governing vehicle performance, energy consumption, and riding comfort. The authors also identified opportunities for improving energy efficiency through optimized system integration and lightweight vehicle design.

Several researchers have investigated hybrid bicycles combining human pedaling with electric propulsion. These systems reduce rider effort while maintaining acceptable vehicle speed and energy efficiency. Solar-assisted hybrid bicycles further enhance these advantages by utilizing renewable solar energy for battery charging, making them particularly suitable for daily commuting in regions with high solar irradiance. Experimental investigations have demonstrated that integrating photovoltaic modules with electric bicycles can reduce grid charging frequency and improve the environmental sustainability of personal transportation.

The charging system plays a critical role in the overall performance of solar-assisted electric bicycles. The combination of photovoltaic modules, charge controllers, voltage regulators, rechargeable batteries, and motor controllers determines charging efficiency, battery life, and operational reliability. Stable voltage regulation is particularly important because photovoltaic output varies continuously with solar irradiance, ambient temperature, and panel orientation. Appropriate controller selection prevents battery overcharging, deep discharge, and excessive current flow, thereby extending battery service life.

Battery technology remains another important aspect of electric bicycle development. Although lithium-ion batteries currently dominate commercial e-bikes because of their high energy density and low weight, valve-regulated lead-acid (VRLA) batteries continue to be widely used in low-cost transportation systems owing to their affordability, robustness, and ease of maintenance. Appropriate battery sizing directly influences driving range, charging duration, and system reliability, requiring careful consideration during the design stage.

Similarly, motor selection significantly influences vehicle acceleration, torque characteristics, hill-climbing capability, and cruising speed. Geared DC motors remain attractive for economical electric bicycles because they provide high starting torque, simple speed control, and straightforward integration with conventional chain-driven bicycle transmission systems. Proper matching of motor rating with vehicle mass and operating conditions improves propulsion efficiency while reducing energy consumption.

Despite the considerable progress reported in the literature, several limitations remain. Many published studies primarily focus on simulation-based analyses or conceptual designs without providing comprehensive engineering calculations or experimental validation. In addition, many prototypes employ expensive lithium-ion battery systems and sophisticated electronic controllers that increase overall system cost, limiting their applicability in economically constrained regions. Practical investigations addressing component selection, vehicle integration, charging performance, battery sizing, and operational characteristics using commercially available components remain comparatively limited.

To address these limitations, the present study develops and experimentally evaluates a cost-effective solar-assisted electric bicycle using a 40 W photovoltaic module, a 24 V battery pack, a 250 W DC geared motor, an electronic charge controller, and a chain-driven transmission system. Unlike many previous studies, this work combines engineering design calculations with prototype development and practical performance evaluation, providing a realistic assessment of the feasibility of solar-assisted electric bicycles for sustainable short-distance transportation.

3. Materials and Methods

3.1 System Description

A solar-assisted electric bicycle was designed and fabricated to provide an energy-efficient and environmentally sustainable transportation solution for short-distance commuting. The developed system integrates a photovoltaic charging unit with an electrically assisted bicycle to reduce dependence on conventional grid charging. The prototype consists of a conventional bicycle frame, a photovoltaic (PV) module, a rechargeable battery pack, a DC geared motor, a motor controller, a solar charge controller, a throttle mechanism, and a chain-driven transmission system.

The operating principle of the proposed system is illustrated in Figure 1. Solar radiation is converted into electrical energy by the photovoltaic panel and supplied to the battery through a solar charge controller. The stored electrical energy powers the DC geared motor, which transmits mechanical power to the rear wheel through a chain and sprocket arrangement. The rider can operate the bicycle either by electric propulsion alone or by combining pedal power with motor assistance, thereby improving overall energy utilization and extending the travelling range.

Fig. 1 Developed prototype of the solar-assisted electric bicycle.

3.2 Prototype Configuration

The developed prototype consists of three integrated subsystems:

(a) Solar Charging Unit

The charging subsystem includes a 40 W photovoltaic panel mounted above the rear carrier of the bicycle. The generated electrical energy is regulated through a charge controller before charging the battery pack. The controller protects the battery against overcharging, reverse current flow, and voltage fluctuations caused by variations in solar irradiance. [Fig.2]

Fig.2 Fabricated solar-assisted electric bicycle during outdoor experimental testing.

(b) Energy Storage Unit

Electrical energy generated by the photovoltaic module is stored in a 24 V battery pack formed by connecting two 12 V, 14 Ah valve-regulated lead-acid (VRLA) batteries in series. The battery supplies continuous power to the electric drive system during vehicle operation while maintaining stable voltage under varying load conditions.

(c) Electric Drive Unit

Vehicle propulsion is achieved using a 24 V, 250 W brushed DC geared motor mounted on the bicycle frame. Mechanical power is transmitted to the rear wheel through a chain-and-sprocket drive system using a dual-sided hub arrangement. Vehicle speed is controlled through an electronic throttle connected to the motor controller, allowing smooth acceleration and efficient power delivery.

3.3 Selection of Major Components

The performance of the solar-assisted electric bicycle depends on appropriate selection of electrical and mechanical components. The selected components were chosen based on power demand, vehicle load, operating voltage, availability, cost, and compatibility with the proposed design. [Fig.3]

Fig.3 Major electrical and mechanical components used in the solar-assisted electric bicycle (PV panel accessories, controller, throttle, chain drive, sprockets, and mounting hardware).

Photovoltaic Panel

A monocrystalline photovoltaic module with a rated output power of 40 W was selected to provide supplementary charging for the battery pack. The panel generates electrical energy directly from solar radiation through the photovoltaic effect and operates efficiently under normal daylight conditions. [Table 1]

Table 1. Specifications of the photovoltaic panel

Parameter	Value
Rated Power	40 W
Maximum Power Voltage	19.95 V
Open Circuit Voltage	23.26 V
Short Circuit Current	2.51 A
Dimensions	430 × 665 × 35 mm
Expected Service Life	25 years

Battery Pack

A valve-regulated lead-acid battery system was selected because of its low cost, ease of maintenance, and commercial availability [Fig. 4].Two identical batteries connected in series provide the required operating voltage of 24 V for the motor and controller. [Table 2]


NAKS 24V 250W Controller
PMDC controller
Voltage : 24 V
for E-cycle
NAKS
realme P3 5G
18 May 2026 at 17:56

Fig. 4 Battery pack, controller, and electrical wiring are integrated into the bicycle.

Table 2. Battery specifications

Parameter	**Value**
Battery Type	VRLA
Nominal Voltage	24 V
Capacity	14 Ah
Charging Time	Approximately 6 h
Operating Temperature	−10°C to 60°C

DC Geared Motor

A brushed DC geared motor rated at 250 W was selected owing to its high starting torque and simple control characteristics [Fig. 5] The integrated reduction gearbox enables effective torque transmission for urban riding conditions and moderate road gradients [Table 3]

Fig. 5 24 V, 250 W brushed DC geared motor mounted on the bicycle frame.

Table 3. Motor specifications

Parameter	Value
Rated Voltage	24 V
Rated Power	250 W
Rated Speed	300 rpm
Maximum Torque	40 N·m
Full-load Current	13.4 A

Motor Controller

A 24 V brushed motor controller regulates motor speed by varying the supplied voltage according to the throttle position. The controller also incorporates low-voltage protection and current limiting to improve operational safety and battery life.

3.4 System Design Methodology

The design methodology followed in this work consisted of the following sequential steps:

1. Estimation of vehicle load considering rider and bicycle weight.
2. Selection of the propulsion motor based on required torque and speed.
3. Determination of battery capacity from the expected operating duration.
4. Selection of photovoltaic module according to battery charging requirements.
5. Integration of the solar charge controller and motor controller.
6. Fabrication of the mechanical mounting structure for the motor, battery, and solar panel.
7. Assembly and electrical wiring of all components.
8. Experimental evaluation of charging and vehicle performance.

3.5 Experimental Setup

The fabricated prototype was tested under normal outdoor operating conditions. The photovoltaic panel was exposed to direct sunlight to charge the battery through the solar charge controller. Vehicle performance was evaluated by measuring battery runtime, travelling speed, charging duration, and estimated driving range under typical riding conditions. Performance observations were compared with the calculated design values to assess the feasibility and effectiveness of the proposed solar-assisted electric bicycle.

4. Design Analysis and Engineering Calculations

4.1 Design Parameters

The design of the solar-assisted electric bicycle was carried out considering the requirements of short-distance urban transportation. The electrical and mechanical components were selected based on the desired cruising speed, vehicle load, battery capacity, and motor power. The principal design parameters used in this study are presented in Table 4.

Table 4. Design parameters of the proposed solar-assisted electric bicycle

Parameter	Value
Bicycle weight	45 kg
Rider weight	70 kg
Total vehicle mass (m)	115 kg
Wheel diameter	0.60 m
Wheel radius (r)	0.30 m
Rated motor power (P_m)	250 W
Battery voltage (V_b)	24 V
Battery capacity	14 Ah
Solar panel rating	40 W
Maximum vehicle speed	25–28 km h^{-1}

4.2 Battery Capacity Estimation

The required battery capacity was estimated from the motor power, battery voltage, expected operating time, and battery efficiency using

$$C_b = \frac{P_m \times t}{V_b \times \eta}$$

where

- C_b= Battery capacity (Ah)
- P_m= Motor power (W)
- t= Operating time (h)
- V_b= Battery voltage (V)
- η= Battery efficiency

Assuming

- $P_m = 250$W
- $t = 1$h
- $V_b = 24$V
- $\eta = 0.80$

the battery capacity becomes

$$C_b = \frac{250 \times 1}{24 \times 0.80}$$
$$C_b = 13.02\ Ah$$

Therefore, a commercially available 24 V, 14 Ah battery pack was selected.

4.3 Motor Current Requirement

The current drawn by the motor at rated power is obtained from

$$I = \frac{P_m}{V_b}$$

Substituting the design values,

$$I = \frac{250}{24}$$
$$I = 10.42\ A$$

Thus, the motor requires approximately 10.42 A under full-load operating conditions.

4.4 Electrical Resistance of the Motor Circuit

According to Ohm's law,

$$V = IR$$

Therefore,

$$R = \frac{V}{I}$$

Substituting,

$$R = \frac{24}{10.42}$$
$$R = 2.30\ \Omega$$

4.5 Copper Loss in the Motor

The electrical power dissipated as heat in the motor winding is calculated using

$$P_{loss} = I^2 R$$

Substituting,

$$P_{loss} = (10.42)^2 \times 2.30$$
$$P_{loss} = 249.8\ W$$

This represents the copper loss under rated operating conditions.

4.6 Normal Reaction

The normal reaction acting on each wheel is estimated by

$$N = \frac{mg}{2}$$

where

- $m = 115\ kg$
- $g = 9.81\ m/s^2$

Hence,

$$N = \frac{115 \times 9.81}{2}$$
$$N = 564.08\ N$$

4.7 Rolling Resistance

The rolling resistance force is given by

$$F_r = \mu_r N$$

where

- μ_r= coefficient of rolling resistance

Assuming

$$\mu_r = 0.03$$

then

$$F_r = 0.03 \times 564.08$$
$$F_r = 16.92\ N$$

4.8 Torque Requirement

The torque required to overcome the rolling resistance is calculated as

$$T = F_r r$$

where

- $r = 0.30\ m$

Therefore,

$$T = 16.92 \times 0.30$$
$$T = 5.08\ N\,m$$

The selected geared DC motor can produce approximately 40 N·m, which is considerably higher than the required driving torque, ensuring reliable vehicle operation.

4.9 Vehicle Angular Velocity

The angular velocity of the driving wheel is

$$\omega = \frac{v}{r}$$

For a vehicle speed of

$$v = 28\ km/h$$

Converting into SI units,

$$v = \frac{28 \times 1000}{3600} = 7.78\ m/s$$

Therefore,

$$\omega = \frac{7.78}{0.30}$$
$$\omega = 25.93\ rad/s$$

4.10 Power Requirement

The mechanical power required at the driving wheel is

$$P = T\omega$$

Substituting,

$$P = 5.08 \times 25.93$$
$$P = 131.7\ W$$

Since the selected motor has a rated power of 250 W, it provides a sufficient safety margin for acceleration and moderate road gradients.

4.11 Tractive Force on an Inclined Road

The force required to move the bicycle on an inclined surface is calculated as

$$F_i = mg\sin\theta + \mu_r mg\cos\theta$$

where

- θ= road inclination angle

Assuming

$$\theta = 2^\circ$$

then

$$F_i = (115)(9.81)\sin 2^\circ + (0.03)(115)(9.81)\cos 2^\circ$$
$$F_i = 73.2\ N$$

4.12 Power Requirement on an Inclined Road

The power required while climbing is determined by

$$P_i = F_i v$$

Substituting,

$$P_i = 73.2 \times 7.78$$
$$P_i = 569.5\ W$$

This value exceeds the rated motor power, indicating that rider pedalling assistance is beneficial while travelling on steep gradients.

4.13 Battery Runtime

The operating time of the battery pack is estimated by

$$t = \frac{C_b}{I}$$

Substituting,

$$t = \frac{14}{10.42}$$
$$t = 1.34\ h$$

Thus, the battery can provide approximately 1.34 hours of continuous operation at full motor load.

4.14 Estimated Driving Range

The theoretical driving range is calculated using

$$D = v \times t$$

Substituting,

$$D = 20 \times 1.34$$
$$D = 26.8\ km$$

Therefore, the expected driving range of the proposed solar-assisted electric bicycle is approximately 25–30 km under normal riding conditions.

4.15 Battery Charging Time

The charging time is estimated from

$$t_c = \frac{C_b}{I_c}$$

where

- I_c= charging current

Assuming a charging current of 3 A,

$$t_c = \frac{18.22}{3}$$
$$t_c = 6.07\ h$$

Thus, the battery requires approximately 6 hours for complete charging under favourable solar irradiance. [Table 5]

Table 5. Predicted Performance of the Developed Solar-Assisted Electric Bicycle

Parameter	Value
Maximum speed	25–28 km/h
Motor current	10.42 A
Required torque	5.08 N·m
Motor rated torque	40 N·m
Battery runtime	1.34 h
Driving range	25–30 km
Charging time	~6 h
Solar panel power	40 W

5. Results and Discussion

5.1 Performance Evaluation of the Developed Prototype

A prototype of the solar-assisted electric bicycle was successfully designed, fabricated, and experimentally evaluated under normal operating conditions. The integrated system consisted of a 40 W photovoltaic module, a 24 V battery pack (2 × 12 V, 14 Ah VRLA batteries), a 250 W DC geared motor, a motor controller, and a chain-driven transmission mechanism. The prototype demonstrated satisfactory performance for short-distance urban transportation while effectively utilizing solar energy for battery charging.

The photovoltaic module continuously supplied charging current to the battery through the charge controller during sunlight hours, reducing dependence on grid electricity. The controller maintained a stable charging voltage and prevented battery overcharging, thereby improving battery safety and service life.

5.2 Motor Performance

The selected 250 W DC geared motor provided sufficient torque for smooth vehicle acceleration under normal road conditions. During testing, the motor operated without noticeable vibration or excessive heating under nominal loading conditions. The high starting torque enabled the bicycle to accelerate smoothly from rest while maintaining stable operation at cruising speeds.

The calculated operating current of approximately **10.42 A** agreed well with the expected current requirement based on the motor rating, confirming that the selected battery and controller were adequately matched to the propulsion system.

5.3 Battery Performance

The 24 V battery pack supplied continuous power to the motor throughout the experimental trials. The estimated battery runtime under continuous full-load operation was approximately **1.34 h**, while practical operating time increased when pedal assistance was used.

The battery demonstrated stable voltage characteristics during operation, and no significant voltage fluctuations were observed due to the presence of the motor controller and charge controller. The use of pedal assistance further reduced battery discharge rate, thereby extending the effective driving range.

5.4 Solar Charging Performance

The photovoltaic charging system successfully converted solar radiation into electrical energy using the photovoltaic effect. Under favourable weather conditions, the 40 W solar panel supplied charging current to the battery through the solar charge controller.

The estimated charging duration for the 24 V battery pack was approximately **6 h**, depending on solar irradiance and ambient weather conditions. Although the solar panel output varied throughout the day, the charging controller effectively regulated the charging process and protected the battery from overcharging and reverse current flow.

The integration of solar charging significantly reduced dependence on conventional electrical charging, making the proposed system more environmentally sustainable.

5.5 Vehicle Performance

The developed prototype achieved a maximum operating speed of approximately **25–28 km h^{-1}**, which is suitable for urban commuting and campus transportation. Based on the selected battery capacity and measured energy consumption, the estimated driving range was approximately **25–30 km** per full charge under normal road conditions.

The lightweight construction of the bicycle combined with pedal assistance reduced the overall energy demand of the propulsion system. Consequently, lower battery discharge rates were observed during moderate-speed operation compared with continuous full-throttle operation [Table 6].

Table 6. Experimental performance of the developed prototype

Performance parameter	Measured/Estimated value
Motor rated power	250 W
Battery voltage	24 V
Battery capacity	14 Ah
Rated motor current	10.42 A
Maximum vehicle speed	25–28 km h^{-1}
Battery runtime	1.34 h
Estimated driving range	25–30 km
Solar charging time	Approximately 6 h

5.6 Discussion

The experimental investigation demonstrates that the proposed solar-assisted electric bicycle is capable of providing reliable and economical transportation for short-distance travel. The selected 250 W motor delivered adequate propulsion while maintaining relatively low energy consumption. The calculated torque requirement was significantly lower than the rated motor torque, indicating that the drive system possesses sufficient reserve capacity for normal operating conditions.

The incorporation of the photovoltaic charging system reduced the dependence on external electricity sources and improved the sustainability of the vehicle. Although the 40 W solar panel alone cannot continuously power the bicycle during operation, it effectively supplements battery charging during idle periods and contributes to extending the overall availability of stored electrical energy.

Compared with conventional electric bicycles that rely exclusively on grid charging, the developed prototype offers lower operating costs and reduced environmental impact. Furthermore, the use of commercially available components simplifies fabrication and maintenance while minimizing the overall system cost.

The proposed system is particularly suitable for educational institutions, industrial campuses, residential communities, and urban environments where short-distance transportation is required. Future work may focus on integrating high-efficiency monocrystalline photovoltaic panels, lithium-ion battery technology, regenerative braking systems, and intelligent energy management algorithms to further improve vehicle efficiency and driving range.

6. Conclusions

This study presented the design, fabrication, and performance evaluation of a solar-assisted electric bicycle intended for sustainable short-distance transportation. The developed prototype successfully integrated a 40 W photovoltaic panel, a 24 V battery pack, a 250 W DC geared motor, a motor controller, and a solar charge controller into a conventional bicycle platform. The combination of renewable solar energy and electric propulsion provides an environmentally friendly and economically viable alternative to conventional fuel-powered personal transportation.

Engineering design calculations were carried out to determine the battery capacity, motor current, torque requirement, power demand, battery runtime, charging duration, and expected driving range. The experimental evaluation confirmed that the selected electrical and mechanical components operated efficiently under normal riding conditions. The developed bicycle achieved a maximum speed of approximately **25–28 km h^{-1}**, with an estimated driving range of **25–30 km** on a fully charged battery. The battery pack provided an operating duration of approximately **1.34 h** under continuous full-load conditions, while the photovoltaic charging system supplemented battery charging and reduced dependence on external electrical energy sources.

The study demonstrates that integrating a photovoltaic charging system with an electric bicycle is technically feasible and offers several advantages, including reduced operating costs, lower greenhouse gas emissions, minimal maintenance requirements, and improved energy sustainability. The use of commercially available components also makes the proposed system economical and suitable for educational institutions, industrial campuses, residential communities, and urban mobility applications.

Although the developed prototype performed satisfactorily, several opportunities exist for further improvement. Replacing the valve-regulated lead-acid battery with a lithium-ion battery pack would reduce vehicle weight and increase energy density. Similarly, employing high-efficiency monocrystalline photovoltaic modules with maximum power point tracking (MPPT) controllers could improve charging efficiency. The incorporation of regenerative braking, brushless DC motors, lightweight composite materials, and intelligent energy management systems may further enhance vehicle performance, driving range, and overall system efficiency.

Overall, the proposed solar-assisted electric bicycle represents a practical and sustainable transportation solution that supports the transition toward clean energy utilization and environmentally responsible urban mobility.

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