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ENGINEERING A SOLAR-ASSISTED E-BIKE FOR SUSTAINABLE TRANSPORTATION

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ABSTRACT
This paper presents the design and development of a solar-powered hybrid electric bicycle, aiming to create a sustainable and efficient transportation solution by integrating solar energy with electric bicycle technology. The primary objective is to harness renewable solar power to enhance the range and performance of electric bicycles. The research involves a thorough review of photovoltaic technologies to identify the most suitable solar panels for the bicycle frame. The electrical system, including the motor, battery, and charging circuit, is optimized to effectively utilize solar energy. A power management system is also designed to regulate energy charging and distribution. The prototype demonstrates the feasibility of integrating solar power into electric bicycles, resulting in an extended range, reduced reliance on grid electricity, and lower carbon emissions. This work offers insights into the technical challenges of solar integration and highlights potential pathways for future improvements and commercialization, promoting greener transportation solutions.

Keywords:
Solar Energy System, Lithium ion battery, PMDC, PWM controller, bicycle.

I. Introduction
Electric bicycles (e-bikes) have emerged as a sustainable transportation option, particularly in urban areas facing environmental challenges and traffic congestion. In India, e-bike sales reached 231,338 units in 2022, highlighting a shift towards eco-friendly commuting solutions. While traditional e-bikes predominantly use rechargeable batteries charged via AC mains, there is a significant opportunity to enhance sustainability by incorporating alternative energy sources that allow for simultaneous charging during operation, potentially minimizing operational costs.
Among renewable energy sources, solar energy is particularly promising due to India’s vast solar potential, estimated at around 4,800 to 5,000 trillion kWh annually [1]. This abundance makes solar panels an effective solution for charging e-bikes, facilitating the efficient use of renewable resources while riding. By integrating solar power, e-bikes can extend their range and reduce carbon emissions, thereby promoting greener transportation options [2].
The electric motor is a crucial component of e-bikes, employing various technologies, including brushed and brushless DC motors, induction motors, and direct-drive hub motors. Motor efficiency, power output, and torque characteristics significantly influence overall performance [3]. Research has demonstrated the feasibility of using hybrid energy sources, such as a bicycle powered by both wind and solar energy, to enhance functionality and sustainability [4].
Battery systems play a vital role in determining e-bike performance and range. Common battery types include lead-acid, nickel-cadmium (Ni-Cd), nickel-metal hydride (NiMH), and lithium-ion (Li-ion). Recent studies have focused on enhancing battery capacity, energy density, and charging efficiency, along with the development of battery management systems (BMS) to improve longevity [5]. Notably,

the use of photovoltaic (PV) systems as auxiliary power sources for e-bikes has shown promise for solar integration [6].

Efficient control systems are essential for optimizing power use and ensuring a smooth ride. Various algorithms, such as pulse-width modulation (PWM) and proportional-integral-derivative (PID) control, are utilized to regulate motor speed and torque [7][8]. Furthermore, innovations in electronic components, like motor controllers and regenerative braking systems, contribute to improved energy efficiency and rider control. Research has explored designing economical e-bikes that reduce charging times through multiple energy sources, emphasizing the potential of hybrid systems [8]-[11].

System optimization is critical for maximizing e-bike performance. Literature highlights the importance of factors such as weight reduction, aerodynamics, and drivetrain efficiency in balancing range, speed, and comfort [9]. The integration of advanced materials, like carbon fiber composites, alongside efficient power management strategies, has been explored to enhance overall system performance [10]–[12].

This manuscript proposes a hybrid electric bicycle model that combines solar panels with a dual battery system, leveraging both solar energy and conventional AC mains supply for charging. The design aims to optimize motor technology, battery systems, and control algorithms, enhancing performance while reducing charging times and operational costs. By developing an efficient, reliable, and environmentally friendly electric bicycle, this work aspires to advance sustainable transportation solutions, paving the way for further research and innovation in hybrid electric bicycles.bicycles.

II. Block Diagram of Proposed Model of Solar Powered E-Bicycle

The proposed hybrid electric bicycle system integrates solar power and electric propulsion, presenting a sustainable transportation solution. As depicted in the block diagram (Figure 1), the system's energy flow and control signals are organized through distinct components. Solar panels positioned at the top capture sunlight and convert it into electrical energy [13]. This energy is then directed to a solar charge controller, which regulates voltage and current to optimize battery charging. The battery serves as the energy reservoir, supplying power to the e-bike controller, the system's central processing unit [14]. The e-bike controller manages the interactions among the throttle, motor, and braking system, ensuring seamless operation.

The heart of the system is the permanent magnet DC motor (PMDC), which transforms electrical energy from the battery into mechanical energy to propel the bicycle. The motor faults should be identified in the incipient stage to diagnose it [15]. The throttle enables the rider to modulate power output, providing an intuitive interface for control [16]. Power transmission to the wheels is facilitated through a sprocket and chain drive, ensuring efficiency and responsiveness.

Safety is a priority; the braking system delivers reliable stopping power and communicates with the motor to shut off during braking, preventing any unintended acceleration. This integrated approach not only enhances rider experience but also promotes energy efficiency and sustainability, positioning the hybrid electric bicycle as a forward-thinking solution in modern transportation.

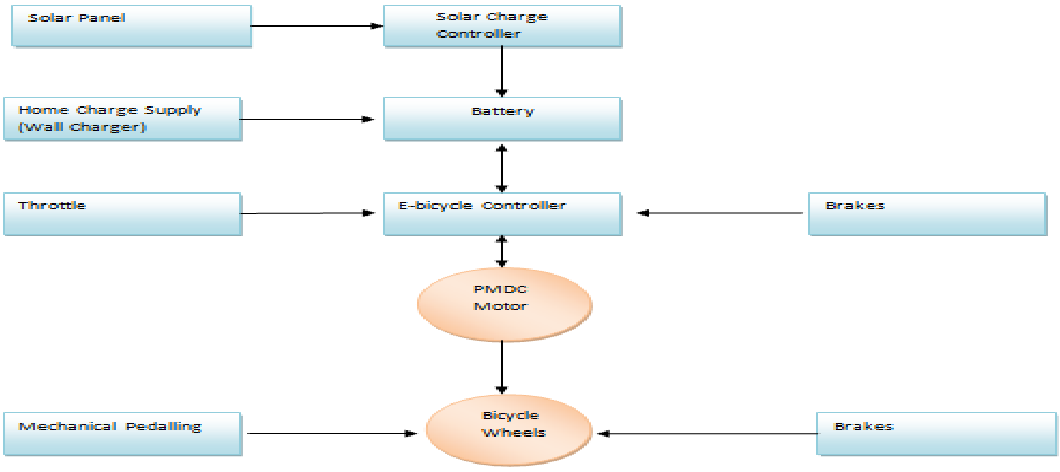

Figure 1: Block Diagram of Solar Powered E-bicycle

III. Internal Architecture of Bicycle

The internal architecture of the hybrid electric bicycle system consists of several interconnected components that work together seamlessly. The heart of the system is the e-bike controller, which integrates various electronic components, including microcontrollers, resistors, and MOSFETs. This controller processes inputs from the throttle and braking system, adjusting the motor's speed and operation accordingly. The solar charge controller plays a critical role by managing the flow of energy from the solar panels to the battery, preventing overcharging and extending battery life. The Li-ion battery, configured with 7 series and 7 parallel cells, provides the necessary energy storage with a capacity of 24V and 18Ah. This configuration allows for efficient energy use while maintaining the required voltage for the PMDC motor [16]. The motor itself, rated at 250W and 300 RPM, converts electrical energy into mechanical motion, propelling the bicycle forward. The different components of bicycle is given below.

i) Solar Panels:

The system utilizes four 10W solar panels, each measuring 30×35 cm and rated at 12V. Two panels are connected in series to achieve a voltage of 24V, and then two sets of these series-connected panels are connected in parallel. This configuration effectively captures solar energy, enhancing the e-bike's sustainability while maintaining a compact design that minimizes aerodynamic impact [10].

Figure 2: Configuration of Solar Panel System for E-bike

ii) Solar Charge Controller:

The PWM (Pulse Width Modulation) solar charge controller is a vital component in solar energy systems, specifically designed to regulate the voltage and current flowing from solar panels to the battery. This device plays a significant role in managing the charging and discharging processes of

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batteries, optimizing their performance, and extending their lifespan. The image of the controller is given by figure 3.

Unlike MPPT (Maximum Power Point Tracking) controllers, which are typically more efficient but come at a higher cost, PWM controllers provide a cost-effective solution for smaller-scale solar installations. They operate by rapidly switching the power output from the solar panels on and off, allowing them to regulate the voltage that reaches the batteries. This functionality helps maintain a steady and appropriate charging voltage, which prevents overcharging and protects the batteries from potential damage [13][14]. Additionally, PWM controllers are favored for their simplicity and reliability, making them particularly suitable for off-grid and remote solar applications, where efficiency and ease of use are paramount.

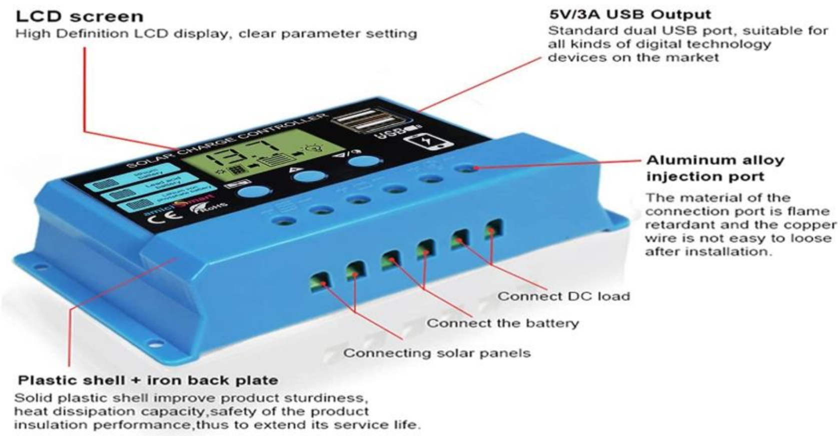

Figure 3: PWM Solar Charge Controller for E-bike

iii)Li-ion Battery:

The e-bike is equipped with a 24V, 18Ah Li-ion battery, made up of 3.7V 2600mAh 18650 cells configured in a 7-series, 7-parallel arrangement. This design provides high energy density and supports an extended range, making it ideal for electric bicycles.

Figure 4: Configuration of Li-ion Battery for E-bike

iv)E-bike Controller:

The e-bike controller functions as the central unit, managing motor operations based on rider input. It connects all electrical components, including the battery, motor, throttle, brakes, and sensors, ensuring seamless interaction among them. The controller also incorporates protective features such as under-voltage and over-current protection, which enhances safety during operation. This integration makes the controller a crucial component in optimizing the performance and reliability of the e-bike.

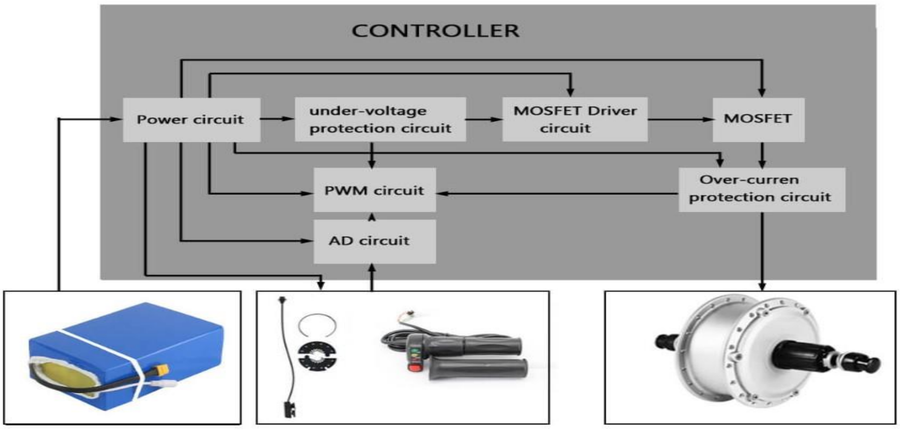

Figure 5: E-bike Controller and System Integration

v) Permanent Magnet DC Motor (PMDC):

The Permanent Magnet DC (PMDC) motor is a key component of the e-bike, rated at 250W and operating at 300 RPM. Unlike traditional DC motors, the PMDC motor utilizes permanent magnets instead of field windings, which are positioned on the inner surface of the cylindrical steel stator. This design generates torque through the interaction between the permanent magnetic field and the armature flux, resulting in improved efficiency and performance.

The specifications for the motor include a rated voltage of 24V DC, a rated power of 250W, and an operational RPM of 300 after reduction. The rated current is 10.41A, with a full-load current of 14.2A and current-limiting protection set at 20A.

Figure 6: PMDC motor used in the project

vi) Throttle:

The throttle on the e-bike enables riders to control the motor's power output, ensuring a smooth and enjoyable riding experience. Similar to a scooter or motorcycle, engaging the throttle propels the bike forward without the need for pedaling. The throttle's modulation capability is crucial, as it determines how gradually power is applied: good modulation provides a steady increase in power, while poor modulation results in abrupt bursts of power, affecting rider comfort and safety.

Figure 7: E-bike Throttle Mechanism

vii) Sprocket and Chain Drive:

The sprocket is essential for transmitting mechanical power from the motor to the rear wheel, facilitating effective bicycle movement. It features evenly spaced teeth and works with a chain, ensuring efficient power transfer. Chain drives consist of multiple sprockets and a chain, commonly used in bicycles and machinery for their robustness and ability to handle high loads.

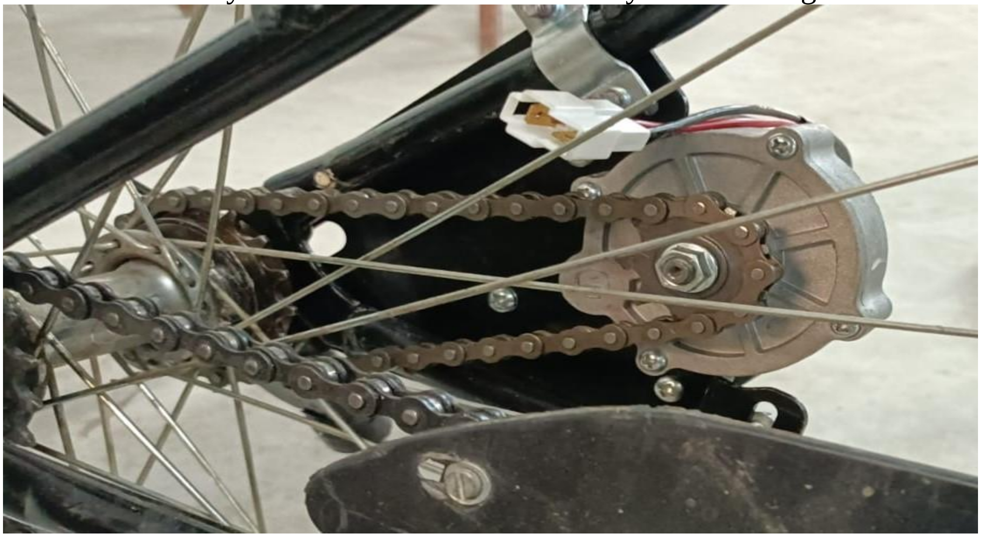

Figure 8: Image of the Chain Drive System

viii) Braking System:

The e-bike features a rim brake system, utilizing brake pads that apply friction to the wheel rims for reliable stopping power. The brake lever not only slows the bike but also signals the controller to shut off the motor, enhancing rider safety during braking.

IV. Design and Fabrication of Solar Powered Hybrid Electric Bicycle

For constructing our prototype, we considered several key parameters. The diameter of the wheel (D) is 60 cm, and the target speed (v) is set at 25 km/h. The weight of the bicycle itself is 35 kg, while the weight of the rider is 75 kg. These data points are crucial for evaluating the overall performance and efficiency of the e-bike prototype.

Normal reaction on each tyre:-

Normal reaction (N)= $\left(\frac{W}{2}\right) \times g\ N$

Where, W = Weight of bicycle + Weight of Rider

g = acceleration due to gravity

$\therefore$ N =$\left(\frac{35+75}{2}\right) \times 9.8$

= 539.55 N

- **Friction force (f) acting on each tyre:-**

1) For Static friction f_s taking constant value u (coefficient of static friction) = 0.03

So Static friction $f_s = u \times N$

$= 0.03 \times 539.55$

$= 16.1865$ N

2) For Dynamic friction f_k taking constant value u= 0.004

So Dynamic friction $f_k = u \times N$

$= 0.004 \times 539.55$

$= 2.1582$ N

- **Torque (T)-**

For Static condition, Ts = fs×R

$= 16.1865 \times (\frac{0.6}{2})$

$= 4.85595$ Nm

For Dynamic condition, $T_k = f_k \times R$

$= 2.1582 \times (\frac{0.6}{2})$

$= 0.64746$Nm

- **Calculation for Angular Velocity (w):-**

$w = V/R$

$= \frac{25000}{0.3 \times 3600}$

$= 23.1481$ rad/sec

- **Calculations for power**

(A) For Plain surface,

Static friction power Ps = Ts×w

= 4.85595×23.1481

= 112.4064 watt

Dynamic friction power $P_k = T_k \times w$

= 0.64746×23.1481

= 14.9874 watt

Net Power requirement for Plain surface= Ps ×2

$= 112.4064\,_k \times 2$

= 224.8128 watt

Calculations for Run-time of the battery

To determine the run-time of the battery pack required to run a 250W DC motor for an E-bicycle, first we need to determine current require to run the motor-

Voltage required by motor to operate = 24V

$\therefore I_{rated} = \frac{250}{24}\ A$

$= 10.41$ A

To fabricate the prototype, we have used 24V Li-ion battery pack with capacity of 18 Ah.

Now, runtime of the battery = $\frac{Capacity\ of\ battery}{Irated}$ hours

$= \frac{18}{10.41}$

$= 1.72$ hours

V. Working Principle of Proposed Model

The proposed hybrid electric bicycle system employs a series-parallel configuration of four solar panels, generating an output power of 40W at 24V. A PWM solar charge controller acts as a crucial interface between the solar array and the battery, ensuring efficient energy transfer to the e-bike's

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controller and motor. The controller is responsible for managing motor operations—including speed regulation, starting, and stopping—by connecting the battery, motor, throttle, and braking system.
Upon connection, the controller supplies voltage to external components. It interprets throttle input to generate a PWM waveform, which modulates the MOSFET, effectively controlling the motor's speed.
The permanent magnet DC motor (PMDC) serves as the prime mover, converting electrical energy into mechanical energy and transferring it to the bicycle wheels through a chain drive system comprising two sprockets linked by a chain. This design ensures efficient power transmission, facilitating smooth movement of the bicycle.
Additionally, the brake lever plays a dual role: it applies friction to decelerate the wheel while simultaneously signaling the controller to deactivate the motor, enhancing safety. This integrated approach allows for comprehensive analysis of operational metrics, such as travel time, range, and overall performance of the e-bike prototype. By leveraging renewable energy and advanced control systems, this model exemplifies a sustainable and efficient solution for modern transportation needs (see Figure 9).

Figure 9: E-Bike System Overview

VI. Results and Discussion

The implementation of a solar-powered bicycle model demonstrates significant potential for sustainable transportation. The primary outcome of the project is the effective integration of solar energy to enhance the bicycle's range and efficiency. With four 10W solar panels configured to deliver 24V, the system allows for real-time battery charging, promoting longer rides without frequent dependence on grid electricity [14][16]. This feature is particularly beneficial for users in remote or off-grid locations, providing an independent mobility solution.
Despite these advantages, the model faces several challenges. One of the main issues is the limited power generation capacity of solar panels, primarily due to their small surface area on bicycles. This constraint can result in insufficient energy collection during cloudy or rainy days, potentially affecting the overall performance and range [16]. Moreover, the additional weight from solar panels and the necessary mounting equipment can impact the bicycle's handling and acceleration, making it less appealing for performance-oriented riders. Cost is another significant barrier; high-quality solar panels and associated components can be expensive, which may deter potential users from adopting this technology. Additionally, the durability of solar panels is a concern, as they must withstand outdoor elements and vibrations, which may require regular maintenance or replacements.
Future enhancements could address these challenges by incorporating lightweight, high-efficiency solar technologies and more robust battery management systems. Innovations in flexible solar panels may also reduce weight and improve integration with bicycle frames. Furthermore, developing

community charging stations or hybrid systems that combine solar energy with traditional power sources could mitigate issues related to weather dependency.

Overall, while the solar-powered bicycle model presents exciting opportunities for eco-friendly transport, addressing these challenges is essential for widespread adoption and user satisfaction. Continued research and development in this field will be crucial to optimize performance and accessibility.

VII. Conclusion

Based on the discussion and testing conducted on electric bicycles equipped with solar panels, several key conclusions can be drawn. First, the performance of these solar-integrated bicycles has proven satisfactory, showcasing a successful blend of solar power and bicycle functionality. The solar panels effectively charged the battery, completing a full charge in approximately 16 hours and 45 minutes. This charging efficiency highlights the practicality of using solar energy for sustained operation, in addition to the option of utilizing a home charging supply when needed. The bicycle achieved a maximum speed of 25 km/h and covered a distance of 43 km while carrying a load of 60 kg, aligning with performance expectations. However, it's essential to note that the rider's weight can affect mileage and travel time, as heavier riders may experience reduced efficiency. In summary, the integration of solar panels in electric bicycles not only meets performance criteria but also demonstrates their capability to function effectively in real-world conditions. These findings underscore the feasibility of solar-powered electric bicycles, offering insights into their potential for sustainable transportation. Future advancements in solar technology and battery management could further enhance their performance and broaden their applications.

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