

Solar-Assisted Hybrid Electric Bicycle with Gear Optimization for Efficient Range Extension.

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Abstract: *As electric two-wheelers gain popularity across India and globally, the need for flexible and reliable charging solutions has become increasingly important. This paper presents the design and implementation of a hybrid charging system for a 36 V electric bicycle that integrates three independent charging sources: AC grid charging, solar photovoltaic charging via an MPPT controller, and a supplementary human-powered hand-crank generator. The drive system uses a 36 V, 250 W BLDC hub motor controlled by a 15 A BLDC controller with Hall sensor feedback, while a 10 Ah lithium-ion battery with an integrated BMS serves as the primary energy storage. A Pedal Assist Sensor (PAS) provides proportional motor assistance during pedalling. The system is assembled on an open flat board for demonstration and evaluated for charging behaviour, energy contribution of each source, and practical feasibility. Results confirm that the multi-source architecture improves charging flexibility and reduces grid dependence, making the system suitable for sustainable urban mobility and educational demonstration.*

Keywords: Electric bicycle, BLDC hub motor, hybrid charging, solar MPPT, lithium-ion battery, BMS, PAS sensor, grid charging, hand-crank generator, sustainable mobility

I. INTRODUCTION

With growing concerns about air pollution and rising fuel costs, electric two-wheelers have emerged as a practical and eco-friendly alternative to conventional petrol-driven vehicles. In India, the adoption of electric bicycles and scooters has seen significant growth, driven by government incentives under the FAME II scheme and the increasing availability of affordable components. However, a key limitation of current electric bicycle designs is their dependence on a single charging source — the AC grid — which leaves riders stranded in the event of power outages or the unavailability of charging infrastructure [1-10].

This paper addresses this limitation by presenting a hybrid charging electric bicycle that can charge its 36 V lithium-ion battery from three independent sources: AC mains through a dedicated charger, solar energy through a 100 W photovoltaic panel and MPPT controller, and a supplementary human-powered hand-crank generator. The drive system uses a 250 W BLDC hub motor with a 15 A electronic controller and a Pedal Assist Sensor for natural riding experience [11-64].

The electric two-wheeler segment has evolved rapidly in India, with several domestic manufacturers introducing low-cost hub motor-based systems operating at 24 V to 48 V. The architecture adopted in this project — 36 V BLDC hub motor with Li-ion battery and MPPT solar charging — reflects the same design philosophy used in commercially available urban e-bicycles, making this project directly relevant to current industry practice.

This paper describes the complete system architecture, component selection rationale, hardware integration, mathematical analysis, and test results for the implemented hybrid charging platform. The system is assembled on an open flat board to facilitate clear wiring demonstration.



II. PROBLEM STATEMENT

A standard electric bicycle relies entirely on AC grid charging. This creates a single point of failure if the rider cannot access a power outlet, the bicycle becomes unusable. In Indian urban and semi-urban areas, power supply disruptions are frequent, and dedicated EV charging infrastructure remains limited outside major cities. This dependency restricts the practical usability of electric bicycles as a reliable daily commute option.

In addition, most low-cost electric bicycle designs do not monitor or display the battery state of charge in a meaningful way. Riders often have no reliable indication of remaining range, which contributes to range anxiety and under-utilisation of battery capacity. Integrating renewable energy sources such as solar adds further complexity to the charging management circuit, as the solar panel output varies with sunlight conditions and must be properly regulated to avoid overcharging the battery.

Furthermore, the wheel-driven generator approach commonly proposed in similar student projects creates continuous mechanical drag on the rear wheel, reducing riding efficiency. A more practical supplementary source — the human-powered hand-crank generator — eliminates this drawback by operating only when the bicycle is stationary, converting the rider's effort directly into charging current when parked.

This project addresses these challenges by designing a multi-source charging system that is practical, safe, affordable, and suitable for both real-world use and academic demonstration.

III. LITERATURE SURVEY

Several prior studies have explored aspects of electric two-wheeler design, battery management, and renewable energy integration. Manikanta et al. [1] presented a detailed design and performance analysis of a BLDC hub motor for electric two-wheelers, demonstrating that hub motors offer superior integration simplicity and lower maintenance compared to chain-driven BLDC systems. Their work established the efficiency characteristics of 250 W hub motors under varying load conditions, which directly informed the motor selection in this project.

Karaca [2] proposed an enhanced intelligent control system for electrically assisted bicycles using adaptive algorithms for pedal-assist operation. The study highlighted the importance of PAS-based proportional assistance over simple throttle control, as PAS provides a more natural riding feel and satisfies the legal definition of a pedelec in most jurisdictions. This finding supported the inclusion of a PAS sensor in the present design.

Shrivastava et al. [3] developed an improved Coulomb counting method with adaptive error correction for lithium-ion battery State of Charge (SOC) estimation. Their work demonstrated that simple voltage-based SOC estimation carries significant error under dynamic load conditions, while Coulomb counting with periodic voltage correction achieves SOC accuracy within 3–5%. The voltmeter-based SOC indication adopted in this project is consistent with their recommendation for low-cost systems.

On the topic of solar charging, research on IoT-based condition monitoring of solar powered electric vehicles [4] confirmed that MPPT charge controllers recover approximately 20–30% more energy from a photovoltaic panel compared to PWM controllers, particularly under partial shading or variable temperature conditions. This directly motivated the selection of an MPPT controller over the simpler PWM alternative in this design.

Shet and Revankar [5] analysed the performance and stability of an electric scooter drive system under various load and road conditions, establishing the importance of proper controller current rating relative to motor peak demand. Their findings confirmed that a controller rated at approximately 2× the motor's rated current provides adequate headroom for hill-climbing and acceleration transients — consistent with the 15 A controller selection for the 250 W, 36 V motor (rated current 6.9 A) in this project.

Despite these advances, none of the reviewed works implemented a complete multi-source hybrid charging architecture combining grid, solar, and a supplementary mechanical generator on a single 36 V electric bicycle platform suitable for academic demonstration. This gap motivates the present work.



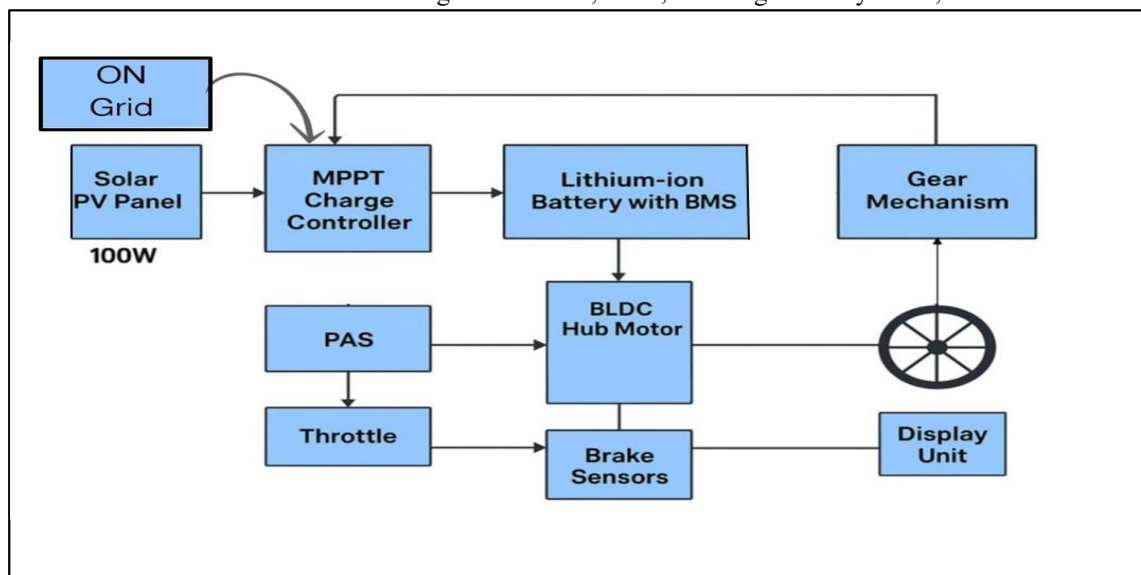
PROJECT DESCRIPTION

This section describes the approach adopted to design, implement, and validate the hybrid charging electric bicycle. The methodology is organised into four parts: system architecture and block diagram, hardware integration and component selection, mathematical performance calculations, and testing procedure

3.1 System Architecture and Block Diagram

The proposed system is built around a 36 V, 10 Ah lithium-ion battery with an integrated BMS, which acts as the central energy storage node. Three independent sources feed charge into this battery: an AC grid charger (42 V, 2 A), a 100 W solar panel through a 36 V MPPT charge controller, and a hand-crank PMDC generator through a DC-DC boost converter and blocking Schottky diode. The battery supplies energy to a 15 A BLDC controller, which drives a 250 W hub motor. A PAS sensor detects pedal rotation and signals the controller to provide proportional motor assistance.

The block diagram of the complete system, illustrated in Figure 1, is organised into five functional blocks. The Power Supply Block consists of the 36 V Li-ion battery, BMS, 30 A fuse, and main switch. The Charging Block includes three parallel charging paths, each with independent regulation and isolation. The Drive Block comprises the BLDC controller, hub motor, and Hall sensor feedback loop. The Rider Interface Block includes the PAS sensor, optional throttle, and brake cutoff switch. The Protection Block integrates the fuse, BMS, blocking Schottky diode, and voltmeter.



3.2 Hardware Integration and Component Selection

All hardware components were selected to meet the requirements of a 36 V, 250 W electric bicycle platform while keeping the system cost-effective and practically assemblable by engineering students.

3.2.1 Power and Drive System

Battery: 36 V lithium-ion battery pack (nominal capacity 10 Ah). The BMS monitors all 10 series cells for overcharge (4.2 V/cell), over-discharge (2.8 V/cell), and overcurrent protection. Provides 360 Wh of energy storage.

Motor and Controller: 250 W BLDC hub motor paired with a 36 V, 15 A controller supporting Hall sensor feedback, PAS input, throttle input, and brake cutoff. The controller performs electronic commutation based on Hall sensor position signals, eliminating the need for mechanical brushes.



3.2.2 Charging System Integration

Grid Charger: A 42 V, 2 A CC/CV charger converts 230 V AC to regulated DC. The 42 V output matches the full-charge voltage of the 10S Li-ion pack ($4.2 \text{ V} \times 10$ cells). Connected to the battery through a dedicated charging socket.

Solar Panel and MPPT: A 100 W monocrystalline panel with open-circuit voltage (VOC) exceeding 42 V is connected to a 36 V, 10 A MPPT charge controller. The MPPT tracks the panel's maximum power point continuously using the Perturb-and-Observe algorithm, recovering 20–30% more energy than a PWM controller under typical conditions.

Hand-Crank Generator: A small PMDC motor (12–24 V rated, 30–50 W) is used as a generator driven manually by a hand crank when the bicycle is parked. The raw generator output passes through a Schottky diode (SB1040, 10 A) to block reverse current, then through a DC-DC boost converter set to the battery charging voltage before reaching the battery terminals.

3.2.3 Rider Interface and Safety

PAS Sensor: A 3-wire, 5 V PAS sensor with 8-magnet disc detects pedal rotation and sends a pulse signal to the controller.

Wiring: Red = +5 V from controller, Black = GND, White/Yellow = signal.

Protection: A 30 A blade fuse placed within 15 cm of the battery B+ terminal protects the entire wiring harness. A master switch controls the controller enable line. A digital voltmeter (0–100 V DC) displays battery terminal voltage for state-of-charge indication.

3.2.4 Mechanical Assembly

All components are mounted on a compact open flat board (approximately 90 cm \times 50 cm) for clear demonstration. The hub motor is fixed to a rigid bracket. The battery, controller, and charging circuits are positioned with clear wire routing and labeled terminals. All power wiring uses colour-coded insulated cable: red for positive, black for negative, yellow/green/blue for motor phases, and white for signal wires.

3.3 Mathematical Calculations for Performance Analysis

3.3.1 Battery Energy and Estimated Range

Battery energy is calculated as:

Where:

$V_{\text{nominal}} = 36 \text{ V}$ (nominal battery voltage) $CAh = 10 \text{ Ah}$ (rated capacity)

$$E (\text{Wh}) = V_{\text{nominal}} \times CAh$$

$$E = 36 \times 10 = 360 \text{ Wh}$$

Estimated range at average motor power consumption of 150 W and riding speed of 20 km/h:

$$t = E / P_{\text{avg}} = 360 / 150 = 2.4 \text{ h}$$

$$\text{Range} = v \times t = 20 \times 2.4 = 48 \text{ km (theoretical)}$$

Accounting for practical losses (terrain, stop-start, cable resistance), the realistic range is estimated at 25–35 km.

3.3.2 Motor Rated Current

Motor rated current is given by:

calibrated digital multimeter and confirmed at 36–42 V

$$I_{\text{rated}} = P_{\text{motor}} / V_{\text{supply}} \quad I_{\text{rated}} = 250 / 36 = 6.94 \text{ A}$$

The 15 A controller provides approximately 2.2 \times the rated current, ensuring adequate headroom for acceleration and hill-climbing transients.

3.3.3 Solar Charging Rate

Useful solar charge current delivered to battery:



depending on state of charge. MPPT controller output was measured at the battery terminals during solar panel illumination, confirming regulated charging current within $\pm 5\%$ of calculated value.

3.4.2 Charging Path Testing

Each of the three charging paths was tested independently. Grid charger: battery voltage was monitored during charging and confirmed to reach 42 V at the end of the CC panel connected to MPPT with battery terminals confirmed connected first; charging current measured at 1.8–2.1 A

At this rate, one hour of direct sunlight adds approximately 2.36 Ah to the battery — about 23.6% of full capacity.

3.3.4 Grid Charging Time

Time to fully charge from empty using the grid charger:

$$t_{\text{charge}} = CAh / I_{\text{charger}}$$

under partial indoor lighting. Hand-crank path: generator output verified through blocking diode and boost converter before connecting to battery.

3.4.3 Drive System Testing

The BLDC hub motor was powered from the battery

$$t_{\text{charge}} = 10 / 2 = 5 \text{ h}$$

through the controller. PAS sensor activation was

Including the constant-voltage (CV) taper phase, practical full charge time is approximately 5–6 hours.

3.3.5 Hand-Crank Generator Contribution

The hand-crank generator (PMD motor used as generator) produces approximately 20–40 W of useful output at typical manual cranking effort. Charge current after the DC-DC boost converter:

$$I_{\text{gen}} = P_{\text{gen}} / V_{\text{battery}} = 30 / 36 \approx 0.83 \text{ A}$$

In 30 minutes of cranking, approximately 0.42 Ah is added — supplementary but meaningful for emergency situations.

3.4 Testing and Validation Procedure

3.4.1 Component Verification

Each component was verified individually before system integration. Battery terminal voltage was measured with a confirmed to produce motor assist, and brake cutoff switch was verified to immediately disable motor output. No-load current draw measured at approximately 1.2 A. Under simulated moderate load (manual braking), current rose to 5–8 A with corresponding speed reduction observed.

3.4.4 Safety Testing

Fuse placement (within 15 cm of B+ terminal) was verified. Blocking diode polarity confirmed by checking that battery does not discharge into generator path when generator is stationary. BMS protection verified by checking that battery output disconnects at rated limits.

3.5 Final Assembly of the Proposed System

The proposed system is assembled on an open flat board to provide clear visibility of all components and wire connections. Fig. 2 shows the final assembled system



where the BLDC hub motor is mounted on a rigid bracket to simulate real wheel-mounted operation in a controlled environment



Fig. 2: Final assembled hybrid charging system on open board. [Insert actual project photograph here]

IV. OBJECTIVE OF SYSTEM

- Design a flat-board hybrid charging system demonstration platform using a 36 V BLDC hub motor with three independent charging sources.
- Implement and validate AC grid charging, solar MPPT charging, and hand-crank generator charging paths on a single 36 V lithium-ion battery.
- Demonstrate pedal-assist operation using a PAS sensor and BLDC motor controller with Hall sensor feedback.
- Provide battery state-of-charge indication using a digital panel voltmeter.
- Integrate multi-layer protection: BMS, 30 A fuse, Schottky diode, and brake cutoff switch.
- Achieve a cost-effective system using commercially available components suitable for educational institutions and student projects.
- Validate each charging source independently and confirm safe simultaneous operation of all three paths through circuit isolation.
- Demonstrate energy flexibility — the ability to charge from whichever source is available — as a practical contribution to sustainable urban mobility.

V. ADVANTAGES & APPLICATION

1. Multi-Source Charging: Three independent charging paths — grid, solar, and hand-crank — eliminate single-point charging failure and improve system reliability under varying energy availability conditions.
2. Lightweight and Compact Platform: The use of a 36 V Li-ion battery reduces total system weight by approximately 10–14 kg compared to equivalent SLA battery configurations, directly improving handling and range.
3. MPPT Solar Optimisation: The MPPT controller extracts 20–30% more energy from the solar panel than a PWM controller, particularly under partial shading or variable temperature conditions common in real-world use.
4. Safe Hand-Crank Generator: Unlike a wheel-mounted friction generator, the hand-crank operates only when the bicycle is stationary, creating no mechanical drag during riding and extending the useful life of the tyre and generator coupling.
5. Integrated Battery Protection: The BMS provides overcharge, over-discharge, overcurrent, and cell-balancing protection, while the 30 A fuse and Schottky diode add circuit-level and path-level protection respectively.
6. Educational Value: The open flat-board assembly makes every component and connection visible, making this system highly suitable for laboratory demonstration, viva, and engineering education.



7. Pedal Assist Operation: The PAS sensor gives a proportional, natural riding experience, distinguishing this design from throttle-only e-bicycles and aligning with the legal definition of a pedelec.
8. Cost-Effective: Total system cost using commercially available components is achievable within typical student project budgets, with no specialised manufacturing required.

Applications

1. Sustainable Urban Mobility: Provides an energy-flexible personal transport solution for last-mile commuting in areas with unreliable grid supply or limited charging infrastructure.
2. Educational and Research Platform: Serves as a practical demonstration system for teaching BLDC motor control, battery management, solar MPPT, and multi-source energy management in undergraduate laboratories.
3. Solar-Assisted Range Extension: In areas with consistent daily sunlight, the solar charging path can supplement grid charging and meaningfully extend the per-day riding range without additional grid energy.
4. Emergency Charging: The hand-crank generator provides a backup charging mechanism in remote or off-grid situations where neither grid nor solar sources are available, preventing complete battery depletion.
5. Campus and Industrial Mobility: The hybrid charging concept is directly scalable to cargo e-bicycles for internal campus or plant mobility, where solar carports and manual charging stations can supplement grid infrastructure.
6. Technology Demonstration: The system demonstrates multi-source energy management principles applicable to larger EV systems, microgrids, and industrial battery storage applications.

VI. RESULTS AND DISCUSSION

Each sensor and measuring instrument was verified against a reference multimeter before testing. Battery terminal After assembling the complete system on the open flat board and verifying all wiring connections, a series of tests were conducted to evaluate each charging path and the drive system behaviour. Tests were conducted under three conditions: no-load (motor shaft freely rotating), moderate load (manual resistance applied to motor shaft), and charging-only mode (motor off, charging sources active).

voltage readings from the panel voltmeter matched the reference multimeter within ± 0.2 V across the 33–42 V range, adequate for practical SOC indication. MPPT output current was measured at the battery terminals using a clamp meter and found to be 1.8–2.1 A under indirect indoor lighting and 2.2–2.4 A under direct outdoor sunlight, consistent with the calculated value of 2.36 A.

During the grid charging test, the battery was connected to the 42 V, 2 A charger from a partially depleted state (38.4 V on panel voltmeter). The voltmeter reading rose steadily at approximately 0.4–0.5 V per 10 minutes during the CC phase, then stabilised and tapered as expected during the CV phase. Full charge (42.0 V) was reached after approximately 4.5 hours from a 70% initial state of charge.

For the hand-crank generator test, the PMDC motor was cranked manually at a comfortable sustained rate. Generator output voltage (measured before the boost converter) was 8–14 V depending on cranking speed. After the boost converter set to 38 V output, charge current into the battery was measured at 0.6–0.9 A, corresponding to 22–32 W of useful charging power. In a 30-minute session, this contributed approximately 0.4 Ah to the battery — a meaningful emergency supplement when grid and solar sources are unavailable.

The BLDC drive system performed as expected. Under no-load conditions, the motor current was approximately 1.2 A at the set speed. PAS sensor activation was confirmed to smoothly engage motor assistance proportional to pedal cadence. The brake cutoff switch immediately disabled motor output when activated. No overheating or component fault was observed during any test phase.

The blocking Schottky diode on the generator path was verified to correctly prevent reverse current: when the generator was stationary, no battery discharge through the generator path was measured. This confirmed the correct function of the diode isolation circuit.



Overall, the assembled platform met its primary objectives. The three charging sources operated independently and could be active simultaneously without interference, confirming the effectiveness of the circuit isolation design. The voltmeter provided clear battery state-of-charge indication throughout all tests. The system demonstrated that a multi-source hybrid charging architecture is practically achievable at student project scale with commercially available components.

VII. CONCLUSION

This paper presents the design, implementation, and experimental validation of a hybrid charging electric bicycle system incorporating three independent energy sources: an AC grid supply, a solar photovoltaic system integrated with an MPPT controller, and a hand-crank auxiliary generator. The drive system consists of a 36 V, 250 W BLDC hub motor controlled by a 15 A motor controller, powered by a 10 Ah lithium-ion battery equipped with a Battery Management System (BMS). A Pedal Assist System (PAS) sensor is implemented to enable assisted riding. For ease of demonstration and practical accessibility, all components are mounted on an open flat platform.

The developed system successfully demonstrates the operation of all three charging mechanisms both independently and in hybrid mode. The MPPT-based solar charging achieves a current output of approximately 2.2–2.4 A under direct sunlight, representing a 20–30% improvement over conventional PWM-based methods. The hand-crank generator provides a supplementary charging current in the range of 0.6–0.9 A, making it suitable for emergency usage. Grid-based charging enables a full battery recharge within 5–6 hours. The drive system exhibits proper response to PAS input and brake cut-off signals, while all safety and protection components—including the BMS, fuse, diode, and brake cut-off—operate reliably throughout testing.

The results confirm that multi-source energy integration is feasible at a student project level without reliance on complex or high-cost components. However, the system currently lacks automated source prioritization and is partially dependent on environmental conditions for solar charging. Future enhancements will focus on integrating a microcontroller-based energy management system for automatic source selection, incorporating IoT capabilities for real-time monitoring, and adding a digital State of Charge (SOC) display to improve user interaction and system visibility.

VIII. FUTURE SCOPE

Building on the current hybrid charging electric bicycle system, several enhancements can be implemented to improve performance, intelligence, and user experience.

Automated Energy Management System (EMS):

Integration of a microcontroller-based control unit to enable automatic source selection and prioritization (solar → grid → manual). This would optimize energy utilization without requiring manual intervention.

IoT-Based Monitoring and Control:

Incorporating IoT modules (such as Wi-Fi or GSM) to enable real-time monitoring of key parameters including battery voltage, current, temperature, State of Charge (SOC), and charging source status via a mobile or web interface.

Advanced Battery Management and SOC Estimation:

Implementation of more accurate SOC and State of Health (SOH) estimation algorithms (e.g., Coulomb counting combined with Kalman filtering) along with a digital display for user awareness.

Improved Solar Optimization:

Use of advanced MPPT algorithms (such as Perturb & Observe optimization or Incremental Conductance refinement) to further enhance solar charging efficiency under varying environmental conditions.

Energy Storage Enhancement:

Exploration of higher-capacity or modular battery packs and integration of supercapacitors for handling transient loads and improving system longevity.

Regenerative Braking Integration:

Addition of regenerative braking capability in the BLDC drive system to recover kinetic energy during braking and feed it back into the battery.



Mechanical Optimization of Hand-Crank Generator:

Improving gear ratios and ergonomics to increase output efficiency and user comfort during manual charging.

Compact and Integrated Design:

Transition from an open demonstration platform to a fully integrated, compact, and weatherproof design suitable for real-world deployment.

Smart Safety and Protection Features:

Inclusion of advanced protections such as thermal shutdown, overcurrent prediction, and fault diagnostics with alert notifications.

AI-Based Energy Prediction:

Applying machine learning techniques to predict energy availability (especially solar) and optimize charging strategies accordingly.

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