



Design and Performance Analysis of Solar Based Vehicle

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Abstract

The growing demand for sustainable transportation and the depletion of fossil fuel reserves have collectively intensified interest in solar-powered vehicles. This paper presents the comprehensive design, fabrication, and performance analysis of a solar-based vehicle prototype that utilizes photovoltaic (PV) panels to convert solar energy into electrical energy for vehicular propulsion. The integrated system employs monocrystalline solar panels rated at 300W ($2 \times 150W$), a 20A Maximum Power Point Tracking (MPPT) charge controller, a 48V 26Ah lithium-ion battery storage system, and a 750W Brushless DC (BLDC) hub motor. Extensive performance tests were conducted under varying solar irradiance conditions in Central India (Bhopal, 23.25°N latitude) during March 2024. Experimental results demonstrate that the prototype achieves a maximum speed of 28 km/h with an operational range of 45–55 km under ideal solar irradiance conditions and 35–40 km without direct solar input. The system shows an estimated payback period of approximately 4.2 years when compared against conventional petrol scooters for a 30 km daily usage pattern. Challenges pertaining to PV energy density, weather dependency, initial cost, and payload capacity are critically examined. Future improvements including lightweight composite materials, vehicle-integrated photovoltaics (VIPV), Perovskite solar cells, and IoT-based energy monitoring systems are also discussed.

Keywords: solar vehicle, photovoltaic cells, MPPT, BLDC motor, renewable energy, sustainable transport, lithium-ion battery, energy efficiency

I. INTRODUCTION

The transportation sector is one of the most significant contributors to global greenhouse gas emissions, accounting for nearly 24% of all CO₂ emissions from fuel combustion worldwide [1]. With fossil fuel reserves facing accelerated depletion and global energy costs continuing to rise, the transition toward renewable energy-based transportation systems has become not merely desirable but critically necessary. Among the available renewable resources, solar energy stands out as particularly promising for transportation applications due to its universal availability and zero-emission characteristics.

India presents an exceptionally favorable environment for solar-based transportation. With more than 300 clear sunny days annually and average solar irradiance levels exceeding 5 kWh/m²/day across most of the country, India possesses some of the highest solar energy potential globally [2]. The Indian government, through the Ministry of New and Renewable Energy (MNRE), has actively promoted solar energy integration in the transport sector as part of its broader Nationally Determined Contributions (NDCs) under the Paris Agreement.



Solar vehicles represent a direct and elegant solution to the dual challenges of fossil fuel dependence and vehicular pollution. These vehicles convert sunlight to electricity using photovoltaic cells integrated into or mounted upon the vehicle structure, thereby offering zero tailpipe emissions and significantly reduced operational costs. For short-distance urban and peri-urban applications — such as campus transport, last-mile connectivity, and municipal service vehicles — solar-electric vehicles offer a particularly compelling value proposition.

The primary objective of this research is to design, fabricate, and experimentally evaluate a low-cost solar vehicle prototype optimized for short-distance urban transport under Indian climatic conditions. The scope of investigation is deliberately limited to lightweight, low-speed vehicles suitable for campus mobility and last-mile transport applications, where speed requirements are modest but reliability, cost-effectiveness, and environmental performance are paramount.

This paper is organized as follows: Section II reviews the relevant prior literature on solar vehicle technology, MPPT charge controllers, and BLDC motor selection. Section III details the system methodology including component selection, working principle, and design calculations. Section IV presents and discusses experimental results. Section V addresses key challenges and limitations. Section VI concludes the paper and outlines future research directions.

II. LITERATURE REVIEW

A substantial body of research has established the technical and economic viability of solar-assisted electric vehicles across varying geographic and climatic contexts. The following review synthesizes the most pertinent findings relevant to the present work.

A. Solar Energy Yield in Indian Conditions

Sharma, Gupta, and Verma [3] conducted a systematic evaluation of solar-assisted electric vehicles under Indian meteorological conditions. Their study established that a 300W solar panel configuration, when deployed on a lightweight vehicle chassis, is capable of providing an operational range of 40–50 km per day under typical Indian solar conditions. This finding is particularly significant given India's high solar irradiance values and positions solar vehicles as a viable solution for daily short-distance commuting without grid-based recharging.

B. MPPT vs. PWM Charge Controllers

The selection of an appropriate charge controller is critical to the overall energy efficiency of a solar vehicle system. Patel and Singh [4] conducted a comprehensive comparative analysis of MPPT (Maximum Power Point Tracking) and PWM (Pulse Width Modulation) charge controller topologies for solar vehicle applications. Their findings demonstrated that MPPT controllers consistently outperform PWM controllers in terms of energy harvest efficiency, with MPPT delivering a 20–25% improvement in power extraction across varying irradiance and temperature conditions. The performance advantage of MPPT is most pronounced under partial shading conditions and during the low-irradiance periods characteristic of early morning and late afternoon operation.



C. BLDC Motor Selection for Traction Applications

Kumar [5] systematically compared available electric motor technologies for solar vehicle traction applications, including permanent magnet DC motors, induction motors, and BLDC motors. The analysis conclusively identified BLDC motors as the preferred choice for this application category, primarily on account of their demonstrated efficiency range of 85–90%, their favorable torque-to-weight ratio, and their maintenance-free operation due to the absence of mechanical brushes. Hub-mounted BLDC configurations were specifically recommended for lightweight vehicle applications as they eliminate the drivetrain losses associated with conventional differential and gearbox arrangements.

D. Hybrid Solar-Battery Energy Systems

Zhang et al. [6] examined hybrid energy system architectures for solar-powered transport platforms. Their research established that standalone solar-only propulsion systems are inherently limited by the intermittency of solar radiation, particularly under cloudy conditions, during nighttime operation, and in periods of peak demand that exceed instantaneous solar generation capacity. The authors concluded that hybrid solar-battery systems, wherein photovoltaic generation is coupled with electrochemical battery storage, have become the de facto standard approach for reliable solar vehicle operation. Such hybrid architectures enable the vehicle to operate even in the absence of direct solar irradiance, drawing on stored energy from the battery while simultaneously recharging whenever sufficient solar input is available.

III. METHODOLOGY

A. System Components

The solar vehicle prototype was designed as an integrated electromechanical system comprising five primary subsystems: the photovoltaic array, the MPPT charge controller, the lithium-ion battery bank, the BLDC motor and controller, and the vehicle chassis. The specifications of each subsystem are detailed below and summarized in Table I.

TABLE I: System Component Specifications

| Component | Parameter | Specification |
|-----------------|------------------|--------------------------|
| PV Array | Configuration | 2 × 150W Monocrystalline |
| | Voltage | 18V per panel |
| | Panel Efficiency | 19% |
| MPPT Controller | Current Rating | 20A |
| | Voltage Range | 12/24/48V Auto-select |
| | Peak Efficiency | 97% |
| Battery | Nominal Voltage | 48V |
| | Capacity | 26Ah (1248Wh) |
| | Chemistry | Lithium-ion |



| | | |
|------------|-------------------|--------------------------|
| BLDC Motor | Power Rating | 750W |
| | Operating Voltage | 48V |
| | Motor Type | Hub motor |
| Chassis | Material | Mild steel tubular frame |
| | Kerb Weight | 150 kg |

The photovoltaic array consists of two monocrystalline silicon panels rated at 150W each, providing a combined peak generation capacity of 300W. Monocrystalline technology was selected over polycrystalline alternatives due to its superior conversion efficiency (19%) and better performance under high-temperature conditions, both of which are critical considerations for vehicle-mounted applications in Central India.

The battery system employs a 48V 26Ah lithium-ion pack with a total energy capacity of 1,248 Wh. Lithium-ion technology was preferred over conventional lead-acid batteries due to its significantly higher energy density (approximately 150–200 Wh/kg versus 30–50 Wh/kg for lead-acid), lower self-discharge rate, and superior cycle life (>1,000 cycles to 80% capacity versus 300–500 cycles for lead-acid).

B. System Working Principle

The power flow architecture of the solar vehicle operates as follows: during daylight hours, the monocrystalline PV panels generate DC electricity proportional to the incident solar irradiance. This output is fed to the 20A MPPT charge controller, which continuously tracks the maximum power point of the PV array using a Perturb and Observe (P&O) algorithm to ensure maximum energy extraction regardless of variations in irradiance or panel temperature.

The MPPT controller regulates the optimized DC output to charge the 48V lithium-ion battery bank while simultaneously supplying the BLDC motor controller. The motor controller converts the DC battery voltage to the variable-frequency, variable-voltage AC waveform required to drive the hub motor at the desired speed and torque. During periods of peak solar irradiance, the PV panels directly supplement the motor's power requirement, with any surplus generation directed toward battery charging. During low-irradiance or night-time conditions, the motor draws exclusively from the stored battery energy.

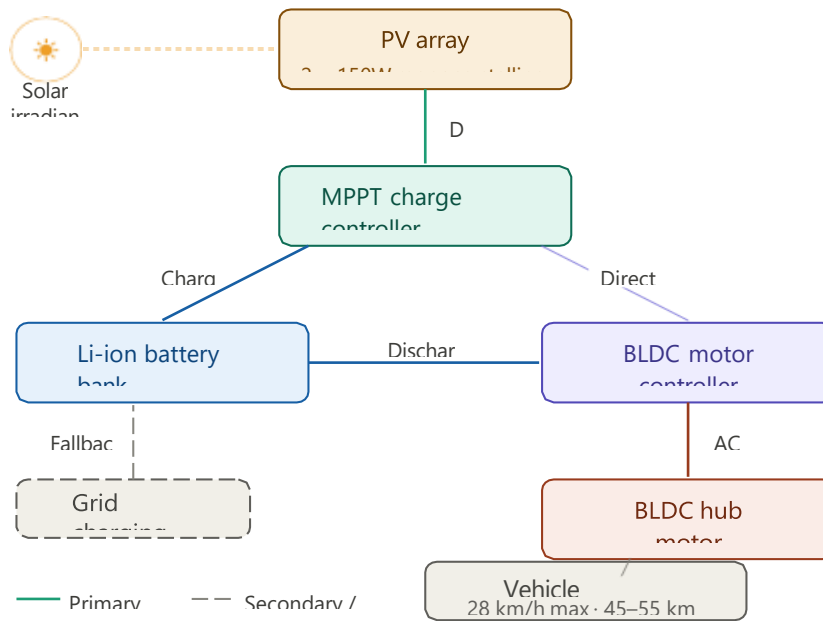


Fig. 1. System architecture and power flow of the solar vehicle prototype.

C. Design Calculations

The vehicle's traction power requirement was calculated based on the total loaded mass, target speed, and rolling resistance coefficient of the terrain. For a total loaded mass of 220 kg (150 kg vehicle kerb weight + 70 kg rider) operating at a target speed of 25 km/h (6.94 m/s) on a flat paved road surface with a rolling resistance coefficient (μ) of 0.05:

$$P = F \times v = \mu \times m \times g \times v = 0.05 \times 220 \times 9.81 \times 6.94 \approx 763 \text{ W}$$

Based on this calculation, a 750W BLDC hub motor was selected, providing a safety factor of approximately 0.98 at the design operating point — sufficient for the intended flat-terrain urban application. For gradient conditions, the battery provides supplementary power.

The daily solar energy budget was calculated based on an average of 5 peak sun hours per day, a total PV capacity of 300W, and a system derating factor of 0.75 (accounting for wiring losses, controller inefficiency, and thermal derating):

$$E_{\text{solar}} = 300\text{W} \times 5\text{h} \times 0.75 = 1,125 \text{ Wh/day}$$

The total daily energy available to the vehicle is the sum of solar-generated energy and stored battery energy:

$$E_{\text{total}} = 1,125 \text{ Wh} + 1,248 \text{ Wh} = 2,373 \text{ Wh}$$

Assuming a vehicle energy consumption of 30 Wh/km (typical for lightweight electric vehicles at low speed), the theoretical maximum range under ideal conditions is:

$$\text{Range} = 2,373 \text{ Wh} \div 30 \text{ Wh/km} \approx 79 \text{ km (theoretical maximum)}$$

The optimal panel tilt angle for Bhopal (latitude 23.25°N) was calculated as equal to the latitude angle (23°), which maximizes annual average solar yield for fixed-tilt installations.



IV. RESULTS AND DISCUSSION

Comprehensive performance testing of the solar vehicle prototype was conducted in Bhopal, Madhya Pradesh (23.25°N, 77.40°E) during March 2024, representing conditions close to the spring equinox with high solar irradiance typical of Central India's pre-summer period. Tests were conducted across multiple days under varying sky conditions to capture the full range of operational performance.

A. Performance Metrics

The key performance parameters measured during field trials are summarized in Table II. The prototype demonstrated a maximum achievable speed of 28 km/h, which is appropriate for the target application of campus and last-mile urban mobility where speed limits typically range from 20–30 km/h.

TABLE II: Experimentally Observed Performance Parameters

| Parameter | Observed Value |
|--------------------------------------|------------------------|
| Maximum Speed | 28 km/h |
| Range (Full Sun Conditions) | 45–55 km |
| Range (Battery Only, No Sun) | 35–40 km |
| Solar Charging Time (Full Cycle) | 6–8 hours |
| Grid Charging Time (Full Cycle) | 3–4 hours |
| Performance Reduction on Cloudy Days | 40–60% |
| Optimal Panel Tilt Angle | 23° (= latitude) |
| Payback Period vs. Petrol Scooter | ~4.2 years (30 km/day) |
| Prototype Cost | ₹85,000–₹1,10,000 |

B. Range Analysis

The measured operational range of 45–55 km under full solar irradiance conditions represents approximately 57–70% of the theoretical maximum range of 79 km calculated in the design phase. This shortfall is attributable to several real-world factors not fully captured in the design calculations: aerodynamic drag (which becomes significant even at modest speeds), drivetrain losses, battery charge/discharge cycle inefficiencies, and variations in solar irradiance throughout the day.

Under battery-only conditions (no solar input), the prototype achieved a range of 35–40 km, which corresponds to an energy consumption of approximately 31–36 Wh/km — consistent with the design assumption of 30 Wh/km and confirming the accuracy of the energy model. The solar contribution therefore adds an incremental range of 10–15 km per day under clear-sky conditions, representing a 25–40% range extension attributable solely to photovoltaic energy harvesting.

C. Weather Dependency

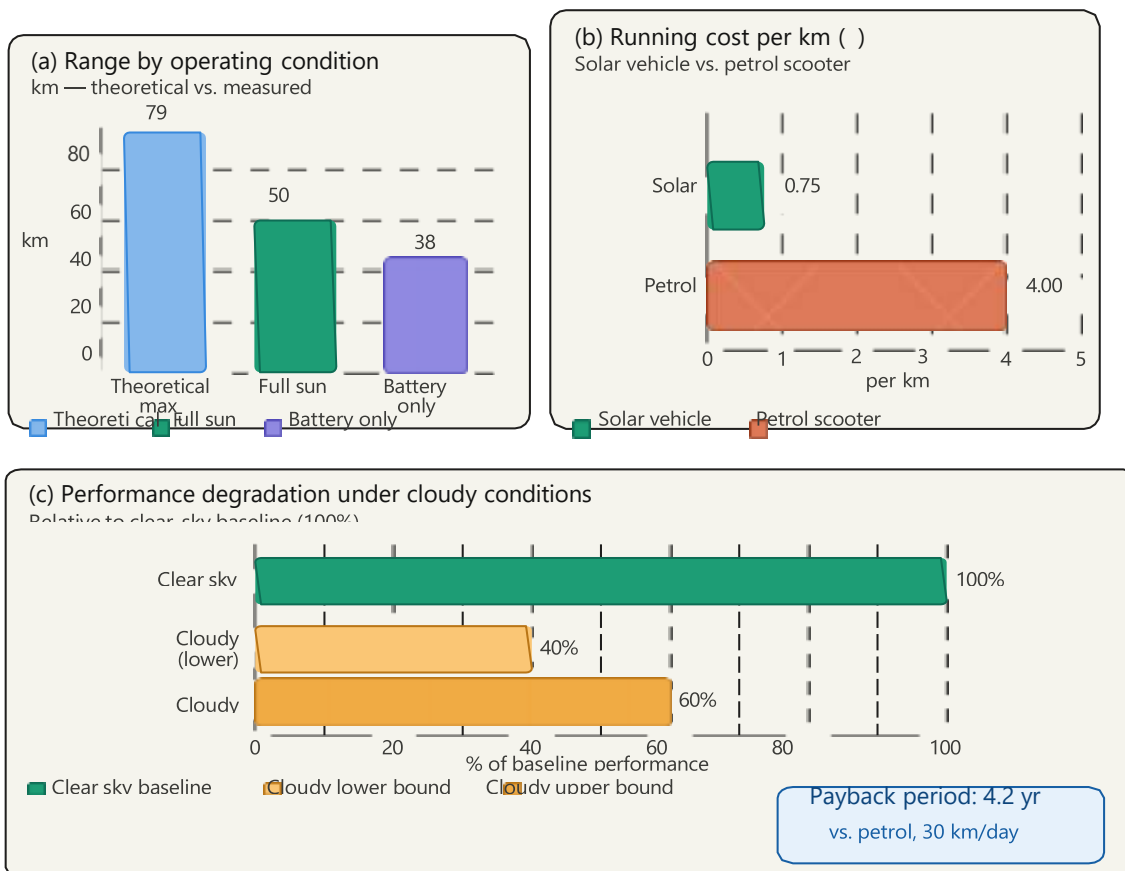
Performance degradation under cloudy conditions was one of the most significant findings of the experimental evaluation. On overcast days, the prototype's performance dropped by

40–60% relative to clear-sky baseline performance. This substantial reduction is primarily due to the reduction in solar irradiance incident on the PV panels: a fully overcast sky typically reduces global horizontal irradiance by 70–90% compared to clear-sky conditions, with the MPPT controller operating at significantly sub-optimal power points as a result.

This weather dependency has important implications for the reliability and utility of the vehicle as a primary transport mode. For users relying on the vehicle for daily commuting over distances at the upper end of the range specification, cloudy periods represent a potential operational constraint. The dual charging capability (solar + grid) mitigates this limitation to a significant degree by allowing overnight grid charging as a fallback when solar generation is insufficient.

D. Economic Analysis

The prototype construction cost ranged from ₹85,000 to ₹1,10,000, representing a significant premium over conventional petrol-powered two-wheelers of comparable capability (approximately ₹60,000–80,000 for entry-level models). However, the substantially lower per-kilometer operating cost of the solar vehicle — estimated at ₹0.5–1.0/km versus ₹3.5–4.5/km for a petrol scooter at prevailing fuel prices — results in an estimated payback period of approximately 4.2 years for a user traveling 30 km daily. This payback period is expected to decline over time as PV panel costs continue to fall and petrol prices rise.



(a) range under varying solar conditions · (b) per-km cost vs. petrol scooter · (c) weather degradation and payback period

Fig. 2. Operational performance and economic comparison of the solar vehicle prototype.

V. CHALLENGES AND LIMITATIONS

Despite the demonstrated technical feasibility and economic viability of the solar vehicle prototype, several significant challenges must be acknowledged and addressed before widespread commercial deployment becomes viable:

- **Low Energy Density of Photovoltaic Panels:** The relatively low energy density of current silicon PV technology necessitates a panel area of 1.8–2.0 m² to achieve the required 300W peak generation capacity. This area constraint limits the architectural flexibility of solar vehicle design and imposes weight penalties on the vehicle structure.
- **Weather and Irradiance Dependency:** The 40–60% performance degradation observed under cloudy conditions fundamentally limits the vehicle's reliability as a standalone daily commute solution in regions with significant cloud cover or during monsoon seasons.
- **High Initial Capital Cost:** The prototype cost of ₹85,000–1,10,000 represents approximately 1.2–1.6× the cost of a comparable conventional two-wheeler, presenting a barrier to adoption for cost-sensitive consumers despite favorable long-term economics.
- **Limited Speed and Payload Capacity:** The maximum speed of 28 km/h and total permissible loaded mass of 220 kg restrict the vehicle's applicability to low-speed urban environments and single-rider or light-cargo applications.
- **Charging Infrastructure and Time:** Solar charging requires 6–8 hours for a full battery cycle under clear-sky conditions, necessitating either overnight solar pre-charging or access to grid charging facilities for users requiring multiple daily charges.

VI. CONCLUSION AND FUTURE SCOPE

This paper has presented the design, fabrication, and comprehensive performance evaluation of a solar-based vehicle prototype integrating monocrystalline PV panels, an MPPT charge controller, a lithium-ion battery bank, and a BLDC hub motor. The experimental results demonstrate the technical feasibility of solar vehicles for short-distance urban transport in Indian conditions, with the prototype achieving a maximum speed of 28 km/h and an operational range of 45–55 km under clear-sky solar conditions.

The system's estimated payback period of approximately 4.2 years relative to conventional petrol scooters at 30 km/day confirms economically viable long-term performance, while the zero tailpipe emission profile aligns with India's national sustainability objectives. The key identified limitations — weather dependency, PV area constraints, initial cost, and range limitations — provide a clear roadmap for future technological improvements.

Future research and development directions for solar vehicle technology include:

- Integration of lightweight composite materials (carbon fiber reinforced polymers, aluminium alloys) for chassis construction to reduce vehicle kerb weight and improve energy efficiency.
- Deployment of Vehicle-Integrated Photovoltaics (VIPV) — flexible, conformal PV cells



embedded in the vehicle body panels — to maximize solar collection area without increasing vehicle footprint.

- Adoption of next-generation Perovskite solar cells, which have demonstrated laboratory efficiencies exceeding 25% and potential for low-cost mass production, to improve energy density per unit area.
- Development of aerodynamically optimized body designs to reduce drag losses and extend range at higher speeds.
- Implementation of IoT-based energy monitoring and management systems for real-time tracking of battery state-of-charge, solar generation, and predictive range estimation.
- Hybrid charging architectures combining solar, grid, and regenerative braking energy recovery to maximize system reliability and range under diverse operating conditions.

ACKNOWLEDGMENT

The author gratefully acknowledges the support of the KNP College of Science and Technology, Bhopal, for providing laboratory facilities and equipment access throughout the duration of this research. Solar irradiance data used in the performance calculations and experimental analysis was sourced from the Ministry of New and Renewable Energy (MNRE), Government of India. The author also acknowledges the constructive feedback of the anonymous reviewers.

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International Journal of Research and Technology (IJRT)

International Open-Access, Peer-Reviewed, Refereed, Online Journal

ISSN (Print): 2321-7510 | ISSN (Online): 2321-7529

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