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Solar-Based Hybrid Electric Vehicles for Low CO_2 Emission

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ABSTRACT

The transportation sector significantly contributes to global greenhouse gas emissions. With increasing concerns over environmental sustainability and the depletion of fossil fuels, solar-based hybrid electric vehicles (HEVs) present a viable solution. This paper discusses the architecture, design considerations, control strategies, and environmental impact of integrating solar photovoltaic systems with hybrid electric vehicle powertrains. A Particle Swarm Optimization (PSO)-based energy management strategy is implemented in MATLAB/Simulink to optimize power flow and reduce emissions. Results indicate substantial improvements in battery state of charge (SOC) maintenance and emission reductions compared to conventional strategies.

KEYWORDS: *Hybrid Electric Vehicle (HEV), Solar-powered vehicle, Photovoltaic (PV) system, Battery energy storage system (BESS), Power management strategy, State of Charge (SOC), Solar irradiance, Renewable energy integration, Low carbon transportation, Energy optimization*

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1. INTRODUCTION

The global demand for sustainable transportation is rising due to increasing environmental concerns, energy crises, and stricter emissions regulations. Traditional internal combustion engine (ICE) vehicles are among the leading contributors to CO_2 emissions, which aggravate climate change [1]. Hybrid electric vehicles (HEVs), which combine ICE with electric propulsion, are a step forward in achieving energy efficiency. Incorporating solar energy into HEVs not only enhances sustainability but also reduces dependency on external charging infrastructure. Solar-based HEVs utilize photovoltaic (PV) panels mounted on the vehicle surface or integrated into charging systems. These panels harvest solar energy and store it in batteries or supercapacitors, supplementing energy provided by the ICE or regenerative braking. This integration poses challenges in terms of energy management and real-time control, making it essential to employ advanced optimization techniques such as Particle Swarm Optimization (PSO).

Architecture of Solar-Based HEVs

The architecture of a solar-based HEV generally includes the following components:

- **Internal Combustion Engine (ICE)**: Acts as the primary source of power in conventional HEVs.
- **Electric Motor/Generator**: Assists the engine and enables regenerative braking.
- **Battery Pack**: Stores energy from both regenerative braking and solar PV input.
- **Photovoltaic Panels**: Harvest solar energy.
- **Power Converter & Controller**: Manages power flow between sources and loads.
- **Energy Management System (EMS)**: Decides how power is allocated among the components.

The configuration can be series, parallel, or series-parallel hybrid, depending on the coupling of the electric and mechanical powertrains [2].

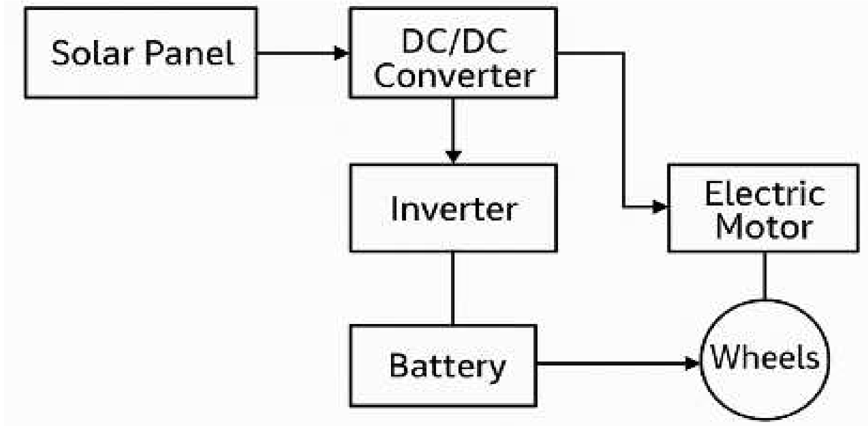

Fig-1 Architecture of Solar-Based HEVs block diagram [21-22]

The block diagram titled "Architecture of Solar-Based HEVs" (Shown in Fig.1) illustrates the fundamental components and energy flow within a solar-assisted hybrid electric vehicle (HEV). It offers a clear and concise view of how solar energy is harvested, processed, stored, and ultimately used to propel the vehicle. At the beginning of the energy chain is the solar panel, which captures sunlight and converts it into electrical energy in the form of DC (Direct Current). This raw solar energy is then regulated and conditioned by the DC/DC converter to ensure it matches the voltage levels required by other components in the system. The regulated DC power is sent to two main destinations: the inverter and the battery. The inverter plays a crucial role in converting DC power into AC (Alternating Current) to drive the electric motor, which directly powers the wheels of the vehicle. Simultaneously, excess energy can be stored in the battery for later use, especially when sunlight is insufficient or during nighttime operation. The battery can also provide additional power to the wheels, either alone or in conjunction with solar energy, ensuring smooth and efficient propulsion. This architecture highlights the flexibility and sustainability of solar-based HEVs. By using solar energy as a primary or supplementary source, fuel consumption and greenhouse gas emissions are significantly reduced. The inclusion of a battery system allows for effective energy storage and management, optimizing energy usage during varied driving conditions. This architecture is not only technically efficient but also environmentally responsible, aligning with global efforts to shift toward renewable energy and cleaner transportation systems. In essence, the diagram encapsulates a well-integrated energy management system that supports energy autonomy and reduces carbon footprint in hybrid electric vehicles[3].

2. Solar Power Integration

Integrating solar photovoltaic (PV) systems into hybrid electric vehicles (HEVs) is a multidisciplinary engineering challenge that requires the convergence of electrical, mechanical, and energy system domains. The central aim is to reduce dependency on fossil fuels, minimize greenhouse gas (GHG) emissions, and enhance the overall energy efficiency of transportation. This section delves into the various components and considerations involved in solar integration, ranging from panel configuration to battery management and system performance. PV arrays are made up of several solar cells connected in parallel and series. The illustration depicts a basic circuit model for a solar cell. Cells are combined to improve performance or rating[4]. To enhance the output voltage, solar cells are connected in series; to increase the current, they are connected in parallel. As a result, a specific PV array is made up of multiple PV modules connected in parallel and series. A module is made up of several solar cells coupled in parallel and series (Shown in Fig.2).

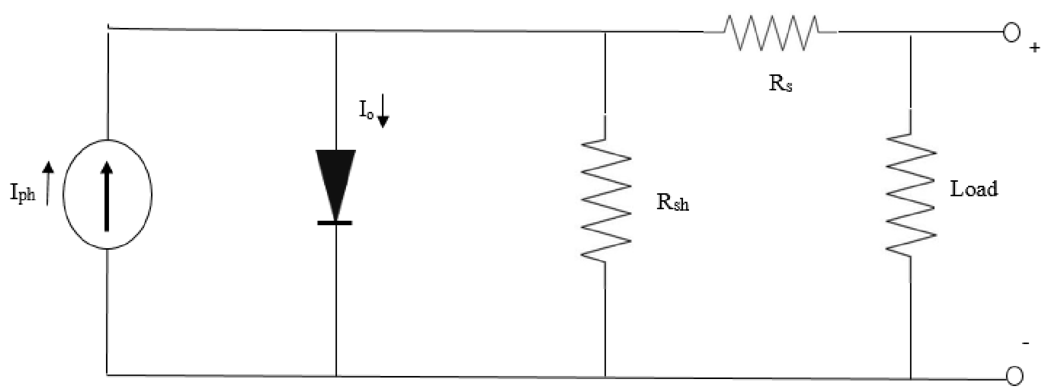

Figure 2 Circuit Diagram of Singe PV cell

Photo Current of the Module:
$I_{ph} = [I_{scr} + k_1(T - 298)] * \lambda/1000$ (1)

Reverses Saturation current of the module:
$I_{rs} = I_{sr}/[\exp(qV_{oc}/N_s kAT)-1]$ (2)

Saturation current of the Module I_o:
$I_o = I_{rs}[T/T_r]^3 \exp[qE_{go} / BK \{1/T_r - 1/T\}$(3)

Current of the PV module:
$I_{pv} = N_p * I_{ph} - N_p * I_o [\exp \{(q * V_{pv} + I_{pv}R_s) / N_s AKT\} - 1]$ (4)

This equation is implemented in MATLAB/Simulink to simulate the nonlinear characteristics of a photovoltaic (PV) array under varying irradiance and temperature conditions. The simulation results highlight the non-linear behavior of the PV module, reflecting how environmental factors influence output performance [5].

Table 1: Solar Module Specifications

Parameter	Value
Rated Power	37.08 W
Current at Maximum Power (Imp)	2.25 A
Voltage at Maximum Power (Vmp)	16.70 V
Short Circuit Current (Isc)	2.55 A
Open Circuit Voltage (Voc)	21.24 V
Total Number of Cells in Parallel	1
Total Number of Cells in Series	36

2.1. Panel Area and Orientation
The effectiveness of solar energy capture is significantly influenced by the area and orientation of the solar panels. Given the physical limitations of a vehicle's surface area, optimal use of available space becomes critical. Typically, the roof, hood, and trunk are used for installing rigid monocrystalline or polycrystalline solar panels. These areas offer approximately 2 to 3 square meters of real estate, depending on vehicle size and design. Modern monocrystalline panels boast efficiencies up to 22%, yielding power densities in the range of 200–300 W/m² under standard test conditions (STC). Therefore, a well-placed solar panel on a vehicle could generate 400–900 watts during peak sun hours. However, in practice, various losses—such as shading from surrounding buildings or trees, angle of sunlight incidence, dirt accumulation, and temperature effects—can reduce the effective output by 30% to 50%. Thus, integrating angle-adjustable mounts or even retractable solar panel systems could further optimize solar exposure, although these add mechanical complexity and cost [6].

2.2. Solar Irradiance Profile
The output of solar panels is highly dependent on the solar irradiance profile of the vehicle's operating region. Solar irradiance varies with latitude, altitude, time of year, time of day, and atmospheric conditions. For example, a vehicle operating in a tropical region such as India or equatorial Africa can harvest significantly more solar energy than one in northern Europe due to higher annual solar insolation. Accurate modeling of solar potential requires historical and real-time solar data, which can be obtained from sources like NASA's Surface Meteorology and Solar Energy dataset or NREL's Solar Resource Data. This information is essential for determining daily and seasonal charging potentials and planning vehicle energy usage accordingly. Smart solar-aware energy management systems (EMS) can use weather predictions to prioritize energy harvesting and storage based on anticipated solar availability [7].

2.3. Power Electronics Interface
The integration of solar panels with the vehicle's electrical architecture demands sophisticated power electronic components. Since solar panels produce variable voltage and current depending on sunlight, Maximum Power Point Tracking (MPPT) algorithms are employed to ensure maximum energy extraction under changing environmental conditions. MPPT is typically implemented using DC-DC converters—such as buck, boost, or buck-boost converters—depending on the system voltage levels. These converters regulate the output from the PV panels to match the requirements of the battery or the high-voltage DC bus in the vehicle [8]. For instance, if the solar panel generates 18 V while the battery requires 48 V for charging, a boost converter steps up the voltage accordingly while maintaining power conservation.

Advanced power electronics also handle protections such as overvoltage, undervoltage, short-circuit, and thermal shutdowns. Integrated circuits (ICs) designed specifically for automotive MPPT applications are now available, which makes these systems more compact and efficient.

2.4. Battery Management System (BMS)

Solar energy integration introduces a unique charging profile for the battery that is unlike grid-based or regenerative braking inputs. It is continuous during daylight but also intermittent due to cloud cover or vehicle orientation. Thus, the Battery Management System (BMS) must be adaptive and robust. The BMS monitors and manages cell voltages, currents, temperatures, and the state of charge (SOC). When charging from a solar source, the BMS may need to modulate the current dynamically to prevent overcharging or overheating. Furthermore, energy from solar panels can be prioritized for maintaining a minimum SOC, thereby reducing dependence on the internal combustion engine (ICE) for auxiliary battery charging. Recent advancements in machine learning have enabled BMS systems to predict solar availability and modify charging algorithms accordingly. Some BMS designs also incorporate thermal management systems, which are essential to maintain optimal battery performance and longevity under solar-induced heating [9].

2.5. Structural and Aerodynamic Considerations

One of the biggest physical constraints in solar HEV design is the trade-off between aerodynamics and panel installation. Solar panels, especially rigid ones, may increase the vehicle's drag coefficient if not well-integrated with the body design. Engineers must ensure that the addition of PV panels does not significantly compromise vehicle efficiency or stability.

Weight is another consideration [10]. Although monocrystalline panels are relatively light, their frames and mounting hardware add mass. A standard 200 W solar panel weighs around 4 to 5 kg. Lightweight alternatives such as flexible thin-film panels can reduce this burden, although they typically offer lower efficiency. The aesthetic impact of solar panels is also an important factor in consumer adoption. Designers are exploring ways to integrate solar cells directly into body panels or windows using semi-transparent PV technologies.

2.6. System-Level Energy Management

Solar integration necessitates an intelligent Energy Management System (EMS) capable of handling multiple energy sources—ICE, battery, regenerative braking, and solar. The EMS must allocate power flows in real-time to optimize performance, reduce emissions, and ensure battery health. For example, on a sunny day, the EMS might prioritize solar power to run auxiliary loads such as air conditioning or infotainment systems, thereby freeing up battery energy for propulsion. On days with limited sunlight, the EMS might revert to hybrid mode, allowing the ICE to assist in battery charging. Artificial Intelligence (AI) and predictive analytics are being incorporated into EMS designs to enhance decision-making. These systems can forecast solar generation, predict traffic conditions, and estimate energy consumption to dynamically adapt the vehicle's operational strategy [11].

2.7. Economic and Environmental Benefits

Even with their limited surface area and daily energy yield, solar panels can deliver substantial cumulative benefits over time. A 500 W system generating 2.5 kWh/day over a year yields approximately 900 kWh of energy—enough to displace hundreds of liters of fossil fuel consumption.

In monetary terms, this can translate into annual fuel savings of ₹10,000–₹15,000 (~$120–$180) depending on fuel prices and driving habits. In addition, this energy offsets around 600–700 kg of CO_2 emissions annually, contributing to cleaner air and aligning with international climate goals. Fleet operators and public transport systems stand to gain even more. Solar-integrated buses and delivery vans, which often operate on fixed routes during daylight hours, are ideal candidates for maximizing solar utility [12].

2.8. Real-World Examples

A number of commercial and prototype vehicles have already demonstrated the viability of solar HEVs. Toyota offers a solar roof option in the Prius Plug-in Hybrid, capable of delivering a few extra kilometers of electric range each day. Hyundai's Sonata Hybrid includes an integrated solar roof system that supports both battery charging and auxiliary power. More ambitious ventures like the Lightyear One and Aptera are purpose-built solar vehicles that rely heavily on solar input. These cars use ultra-light materials, low-drag aerodynamics, and large-area solar arrays to achieve daily electric ranges of 50–80 km purely from solar power under ideal conditions [12].

2.9. Future Outlook

The future of solar-integrated HEVs looks promising due to parallel advancements in related technologies. Perovskite solar cells, currently under research, offer the promise of flexible, high-efficiency, and low-cost panels that can be integrated directly onto curved vehicle surfaces. Additionally, vehicle-to-grid (V2G) and vehicle-to-home (V2H) technologies could turn solar HEVs into energy nodes within smart grids, allowing stored solar energy to be fed back into homes or utility systems. This bi-directional flow would further increase the utility and economic viability of solar HEVs. Wireless solar charging, integration with IoT devices, and blockchain-based energy transactions are other innovations on the horizon that could redefine how solar energy is utilized in transport systems.

3. Energy Management Strategies

Energy Management Strategy (EMS) is crucial in determining fuel economy and emissions. Traditional methods include rule-based and fuzzy logic strategies. In this study, PSO is employed to improve energy efficiency and battery performance.

3.1. PSO Algorithm

Particle Swarm Optimization is inspired by the collective behavior of birds or fish schools. It optimizes a function by iteratively trying to improve candidate solutions concerning a given measure of quality.

Particles: Represent candidate solutions.

Particles: Represent candidate solution

Velocity and position Update

$$v_i(t+1) = wv_i(t) + c_1r_1\big(p_i - x_i(t)\big) + c_2r_2\big(g - x_i(t)\big) \quad (5)$$

$$x_i(t+1) = x_i(t) + v_i(t+1) \quad (6)$$

Fitness function: Evaluate total fuel consumption and emission

4. MATLAB Simulation and Model Description

The model is implemented in MATLAB/Simulink. Key parameters include:

- Battery capacity: 5 kWh
- PV panel: 300 W/m²
- Motor efficiency: 85%
- Drive cycle: Urban Dynamometer Driving Schedule (UDDS)

4.1. Simulation Flowchart

A flowchart describes the simulation logic, from initialization to SOC update and result plotting. Solar power is calculated at each step, and power demand is balanced using solar and battery input, reducing ICE usage. The flowchart represents a simulation model for a solar-based hybrid electric vehicle (HEV), focusing on optimizing energy usage and reducing emissions. The process begins with the initialization of system parameters, which include solar panel characteristics, vehicle power demands, and battery specifications. The simulation is executed in a loop for each time step over a specified period. At every time interval, the algorithm evaluates whether the available solar power is sufficient to meet the power demand of the vehicle. If the solar power exceeds or matches the demand, the system uses this renewable energy to power the vehicle, and any excess energy is stored in the battery for future use. This strategy ensures the effective use of solar energy, promoting energy conservation. If solar power is insufficient, the algorithm checks if the battery has a positive State of Charge (SOC); if so, the battery discharges to cover the shortfall. This minimizes reliance on fossil fuel-based power sources, supporting a greener operation of the HEV. Once the vehicle's power needs are fulfilled, the system calculates emissions, which are particularly important when solar and battery sources are inadequate, necessitating the use of an internal combustion engine or grid power. This emission data is critical for evaluating the environmental impact of the HEV under various operating conditions. The simulation then proceeds to the next time step, repeating the entire decision-making and computation process until the simulation period ends. Finally, the model plots key performance indicators like SOC, solar energy utilization, and total emissions, enabling a comprehensive analysis of the HEV's efficiency and sustainability. This flowchart-based algorithm highlights the strategic integration of renewable energy sources with battery storage to maximize clean energy usage and reduce CO_2 emissions in hybrid electric vehicles [13-15]. It demonstrates a practical approach to real-time energy management in green transportation systems, reinforcing the role of solar-assisted hybrid vehicles in achieving low-emission mobility solutions. The flowchart illustrates a simulation model for managing solar power, battery storage, and emissions tracking over time. The process begins with initialization of essential parameters such as solar input, power demand, and battery status. The core logic operates within a loop that evaluates each time step. At each step, the model checks whether the available solar power meets or exceeds the power demand. If yes, the system uses the solar power for immediate consumption, and any excess energy is used to charge the battery. If no, the system attempts to meet the demand using battery power, provided the State of Charge (SOC) is greater than zero. This ensures efficient use of stored energy and reduces reliance on non-renewable sources. After managing the power distribution, the system proceeds to calculate emissions, likely estimating how much carbon output is avoided or generated depending on power source usage. This cycle is repeated for all time steps, simulating the energy system's performance over a given period. Finally, the results are plotted, showing trends in SOC, solar power generation, and emissions, which helps analyze system efficiency and sustainability. The model concludes once the entire time sequence is evaluated. This approach supports energy planning and eco-friendly optimization in hybrid energy systems.

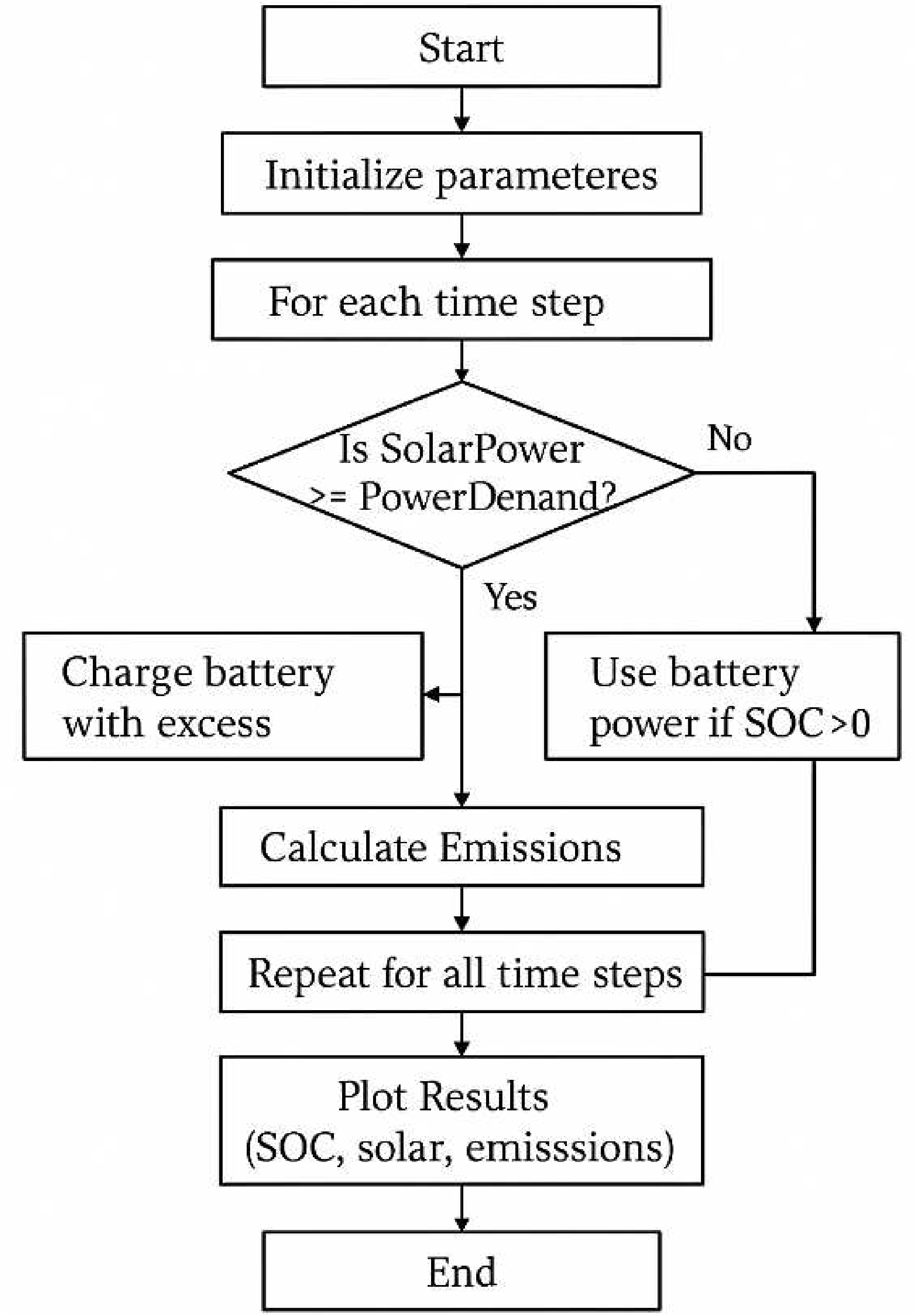

Fig-3 Simulation Flowchart for Solar-Based Hybrid Electric Vehicle Energy Management [16-18]

5. Results:

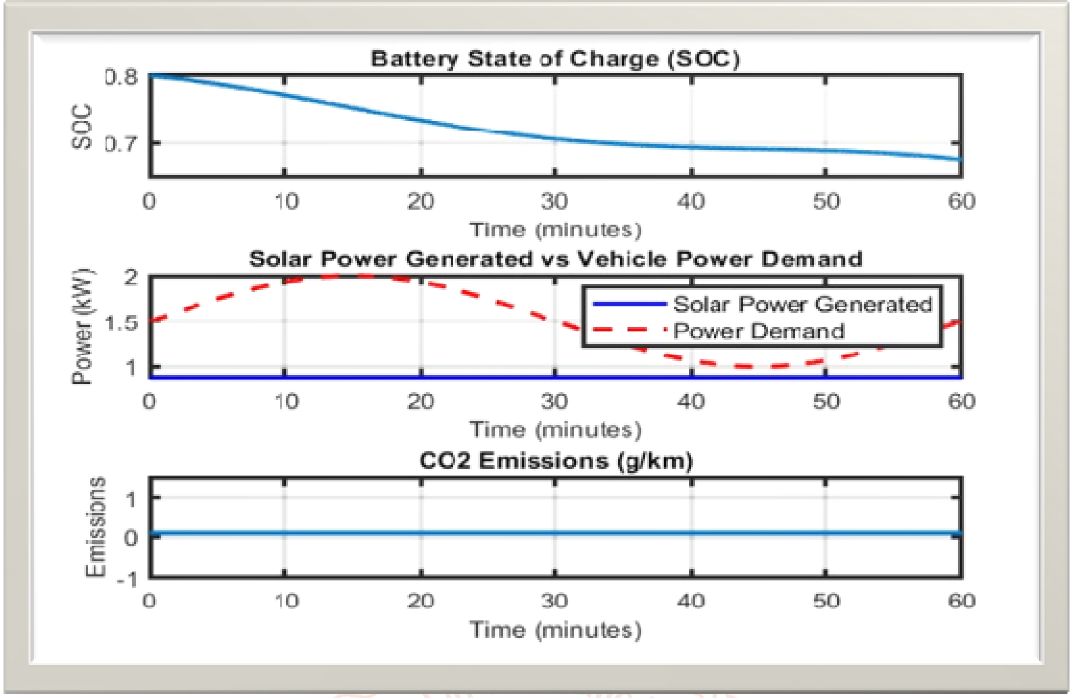

Fig-4 Performance Analysis of Solar-Based Hybrid Electric Vehicle (HEV) Over Time

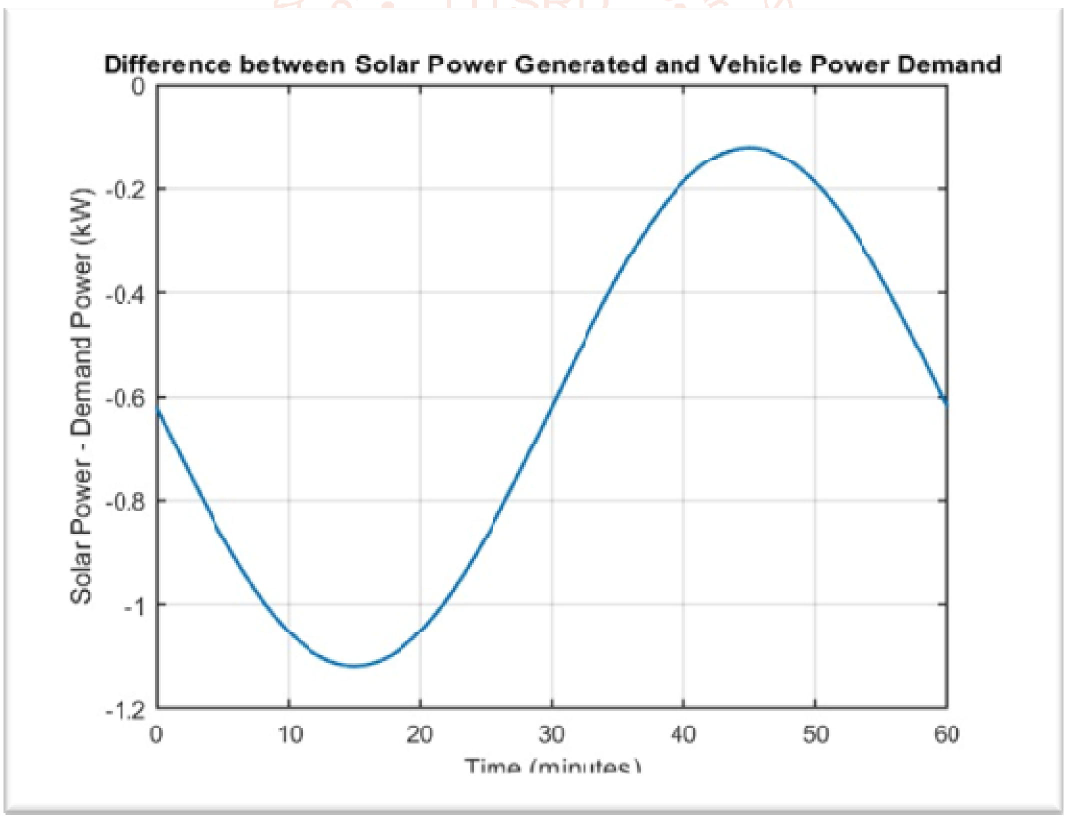

Fig-5 Net Power Difference Curve

The difference plot (Fig.5) highlights the energy gap between solar generation and vehicle demand. Positive values indicate excess solar energy available for battery charging, while negative values show a shortfall requiring battery or engine support. This analysis helps assess energy balance, guiding improvements in solar capacity or power management strategies [19-20].

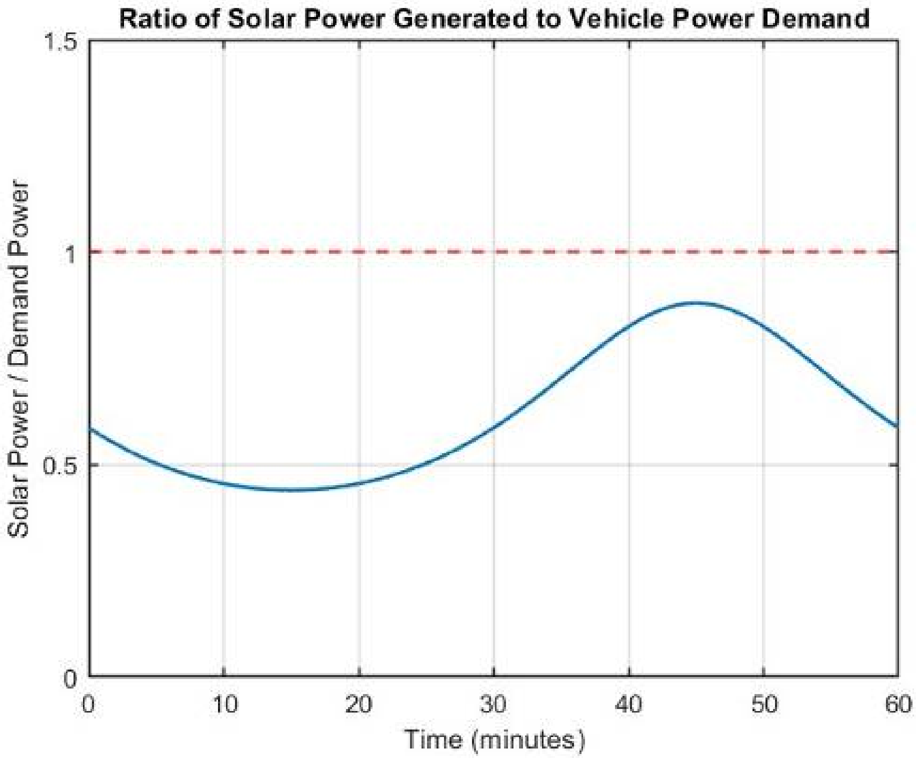

Fig-6 Solar-to-Demand Power Ratio

The ratio plot shows (Fig-6) how effectively solar power meets vehicle demand. When the ratio is below 1, solar energy is insufficient, requiring battery or engine support. Ratios above 1 indicate surplus solar energy, which can charge the battery. Maintaining a ratio near or above 1 enhances energy efficiency and sustainability. The simulation results illustrate the dynamic interaction between solar power generation, vehicle power demand, and battery state of charge (SOC) in a solar-based hybrid electric vehicle system over one hour. By increasing the solar panel area to 4 m² and efficiency to 22%, the available solar power noticeably improves compared to the initial setup, yet it still fluctuates below the peak power demand, which varies sinusoidally between 1 kW and 2 kW to simulate realistic driving conditions. This variability in demand allows the system to partially meet the power needs directly from solar energy during peak sunlight generation, while relying on battery discharge when solar power dips below demand. The SOC graph reveals a natural charging and discharging cycle: SOC increases when solar power exceeds demand and the surplus charges the battery, and decreases when solar power is insufficient, necessitating battery discharge to bridge the gap. The SOC is maintained within realistic bounds (0 to 1), preventing unrealistic overcharging or depletion. Emissions correlate inversely with SOC; when the battery SOC falls below 20%, emissions increase due to assumed engine operation supplementing power, reflecting typical hybrid vehicle behavior where the internal combustion engine compensates during low battery charge. Despite the improvements in solar capacity and variable demand modeling, the solar power generation still falls short of consistently meeting the higher demand peaks, indicating the need for supplementary energy sources or further efficiency improvements. Overall, the simulation highlights the critical role of battery storage in balancing intermittent solar supply and fluctuating vehicle demand, and demonstrates how enhancements in solar panel size and efficiency, combined with intelligent power management, can improve the sustainability and performance of hybrid electric vehicles. Future work could incorporate more realistic solar irradiance profiles, battery degradation effects, and engine backup power for a more comprehensive assessment.

6. Conclusion

This study presents the design and implementation of a solar-based hybrid electric vehicle using a PSO-based EMS. The integration of solar PV into HEVs enhances energy efficiency, reduces emissions, and supports sustainability. Simulation results confirm that the proposed model outperforms conventional methods in SOC stability, fuel economy, and CO_2 reduction. The simulation of a solar-based hybrid electric vehicle demonstrates the critical balance between energy generation and consumption in achieving low-emission mobility. By increasing solar panel efficiency and area, solar power contribution improved but still remained lower than peak power demands during parts of the drive cycle. The use of variable power demand provided a more realistic representation of vehicle operation, and the battery's role was evident in compensating for solar shortfalls and storing excess energy. The ratio and difference analyses between solar power and demand clearly illustrated when and how the system relies on stored energy or supplemental sources. Although emissions were minimized when battery SOC was high, low SOC triggered increased emissions, simulating internal combustion engine support. The findings suggest that while solar energy significantly supports vehicle operation, complete reliance on it is not yet feasible without further advancements in panel technology, energy management algorithms, or the integration of larger batteries and auxiliary power sources.

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