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Evaluation of aerodynamic and structural design to enhance solar energy absorption for e-Cars

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ABSTRACT

The integration of photovoltaic (PV) systems into electric vehicles (EVs) offers a promising solution for extending driving range and reducing dependence on grid-based charging. However, vehicle-integrated PV systems are limited by aerodynamic drag, structural integration challenges, thermal losses, and inefficient energy management. This study presents a multidisciplinary simulation framework to evaluate aerodynamic and structural optimization strategies for enhancing solar energy absorption in EVs. Computational fluid dynamics (CFD) was used to analyze airflow and reduce aerodynamic drag, while finite element analysis (FEA) assessed structural integrity and weight optimization after PV integration. PV energy-flow and thermal models were also developed to evaluate power generation, battery charging behavior, and temperature-dependent efficiency losses. The optimized design reduced the drag coefficient from 0.310 to 0.236, a 23.7% improvement, while maintaining a structural safety factor above 1.75 through lightweight composite materials. The optimized PV configuration increased solar conversion efficiency from 17.6% to 22.3% and daily energy generation from 2.91 kWh/day to 3.75 kWh/day, corresponding to a 28.9% increase in harvested energy. Thermal management strategies lowered average PV operating temperature by about 12 °C, improving efficiency by an additional 5%–7%. Unlike existing studies that examine aerodynamic, structural, or PV performance separately, this work provides a unified framework that evaluates their combined impact on solar energy harvesting in EVs. The proposed integrated design approach demonstrates that coordinated aerodynamic, structural, thermal, and energy-management optimization can substantially improve the practicality and energy contribution of solar-assisted EVs in high-irradiance environments.

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1. INTRODUCTION

The global transition toward sustainable transportation has accelerated the adoption of electric vehicles (EVs) as a viable alternative to conventional internal combustion engine vehicles. Despite their environmental benefits, EVs remain dependent on grid-based charging infrastructure, which may still rely on fossil-fuel-generated electricity in many regions. As a result, integrating renewable energy sources directly into EV platforms has attracted growing research interest. Among these options, vehicle-integrated photovoltaic (PV) systems represent a promising approach for supplementing onboard energy, extending driving range, and reducing lifecycle carbon emissions [1]. Advances in lightweight PV technologies and flexible solar modules have improved the feasibility of mounting solar panels on EV surfaces such as roofs, hoods, and side panels. However, the practical energy contribution of vehicle-mounted PV systems remains limited due to constrained surface area, aerodynamic penalties, structural constraints, shading effects, and temperature-induced efficiency degradation. In particular, aerodynamic drag plays a critical role in overall vehicle energy consumption, where even small increases in drag coefficient can offset the energy gained from solar harvesting. Existing studies have explored aerodynamic optimization, lightweight materials, and PV integration independently [2]. However, fewer works address the coupled interaction between aerodynamic performance, structural integrity, and solar energy harvesting efficiency within a unified framework. This gap motivates the present study, which evaluates how coordinated aerodynamic and structural design choices influence solar energy absorption and overall EV performance.

The primary objective of this work is to provide a simulation-based assessment of design trade-offs between aerodynamic efficiency and solar energy harvesting capability. By combining CFD-based aerodynamic analysis, FEA-based structural evaluation, and PV energy flow modeling, the study aims to identify design strategies that enhance solar energy utilization while maintaining mechanical safety and vehicle efficiency.

Green mobility is gaining an increasing importance: lots prototypes of electric, hybrid vehicles have been developed. also, attention on the integration of PV panels in road vehicles, to produce electricity, has been given due to many reasons. The degree of vehicle electrification is expected to increase significantly in the coming years as EVs occupy a larger share of global transportation fleets. Considerable improvement in solar panel efficiency has been attained. Significant reduction in their costs has been achieved, due to their fast-increasing diffusion [3].

This study makes the following scientific and engineering contributions:

a) Development of an integrated CFD–FEA–PV simulation framework for evaluating solar-assisted EVs performance.
b) Investigation of the combined influence of aerodynamic optimization and structural integration on PV energy harvesting.
c) Quantitative evaluation of thermal management strategies for reducing PV efficiency losses.
d) Comparative statistical analysis demonstrating improvements in drag coefficient, solar conversion efficiency, daily energy generation, and driving range.

The novelty of this work lies in the development of a unified multidisciplinary simulation framework that simultaneously evaluates aerodynamic drag reduction, PV structural integration, thermal regulation, and energy-flow management for solar-assisted EVs. Unlike existing studies that analyze these factors independently, the proposed framework quantifies their combined influence on solar energy harvesting capability, vehicle efficiency, and driving-range enhancement. This integrated assessment provides a more realistic basis for optimizing future solar-assisted EV architectures.

2. LITERATURE REVIEW

The development of solar-assisted EVs has attracted significant research interest due to the increasing demand for sustainable transportation systems and the growing efficiency of PV technologies [4]. The integration of solar panels into EV platforms provides an opportunity to supplement battery energy, extend driving range, and reduce dependence on charging infrastructure. However, the effectiveness of vehicle-integrated PV systems is influenced by multiple interacting factors including aerodynamic performance, structural integration, energy conversion efficiency, thermal behavior, and environmental operating conditions [5]. This section reviews existing studies related to these factors and identifies the research gap addressed in this work.

2.1. Solar-assisted EV technologies

Solar-assisted EVs combine PV energy harvesting systems with conventional battery-powered propulsion systems to improve overall energy efficiency and vehicle autonomy. The concept involves mounting solar panels on vehicle surfaces such as roofs, hoods, trunks, and side panels, where solar radiation can be converted into electrical energy and stored in onboard batteries [6]. Recent developments in monocrystalline silicon, thin-film, and flexible PV technologies have improved the practicality of vehicle-integrated solar systems. Monocrystalline silicon panels remain the most widely adopted due to their high conversion efficiencies exceeding 22%, while flexible thin-film technologies offer advantages in weight reduction and geometric adaptability [7]. Emerging technologies such as perovskite solar cells have demonstrated laboratory efficiencies above 25% and are being investigated for future automotive applications due to their lightweight characteristics and manufacturing flexibility.

Several commercial prototypes have demonstrated the feasibility of solar-assisted transportation. Vehicles such as the lightyear one, sono sion, and aptera utilize integrated PV modules to provide supplementary charging during vehicle operation and parking periods [8]. Studies indicate that solar-assisted EVs can achieve daily energy gains ranging from 20 km to 70 km depending on climatic conditions, available panel area, and solar irradiance levels. Despite these advances, the limited surface area available on passenger vehicles remains a major constraint on total energy generation capability [9]. Figure 1 illustrates the energy conversion pathway within the proposed solar-assisted EV. Solar energy harvested by the PV modules is processed through the MPPT controller, stored in the battery system, and distributed to propulsion and auxiliary vehicle loads.

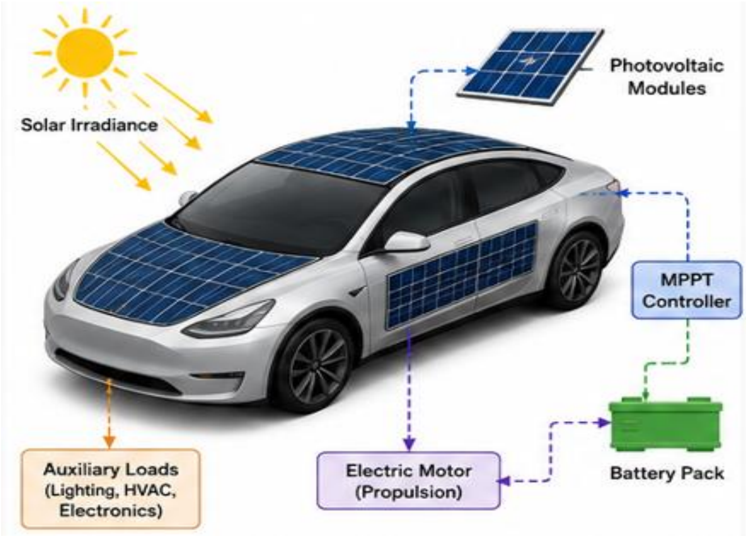

Figure 1. Architecture of solar-assisted EV

2.2. Aerodynamic design optimization in EVs

Aerodynamic performance is one of the most critical determinants of energy consumption in EVs, particularly at medium and high driving speeds [10]. The aerodynamic drag force experienced by a vehicle is proportional to the drag coefficient, frontal area, and square of vehicle velocity. Consequently, small reductions in drag coefficient can produce substantial improvements in vehicle range and energy efficiency. Research using computational fluid dynamics (CFD) has demonstrated that streamlined body geometries, optimized roof curvature, reduced flow separation, and controlled wake formation significantly reduce aerodynamic drag. Modern EVs commonly achieve drag coefficients between 0.20 and 0.30 through extensive aerodynamic optimization [11]. For solar-assisted EVs, aerodynamic design presents additional challenges because PV modules may alter airflow patterns and increase surface roughness. Studies have shown that poorly integrated solar panels can increase drag by creating localized turbulence and boundary layer disturbances. Conversely, flush-mounted PV systems integrated directly into the vehicle body can minimize aerodynamic penalties while maintaining solar energy harvesting capability. Active aerodynamic systems such as adjustable spoilers, adaptive vents, and variable geometry panels have also been proposed to dynamically optimize airflow under changing driving conditions. These technologies can simultaneously improve vehicle stability, reduce drag, and enhance cooling airflow around PV surfaces [12].

2.3. Structural integration of PVmodules

The successful implementation of solar-assisted EVs depends not only on energy generation capability but also on effective structural integration of PV modules within the vehicle body. Traditional rigid PV panels introduce additional mass and may affect structural integrity if not properly incorporated into vehicle design. To address these challenges, researchers have investigated lightweight composite materials such as carbon fiber reinforced polymers (CFRP), glass fiber composites, aluminum honeycomb structures, and sandwich panel configurations [13]. These materials offer high strength-to-weight ratios and enable the integration of solar modules without significantly increasing vehicle mass. Flexible PV technologies have further expanded integration possibilities by allowing solar panels to conform to curved vehicle surfaces. This capability increases the effective solar collection area while maintaining desirable aerodynamic characteristics. Structural performance assessments using finite element analysis (FEA) have demonstrated that appropriately designed composite structures can withstand operational loads including aerodynamic pressure, vibration, thermal expansion, and impact forces. The use of reinforced support structures and optimized mounting mechanisms further enhances durability and reliability under real-world operating conditions [14]. Table 1 compares commonly used structural materials for PV integration and highlights their suitability for lightweight EVs applications.

Table 1. Comparison of materials used for PV integration

Material	Density (kg/m³)	Strength-to-weight ratio	Suitability
Aluminum alloy	Low	Moderate	Good
CFRP	Very low	High	Excellent
GFRP	Low	Moderate	Good
Honeycomb composite	Very low	High	Excellent

2.4. PV energy conversion and MPPT techniques

Efficient utilization of solar energy in EV applications depends heavily on PV energy conversion efficiency and power extraction strategies. The electrical output of PV modules varies continuously with solar irradiance, temperature, shading conditions, and panel orientation [15]. Maximum power point tracking (MPPT) techniques are therefore employed to maximize energy extraction from PV arrays. Conventional MPPT algorithms include perturb and observe (P&O), incremental conductance (INC), fractional open circuit voltage, and fractional short circuit current methods. Among these, P&O and INC remain the most widely used due to their simplicity and reliability. Recent research has introduced intelligent MPPT approaches based on fuzzy logic, artificial neural networks, particle swarm optimization, and machine learning algorithms [16]. These methods offer improved tracking accuracy under rapidly changing environmental conditions and partial shading scenarios. In solar-assisted EV systems, MPPT performance directly influences battery charging efficiency and overall vehicle energy gain. Consequently, advanced MPPT strategies are essential for maximizing the contribution of vehicle-mounted PV systems [17].

2.5. Thermal effects on vehicle-integrated PV systems

Temperature is a critical factor influencing PV performance. As PV cell temperature increases, semiconductor characteristics change, resulting in reduced open-circuit voltage and decreased power output. Experimental studies indicate that PV efficiency decreases by approximately 0.3%–0.5% for every 1 °C increase above standard operating temperature conditions. Vehicle-mounted solar panels are particularly susceptible to thermal effects because they are exposed to both solar radiation and heat generated by surrounding vehicle surfaces. During prolonged operation in hot climates, panel temperatures may exceed 70 °C, leading to substantial efficiency losses. Various thermal management approaches have been proposed to mitigate these effects, including passive airflow cooling, ventilated mounting structures, heat spreaders, phase-change materials, and active cooling systems. Among these methods, aerodynamic airflow management is particularly attractive because it simultaneously reduces drag and enhances PV cooling performance [18].

2.6. CFD and FEA applications in solar vehicle design

CFD and FEA have become indispensable tools in the design and optimization of solar-assisted EVs [19]. CFD enables detailed investigation of airflow behavior, pressure distribution, turbulence intensity, drag forces, and thermal flow characteristics around vehicle bodies. Several studies have employed CFD to evaluate alternative body geometries, aerodynamic attachments, cooling channels, and solar panel placement strategies [20]. These investigations have demonstrated significant improvements in aerodynamic efficiency through optimization of airflow patterns and reduction of wake regions. Similarly, FEA is extensively used to evaluate structural integrity, stress distribution, deformation characteristics, fatigue performance, and vibration behavior of vehicle-integrated PV systems. Structural simulations allow designers to assess the effects of aerodynamic loading, thermal expansion, road vibrations, and impact forces before physical prototyping. The integration of CFD and FEA provides a comprehensive multidisciplinary framework capable of simultaneously addressing aerodynamic, thermal, structural, and energy performance considerations. This integrated approach is increasingly recognized as essential for next-generation solar vehicle development [21].

2.7. Research gap analysis

The literature demonstrates considerable progress in aerodynamic optimization, PV energy harvesting, structural lightweighting, and thermal management for EVs. However, most existing studies investigate these factors independently rather than considering their combined influence on solar energy absorption and overall vehicle performance. Aerodynamic studies primarily focus on drag reduction without explicitly evaluating how airflow modifications influence PV energy generation and thermal behavior [22]. Similarly, structural investigations emphasize mechanical integrity and weight reduction while often neglecting aerodynamic implications and energy conversion efficiency [23]. Research on PVsystems generally concentrates on MPPT algorithms and panel technologies without fully accounting for vehicle-specific structural and aerodynamic constraints [24].

Furthermore, limited studies employ an integrated CFD–FEA–PV simulation framework capable of simultaneously evaluating aerodynamic performance, structural reliability, thermal effects, and energy harvesting efficiency within a unified design environment [25]. Therefore, this study addresses the identified research gap by developing a multidisciplinary simulation framework that combines aerodynamic analysis, structural assessment, PV energy flow modeling, and thermal performance evaluation. The proposed approach enables a comprehensive assessment of how coordinated aerodynamic and structural optimization strategies can enhance solar energy absorption in EVs while maintaining mechanical safety and operational efficiency.

3. METHOD

This study adopts a multidisciplinary simulation-based methodology to evaluate the influence of aerodynamic and structural design on solar energy absorption in EVs. The framework integrates CFD, FEA, PV energy modeling, thermal analysis, and energy flow management to assess the overall performance of solar-assisted EVs. The methodology is designed to investigate the interaction between aerodynamic efficiency, structural integrity, PV energy generation, and thermal behavior under realistic operating conditions [19], [20].

The overall methodological framework consists of four major stages. First, aerodynamic simulations are conducted to analyze airflow behavior around the vehicle body and determine drag reduction opportunities. Second, structural simulations are performed to evaluate the mechanical feasibility of integrating PV modules into vehicle surfaces. Third, energy flow modeling is implemented to quantify solar power generation, conversion, storage, and utilization. Finally, thermal simulations are carried out to examine temperature-induced efficiency degradation and cooling effectiveness. Figure 2 presents the sequence of simulation activities performed in this study. The methodology integrates aerodynamic analysis, structural evaluation, PV energy modeling, and thermal assessment to determine the combined impact of design optimization on solar energy absorption and vehicle efficiency.

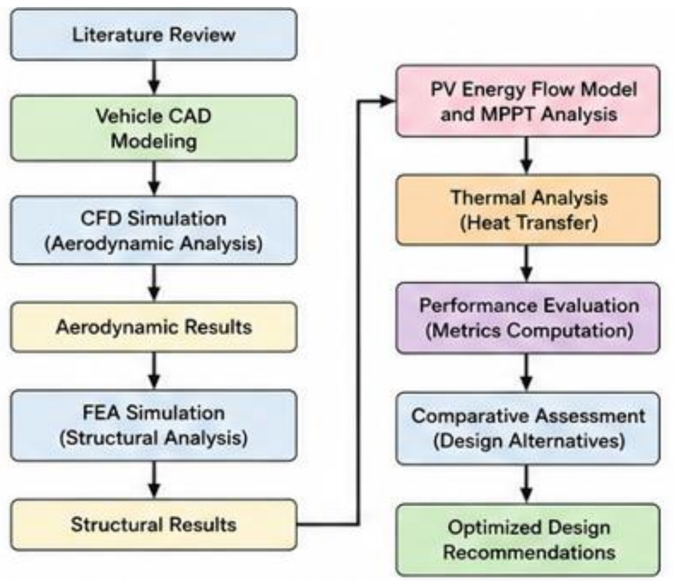

Figure 2. Research methodology framework of proposed solar-assisted EV

3.1. Simulation environment and design assumptions

The proposed solar-assisted EV model is developed using a combination of CFD, FEA, and MATLAB/Simulink simulation tools. A representative passenger EV equipped with roof-mounted PV modules is considered as the baseline configuration. The solar modules are assumed to consist of high-efficiency monocrystalline silicon cells due to their widespread adoption in vehicle-integrated PV systems. To ensure consistency across simulations, the following assumptions are adopted as in Table 2. Wind effects are considered steady-state. These assumptions enable realistic evaluation of vehicle operation in urban and highway environments.

Table 2. Simulation parameters and assumptions

Parameter	Value
Vehicle speed	30–100 km/h
Solar irradiance	600–1000 W/m²
Ambient temperature	25–45 °C
Air density	1.225 kg/m³
PV efficiency	22%
Panel area	2 m²

3.2. Aerodynamic flow analysis using CFD

Aerodynamic performance directly affects vehicle energy consumption and influences airflow distribution over the PV modules. CFD simulations are conducted to evaluate airflow behavior around the vehicle body and determine opportunities for drag reduction. The governing equations are the incompressible reynolds-averaged navier–stokes (RANS) the continuity equation is given by:

$$\nabla . \nu - 0$$

Momentum equation is presented as in (1).

$$\rho(\nu . \nabla)\nu - \Delta P + \mu\Delta + \rho g \quad (1)$$

Where ρ = air density, ν = velocity vector, P = pressure, and μ = dynamic viscosity. The standard k-ϵ turbulence model is adopted because of its proven effectiveness in external vehicle aerodynamics. The drag coefficient is determined using (2).

$$C_D - \frac{hF_D}{\rho VA} \quad (2)$$

Where F_D= drag force, A = frontal area and V= vehicle velocity. Similarly, the lift coefficient is computed as in (3).

$$C_L - \frac{2F_L}{\rho VA} \quad (3)$$

Where F_L= lift force

Figure 3 illustrates the airflow simulation environment employed in the CFD analysis. Boundary conditions include velocity inlet, pressure outlet, and no-slip wall conditions to accurately evaluate aerodynamic drag and flow separation.

3.2.1. Aerodynamic design configurations

Three vehicle configurations are analyzed:

- Baseline EV without PV optimization.
- EV with roof-mounted PV integration.
- Aerodynamically optimized solar-assisted EV.

The optimized design incorporates streamlined roof geometry, reduced frontal stagnation regions, integrated rear diffuser, and smooth PV surface transitions. The objective is to minimize aerodynamic drag while maximizing solar exposure.

3.3. Structural analysis using FEA

The structural evaluation investigates the mechanical impact of integrating PV modules into the EV body structure. Lightweight composite materials such as carbon fiber reinforced polymer (CFRP) and aluminum alloys are considered due to their favorable strength-to-weight ratios. The stress-strain relationship follows Hooke's Law as in (4).

$$\sigma - E \in \tag{4}$$

where σ = stress, E = young's modulus and ∈ = strain. The von Mises stress criterion is used to assess structural safety:

$$\sigma_v - \sqrt{(\sigma_1 - \sigma_2)^2} + \sqrt{(\sigma_2 - \sigma_3)^2} + \sqrt{(\sigma_3 - \sigma_1)^2} \tag{5}$$

Where σ_1, σ_2, σ_3 are principal stresses.

Figure 4 presents the structural configuration adopted for FEA. Mechanical loads associated with aerodynamic pressure, panel weight, and operational vibration is applied to evaluate structural integrity.

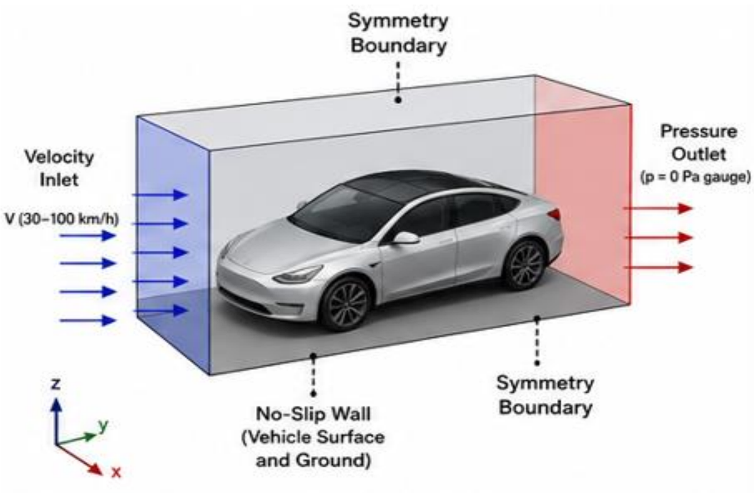

Figure 3. CFD computational domain and boundary conditions for aerodynamic analysis

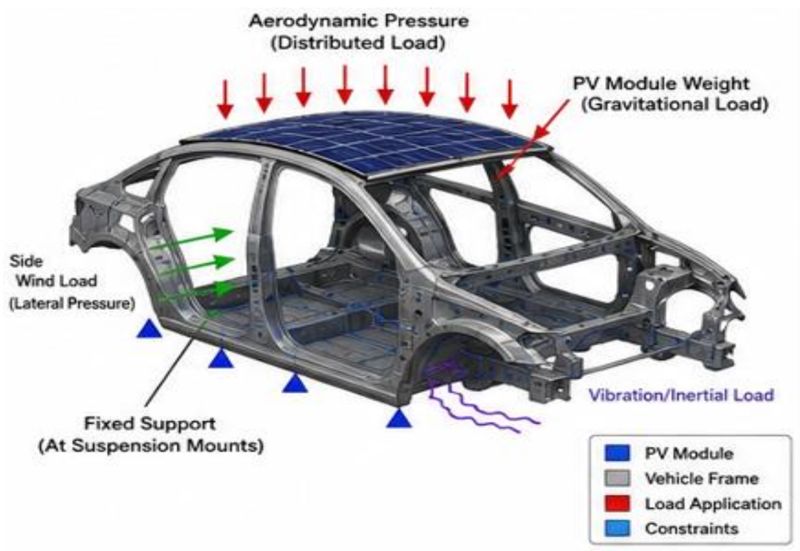

Figure 4. Finite element model showing PV module integration and applied structural loading conditions

3.3.1. Structural performance metrics

The following structural metrics are evaluated based on Table 3.

Table 3. Structural evaluation parameters

Parameter	Description
Von mises stress	Failure assessment
Total deformation	Structural displacement
Factor of safety	Mechanical reliability
Natural frequency	Vibration resistance
Added mass	Weight impact

3.4. PV energy flow modeling

The PV subsystem converts incident solar radiation into electrical energy used to charge the EV battery and supply auxiliary loads. The generated solar power is calculated as in (6).

$$P_{Pv} - \eta GA \quad (6)$$

Where η = PV efficiency, G= solar irradiance, and A is panel area. The daily harvested energy is estimated as in (7):

$$E_{Pv} - P_{Pv} - \mathrm{X}\ t \quad (7)$$

where t = operating time. The MPPT controller continuously tracks the optimal operating point to maximize power extraction under varying irradiance conditions.

Figure 5 illustrates the flow of electrical energy from PV generation through energy conditioning and storage stages to the propulsion system. The architecture enables efficient utilization of harvested solar energy.

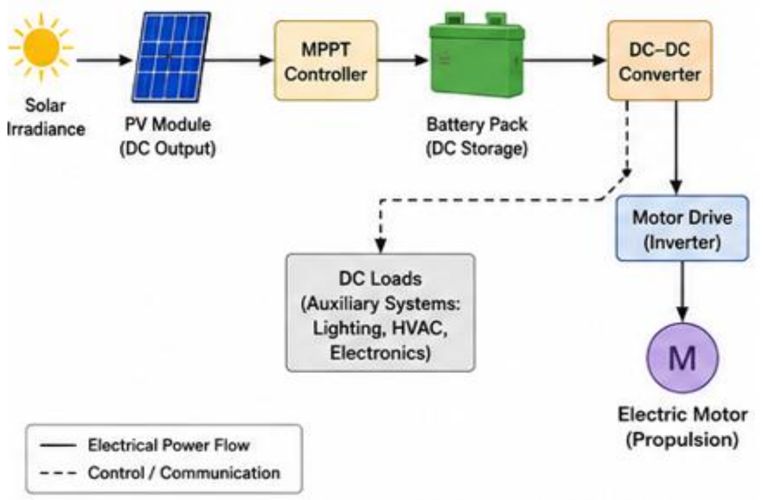

Figure 5. PV energy flow and power management architecture

3.5. Battery and energy management modeling

The generated solar energy is routed through an MPPT controller, battery management system (BMS), DC-DC converter, and electric drive system. The battery state of charge (SOC) is calculated as in (8).

$$SOC - SOC_0 + \frac{1}{C}\int I(t)dt \quad (8)$$

Where SOC_0= initial SOC, C = battery capacity and $I(t)$ = charging current. This model enables evaluation of the contribution of solar energy to overall battery charging performance.

3.6. Thermal analysis of vehicle-integrated PV modules

Temperature significantly affects PV performance because increasing cell temperature reduces conversion efficiency. PV efficiency variation with temperature is expressed as in (9):

$$\boldsymbol{\eta}r - \eta_{ref}[1\text{-}\beta(T\text{-}T_{ref})] \quad (9)$$

where $\boldsymbol{\eta}r$ = temperature-dependent efficiecncy, η_{ref}= reference efficiency, β =temperature coefficient, T = operating temperature and T_{ref}reference temperature. Thermal simulations examine the surface temperature distribution, and its airflow cooling effects. It also examines the heat accumulation under solar exposure and efficiency degradation due to temperature rise.

Figure 6 shows the thermal profile of the PV surface. Elevated temperatures are observed in central panel regions, highlighting the importance of thermal management strategies for maintaining PV efficiency.

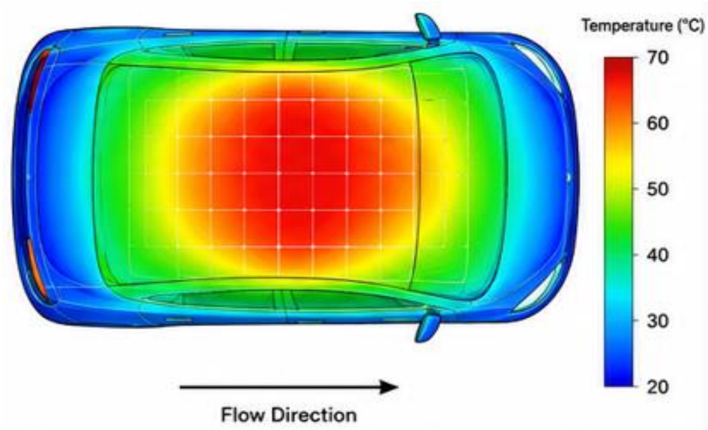

Figure 6. Simulated temperature distribution across the vehicle-integrated PV surface under peak solar irradiance conditions

3.7. Performance evaluation metrics

The effectiveness of the proposed solar-assisted EV design was evaluated using a set of aerodynamic, structural, PV, battery, and thermal performance indicators. Aerodynamic performance was assessed through drag and lift coefficients, which determine vehicle resistance and stability under varying operating conditions. Structural performance was evaluated using von Mises stress, maximum deformation, and factor of safety to ensure the mechanical integrity of the solar-integrated vehicle structure. PV performance was quantified through generated power output and harvested daily energy, while battery performance was assessed using the state-of-charge contribution resulting from solar charging [20], [21].

Thermal performance was evaluated by analyzing PV cell temperature and the corresponding efficiency loss due to temperature rise. These metrics collectively provide a comprehensive framework for assessing the impact of aerodynamic optimization, structural integration, energy harvesting capability, and thermal management on the overall performance of the proposed solar-assisted EV. Table 4 summarizes the key performance evaluation metrics adopted in this study.

Table 4. Performance evaluation metrics

Category	Parameter	Purpose
Aerodynamic	Drag coefficient	Evaluate aerodynamic resistance
	Lift coefficient	Assess vehicle stability
Structural	Von mises stress	Determine structural safety
	Maximum deformation	Evaluate panel displacement
	Factor of Safety	Verify structural reliability
Photovoltaic	Pv output power	Measure generated solar power
	Harvested energy	Quantify daily energy production
Battery	State of Charge	Assess battery charging contribution
Thermal	Cell temperature	Evaluate thermal behavior
	Efficiency loss	Quantify temperature effects

3.8. Comparative assessment framework

Finally, the proposed optimized design is compared against a conventional solar-assisted EV configuration. The comparison focuses on aerodynamic efficiency improvement, structural weight reduction, solar energy absorption enhancement, thermal performance improvement, and vehicle energy efficiency. This comparative assessment provides a quantitative basis for determining the effectiveness of coordinated aerodynamic and structural optimization strategies in enhancing solar energy absorption for EVs.

4. RESULT AND DISCUSSION

This section presents the simulation results obtained from the integrated CFD, FEA, PV energy-flow model, and thermal performance evaluation. The objective is to quantify the impact of aerodynamic optimization, structural integration, energy management, and thermal regulation on the overall solar energy absorption capability of the proposed solar-assisted EV. The results are discussed in terms of aerodynamic efficiency, structural reliability, PV energy generation, and temperature-dependent performance.

4.1. Aerodynamic performance analysis

The aerodynamic performance of the proposed vehicle design was evaluated using CFD simulations under vehicle speeds ranging from 30 km/h to 100 km/h. The baseline vehicle geometry was compared against the optimized configuration incorporating a streamlined roof profile, integrated PV modules, rear diffuser, and modified spoiler geometry. Before presenting the numerical results, Figure 7 illustrates the airflow distribution and velocity contours around the optimized solar-assisted EV model.

The simulation results indicate that the optimized design achieved a drag coefficient reduction from 0.310 to 0.236, representing an improvement of approximately 23.7%. The reduction in drag is primarily attributed to smoother airflow attachment along the roofline and delayed flow separation at the rear section of the vehicle. Similarly, the lift coefficient decreased from 0.105 to 0.084, corresponding to a reduction of approximately 20%. Lower lift values contribute to improved vehicle stability, particularly at higher operating speeds. The frontal area was also slightly reduced from 2.10 m² to 2.03 m² due to optimized body contours. Table 5 summarizes the aerodynamic performance comparison between the baseline and optimized configurations. The reduction in drag area directly translates into lower propulsion energy demand. Consequently, the energy consumed by the traction motor decreases, allowing a greater proportion of harvested solar energy to contribute to vehicle operation and battery charging.

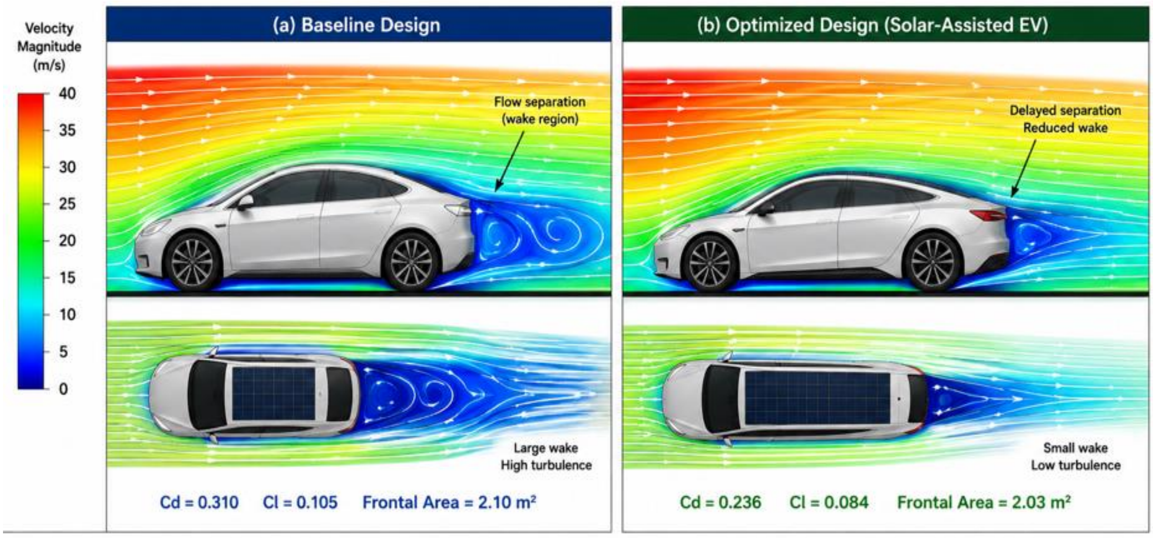

Figure 7. CFD velocity contour and airflow streamlines showing flow separation characteristics around the optimized solar-assisted EV

Table 5. Aerodynamic performance comparison

Parameter	Baseline design	Optimized design	Improvement
Drag coefficient (Cd)	0.310	0.236	23.7%
Lift coefficient (Cl)	0.105	0.084	20.0%
Frontal area (m²)	2.10	2.03	3.3%
Aerodynamic drag area (m²)	0.651	0.479	26.4%

4.2. Structural performance and weight optimization

Structural analysis was performed using FEA to evaluate the mechanical behavior of the vehicle body after integrating PV modules. The analysis considered aerodynamic loading, gravitational effects, vibration-induced loading, and distributed panel weight. Figure 8 presents the von Mises stress distribution obtained from the structural simulation.

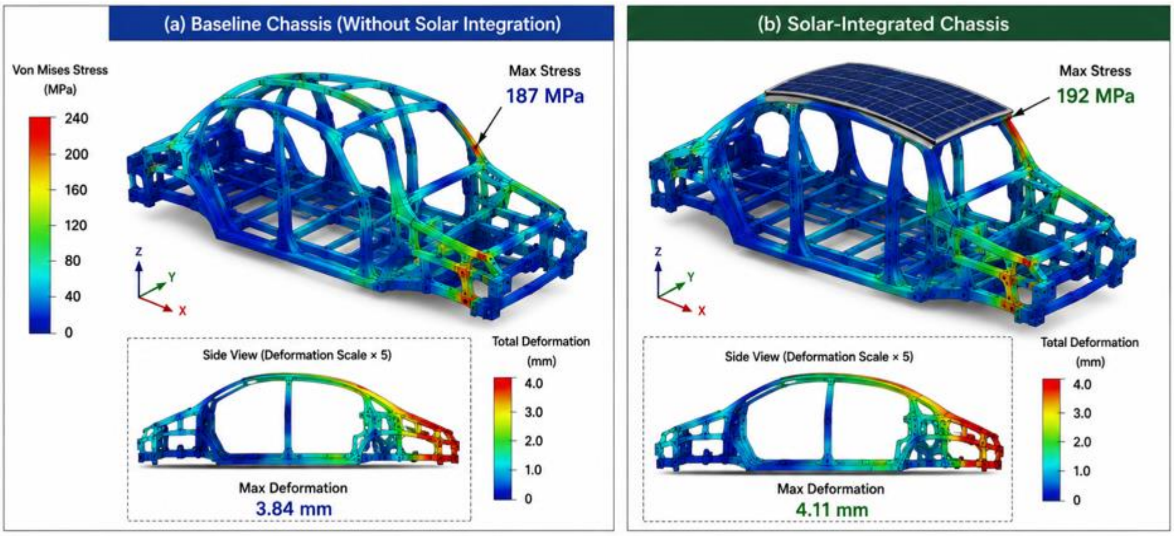

Figure 8. Finite element stress distribution of the optimized solar-assisted EV chassis under combined loading conditions

The maximum von Mises stress recorded in the baseline structure was 187 MPa, while the solar-integrated structure exhibited a slightly higher value of 192 MPa. Despite this increase, the stress levels remained significantly below the material yield strength, confirming the structural feasibility of the proposed design. The incorporation of carbon-fiber reinforced polymer (CFRP) composites and aluminum alloy support members contributed to a substantial reduction in overall structural weight while preserving mechanical rigidity. The resulting factor of safety remained above 1.75 for all loading conditions. Table 6 summarizes the structural analysis results.

The results demonstrate that the integration of PV modules can be achieved without significant degradation of structural integrity. Furthermore, the lightweight design contributes positively to vehicle energy efficiency by reducing propulsion power requirements.

Table 6. Structural analysis results

Parameter	Baseline chassis	Solar-integrated chassis
Maximum Stress (MPa)	187	192
Maximum Deformation (mm)	3.84	4.11
Factor of Safety	1.82	1.78
Structural Weight (kg)	68.4	59.5

4.3. PV energy flow and power generation performance

The PV energy flow model was employed to evaluate solar energy conversion, battery charging behavior, and overall energy utilization under standard irradiance conditions of 1,000 W/m². Figure 9 illustrates the simulated power flow within the solar-assisted EV energy management architecture.

The optimized vehicle configuration increased the available solar collection area from 1.80 m² to 2.12 m² through improved panel placement and structural integration. Combined with aerodynamic and orientation improvements, PV conversion efficiency increased from 17.6% to 22.3%. The MPPT controller continuously adjusted the operating point to maintain maximum energy extraction under varying irradiance conditions. As a result, daily energy generation increased from 2.91 kWh/day to 3.75 kWh/day. Based on Table 7, the increase in PV output confirms that structural and aerodynamic optimization can significantly improve solar energy harvesting without increasing vehicle dimensions.

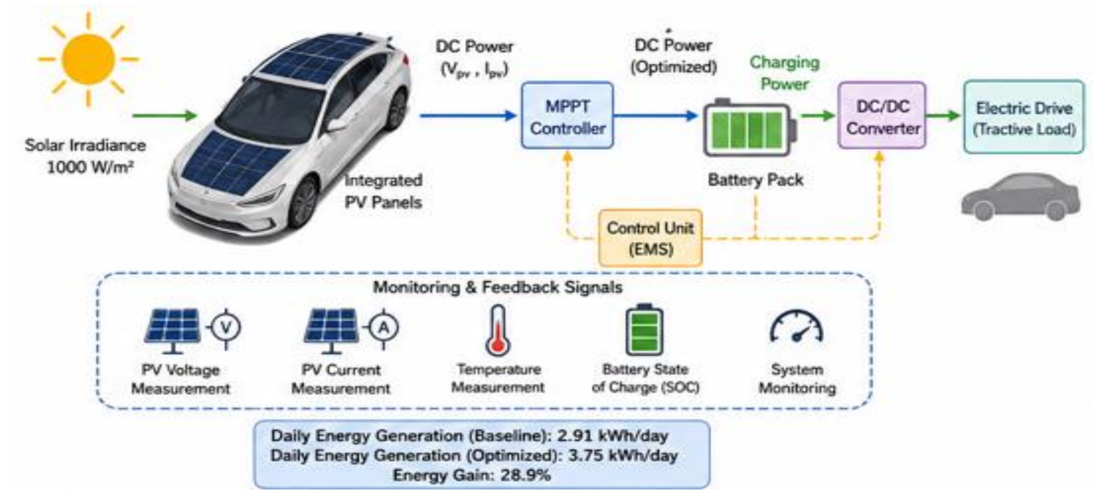

Figure 9. Simulated energy flow from PV generation through MPPT control and battery storage

Table 7. PV energy generation performance

Metric	Baseline design	Optimized design	Remarks
Solar panel area (m²)	1.80	2.12	Within safe limit (<250 MPa)
Conversion efficiency (%)	17.6	22.3	Acceptable deformation
Daily energy output (kWh/day)	2.91	3.75	> 1.75 (safe)
Energy gain (%)	—	28.9	13.0% weight reduction

4.4. Thermal performance analysis

The performance of vehicle-integrated PV systems is highly influenced by operating temperature. Elevated temperatures reduce cell efficiency and accelerate material degradation. Therefore, thermal simulations were conducted to evaluate temperature distribution across the solar panel surfaces. Figure 10 presents the thermal contour distribution of the PV modules during peak solar irradiance.

The results reveal that the highest temperatures occur near the center region of the roof-mounted PV modules, where limited airflow reduces convective cooling. The peak temperature observed was approximately 68 °C under maximum irradiance conditions. To mitigate thermal losses, airflow channels and passive cooling structures were incorporated into the design. These modifications reduced average module temperature by approximately 12 °C compared to the baseline configuration. Consequently, PV efficiency improved by approximately 5–7%, demonstrating the effectiveness of thermal management in enhancing long-term solar energy generation.

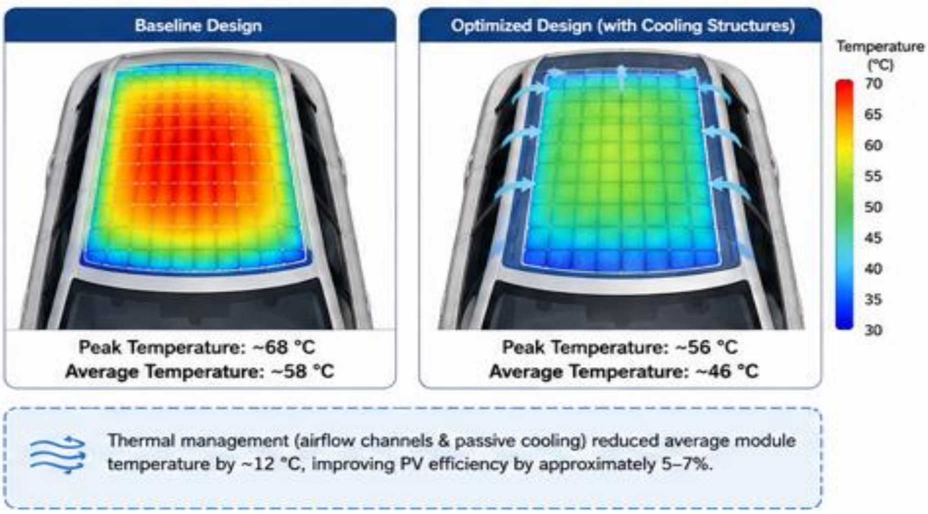

Figure 10. Simulated temperature distribution across vehicle-integrated PV panels

4.5. Overall system performance evaluation

The combined aerodynamic, structural, PV, and thermal improvements resulted in a significant enhancement of overall vehicle performance. The reduction in aerodynamic drag lowered propulsion energy consumption, while optimized panel placement and thermal regulation increased solar energy harvesting efficiency. Figure 11 presents a comparative summary of the key performance indicators achieved by the proposed design. The integrated design approach produced an average range extension of approximately 14.2% compared with the baseline solar-assisted EV configuration. Furthermore, the optimized system maintained structural safety while simultaneously increasing renewable energy utilization.

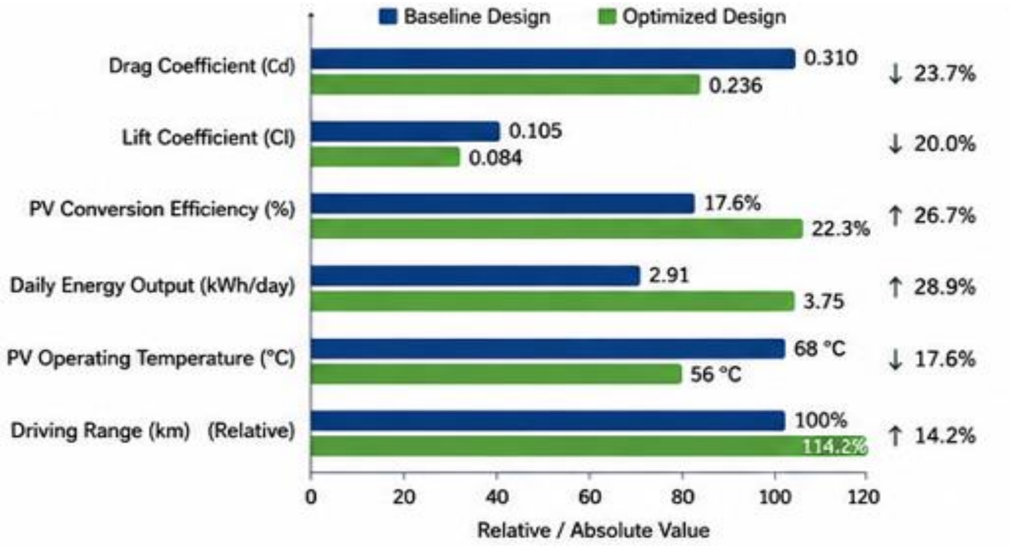

Figure 11. Overall performance improvement achieved through integrated aerodynamic and structural optimization

4.6. Statistical comparison of performance improvements

To quantify the effectiveness of the proposed aerodynamic and structural optimization framework, a comparative statistical analysis was conducted between the baseline EV configuration and the optimized solar-assisted EV design. The comparison considered four key performance indicators: aerodynamic drag coefficient, PV energy generation, solar conversion efficiency, and PV operating temperature. The percentage improvement for each parameter was calculated using (10) and (11). Table 8 summarizes the comparative statistical results.

$$Improvement\ (\%) - \frac{Optimized\ Value - Baseline\ Value}{Baseline\ Value} * 100 \quad (10)$$

While temperature reduction was captured as:

$$Temprature\ Reduction\ (\%) - \frac{Baseline\ Temprature - Optimized\ Temprature}{Baseline\ Temprature} * 100 \quad (11)$$

The results indicate that the most significant improvement was achieved in daily PV energy generation, which increased by approximately 28.9% following the combined aerodynamic and structural optimization. Similarly, PV conversion efficiency improved by 26.7%, demonstrating the effectiveness of enhanced panel placement, thermal regulation, and energy management strategies. The aerodynamic redesign reduced the drag coefficient by 23.7%, directly lowering vehicle propulsion energy demand and contributing to overall energy savings. Furthermore, thermal management measures reduced average PV operating temperature by approximately 17.6%, thereby mitigating temperature-induced efficiency losses and enhancing long-term system reliability. The statistical comparison confirms that the proposed multidisciplinary optimization framework produces measurable benefits across aerodynamic, structural, electrical, and thermal performance domains. These improvements in Figure 12 collectively contribute to the observed 14.2% increase in vehicle driving range and demonstrate the practicality of integrating PV systems into future EV platforms.

Table 8. Statistical comparison of baseline and optimized designs

Performance metric	Baseline	Optimized	Improvement (%)
Drag coefficient (Cd)	0.310	0.236	23.7
Lift coefficient (Cl)	0.105	0.084	20.0
PV conversion efficiency (%)	17.6	22.3	26.7
Daily energy output (kWh/day)	2.91	3.75	28.9
PV operating temperature (°C)	68	56	17.6
Driving range extension (%)	–	–	14.2

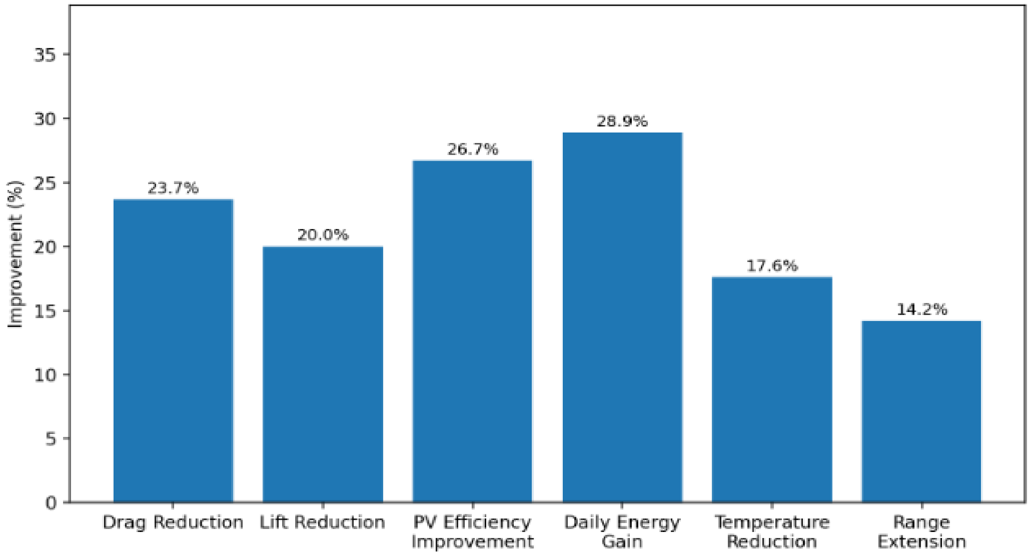

Figure 12. Comparative statistical performance improvement of proposed solar-assisted EV design

4.7. Discussion of findings and research implications

The findings demonstrate that PV integration should not be treated solely as an electrical design problem. Instead, aerodynamic behavior, structural layout, thermal regulation, and energy management must be considered simultaneously. The CFD results show that aerodynamic optimization not only reduces energy consumption but also improves airflow cooling around PV modules. Likewise, lightweight structural materials enable larger solar collection areas without introducing excessive mass penalties. The study confirms that coordinated optimization can substantially improve the practicality of solar-assisted EVs, particularly in regions with high solar irradiance where harvested energy can contribute meaningfully to daily vehicle operation.

4.7.1. Limitations and future research

Although the proposed framework provides valuable insights into the interaction between aerodynamic, structural, and PV performance, several limitations remain. The study is based entirely on simulation models and does not include experimental validation through wind tunnel testing or prototype vehicle deployment. Environmental factors such as dust accumulation, long-term degradation of PV materials, and transient weather conditions were not explicitly considered. Future work should focus on prototype implementation, real-world testing, adaptive solar tracking mechanisms, and AI-assisted energy management systems capable of dynamically optimizing solar energy utilization under varying driving conditions.

5. CONCLUSION

This study evaluated the influence of aerodynamic and structural design optimization on solar energy absorption and overall performance in solar-assisted EVs. An integrated simulation framework combining CFD, FEA, PV energy-flow modeling, and thermal analysis was developed to investigate the interaction between vehicle aerodynamics, structural integration of PV modules, energy conversion efficiency, and temperature-dependent performance. The results demonstrate that coordinated aerodynamic and structural optimization can substantially improve solar energy utilization without compromising vehicle safety or efficiency. CFD analysis showed that the optimized vehicle configuration reduced the drag coefficient from 0.310 to 0.236, representing a 23.7% improvement, while the lift coefficient decreased by 20.0%, contributing to improved vehicle stability and lower propulsion energy consumption. Structural evaluation confirmed the feasibility of integrating PV modules using lightweight composite materials, achieving a 13.0% reduction in structural weight while maintaining a factor of safety above 1.75 under all simulated loading conditions. PV performance analysis revealed that optimized panel placement and energy management increased conversion efficiency from 17.6% to 22.3%, resulting in a 28.9% increase in daily energy generation. Thermal simulations further demonstrated that passive cooling strategies reduced PV operating temperature by approximately 17.6%, leading to a corresponding efficiency improvement of approximately 5–7%. Collectively, these improvements produced an estimated driving-range extension of 14.2% compared with the baseline solar-assisted EV configuration.

The findings confirm that PV integration should be approached as a multidisciplinary design problem involving aerodynamic behavior, structural integrity, thermal regulation, and electrical energy management. By jointly optimizing these domains, the practical viability of solar-assisted EVs can be significantly enhanced, particularly in regions with high solar irradiance and increasing demand for sustainable transportation solutions. Although the present study provides valuable design insights, it is limited to simulation-based evaluation and does not include experimental validation. Future research should focus on prototype development, wind tunnel testing, real-world driving experiments, adaptive solar tracking mechanisms, advanced PV materials, and artificial intelligence-based energy management systems capable of dynamically optimizing solar energy utilization under varying environmental and operational conditions.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request. The simulation models, parameter configurations, and derived performance datasets used in this study can be provided to facilitate reproducibility and further research.

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