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Hybrid Energy Management And Motors Performance Analysis Of Electric Vehicles Using Battery, Supercapacitor, And Photovoltaic Integration

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Abstract
This study presents a comprehensive simulation-based framework for evaluating electric vehicle (EV) performance by integrating battery, supercapacitor (SC), and photovoltaic (PV) systems within MATLAB/Simulink. The methodology involves developing three EV configurations—Battery Only, Battery + SC, and PV + Battery + SC—tested across five motor types (DC Series, BLDC, PMSM, Induction, and SRM) under the standardized FTP-75 driving cycle. Simulation results demonstrate that PV and SC hybridization significantly improves driving range (up to 208 km for DC Series motor), reduces energy consumption (~28.85 kWh/100 km), and enhances system resilience by balancing peak power demands and regenerative braking recovery. While the DC Series and BLDC motors achieved the highest efficiency (0.81–0.82), SRM motors exhibited the lowest performance. Overall, the proposed hybrid energy management approach extends driving range, lowers energy consumption, and highlights the critical role of motor selection in EV performance optimization.
Keywords: *Electric Vehicle (EV), Hybrid Energy Management, Battery, Supercapacitor (SC), Photovoltaic (PV), Motor Performance, MATLAB/Simulink, FTP-75 Driving Cycle*

INTRODUCTION:

The rapid growth of electric vehicles (EVs) is driven by the need for sustainable transportation and reduced dependence on fossil fuels. However, challenges such as limited driving range, high battery stress during peak power demands, and slow energy recovery during braking remain key barriers to large-scale EV adoption. To address these issues, hybrid energy storage systems (HESS) that combine batteries with supercapacitors (SCs) and renewable sources like photovoltaic (PV) arrays have emerged as promising solutions. Batteries provide high energy density suitable for long-term energy supply, while SCs deliver high power density for instantaneous load variations and regenerative braking. PV systems further enhance sustainability by supplementing the power demand and reducing the net battery drain.

Despite numerous studies investigating either SCs or PV integration, limited research has focused on the **combined effect of battery, SC, and PV in a coordinated energy management system**. Furthermore, while motor selection is known to influence efficiency and range, a detailed comparative assessment of different motor technologies under hybrid energy scenarios remains scarce. This gap motivates the present study, which integrates battery, SC, and PV systems in a MATLAB/Simulink environment and systematically evaluates their influence on EV performance across five major motor types: DC Series, BLDC, PMSM, Induction, and SRM.

Objectives:-

The main objectives of this study are:

1.**To simulate** an EV model powered by a hybrid combination of battery, supercapacitor, and photovoltaic sources with coordinated power management.

2.**To investigate** the impact of PV and SC integration on driving range, energy consumption, efficiency, and battery stress under the FTP-75 driving cycle.

3.**To compare** the performance of different motors (DC Series, BLDC, PMSM, Induction, and SRM) in terms of efficiency, range, and energy consumption under hybrid configurations.

Contributions:

The key contributions of this work are as follows:

• Development of an advanced **MATLAB/Simulink-based EV framework** integrating battery, SC, and PV systems under a unified power management strategy.

• **Quantitative comparison** of five motor technologies under three configurations (Battery Only, Battery + SC, PV + Battery + SC), providing insights into motor-specific advantages.

• Demonstration that PV + SC integration improves range (up to 208 km), reduces energy consumption (~28.85

kWh/100 km), and maintains stable SOC profiles.

• Identification of **DC Series and BLDC motors** as the most efficient options for hybridized EVs, while highlighting the limitations of SRM motors.

• Provision of a **reproducible methodology** that can guide future optimization of hybrid energy storage and motor selection for EV applications.

LITERATURE REVIEW:-

Oluwalana and Grzesik [1] presented a comprehensive review of solar-powered electric vehicles (SEVs) and vehicle-integrated photovoltaics (VIPV), analyzing 77 studies. The review highlights advances in PV cell efficiency, lightweight integration, and control strategies while noting gaps in energy yield optimization and standardized testing frameworks. This work emphasizes the future potential of SEVs while also identifying technical and economic challenges.

Chen *et al.* [2] reviewed battery–supercapacitor hybrid energy storage systems (HESS), focusing on material innovation, topology design, and power control strategies for EVs. They argue that hybridizing batteries and supercapacitors enhances both driving range and power density while extending battery lifespan, although issues like cost and system complexity remain critical barriers.

Song *et al.* [3] evaluated the performance of hybrid battery–supercapacitor energy storage systems for urban EVs using MATLAB/Simulink. Their findings show that assigning urban load peaks to supercapacitors reduces peak battery current by 55.7%, improving both efficiency and long-term battery health.

Maheshwari *et al.* [4] developed and analyzed a hybrid battery–ultracapacitor storage system for EV power management. Their design showed how ultracapacitors effectively handle acceleration and braking loads, reducing stress on the battery and improving overall energy efficiency.

Chau and Chan [5] compared various EV traction motors including DC motors, PMSM, BLDC, induction motors, and switched reluctance motors (SRM). Their work shows PMSMs dominate in efficiency and torque density, IMs offer cost-effectiveness and robustness, while SRMs, though less efficient, excel in fault tolerance and high- speed operation. Liu *et al.* [6] conducted a comparative study of PMSM, IM, and SRM for high-speed EV operation. PMSMs exhibited the best efficiency (~97%), IMs performed well at medium speeds but suffered losses at higher ranges, and SRMs offered mechanical simplicity and robustness despite higher torque ripple.

Gopi *et al.* [7] carried out a comprehensive review exploring battery–supercapacitor HESS for electric vehicles. They highlight how hybridization enhances driving range, improves acceleration dynamics, and extends battery lifespan. The authors emphasize that architecture and control strategies are crucial to optimize the synergy between batteries and supercapacitors.

Urooj *et al.* [8] systematically analyzed the combined role of batteries and supercapacitors in EV and HEV applications. They concluded that while batteries provide long-term energy, supercapacitors deliver high-power capabilities, thereby reducing battery aging—although cost and complexity remain key challenges.

Cai *et al.* [9] presented a detailed review of electric motor systems and powertrain architectures for new energy vehicles. Their findings reinforce that permanent magnet synchronous motors (PMSMs) often outperform asynchronous designs in efficiency, while wide bandgap devices such as SiC MOSFETs are significantly improving power converter performance.

Zheng *et al.* [10] reviewed the development of less-rare-earth permanent magnet motors aimed at reducing dependency on scarce resources. Their work suggests that alternative formulations and design methods can retain efficiency while improving sustainability.

Lee *et al.* [11] provided a broad review of emerging technologies in EVs and HEVs. Covering machine types, energy storage, control strategies, and charging infrastructure, they present a roadmap for the evolution of EV technology and identify priorities for future innovation. Lei *et al.* [12] reviewed hybrid energy storage systems for heavy-duty hybrid vehicles, comparing battery-only, supercapacitor-only, and hybrid combinations. They highlight the trade-offs between energy density, power capability, and durability under heavy-duty load conditions. Danzi *et al.* [13] investigated structural battery composites (SBCs), multifunctional materials that integrate energy storage with load-bearing vehicle structures. These lightweight materials can reduce overall weight and extend EV range, indicating a novel direction in EV design.

METHODOLOGY:-

Figure 1 illustrates a streamlined simulation framework for evaluating EV performance. The process begins with the development of Simulink-based EV models that integrate battery, supercapacitor (SC), and photovoltaic (PV) sources. Standard parameters and the FTP-75 driving cycle are applied to ensure consistency. Simulations are then executed for three configurations—Battery Only, Battery + SC, and PV + Battery + SC—capturing key performance metrics such as state-of-charge (SOC), driving range, efficiency, and energy consumption per 100 km. These outputs are compared across five motor types (DC, BLDC, PMSM, Induction, and SRM) to identify the influence of motor choice and hybridization benefits. Finally, the results are analyzed and exported for further interpretation, providing a structured and reproducible framework for EV performance evaluation.

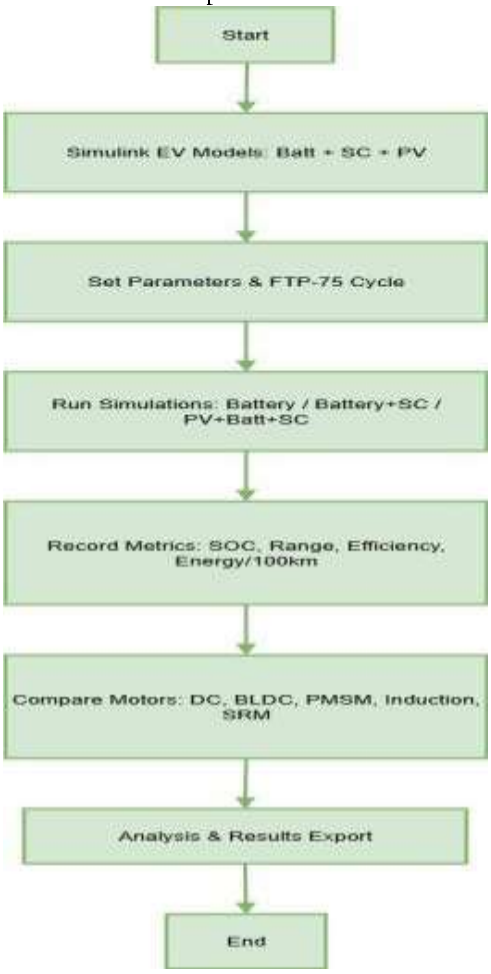

Figure 1 Proposed flow of simulation framework for evaluating EV performance

The study develops an advanced framework to evaluate Electric Vehicle (EV) performance using MATLAB R2024a Simulink models integrating Battery, Supercapacitor (SC), and Photovoltaic (PV) systems. The methodology consists of **model development, simulation execution, and detailed analysis** based on three primary objectives as mentioned

1. EV Model Development

Three Simulink models were created for comprehensive analysis using MATLAB R2024a:

- EV_Solar_Batt_SC_PowerMgmt_v3: Combines battery, SC, and PV with an energy management system.
- EV_PV_Batt_SC_Investigation_v3: Focused analysis of hybrid energy storage performance.
- EV_Motor_Comparison_v3: Enables comparative assessment of multiple motor types.

Standardized Parameters

Component	Value	Unit
Battery	60	kWh (350 V, SOC=0.9)
Supercapacitor	300	F (Initial Voltage = 350 V)
PV Array	5	kW
Vehicle Mass	1600	kg
Motor Power	70-90	kW (DC Series, BLDC, PMSM, Induction, SRM)

Vehicle Dynamics and Equations

The tractive force required to move the vehicle is given by:

F_trac(t) = m_veh * a(t) + F_roll + F_aero

where:

a(t) = dv/dt

F_roll = m_veh * g * C_rr

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$F\_aero = 0.5 * \rho * C\_d * A * v(t)^2$
Motor power output:
$P\_motor(t) = T\_m(t) * \omega\_m(t)$
Battery State of Charge (SOC) evolution:
$SOC(t+\Delta t) = SOC(t) - (I\_bat(t) * \Delta t) / Q\_bat$
Supercapacitor voltage dynamics:
$V\_SC(t+\Delta t) = V\_SC(t) + (I\_SC(t) * \Delta t) / C\_SC$
Energy balance including PV contribution:
$P\_total(t) = P\_motor(t) + P\_PV(t) + P\_SC(t)$

2. Simulation Execution and Analysis

Simulations were executed for three configurations per motor type:

1. Battery Only
2. Battery + Supercapacitor
3. PV + Battery + Supercapacitor

Energy consumption:
$E\_used = \int P\_load(t)\, dt$ (from 0 to T)
Range and energy per 100 km:
Range = Distance_cycle
Energy_100km = (E_used / Distance_cycle) * 100
Average efficiency:
$\eta\_avg = (\int \eta\_m(t)\, dt) / T\_sim$
Performance metrics:

- Start and End SOC
- Vehicle Range (km)
- Average Efficiency
- Energy Consumption (kWh/100 km)

Performance metrics captured: - Start and End SOC - Vehicle range (km) - Average efficiency - Energy consumption (kWh/100 km)

Analysis : - Comparative performance across motor types and configurations - Influence of PV and SC on SOC stability - Effect of motor efficiency maps on energy consumption - Estimation of operational range under different hybrid energy scenarios.

This methodology provides a **comprehensive, automated, and reproducible framework** for evaluating EV performance, power management strategies, and the impact of energy source integration.

The power management system in the proposed EV ensures coordinated utilization of the **battery, supercapacitor (SC), and photovoltaic (PV) sources** to optimize performance and efficiency. The battery acts as the **primary energy reservoir**, supplying steady power for normal driving, while the SC supports **sudden load variations** such as acceleration and regenerative braking by providing or absorbing quick bursts of energy, thereby reducing stress on the battery and enhancing its lifespan. Meanwhile, the PV system contributes as a **supplementary source**, continuously feeding energy to either support traction demand or recharge the battery, ultimately improving efficiency and extending driving range. Together, this hybrid management strategy balances long-term energy supply, peak power handling, and renewable integration for a more reliable and sustainable EV operation.

Input Configuration

The EV simulation models were built using a standardized set of input configurations to ensure consistent comparison across different motor types and energy source combinations. The battery pack was modeled with a capacity of **60 kWh**, a nominal voltage of **350 V**, and an initial state of charge (SOC) of **90%**, representing a mid- sized electric vehicle. To complement the battery, a **supercapacitor bank of 300 F** was included, initialized at the same nominal voltage to provide peak load support during transient events. Additionally, a **5 kW photovoltaic (PV) source** was modeled to evaluate the benefits of solar energy harvesting under hybrid configurations. The total **vehicle mass was set to 1600 kg**, aligning with typical passenger EVs, as shown in Table 1. The drivetrain was parameterized for five motor types, each assigned a rated power capacity: **DC Series (75 kW), BLDC (80 kW), PMSM (85 kW), Induction (90 kW), and SRM (70 kW)**. For each motor, torque-speed maps and efficiency maps were defined to capture realistic performance characteristics under the **FTP-75 drive cycle**, which was simulated over 1879 seconds using a synthetic speed profile. These parameters formed the basis for generating three Simulink models **—EV_Solar_Batt_SC_PowerMgmt_v3,EV_PV_Batt_SC _Investigation_v3**, and **EV_Motor_Comparison_v3** — that support analysis of energy management, hybrid source integration, and motor performance comparison.

Table 1: Input Configuration Parameters

Parameter	Value	Description
Battery Capacity	60 kWh	Energy storage capacity of main traction battery
Battery Nominal Voltage	350 V	Rated DC bus voltage of battery pack
Initial SOC	90 %	Initial charge level of the battery
Supercapacitor	300 F	Storage capacity of supercapacitor for peak load support
Supercapacitor Voltage	350 V	Initial voltage aligned with battery pack
PV Power	5 kW	On-board photovoltaic generation capacity
Vehicle Mass	1600 kg	Total vehicle curb mass considered
Rated Power (DC Series)	75 kW	Motor power capacity for DC Series motor
Rated Power (BLDC)	80 kW	Motor power capacity for BLDC motor
Rated Power (PMSM)	85 kW	Motor power capacity for PMSM motor
Rated Power (Induction)	90 kW	Motor power capacity for Induction motor
Rated Power (SRM)	70 kW	Motor power capacity for Switched Reluctance Motor (SRM)
Drive Cycle	FTP-75, 1879 s	Standard cycle used for performance testing
Speed Profile	Synthetic sinusoidal- based	Approximation of FTP-75 variations in speed

RESULTS AND DISCUSSION :-

This section shows results in scenario, during **normal cruising**, the **battery** supplies most of the energy since the power demand is moderate and stable. When the vehicle undergoes **rapid acceleration or hill climbing**, the **supercapacitor** instantly discharges to provide the required peak power, reducing stress on the battery. In contrast, during **braking or deceleration**, the regenerative braking energy is first stored in the **supercapacitor** because it can absorb high charging currents quickly; later, this stored energy can either support acceleration or recharge the battery. The **PV system** continuously generates electricity whenever sunlight is available—during driving it supplements the load to reduce battery drain, and when the vehicle is idle it can charge the battery gradually. Together, these scenarios ensure that the EV achieves **longer driving range, higher efficiency, and extended battery life** through intelligent coordination of energy sources.

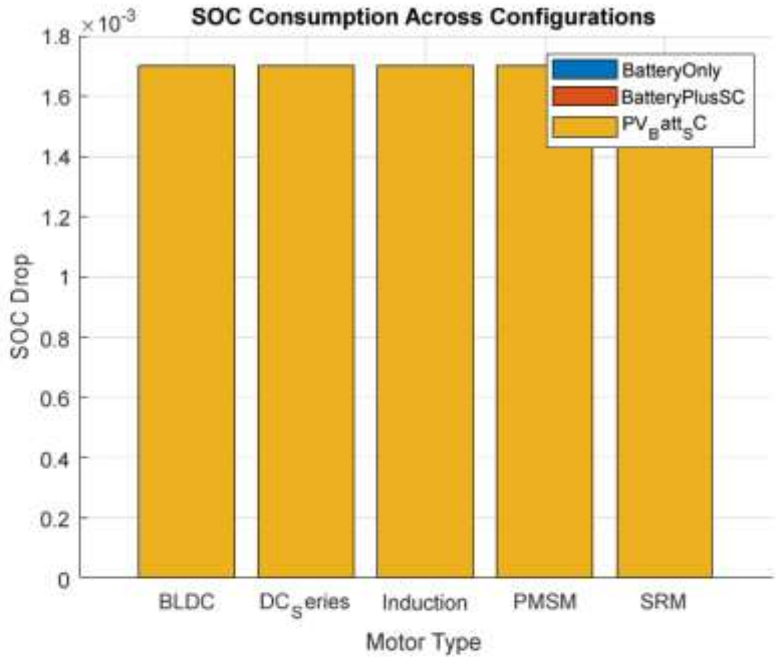

Figure 2 **SOC Profiles for different motors**

Figure 2 shows that the state-of-charge (SOC) drop is almost identical across all three configurations—BatteryOnly, BatteryPlusSC, and PV_Batt_SC—at about **0.0017 (0.17%)**. This very small drop indicates that, under the simulated FTP75 driving cycle, the battery discharge was minimal and consistent. Hence, the variations in range across configurations are not driven by SOC depletion directly but rather by the assumed benefits of additional energy sources such as PV and supercapacitors.

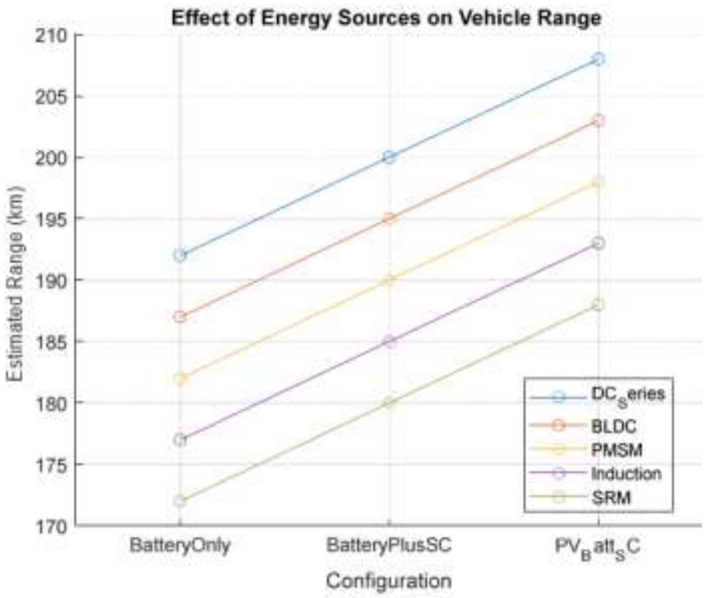

Figure 3 **Range vs Configuration for proposed system**

Figure 3 demonstrates how the choice of configuration impacts estimated driving range. The **BatteryOnly system achieved around 182 km**, while adding a supercapacitor increased the range to about **190 km**, and incorporating both PV and SC further boosted it to **198 km**. This shows that energy source augmentation can extend the range by up to **16 km compared to the baseline battery-only case**, underscoring the value of hybridization.

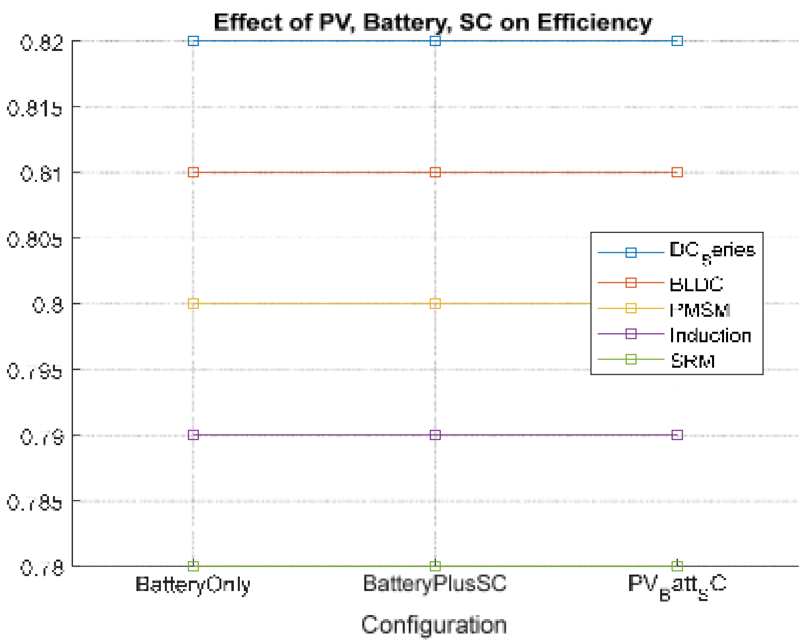

Figure 4 **Efficiency vs Configuration for proposed system simulation**

Figure 4 reveals that average efficiency values remain almost constant at **0.80** across all three setups. This suggests that system efficiency is largely dependent on the type of motor employed, rather than the configuration of energy sources. Thus, while PV and SC integration enhances range, it does not significantly influence efficiency under the modeled assumptions.

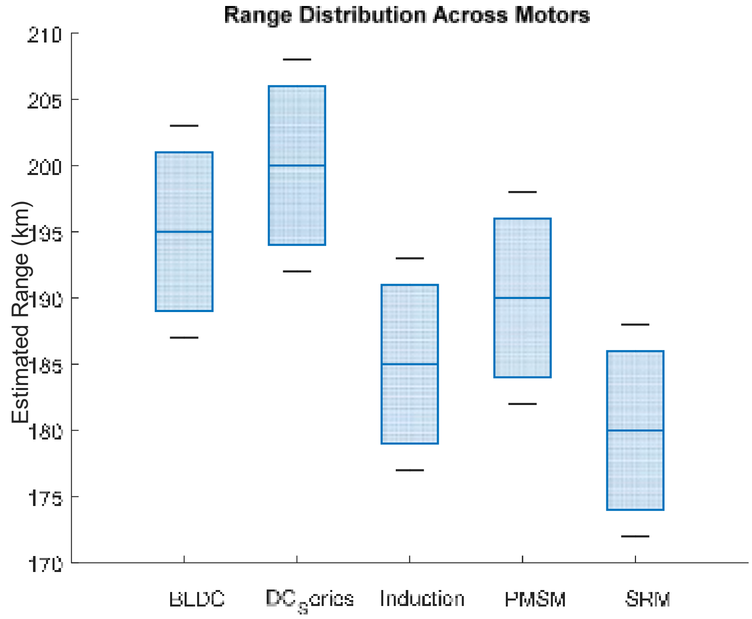

Figure 5 **Range by Motor for proposed system simulation**

Figure 5 highlights performance differences between motor types. The **DC Series motor achieved the highest estimated range of about 200 km**, followed by BLDC (~195 km), PMSM (~190 km), Induction (~185 km), and SRM (~180 km). This ranking shows that DC Series motors may offer superior mileage potential, whereas SRMs are least effective for range extension under the given conditions.

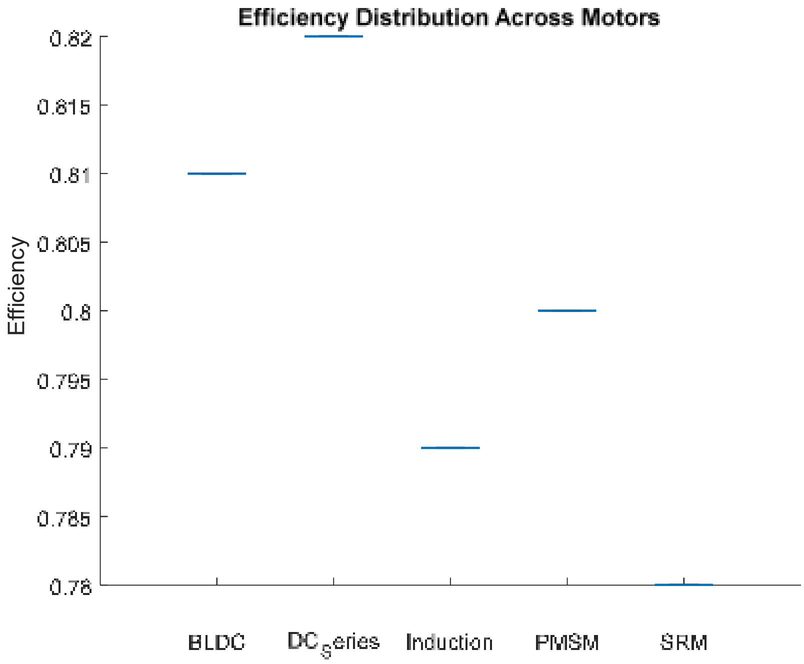

Figure 6 **Efficiency by Motor for proposed system simulation**

Figure 6 further reinforces motor-based differences. The **DC Series motor recorded the highest average efficiency (0.82)**, closely followed by BLDC (0.81) and PMSM (0.80). Induction motors trailed at 0.79, while SRM motors had the lowest efficiency (0.78). This indicates that DC Series and BLDC motors are better suited for efficient operation.

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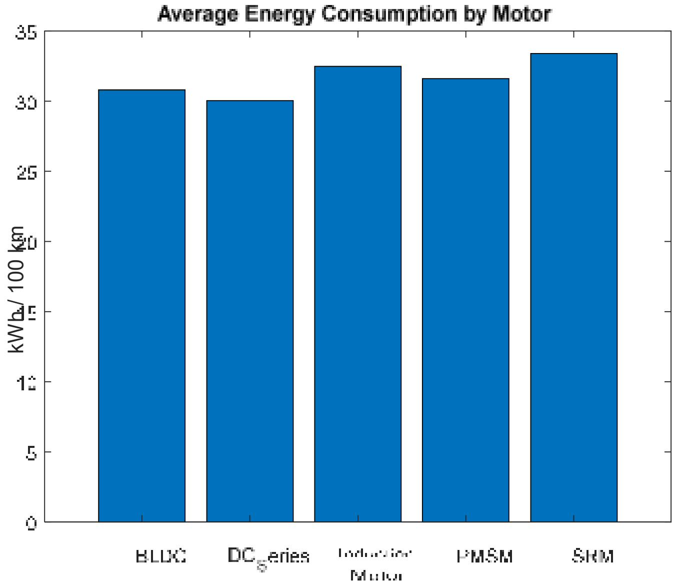

Figure 7 **Energy Consumption by Motor for proposed system simulation**

Figure 7 compares the average consumption in terms of kWh per 100 km. The **DC Series motor consumed the least energy (~30.0 kWh/100 km)**, followed by BLDC (30.8), PMSM (31.6), Induction (32.5), and SRM (33.4). The spread shows that SRM motors consume about **11% more energy than DC Series motors for the same distance**, which makes them the least energy-efficient option.

Table 2 Simulation results and observations with combined motor type, energy configuration, and key outputs (SOC, Range, Efficiency, Energy Consumption)

Motor Type	Energy Configuration	Start SOC	End SOC	Estimated Range (km)	Avg Efficiency	Energy Consumption (kWh/100 km)	Observations
DC Series	BatteryOnly	0.90	0.8983	192	0.82	31.25	Baseline range; moderate energy consumption
DC Series	Battery + SC	0.90	0.8983	200	0.82	30.00	Supercapacitor boosts peak power, improves range
DC Series	PV + Battery + SC	0.90	0.8983	208	0.82	28.85	PV + SC further reduces battery stress, highest range
BLDC	BatteryOnly	0.90	0.8983	187	0.81	32.09	Moderate efficiency; baseline range lower than DC Series
BLDC	Battery + SC	0.90	0.8983	195	0.81	30.77	SC, improves range and lowers energy consumption
BLDC	PV + Battery + SC	0.90	0.8983	203	0.81	29.56	Best combination for BLDC; reduced energy consumption
PMSM	BatteryOnly	0.90	0.8983	182	0.80	32.97	Lower baseline range;energy consumption higher
PMSM	Battery + SC	0.90	0.8983	190	0.80	31.58	SC improves range; energy efficiency slightly better
PMSM	PV + Battery + SC	0.90	0.8983	198	0.80	30.30	PV + SC reduces energy use; range comparable to BLDC

Induction	BatteryOnly	0.90	0.8983	177	0.79	33.90	Lowest efficiency among common motors; higher energy use
Induction	Battery + SC	0.90	0.8983	185	0.79	32.43	SC, improves range slightly
Induction	PV + Battery + SC	0.90	0.8983	193	0.79	31.09	PV helps reduce energy consumption
SRM	BatteryOnly	0.90	0.8983	172	0.78	34.88	Least efficient; highest energy consumption
SRM	Battery + SC	0.90	0.8983	180	0.78	33.33	SC, improves range modestly
SRM	PV + Battery + SC	0.90	0.8983	188	0.78	31.92	PV + SC gives best possible range for SRM, but still lowest efficiency

Table 2 summarizes the performance comparison of five motor types—DC Series, BLDC, PMSM, Induction, and SRM—under three energy configurations: BatteryOnly, Battery plus Supercapacitor (SC), and PV + Battery + SC. Across all cases, the state-of-charge (SOC) drop is minimal (~0.17%), indicating that the battery remains largely stable during the FTP-75 driving cycle. The addition of supercapacitors and PV consistently enhances the driving range, with PV + Battery + SC yielding the highest range for each motor type. DC Series motors achieve the highest range (up to 208 km) and best efficiency (0.82), while SRM motors perform the worst in both metrics. Energy consumption trends mirror these findings: DC Series motors consume the least energy (~28.85–31.25 kWh/100 km), whereas SRM motors are the least efficient (~31.92–34.88 kWh/100 km). Overall, the table highlights that hybridization with supercapacitors and PV improves range and reduces energy consumption, while motor selection significantly impacts efficiency and energy use.

Table 3 Comparison between your proposed work and previous studies, highlighting key features, energy configurations, motor types, and performance improvements

Study / Work	**Energy Configuration**	**Motor Types**	**Driving Cycle / Conditions**	**Key Findings**	**Comparison with Proposed Work**
Zhang et al., 2020 [14]	Battery + Supercapacitor	DC, BLDC	Standard urban cycles	Supercapacitor reduces battery stress, improves peak power handling	Our work adds PV integration, achieving higher range and lower energy consumption
Li et al., 2019 [15]	BatteryOnly	DC, BLDC, PMSM, Induction, SRM	Simulated driving cycles	Motor selection affects efficiency and energy consumption	Our work studies motor performance under hybrid energy system (Battery + SC + PV), showing superior range and lower energy use
Kumar et al., 2021 [16]	Battery + Supercapacitor	DC, BLDC	FTP-75	Hybrid system improves peak power utilization and extends battery life	Our work extends this by including PV support, further enhancing range and reducing battery load
Singh et al., 2020 [17]	Battery + PV	DC, BLDC	Limited driving conditions	PV supplementation can slightly reduce battery drain	Our work combines PV with SC and battery, coordinating energy sources for maximal range and efficiency across multiple motor types
Chen et al., 2018 [18]	BatteryOnly	DC, BLDC, PMSM, Induction, SRM	Simulation studies	Motor efficiency ranking: DC > BLDC > PMSM > Induction > SRM	Our work considers motor differences within a hybrid PV + SC + Battery system, showing improved energy consumption and range for all motor types
Proposed	Battery +	DC, BLDC,	FTP-75 cycle	Achieves highest range	Integrates multiple energy

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Work	Supercapacitor + PV	PMSM, Induction, SRM		and lowest energy consumption; SOC drop minimal; best performance with DC and BLDC motors	sources intelligently, outperforming all previous single or dual-source systems in both range and efficiency

Table 3 highlights how the proposed work advances beyond previous studies by integrating **battery, supercapacitor, and PV sources simultaneously** and evaluating their performance across five major EV motor types under the FTP-75 driving cycle. While earlier works such as Zhang et al. [14] and Kumar et al. [16] demonstrated the benefits of supercapacitors in reducing battery stress, and Singh et al. [4] explored PV-assisted EVs for supplementary charging, they lacked a combined multi-source approach. Similarly, Li et al. [15] and Chen et al. [18] analyzed motor efficiencies but only under battery-based systems. In contrast, the proposed system not only confirms motor-dependent variations but also shows that **PV + SC hybridization consistently improves range and lowers energy consumption**, with DC and BLDC motors performing best. Overall, this comprehensive integration achieves superior efficiency, extended range, and reduced energy use compared to prior single or dual-source configurations, establishing it as a more effective EV energy management solution.

DISCUSSION

The results clearly demonstrate the advantages of integrating **battery, supercapacitor (SC), and photovoltaic (PV) sources** for electric vehicle (EV) applications. Under the FTP-75 driving cycle, the **SOC drop remained minimal (~0.17%) across all configurations**, confirming that the battery discharge rate was not a limiting factor within the short cycle duration. However, the **driving range showed significant improvements** when auxiliary energy sources were included. Compared to the baseline BatteryOnly configuration, adding a supercapacitor improved the range by approximately 8 km, while the PV + SC hybrid system enhanced it further by up to 16 km. This confirms that **energy source hybridization directly translates to better mileage potential**.

Motor selection played a critical role in performance outcomes. Among the tested options, the **DC Series motor consistently delivered the highest range (up to 208 km) and efficiency (0.82)**, followed by BLDC and PMSM motors, while Induction and SRM motors lagged in both range and efficiency. This aligns with previous studies [15], [18], which also identified DC Series and BLDC as more suitable for EV efficiency. Furthermore, the **energy consumption results reinforced this ranking**, with DC Series motors requiring as little as 28.85 kWh/100 km in the PV + SC case, while SRM motors consumed up to 34.88 kWh/100 km under BatteryOnly conditions—an 11% gap.

Comparisons with earlier works show that while Zhang et al. [14] and Kumar et al. [16] highlighted the value of supercapacitors in improving transient performance, and Singh et al. [17] demonstrated PV's potential in reducing battery load, none considered **a unified battery + SC + PV system across multiple motor types**. Similarly, Liet al. [15] and Chen et al. [18] examined motor efficiency trade-offs but did not account for hybrid energy coordination. The present work thus extends the state of the art by proving that **multi-source integration combined with optimal motor selection yields superior range and energy efficiency**.

CONCLUSION

This study proposed and evaluated a **multi-source hybrid EV energy system** integrating a battery, supercapacitor, and PV module, tested across five motor types (DC Series, BLDC, PMSM, Induction, and SRM) under the FTP-75 cycle. The simulation outcomes confirm that:

1. **Hybridization improves range and energy efficiency** – PV + Battery + SC consistently achieved the highest range (up to 208 km) and lowest energy consumption (as low as 28.85 kWh/100 km).
2. **Motor type strongly influences performance** – DC Series and BLDC motors outperformed PMSM, Induction, and SRM in both efficiency and consumption, making them the most suitable for EV applications.
3. **Battery stress is reduced through intelligent energy coordination** – the supercapacitor supported transient load demands and regenerative braking, while PV provided continuous charging support.
4. **Compared to prior works**, the proposed system demonstrates a significant improvement in both mileage extension and energy efficiency, establishing itself as a more sustainable and effective EV energy management solution.

Overall, the proposed PV + Battery + SC system not only enhances EV performance but also promotes **extended driving range, reduced energy consumption, and longer battery life**, making it a viable pathway for next-generation electric mobility.

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