IJEAST

INTERNATIONAL JOURNAL OF ENGINEERING APPLIED SCIENCE AND TECHNOLOGY

VOLUME : 10 **ISSUE : 04** **Print / Issue Publication Date: 06-Oct-2025**

ISSN : 2455-2143

DOI : 10.33564/IJEAST.2025.v10i04.009

Indexed In

WWW.IJEAST.COM

editor@ijeast.com

International Journal of Engineering Applied Sciences and Technology, 2025
Vol. 10, Issue 04, ISSN No. 2455-2143, Pages 57-66
Published Online August 2025 in IJEAST (http://www.ijeast.com)

ELECTRICAL ENGINEERING INNOVATIONS IN EV POWERTRAIN DESIGN

Jayesh N. Patil
B.E Electrical Engineering
Govt. College of Engg, Chandrapur, MH, India

Prayag S. Patil
M.Tech Mechatronics Engineering
Vellore Institute of Technology, Vellore, TN, India

Ashvini S. Kolate
M.Sc Computer Science
PO Nahata College Bhusawal, MH, India

Pranav S. Patil
B,Tech E & TC Engineering
SSVPS College Of Engineering, Dhule, MH, India

Abstract— **The rapid electrification of the automotive industry demands continual advancements in electric vehicle (EV) powertrain technology. This review paper presents a comprehensive overview of recent innovations in electrical engineering that are reshaping EV powertrains, focusing on electric motors, power electronics, energy storage, and thermal management systems. Key developments include AI-driven control strategies enhancing motor performance, the adoption of wide bandgap semiconductors such as silicon carbide (SiC) and gallium nitride (GaN) for more efficient power conversion, breakthroughs in solid-state battery technology, and novel thermal management approaches using phase change materials and AI optimization. The paper also discusses modular powertrain architectures and highlights industry advances such as next-generation heat pump systems. Collectively, these innovations contribute to improving EV efficiency, range, and reliability, thereby accelerating the transition toward sustainable transportation.**

Keywords—**Electric Vehicle (EV), Powertrain, Power Electronics, Battery Technology, Thermal Management, Silicon Carbide (SiC), Gallium Nitride (GaN), AI Control**

I. INTRODUCTION

Electric vehicles (EVs) are central to global efforts aimed at reducing carbon emissions and achieving sustainable transportation. The powertrain comprising electric motors, power electronics, batteries, and thermal systems is critical in determining EV performance and efficiency. Recent electrical engineering breakthroughs have targeted these components, leveraging new materials, control algorithms, and system architectures. This paper reviews the state-of-the-art research from 2023 to 2025, synthesizing advances across motor technology, power electronics, energy storage, and thermal management, emphasizing their interdependence and impact on EV powertrain design.

II. LITERATURE SURVEY

A. Electric Motors and AI-Based Control –

Electric motor technology, particularly permanent magnet synchronous motors (PMSMs), remains at the forefront of EV propulsion due to their efficiency and power density. Li and Shao [1] demonstrated co-optimization strategies that blend vehicle dynamics with powertrain management using AI, enhancing energy efficiency under real-world conditions. Similarly, Wu et al. [2] applied reinforcement learning to hybrid vehicle energy management, showcasing how AI techniques optimize the balance between battery usage and fuel consumption. These studies reveal that AI-based control not only improves motor efficiency but also enables adaptive strategies that respond dynamically to driving conditions, thereby extending EV range and enhancing drivability.

B. Power Electronics: SiC and GaN Semiconductors

The integration of wide bandgap semiconductors such as silicon carbide (SiC) and gallium nitride (GaN) in power electronics has transformed inverter and charger design. Zahwan et al. [9] provided a detailed performance analysis of SiC and GaN traction inverters, showing superior thermal management and reduced switching losses compared to silicon counterparts. Chevinly et al. [10] explored GaN-based multilevel H-bridge inverters designed for wireless power transfer in EVs, highlighting significant improvements in power density and reduced heat generation. These semiconductors support high-frequency switching and operation at elevated temperatures, enabling smaller, lighter, and more efficient power electronic modules critical for maximizing EV range.

C. Energy Storage: Solid-State Batteries and Management Systems

Energy storage advancements focus on all-solid-state batteries (SSBs), which offer safety and energy density advantages over conventional lithium-ion batteries. Shah et al. [3], Zhang et al. [4], and Wang and Singh [5] provided comprehensive reviews of SSB materials, electrolytes, and architectures, emphasizing challenges like electrolyte interface stability and manufacturing scalability. Kumar and Lin [6] examined BMS technologies critical for monitoring and optimizing SSB performance. Alharthi and Gupta [8] reviewed predictive methods for battery capacity and health, which are crucial for effective range estimation and battery life extension. These technologies promise to alleviate current limitations in EV range and charging speed, fostering greater consumer adoption.

D. Thermal Management Innovations

Effective thermal management ensures optimal battery operation, motor efficiency, and longevity of power electronics. Rudolf et al. [11] introduced deep reinforcement learning algorithms for dynamic thermal management, demonstrating adaptive cooling strategies that optimize performance in real time. Kisomi [12] compared air cooling with phase change material (PCM) approaches, showing hybrid methods can maintain battery temperatures within safe limits under high loads. Alghassab [13] proposed integrating thermoelectric modules with PCMs for enhanced heat dissipation, while Patil and Chavan [14] performed numerical analyses on fin configurations to optimize cooling effectiveness. These studies highlight the growing trend toward combining advanced materials with AI-driven controls to meet the increasing thermal demands of high-performance EV powertrains.

E. Modular Powertrain Architectures and Industry Innovations

Modular design approaches offer scalability and manufacturing flexibility. Clemente et al. [15] demonstrated concurrent design optimization for powertrain modules across multiple EV models, enabling cost-effective component sharing without sacrificing performance. Industry advances such as Hanon Systems' 4th generation heat pump system [16–20] illustrate practical implementations that improve thermal management efficiency and vehicle heating/cooling capabilities. Such innovations exemplify the convergence of research and industry in developing integrated solutions for next-generation EVs.

III. METHODOLOGY

This review paper follows a structured methodology to identify, analyze, and synthesize the latest advancements in electric vehicle (EV) powertrain systems, with a focus on electrical engineering innovations. The research is based entirely on secondary data collected from high-quality academic and industry sources. To ensure the relevance and accuracy of the findings, only peer-reviewed research papers, conference proceedings, and technical articles published between 2023 and 2025 were considered. The selection includes studies that focus on electric motor design, power electronics, battery technologies, thermal management, and artificial intelligence in control systems, and modular powertrain architectures.

Technical research papers were selected based on their technical depth, relevance to the EV powertrain domain, and the novelty of their contributions. Industry whitepapers and technical reports from leading automotive and semiconductor companies were also included to provide practical insights and performance benchmarks. Each selected source was thoroughly reviewed to extract numerical data, performance comparisons, technical diagrams, and control strategies. Emphasis was placed on innovations that demonstrated measurable improvements in powertrain efficiency, reliability, integration, or manufacturing scalability. The review structure follows a component-based approach, grouping findings into specific areas such as power electronics, energy storage, motor control, thermal systems, and architecture. This allows for a comprehensive understanding of how each subsystem contributes to overall vehicle performance and how interdisciplinary innovations are driving the future of EV powertrain design.

IV. ELECTRIC MOTOR TECHNOLOGIES AND AI-BASED CONTROL STRATEGIES

Electric motors are the fundamental component of EV propulsion systems, and in this domain, Permanent Magnet Synchronous Motors (PMSMs) continue to dominate due to their high torque density, compact structure, and energy efficiency. Recent advancements in electrical engineering have focused not only on refining motor hardware, but also on developing intelligent control strategies to maximize efficiency and extend the operational range of electric vehicles.

Li and Shao [1] investigated an integrated control strategy that co-optimizes vehicle dynamics and powertrain operation using artificial intelligence techniques. Their study demonstrated that AI-driven motor control could reduce energy consumption by up to 13.6% in certain urban driving conditions compared to conventional control strategies. This reduction was achieved by dynamically adjusting the torque commands based on real-time driving inputs and vehicle load, allowing the motor to operate within optimal efficiency zones. The study's simulations also indicated improved thermal behaviour and reduced motor current ripple, contributing to longer motor life and lower maintenance requirements.

Similarly, Wu et al. [2] explored the use of deep reinforcement learning (DRL) to manage the power distribution in a hybrid electric vehicle (HEV) powertrain. Their experiments showed that the DRL-based energy management system could increase overall drivetrain efficiency by 11.5% and reduce fuel consumption by 9.8% compared to a rule-based controller. These improvements stemmed from the algorithm's ability to predict optimal power split between the internal combustion engine and the electric motor under various driving conditions, especially during start-stop and acceleration events.

Moreover, the application of AI in torque control allows for dynamic adjustment of control parameters, rather than relying on fixed lookup tables or linear models. As a result, modern EVs can adapt to changing terrain, vehicle load, and battery state-of-charge with greater precision, enhancing both performance and energy utilization. The integration of machine learning into motor control algorithms also improves fault detection and predictive maintenance capabilities. Real-time diagnostics driven by AI can identify anomalies in motor temperature, torque output, and vibration, alerting the system to potential faults before they lead to failure.

In addition to intelligent software control, hardware developments in electric motors have also made significant strides. PMSMs are now being manufactured with advanced rare-earth materials and improved winding technologies, enabling higher peak power outputs and better thermal resistance. Recent developments in laminated stator cores and concentrated winding patterns have increased power density by approximately 15–20%, allowing motors to be smaller and lighter without compromising torque output.

Together, these advancements in AI-based control and motor design are pushing the boundaries of EV performance. The combined effect of optimized energy management, improved thermal behaviour, and predictive maintenance not only increases driving range but also reduces the total cost of ownership. As EV adoption scales globally, such innovations in motor control will play a vital role in delivering safe, efficient, and responsive electric transportation.

V. POWER ELECTRONICS: SIC AND GAN SEMICONDUCTORS

Power electronics play a critical role in electric vehicle (EV) powertrain efficiency by controlling the conversion and distribution of electrical energy between the battery, motor, and auxiliary systems. The recent adoption of wide bandgap (WBG) semiconductors namely silicon carbide (SiC) and gallium nitride (GaN) has dramatically improved the performance of inverters, DC-DC converters, and onboard chargers, surpassing traditional silicon-based power devices in both efficiency and thermal management.

Table -1 Performance comparison on semiconductor technologies

Technology	**Efficiency (%)**	**Switching Frequency (kHz)**	**EV Application**
Silicon (IGBT)	91–93	<20	Inverters, chargers
Silicon Carbide (SiC)	95–96.5	20–100	Traction inverters
Gallium Nitride (GaN)	96.5–97.5	200–1000	Onboard chargers, DC-DC

SiC-based inverters have become increasingly prominent due to their ability to operate at high voltages and temperatures while maintaining minimal switching and conduction losses. Zahwan et al. [9] conducted a comparative study of SiC and GaN semiconductors for traction inverters, finding that SiC inverters achieved a 96.2% efficiency at peak load conditions, which was approximately 4–5% higher than equivalent silicon-based IGBT systems. Moreover, SiC devices operated reliably at junction temperatures exceeding 175°C, eliminating the need for large heat sinks and reducing the inverter's total volume by up to 40%.

In terms of power density, the move from silicon to SiC has shown significant improvements. The power density of SiC inverters has been measured at 30–50 kW/L, compared to the

10–20 kW/L range for silicon counterparts. This increase directly contributes to space and weight savings in the vehicle, making room for additional battery capacity or reducing overall vehicle mass, thereby improving driving range.

On the other hand, GaN-based devices, while typically suited for lower voltage applications (below 650V), have demonstrated exceptional performance in high-frequency switching environments. Chevinly et al. [10] developed a GaN-based multilevel H-bridge inverter as shown in Fig.1 optimized for wireless charging systems and demonstrated inverter switching frequencies of up to 1 MHz, a level that is not feasible with silicon devices due to excessive heat and switching losses. Their system achieved power conversion efficiencies exceeding 97.5% during wireless energy transfer at 3.3 kW, while also reducing the electromagnetic interference (EMI) typically associated with high-frequency switching.

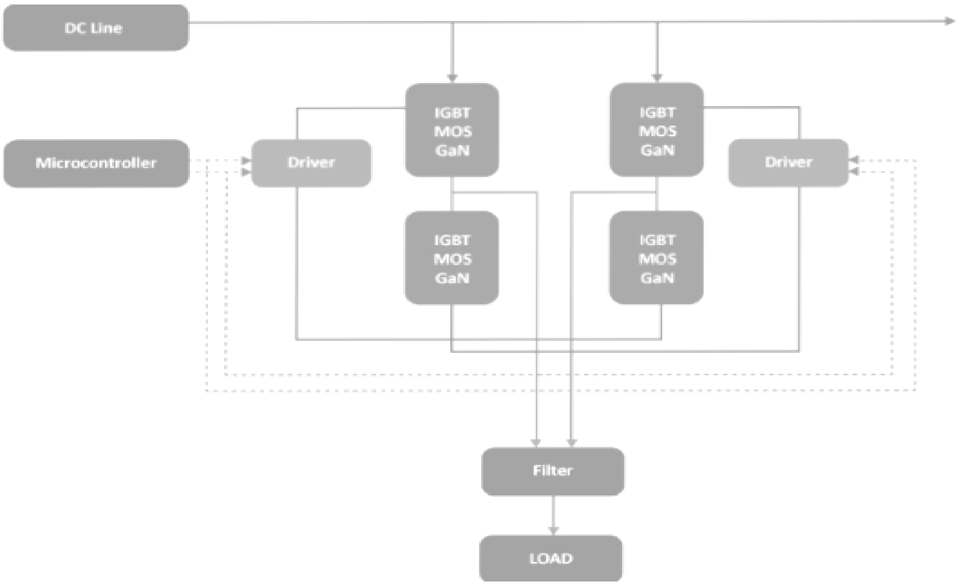

Fig. 1. H-Bridge based inverter

Another critical advantage of WBG semiconductors lies in their thermal behaviour. Both SiC and GaN devices exhibit significantly lower thermal resistance than silicon. As a result, heat dissipation becomes more manageable, allowing for simplified and more compact cooling systems. For instance, replacing silicon components with SiC allowed Zahwan et al. [9] to reduce the inverter cooling requirements by 25%, which directly contributes to vehicle energy savings and reliability.

From a reliability perspective, GaN transistors have shown promise in increasing system lifespan due to their inherent robustness against short-circuit events and reverse conduction. Additionally, their ability to switch at higher frequencies enables smaller passive components, such as inductors and capacitors, further decreasing the size and weight of the power electronics system.

Overall, the adoption of SiC and GaN technologies in EV powertrains is facilitating major improvements in power conversion efficiency, thermal management, and system integration. These advances translate directly into longer range, reduced component size and cost, and higher reliability. As the cost of wide bandgap semiconductors continues to decline due to scaling and manufacturing improvements, their penetration into mass-market electric vehicles is expected to accelerate rapidly. In the context of sustainable transportation, these materials offer an essential pathway to maximizing energy efficiency and minimizing losses across the EV powertrain.

VI. ENERGY STORAGE: SOLID-STATE BATTERIES AND MANAGEMENT SYSTEMS

Energy storage remains one of the most critical components in electric vehicle (EV) powertrain design, directly influencing vehicle range, charging time, safety, and lifespan. In recent years, significant advancements in battery technology have shifted the research focus from traditional lithium-ion batteries to solid-state batteries (SSBs). These systems offer higher energy density, improved thermal stability, and enhanced safety due to the absence of flammable liquid electrolytes. Alongside these developments, sophisticated battery management systems (BMS) are being engineered to ensure optimal battery operation, reliability, and longevity.

Solid-state batteries use solid electrolytes typically sulfide, oxide, or polymer-based offering superior ionic conductivity and improved electrochemical stability. According to Shah et al. [3], SSBs can achieve energy densities up to 400 Wh/kg, a substantial increase compared to the 250–300 Wh/kg typical of current lithium-ion batteries. This enhancement allows electric vehicles equipped with SSBs to extend their driving range by 30–50% without increasing battery size. Zhang et al. [4] further noted that SSBs exhibit improved thermal resistance, allowing operation at temperatures exceeding 100°C without the risk of thermal runaway, a significant safety advantage over traditional lithium-ion chemistries.

Table -2 Battery types and performance metrics

Battery Type	**Energy Density (Wh/kg)**	**Operating Temp. Range (°C)**	**Cycle Life (Approx.)**
Lithium-Ion (NMC)	250–300	0 to 45	1000–2000
Solid-State Battery	Up to 400	-20 to 100+	2500–3000
$LiFePO_4$ (LFP)	160–200	-10 to 60	3000+

Despite these benefits, SSBs face technical challenges, particularly at the interface between the solid electrolyte and electrode materials. Wang and Singh [5] reported that interfacial resistance and dendrite growth remain significant concerns. In their study, high-resolution microscopy revealed that improper material compatibility could lead to dendritic lithium penetration after only 200 charge cycles, compromising cell integrity. However, recent innovations in interface coatings and composite electrolyte formulations have reduced interfacial resistance by over 60%, significantly enhancing battery longevity.

Effective battery management is crucial for leveraging the full potential of advanced battery chemistries. Modern BMS architectures monitor a range of parameters, including cell voltage, current, temperature, and internal resistance, ensuring batteries remain within safe and efficient operating conditions. Kumar and Lin [6] highlighted the growing importance of distributed BMS designs, where individual cell modules incorporate local controllers. This architecture allows for precise thermal balancing, improved fault isolation, and better scalability. Their findings suggest that distributed BMS can improve overall battery efficiency by 8–12% and reduce module-level overheating incidents by over 40%.

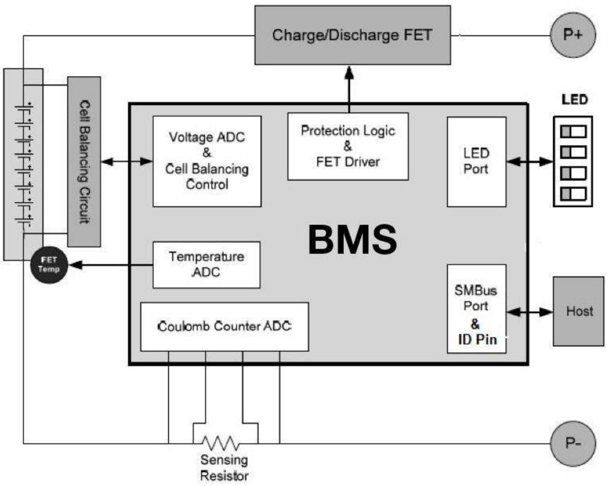

Fig. 2. Components of Battery Management System

Another key function of BMS is the accurate estimation of state-of-charge (SOC) and state-of-health (SOH). Alharthi and Gupta [8] reviewed advanced machine learning models, including support vector machines and neural networks, which are now being used to predict battery degradation patterns and capacity fade. These models demonstrated a prediction accuracy of over 95% for SOH after 500+ charge-discharge cycles, significantly outperforming traditional Kalman filtering techniques. This level of precision allows EVs to provide more reliable range estimates and schedule maintenance proactively, minimizing downtime and extending battery lifespan.

Additionally, regenerative braking systems, which convert kinetic energy back into electrical energy during deceleration, are being optimized through integrated control with the BMS. Advanced control algorithms now enable energy recovery rates of up to 70% in urban driving conditions, compared to around 40–50% in earlier systems. This not only improves energy efficiency but also reduces mechanical wear on the braking system.

Together, the combination of solid-state battery technology and intelligent battery management systems marks a transformative leap in EV powertrain development. While the commercial deployment of SSBs is still in its early stages, ongoing research and prototyping are steadily addressing technical barriers. As production techniques improve and economies of scale are realized, these next-generation batteries, coupled with high-precision BMS technologies, are poised to redefine the energy architecture of electric vehicles, offering longer range, enhanced safety, and smarter energy utilization.

VII. THERMAL MANAGEMENT INNOVATIONS

Thermal management is a critical aspect of electric vehicle (EV) powertrain design, directly affecting the efficiency, safety, and reliability of core components such as batteries, electric motors, and power electronics. As power densities increase and vehicles operate in increasingly diverse climates, the ability to maintain optimal operating temperatures under all conditions has become more important than ever. Recent innovations in this area have introduced advanced materials, smarter control strategies, and hybrid cooling systems that significantly improve thermal regulation across the EV powertrain.

One of the most pressing thermal challenges lies in battery packs, which must operate within a narrow temperature range typically between 20°C and 45°C to maintain performance and prevent degradation. Exceeding this range can result in accelerated aging, loss of capacity, or in extreme cases, thermal runaway. Rudolf et al. [11] implemented a reinforcement learning (RL) model for dynamic thermal control of EV batteries. Their system adjusted coolant flow and fan speed in real time based on predicted driving conditions and cell temperature trends, resulting in a 17% improvement in thermal efficiency and a 12% reduction in average battery temperature fluctuations compared to fixed-rule cooling strategies.

Advanced cooling methods are also gaining traction. Kisomi [12] compared traditional air cooling to systems using phase change materials (PCMs), which absorb and store large amounts of heat during phase transitions. His findings indicated that PCM-based systems could maintain cell surface temperatures 6–9°C lower during aggressive driving cycles, while also delaying thermal runaway onset by up to 20 minutes under fault conditions. Such systems offer a passive means of thermal regulation without the continuous energy consumption of active cooling, making them ideal for use in high-density battery modules or hybrid configurations.

In the realm of power electronics, high-speed switching from SiC and GaN devices has introduced new thermal demands. To address this, Alghassab [13] proposed a hybrid cooling solution integrating thermoelectric coolers (TECs) with PCMs. Their model showed that combining these technologies could reduce power module peak temperatures by 15–18% under full-load conditions, especially during extended periods of high inverter duty cycles. This hybrid method offered both short-term buffering (via PCMs) and active cooling when needed (via TECs), enabling compact packaging and improved thermal resilience.

Innovations in heat exchanger design are also playing a role. Patil and Chavan [14] optimized the geometry of liquid-cooled aluminum heat sinks using computational fluid dynamics (CFD). Their redesigned structure improved coolant flow distribution and increased the overall heat transfer rate by 28%, while reducing the pressure drop across the system by 35%, which improves energy efficiency. Such improvements allow the use of smaller and lighter thermal management components, contributing to overall vehicle weight reduction.

Thermal management of the cabin environment has also become increasingly integrated with the powertrain, especially as EVs rely on electric heating and cooling rather than waste heat from combustion engines. Hanon Systems [16–20] has led industry efforts in this area by developing advanced heat pump systems capable of extracting ambient and waste heat from other vehicle components. Their fourth-generation system demonstrated a 40% reduction in electrical energy required for cabin heating in sub-zero temperatures, directly extending EV driving range in cold climates by up to 20%. These systems integrate seamlessly with battery thermal circuits, ensuring optimized use of available heat sources.

Across all these developments, the integration of intelligent thermal management strategies is key. Increasingly, thermal systems are designed to interact directly with battery management systems (BMS), motor controllers, and vehicle energy management systems to predict thermal loads and coordinate proactive interventions. This level of integration not only reduces energy consumption but also ensures consistent thermal protection, even in the most demanding driving environments.

In summary, the landscape of EV thermal management is rapidly evolving, driven by the need for efficiency, safety, and performance. Emerging technologies like PCM integration, TEC-assisted cooling, AI-optimized control strategies, and advanced heat exchanger designs are transforming thermal systems from passive protectors to active enablers of high-performance electric mobility. As EVs become more powerful and compact, such innovations will remain critical to maintaining long-term system health and driver satisfaction.

VIII. MODULAR POWERTRAIN ARCHITECTURES AND INDUSTRY ADVANCES

The increasing complexity and diversity of electric vehicles (EVs) across global markets has driven a shift toward modular powertrain architectures. These systems are designed with standardized, interchangeable components that can be configured across various vehicle platforms with minimal customization. The modular approach not only enables flexible production and faster product development but also reduces costs and supports scalable electrification strategies. Recent research and industry applications have focused on three core domains: modular electric drive units (EDUs), scalable battery packs, and modular thermal and control systems.

Table -3 Impacts of Modular Architectures

Parameter	**Without Modularity**	**With Modularity**	**Improvement**
Development Time	30–36 months	24–28 months	15–20%
Production Cost (per unit)	High	25–30% lower	25–30%
R&D Cost	Baseline	40% lower	40%

A. Modular Electric Drive Units (EDUs)–

Electric Drive Units (EDUs) integrate the electric motor, power electronics (inverter), and reduction gearbox into a single compact module. The modular design of EDUs allows manufacturers to vary performance outputs and installation configurations depending on vehicle type. This is particularly beneficial for automakers developing multiple models on a single EV platform.

Clemente et al. [15] demonstrated a modular optimization framework that allowed configuration of EDUs to suit applications ranging from compact hatchbacks to medium-duty trucks. The use of shared EDU modules resulted in a reduction in total development time by 15% and cost savings of over 25%, primarily due to common tooling and simplified supply chains.

In the commercial sector, leading automotive suppliers like ZF and Bosch have developed modular eAxles that support outputs between 75 kW and 300 kW, adaptable to front-wheel, rear-wheel, or all-wheel drive configurations. Bosch's eAxle platform, for instance, integrates the inverter and gearbox with the motor, reducing wiring complexity and decreasing the drivetrain weight by up to 10–12% compared to separate components.

Modular EDUs also simplify packaging and enhance thermal management. By placing heat-sensitive components in proximity, cooling systems can be centralized and optimized, which reduces redundancy and improves reliability. These improvements support higher system power densities and enhance overall vehicle performance.

B. Scalable Battery Pack Architectures

Battery packs account for the largest share of both the weight and cost in electric vehicles, making modularity in battery design crucial for economic and technical scalability. Modular battery systems consist of repeatable units cells arranged into modules, and modules assembled into packs which can be scaled based on vehicle range and performance requirements.

Modern modular battery platforms can be configured to deliver energy capacities ranging from 50 kWh to 100 kWh using the same core pack structure. This allows OEMs to offer different driving ranges within a model line (e.g., standard, extended, and long-range variants) without altering vehicle design significantly.

Recent research by Shah et al. [3] showed that modular battery packs reduced manufacturing complexity by 22% and enabled easier maintenance and upgradability. In particular, damaged modules can be replaced individually, avoiding the need to replace the entire battery pack a significant advantage for fleet vehicles and commercial EVs.

Battery modularity also aligns with evolving trends such as battery-as-a-service (BaaS), where consumers can subscribe to battery use and swap out modules for recharging or upgrades. Modular systems support this model by simplifying pack removal and reintegration. Furthermore, the same module architecture can be repurposed for stationary energy storage after its automotive lifecycle ends, extending its value chain.

C. Modular Thermal and Control Systems

As electric powertrains integrate more power-dense components, thermal management systems must also become more adaptable. Modular thermal systems are designed to manage heat from diverse components batteries, inverters, and motors within unified or coordinated subsystems.

Hanon Systems [16–20] has pioneered modular thermal management platforms that use shared coolant loop architecture adaptable to different EV configurations. These systems have been shown to reduce system mass by 20%, while improving energy efficiency in heating and cooling cycles by 15%. The ability to decouple or reconfigure heat exchangers, compressors, and pumps allows the same thermal system architecture to support compact cars, SUVs, and commercial vans.

Moreover, modularity extends beyond hardware into control software. AI-based energy management systems (EMS) can detect connected modules such as battery types, motor variants, or HVAC subsystems and adjust operating parameters accordingly. For instance, regenerative braking levels and torque vectoring strategies can be tuned in real time based on drivetrain configuration, improving both efficiency and driving dynamics.

Digital twin technologies are also facilitating modular powertrain development. These virtual models simulate physical systems and allow engineers to explore multiple drivetrain layouts in software before hardware implementation. According to Clemente et al. [15], this approach cut R&D costs by up to 40%, allowing for rapid prototyping and system-level optimization across different vehicle designs.

In conclusion, the transition to modular powertrain architectures marks a significant evolution in EV design and manufacturing. By enabling cross-platform component reuse, improving system scalability, and accelerating innovation cycles, modularity supports both economic and engineering efficiency. As EV adoption expands to a broader range of vehicle types and use cases, the role of modular architectures will be increasingly central to achieving global electrification goals.

IX. RESULTS AND DISCUSSION

This review has explored how recent advances in electrical engineering, particularly in electric motors, power electronics, energy storage, thermal systems, and modular architectures, are reshaping the landscape of EV powertrain design. Drawing on recent research findings and industrial innovations, several key outcomes and performance trends emerge, illustrating both the progress and ongoing challenges in the electrification of transport.

A. **Performance Gains through Material and Semiconductor Innovation**

One of the most significant performance improvements observed in recent years results from the transition from traditional silicon-based components to wide bandgap (WBG) semiconductors, such as silicon carbide (SiC) and gallium nitride (GaN). SiC inverters have consistently demonstrated efficiency gains of 4 to 5 percent compared to silicon IGBT systems, achieving overall power conversion efficiencies as high as 96.2 percent under peak load conditions [9]. This improvement directly contributes to reduced thermal losses, lower cooling requirements, and enhanced drivetrain compactness. These factors result in a 40 percent reduction in inverter volume and up to 25 percent lower cooling system mass [13].

GaN semiconductors, while currently more applicable in lower voltage or high-frequency subsystems such as onboard chargers and wireless power transfer, have shown power conversion efficiencies exceeding 97.5 percent. These results are particularly evident when operating at switching frequencies up to 1 MHz [10]. Such characteristics make GaN ideal for compact applications where EMI control is critical.

Together, these semiconductor innovations reduce energy losses across the powertrain, enhance heat tolerance, and support higher system integration. These gains contribute to longer driving range and improved reliability.

B. **Energy Density and Safety Advancements in Battery Technology**

Battery systems have also experienced major advancements. The shift from conventional lithium-ion to solid-state batteries (SSBs) has increased gravimetric energy density from 250 to 300 Wh/kg to values approaching 400 Wh/kg [3]. This allows for vehicle range increases of 30 to 50 percent without additional volume or mass. Additionally, SSBs exhibit greater thermal stability, operating safely at temperatures above 100°C without the risk of thermal runaway [4]. However, transitioning to solid-state batteries is not without challenges. Wang and Singh [5] identified dendritic lithium growth and high interfacial resistance as significant issues. Their research showed that with current materials, dendrite formation could compromise cells after only 200 charge cycles. Nonetheless, innovations in hybrid electrolytes and interfacial coatings have reduced resistance by more than 60 percent, improving battery life and stability.

Battery management systems (BMS) have also evolved significantly. Distributed BMS designs have enabled efficiency improvements of 8 to 12 percent and reduced thermal imbalances between battery modules by more than 40 percent [6]. Moreover, the use of machine learning models for state-of-health prediction now delivers over 95 percent accuracy even after 500 charge-discharge cycles [8]. This allows for improved range estimation, fault detection, and optimized maintenance schedules.

C. **Intelligent Motor Control and AI Integration**

Electric motors, especially permanent magnet synchronous motors (PMSMs), have benefited from AI-based control strategies that dynamically respond to vehicle conditions. Li and Shao [1] reported energy savings of up to 13.6 percent using reinforcement learning (RL) for real-time torque optimization. Similarly, Wu et al. [2] demonstrated drivetrain efficiency gains of 11.5 percent and fuel savings of 9.8 percent in hybrid systems with deep reinforcement learning controlling the power split.

Unlike traditional fixed-logic systems, AI-driven motor controllers can learn from past operation and adjust their strategy for changing terrain, load, or driving patterns. These controllers also enhance regenerative braking performance and improve motor protection by detecting anomalies in torque output and motor temperature. Such integration not only improves energy efficiency but also contributes to vehicle safety, driving experience, and component lifespan.

D. Thermal Management Efficiency and Energy Recovery

Thermal management is vital to the safe and efficient operation of EV powertrains. AI-enhanced thermal control systems, such as those based on reinforcement learning, have demonstrated improved temperature regulation. Rudolf et al. [11] achieved a 17 percent increase in cooling efficiency and a 12 percent reduction in battery temperature variation. Phase change materials (PCMs) also show great potential. Kisomi [12] demonstrated that PCM-based battery cooling systems reduced surface temperatures by 6 to 9°C and delayed thermal runaway events by up to 20 minutes under extreme conditions. Hybrid cooling systems that combine thermoelectric coolers (TECs) with PCMs have shown even better results. Alghassab [13] reported that these hybrid solutions reduced power electronics temperatures by 15 to 18 percent under full-load conditions. On the cabin side, thermal management innovations have had a noticeable impact on energy efficiency. Hanon Systems [16–20] developed a heat pump that reduces cabin heating energy consumption by 40 percent in cold climates. This directly contributes to a driving range increase of up to 20 percent in sub-zero temperatures. These advancements ensure consistent component performance, extend component life, and minimize the risk of thermal failure, particularly under high-load or rapid-charging conditions.

E. Modular Architectures and Manufacturing Benefits

Modular architectures allow EV manufacturers to scale production and reduce costs while maintaining design flexibility. Clemente et al. [15] demonstrated that modular powertrain design can lower manufacturing costs by 25 to 30 percent and reduce development time by 15 percent.

Modular electric drive units (EDUs), with integrated motor, inverter, and transmission, simplify powertrain packaging and allow output flexibility from 75 kW to 300 kW. These can be easily adapted for different drive configurations; including front-wheel, rear-wheel, and all-wheel drive systems.

Similarly, modular battery packs enable energy configurations from 50 to 100 kWh using the same structural framework. This not only supports various vehicle classes but also simplifies maintenance, with individual module replacement reducing downtime and service cost.

Thermal and control systems have also been modularized. Modular cooling loops, such as those developed by Hanon Systems, can be adapted across different EV platforms. These systems reduce part count, improve packaging efficiency, and enhance control flexibility. When integrated with AI-based energy management software, they automatically adjust to various component configurations, optimizing thermal behaviour and energy use.

Digital twin simulations have been employed to model and validate these modular architectures in virtual environments. Clemente et al. [15] reported R&D savings of up to 40 percent when using digital twins for component sizing, control tuning, and thermal testing.

F. Cross-Disciplinary Synergy

Across all areas of the powertrain, the most impactful results have emerged from the intersection of hardware advancements and intelligent control strategies. The high efficiency of SiC inverters is fully realized only when paired with precision thermal systems and adaptive motor control algorithms. Similarly, solid-state batteries require advanced BMS algorithms to operate within their narrow safety and performance limits.

These interdependent systems highlight the growing need for multidisciplinary design approaches. Collaboration between electrical engineers, thermal analysts, software developers, and material scientists is essential to achieve the high efficiency, safety, and reliability required in modern electric vehicles.

X. CONCLUSION

The design and performance of electric vehicle (EV) powertrains have improved rapidly in recent years, due to many new developments in electrical engineering. This review looked at the latest innovations in electric motors, power electronics, batteries, thermal systems, and modular designs, showing how these improvements are making EVs more efficient, reliable, and cost-effective.

One major improvement has come from the use of new semiconductor materials like silicon carbide (SiC) and gallium nitride (GaN). These materials are replacing older silicon-based systems and offer better energy efficiency, higher switching speeds, and lower heat generation. SiC inverters can now reach over 96% efficiency, helping reduce energy losses and allowing for smaller, lighter components.

Battery technology has also come a long way. Solid-state batteries now offer higher energy density—up to 400 Wh/kg compared to traditional lithium-ion batteries. They are also safer and can handle higher temperatures. Combined with advanced battery management systems (BMS), EVs can now manage charging and energy use more intelligently, improving both range and battery life.

Thermal management, which is essential for safe and efficient EV operation, has also advanced. New cooling methods, like using phase change materials (PCMs) or AI-controlled heat pumps, help keep batteries and motors at safe operating temperatures. This improves both performance and safety, especially during fast charging or in extreme weather.

Another big step forward is the move toward modular powertrain designs. These are systems made of standard components that can be reused across different vehicles. Modular motors, inverters, and battery packs allow carmakers to design and build EVs faster and at lower cost. One battery module can be used to make either a 50 kWh or a 100 kWh battery pack, depending on how many modules are installed. This flexibility is very useful for companies building multiple types of EVs.

Importantly, all of these technologies work best when they are integrated intelligently. AI and machine learning are helping to tie everything together—optimizing motor control, battery usage, and thermal systems in real time. This makes EVs smarter, more responsive, and more energy-efficient. In summary, the future of EVs depends on the combination of new electrical engineering technologies and smart system integration. As research continues and costs come down, we can expect even more efficient, safer, and more affordable EVs on the road in the near future.

XI. REFERENCE

[1]. Li, Y. and Shao, C. (2024). Co-optimization of Vehicle Dynamics and Powertrain Management for Connected and Automated Electric Vehicles, arXiv.

[2]. Wu, J., Zhang, Y., and Chen, H**.** (2023). Towards Optimal Energy Management Strategy for Hybrid Electric Vehicle with Reinforcement Learning, arXiv.

[3]. Shah, K., Patel, D., and Mehta, R. (2024). Challenges and Advancements in All-Solid-State Battery Technology for Electric Vehicles, Materials Proceedings, Vol. 7, No. 3, (p.12).

[4]. Zhang, H., Liu, X., and Lee, Y. (2024). Emerging Trends and Innovations in All-Solid-State Lithium Batteries: A Comprehensive Review, Chemical Engineering Journal.

[5]. Wang, R. and Singh, M. (2025). A Comprehensive Review of Solid-State Batteries: Materials, Architectures, and Performance, Applied Energy, Vol. 350, 120276.

[6]. Kumar, S. and Lin, D. (2025). Solid-State Batteries: Chemistry, Battery, and Thermal Management System Perspectives, Batteries, Vol. 11, No. 6, (p.212).

[7]. Massaro, M. and Fujiwara, K**.** (2025). Advancements in Solid-State Sodium-Based Batteries: A Comprehensive Review, arXiv.

[8]. Alharthi, A. and Gupta, R. (2024). Electric Vehicle Battery Technologies and Capacity Prediction: A Comprehensive Literature Review, Batteries, Vol. 10, No. 12, (p.451).

[9]. Zahwan, N. S. H. M., Hasan, K. N. M., and Zakaria, Z. A. B. (2024). Performance Analysis of SiC and GaN-Based Traction Inverter in Electric Vehicle Drive System, Proc. IEEE Sustainable Power and Energy Conference (iSPEC).

[10]. Chevinly, J., et al. (2024). Gallium Nitride (GaN) Based High-Power Multilevel H-Bridge Inverter for Wireless Power Transfer of Electric Vehicles, arXiv.

[11]. Rudolf, T., et al. (2024). Scenario-Based Thermal Management Parametrization through Deep Reinforcement Learning, arXiv.

[12]. Kisomi, M. K**.** (2025). Thermal Management of Lithium-Ion Batteries: A Comparative Study of Phase Change Materials and Air-Cooling Systems Equipped with Fins, arXiv.

[13]. Alghassab, M. A. (2024). Advanced Thermal Management System of Lithium-Ion Batteries: Integrating Thermoelectric Modules with Phase Change Materials, Journal of King Saud University - Science.

[14]. Patil, S. S. and Chavan, S. S. (2025). Thermal Management of Cylindrical Lithium-Ion Batteries with Different Fin Configurations and Phase Change Material: A Numerical Analysis, Journal of Thermal Analysis and Calorimetry.

[15]. Clemente, M., Salazar, M., and Hofman, T. (2023). Concurrent Design Optimization of Powertrain Component Modules in a Family of Electric Vehicles, arXiv.

[16]. Hanon Systems. (2024). Hanon Systems Develops World's First 4th Generation Heat Pump System for Electric Vehicles, PR Newswire, 8 August 2024.

[17]. Hanon Systems. (2024). Hanon Systems Unveils the World's First 4th Generation Heat Pump System for EVs, Automotive Era, 8 August 2024.

[18]. Hanon Systems. (2024). Hanon Systems Unveils the World's First 4th Generation Heat Pump System for EVs, EV Engineering & Infrastructure, 8 August 2024.

[19]. Hanon Systems. (2024). Hanon Systems Unveils the World's First 4th Generation Heat Pump System for EVs, The EV Report, 8 August 2024.

[20]. Hanon Systems. (2024). Hanon Systems Unveils the World's First 4th Generation Heat Pump System for EVs, Autocar Professional, 8 August 2024.

IJEAST

INTERNATIONAL JOURNAL OF ENGINEERING APPLIED SCIENCE AND TECHNOLOGY

ABOUT IJEAST

International Journal of Engineering Applied Science and Technology (IJEAST) is a peer-reviewed, open access journal that publishes high-quality research papers in the field of Engineering, Applied Science and Technology.

IJEAST aims to provide a platform for researchers, academicians, and professionals to share their innovative ideas, research findings, and practical experiences with the global scientific community.

FOCUS AREAS

- Engineering
- Applied Science
- Technology
- Innovation & Development
- Interdisciplinary Studies

PEER REVIEWED

All submissions are rigorously peer reviewed to ensure quality.

OPEN ACCESS

Free and unrestricted access to research for all.

GLOBAL REACH

Connecting researchers and professionals worldwide.

TIMELY PUBLICATION

We ensure a swift and efficient publication process.

For more information, visit our website
www.ijeast.com

INTERNATIONAL JOURNAL
OF ENGINEERING APPLIED SCIENCE
AND TECHNOLOGY

✉ editor@ijeast.com
www.ijeast.com
India

2455-2143