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High-Performance Polymers for Faster Cars: Advancing Electric Vehicle Battery Systems- A Comprehensive Review

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Abstract- The electric vehicle (EV) revolution demands new materials that address performance, safety, and sustainability imperatives. High-performance polymers are emerging as essential replacements for heavy metals and brittle glass in electric vehicle battery systems, where they offer weight reduction, insulation, thermal management, and fire hazard solutions. This paper explores how high-performance polymers can help enhance EV performance by offering lightweight, high-durability, thermally and electrically feasible alternatives to traditional metals and glass. By the analysis of some of the most significant polymer families, such as polyurethanes, epoxies, and glass-filled nylons. A comprehensive analysis of over 40 peer-reviewed papers, industry reports, and technical standards was conducted to analyze and detail their specific applications in thermal management, electrical insulation, and mechanical protection in high-voltage battery systems. The findings emphasize the key role of polymers in the development of faster, safer, and more efficient electric vehicles.

Keywords: Electric vehicles, high-performance polymers, high voltage battery systems, thermal management, lightweight materials, sustainability, electrical insulation, sealing and bonding, AIOps, Industry 4.0, lightweight composites, e-mobility innovation, advanced battery safety systems.

1. Introduction

Electric vehicles (EVs) have made a remarkable transformation from niche prototypes in the early 20th century to mass produced automotive technology in the 21st century. Initially dominating the U.S. market in the early 1900s due to their low noise while running and ease of use, EVs lost prominence with the extensive mass production of internal combustion engine (ICE) vehicles. However, growing awareness of climate change, air pollution, and dependence on fossil fuels has stimulated renewed interest in zero-emission transport (Hannan et al., 2014). The commercial success of the lithium-ion battery by SONY in 1991 spurred the growth of EVs by enabling lightweight, high-capacity, and efficient energy storage. Battery electric vehicles (BEVs) are currently leading the decarbonization of the world.
Although they quickly obtained very considerable traction in the market, EVs face very severe engineering problems. Large battery packs carry considerable weight, reducing driving range and efficiency as well as presenting risks of thermal runaway and electrical hazards in high-voltage environments.
Traditional application of metals to battery enclosures, cooling, and protective components provides little design freedom and increases weight.

These constraints require substitute materials capable of prov iding mechanical strength, thermal stability, and electrical insulation without compromising safety or performance.
While high-performance polymers are current promises—with low density, chemical resistance, and complex formability, their use in high-voltage EV battery applications is currently yet to be thoroughly explored in the fields of optimal choice of materials, processes, and long-term response to thermal and mechanical stress (Saeed et al., 2019; Zhang & Zhou, 2020). This gap is particularly intense in multifunctional polymer system integration capable of substituting metals for thermal management, insulation, mechanical shielding, and adhesion applications.

This study endeavors to evaluate the potential of high-performance polymers in EV battery systems by:

1. Identifying the most significant polymer families and their functional performance compared to metal.

2. Discussing their use in thermal management, electric insulation, mechanical reinforcement, and bonding applications.

3. Measuring their impact toward weight reduction, safety enhancement, and design flexibility in high-voltage applications.

This research has potential to significantly impact the material selection process for clean energy vehicles and other high voltage products. Replacing the existing high weight materials like metals, Original Equipment Manufacturers (OEMs) can improve driving range, robustness and vehicle efficiency. Moreover, this research contributes to academic knowledge in the field of automotive, polymer and material sciences. The findings further contribute to industrial practice, offering a summarized materials knowledge to leverage for right material selection for the correct application that balances performance, manufacturability and safety in the next gen Battery Electric Vehicles (BEVs).

2. Best Polymers for High-Voltage Battery Applications

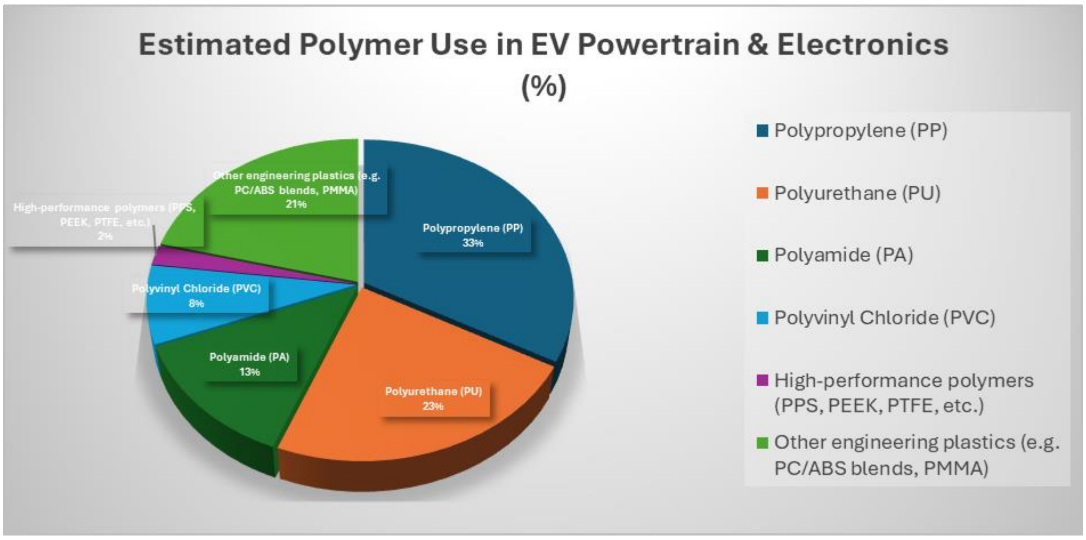

Figure 1. Estimated distribution of polymer types used in electric vehicle powertrain and electronics applications. The majority is composed of polypropylene (33%), polyurethane (23%), polyamide (13%), and PVC (8%), with smaller contributions from high-performance polymers and other engineering plastics. *Sources: ACT Group (2024); Kuraray Elastomer (2023); ResearchGate (2020).*

High-voltage (HV) battery systems in electric vehicles demand materials that can withstand extreme thermal, electrical, and mechanical stress while offering cost-effectiveness, weight savings, and environmental durability. Over the past decade, polymers have gained importance in this application space, often replacing heavier metals in structural and functional roles. Several key classes of polymers have emerged as top contenders in HV battery environments, including thermoplastics, thermosets, and elastomers, each offering unique strengths and limitations. The popular polymer families used is shown in *Figure 1*.

2.1 Epoxy Resins

Among thermosets, epoxy resins are widely used due to their excellent dielectric strength, chemical resistance, and thermal stability. Their low shrinkage and dimensional stability during curing make them ideal for potting and encapsulation of battery cells (Chen et al., 2021; Zhang & Zhou, 2020). Epoxies can be modified with fillers like aluminum oxide or boron nitride to improve thermal conductivity while maintaining insulation properties (Zhou et al., 2023).

2.2. Polyurethanes (PU)

Polyurethanes (PU) are known for their flexibility, adhesion, and ability to absorb vibrations, making them useful for bonding and cushioning within battery modules. While standard PUs have limited thermal resistance, high-performance formulations can achieve operating temperatures up to 120°C. Some hybrid PU systems are tailored with fire retardant properties to meet UL 94 V-0 standards (Singh & George, 2021).

2.3 Polypropylene (PP) & Polyamide (PA)

In the thermoplastic family, glass fiber-reinforced polypropylene (PP-GF) and polyamide (PA) variants are widely adopted in structural components like battery enclosures, coolant channels, and module frames. PP-GF offers high stiffness, low cost, and excellent chemical resistance, though its performance at sub-zero temperatures can be a drawback (Saeed et al., 2019). Polyamides such as PA6, PA66, and PA12 exhibit superior strength, wear resistance, and thermal stability, making them suitable for parts exposed to mechanical and thermal cycling. However, polyamides are hygroscopic, which requires controlled processing and conditioning (Kulkarni & Maiti, 2019).

2.4 Polyether ether ketone (PEEK)

Polyether ether ketone (PEEK) and other high-temperature engineering polymers like polyphenylene sulfide (PPS) and polyimides (PI) are gaining ground in premium EV applications where thermal endurance beyond 200°C is necessary. PEEK, for example, offers exceptional creep resistance, flame retardancy without additives, and compatibility with high-voltage environments. These polymers are ideal for high-reliability connectors, cable insulation, and contactor housings (Zhou et al., 2023).

2.5 Elastomers

Elastomers such as EPDM and fluoroelastomers (FKM) are commonly employed for sealing and gasketing.

EPDM exhibits excellent ozone, UV, and weather resistance, making it suitable for pack perimeter seals. FKM provides outstanding chemical resistance to aggressive battery electrolytes and high service temperatures, albeit at a higher cost (Singh & George, 2021; Wang et al., 2023).

2.6 High-density polyethylene (HDPE), although less common in functional battery internals, is used for non-critical protective casings and routing channels due to its impact resistance and lightweight nature. However, its limited thermal and flame resistance restricts its use in more demanding applications (Chen et al., 2021).

Emerging materials such as liquid crystal polymers (LCPs) and polyaryletherketones (PAEKs) are also being explored for ultra-high performance in niche applications due to their unique molecular structures that enable high dielectric strength and low water absorption (Zhang & Zhou, 2020).

Overall, no single polymer meets all performance criteria. The choice of material is highly application-specific and often involves trade-offs between cost, weight, processing, and safety compliance as listed in *Table 1*. With increasing regulatory pressure for recyclability and sustainability, bio-based flame-retardant polymers and thermoplastic composites are poised to play a larger role in future battery system design (Sustainable Polymers EV, 2024).

Table 1. Common polymers in EV battery systems and their key traits

Polymer	Key Properties & Advantages	Limitations
PU	Good Flexibility, adhesion, sealing, vibration dampening	Limited thermal resistance (Zhou et al., 2023)
Epoxy	Excellent electrical insulation, structural strength	Brittle, limited flexibility (Chen et al., 2021)
PP (Glass Filled)	Lightweight, cost-effective, chemical resistance	Poor impact resistance at low temps (Saeed et al., 2020)
PA12, PA6, PA66	High strength, chemical resistance, thermal stability	Hygroscopic, needs drying (Zhang et al., 2020)
PPS, PEEK, PI	High temperature, stability, flame retardancy	Expensive, complex processing (Zhou et al., 2023)
EPDM	Weather and chemical resistance, sealing	Poor mechanical strength (Singh & George, 2021)
FKM	Exceptional chemical and temperature resistance	Expensive, less flexible (Wang et al., 2023)
HDPE	Lightweight, impact resistant	Lower temperature resistance (Kulkarni & Maiti, 2019)
LCP, PAEK	High dielectric strength, low moisture absorption	High cost, niche applications (Zhang & Zhou, 2020)

To understand the environmental impacts of each listed material, quantitative lifecycle analysis comparison is shown in Figure 2. When the different polymer families to the widely used metals – aluminum and steel are compared, we analyzed the two key indicators of sustainable materials, i.e. the carbon footprint in CO_2e/kg and energy consumption in manufacturing in MJ/kg. Aluminum takes the highest carbon footprint of approximately 12 kg CO_2e/kg and ~200 MJ/kg energy to manufacture due to its smelting process: steel, although heavier and less fuel efficient has a much lower carbon footprint of 2.5 kg CO_2e/kg and ~35 MJ/kg energy requirements. To overcome this challenge of choosing between greener material or lighter material, advanced polymers can provide the right balance between weight and their environmental impact. Common engineering polymers like Polypropylene (1.65 kg CO_2e/kg) and polyethylene (1.48 kg CO_2e/kg) gives us larger carbon savings. Nylons, especially PA66 and glass filled as seen in the analysis have higher energy consumption in the range of 150 to 180 MJ/kg due to its energy intensive and chemically complex processing. The bio-composites have significantly lower footprints and showcase a strong sustainability case, their adoption in automotive is limited currently due to the performance challenges like mechanical strength and thermal limitations (Koronis et al., 2013; Pil et al., 2016).

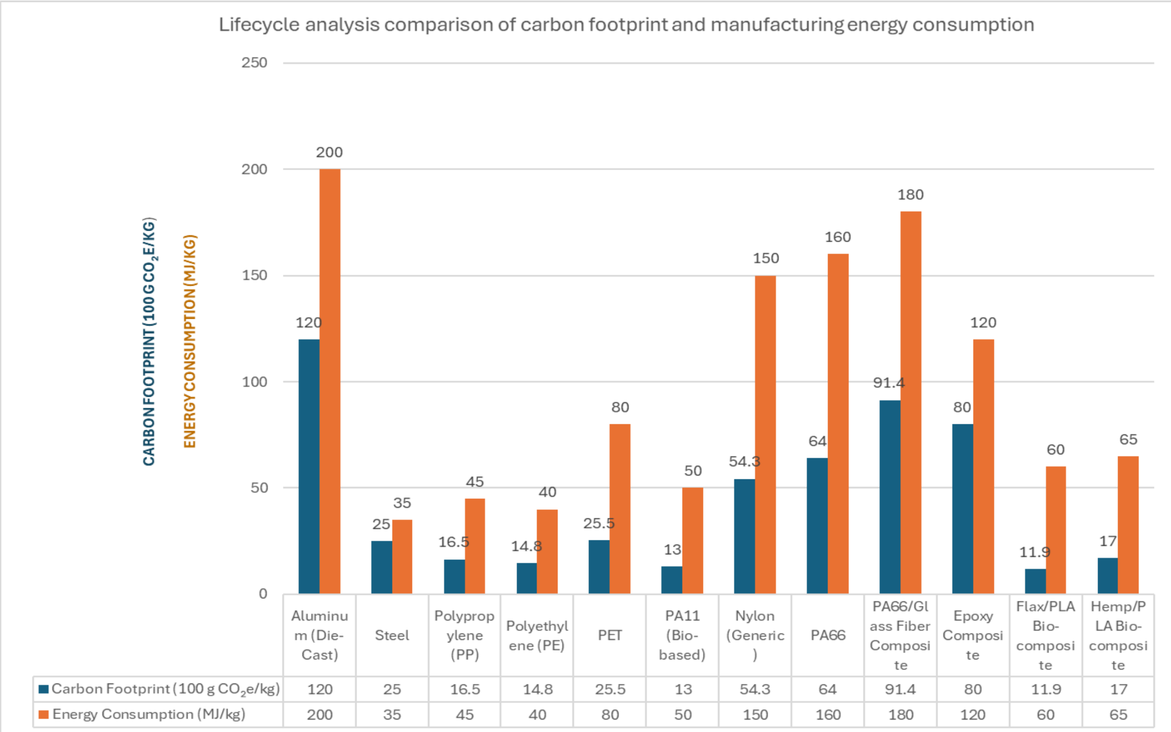

Figure 2. Lifecycle analysis comparison of carbon footprint and manufacturing energy consumption for metals and polymers used in EV battery applications. *Note.* Carbon footprint and energy consumption values compiled from Arkema (2024), CarbonCloud (n.d.), PlasticsEurope (2014), U.S. Department of Energy (2022), and Wu et al. (2021).

3. **Polymer Capabilities in EV Battery Packs**

As shown in Figure 3, polymer composites are integrated into multiple systems within an electric vehicle powertrain. In current EV battery pack designs, these materials serve critical roles across four main application areas: thermal management, electrical insulation and protection, mechanical and environmental sealing, and adhesion/bonding. The following subsections examine each of these categories in detail, highlighting the specific functions, material choices, and design considerations that enable optimal battery performance and safety.

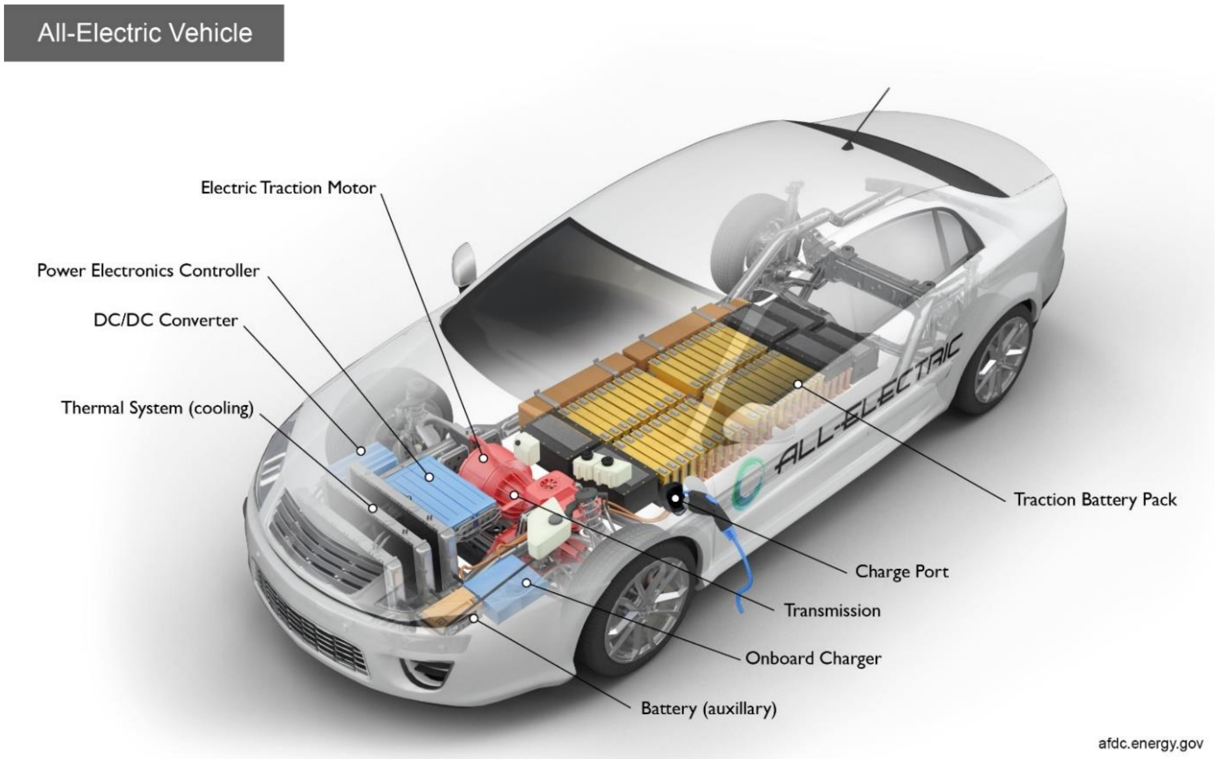

Figure 3. Electric vehicle powertrain layout showing major components. This image illustrates areas where plastics are typically applied, such as motor housing, battery packs, and electronic controllers, *Reproduced from* EVReporter (2023).

3.1 Thermal Management

Plastics, as generally considered poor conductors of heat, support a wide variety of thermally resistant components in the car. Especially when heat can be sensitive in the powertrain, as it directly impacts the lifespan, safety, and performance of the battery pack. This is one of the most critical applications polymers are considered. Electric Vehicles, when first gaining popularity in the 2010s, had several accidents involving fires due to the battery pack experiencing thermal runaway. This caused the consumer to slow down EV adoption. Integrating AIOps into battery management systems enables automated anomaly detection, real-time performance monitoring, and predictive maintenance, helping prevent thermal runaway before it occurs.

3.1.1 Potting & Encapsulation

A wide variety of polymers are working to make the cars thermally stable in powertrains. One of the major costs per car is the potting and cell encapsulation. Two-part polymer systems that cure in place when poured over battery cells have been adopted to stop the thermal runaway. Though the weight and cost of these systems are something the top EV companies are currently working on improving, the effectiveness for thermal management and stability is unmatched. *Figure 4* explains how encapsulation can limit the thermal runaway to only one cell and protect the fire from propagating. Common polymers used are epoxy, PU, and silicone systems are used for encapsulating battery cells to improve shock resistance and thermal insulation (Zhang & Zhou, 2020).

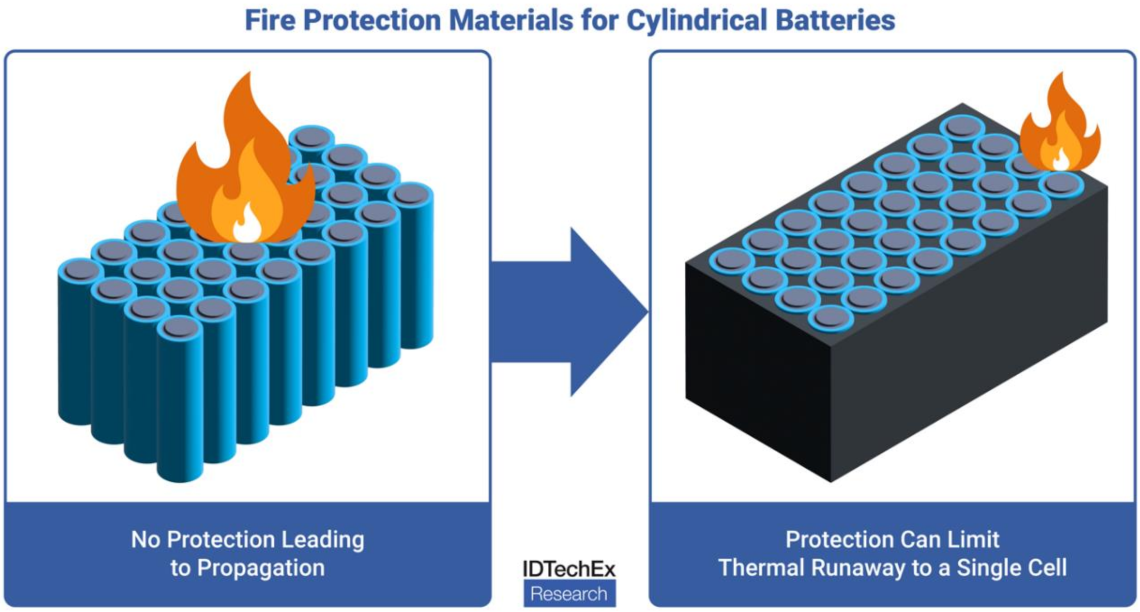

Figure 4. The use of protective materials around cells can prevent or delay thermal runaway propagation. *Source: IDTechEx (2023)*

3.1.2 Thermal Manifolds

Another key requirement for achieving battery performance for longer range is maintaining the Li-ion battery cells temperature typically between 15°C and 35°C (59°F to 95°F). Coolant Circulation systems are designed to circulate the coolant in and out of the battery cell. Nylon and PP composites are used in coolant channel housings due to their thermal resistance (Chen et al., 2021). The hoses can be of a greater complexity in design to route the most optimum way to reach most cells in the shortest time possible, depending on the infrastructure. This required injection molded connectors, usually with glass-filled polymers to provide the mechanical strength to hold the extruded pipelines together. The connections are critical sealing joints that are made with barb heights, O-rings, and wedding bands.

3.1.3 Insulation Covers

High-voltage components such as battery packs, inverters, and electric motors generate significant heat during operation, which, if unmanaged, can lead to reduced efficiency, shortened component life, or safety hazards like thermal runaway. To address these challenges, advanced polymer-based insulation materials—including silicone foams, mica composites, and aerogels—are widely adopted for their lightweight structure, high dielectric strength, and excellent thermal resistance (IDTechEx, 2023; Kuraray, 2023). These materials are typically integrated into cell-to-cell barriers, module housings, and encapsulants to limit thermal propagation and improve thermal management in confined spaces (Thermtest, 2024). In particular, the use of flame-retardant polymers with low thermal conductivity helps to isolate high-energy cells and prevent cascading failure events in battery systems (MDPI, 2023). High-performance polymers are integral to advanced battery safety systems, serving as thermal barriers, impact absorbers, and flame-retardant enclosures to mitigate the effects of cell failure.

3.2 Electrical Applications

Not just limited to powertrain systems, most electronics in an electric vehicle use polymers for protective enclosures, brackets, and covers.

Several electrical components need a safe covering to either hold or protect the contact with other components. These covers can range from a simple injection molded or thermoformed part to as complicated as an insert molding with tens of sub-components and intricate features. These can enhance operator safety while installing or working close to any conductors carrying electricity or heat. Multi-layer PP/PA structures provide flame retardant and thermal shielding capabilities (Wang et al., 2023). These covers offer not just insulation but also help the shelf life of the part, offering corrosion resistance. There have been advancements in the coating processes, like powder coating the long and complex profiles like low or medium-voltage busbars. This powder-coated covering, usually referred to as sleeves, enhances the operator's safety, durability, and electrical insulation. The polymers mainly used for such applications are epoxy resins.

As also listed in Table 2, Housing for PCBAs and Connectors mainly use nylons. Glass-filled PA66 and epoxy composites offer dimensional stability and electrical insulation (Kulkarni & Maiti, 2019). Whereas, in USB Modules, miniaturized components benefit from polymers like PC/ABS blends with flame-retardant additives (RadiciGroup, 2024).

Table 2. Plastics Used in Electrical Components of EV Electronics

Component	Plastic / Polymer	Function in EV Electronics
PCB Substrate (PCBA)	FR-4 epoxy glass fiber (or polyimide)	Provides structural board support, thermal stability
PCBA Enclosure / Housing	PA6 GF, PC/ABS	Mechanical protection, flame retardancy, insulation
Connector / Wire Overmold	PVC, PBT, TPE	Electrical insulation, environmental and vibration sealing
Conformal Coating / Potting	Epoxy, Acrylic, Silicone/Urethane	Moisture and vibration protection, anti-EMI
USB/Infotainment/Sensor Housing	PC/ABS, Silicone, Acrylic	EMI shielding, vibration resistance, user safety enclosure

3.3 Environmental and Mechanical Protection

Battery packs, being a highly safety critical system, need isolation from debris and moisture for its optimum performance. Polymers are extensively employed in the form of foam gaskets, overmolded seals, and liquid-applied sealants to safeguard the battery pack from moisture, dust, thermal stress, and mechanical shock as shown in *Figure 5*. The environmental sealing is designed from materials like silicone foam, butyl-coated PVC, or PU. Foam structures made from PU or EPDM also absorb environmental stress (Singh & George, 2021). EPDM and FKM-based gaskets prevent ingress of moisture and dust in pack assemblies (Sustainable Polymers EV, 2024).

Over molded seals, typically manufactured using elastomeric materials, provide enhanced protection against environmental ingress and offer dimensional stability, even in complex housing geometries (Envalior, 2024). Room temperature vulcanizing (RTV) silicones and liquid gaskets are applied for gap filling and offer excellent adhesion, flexibility, and thermal resistance, making them ideal for use between modules or around cable penetrations (Arkema, 2023). These sealing materials must meet stringent automotive standards for ingress protection (IP67/IP69K) and chemical resistance to battery electrolytes and coolants, emphasizing the importance of polymer formulation and material selection in high-voltage applications (Wang et al., 2023).

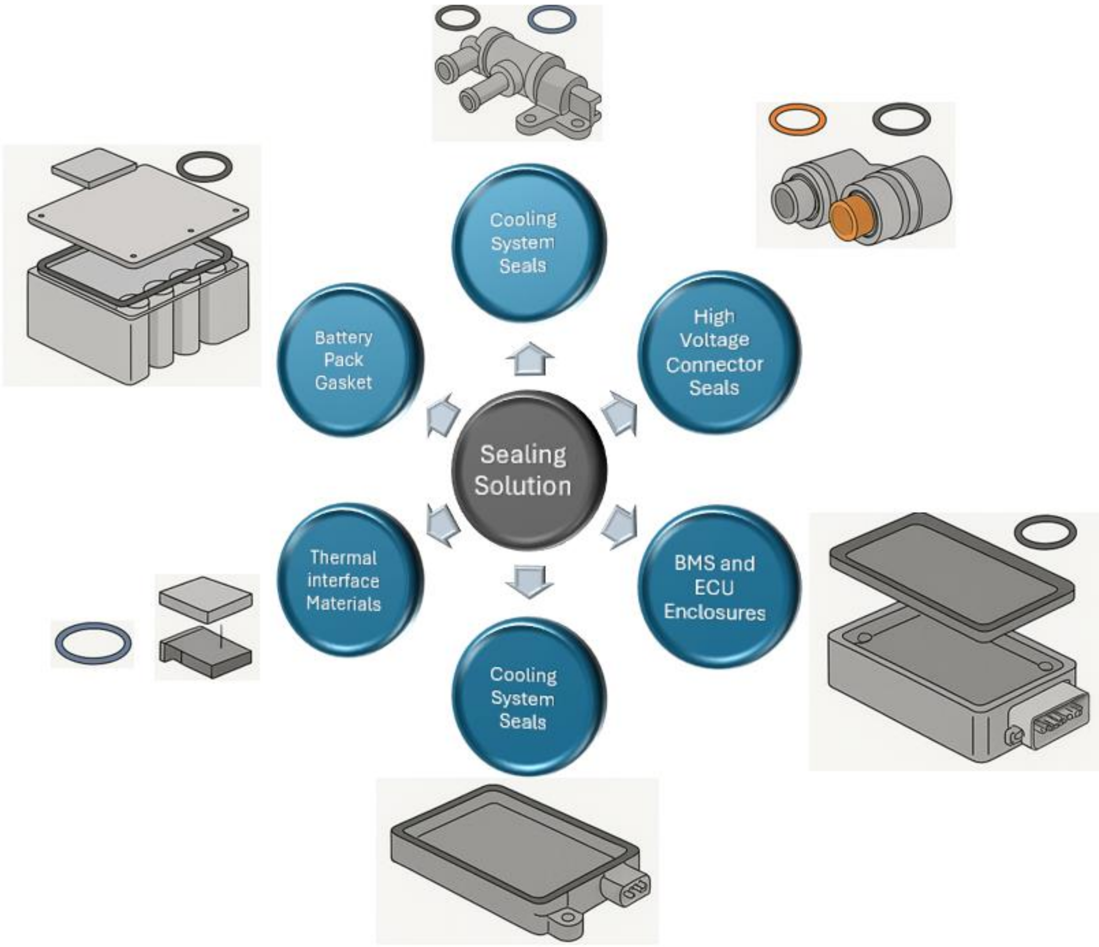

Figure 5. Sealing and thermal management components in EV electronics. The illustration shows common materials and designs used for battery pack gaskets (e.g., silicone foam, EPDM), high-voltage connector seals (PBT O-rings, FKM), BMS and ECU enclosures (PC/ABS, rubber gaskets), thermal interface materials (gap pads, thermally conductive silicone), and cooling system seals (EPDM, fluorosilicone).

3.4 Adhesion and Bonding

Adhesives are extensively used to mate components with or without a secondary sealing like mechanical fasteners, welding, or crimping, depending on design and service requirements (Loh et al., 2020). In high-voltage battery systems, adhesives not only bond parts together but also contribute to structural integrity, vibration damping, gap filling, and thermal management (Zhang et al., 2022).

One of the main applications is Room Temperature Vulcanizing (RTV) Sealants which are Silicone-based RTVs widely used for flexible sealing (Arkema, 2023). This is a good option for enclosing the top and bottom halves of the battery enclosures and provide safety against environmental contaminants. Integration of adhesives with elastomeric seals is an increasingly common design approach, where liquid gaskets, over-molded seals, or form-in-place gaskets (FIPG) are used in conjunction with mechanical fastening to ensure redundancy and improved sealing performance (BASF, 2022).

4. Challenges and Future Trends

The most critical and emerging issue is the circularity of polymers. End of life recycling needs to be further increased as the current global percentage of plastic waste recycled is projected to reach only 17% by 2060 without major policy intervention (OECD, 2022). Research is going on to study recycled thermoset matrices, as thermosets don't have the ability to melt or reshape. To improve sustainability and regulation compliance, bio-based flame retardants are researched further (Patil et al., 2023).

Lightweighting has great benefits to the overall range for powertrain, giving more miles in full charge by reducing energy consumption per mile. (Alonso et al., 2021). This ever-emerging demand to light weight has opened more possibilities for composites and polymers to replace metals and glasses in the car. Fiber-reinforced composites and engineering polymers can deliver 20–50% weight reduction compared to traditional aluminum or steel components with similar mechanical performance (Das et al., 2020). Hybrid polymer-metal designs have an upward trend in lightweighting solutions, making polymer-based solutions even more competitive in structural and semi-structural battery components (Kakroodi et al., 2022).

Another technical challenge for the implementation of polymers in battery packs is balancing between thermal conductivity and electrical insulation. Most neat polymers have thermal conductivity in the range of 0.1–0.5 W/m·K, which is insufficient for efficient heat dissipation in densely packed modules (Wang et al., 2021). Incorporating filler such as boron nitride, alumina, or graphene, can increase thermal conductivity while maintaining insulation, but often at the expense of processability or mechanical toughness (Goli et al., 2013; Hu et al., 2020).

Some challenges from a manufacturing standpoint have long been the flashing of molten polymers between parting lines, smooth de-gating, warpage, shrinkage and maintaining profiles. Advanced CAE simulations are employed to predict the mold design accuracy in development stages. (RadiciGroup, 2024; Lan et al., 2023) The adoption of Industry 4.0 technologies, such as IoT-enabled molding equipment and data-driven quality control, is optimizing the production of high-performance polymers for EV battery enclosures.

5. Integration of Polymers in EV Battery Pack Design

With the options of manufacturable polymer and composites growing every day, it is important to choose the most cost-effective material that can serve all the requirements of the part in the battery lifespan. For example, glass fiber–reinforced polyamides and polypropylene composites are widely used for module frames and coolant distribution components, delivering high stiffness, lightweighting, and chemical resistance (RadiciGroup, 2024). Elastomers such as EPDM and fluorosilicone provide environmental sealing, enabling high ingress protection ratings and accommodating thermal expansion mismatches (BASF, 2022; Lan, Wang, & Hu, 2023).

Overmolding, insert molding, sandwich compression molding are some of the newer approaches to building parts with several different plastic, rubber and metals combined, significantly increasing the functionality of a single part. This improves the seal integrity in the long term as well (BASF, 2022). In addition, co-extrusion and multi-material molding enable the integration of electrical insulation layers directly into structural housings, further improving assembly efficiency (Lu et al., 2021). Proper interface adhesion between dissimilar polymers is critical to avoid delamination during vibration or thermal cycling, a challenge addressed through surface treatments and primer chemistries (Zhang, Sun, & Luo, 2022).

6. Conclusion

Today, we are maximizing the purpose every single component serves in the powertrain, fighting to save every millimeter of space and gram of weight possible. Polymers and composites have enabled some of the most powerful and efficient electric vehicles ever built, offering multifunctionality that goes far beyond simple structural support (Alonso et al., 2021; Kakroodi et al., 2022). The continued advancement of material science, manufacturing technology, and design innovation can push the boundaries of what engineering can achieve in e-mobility innovation. With each passing day, we collect more data on polymer performance under real-world EV conditions, deepening our understanding of their true capabilities (Lan et al., 2023). This growing knowledge base fuels a cycle of innovation—where insights from field performance inform the next generation of polymer formulations, designs, and applications—ultimately leading to lighter, safer, and more sustainable electric vehicles.

Emerging priorities include the development of thermally conductive yet electrically insulating polymer composites, bio-based flame-retardant materials, and design-for-recyclability approaches that meet global regulatory targets (Patil et al., 2023; Hu et al., 2020). With the transition toward solid-state batteries, polymer roles will continue to evolve—shifting toward dielectric optimization, multifunctional integration, and compatibility with next-generation manufacturing technologies (Lu et al., 2021).

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