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Research Paper**ADVANCES AND EMERGING RESEARCH TRENDS IN ELECTRIC VEHICLE TECHNOLOGIES: A COMPREHENSIVE REVIEW**G. Naveen kumar^{1a}, T. Rajesh²,¹PG Student, Department of EEE, Malla Reddy Engineering College, Secunderabad, Telangana, India.²Department of EEE, Malla Reddy Engineering College, Secunderabad, Telangana, India.Corresponding Author: ^anaveenguguloth493@gmail.com,

Abstract- The Electric Vehicle (EV) technology is at an unprecedented stage of global expansion owing to environmental issues, energy security, and the rapid technological advances in batteries, power electronics, and intelligent charging facilities. The innovations that have been made in high-energy-density battery materials, the creation of solid-state electrolytes, innovative thermal management solutions, and high-efficiency electric propulsion systems have been very beneficial to modern EVs, such as Battery Electric Vehicles (BEVs), Hybrid Electric Vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs), and Fuel Cell Electric Vehicles (FCEVs). The current studies are very much devoted to new technologies like Vehicle-to-Grid (V2G) integration, wireless dynamic charging, smart routing, cloud-enabled mobility, and AI-based energy management. In spite of these significant progresses, EV usage is still hindered by the range restrictions, the lack of charging infrastructure, thermal instability, fast-charging degradation, and hindrances to battery recycling. In this paper, the details on the modern achievements in EV technologies are synthesized and organized, the research issues are defined, and the opportunities in the future are proposed.

Keywords: *Electric Vehicles; Energy storage; Lithium-Ion Batteries; Solid-State Batteries; Wireless Charging; Vehicle to grid; EV Thermal Management; Sodium-Ion Batteries; EV Propulsion; Hydrogen Fuel Cell Vehicles.*

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I. INTRODUCTION

Fossil The increase in CO₂ emissions, the strictness of emission requirements at the international level, and the necessity to provide mobility sustainably are the driving forces of the rapid electrification of transportation. EVs have several benefits compared to Internal Combustion Engine (ICE) vehicles, including not emitting pollutants through the tailpipe, greater energy efficiency, requiring fewer services, and being compatible with renewable energy-based chargers.[1] Within the last ten years, lithium-ion chemistry, power electronics, and smart charging breakthrough innovations have improved EV adoption.

II OVERVIEW OF EV ADVANCEMENTS

New developments in the Electric Vehicle (EV) technologies have provided great performance, efficiency, and convenience to the users. Modern EV propulsion systems are based to a considerably greater extent on high-efficiency electric motors such as Permanent Magnet Synchronous Motors (PMSM) and robust

induction motors based on wide-bandgap semiconductors such as SiC and GaN devices that allow faster switching and high-speed charging operations, as well as lower energy losses.[2] Power electronic converters such as DC/DC converters and complex inverters are therefore of key importance for optimization of the energy flow from the battery to the wheels. Meanwhile, EV charging infrastructure has developed fast and ultra-fast charging systems (50350 kW), inductive charging, and dynamic in-road charging systems that facilitate the provision of energy throughout driving. Intelligent energy management systems and charging stations with smart grids are another step to better grid stability and the development of the EV ecosystem.[3]

a. Energy Storage Systems

Major The achievement of high-capacity lithium-ion chemistries, in the form of NMC, NCA and LFP, and the incorporation of silicon-rich and silicon-dominant anodes to maximize density is driving major changes in the energy storage technology, as well as the introduction of Solid-

State Batteries (SSBs) based on ceramic or polymer electrolytes and the use of sodium-ion batteries as viable low-cost alternatives.[4]

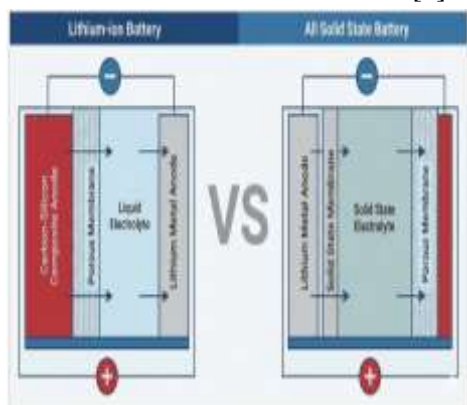


Figure 1: Internal structure comparison: Li-ion vs solid-state battery

These structural innovations are further complemented by better battery thermal management that is aimed at maximizing performance and energy use.

Table 1: Comparison of Emerging Battery Technologies

PARAMETER	LI-ION (NMC)	SOLID-STATE BATTERY	SODIUM-ION BATTERY
Energy Density	High	Very High	Medium
Safety	Medium	Very High	High
Cost	High	Very High	Low
Cycle Life	High	Very High	Medium
Commercial Maturity	High	Low	Medium

b. Electric Propulsion and Power Electronics

Electric propulsion: the heart of the Electric Vehicles (EVs) is the high-performing electric machine and power electronic converter to realize high performance and energy efficiency. Permanent Magnet Synchronous motors (PMSM) dominate among other motor technologies with their high torque density, rapid dynamic response and high efficiency, whereas induction motors are still extensively used because of their strength and affordability.[5] Conditioning and control of energy flow in the propulsion system are very much dependent on power electronics, especially DC/DC converters and inverter stages, which provide controlled AC to run the motor using battery DC power. Recent developments in wide-bandgap semiconductor technologies like Silicon Carbide (SiC) and Gallium Nitride (GaN) have provided the ability to switch at high frequencies,

minimize thermal losses, increase efficiency and design converters in a small size. All these together will boost the overall propulsion performance, driving range and aid fast-charging compatibility in the next generation EVs.[6]

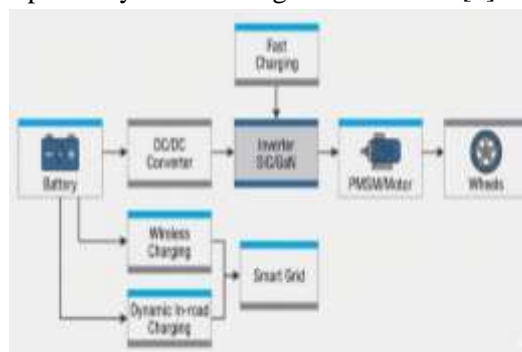


Figure 2: Detailed EV Powertrain and Advanced Charging Architecture

C. Charging Infrastructure

To facilitate the mass adoption of EVs, it is required to have a properly developed charging

infrastructure, and this should provide various levels of charging to meet various types of applications. Level 1 AC charging is 23 kW, and is mostly installed at home, and takes 812 hours to charge fully. Level 2 AC chargers offer greater power rates of 7-22 kW and also reduce the charging time to 3-5 hours, which makes them applicable in the installation of the chargers both in public and at home. In the long-distance transportation and highway systems, DC fast-

charging systems with 50-150 kW rating can greatly reduce the time required to charge to 30-60 minutes. High-performance EVs have shorter recharging times of under 20 minutes with ultra-fast DC chargers with a range of 250 to 350 kW. Wireless charging technologies, which work at the 3- 20 kW level, provide convenient charging without cables with 4-8 hours of standard time and are getting more popular in smart mobility hubs and automatic charging bays.[7]

Table 2: Types of EV Charging Technologies

CHARGING TYPE	POWER RATING	CHARGING TIME	APPLICATION
Level 1 AC	2–3 kW	8–12 hours	Home
Level 2 AC	7–22 kW	3–5 hours	Public/Residential
DC Fast Charging	50–150 kW	30–60 mins	Highways
Ultra-fast DC	250–350 kW	<20 mins	Long-distance travel
Wireless Charging	3–20 kW	4–8 hours	Smart mobility hubs

D. Intelligent and Interconnected EV System
 Smart and connected EV systems use modern digital technologies, including artificial intelligence (AI), cloud-based computing, Internet of Things (IoT) and digital twins, to make vehicles much smarter, safer and more efficient in operations. The sensors in all areas of the car acquire real-time information on battery level, motor, as well as thermal state, and driving behaviours. This information is sent to cloud servers, where AI and machine-learning models handle it and process it to be able to do predictive maintenance, fault detection, and optimized energy control. Digital twin models are a virtual version of the real-life EV in a virtual environment that can be monitored in real-time, simulated, and predict the performance under different operating conditions. All of these features allow making smart decisions, streamlining the processes of charging, making it individual to the user, and connecting it to smart grids and other advanced driver-assistance

systems (ADAS) to create a complete smart EV ecosystem.[8]

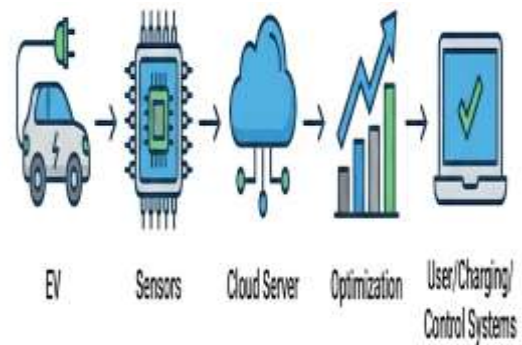


Figure 5: Modern Smart EV Ecosystem Flowchart

III. SUMMARY OF TECHNICAL SUMMARY CONDENSED

Connected and smart EV systems introduce sensors to the IoT, cloud computing, AI algorithms, and digital twins to make vehicles more intelligent and efficient in their functions. Onboard sensors also provide real-time information that is delivered to the cloud environment to facilitate AI-driven diagnostics,

which can enable predictive maintenance, energy management, and fault detection.[9] Digital twin technology is a virtual copy of the EV, which helps in the constant monitoring of the performance and simulation in dynamic conditions. These interrelated systems enhance

coordination in charging, improve the interactions with people, enable a flawlessly integrated connection with smart grids and autonomous driving capabilities and create an extremely versatile and data-focused EV ecosystem.[10]

Table 3: Challenges and Solutions in EV Technology

KEY CHALLENGES	PRIMARY SOLUTIONS	MECHANISM OF ACTION
Limited Range	Solid-State Batteries (SSBs) SiC / GaN Semiconductors	SSBs: Higher energy density stores more power in the same space. SiC/GaN: Reduces power loss in inverters by up to 50%, extending range.
Charging Gaps	Dynamic Wireless Charging AI Smart Routing	Dynamic: Charges vehicle <i>while driving</i> via road coils (no stops needed). AI: Predicts precise range and routes to guaranteed available chargers.
Battery Aging	Solid-State Batteries (SSBs) AI Battery Management	SSBs: Eliminates liquid electrolytes, reducing degradation from heat. AI: Optimizes charging cycles to prevent stress and extend life by 20%+.
High Cost	SiC / GaN Semiconductors Dynamic Charging	SiC/GaN: Allows for smaller, cheaper cooling systems and passive components. Dynamic: Enables smaller, lighter (and cheaper) battery packs.

IV. IMPROVEMENTS IN BATTERY TECHNOLOGY

The battery technology has been highly developed in the past decade as a result of the rising demand for electric vehicles (EVs) and renewable-energy storage worldwide, as well as high-performance portable electronic devices. Lithium-ion (Li-ion) batteries are the most common type of electrochemical storage systems because they have a high energy profile, prolonged cycle life, and good power

characteristics.[11] The current trends in research are seen to be aimed at enhancing material chemistry, safety, cost reduction, and sustainable recycling processes to satisfy the energy needs in the future.

a. New Advances in the Lithium-Ion Technology

Li-ion batteries are still being improved by refining the cathode material, anode structure and electrolyte. Johnson and Johnson NMC and NCA cathode chemistries use high-nickel chemistries,

which have led to improved specific energy, although at the cost of reduced reliance on cobalt. Electrolyte additive engineering and separators that are thermally resilient have enhanced the solid-electrolyte interphase (SEI), the thermal stability and cycling characteristics.[12] Also, other materials that have improved the energy density of electrodes without reducing their lifespan include new electrode manufacturing methods, including high-area-loading electrodes, dry-coating processes and thinner current collectors.

b. Silicon-Based Anodes

Silicon has become a promising anode material due to its high theoretical capacity. Nevertheless, it exhibits a high volumetric increase during lithiation, leading to structural instability and rapid capacity decay. The recent advances in nanoscale silicon fabrication, silicon-carbon composites and flexible polymer binders have made silicon-enhanced anodes that can sustain a higher charge capacity with enhanced mechanical stability.[13] The developments provide accelerated charging, increased storage of energy, and a longer battery.

c. Batteries of Lithium-Metal and Solid-State.

Lithium-metal batteries are the biggest advancement over the traditional Li-ion battery because they have a higher specific capacity. Nevertheless, the formation of dendrites and the instability of electrolytes restrict mass usage. A possible solution is solid-state batteries (SSBs), which involve substituting liquid-based electrolytes with solid ionic conductors as they are safer, with greater energy density, and lifecycle performance. The development of sulfide-based, oxide-based based and polymer-based solid electrolytes and interface engineering methods is gradually handling issues concerning interfacial resistance, manufacturability and long-term stability.

d. Sodium-Ion and Adventure Chemistries

The beginning of substituting lithium-based systems with higher costs and demand has

intensely focused on sodium-ion (Na-ion) batteries as beneficial and sustainable solutions. The large amount of sodium and the extensive spread of the element across geographical locations render the Na-ion technology exceptionally appealing to grid storage and low-cost applications.[14] However, on the energy density and low-temperature front, recent advancements have seen the use of Na-ion cells compete in certain areas with LFP-based Li-ion batteries. Similar studies on lithium-sulfur, zinc-based aqueous batteries and redox-flow systems are being pursued to seek alternatives to high-energy, long-duration storage.

e. System-Level Innovations

Beyond materials science on the scale of systems, the next generation performance of energy storage is being stacked. Ultra-fast charging. It is now possible to do ultra-fast charging by using high-voltage EV architectures (800–1000 V) minimizing resistive losses. New battery management systems (BMS) are now equipped with complex algorithms, diagnostics with artificial-intelligence support, and real-time thermal control to enhance the safety and increase battery life. The use of thermo-management technologies, such as liquid-cooling plates, phase change materials and adaptive coolant flow approaches, adds further safety measures to provide high-power operation.

f. Recycling and Sustainability

Due to the increase in battery implementation around the world, recyclable and sustainable disposal measures have become a necessity. Techniques in lithium, nickel, cobalt and manganese are being developed by hydrometallurgical methods, pyrometallurgical methods, and direct-recycling methods to extract valuable materials out of end-of-life batteries.[15] Direct recycling, in its turn, is promising in terms of recycling cathode materials with minimum processing. Circular-economy approaches (recycling, second-life, and green manufacturing) are getting incorporated in supply chains in

energy storage.

V. CONCLUSION

The technology of electric vehicles (EVs) is improving at an unprecedented rate because of the breakthroughs in battery chemistry, highly efficient power electronics, intelligent charging infrastructure, and intelligent mobility infrastructure. Ongoing advancements in lithium-ion and new-generation solid-state batteries are possible to increase the energy density, speed of charge, and lifetime, as well as wide-bandgap devices like SiC and GaN are enhancing the efficiency of the entire drive train. The growing Lane speed chargers or wireless charging and infrastructure grid integration are bolstering the

large-scale EV adoption. Moreover, technology and AI-based digital twins, predictive maintenance systems and connected vehicle technologies are continually improving the experience and safety as well as reliability. The next stage of development will occur on the basis of sustainable production of batteries, the possibility to charge at any place, hydrogen filling stations, and improved AI codes to optimize energy and traffic. EVs have a great potential of becoming the most important mobility solution with a robust policy backing and worldwide research activities that will help in enhancing cleaner transportation and a sustainable energy ecosystem.

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