

Overview of the Current Status and Future Development Trends of Core Technologies in Electric Vehicles

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Abstract

Driven by the dual goals of global carbon neutrality and the transformation and upgrading of the automotive industry, electric vehicles have become a strategic core area for addressing climate change and ensuring energy security. This article systematically reviews the research progress in the field of electric vehicles, focusing on five mainstream research directions: power battery technology, optimization of electric drive systems, intelligence and autonomous driving, lightweight and material innovation, charging and swapping, and energy interconnection. It comprehensively analyzes the technological breakthroughs, application status, and existing bottlenecks in various fields. Research has shown that high-energy density solid-state batteries, silicon carbide electric drive modules, Level 3 or above autonomous driving, integrated lightweight technology, and V2G energy interconnection systems are current and future core research hotspots. Finally, based on the needs of industrial development, the future research focus and development path of electric vehicle technology were discussed, providing a reference for academic research and industrial practice.

Keywords

Electric Vehicles, Power Battery, Electric Drive System, Intelligentization, Lightweight, Energy Interconnection

1. Introduction

1.1. Research Background

Global climate change and the energy crisis have become common challenges faced by human society. As one of the main sources of carbon emissions, the green

transformation of the transportation sector is urgent. In this context, major economies have successively introduced a timetable for banning the sale of fuel vehicles, accelerating the electrification process of the automotive industry. China has proposed the dual carbon goal of “peaking carbon emissions before 2030 and achieving carbon neutrality before 2060”, and has listed new energy electric vehicles as a strategic emerging industry. By 2023, China’s electric vehicle sales will reach 9.49 million units, with a market penetration rate of 31.6%, ranking first in the world for nine consecutive years and becoming the core driving force for the development of the global electric vehicle industry [1].

The development of electric vehicles is not only a revolution in the form of automotive products, but also a technological revolution involving multiple fields such as energy, materials, and electronic information. After years of development, electric vehicles have made significant progress in terms of range, charging efficiency, and product reliability. However, they still face bottlenecks such as insufficient battery energy density, incomplete charging facilities, and the need to improve intelligent experiences. As the key milestone of the “14th Five-Year Plan”, electric vehicle technology is entering a critical leap stage from “usable to easy to use” in 2025. Sorting out the current mainstream research directions and summarizing the laws of technological development are of great significance for promoting high-quality industrial development.

1.2. Research Purpose and Significance

This article aims to systematically review the core research directions and technological progress in the field of electric vehicles, clarify current research hotspots, and future development trends. By integrating domestic and foreign academic research results, industry technology reports, and authoritative institution data, comprehensively analyze the technological breakthroughs and application status in key fields such as power batteries, electric drive systems, and intelligent technology, and analyze the shortcomings of existing research. The research results can provide important references for researchers to clarify research directions, enterprises to formulate technology strategies, and policymakers to improve industry support policies, helping the electric vehicle industry achieve technological iteration and sustainable development.

1.3. Research Scope and Content Framework

This article focuses on the mainstream research directions in the field of electric vehicle technology, with a focus on five core areas for review: power battery technology innovation (solid-state batteries, sodium ion batteries, battery management system optimization), efficiency improvement of electric drive systems (silicon carbide power modules, multi-in-one electric drive integration), intelligent and autonomous driving technology (L3 level and above autonomous driving, intelligent cockpit, vehicle road coordination), lightweight and material technology innovation (high-performance material applications, integrated molding processes),

and charging swapping and energy interconnection systems (supercharging technology, swapping mode, V2G technology).

The article structure is as follows: Firstly, it elaborates on the development background and research significance of the electric vehicle industry; Secondly, a detailed review of the research status, technological breakthroughs, and application cases of the five mainstream research directions will be conducted in each chapter; Subsequently, analyze the common challenges faced by current research; Finally, looking forward to future research trends and development paths.

2. Mainstream Research Directions and Technological Progress of Electric Vehicles

2.1. Innovation in Power Battery Technology

As the core component of electric vehicles, the energy density, safety, cost, and cycle life of power batteries directly determine the core performance of the vehicle, making it a top priority in current research on electric vehicles. In recent years, power battery technology has shown a dual-track development pattern of “breakthroughs in new battery systems + optimization of existing technologies”.

2.1.1. Research and Industrialization of High Energy Density Solid State Batteries

Solid-state batteries replace traditional liquid electrolytes with solid-state electrolytes, which have revolutionary advantages in energy density, safety, and other aspects, and have become the core direction for breaking through range anxiety. Solid-state electrolytes eliminate the leakage and combustion risks of liquid electrolytes and can also be adapted to high-energy density electrode materials, greatly improving battery energy density. In 2024, Toyota announced that its developed solid-state battery samples have an energy density of 400 Wh/kg, which is 1.5 times that of existing commercial lithium batteries. The charging time can be shortened to less than 10 minutes, and the range is expected to exceed 1000 kilometers [2].

Chinese companies have also made significant progress in the field of solid-state batteries. CATL plans to achieve small-scale production of solid-state batteries at its Yibin factory by 2025, with an initial production capacity of 10 GWh and a target energy density of 350 Wh/kg for mass-produced products. From a technical perspective, current mainstream research focuses on three types of solid electrolytes: sulfides, oxides, and polymers. Sulfide electrolytes have high ionic conductivity and good processability, but their stability needs to be improved; Oxide electrolytes have excellent stability, but high interface impedance; Polymer electrolytes have low cost and good flexibility, but their ionic conductivity is insufficient. The current research hotspots include electrolyte material modification, electrode electrolyte interface optimization, and innovation in solid-state battery preparation processes, aiming to solve key technical bottlenecks such as interface impedance and cycling stability. According to Bloomberg New Energy Finance (BNEF), the global solid-state battery market is expected to exceed \$5 billion by

2025, with a penetration rate of 5%, mainly used in high-end electric vehicle models.

2.1.2. Development and Application Expansion of Sodium Ion Battery Technology

Sodium-ion batteries have become an important supplement to lithium batteries due to their abundant raw materials (sodium resources), wide distribution, low cost, excellent low-temperature performance, and safety performance, especially suitable for economical electric vehicles and energy storage scenarios. In recent years, the energy density of sodium-ion batteries has continued to increase, gradually meeting the conditions for vehicle application. In 2024, CATL will launch the first generation of sodium-ion batteries with an energy density of 160 Wh/kg and a cost reduction of 0.3 yuan/Wh, which is 20% lower than lithium iron phosphate batteries. The cycle life will exceed 3000 times [3].

The research focus of sodium ion batteries is on the development of electrode materials and the optimization of battery performance. In terms of positive electrode materials, layered oxides, polyanionic compounds, and Prussian blue analogues are the three mainstream systems currently being studied, which improve capacity and cycling stability through methods such as element doping and structural modification. In terms of negative electrode materials, hard carbon materials have become a research hotspot due to their high sodium storage capacity and low cost. By optimizing the preparation process, conductivity and structural stability can be improved; In terms of electrolyte, develop electrolyte systems with high ionic conductivity and a wide electrochemical window to improve electrode electrolyte interface compatibility.

In terms of industrial application, BYD plans to launch the Seagull model equipped with sodium-ion batteries by 2025, with a range of 400 kilometers and a price controlled within 80,000 yuan, which is expected to further reduce the threshold for purchasing electric vehicles. It is expected that the market size of sodium-ion batteries will reach 10 billion yuan by 2025, mainly applied in A0-level and below economical electric vehicles, low-speed electric vehicles, and other fields, forming a complementary market pattern with lithium batteries.

2.1.3. Intelligent Upgrade of Battery Management System (BMS)

The battery management system, as the “brain” of power batteries, is responsible for battery status monitoring, charge and discharge control, thermal management, and fault warning, directly affecting the safety, reliability, and service life of batteries. With the development of power battery technology, BMS is moving towards intelligence, precision, and a cloud-based direction [4].

The integration of artificial intelligence and big data technology is currently a core hotspot in BMS research. Tesla optimized the BMS control strategy through AI algorithms, combined with multi-dimensional data such as battery cell voltage, temperature, and cycle times, to establish an accurate battery state estimation model. The battery cycle life was increased from 1500 to 2000 times, and the probability of thermal runaway was reduced to 0.001%. The “Cloud BMS” system de-

veloped by CATL achieves real-time uploading of battery data through vehicle networking technology, uses cloud big data to analyze battery health status (SOH), remaining charge (SOC), and safety risks, and realizes remote fault warning and control strategy optimization. By 2025, this technology will be popularized in mainstream car companies in China, and it is expected to reduce battery failure rates by 30%.

The key technologies currently being researched in BMS include high-precision SOC/SOH estimation methods (based on algorithms such as Kalman filtering and neural networks), thermal runaway warning and suppression technology, multi-battery pack collaborative management strategy, and battery protection technology under extreme working conditions. With the application of new battery systems such as solid-state batteries and sodium-ion batteries, BMS needs to optimize control strategies specifically to adapt to the electrochemical characteristics of different batteries, which will become an important direction for future research.

2.2. Efficiency Optimization of Electric Drive System

The electric drive system is the “power heart” of electric vehicles, consisting of core components such as motors, electronic controls, and reducers. Its efficiency, power density, and reliability directly affect the vehicle’s power performance and energy consumption level. In recent years, electric drive systems have shown a development trend of “high efficiency, integration, and lightweight”, with core technological breakthroughs focused on the application of silicon carbide power devices and the integration of multi-in-one electric drives.

2.2.1. Research and Popularization of Silicon Carbide (SiC) Power Modules

Silicon carbide, as a third-generation semiconductor material, has excellent characteristics such as high voltage resistance, high thermal conductivity, and low conduction loss. Compared with traditional silicon-based IGBT devices, it can significantly reduce energy consumption in electronic control systems and improve system efficiency. Research has shown that electronic control systems using silicon carbide power modules can reduce switch losses by over 70%, improve overall system efficiency by 3% - 5%, and correspondingly increase the range of electric vehicles by about 10% [5].

BYD has made significant breakthroughs in the field of silicon carbide technology. The independently developed SiC electronic control system has been applied to Han EV models, with system efficiency increased to 97.5%, energy consumption reduced by 10%, and a range exceeding 700 kilometers. The Tesla Model 3 also uses silicon carbide power devices, and its electronic control system has a maximum efficiency of 98%. The current key directions of silicon carbide research include: optimization of silicon carbide chip preparation process (reducing defect rate, improving yield), innovation of packaging technology (improving heat dissipation performance, enhancing reliability), and cost control of silicon carbide modules (reducing unit price through large-scale production).

With the maturity of technology and the release of production capacity, the cost of silicon carbide modules continues to decline. It is expected that the cost will decrease by 40% by 2025, and the market penetration rate will increase to 30%. According to data from the China Association of Automobile Manufacturers, the range of electric vehicles equipped with SiC electronic control systems will generally exceed 700 kilometers by 2025, becoming a standard for mid to high-end electric vehicles. Future research will further focus on optimizing the matching between silicon carbide and vehicle electronic control systems, developing efficient control strategies adapted to silicon carbide devices, and fully leveraging their low-loss advantages.

2.2.2. Integration Technology of Multi-in-One Electric Drive System

The multi-in-one electric drive system can effectively reduce the number of components, shrink the volume, and reduce the weight by highly integrating the motor, electronic control, reducer, DC/DC converter, and other parts, while improving system efficiency and reliability. Compared to traditional decentralized electric drive systems, the multi-in-one electric drive system can reduce its volume by more than 40%, reduce its weight by about 30%, and improve system efficiency by 2% - 3%.

The DriveOne multi-in-one electric drive system launched by Huawei is a benchmark product in the industry. The system integrates multiple components such as motors, electronic controls, reducers, and car chargers, reducing its volume by 40% and weight by 30%. It has been successfully applied to the WENJIE M7 model, reducing vehicle energy consumption by 8% and increasing range by 10%. Xiaopeng Motors plans to adopt a multi-in-one electric drive system for all models by 2025, reducing the overall weight by 100 kilograms and increasing the range by 15% through integrated design.

The current research hotspots of multi-in-one electric drive systems include: integrated architecture optimization design (balancing integration and maintenance convenience), component collaborative control strategy (improving overall system efficiency), thermal management system integration (solving the heat dissipation problem caused by high-density integration), and lightweight material application (further reducing system weight). With the continuous improvement of integration, the multi-in-one electric drive system is developing from “three-in-one” and “five-in-one” to “multi-in-one” full-stack integration. In the future, it will achieve deep integration of electric drive, charging, thermal management, and other systems, becoming the mainstream form of electric vehicle powertrain. It is expected that by 2025, the multi-in-one electric drive system will occupy 50% of the market share of electric vehicles priced over 200,000 yuan, becoming the core configuration of mid to high-end models [6].

2.3. Intelligence and Autonomous Driving Technology

Intelligence is the core competitiveness that distinguishes electric vehicles from traditional fuel vehicles, and it is also one of the most active areas of research in

electric vehicles at present. With the development of artificial intelligence, sensors, and vehicle networking technology, the intelligence of electric vehicles is moving from “assisted driving” to “autonomous driving”, “intelligent cockpit”, and “vehicle road collaboration” in a multi-dimensional collaborative manner, building a comprehensive intelligent travel experience.

2.3.1. Commercialization of Level 3 and above Autonomous Driving Technology

According to the SAE classification standards, autonomous driving technology is gradually evolving from L0 (no automation) to L5 (fully automated), and the core focus of current research and industrial applications is the commercialization of L3 level (conditional autonomous driving) technology. L3 level autonomous driving allows vehicles to autonomously complete operations such as following, changing lanes, and avoiding obstacles in specific scenarios (such as highways and urban expressways). Drivers do not need to continuously monitor, but need to take over the vehicle in a timely manner when requested by the system [7].

In 2024, Mercedes-Benz will become the first car company in the world to obtain approval of the L3 autonomous driving system in Germany. Its DRIVE PILOT system can be opened on the expressway at a speed of no more than 60 km/h. It supports functions such as autonomous car following, lane keeping, and automatic obstacle avoidance. It has been installed on S-class and EQS models. China is making rapid progress in the field of L3-level autonomous driving. Xiaopeng Motors plans to launch urban NGP (navigation-assisted driving) systems in cities such as Guangzhou and Shenzhen by 2025, covering urban expressways and main roads, supporting complex scene functions such as traffic light recognition, unprotected left turns, and automatic parking. It is expected that the penetration rate will increase to 10%.

The current research focus of L3 level autonomous driving includes high-precision perception technology (multi-sensor fusion, laser radar and vision fusion scheme), high reliability decision algorithms (complex scene decision-making based on deep learning, emergency response strategies for extreme working conditions), functional safety and expected functional safety technology (avoiding risks caused by system failures and design defects), data security and privacy protection technology. In addition, the commercialization of L3-level autonomous driving also faces non-technical issues such as laws and regulations, responsibility determination, and ethical and moral standards, which require simultaneous promotion of technology research and institutional construction.

Future research will gradually evolve towards L4 level (highly autonomous driving), with a focus on breaking through the technology of autonomous driving in complex urban road scenarios, achieving all-weather and all-scenario autonomous driving capabilities. The International Energy Agency (IEA) predicts that the global penetration rate of Level 3 and above autonomous electric vehicles will exceed 20% by 2030, becoming an important component of intelligent transportation systems.

2.3.2. Intelligent Cockpit and Vehicle to Road Collaboration (V2X) Technology

Intelligent cockpit is the core carrier for enhancing user experience, which integrates display technology, voice interaction, ergonomics, and other fields to build an intelligent terminal for “human vehicle interaction”. The current research hotspots in intelligent cockpit include multimodal interaction technology (fusion of voice, gesture, and eye recognition), flexible display and AR-HUD technology (improving the intuitiveness of information display), and personalized scene customization (automatically adjusting seats, air conditioning, and entertainment systems according to user habits) [8]. Notably, over-the-air (OTA) software updates have emerged as a critical enabler for the continuous optimization and personalization of intelligent cockpits, allowing manufacturers to remotely upgrade functional modules, fix system vulnerabilities, and tailor user experiences based on real-time usage data, thereby significantly enhancing the lifecycle value of the cockpit system.

The 17-inch central control screen of Tesla Model S, NIO’s NOMI voice assistant, and Ideal Auto’s four-screen interactive system are all typical applications of intelligent cockpits. Research has shown that the interactive response speed, recognition accuracy, and scene adaptability of intelligent cockpits are key indicators of user satisfaction. Currently, research is developing towards personalized experiences with “thousands of people and thousands of faces”, learning user habits through AI algorithms, and achieving adaptive optimization of interaction methods.

Vehicle to Road Collaboration (V2X) technology enhances the safety and reliability of autonomous driving through information exchange between vehicles (V2V), vehicles and roads (V2I), and vehicles and the cloud (V2C), and is an important supplement to intelligent technology. V2X technology can enable vehicles to perceive information such as road congestion, traffic accidents, and changes in traffic signals ahead in advance, overcoming the limitations of single vehicle perception. Current V2X research focuses include: 5G-V2X communication technology optimization (improving transmission rate and reliability), vehicle road collaboration standard system construction (unified communication protocol and data format), edge computing and cloud collaboration (reducing data transmission delay).

China has a leading layout in the field of vehicle road collaboration. It has carried out the construction of intelligent connected vehicle demonstration areas in several cities. By deploying roadside sensors, edge computing nodes, 5G base stations, and other infrastructure, it has built a vehicle road collaborative testing and application environment. By 2025, vehicle road collaboration technology will be deeply integrated with L3-level autonomous driving, achieving large-scale applications in scenarios such as highways and urban expressways, significantly improving the safety and traffic efficiency of autonomous driving.

2.4. Lightweight and Material Technology Innovation

Lightweight is one of the key ways to improve the range and reduce energy con-

sumption of electric vehicles. Research has shown that for every 10% reduction in vehicle weight, the range can be increased by 5% - 8% and energy consumption can be reduced by 6% - 7%. The lightweight technology of electric vehicles is mainly achieved through material innovation and process optimization, with a focus on researching the application of new materials with high strength and low density, as well as integrated molding processes [9].

2.4.1. Research and Application of High-Performance Lightweight Materials

The current lightweight materials for electric vehicles mainly include high-strength steel, aluminum alloy, magnesium alloy, carbon fiber composite materials, etc. Different materials have their own advantages in cost, performance, and processing technology, presenting a development trend of “mixed application of multiple materials”.

Aluminum alloy has become the mainstream material for lightweight electric vehicles due to its high strength, low density (only one-third of steel), and good processing performance. It is widely used in components such as car bodies, chassis, and battery pack casings. The Tesla Model Y adopts an all-aluminum body frame, which reduces the weight by more than 20% compared to a traditional steel body. The battery pack shell of BYD Han EV is made of aluminum alloy material, which reduces weight by 15% and improves impact resistance.

Carbon fiber composite materials have become an ideal material for lightweight high-end electric vehicles due to their high specific strength, corrosion resistance, and good fatigue performance. However, their high cost limits their large-scale application. The body of the BMW i3 is made of carbon fiber reinforced polymer (CFRP), which reduces weight by 30%, but the manufacturing cost is more than three times that of traditional steel bodies. The current research focus includes: low-cost preparation process of carbon fiber composite materials (reducing raw material and processing costs), connection technology between carbon fiber and metal (improving structural reliability), and recycling technology (improving resource utilization). It is expected that by 2025, the application rate of carbon fiber composite materials in electric vehicles will increase to 5%, mainly used in the body and chassis components of high-end car models.

In addition, materials such as magnesium alloy and titanium alloy are gradually being used in electric vehicles. Magnesium alloy has a density only 2/3 of aluminum alloy, making it the lightest metal structural material currently used in practical applications, suitable for components such as seat frames and instrument panel brackets. Titanium alloy has high strength and good corrosion resistance, but its cost is relatively high, and it is mainly used as a key structural component in high-end car models. Future material research will focus on the development of low-cost, high-performance, and easily recyclable lightweight materials, as well as the optimized combination application of different materials.

2.4.2. Innovation of Integrated Molding Process

The integrated molding process achieves lightweight and high-strength of the body

and chassis by reducing the number of components and optimizing structural design, which is an important development direction for the lightweight of electric vehicles. The current mainstream integrated molding technologies include integrated die-casting, 3D printing, and roll forming, among which integrated die-casting technology has developed the most rapidly [10].

Tesla is a leader in integrated die-casting technology. Its Model Y model uses a 6000 ton die-casting machine to produce the rear floor assembly, which integrates the original rear floor composed of more than 70 components into one integral die-casting part, reducing weight by 30%, increasing production efficiency by 40%, and reducing manufacturing costs by 20%. Chinese car companies have followed suit, with companies such as Xiaopeng, NIO, and Ideal all deploying integrated die-casting technology. The Xiaopeng G6 model adopts integrated die-casting for the front cabin and rear floor, increasing the torsional stiffness of the entire vehicle by 30% and reducing weight by 15%.

The research hotspots of integrated molding process include: design and manufacturing technology of large die-casting molds (suitable for complex structural component molding), research and development of high-performance die-casting alloy materials (improving casting strength and toughness), optimization of molding process parameters (reducing casting defects), and innovation of post-processing technology (improving dimensional accuracy). In the future, integrated molding technology will develop towards larger sizes, more complex structures, and higher production efficiency. It is expected that by 2025, the penetration rate of integrated die-casting technology in the mid to high-end electric vehicle market will reach 40%, becoming the mainstream process for vehicle body manufacturing.

2.5. Charging and Energy Interconnection System

Charging and swapping infrastructure is an important support for the development of the electric vehicle industry, directly affecting the convenience of use for users. The current charging and swapping technology is showing a development trend of “overcharging, swapping, and energy interconnection”, while V2G (vehicle to grid) technology is gradually emerging, transforming electric vehicles from energy consumers to important nodes for energy storage and dispatch [11].

2.5.1. Supercharging Technology and Network Construction

Supercharging technology improves charging power, optimizes charging strategies, shortens charging time, and solves the problem of “charging anxiety” for users. The current mainstream supercharging technologies include 800 V high-voltage platforms, high-power charging modules, efficient cooling systems, etc. The charging power has evolved from the current 150 kW to 350 kW, 500 kW, and even higher power.

The S4 supercharging station launched by Xiaopeng Motors has a maximum power of 480 kW and a peak current of 670 A, which can achieve a charging experience of “charging for 10 minutes and a range of 400 kilometers”. It has been

deployed in multiple cities across the country; Tesla's V3 supercharging station has a maximum power of 250 kW and can provide a range of 250 kilometers after 15 minutes of charging. The 800 V high-voltage platform is the core technology foundation for achieving overcharging. Compared to the traditional 400 V platform, the 800 V platform can increase charging power at the same current while reducing line losses. In 2024, BYD Han EV, Xiaopeng G6, Ideal MEGA, and other models will all be equipped with 800 V high-voltage platforms. It is expected that by 2025, the 800 V high-voltage platform will be popularized in models priced over 200,000 yuan, with a penetration rate of 50%.

The research focus of supercharging technology includes the development of high-power charging modules (improving conversion efficiency and reducing volumetric weight), optimization of battery fast charging compatibility (avoiding the impact of fast charging on battery life), standardization of charging interfaces (unifying charging interfaces for different car manufacturers), and optimization of supercharging network layout (improving coverage density and user convenience). According to the prediction of the China Association of Automobile Manufacturers, the number of supercharging stations in China will exceed 500,000 by 2025, forming a supercharging network with "full coverage of county towns and dense layout in key areas" [12].

2.5.2. Battery Swapping Mode and Standardization

The battery swapping mode provides a "5-minute recharge" experience by quickly replacing the battery pack, effectively solving the problem of slow charging. It is particularly suitable for operating vehicles such as taxis and ride-hailing services, as well as users who have high requirements for recharging efficiency. The core advantages of battery swapping mode lie in centralized battery management, extended battery life, and reduced purchase costs (battery leasing mode), but it faces challenges such as battery standardization, high construction costs of swapping stations, and operational efficiency.

NIO is a staunch promoter of battery swapping mode, having built over 2000 battery swapping stations nationwide and developed a battery swapping platform that is compatible with multiple vehicle models, with a swapping time of only 3 minutes. In addition, the "Chocolate Battery Swap Block" launched by CATL and the battery swapping station project jointly developed by Sinopec and Aodong New Energy are both promoting the commercialization of battery swapping models. The current research focus on battery swapping technology includes: standardized battery pack design (to achieve battery compatibility for different car manufacturers and models), research and development of fast swapping mechanisms (to improve swapping efficiency and reliability), intelligent scheduling systems for swapping stations (to optimize battery storage and distribution), and battery health status assessment (to ensure the safety of swapping batteries).

In 2023, the Chinese Ministry of Industry and Information Technology and other departments jointly issued the "Implementation Opinions on Further Improving the Service Guarantee Capability of Electric Vehicle Charging Infrastruc-

ture”, proposing to “accelerate the promotion and application of battery swapping modes and promote the standardization of battery swapping standards”. It is expected that by 2025, the penetration rate of battery swapping mode in the operating vehicle market will reach 30%, and the penetration rate in the private user market will reach 5%, forming a complementary energy replenishment pattern of “overcharging + battery swapping” [13].

2.5.3. Development of V2G (Vehicle to Grid) Technology

V2G technology allows electric vehicles to charge and store energy during low load periods on the grid, and to feed back the stored energy from the battery to the grid during peak load periods, achieving bidirectional energy flow between the vehicle and the grid. This helps to smooth out grid load fluctuations and enhance renewable energy consumption capacity. V2G technology can not only bring additional benefits to users, but also improve the stability of the power grid. It is an important part of the energy Internet [14].

The current research focus of V2G technology includes: research and development of bidirectional charging and discharging technology (to improve conversion efficiency and reduce costs), optimization of V2G scheduling strategy (to balance user travel needs and grid scheduling needs), formulation of communication protocols and standards (to achieve coordinated control between vehicles and the grid), and innovation of business models (to explore win-win models for users, grid companies, and automakers). There are already multiple V2G demonstration projects abroad, such as the V2G pilot project in California, USA, and the eMobility demonstration project in Germany, which incentivize users to participate in grid dispatching through subsidy policies [15].

China has made rapid progress in the field of V2G technology, and both Southern Power Grid and State Grid have launched V2G pilot projects, deploying bidirectional charging and discharging piles in cities such as Shenzhen, Guangzhou, and Beijing to explore commercial operation models. It is expected that by 2025, V2G technology will be widely applied in demonstration cities for new energy vehicles, with over one million electric vehicles connected to the power grid, becoming a distributed energy storage resource for the grid and helping to achieve coordinated development of “source grid load storage”.

3. Challenges Faced by Electric Vehicle Research

Although electric vehicle technology has made significant progress, it still faces many challenges in core technology, industrial ecology, policies, and regulations, which restrict its further development.

In the field of power batteries, solid-state batteries face problems such as high interface impedance, insufficient cycling stability, and high preparation costs. Large-scale production still needs to break through key technological bottlenecks; The energy density of sodium ion batteries needs to be improved, and their competitiveness with lithium batteries still needs to be strengthened; The battery recycling technology is not yet mature, and the efficiency of resource recycling is relatively

low.

In terms of electric drive systems, the low yield of silicon carbide chip preparation results in high costs, which limits its application in mid to low end vehicle models; The improved integration of multi-in-one electric drive systems brings about difficulties in heat dissipation and inconvenient maintenance; Further research is needed to optimize the NVH (noise, vibration, and acoustic roughness) performance of electric drive systems [16].

In the field of intelligent technology, the decision-making ability in complex scenarios and adaptability to extreme working conditions of Level 3 and above autonomous driving need to be improved; The interactive experience of intelligent cockpit still needs to be optimized, and the accuracy of speech recognition and multimodal interaction collaboration need to be further improved; Vehicle road collaboration technology faces issues such as inconsistent standards, high infrastructure construction costs, and data security [17].

In terms of lightweight technology, high-performance lightweight materials (such as carbon fiber composite materials) have high costs and limited large-scale applications. The development cost of molds using integrated molding technology is high, and the cycle is long. Breakthroughs are still needed in the connection technology and recycling technology of different lightweight materials.

In the field of charging, swapping, and energy interconnection, overcharging technology has a significant impact on the load of the power grid and requires supporting grid upgrades; The standardization issue of battery in battery swapping mode has not been fully resolved, and the compatibility between different car models from different manufacturers is poor; The business model of V2G technology is still unclear, lacking mature profit mechanisms, and user engagement needs to be improved [18].

In addition, the electric vehicle industry also faces common challenges such as industry chain and supply chain security, fluctuations in key raw material prices, talent shortages, and incomplete policies and regulations, which require coordinated responses from the government, enterprises, and research institutions. Overall, these challenges converge around three overarching themes: the need for enhanced supply chain security and stability, the establishment of unified industry-wide standards across technology domains, and the mitigation of risks associated with volatile raw material costs, all of which are critical to the sustainable advancement of the electric vehicle industry.

4. Future Research Trends and Prospects

In the next 5 - 10 years, electric vehicle technology will enter an accelerated iteration period, and the core research direction will revolve around the goals of “higher performance, lower cost, safer and more reliable, and more intelligent and environmentally friendly”, presenting the following development trends:

In the field of power batteries, solid-state batteries will gradually achieve a leap from laboratory to industrialization, with the goal of achieving an energy density

of 500 Wh/kg and a range exceeding 1500 kilometers by 2030; The energy density of sodium ion batteries will be increased to over 200 Wh/kg, achieving large-scale applications in the fields of economical electric vehicles and energy storage; The battery recycling technology will achieve breakthroughs and form a closed-loop industrial chain of “raw materials battery recycling reuse” [19].

The electric drive system will develop towards the direction of “high efficiency, integration, and carbonization”. Silicon carbide power modules will be fully popularized, and the system efficiency will be improved to over 99%; The multi-in-one electric drive system will achieve deep integration of electric drive, charging, thermal management, braking energy recovery and other functions, further reducing volume and weight; The technology of wheel hub motors will gradually mature, providing support for the innovation of electric vehicle chassis architecture [20].

Intelligent technology will achieve the comprehensive commercialization of L3 level autonomous driving and scenario-based application of L4 level autonomous driving. Autonomous driving algorithms will develop towards “end-to-end cloud collaboration” and combine vehicle road collaboration technology to achieve full scene coverage; The intelligent cockpit will become a “mobile intelligent terminal”, achieving seamless interconnection with smart homes and smart cities; Human computer interaction will develop towards a “natural and emotionless” direction, with deep integration of multimodal interactions such as voice, gestures, and eye contact.

Lightweight technology will focus on the research and application of low-cost carbon fiber composite materials, new magnesium alloys, and other materials, achieving a significant reduction in material costs; The integrated molding process will develop towards the direction of “large-scale, integrated, and rapid molding”, and the integrated die-casting of the vehicle body will evolve from “front and rear floor” to “vehicle integration”; Multi material hybrid application technology will become more mature, achieving the optimal combination of different materials.

In the field of charging, swapping, and energy interconnection, supercharging technology will evolve towards power above 1000 kW, reducing charging time to less than 5 minutes; The battery swapping mode will achieve standardization of batteries and networking of swapping stations, forming a business model of “vehicle power separation and on-demand energy replenishment”; V2G technology will be deeply integrated with new energy generation and energy storage systems, becoming an important component of the smart grid and achieving collaborative optimization of “source grid load storage”.

In addition, the electric vehicle industry will develop towards a “green, low-carbon” full life cycle, achieving carbon reduction in every link from raw material extraction, production and manufacturing to recycling and utilization; The industrial and supply chains will develop in a coordinated manner towards globalization and regionalization, and the independent and controllable capabilities of core

technologies will be significantly enhanced; The policy and regulatory system will gradually improve, providing institutional guarantees for the commercialization of new technologies such as autonomous driving and V2G [21]. It should be noted, however, that the pace of these developments may be moderated by non-technical hurdles, including insufficient grid infrastructure to support widespread supercharging and V2G deployment, as well as socio-economic disparities that could limit equitable access to advanced electric vehicle technologies.

5. Conclusions

As the core direction of the electrification and intelligent transformation of the automotive industry, electric vehicles have become an important carrier for the global energy revolution and industrial upgrading. This article systematically reviews the five mainstream research directions in the field of electric vehicles: innovation in power battery technology, optimization of electric drive system efficiency, intelligence and autonomous driving technology, lightweight and material technology innovation, and charging and swapping and energy interconnection systems. It analyzes the technological breakthroughs, application status, and challenges faced by each field, and looks forward to future research trends.

Research has shown that high-energy density solid-state batteries, silicon carbide electric drive modules, Level 3 or above autonomous driving, integrated lightweight technology, supercharging, and V2G energy interconnection are current and future core research hotspots. These technological breakthroughs will drive a qualitative leap in electric vehicles in terms of range, charging efficiency, intelligent experience, and safety, and accelerate the process of electric vehicles replacing traditional fuel vehicles. From a consumer perspective, this leap will be manifested in the complete elimination of range anxiety through longer battery life and faster charging, a significant reduction in the total cost of ownership due to technological maturity and economies of scale, and a substantial enhancement in vehicle safety via advanced autonomous driving and intelligent monitoring systems.

At the same time, the development of electric vehicle technology still faces challenges in core materials, key processes, standard systems, business models, and other aspects. It is necessary for the government, enterprises, and research institutions to strengthen collaborative innovation, increase research and development investment, improve policy support, and promote technological breakthroughs and industrial applications. In the future, with the continuous maturity and industrialization of various core technologies, electric vehicles will gradually achieve the development goals of “safer, more efficient, smarter, and more environmentally friendly”, providing important support for achieving global carbon neutrality and green transformation in the transportation sector.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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