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Review of Application Expansion, Technical Bottlenecks and Optimization Path of Graphene Supercapacitors

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ABSTRACT
Graphene, with its exceptional electrical conductivity, large specific surface area, and outstanding mechanical properties, has emerged as a pivotal material driving technological innovation in supercapacitors. Graphene supercapacitors combine the rapid charging/discharging capabilities of traditional capacitors with the high energy storage efficiency of batteries, featuring fast charging, high power density, and long cycle life. These advantages make them highly valuable in critical fields such as new energy transportation, defense equipment, and smart grids. This paper systematically reviews the global R&D progress and industrial applications of graphene supercapacitors, while analyzing three core bottlenecks hindering large-scale development: low energy density, high production costs, and inadequate environmental adaptability. Through dimensions like material system optimization, preparation process innovation, and device structure design, the study outlines targeted technical breakthrough pathways. Research indicates that innovations in composite electrode materials, development of low-cost production processes, and multi-dimensional environmental adaptation upgrades are key to overcoming existing challenges. This work provides valuable references for technological iteration, industrial transformation, and application promotion of graphene supercapacitors, helping them achieve broader scenario coverage under the "dual carbon" strategy.

KEYWORDS
Graphene supercapacitor; Application scenarios; Energy density; Cost control; Environmental adaptability

1 Introduction

1.1 Research Significance

Graphene, a novel two-dimensional nanomaterial with a single-atom-layer honeycomb structure, serves as the fundamental building block for carbon materials like fullerenes and carbon nanotubes. Its exceptional properties—including ultra-high electrical conductivity (10^4 S/m), massive specific surface area (2630 m^2/g), outstanding thermal conductivity, and remarkable strength—have established it as an irreplaceable material in energy storage, optoelectronic devices, and chemical catalysis [1]. Developing the graphene industry not only drives technological upgrades in downstream sectors and enhances overall innovation capabilities, but also provides critical technical support for implementing the "dual carbon" strategy by optimizing energy efficiency and reducing CO_2 emissions.

With the maturation of preparation technologies and the expansion of application scenarios, coupled with the growth of downstream industries such as consumer electronics and new energy, the market size of China's graphene has steadily expanded. According to data from the China Business Industry Research Institute, the market size of China's graphene reached 38.6 billion yuan in 2023 (a year-on-year increase of 15.22%), and further increased to 41.1 billion yuan in 2024. In terms of application structure, the new energy sector accounted for the highest proportion at 51%; the thermal management sector accounted for 15%, while the health and coatings sectors each accounted for 8%, with the top four sectors collectively accounting for over 80%. Graphene-based supercapacitors, as an important innovation in the energy storage field, provide a new solution to address industry pain points such as range anxiety in new energy vehicles and instantaneous power supply for military equipment [2].

1.2 Scope and logical framework of the review

This paper explores the core research and applications of graphene supercapacitors, covering five key dimensions: domestic and international technological advancements, industrial market landscape, major application scenarios, core technical bottlenecks, and optimization pathways. Following a progressive logic of "current status review-problem analysis-solution exploration": it first presents technological developments and market competition dynamics, then analyzes key industrialization barriers, subsequently elaborates optimization strategies from material, process, and structural perspectives, and finally outlines future trends to provide references for subsequent research and practical applications.

2 Research Status and Application Scenarios of Graphene Supercapacitors

2.1 Domestic and International Research and Industrial Progress

2.1.1 Technological Iteration and Market Size

China's graphene supercapacitor industry is in a period of accelerated development, with the market size expected to grow at a compound annual growth rate of 28.5% from 2025 to 2030, and is expected to exceed 50 billion yuan by 2030. GGAI data shows that the industry scale reached 7.8 billion yuan in 2023 and will surpass the 15 billion yuan threshold by 2025. Technologically, key breakthroughs have been achieved in preparation processes: the production cost of chemical vapor deposition (CVD) has been reduced to one-fifth of that in 2015, and the yield of single-layer graphene prepared by the redox method exceeds 92%, supporting an energy density increase to 15-20 Wh/kg (35 times higher than traditional supercapacitors) [3]. McKinsey predicts that China's market size will exceed 30 billion yuan by 2030, with 30-35% of the high-end product market dominated by international companies.

2.1.2 International Market Competition Pattern

Globally, leading companies such as Tesla's Maxwell Technologies and NEC Tokin are accelerating their presence in the China market. Maxwell has expanded its Tianjin production base, achieving an annual electrode material capacity of 1.2 million square meters (accounting for 35% of the global total), with plans to achieve 90% domestic production of automotive supercapacitor modules by 2025. NEC Tokin has adopted a technology licensing model to co-establish joint laboratories with CATL, CALB, and other enterprises. Its flexible all-solid-state supercapacitors shipped 12 million units in 2023, achieving large-scale applications in the smart wearable field [4]. International companies dominate over 45% of the high-end market share, while domestic enterprises still face challenges in achieving core technology autonomy.

2.1.3 Core Material R& D Breakthrough

Innovations in electrode materials are pivotal for performance enhancement. By integrating graphene with polyaniline through in-situ polymerization, the synergistic effects of double-layer capacitance and Faradaic capacitance are harnessed to significantly boost specific capacitance. Characterization via scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), and X-ray diffraction (XRD) reveals that polyaniline nanowires are tightly bonded with graphene layers, fully leveraging the pseudocapacitive effect. Moreover, the heterostructure formed by graphene and MXene achieves an energy density of 21.4 Wh/kg—1.8 times higher than conventional methods—providing a new direction for developing high-performance electrode materials [5].

2.2 Extended Main Application Scenarios

2.2.1 New Energy Transportation

The demand for high-power-density energy storage devices in new energy vehicles is driving industry development. It is expected that after 2025, the penetration rate of graphene supercapacitors in drive systems and energy recovery devices will exceed 18%. These devices can be charged in just a few minutes, with a cycle life of over 500,000 cycles, making them suitable for scenarios such as urban public transportation and short-distance logistics. In the consumer electronics sector, companies like Huawei and OPPO are developing fast-charging modules based on this technology. Laboratory data shows that a 6000mAh battery can be charged to 80% in just 5 minutes [6].

2.2.2 Defense and Special Equipment

The ultra-high power density makes it suitable for electromagnetic railguns, laser weapons, and carrier-based electromagnetic catapult systems, meeting the demands for instantaneous high-power energy supply and frequent charge-discharge cycles. Extended applications include: terahertz graphene chips (with computing speeds 1,000 times faster than silicon-based chips) to enhance fire control system accuracy; ultra-sensitive detectors (with sensitivity millions of times higher) for night vision devices; and graphene-silk composite materials for lightweight bulletproof vests.

2.2.3 Smart Grids

The China Southern Power Grid's dynamic reactive power compensation demonstration project has demonstrated millisecond-level response capabilities, effectively stabilizing voltage, suppressing fluctuations, and enhancing transmission efficiency. This technology provides crucial technical support for large-scale grid integration of renewable energy sources like wind and solar power, driving smart grid upgrades. The application's success is closely tied to graphene's exceptional electrical conductivity, where its ultra-large specific surface area and rapid charge transport enable timely dynamic regulation.

3 Core Technical Bottlenecks of Graphene Supercapacitors

3.1 Energy Density Needs to be Improved

Commercial graphene supercapacitors achieve an energy density of approximately 100 Wh/kg, while laboratory-grade versions reach about 90 Wh/kg—both significantly lower than ternary lithium batteries (200-300 Wh/kg) and lithium iron phosphate batteries (120-160 Wh/kg)[1]. Although some graphene-based batteries claim energy densities exceeding 300 Wh/kg, they have yet to achieve mass production due to high costs. Currently, they require integration with lithium batteries to form hybrid power systems, which only meet short-distance application needs [7].

3.2 Production Costs Remain High

Traditional manufacturing relies on expensive graphite and high-temperature graphitization processes, while the complex production workflow of composite electrodes drives up costs. Although cost reductions through biomass conversion and copper foil substrate substitution have been achieved, the overall price remains higher than conventional energy storage devices, hindering large-scale adoption. The high-end market has long been dominated by international players. The core challenge stems from the dual constraints of raw material costs and process complexity, with existing technologies yet to establish a closed-loop system for low-cost, large-scale production.

3.3 Insufficient Adaptability to Extreme Environments

Extreme temperatures, high humidity, and intense vibrations can cause performance degradation: Low temperatures reduce electrolyte ion transport efficiency; high humidity triggers electrode-electrolyte interface reactions; vibrations compromise structural integrity and packaging durability. These limitations restrict their applications in aerospace, deep-sea exploration, and polar research. The primary causes of environmental adaptability shortcomings lie in inadequate material interface stability and packaging technology.

4 Technical Optimization Path of Graphene Supercapacitor

4.1 Energy Density Improvement Strategy

4.1.1 Optimization of Electrode Material System

By nano-mating materials or developing high-capacity materials, the specific surface area and active sites of electrodes can be enhanced. Composite materials combining graphene with activated carbon, carbon nanotubes, manganese dioxide (MnO_2), or polypyrrole synergistically improve energy storage performance. Novel composite electrode materials (e. g., Ni(OH)Cl ICA GQDs) demonstrate a cycle life of 20, 000 cycles with 91.5% performance retention, indirectly optimizing energy utilization efficiency [8].

4.1.2 Electrolyte Selection and Device Structure Design

By employing electrolytes with wide voltage windows such as ionic liquids and organic solvents, the energy density is directly enhanced. The three-dimensional porous structure (achieving 212 F/cm^3 volumetric capacitance) combined with asymmetric design improves ionic conduction and energy storage capacity. Interface engineering reduces resistance losses, while thermal management technology prevents thermal runaway in high-power scenarios. These design concepts are deeply compatible with graphene's structural characteristics, fully leveraging its advantage of ultra-large specific surface area.

4.1.3 Development of New Device Structures

The flexible thin-film capacitor expands application scenarios. The 3D honeycomb graphene gel film achieves an energy density of 35 Wh/kg (mass) and 49 Wh/L (volume), approaching lead-acid battery levels, making it suitable for portable and flexible electronic devices. This structural design optimizes material stacking to enhance energy density while preserving graphene's high conductivity.

4.2 Cost control Techniques

4.2.1 Preparation Process Innovation

The direct biomass conversion method transforms agricultural waste into reduced graphene oxide (RGO) at ambient temperature and pressure, achieving a 98% reduction in energy consumption (from 7.62×10^6 kJ/g to 2.28×10^2 kJ/g) with a 33% yield, significantly lowering raw material and equipment costs. By bypassing the traditional high-temperature graphitization step, this process provides a viable pathway for low-cost mass production.

4.2.2 Substrate Replacement and Auxiliary Cost Reduction Technology

By replacing traditional substrates (115 yuan/m^2) with low-cost copper foil (1 yuan/m^2) for lithium-ion batteries, the production cost is reduced by 100-fold. The weak acid oxidation method enables mass production of low-defect graphene, while the graphene-MXene heterostructure achieves both performance and cost efficiency. These innovations, through material substitution and process simplification, effectively reduce the cost of the entire industrial chain.

4.3 Extreme Environment Adaptability Improvement Plan

4.3.1 Material Modification and Interface Optimization

Surface functionalization of graphene (through hydroxyl and carboxyl group introduction) enhances electrolyte compatibility, while its composite with manganese dioxide and polypyrrole improves mechanical strength and ionic transport efficiency. The use of ionic liquids (operating at-50°C to 150°C) with solid electrolytes addresses temperature adaptation and leakage issues, significantly expanding the device's operational range.

4.3.2 Structural Design and Packaging Process Upgrade

The flexible polyimide substrate ensures the integrity of the conductive network, while the three-dimensional porous structure enhances stability. PTFE and DLC coatings effectively block moisture and corrosive gases, with an intelligent temperature control system maintaining stable operating temperatures. These enhancements improve device reliability through structural protection and environmental regulation.

4.3.3 Innovation in Testing and Optimization Methods

By conducting multi-dimensional aging experiments to simulate harsh environments, combined with cyclic voltammetry and constant current charge-discharge tests to identify optimal solutions, machine learning predicts material degradation mechanisms, accelerating formula and structural optimization. This approach significantly shortens the R&D cycle for environmental adaptation technologies, providing data-driven support for extreme scenario applications.

5 Future Development Trends and Outlook

Technologically, the multifunctional doping and heterostructure design of composite electrodes will further enhance energy density and stability. Integrated optimization across materials, structures, processes, and packaging will deepen, while machine learning and related technologies will accelerate R&D progress. The trends toward flexibility, thin-film integration, and miniaturization will expand applications in wearable devices and aerospace fields. These advancements will drive graphene supercapacitors toward higher performance, lower costs, and broader compatibility.

At the industrial level, the core task is to promote low-cost processes on a large scale, requiring optimization of biomass conversion and CVD technologies to reduce costs. Industry standardization will drive product specification unification and quality control upgrades, fostering supply chain collaboration. Application scenarios will expand into extreme environments, deeply integrating with carbon neutrality-related industries.

Chinese enterprises must strengthen independent R&D in core technologies to overcome bottlenecks in high-end materials and equipment. By building an integrated innovation ecosystem that combines industry, academia, research, and application, they can enhance global competitiveness and provide technological support for national energy security and defense modernization. With ongoing technological breakthroughs, graphene supercapacitors are poised to achieve large-scale applications in more critical sectors, serving as a vital technical backbone for implementing China's dual-carbon strategy.

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