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A Review on Carbon-based Electrode Materials for Supercapacitors: Recent Advances and Commercialisation Challenges

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Abstract

Supercapacitors have emerged as a compelling alternative to traditional batteries, offering unique advantages such as high-power density, fast charge and discharge rates, and extended operational lifespans. A key focus in advancing supercapacitor technology lies in the development of carbon-based materials, particularly for Electric Double Layer Capacitors (EDLCs). Carbon materials are highly prized for their remarkable properties, including high electrical conductivity, a large specific surface area, and excellent chemical and mechanical stability. These attributes enable EDLCs to achieve superior cyclic performance and maintain stability over extended lifetimes, making them ideal for applications requiring rapid energy delivery and frequent charge-discharge cycles. This review delves into a broad spectrum of carbon-based materials—graphene, Carbon Nanotubes (CNTs), activated carbon, carbon aerogels, bio-derived carbons, and hybrid carbon composites—analysing their unique properties, advantages, and limitations. Beyond standard options, advanced carbon nanostructures like fullerenes, quantum dots, and hierarchical pores are rising in prominence due to their tunable electronics and rapid ion transport. Merging these with pseudocapacitive materials—such as MXenes or metal oxides—creates hybrid electrodes that boost performance through synergistic energy storage. However, full commercialisation depends on overcoming hurdles in performance optimisation, industrial scalability, and cost reduction. Addressing these barriers is vital for integrating supercapacitors into modern energy grids and accelerating the shift toward sustainable technology.

Keywords: Carbon Commercialisation, Supercapacitor

1. Introduction

Global energy demand is surging due to a variety of factors, including rapid urbanisation, democratic growth, changes in lifestyle, and advancements in technology[1-3]. This increased demand is accelerating the depletion of traditional energy resources, prompting an urgent need to identify alternative, sustainable energy sources such as solar, wind, hydro, and geothermal power[4-6]. However, energy derived from these renewable sources remains unreliable unless it is effectively stored for future use. In the realm of energy storage, batteries have become the backbone of most established technologies, yet they still face significant limitations. These challenges include insufficient power density, long charging times, and application restrictions[7,8].

In addition to batteries, another energy storage device emerged in the 1950s: a system that utilises porous carbon to store energy in an aqueous medium[9]. Researchers subsequently discovered that charge storage in these devices occurs at the interface between the electrode and electrolyte, a principle that led to the development of the supercapacitor. Continuous advancements in technology and sustained research efforts have propelled supercapacitors to a new level of commercialisation. They are now used in a wide range of applications, including electronic devices like cameras for quick charging and backup power, cranes and elevators for rapid charge and discharge cycles, electric vehicles, and electrical grids for storing excess energy[10-11].

Supercapacitors are typically classified into three main types based on their charge storage mechanisms: Electric

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Double Layer Capacitors (EDLCs), pseudocapacitors, and hybrid capacitors[12]. EDLCs store charge through electrostatic charge accumulation at the electrode–electrolyte interface without involving Faradaic reactions, which contributes to their excellent stability, long cycle life, and rapid charge–discharge capability. However, their energy density is generally lower compared to other types of supercapacitors[13].

In contrast, pseudocapacitors store energy via Faradaic processes such as redox reactions, intercalation, or electrosorption, where charge is transferred through chemical reactions between the electrode and electrolyte. This allows pseudocapacitors to achieve higher energy densities than EDLCs, though they suffer from a shorter lifespan due to material degradation over time[14]. Hybrid capacitors, on the other hand, combine the strengths of both EDLCs and pseudocapacitors. In these devices, one electrode functions as an EDLC, utilising electrostatic charge storage, while the other relies on the redox reactions of a pseudocapacitor. This hybrid structure aims to offer both the high power density of EDLCs and the greater energy density of pseudocapacitors, providing a more versatile energy storage option[15].

Our key area of supercapacitor research focuses on carbon-based materials, particularly in EDLCs. Carbon materials are highly valued for their large surface area, excellent conductivity, and high-power density, offering superior cyclic performance compared to pseudocapacitors. These properties make carbon-based EDLCs particularly attractive for applications that require fast charge/discharge cycles and long-term stability, positioning them as a highly efficient solution for energy storage systems that prioritise both longevity and performance[16].

Simultaneously, there has been a growing global emphasis on dielectric engineering—including solid-state electrolytes, ion-gels, pseudocapacitive interfaces, and high-k dielectric coatings—to increase the energy density and safety of supercapacitors. Research efforts are increasingly interdisciplinary, integrating materials science, nanotechnology, and computational modelling to optimise performance across multiple scales.

This review consolidates the latest developments (primarily from 2020-2025) in carbon-based electrode technologies while expanding its scope to cover emerging dielectric materials and strategies. The goal is to provide a forward-looking perspective on the breakthroughs and bottlenecks that define the commercialisation potential of supercapacitor technologies in the current decade.

2. Various Carbon-based Materials

2.1 Graphene

Graphene, a single-atom-thick Two-Dimensional (2D) allotrope of carbon, was first successfully isolated in 2004 by Andre Geim and Konstantin Novoselov at the University of Manchester [17]. Structurally, graphene consists of a monolayer of sp^2-hybridised carbon atoms arranged in a hexagonal honeycomb lattice and can be considered a fundamental building block of graphite[18]. This breakthrough marked a paradigm shift in nanomaterials research due to the unprecedented physical and chemical properties exhibited by graphene.

Possessing a zero bandgap and behaving as a semi-metal, graphene demonstrates outstanding electrical conductivity with negligible resistive losses. Its theoretical specific surface area reaches up to 2630 $m^2 \cdot g^{-1}$, and its high aspect ratio contributes significantly to surface-dominated phenomena, particularly in electrochemical applications[19]. In addition to its electrical properties, graphene offers superior thermal conductivity, exceptional carrier mobility (~200,000 $cm^2 \cdot V^{-1} \cdot s^{-1}$), excellent optical transparency (~97.7%), mechanical robustness, and intrinsic flexibility, rendering it a versatile platform for next-generation nanoelectronic, optoelectronic, and energy storage devices[20].

In the context of energy storage, graphene is especially promising as an electrode material for Supercapacitors (SCs), primarily due to its large accessible surface area and rapid charge transport capabilities. The material's theoretical electric double-layer capacitance can reach values as high as 550 $F \cdot g^{-1}$. Ultra-thin graphene-based electrodes facilitate efficient ion diffusion and charge accumulation, thereby enhancing the overall energy and power density of supercapacitor systems[21].

Despite these theoretical advantages, the experimentally measured specific capacitance of graphene-based materials often falls short of expected values. This deviation is largely attributed to the pronounced π–π stacking interactions that occur between adjacent graphene sheets during post-synthesis processing, such as the reduction of Graphene Oxide (GO) to reduced graphene oxide (rGO). These interactions promote restacking and agglomeration, which in turn limit ion accessibility, introduce structural defects, and reduce the effective surface area available for charge storage[22].

To address these limitations, a variety of material engineering strategies have been developed. One of the most

effective involves the incorporation of conductive polymers or nanostructured additives within the interlayer spacing of graphene sheets. These intercalating agents act as physical spacers, mitigating Vander Waals-induced aggregation and preserving inter-sheet separation. This approach maintains electrochemically accessible surface area, enhances ion transport kinetics, and substantially improves charge storage performance[23].

Among graphene's derivatives, GO is often favoured for its chemical versatility and stability under oxidative conditions. However, GO suffers from poor electrical conductivity. In contrast, rGO exhibits significantly enhanced electrical transport properties, making it more appropriate for electronic and electrochemical applications. Nevertheless, the trade-off between conductivity and chemical processability remains a critical challenge[24].

Currently, Chemical Vapour Deposition (CVD) is one of the predominant methods used for the synthesis of high-quality graphene, particularly for electronic applications[25]. However, the scalability, cost-efficiency, and environmental impact of this method pose significant barriers to commercial deployment. Furthermore, issues related to long-term material stability, toxicity, and reproducibility must be thoroughly addressed to facilitate the widespread adoption of graphene-based technologies across industries.

2.2 Carbon Nanotube (CNT)

Carbon Nanotubes (CNTs), first reported by Japanese physicist Sumio Iijima in 1991, are one-Dimensional (1D) carbon nanostructures characterised by their unique tubular morphology derived from rolled graphene sheets. These structures are classified into two main types based on their wall configuration: Single-Walled Carbon Nanotubes (SWCNTs), comprising a single graphene cylinder, and Multi-Walled Carbon Nanotubes (MWCNTs), consisting of multiple concentric graphene layers[26].

CNTs represent a critical class of carbon allotropes, conceptually situated between zero-dimensional fullerenes and two-dimensional graphene. Their atomic configuration consists of sp^2-hybridised carbon atoms arranged in a hexagonal honeycomb lattice, conferring them with remarkable mechanical, electrical, and thermal properties. The cylindrical geometry of CNTs yields high surface area-to-volume ratios and exceptional electron mobility, attributes that are particularly advantageous in energy storage applications[27].

In supercapacitor systems, CNTs have emerged as promising electrode materials due to their inherent chemical stability, high electrical conductivity, and ability to support rapid ion transport. Their mesoporous architecture—with pore diameters typically ranging from 2 to 50 nanometers—facilitates efficient electrolyte diffusion, thereby minimising internal resistance and enhancing both power density and charge–discharge efficiency[28]. These features position CNTs at the forefront of research into next-generation electrochemical energy storage devices, with significant potential for commercial deployment.

The versatility of CNTs also allows for integration into hybrid architectures and micro/nano-engineered systems. By combining CNTs with conductive polymers, metal oxides, or other nanomaterials, researchers aim to leverage synergistic effects that further enhance performance metrics such as capacitance, cycling stability, and energy density[29].

Fabrication of CNTs involves both top-down and bottom-up synthetic approaches. Top-down methods, such as arc discharge and laser ablation, break down bulk carbon into nanoscale structures, while bottom-up techniques—like Chemical Vapour Deposition (CVD)—allow controlled assembly of CNTs from molecular precursors. The most widely accepted growth mechanisms are (i) the tip-growth model, wherein the catalyst particle lifts off from the substrate during elongation, and (ii) the base-growth (or root-growth) model, in which the catalyst remains anchored to the substrate, promoting vertical nanotube formation[30].

Catalyst nanoparticles, typically composed of transition metals such as Fe, Ni, or Co, play a pivotal role in governing the nucleation, alignment, chirality, and length of CNTs. These metals facilitate the decomposition of carbon precursors and the subsequent incorporation of carbon atoms into the growing nanotube structure[31].

Nevertheless, several critical challenges must be addressed to enable large-scale commercialisation of CNT-based supercapacitors. These include cost-effective and scalable synthesis, consistent control over structural parameters (*e.g.*, diameter, length, chirality), and effective integration into device architectures[32]. Furthermore, uniform dispersion within electrode matrices and long-term electrochemical stability remain ongoing areas of investigation.

Advancing the field requires not only continued optimisation of synthesis protocols but also a deeper mechanistic understanding of CNT growth dynamics and interactions with other electrode materials. As research progresses, CNTs are expected to play a transformative

role in high-performance, scalable, and sustainable energy storage technologies.

2.3 Activated Carbon

Activated Carbon (AC), also known as activated charcoal, is a highly porous form of carbon that has played a pivotal role across a wide range of applications throughout history, owing to its exceptional adsorptive and surface characteristics. The earliest documented uses of activated carbon trace back to around 1500 BC, when ancient Egyptians employed it for preservation purposes due to its ability to retard decomposition processes[33]. By 400 BC, civilisations such as the Hindus and Phoenicians recognised its efficacy in water purification, utilising its adsorptive capacity to remove impurities.

The modern scientific understanding of activated carbon began in 1773 when Swedish chemist Carl Wilhelm Scheele discovered its ability to adsorb gases[34]. This discovery catalysed subsequent research during the 19th century, where the capacity of activated carbon to sequester toxic substances was extensively studied. These findings laid the foundation for its application in protective gear, notably in gas masks used during World War I.

The post-World War II era marked a significant upsurge in the production and industrial utilisation of activated carbon, spurred by technological advancements and a deeper appreciation of its physicochemical properties. Its application expanded rapidly into sectors such as water treatment, chemical processing, and environmental remediation[35]. Key breakthroughs were achieved when it was discovered that treating carbonaceous materials with superheated steam or carbon dioxide at elevated temperatures could create a highly porous architecture, significantly enhancing the material's Specific Surface Area (SSA).

In contemporary energy storage research, this high surface area and well-developed pore structure have rendered activated carbon an ideal candidate for supercapacitor electrodes. The enhanced interfacial area between the electrode and electrolyte facilitates efficient charge accumulation via electric double-layer formation, thereby improving capacitance and energy delivery performance.

The activation technique employed is critical to defining the electrochemical performance of activated carbon materials. The activation process influences essential parameters such as SSA, pore size distribution, and surface functional groups—all of which collectively determine ion accessibility and charge storage dynamics in supercapacitors[36]. Activation methodologies are broadly classified into two categories:

1. *Physical activation* – This involves the pyrolysis of carbonaceous precursors followed by gasification with oxidising agents such as Carbon Dioxide (CO_2), Oxygen (O_2), air, steam, or their combinations.
2. *Chemical activation* – This technique utilises chemical agents like potassium hydroxide (KOH), sodium hydroxide (NaOH), phosphoric acid (H_3PO_4), and zinc chloride ($ZnCl_2$) to induce porosity during the carbonisation stage.

Physically activated carbons exhibit properties that are heavily influenced by the type of precursor, oxidising agent, activation temperature, and the duration of activation. These variables determine the final surface chemistry and pore architecture. Among chemical activators, KOH has proven particularly effective, enabling the fabrication of activated carbons with surface areas as high as ~4000 $m^2 \cdot g^{-1}$[37,38]. Despite being one of the most prevalent materials in commercial Electric Double-Layer Capacitors (EDLCs), activated carbon has limitations, particularly in stability under high current densities. These drawbacks can be mitigated through optimisation of the carbonisation and activation protocols to tailor the porosity and surface functionality[39].

However, the superior electrical conductivity, thermal and chemical resilience, cost-effectiveness, and wide availability of activated carbon make it a cornerstone material in modern supercapacitor technology. Ongoing research continues to refine its structural and electrochemical properties to meet the evolving demands of high-performance energy storage systems.

2.4 Biomass-Derived Carbon

The concept of biomass-derived activated carbon has gained attention due to its potential applications in sustainable development, though there are some environmental concerns. Biomass refers to organic materials such as animal waste, plant-based waste, household waste, marine and aquatic waste, and similar resources. These materials can be converted into valuable products known as "green carbon." This conversion process contributes to sustainable development and is eco-friendly[40]. According to a survey conducted, approximately 80% of the carbon content in biomass comes from plants. By utilising green carbon, ecological balance can be maintained, particularly through effective waste management systems. Researchers are increasingly interested in biomass-derived carbon because of its high

surface area, porosity, renewability, and environmental benefits[41].

Biomass-derived carbon can be synthesised through processes like pyrolysis and chemical activation. This method is more cost-effective than producing conventional activated carbon. The physical and chemical properties of this type of carbon are also more stable, making it highly conducive to ion transport. Additionally, the carbon often contains elements like nitrogen and phosphorus, which provide extra active sites for charge transfer in supercapacitors[42]. This development has led to the successful creation of electrode materials for supercapacitors from biomass-derived carbon. However, further optimisation and careful selection of biomass sources are necessary to maximise production and commercial viability.

2.5 Carbon Aerogel

Carbon Aerogels (CAs), a class of advanced carbonaceous materials first developed in the 1980s, are distinguished by their unique three-Dimensional (3D) porous architecture, comprising a highly interconnected network of ultra-fine carbon nanoparticles[43]. This intrinsic structural arrangement imparts exceptionally high SSA, low bulk density, and high porosity, predominantly within the mesoporous regime, with minimal micropore presence. The confluence of these attributes confers CAs with superior physicochemical properties, including excellent electrical conductivity, low thermal conductivity, and mechanical resilience, rendering them promising candidates for high-performance electrochemical energy storage systems, particularly supercapacitors[44,45].

The synthesis of carbon aerogels typically involves a sol–gel polymerisation route, utilising precursors such as resorcinol and formaldehyde to form organic hydrogels. These gels are then subjected to carbonisation, following solvent exchange and drying. Traditionally, supercritical drying techniques have been employed to preserve the pore structure during the liquid–gas transition phase. However, this method necessitates high-pressure equipment and elevated temperatures, making the process energy-intensive and limiting scalability[46]. As a response, recent advancements have introduced ambient pressure drying protocols that facilitate the formation of aerogels under atmospheric conditions and room temperature, greatly simplifying the manufacturing process and enhancing commercial viability.

In the context of supercapacitors, CAs offer a combination of hierarchical porosity and electrical conductivity that is superior to conventional activated carbons. Their 3D framework facilitates multi-scale ion transport:1. Macropores serve as ion reservoirs or buffering zones, 2. Mesopores enable rapid ion diffusion, and 3. Micropores support effective charge storage. This hierarchical architecture significantly boosts double-layer capacitance and power density, essential parameters in energy storage devices[47,48].

Recent innovations have extended the architecture of carbon aerogels by integrating CNTs into their matrix. These composite structures benefit from enhanced mechanical integrity and flexibility due to van der Waals interactions between CNTs and the aerogel matrix, as well as improved electronic pathways for charge conduction. The result is a flexible, lightweight, and conductive electrode material with enhanced electrochemical performance, suitable for use in flexible and wearable energy devices[49].

Despite their advantages, carbon aerogels are not without challenges. The synthesis process remains time-intensive and often requires careful environmental control, especially due to the hygroscopic nature of the material, which can compromise electrochemical performance under humid conditions. This sensitivity poses obstacles to storage and device longevity[50]. Moreover, achieving reproducibility and scalability while maintaining consistent material properties continues to be an area of active research.

3. Recent Trends in Supercapacitor Dielectric Materials

While carbon-based materials remain at the forefront of electrode design in supercapacitors, recent research efforts have increasingly turned toward innovation in dielectric components to enhance energy density, operating voltage, and long-term stability. The following are key trends in supercapacitor dielectric development:

3.1 Pseudocapacitive and Redox-Active Dielectrics

Pseudocapacitors utilise dielectric materials that store charge through Faradaic redox reactions, providing higher energy density compared to traditional EDLCs. Transition metal oxides (*e.g.*, MnO_2, RuO_2, $NiCo_2O_4$) and conductive polymers (*e.g.*, polyaniline, polypyrrole) have shown promise in enhancing dielectric behaviour by combining high capacitance with reasonable cycle stability[51]. Research is now focused on nanostructuring these materials or forming hybrid composites with carbon

to balance conductivity, surface area, and mechanical integrity.

3.2 Solid-State Electrolyte Dielectrics

To improve device safety and flexibility, solid-state supercapacitors with solid electrolytes functioning as dielectrics are gaining attention. These include polymer electrolytes (*e.g.*, PVA/H_3PO_4), ion gels, and solid polymer ionic conductors. These systems offer mechanical strength and non-volatility, making them suitable for wearable and flexible electronics[52]. However, ion transport limitations are being addressed through nanofiller doping and gel-hybridisation techniques.

3.3 Dielectric Constant Engineering

Enhancing the dielectric constant of the separator or electrode–electrolyte interface is another area of active research. Materials such as Metal–Organic Frameworks (MOFs), perovskite-type oxides, and 2D materials (MXenes, MoS_2) are being integrated to modify the dielectric environment, which can lead to higher charge storage capability through interfacial polarisation and redox activity[53].

3.4 Ionic Liquid and Gel Electrolytes

Ionic liquids and ion gels function both as dielectrics and electrolytes. These materials offer wide electrochemical windows (up to 3–5 V), non-flammability, and good thermal stability[54]. Research trends involve combining these with polymer hosts or nanostructured matrices to enhance ion transport and stability under mechanical deformation.

3.5 Bio-Inspired and Green Dielectrics

Environmentally benign dielectric materials derived from natural sources (*e.g.*, cellulose, chitosan, silk fibroin) are being developed for sustainable energy storage[55]. These biopolymers, often doped with salts or acids, can act as solid-state electrolytes with moderate dielectric properties, while being biodegradable and safe.

3.6 Emerging Carbon Nanostructures and Hybrid Architectures

Beyond widely used carbon materials such as graphene, carbon nanotubes, and activated carbon, a variety of emerging carbon nanostructures are being explored for advanced supercapacitor electrodes. Materials including fullerenes, carbon quantum dots, nanodiamonds, hierarchical porous carbons, and carbon–metal hybrid composites have recently attracted significant attention due to their favourable electrochemical characteristics and potential to enhance charge storage performance[56].

Fullerenes, particularly C_{60} and C_{70} molecules, are zero-dimensional carbon allotropes characterised by closed cage-like structures formed from sp^2-hybridised carbon atoms. These molecules exhibit strong electron-accepting behaviour and good electrical conductivity, which can facilitate efficient charge transfer in electrochemical devices[57]. When incorporated into composite electrodes with graphene or carbon nanotubes, fullerene derivatives can improve electron transport and increase the effective surface area available for charge storage, thereby enhancing capacitance and cycling stability.

Carbon Quantum Dots (CQDs) have also emerged as promising nanoscale carbon materials because of their small size, rich surface functional groups, and good electrical properties. Their large surface-to-volume ratio promotes efficient ion adsorption and rapid electron movement, making them useful as additives in composite electrode structures[58]. CQDs are frequently combined with porous carbon frameworks or conductive polymers to improve both capacitance and long-term electrochemical stability.

Another notable carbon nanomaterial is nanodiamond, which consists of sp^3-bonded carbon atoms arranged in a diamond-like lattice at the nanoscale. Nanodiamonds exhibit excellent chemical stability and can be readily functionalised to introduce active surface groups[59]. These properties allow them to integrate effectively with conductive matrices and provide additional electrochemically active sites, thereby enhancing the mechanical and structural stability of composite electrodes.

Hierarchical Porous Carbons (HPCs) have received considerable interest in supercapacitor research because of their multi-level pore structure[60]. These materials typically contain interconnected micropores, mesopores, and macropores. Micropores contribute to a high surface area for charge storage, mesopores facilitate efficient ion transport, and macropores serve as ion buffering pathways. Such a hierarchical architecture improves electrolyte accessibility and enhances both capacitance and power density.

In addition, carbon–metal hybrid systems, particularly composites formed by combining carbon frameworks with transition metal oxides or sulfides, have demonstrated enhanced electrochemical performance[61]. Materials such as MnO_2, $NiCo_2O_4$, and MoS_2 integrated with conductive

carbon matrices can contribute pseudocapacitance alongside electric double-layer capacitance. This synergistic interaction can significantly increase energy density while maintaining high power capability.

Recent progress in two-dimensional materials, including MXenes and Transition Metal Dichalcogenides (TMDs), has further broadened the design strategies for supercapacitor electrodes[62]. When integrated with carbon-based materials, these layered structures can improve electrical conductivity, surface wettability, and electrochemical reactivity, ultimately leading to improved charge storage behaviour.

Overall, the incorporation of these emerging carbon nanostructures and hybrid material systems represents a promising pathway toward developing next-generation supercapacitors with higher energy density, improved ion transport, and enhanced long-term stability.

4. Challenges in Grid-Scale Supercapacitor Commercialisation

While supercapacitors are well-established in commercial applications such as power backup for consumer electronics, regenerative braking systems, and IoT devices, scaling their use for electric grid applications presents a distinct set of challenges. These systems demand not only high power but also substantially higher energy storage capacity, long service life, integration with renewable sources, and stringent safety protocols.

4.1 Limited Energy Density and Voltage Window

The most significant limitation for grid-scale use is the low energy density of commercial supercapacitors (~5–10 Wh/kg), which is inadequate for bulk energy storage over extended durations. Achieving energy densities comparable to lithium-ion batteries (100-200 Wh/kg) remains a challenge[63]. Efforts are underway to develop hybrid and asymmetric supercapacitors and to employ pseudocapacitive or dielectric-enhanced architectures to bridge this gap.

Moreover, the limited voltage window (~2.7–3 V per cell) necessitates series stacking, which introduces complexity in voltage balancing and system design for high-voltage operations.

4.2 Series Integration and Balancing

For grid applications, hundreds of cells must be connected in series to meet voltage requirements (*e.g.*, 400-1000 VDC). Maintaining uniform voltage distribution is difficult due to variation in Equivalent Series Resistance (ESR) and leakage current between cells. This can lead to premature cell failure and efficiency loss[64]. Active balancing circuits or passive resistive balancing are used, but they add to the system cost and complexity.

4.3 Thermal Management and Cycle Stability

Frequent charge–discharge cycles and high-current operation generate significant heat, which must be effectively dissipated in large-scale systems. Thermal runaway, though less likely than in batteries, can still degrade the electrolyte and compromise longevity. Developing heat-resistant electrolytes and efficient thermal management systems is critical.

4.4 Integration with Renewable and Smart Grids

Supercapacitors are ideally suited for short-duration storage and fast response, making them attractive for grid applications like frequency regulation, load levelling, and renewable smoothing. However, integrating them with solar or wind systems requires robust power electronics, charge control algorithms, and real-time management systems.

Additionally, regulatory standards for grid compliance, modular scalability, and lifecycle impact assessment need to be addressed to enable wide-scale deployment.

4.5 Standardisation and Cost Factors

The absence of universal testing standards for large-format supercapacitors creates inconsistency in performance reporting and market adoption[65]. Cost-per-kWh remains higher than battery technologies, though longer cycle life (>10^5 cycles) can reduce lifecycle cost if system integration challenges are solved. While carbon-based materials offer numerous advantages and are widely used in various applications, several factors limit their full-scale commercialisation in supercapacitors.

5. Conclusion

The advancement of carbon-based electrodes for supercapacitor applications is fundamentally intertwined with progress in science and technology. This emerging category of green energy storage devices holds significant potential appeal for various industries

across the market due to its eco-friendly nature and high-power capabilities. Nevertheless, several challenges persist that limit the full commercialisation and market adoption of supercapacitors. Key issues include the high production costs, relatively low energy density in comparison to batteries, and the absence of standardised manufacturing practices. Addressing these obstacles is essential to enhancing the performance and economic feasibility of supercapacitors, paving the way for their broader integration into industrial applications in the future.

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