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Supercapacitors and Their Applications in Energy Devices

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Abstract: This comprehensive review examines supercapacitors as advanced energy storage devices, focusing on their construction, working principles, and various types. Supercapacitors bridge the gap between conventional batteries and standard capacitors, offering unique combinations of high-energy storage capacity and rapid power delivery. The study analyzes their performance metrics, including maximum energy (Emax) and maximum power (Pmax), while addressing current limitations in stability, electrochemical potential windows, and operational lifespans. The research explores different capacitor technologies, including ceramic, electrolytic, film, polymer, hybrid, and glass capacitors, examining their distinct characteristics and applications. Current commercial supercapacitors, typically utilizing aqueous or organic electrolytes with activated carbon electrodes, achieve energy densities of 4-5 Wh kg^{-1} and power densities of 1-2 kW kg^{-1}. The paper highlights significant applications in automotive industries, particularly in hybrid and electric vehicles, where over 600,000 vehicles currently employ supercapacitors in stop-start systems. This review also addresses manufacturing processes and emerging trends in solid-state supercapacitors, suggesting potential pathways for future development in energy storage technology.

Keywords: Double-layer capacitance, Electrode materials, Energy storage devices, Power density, Supercapacitors.

I. Introduction

Supercapacitors, or electrochemical capacitors, are advanced energy storage devices designed to fill the gap between conventional batteries and standard capacitors [1]. They combine the high-energy storage capacity typically associated with batteries and the rapid power delivery characteristic of conventional capacitors. This unique combination makes them highly desirable for a diverse range of applications, including power backup systems in hybrid electric vehicles (HEVs), portable electronic devices, medical equipment, and military hardware. However, the widespread adoption of supercapacitors faces a significant challenge: their performance limitations [2]. These include issues with stability, restricted electrochemical potential windows, and relatively short operational lifespans. These limitations are largely influenced by the properties of the electrolytes used in the supercapacitors [3]. The performance of a supercapacitor can be quantified using two key metrics: maximum energy (Emax) and maximum power (Pmax). These are defined by the following equations: $E_{max} = (CV^2) / 2$ and $P_{max} = V^2 / (4R)$. In these equations, C stands for capacitance, V denotes the cell voltage, and R represents the total equivalent series resistance [4]. These formulas highlight the critical role that voltage plays in determining both the energy and power capabilities of supercapacitors, underscoring the importance of developing electrolytes that can support higher operating voltages while maintaining long-term stability and performance [5]. Developing high-performance supercapacitors requires improving energy and power densities, enhancing safety, and extending their lifespan. It is important to address the limitations of current electrode materials and organic electrolytes [6]. Commercial supercapacitors today primarily use aqueous or organic electrolytes, both of which have restrictive electrochemical windows. This constraint results in low cell voltages - Aqueous electrolytes typically allow a voltage of around 1.2 V, while organic electrolytes permit a higher range of 2-3 V, which limits the energy and power densities achievable by these devices [7]. Another challenge arises from the phenomenon known as electrolyte depletion. As ions from the electrolyte migrate into the double layers at the interfaces between the electrode and electrolyte, they accumulate, creating a charge separation that stores energy within the supercapacitor, and the salt concentration in the electrolyte decreases. This depletion reduces the capacitor's energy density and increases the cell's resistance, impacting overall performance. Thereby reducing the maximum achievable power density.

Consequently, supercapacitors currently available in the market, which typically use these electrolytes in combination with activated carbon electrodes, exhibit relatively low energy density (around 4-5 Wh kg^{-1}) and power density (approximately 1-2 kW kg^{-1}) [8]. Moreover, certain organic electrolytes pose significant safety risks due to their volatile, flammable, and toxic nature, which limits their operational temperature range [9]. Looking ahead, the next generation of portable devices will necessitate solid-state supercapacitors that provide high energy and power densities. Along with the flexibility to adapt to various design and power requirements [10]. These advancements are necessary to overcome the limitations of current technologies and meet the evolving needs of modern electronic devices [11]. Supercapacitors are being investigated as a viable alternative to conventional batteries for electric vehicles. Also referred to as electrochemical capacitors, supercapacitors, or ultracapacitors, these electrical components are designed to store and manage precise amounts of energy [12]. The development of these devices started in the 1950s, with initial experiments carried out by American companies General Electric (GE) and Standard Oil of Ohio (SOHIO) during the 1950s to 1970s. The early electrochemical supercapacitors achieved capacities of around 1 Farad [13]. SOHIO patented this type of supercapacitor in 1971. The first commercially available supercapacitor, known as the "Gold Cap," was launched by Panasonic in 1982. However, this early model was characterized by a high equivalent series resistance (ESR) [14]. The history of supercapacitors spans several decades, highlighting the gradual improvement in their design and performance. From their humble beginnings with capacities around 1 Farad to their current status as potential alternatives to conventional batteries in electric vehicles, supercapacitors have undergone significant development [15]. This evolution reflects the ongoing efforts to enhance energy storage technologies for various applications, including Supercapacitors find applications in scenarios requiring rapid storage or release of substantial energy [16]. Today, their main application is in the automotive industry, particularly in Hybrid Electric Vehicles (HEVs), Electric Vehicles (EVs), and Fuel Cell Vehicles (FCVs), including passenger cars, trains, and trolleybuses [17]. Another important area of application is in electronic devices, especially in Uninterruptible Power Supplies (UPS) and volatile memory backups for personal computers. Furthermore, supercapacitors serve a complementary function alongside traditional batteries in energy harvesting systems, such as solar panels and wind turbines. [18]. The automotive industry's adoption of supercapacitors offers numerous benefits. In hybrid electric vehicles, these devices enhance efficiency in several ways. Modern hybrid vehicles often feature a system that completely shuts off the engine when the vehicle comes to a stop and then efficiently restarts it using energy stored in supercapacitors. Currently, over 600,000 Hybrid Electric Vehicles (HEVs) employ supercapacitors in their stop-start systems [19]. Some manufacturers have also created supercapacitor-based alternatives to traditional vehicle batteries. These designs include supercapacitors connected in parallel with a smaller lead-acid battery, aiming to handle peak power demands, such as during engine starts, thus minimizing overall energy consumption from the batteries [20].

This innovative application of supercapacitors in the automotive sector highlights their potential to enhance energy efficiency and performance across a range of vehicle types, including hybrid and electric cars as well as public transportation systems. Batteries live longer when discharge is small and consistent. Supercapacitors in a "hybrid lead-acid battery" design balance energy demands on the battery. Battery technology, despite its widespread use in applications ranging from toys to medical implants, faces several challenges. These include short lifespan, limited power density, slow charging, overheating issues, and environmental concerns. Supercapacitors (SCs) have emerged as a promising option in the field of energy storage.

These devices uniquely combine the properties of batteries and traditional capacitors, featuring extraordinarily high capacitance in a single unit. Recent advancements in supercapacitor technology have displayed its potential to transform energy storage systems. Compared to conventional batteries or capacitors, supercapacitors offer notable benefits [21]:

- *Swift Charging:* Supercapacitors can recharge significantly faster than standard batteries.
- *Efficient Energy Release:* They can discharge power in a manner akin to traditional batteries.
- *Lightweight Design:* Generally, supercapacitors weigh less than their conventional counterparts.
- *Eco-Friendly Attributes:* They present fewer environmental hazards than many battery types.

The continuous evolution and improvement of supercapacitors underscore their increasing significance in energy storage. As this technology matures, it shows promise in addressing many shortcomings of current battery systems. This progress opens doors to more efficient and sustainable energy solutions across diverse industries and applications, potentially reshaping the future of energy storage and utilization [22].

II. Construction and Working of Supercapacitor

Supercapacitors (SCs) differ from traditional capacitors in their energy storage mechanisms. While conventional capacitors store energy by electron transfer between electrodes, SCs utilize advanced materials to achieve higher capacitance. Carbon-based SCs leverage the electric double-layer effect, capitalizing on their increased surface area. In contrast, SCs using metal oxides or polymers primarily employ pseudo-capacitance for charge storage [23]. Although SCs and electrolytic capacitors share fundamental capacitance principles, SCs achieve superior performance due to their thinner dielectric layers and electrodes with greater surface area. This unique configuration allows SCs to effectively bridge the gap between batteries and traditional capacitors regarding energy and power density [24]. The Ragone plot visually represents the performance characteristics of different energy storage devices. On this graph, SCs occupy a middle ground between batteries and capacitors. This positioning highlights their distinctive advantage: the ability to deliver high power output in short time frames, making them invaluable for applications with such requirements [25]. Supercapacitors (SCs) utilize a unique configuration where a dielectric material separates carbon-based electrodes, functioning as both an insulator and a performance-influencing component. Unlike conventional capacitors, SCs store charges electrostatically. When voltage is applied, the resulting electric field polarizes the electrolyte, causing ions to diffuse through the dielectric to the oppositely charged porous electrodes. This forms an electric double layer at each electrode, effectively decreasing the inter-electrode distance while increasing the electrode surface area [26]. The energy storage capacity of supercapacitors (SCs) is influenced by the active material of the electrolyte. The electrode surface area and the utilization rate of the porous electrode's micro-holes. This mechanism allows SCs to achieve higher capacitance and bridge the gap between batteries and traditional capacitors in terms of energy and power density, making them particularly valuable for applications requiring rapid, high-power energy delivery [27]. Supercapacitors are energy storage devices that consist of two porous electrodes, usually constructed from high-surface-area carbon materials, with an electrolyte and a thin, porous membrane in between. When a voltage is applied, ions from the electrolyte move towards the oppositely charged electrodes, creating an electric double layer at the electrode-electrolyte interface. This double layer stores energy electrostatically without any chemical reactions, enabling rapid charging and discharging cycles. Additionally, some supercapacitors utilize pseudocapacitance, which involves fast and reversible redox reactions at the electrode surface to enhance charge storage. This design allows supercapacitors to achieve high power density and long cycle life, effectively bridging the gap between traditional capacitors and batteries. Their performance is primarily influenced by the surface area of the electrode material, the properties of the electrolyte, and the characteristics of the separator, making them ideal for applications that require quick bursts of power [28].

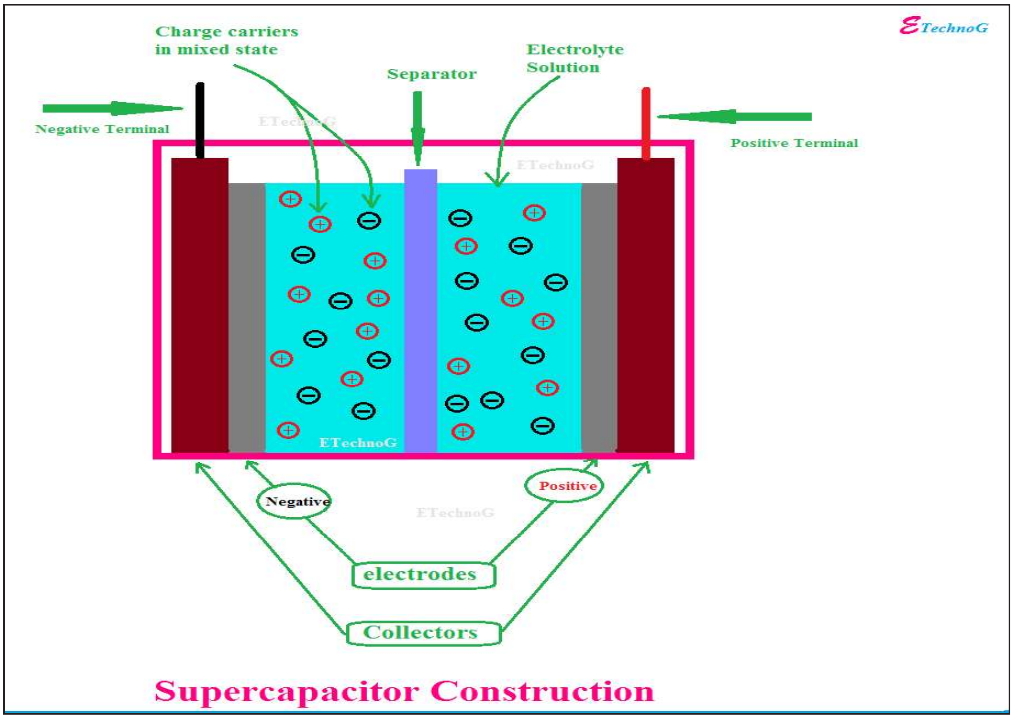

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Fig. 1: Construction of Supercapacitors

III. How Supercapacitors Are Made?

Supercapacitors are manufactured through a multi-step process that combines precision engineering with advanced materials science. The production begins with the preparation of electrodes, typically employing carbon-based materials such as activated carbon, graphene, or carbon nanotubes [29]. These materials are mixed with binders and conductive additives to create a paste, which is then applied to metal foil current collectors, usually made of aluminium or copper. After drying and cutting, these electrodes are paired with a carefully prepared separator – a porous material designed to prevent direct contact between the electrodes while allowing ion movement [30]. Simultaneously, an appropriate electrolyte solution is prepared, which can be aqueous, organic, or an ionic liquid, depending on the desired characteristics of the final product. The assembly phase involves stacking or rolling the electrodes with the separator between them, placing this structure in housing, and adding the electrolyte. The unit is then meticulously sealed to prevent leakage and contamination. Following assembly, the supercapacitor undergoes a conditioning process involving initial charging and discharging cycles to stabilize its performance [31]. Quality control is a crucial final step, where each unit is rigorously tested for key parameters such as capacitance, internal resistance, and leakage current. Once approved, the supercapacitors are packaged and labelled for distribution. This intricate process, which may vary slightly among manufacturers and for different types of supercapacitors, combines materials science, electrochemistry, and precision engineering to create these high-performance energy storage devices. Supercapacitor manufacturing begins with electrode preparation, where carbon materials are mixed with binders and conductive additives, and then applied to current collectors. Simultaneously, the electrolyte is prepared, and a porous separator is cut to size. The assembly process involves layering the electrodes and separator, then rolling or stacking them into the desired shape. This assembly is inserted into a casing, filled with electrolytes under controlled conditions, and sealed to prevent leakage. The sealed unit then undergoes conditioning through initial charge-discharge cycles to stabilize performance. Finally, each supercapacitor is rigorously tested for capacitance, internal resistance, and leakage current before being packaged and labelled for distribution. Throughout the process, manufacturers may employ proprietary techniques to enhance performance or efficiency, but these core steps form the basis of most supercapacitor production methods [32].

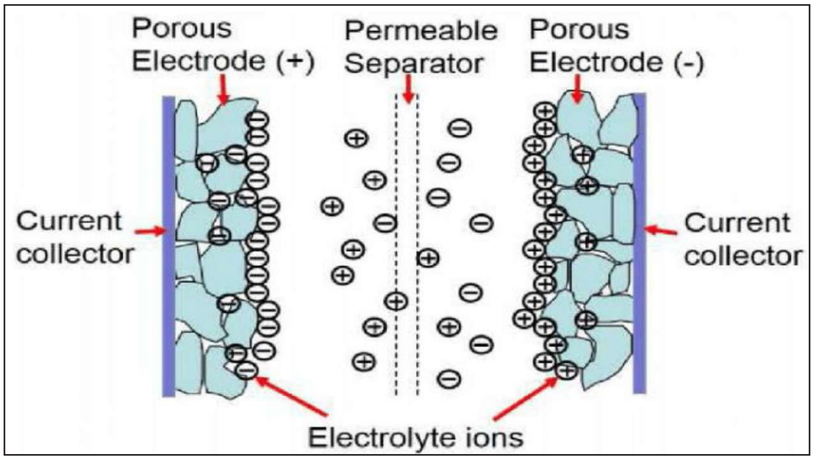

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Fig. 2: A Schematic Diagram of a Supercapacitor at the Charged State

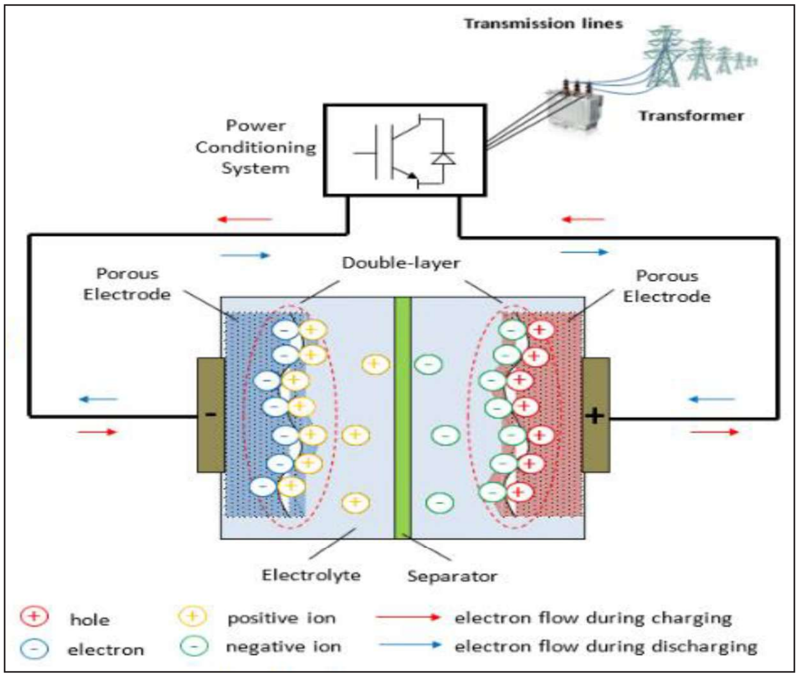

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Fig. 3: Schematic Diagram of Electrochemical Double-Layer Capacitor

IV. Types of Capacitors

Capacitors are vital components in electronic circuits, storing electrical energy in an electric field. With rapid advancements in technology, capacitors have evolved in terms of materials, construction techniques, and performance.

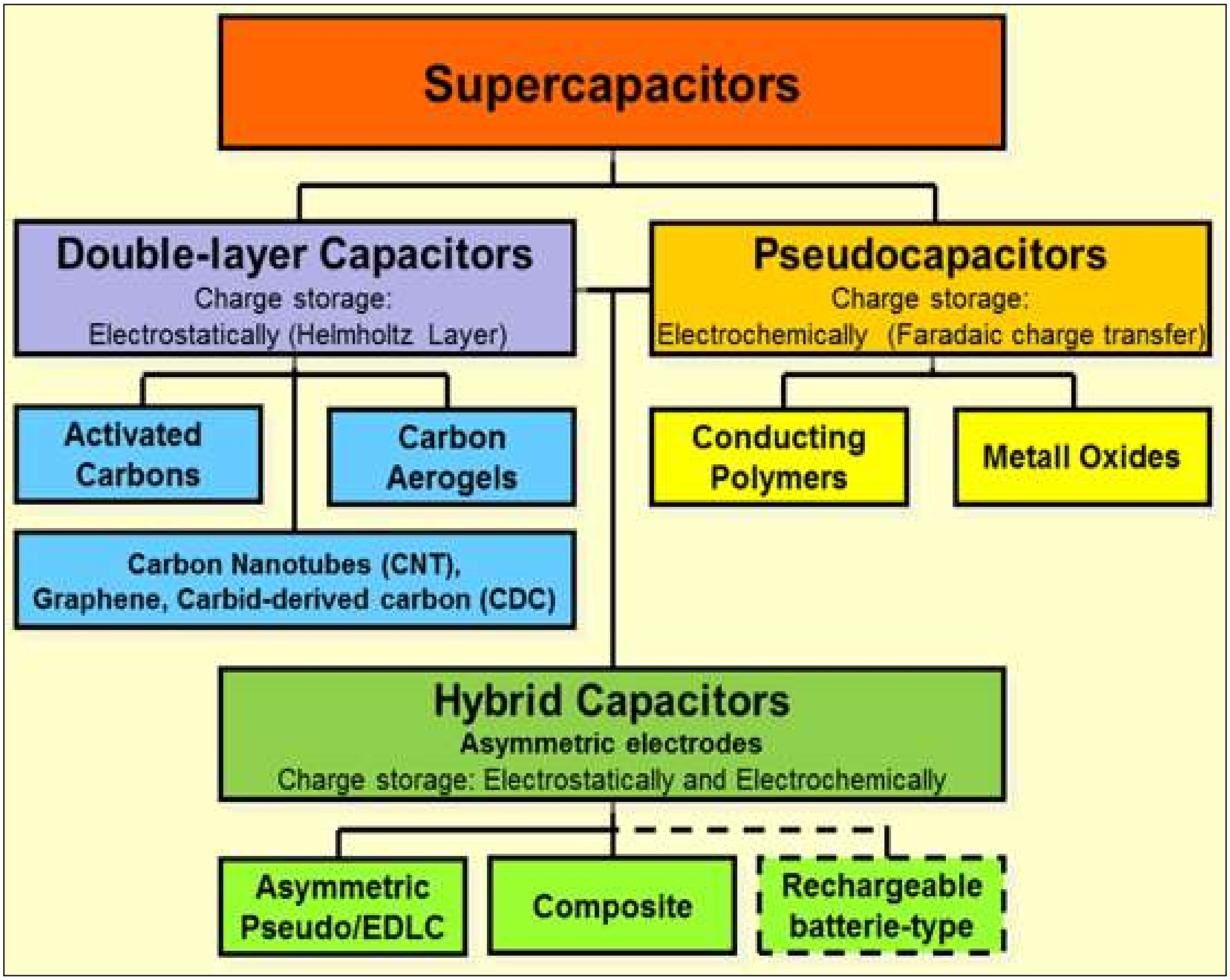

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Fig. 4: The Family Tree of Supercapacitor Types Includes Double-Layer Capacitors, Pseudocapacitors, and Hybrid Capacitors, Which are Categorized Based on Their Electrode Designs

A. Ceramic Capacitors

Ceramic capacitors are widely used passive electronic components that store electrical energy in the form of an electric field. They are characterized by their use of ceramic material as the dielectric, which provides several advantages, including small size, high capacitance stability, and low cost. Due to these properties, ceramic capacitors are found in a variety of applications, including power supply filtering, signal coupling, decoupling, and high-frequency circuit design.

Ceramic capacitors are constructed with a ceramic dielectric material sandwiched between two conductive plates (electrodes). The ceramic material is usually composed of titanium dioxide (TiO_2) or barium titanate ($BaTiO_3$), which are known for their high dielectric constant. This high dielectric constant allows for a relatively large capacitance in a small physical package. The electrodes are typically made from metals such as silver, palladium, or copper.

There are two main categories of ceramic capacitors based on the dielectric material.

- *Class I Ceramic Capacitors:* These capacitors offer high stability and low losses, making them suitable for high-frequency applications. Class I capacitors are typically made with low-loss ceramics, such as titanium dioxide, which allows them to maintain their capacitance over a wide range of temperatures and frequencies [33].
- *Class II Ceramic Capacitors:* Class II capacitors offer higher capacitance values but are less stable in terms of temperature and voltage dependence. They are often made with high-permittivity ceramics like barium titanate, which allows for higher capacitance densities. Class II capacitors are commonly used in decoupling and bypass applications where capacitance stability is less critical [34].

Ceramic capacitors store energy by accumulating electrical charges on the plates separated by the ceramic dielectric. When a voltage is applied across the capacitor, an electric field is generated within the dielectric material, which causes the charges to accumulate on the electrodes. The charge stored in the capacitor is directly proportional to both the capacitance and the applied voltage. The ceramic material used in the dielectric determines the capacitor's capacitance value, voltage rating, and temperature performance. The dielectric's properties, such as its permittivity, influence how well the capacitor can store energy [35]. A study carried out by [36] highlighted improvements in ceramic capacitors for high-temperature automotive applications. These new capacitors exhibit enhanced thermal stability and dielectric performance, making them highly reliable in harsh environments. [37] Stated that the use of advanced ceramic materials in MLCCs has increased capacitance density and reduced size, enabling their integration into compact devices. Their low equivalent series resistance (ESR) and ability to operate at high frequencies make them ideal for decoupling and filtering applications. However, the sensitivity of ceramic capacitors to temperature and voltage stress remains a challenge for their use in extreme environments. Overall, advancements in materials science have significantly improved the performance and reliability of ceramic capacitors, solidifying their importance in modern electronics.

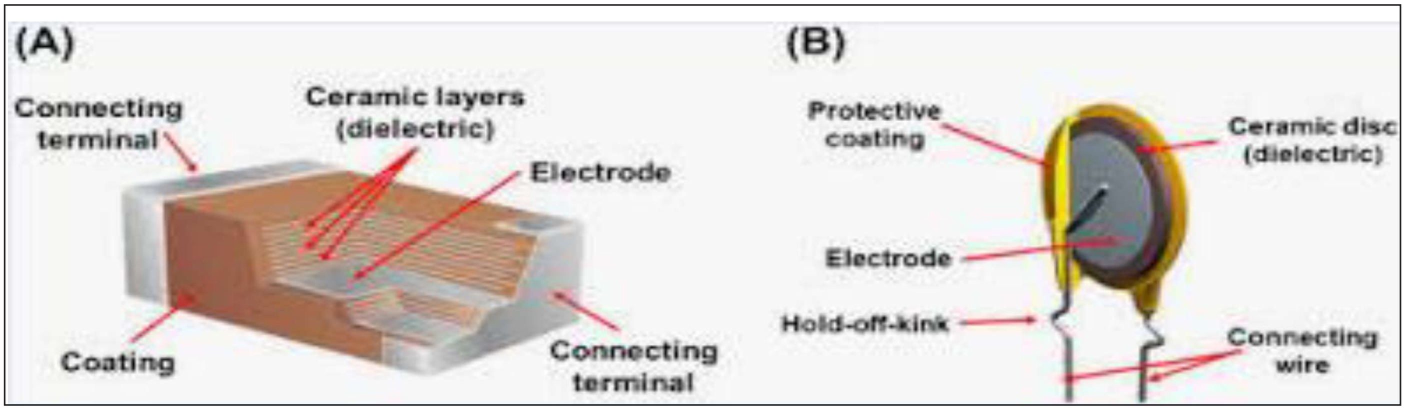

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Fig. 5: Ceramic Capacitors

B. Electrolytic Capacitors

Electrolytic capacitors are a specific type of polarized capacitor that uses an electrolyte to attain a higher capacitance compared to other capacitor types. They are commonly found in electronic circuits where high capacitance is required in a compact size, making them essential in power supplies, audio systems, and filtering applications. The key characteristic of electrolytic capacitors is their high capacitance-to-volume ratio, which is achieved by using a thin dielectric layer and a liquid or solid electrolyte.

An electrolytic capacitor typically consists of an anode made from metal, usually aluminium or tantalum, covered by an oxide layer that serves as the dielectric. The electrolyte, which can be liquid or solid, functions as the cathode. The oxide layer is extremely thin, which allows for a high capacitance value in a compact size. Capacitance is directly proportional to the surface area of the anode and inversely proportional to the thickness of the dielectric, leading to the high capacitance values commonly seen in these capacitors [38].

There are three main types of electrolytic capacitors based on the metal used for the anode**.**

- *Aluminum Electrolytic Capacitors:* These are the most common type and are known for their cost-effectiveness and large capacitance range. Aluminium capacitors are typically used in power supplies and energy storage applications [39].
- *Tantalum Electrolytic Capacitors:* Tantalum capacitors are more expensive than aluminium but offer better stability, higher capacitance per unit volume, and longer life spans. They are often used in high-reliability applications such as aerospace and medical devices [40].

- *Niobium Electrolytic Capacitors:* Niobium capacitors are less common but have been developed as an alternative to tantalum capacitors. They provide similar performance and are used in applications where tantalum's availability or cost is a concern [41].

Electrolytic capacitors store electrical energy by accumulating charges on the opposite surfaces of the dielectric material. When a voltage is applied, positive ions in the electrolyte move towards the anode, and negative ions move towards the cathode, creating an electric field across the dielectric. The polarity of electrolytic capacitors is essential for their correct operation. Applying reverse voltage can damage the oxide layer, leading to capacitor failure. Therefore, they are often marked with a "+" or "-" symbol to indicate proper installation [42].

[43] Stated that these capacitors are recognized for their high volumetric efficiency, allowing for larger capacitance in compact sizes. However, one drawback is their relatively high equivalent series resistance (ESR), which can limit performance in high-frequency applications. [44] Asserted that their polarity makes them unsuitable for AC applications. Recent developments have focused on improving the longevity and reliability of these capacitors, particularly in power supply and energy storage systems. Electrolytic capacitors remain critical components in power electronics, especially for smoothing out voltage fluctuations in power supplies and audio circuits.

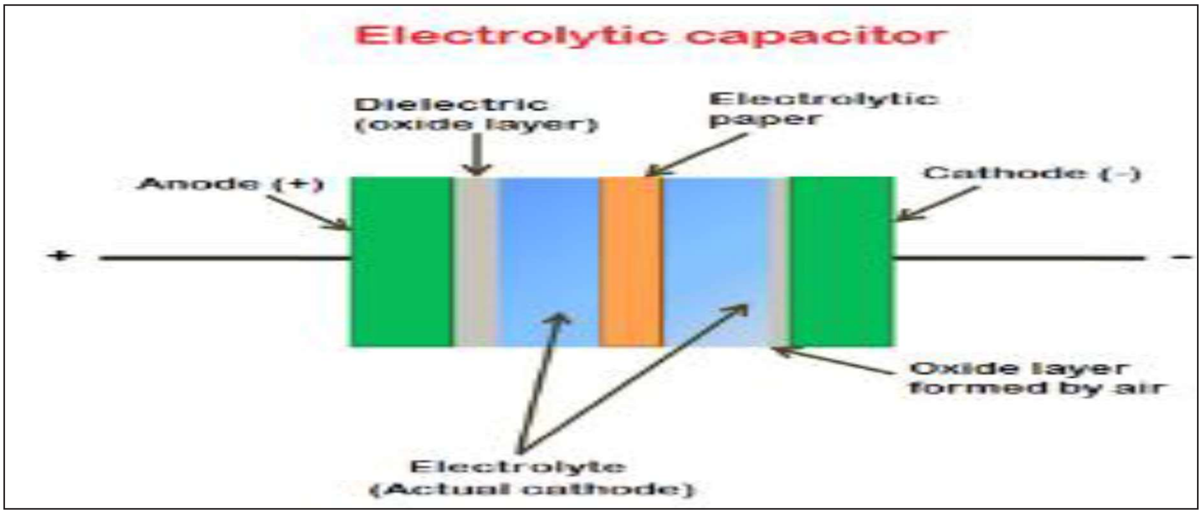

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Fig. 6: Electrolytic Capacitors

C. Film Capacitors

Film capacitors are a type of capacitor that employs thin plastic films as the dielectric material. They are renowned for their outstanding electrical properties, including low dielectric loss, high insulation resistance, and stability over time. These characteristics make them ideal for various applications in power electronics, automotive systems, industrial applications, and beyond. Their versatility and reliability have established them as one of the most commonly used types of capacitors in contemporary electronics.

Film capacitors consist of a plastic dielectric film, such as polypropylene (PP), polyester (PET), or polycarbonate, sandwiched between two metal electrodes. The film is either wound into a cylindrical shape or stacked in a flat configuration, depending on the application requirements. The dielectric material determines many of the capacitor's characteristics, such as capacitance, voltage rating, and temperature stability [45]. When voltage is applied to a film capacitor, an electric field is generated across the dielectric film, causing charge separation on the electrodes. The capacitor stores energy in this electric field until the voltage is removed, allowing it to release the stored energy. One of the advantages of film capacitors is that they do not rely on chemical reactions for energy storage, which enhances their longevity and cycle life compared to electrolytic capacitors [46].

Film capacitors are broadly classified based on the type of dielectric film used.

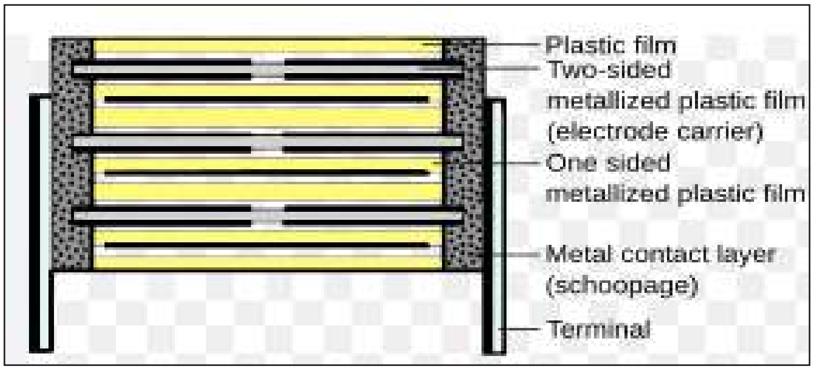
- *Polypropylene (PP) Capacitors:* These are among the most commonly used film capacitors, thanks to their low dielectric loss and high insulation resistance. They are suitable for high-frequency and high-voltage applications, such as power supplies and inverters [47].
- *Polyester (PET) Capacitors:* Polyester capacitors offer a higher dielectric constant than polypropylene, which allows for smaller capacitor sizes. However, they have slightly higher dielectric losses and are less stable at high temperatures, making them ideal for general-purpose applications [48].

- *Polycarbonate Capacitors:* These capacitors provide excellent temperature stability and are used in precision timing and filtering applications, although they are less common due to the high cost of polycarbonate materials [49].

[50] mention that One of the primary advantages of film capacitors is their excellent stability over time and across temperature variations. Unlike electrolytic capacitors, which may degrade or lose capacitance with time and use, film capacitors maintain consistent performance over long periods. [51] stated that Film capacitors exhibit very low dielectric loss, which refers to the energy dissipated as heat when the capacitor is charged and discharged. This low loss makes them highly efficient and suitable for use in high-frequency applications, such as filters, oscillators, and audio circuits. The capacitors can handle high voltages and currents without significant degradation. This makes them ideal for power electronics, including motor drives, power factor correction, and renewable energy systems, where high voltage and current demands are common as stated by [52]. [53] explained that the capacitors have an extremely long lifespan, often exceeding 100,000 hours under normal operating conditions. This long life is due to the physical nature of their energy storage mechanism, which does not involve electrochemical reactions that could lead to degradation over time.

[45] stated that the capacitors are used in inverters, power supplies, and converters due to their ability to handle high currents and voltages. They play a critical role in energy conversion and storage systems in electric vehicles, solar inverters, and industrial motor drives. [48] Further explains that their high stability and low loss make film capacitors ideal for AC applications, including power factor correction and filtering in the power grid. Film capacitors are favoured for their low distortion and excellent frequency response, ensuring high-fidelity signal transmission [54].

[49] contended that the primary challenge of film capacitors is their size; film capacitors are generally larger than electrolytic capacitors with the same capacitance, which can be a drawback in space-constrained designs. Additionally, their performance at extremely high temperatures may be limited compared to other types of capacitors.



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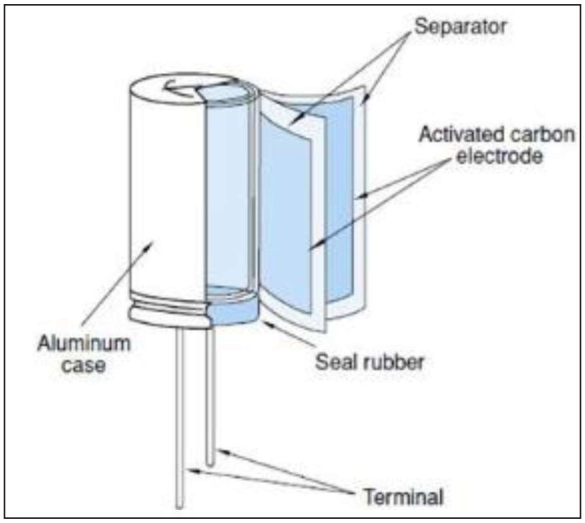

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Fig. 7: Film Capacitors

D. Polymer Capacitors

Polymer capacitors, also known as polymer electrolytic capacitors, are a class of capacitors that utilize a solid conductive polymer as the electrolyte instead of the traditional liquid electrolyte found in electrolytic capacitors. These capacitors offer several advantages, such as lower Equivalent Series Resistance (ESR), better frequency characteristics, and improved reliability, making them suitable for a range of modern electronic applications, including power supplies, automotive systems, and high-frequency circuits.

Polymer capacitors typically consist of an anode made of a conductive metal, often aluminium or tantalum, an oxide layer serving as the dielectric, and a conductive polymer electrolyte that replaces the liquid electrolyte found in traditional capacitors. The conductive polymer, often made from materials like polypyrrole (PPy) or polythiophene derivatives, enhances the overall conductivity of the capacitor, reducing internal resistance and allowing for higher efficiency in charge and discharge cycles [60].

A study carried out by [61] found that polymer capacitors performed exceptionally well in high-temperature automotive applications, where they maintained low ESR and stable capacitance even at temperatures exceeding 125 °C. Their solid-state construction makes them less prone to drying out, a common issue with traditional electrolytic capacitors. Polymer capacitors are also noted for their long life and reliability in high-frequency circuits. However, their relatively higher cost compared to other capacitor types limits their use in cost-sensitive applications. Nevertheless, they are widely used in telecommunications, computing, and automotive electronics, where reliability and performance outweigh cost concerns [62].

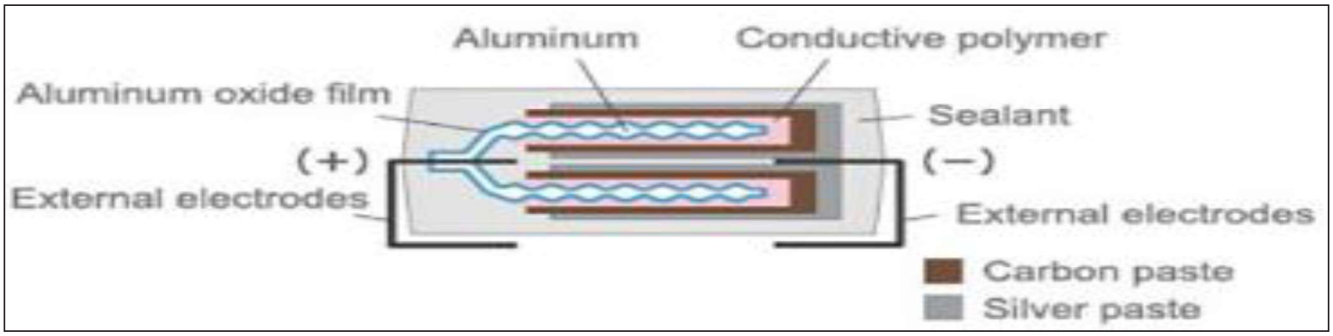

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Fig. 8: Polymer Capacitors

E. Hybrid Capacitors

Hybrid capacitors are an advanced class of capacitors that combine features of both conventional electrochemical capacitors (supercapacitors) and electrostatic capacitors. These capacitors provide a balance between high energy density and high power density, positioning them between batteries and traditional capacitors in terms of performance. By merging the advantages of electrochemical and electrostatic storage mechanisms, hybrid capacitors have become pivotal in uses like energy storage systems, electric vehicles, and portable electronic devices. A hybrid capacitor typically consists of two electrodes: one resembling a supercapacitor and the other more like a battery electrode. The design of hybrid capacitors often involves asymmetry, with one electrode designed for high capacitance (using materials such as activated carbon or graphene) and the other for higher energy storage (utilizing materials like lithium titanate or metal oxides). This combination allows hybrid capacitors to store more energy than traditional capacitors while maintaining the rapid charge and discharge cycles characteristic of supercapacitors [63]. Hybrid capacitors store energy through both electrostatic and electrochemical processes. The electrostatic component, found in conventional capacitors, stores energy by separating charges across a dielectric. On the other hand, the electrochemical mechanism, similar to that in batteries, involves ion insertion or intercalation into the electrode material, which allows for increased energy storage. This dual mechanism enables hybrid capacitors to achieve a higher energy density than standard capacitors while maintaining a higher power density than batteries [64].

[65] study demonstrated that hybrid capacitors could achieve energy densities higher than traditional supercapacitors while maintaining rapid charge and discharge capabilities. These capacitors typically consist of one battery-like electrode and one capacitor-like electrode, providing a balance between energy storage capacity and charge rate. [66] stated that Hybrid capacitors are increasingly used in grid energy storage, electric vehicles, and renewable energy systems, where both energy density and fast response times are critical. Although hybrid capacitors are relatively new, ongoing research continues to improve their performance, particularly in terms of cycle life and energy retention.

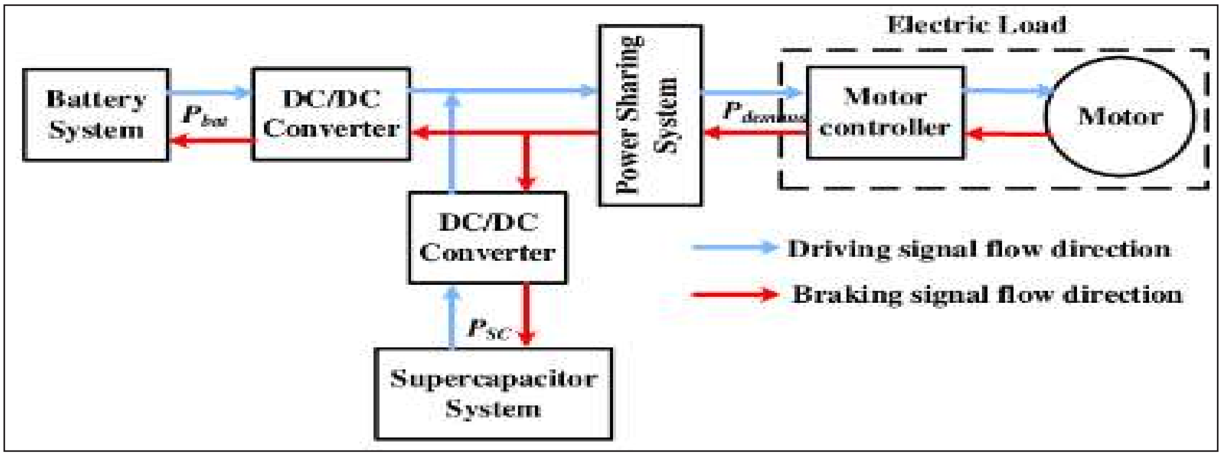

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Fig. 9: Hybrid Capacitors

F. Glass Capacitors

Glass capacitors are a specialized type of capacitor that uses glass as the dielectric material, offering several unique advantages including high thermal stability, low dielectric loss, and excellent insulation properties. These characteristics make glass capacitors ideal for use in high-frequency, high-voltage, and precision applications such as aerospace, military, and medical devices. Like other capacitors, Glass capacitors are composed of two conductive plates that are separated by a dielectric material, specifically glass in this case. The dielectric material plays a crucial role in determining the capacitor's performance, as it stores energy by polarizing when subjected to an electric field. The dielectric constant of glass varies depending on its composition, but it typically offers a moderate dielectric constant (around 5 to 10), providing a balanced performance between energy storage and stability [67]. Glass capacitors operate by storing electrostatic energy in the dielectric material. When a voltage is applied, the electric field induces charge separation within the dielectric, allowing the capacitor to store energy. The unique properties of glass as a dielectric material, such as its chemical inertness and high breakdown voltage, allow these capacitors to operate in extreme conditions without significant performance degradation [68].

[69] stated that One of the most significant advantages of glass capacitors is their excellent thermal stability. Glass can withstand extreme temperatures, making these capacitors suitable for environments with high thermal stress, such as aerospace applications. This thermal stability ensures consistent performance across a wide temperature range, typically from -55 °C to +200 °C, [67] explains that Glass capacitors exhibit very low dielectric loss, which refers to the loss of energy in the form of heat when a capacitor is charged and discharged. This low loss makes them highly efficient in high-frequency applications, where energy dissipation can be a critical issue. As a result, glass capacitors are often employed in RF circuits, filters, and precision timing devices. The use of glass as a dielectric material also provides high insulation resistance, which helps to minimize leakage current. This property is particularly beneficial for applications requiring long-term energy storage or high-voltage operation, as it ensures the capacitor retains its charge over extended periods without significant energy loss [68]. Glass is mechanically robust and chemically inert, which gives glass capacitors excellent durability and resistance to environmental degradation. Unlike other capacitors that may degrade over time due to exposure to moisture or chemicals, glass capacitors remain stable in harsh environments, further extending their lifespan. [69] asserted that the high reliability and stability of glass capacitors make them ideal for mission-critical aerospace systems, such as communication and navigation equipment, where failure is not an option. Glass capacitors are also used in medical devices, where precision and long-term reliability are essential. Their low dielectric loss and high insulation resistance ensure accurate signal processing in sensitive medical instrumentation. While glass capacitors offer numerous advantages, they do have some limitations. The primary drawback is their cost, as glass is more expensive to manufacture and process compared to other dielectric materials like ceramics. Additionally, glass capacitors tend to be bulkier than their ceramic counterparts, which can limit their use in space-constrained applications as explained by [67].

[68] disclosed that recent advancements in materials science have resulted in the creation of new types of glass-based dielectrics with improved performance characteristics. For instance, research into glass-ceramic composites has demonstrated improved dielectric constants and breakdown voltages, making them even more suitable for high-voltage and high-frequency applications. These developments are opening new possibilities for glass capacitors in emerging technologies like 5G and electric vehicles.

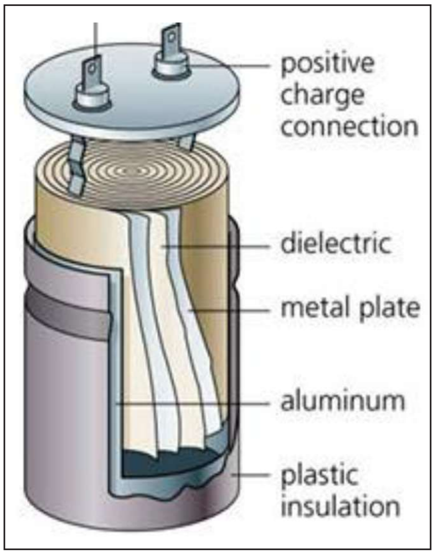

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Fig. 10: Glass Capacitors

V. CONCLUSION

In conclusion, this comprehensive review underscores the pivotal role of supercapacitors as advanced energy storage solutions that effectively bridge the gap between conventional batteries and standard capacitors. By offering a unique combination of high-energy storage capacity and rapid power delivery, supercapacitors demonstrate significant potential across various applications, particularly in the automotive industry, where they enhance the efficiency of hybrid and electric vehicles. While current technologies achieve energy densities of 4-5 Wh kg^{-1} and power densities of 1-2 kW kg^{-1}, challenges remain in stability, electrochemical potential windows, and operational lifespans. The exploration of various capacitor technologies—ceramic, electrolytic, film, polymer, hybrid, and glass—reveals their distinct characteristics and applications, paving the way for innovation. Furthermore, this review highlights the ongoing advancements in manufacturing processes and the emergence of solid-state supercapacitors, suggesting promising avenues for future research and development in the energy storage sector. Overall, supercapacitors are positioned to play a crucial role in the evolution of energy storage technology, driving progress towards more efficient and sustainable energy solutions.

REFERENCES

[1] J. Sun, C. Xu, and H. Chen, "A review on the synthesis of $CuCo_2O_4$-based electrode materials and their applications in supercapacitors," *J. Materiomics*, vol. 7, no. 1, pp. 98-126, Jan. 2021, doi: https://doi.org/10.1016/j.jmat.2020.07.013.

[2] L. Sun, Y. Gong, D. Li, and C. Pan, "Biomass-derived porous carbon materials: Synthesis, designing, and applications for supercapacitors," *Green Chem.*, vol. 24, no. 10, pp. 3864-3894, May 2022, doi: https://doi.org/10.1039/D2GC00099G.

[3] S. Huang, X. Zhu, S. Sarkar, and Y. Zhao, "Challenges and opportunities for supercapacitors," *APL Materials*, vol. 7, no. 10, Oct. 2019. Accessed: Oct. 17, 2024. [Online]. Available: https://pubs.aip.org/aip/apm/article/7/10/100901/149102

[4] Z. Li, J. Lin, B. Li, C. Yu, H. Wang, and Q. Li, "Construction of heteroatom-doped and three-dimensional graphene materials for the applications in supercapacitors: A review," *J. Energy Storage*, vol. 44, p. 103437, Dec. 2021, doi: https://doi.org/10.1016/j.est.2021.103437.

[5] Z. Pang *et al.*, "Molten salt synthesis of porous carbon and its application in supercapacitors: A review," *J. Energy Chem.*, vol. 61, pp. 622-640, Oct. 2021, doi: https://doi.org/10.1016/j.jechem.2021.02.020.

[6] X. Chen, M. Cheng, D. Chen, and R. Wang, "Shape-controlled synthesis of Co_2P nanostructures and their application in supercapacitors," *ACS Applied Materials & Interfaces*, vol. 8, no. 6, Jan. 2016. Accessed: Oct. 17, 2024. [Online]. Available: https://pubs.acs.org/doi/abs/10.1021/acsami.5b10785

[7] J. Libich, J. Máca, J. Vondrák, O. Čech, and M. Sedlaříková, "Supercapacitors: Properties and applications," *J. Energy Storage*, vol. 17, pp. 224-227, Jun. 2018, doi: https://doi.org/10.1016/j.est.2018.03.012.

[8] X. Cao, Z. Yin, and H. Zhang, "Three-dimensional graphene materials: preparation, structures and application in supercapacitors," *Energy Environ. Sci.*, vol. 7, no. 6, pp. 1850-1865, 2014, doi: https://doi.org/10.1039/C4EE00050A.

[9] T. Zhu, B. Xia, L. Zhou, and X. W. (David) Lou, "Arrays of ultrafine CuS nanoneedles supported on a CNT backbone for application in supercapacitors," *J. Mater. Chem.*, vol. 22, no. 16, pp. 7851-7855, Mar. 2012, doi: https://doi.org/10.1039/C2JM30437F.

[10] H.-B. Zhao *et al.*, "Biomass-based mechanically strong and electrically conductive polymer aerogels and their application for supercapacitors," *ACS Appl. Mater. Interfaces*, vol. 8, no. 15, pp. 9917-9924, Apr. 2016, doi: https://doi.org/10.1021/acsami.6b00510.

[11] H. Li, Y. Gao, Y. Shao, Y. Su, and X. Wang, "Vapor-phase atomic layer deposition of Co_9S_8 and its application for supercapacitors," *Nano Lett.*, vol. 15, no. 10, pp.

6689-6695, Oct. 2015, doi: https://doi.org/10.1021/acs.nanolett.5b02508.

[12] S. Liu, L. Wei, and H. Wang, "Review on the reliability of supercapacitors in energy storage applications," *Appl. Energy*, vol. 278, p. 115436, Nov. 2020, doi: https://doi.org/10.1016/j.apenergy.2020.115436.

[13] M. Conte, "Supercapacitors technical requirements for new applications," *Fuel Cells*, vol. 10, no. 5, pp. 806-818, 2010, doi: https://doi.org/10.1002/fuce.201000087.

[14] Y.-T. Wang, A.-H. Lu, H.-L. Zhang, and W.-C. Li, "Synthesis of nanostructured mesoporous manganese oxides with three-dimensional frameworks and their application in supercapacitors," *J. Phys. Chem. C*, vol. 115, no. 13, pp. 5413-5421, Apr. 2011, doi: https://doi.org/10.1021/jp110938x.

[15] A. G. Olabi, Q. Abbas, A. Al Makky, and M. A. Abdelkareem, "Supercapacitors as next-generation energy storage devices: Properties and applications," *Energy*, vol. 248, p. 123617, Jun. 2022, doi: https://doi.org/10.1016/j.energy.2022.123617.

[16] Muhd. Wasim, F. Shi, J. Liu, Muhd. Rafique Khan, A. Farooq, N. Sanbha, M. Alfred, L. Xin, C. Yajun, and X. Zhao, "Extraction of cellulose to progress in cellulosic nanocomposites for their potential applications in supercapacitors and energy storage devices," *Journal of Materials Science,* vol. 56, pp. 14448-14486, 2021. Accessed: Oct. 17, 2024. [Online]. Available: https://link.springer.com/article/10.1007/s10853-021-06215-3

[17] X. Xu *et al.*, "MXenes with applications in supercapacitors and secondary batteries: A comprehensive review," *Mater. Rep. Energy*, vol. 2, no. 1, p. 100080, Feb. 2022, doi: https://doi.org/10.1016/j.matre.2022.100080.

[18] Y. Q. Wu, X. Y. Chen, P. T. Ji, and Q. Q. Zhou, "Sol-gel approach for controllable synthesis and electrochemical properties of $NiCo_2O_4$ crystals as electrode materials for application in supercapacitors," *Electrochimica Acta*, vol. 56, no. 22, pp. 7517-7522, Sep. 2011, doi: https://doi.org/10.1016/j.electacta.2011.06.101.

[19] H. Shanavaz *et al.*, "Covalent organic frameworks as promising materials: Review on synthetic strategies, topology and application towards supercapacitors," *J. Energy Storage*, vol. 71, p. 108006, Nov. 2023, doi: https://doi.org/10.1016/j.est.2023.108006.

[20] J.-C. Xing, Y.-L. Zhu, Q.-W. Zhou, X.-D. Zheng, and Q.-J. Jiao, "Fabrication and shape evolution of CoS_2 octahedrons for application in supercapacitors," *Electrochimica Acta*, vol. 136, pp. 550-556, Aug. 2014, doi: https://doi.org/10.1016/j.electacta.2014.05.118.

[21] X. Lu *et al.*, "Mechanistic investigation of the graphene functionalization using *p*-phenylenediamine and its application for supercapacitors," *Nano Energy*, vol. 17, pp. 160-170, Oct. 2015, doi: https://doi.org/10.1016/j.nanoen.2015.08.011.

[22] F. Ebrahimi, *Nanocomposites: New Trends and Developments*. BoD – Books on Demand, 2012.

[23] J. Gao, X. Wang, Y. Zhang, J. Liu, Q. Lu, and M. Liu, "Boron-doped ordered mesoporous carbons for the application of supercapacitors," *Electrochimica Acta*, vol. 207, pp. 266-274, Jul. 2016, doi: https://doi.org/10.1016/j.electacta.2016.05.013.

[24] W. Ouyang, J. Sun, J. Memon, C. Wang, J. Geng, and Y. Huang, "Scalable preparation of three-dimensional porous structures of reduced graphene oxide/cellulose composites and their application in supercapacitors," *Carbon*, vol. 62, pp. 501-509, Oct. 2013, doi: https://doi.org/10.1016/j.carbon.2013.06.049.

[25] C. Liu, A. J. Bard, F. Wudl, I. Weitz, and J. R. Heath, "Electrochemical characterization of films of single-walled carbon nanotubes and their possible application in supercapacitors," *Electrochem. Solid-State Lett.*, vol. 2, no. 11, p. 577, Sep. 1999, doi: https://doi.org/10.1149/1.1390910.

[26] H. Wan *et al.*, "Hydrothermal synthesis of cobalt sulfide nanotubes: The size control and its application in supercapacitors," *J. Power Sources*, vol. 243, pp. 396-402, Dec. 2013, doi: https://doi.org/10.1016/j.jpowsour.2013.06.027.

[27] J. Li, X. Wang, Q. Huang, S. Gamboa, and P. J. Sebastian, "Studies on preparation and performances of carbon aerogel electrodes for the application of supercapacitor," *J. Power Sources*, vol. 158, no. 1, pp. 784-788, Jul. 2006, doi: https://doi.org/10.1016/j.jpowsour.2005.09.045.

[28] S. Venkateshalu, and A. N. Grace, "MXenes—A new class of 2D layered materials: Synthesis, properties, applications as supercapacitor electrode and beyond," *Appl. Mater. Today*, vol. 18, p. 100509, Mar. 2020, doi: https://doi.org/10.1016/j.apmt.2019.100509.

[29] J. Hwang, R. Yan, M. Oschatz, and B. V. K. J. Schmidt, "Solvent mediated morphology control of zinc MOFs as carbon templates for application in supercapacitors," *J. Mater. Chem. A*, vol. 6, no. 46, pp. 23521-23530, 2018, doi: https://doi.org/10.1039/C8TA07700B.

[30] P. A. Lu *et al.*, "Synthesis, analysis and characterization of alpha-Fe_2O_3 nanoparticles and their applications in supercapacitors," *J. Mater. Sci. Mater. Electron.*, vol. 34, no. 9, p. 826, Mar. 2023, doi: https://doi.org/10.1007/s10854-023-10246-8.

[31] Y. B. Pottathara, H. R. Tiyyagura, Z. Ahmad, and K. K. Sadasivuni, “Graphene-based aerogels: Fundamentals and applications as supercapacitors,” *J. Energy Storage*, vol. 30, p. 101549, Aug. 2020, doi: https://doi.org/10.1016/j.est.2020.101549.

[32] M. Vangari, T. Pryor, and L. Jiang, “Supercapacitors: Review of materials and fabrication methods,” *J. Energy Eng.*, vol. 139, no. 2, pp. 72-79, Jun. 2013, doi: https://doi.org/10.1061/(ASCE)EY.1943-7897.0000102.

[33] G. Wang, Z. Lu, Y. Li, L. Li, H. Ji, A. Ferreira, D. Zhou, D. Wang, S. Zhang, and I. M. Reaney, “Electroceramics for high-energy-density capacitors: Current status and future perspectives,” *Chemical Reviews*, vol. 121, no. 10, pp. 6124-6172, 2021.

[34] W. Li, Z. Yao, H. Hao, M. Cao, and H. Liu, “High-permittivity and bias-voltage-insensitive (Ba,Sr,Ca) TiO_3•0.03(Bi_2O_3•3TiO_2) ceramics with Y5U specification,” *Crystals*, vol. 13, no. 12, p. 1627, 2023.

[35] K. Laadjal, and A. J. M. Cardoso, “Multilayer ceramic capacitors: An overview of failure mechanisms, perspectives, and challenges,” *Electronics*, vol. 12, no. 6, p. 1297, 2023.

[36] N. Marati, R. G. Gupta, and B. Vaithilingam, “Multilayer ceramic capacitors crisis management in the automotive industry,” in *Proc. 2020 IEEE Int. Conf. Power Electronics, Smart Grid Renewable Energy (PESGRE2020),* Jan. 2020, pp. 1-6.

[37] J. Zhang, “The market trend analysis of the MLCC industry,” *Highlights in Business, Economics and Management*, vol. 30, pp. 334-343, 2024.

[38] Y. Guo, S. Wang, X. Du, Z. Liang, R. Wang, Z. Li, S. Huang, and Y. Xie, “High-performance MIM-type aluminium electrolytic capacitors with durable waterproof and wide temperature window,” *Energy Storage Materials*, vol. 71, p. 103685, 2024.

[39] S. Jeong, A. B. Kareem, S. Song, and J.-W. Hur, “ANN-based reliability enhancement of SMPS aluminium electrolytic capacitors in cold environments,” *Energies*, vol. 16, no. 16, p. 6096, 2023, doi: https://doi.org/10.3390/en16166096.

[40] M. Agrawal, R. Singh, M. Ranitović, Z. Kamberovic, C. Ekberg, and K. K. Singh, “Global market trends of tantalum and recycling methods from waste tantalum capacitors: A review,” *Sustainable Materials and Technologies*, vol. 29, p. e00323, 2021.

[41] B. Swain, J. Lee, B. W. Gu, C.-G. Lee, and J.-H. Yoon, “Sustainable valorization of semiconductor industry tantalum scrap using non-hazardous HF substitute lixiviant,” *Waste Management*, vol. 144, pp. 294-302, 2022, doi: https://doi.org/10.1016/j.wasman.2022.04.005.

[42] J. Torki, C. Joubert, and A. Sari, “Electrolytic capacitor: Properties and operation,” *Journal of Energy Storage*, vol. 58, p. 106330, 2023.

[43] A. Fazakas, M. Purcar, and D. Turcu, “Polarity determination of electrolytic capacitors in power supplies from external terminals,” in *Proc. 2019 IEEE 25th International Symposium for Design and Technology in Electronic Packaging (SIITME)*, 2019, pp. 395-398, doi: https://doi.org/10.1109/SIITME47687.2019.8990836.

[44] H. Liu, B. Du, M. Xiao, K. Chen, and Y. Ma, “Effects of electrothermal ageing on dielectric performance of metallised biaxial orientation polypropylene film capacitors in strong magnetic fields,” *High Voltage*, 2024.

[45] C. Yi, B. Zhang, C. Li, Q. Li, J. Hu, and J. He, “Calculation of current distribution inside the metallized film capacitor element at high frequency,” *IEEE Trans. Dielectr. Electr. Insul.*, 2024.

[46] O. G. Gnonhoue, A. Velazquez-Salazar, É. David, and I. Preda, “Review of technologies and materials used in high-voltage film capacitors,” *Polymers*, vol. 13, no. 5, p. 766, 2021.

[47] S. Mönch, S. Binder, S. Drießen, B. Engel, and M. Graf, “A 99.74% efficient capacitor-charging converter using partial power processing for electrocalorics,” *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 11, no. 4, pp. 4491-4507, Aug. 2023, doi: https://doi.org/10.1109/JESTPE.2023.3270375.

[48] K. Kuang, X. Guo, C. Li, X. Li, X. Xi, and H. Fang, “A novel multiscale perspective based hotspot temperature assessment method for film capacitor in DC-link applications,” *IEEE Trans. Ind. Appl.*, 2024.

[49] Z. Pan *et al.,* “Substantially improved energy storage capability of ferroelectric thin films for application in high-temperature capacitors,” *J. Mater. Chem. A*, vol. 9, no. 14, pp. 9281-9290, 2021.

[50] D. Q. Tan, and X. Wu, “A case study of high-temperature polyetherimide film capacitor fabrication,” *Mater. Today Energy*, vol. 30, 2022, Art. no. 101167, doi: https://doi.org/10.1016/j.mtener.2022.101167.

[51] J. Zhang, M. Gu, and X. Chen, “Supercapacitors for renewable energy applications: A review,” *Micro Nano Eng.*, vol. 21, 2023, Art. no. 100229, doi: https://doi.org/10.1016/j.mne.2023.100229.

[52] A. Pena-Quintal, U. Mustafa, C. Gerada, and M. R. Ahmed, “On accelerated degradation of DC-link film capacitors and data-based lifetime estimation,” *IEEE Access*, 2024.

[53] F. Ahmad *et al.,* “Advances in graphene-based electrode materials for high-performance supercapacitors: A review,” *J. Energy Storage*, vol. 72, p. 108731, 2023.

[54] S. Kumar, G. Saeed, L. Zhu, K. N. Hui, N. H. Kim, and J. H. Lee, “0D to 3D carbon-based networks combined with pseudocapacitive electrode material for high energy density supercapacitor: A review,” *Chem. Eng. J.*, vol. 403, p. 126352, 2021.

[55] M. Pathak *et al.,* “High energy density supercapacitors: An overview of efficient electrode materials, electrolytes, design, and fabrication,” *The Chem. Record*, vol. 24, no. 1, p. e202300236, 2024.

[56] K. Singh, Y. Trabelsi, P. Mahajan, and V. Khanna, “Role of graphene in next-generation electrochemical energy storage systems: Insights and innovations,” *J. Electrochem. Soc.*, vol. 171, no. 10, p. 100501, 2024.

[57] F. Jiang *et al.,* “A comprehensive review of energy storage technology development and application for pure electric vehicles,” *J. Energy Storage*, vol. 86, p. 111159, 2024.

[58] S. Peng, X. Du, Z. Liang, M. Ma, Y. Guo, and L. Xiong, “Multilayer polymer nanocomposites based on interface engineering for high-performance capacitors,” *J. Energy Storage*, vol. 60, p. 106636, 2023.

[59] X. Fan *et al.,* “Engineering hierarchical interfaces in high-temperature polymer dielectrics for electrostatic supercapacitors,” *Mater. Horiz.*, 2024.

[60] Y. Liang, W. Sun, T. Li, Y. Chen, Y. Cheng, and L. Zhang, “All organic polymer dielectrics for high-temperature energy storage from the classification of heat-resistant insulation grades,” *J. Polym. Sci.*, vol. 61, no. 22, pp. 2777-2795, 2023.

[61] M. Qorbani, K. H. Chen, and L. C. Chen, “Hybrid and asymmetric supercapacitors: Achieving balanced stored charge across electrode materials,” *Small*, p. 2400558, 2024.

[62] S. Rudra, H. W. Seo, S. Sarker, and D. M. Kim, “Supercapatteries as hybrid electrochemical energy storage devices: Current status and future prospects,” *Molecules*, vol. 29, no. 1, p. 243, 2024.

[63] G. Sikha, and B. N. Popov, “Performance optimization of a battery–capacitor hybrid system,” *J. Power Sources*, vol. 134, no. 1, pp. 130-138, 2004.

[64] A. M. Adeyinka, O. C. Esan, A. O. Ijaola, and P. K. Farayibi, “Advancements in hybrid energy storage systems for enhancing renewable energy-to-grid integration,” *Sustain. Energy Res.*, vol. 11, no. 1, p. 26, 2024.

[65] J. A. Watson *et al.,* “High-temperature glass capacitors for aerospace applications,” *IEEE Aerospace and Electronic Systems Magazine*, vol. 38, no. 4, pp. 40-47, 2023.

[66] M. L. Sanders, and B. L. Wong, “Thermally stable capacitors: Advances in glass dielectric technology,” *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 13, no. 3, pp. 405-412, 2022.

[67] H. Zhang, and D. Li, “Low dielectric loss capacitors: performance optimization using glass dielectrics,” *IEEE Access*, vol. 11, pp. 29345-29354, 2023.

[68] A. Patel, and J. R. Kumar, “High-voltage capacitors with glass dielectrics for energy storage,” *IEEE Transactions on Power Electronics*, vol. 39, no. 5, pp. 5540-5551, 2024.

[69] S. T. Ray *et al.,* “Environmental durability of glass capacitors in harsh conditions,” *IEEE Transactions on Reliability,* vol. 72, no. 1, pp. 22-30, 2023.