

A Review of Supercapacitor Design, Applications, and Electrode Material Parameters

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Abstract - Excessive usage of non-renewable fossil fuel resources such as oil and coal has resulted in a significant issue in contemporary society's ability to grow sustainably. As a result, the most viable solutions for tackling the aforementioned difficulties are the creation and highly efficient usage of green and renewable resources. Because of its vast availability, sustainability, renewable nature, distinctive structure, and low cost, biomass has been used for many purposes, such as energy storage, solar cells, and water treatment. These biomass-based electrode materials are particularly ideal for fast ion transport during electrochemical charge-discharge applications due to their carbon element richness. In the realm of energy storage and conversion, the use of diverse biomass resources as carbon sources for the fabrication of self-doped porous carbon electrodes has recently become a hot issue. Because of their diverse uses in fixed energy storage systems, electric cars, and portable gadgets, supercapacitors are regarded as one of the possible alternatives among energy-storage systems. Supercapacitors offer three primary benefits over other energy storage devices such as batteries and traditional capacitors: a high specific power of roughly 10 kW kg^{-1} , rapid charge/discharge cycles in seconds, and a long cycle life of $> 10^5$. In this study, we propose ways of improving the electrochemical performance of supercapacitors using carbon materials and nanostructured transition metal oxides or phosphides. The electrode materials have been designed, synthesized, and tested for performance. Furthermore, the morphology and structure of our materials were researched using XRD, SEM, TEM, XPS, BET, and other techniques, yielding positive results, and the electrochemical characteristics of our materials were evaluated as electrode materials for supercapacitors. The research aims at exploring the structure design, growth process, and performance enhancement of carbon materials-based composites as electrode materials, specifically giving a theoretical support and practical framework for the development of supercapacitor electrodes. In this research we will study a brief review and background study of recent literature and reports that investigate in detail the types, parameters, and applications of supercapacitors as well as the types of electrode materials used in

supercapacitors, such as carbon materials derived from biomass, transition metal oxides, and conducting polymers.

Keywords: supercapacitors; nanostructure; composite; electrochemical performance; energy storage.

I. INTRODUCTION

Supercapacitors (SCs) are a distinct type of energy storage system that may bridge the gap between high energy density batteries and regular capacitors with high power density [1-5]. Supercapacitors have emerged as among the most efficient energy conversion and storage systems in renewable and sustainable energy storage devices [6-9] because of their high power density, rapid charge and discharge capabilities, improved capacitance, and prolonged cycle stability. Supercapacitors are electrochemical energy storage devices that come in a variety of configurations based on charge transfer and storage processes [10]. Different sorts of materials are employed to create various components for the gadgets [11]. Various methodologies are used to investigate the materials' unique features. When used in conjunction with end-technology power management systems, the gadget is quite useful [12]. Supercapacitors, also known as ultra-capacitors or double-layer capacitors, are capacitors that span the range between capacitors and batteries [13]. Supercapacitors have better cycle stability than batteries because there are fewer chemical phase shifts in electrodes during continuous charge / discharge operations [14-16]. Supercapacitors are often utilized for energy harvesting and short-term delivery of high-pulse power. Electronic gadgets such as mobile phones [17], wearable devices [18], health monitors [19], detectors [20], LED screens [21], bar code scanners [22], and global positioning system (GPS) chips employ these capacitors [23]. The electrode materials could be used in a variety of applications, including spacecraft, military weaponry [24], telecommunications [25], and hybrid cars [26], depending on the degree and extent of charge storage. Supercapacitors have a greater power density and energy density than batteries and regular capacitors [27-29]. They feature good rate capability, high cycle stability, great power density, and quick charging. Supercapacitors are even being utilized to replace batteries or to integrate with batteries in

hybrid systems. Supercapacitors are classified according to their charge storage techniques and components [30]. On the application of potential, opposing charges are collected or adsorbed/desorbed mostly on the surface of the electrode during supercapacitor charging and discharging. An electric double-layer structure is another name for this [31]. Reversible redox processes occur at the electrode-electrolyte interfaces in a pseudocapacitor, resulting in pseudocapacitance formation [32]. Furthermore, the features of energy storage devices allow them to be employed in a variety of applications. A constant supply of fuel is required in a fuel cell, which is not required by a battery, capacitor, or supercapacitor. As the other three devices are used up, they will need to be recharged. When compared to capacitors and other devices,

supercapacitors have a high power density and a medium energy density [33]. Because of the electric double layer and pseudocapacitance, they have an extremely high capacitance. Because no chemical changes occur throughout the charging and discharging processes, the cycle life of a supercapacitor is quite long. A distinction between the various major types of energy storage systems is listed in Table 1. When comparing the performance of different energy storage devices, Ragone plots are frequently utilized. The x-axis depicts energy density (Wh kg^{-1}) and the y-axis represents power density (W kg^{-1}). The energy density of capacitors is the lowest, while their power density is the highest. Fuel cells offer greater energy density, but their charge storage method is complicated.

Table 1: Performance Comparison between Traditional capacitor, Supercapacitor and Batteries

Participate Number	Traditional capacitors	Supercapacitors	Batteries
Rate charging time	$10^{-6}\sim 10^{-3}$ s	10~120 s	0.5~3h
Rate discharge time	$10^{-6}\sim 10^{-3}$ s	10~120 s	1~5h
Energy density (Wh kg^{-1})	<0.1	5~15	50~150
Power density (W kg^{-1})	>10000	1000~8000	50~300
Charge and discharge efficiency (%)	>90	90~98	70~85
Cycle life (times)	> 10^6	> 10^5	200~1000
Temperature ($^{\circ}\text{C}$)	-70~70	-40~70	-20~50

The energy density of batteries is great, while their power density is low. In terms of performance, supercapacitors are a hybrid between batteries and capacitors. The Ragone plot compares the performance characteristics of several supercapacitor kinds (Figure 1).

II. TYPES OF SUPERCAPACITORS

The energy storage technique, electrode material, electrolyte, and cell design are all factors that may be used to classify supercapacitors [35-37]. Faradic pseudocapacitors and electric double-layer capacitors (EDLCs) are the two primary forms of supercapacitors. The pure electrostatic charge collected at the electrode/electrolyte contact causes the capacitance of EDLC [38, 39]. It is highly dependent on the electrode materials' surface area that is exposed to the electrolyte ions. The thickness of the double layer varies depending on the electrolyte ion size and concentration, although it is typically in the range of 5–10 for concentrated electrolytes [40]. For quite a smooth electrode containing concentrated electrolyte solution, the double-layer capacitance is expected to be around $10\text{--}20 \text{ F/cm}^2$ [41]. There in the electrochemical double layer, the associated electric field is extremely large, reaching up to 10^6 V/cm [42]. EDLCs are built similarly to batteries, with two electrodes submerged in an electrolyte and an ion permeable separator positioned between them (Figure 2) [43]. Each electrode/electrolyte contact in such a device acts as a capacitor. Therefore, the

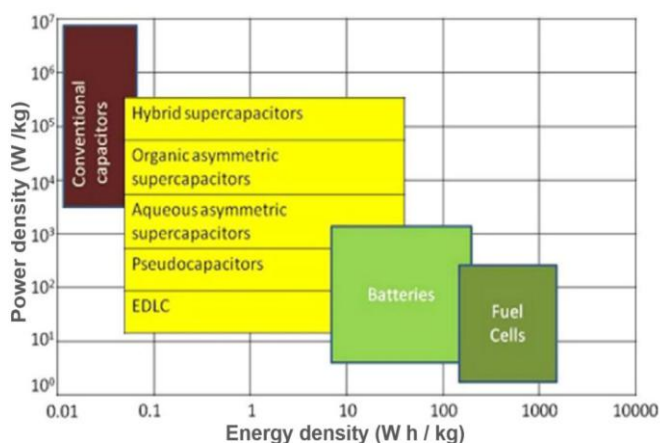


Figure 1: Ragone plot of some electrochemical energy storage devices and supercapacitors [34]

entire cell may be thought of as two capacitors in series. The cell capacitance (C_{cell}) for just a symmetric capacitor will be: [44]

$$1/C_{cell} = 1/C_1 + 1/C_2 \quad (1)$$

Where C_1 and C_2 are the first and second electrode capacitances, respectively.

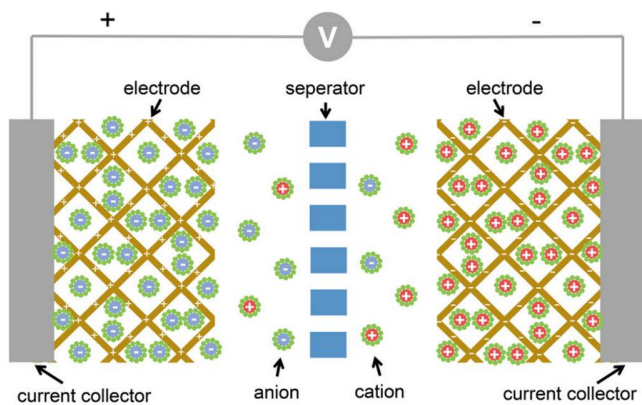


Figure 2: Schematic diagram of energy storage mechanism of EDLCs [45]

Carbon materials are the most commonly utilized in EDLCs because of their low electrical resistance, ease of production, chemical stability, and low cost [46]. Activated carbon, carbide-derived carbon/ordered microporous carbon, nanomaterials, and graphene are examples of common materials [47]. The other is pseudocapacitance, which would be caused by the electrode material's redox interaction with the electrolyte. The transport of electrons produced by oxidation and reduction across the electrolyte/electrode contact [48] is a faradic process that accumulates electrons at the electrode. Metal oxide's theoretical pseudocapacitance may be determined as follows: [49]

$$C = (n \times F) / (M \times V) \quad (2)$$

Where n is the average number of electrons transported in the redox process, F indicates the Faraday constant, M represents the metal oxide's molar mass, and V denotes the working voltage window [50]. Metal oxides and conducting polymers are common materials for pseudocapacitors, because of the various oxidation states of the electroactive substance, redox reactions occur [51]. Reactions frequently do not spread into the bulk material and take place solely at the electrode/electrolyte contact [52]. Conducting polymers including polyaniline, polythiophene, and polypyrrole [53], as well as metal oxides like MnO_2 , Co_3O_4 , and RuO_2 , are common pseudocapacitive materials [54]. Three types of electrode materials are commonly employed in supercapacitor applications: metal oxides, carbon-based compounds, and conductive polymers. All of these materials have various chemical, electrical, and structural characteristics that impact

the supercapacitor's final performance and lifetime. Figure 3 depicts the capacitance of electrodes made of metal oxides, conducting polymers, carbon, and composite materials. Conducting polymers and metal oxides have a larger specific capacitance than carbon-based electrode materials due to the Faradaic charge storage mechanism. Based on the composition of electrode materials, supercapacitor devices are classified as asymmetric, symmetric, or battery supercapacitor hybrid devices [55]. Supercapacitors with the same electrode material are known as symmetric supercapacitors. In an asymmetric supercapacitor, two distinct kinds of electrode material are integrated into a single device assembly. Asymmetric hybrid supercapacitors outperform symmetric supercapacitors in terms of electrochemical performance. Asymmetric construction has two major advantages over symmetric construction: higher capacitance and a wider voltage window. Carbon-based supercapacitors now dominate the industry due to their technical maturity.

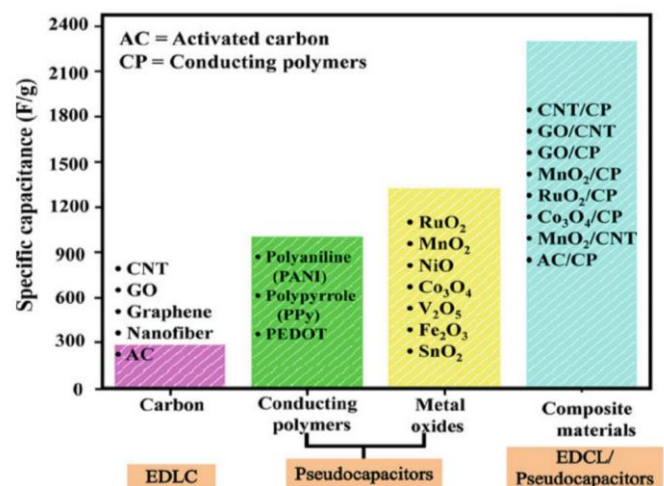


Figure 3: Specific capacitance of electrode materials for different supercapacitors [56]

III. SUPERCAPACITORS PARAMETERS

The specific capacitance (standardized by electrode volume, mass, or area), energy density, power density, cycle stability, and rate capability are the major parameters of supercapacitors [57]. A supercapacitor's energy density (E) is calculated as follows: $E = 1/2CV^2$, where C represents direct current capacitance in Farad, and V indicates nominal voltage. To increase energy and power densities, increase the specific capacitance (C) and operating voltage range (V) of a supercapacitor while decreasing the corresponding series resistance [58]. The capacitance of a supercapacitor is substantially determined by the electrode material's properties, particularly the surface area and pore-size distribution [59]. Because electrode materials have a large porosity and hence a low density, it is often assumed that the volumetric capacitance of every electrode dictates the energy density. The

electrolyte's maximum operating voltage window (V_m) is primarily determined by the electrochemical window of the electrolyte [60]. Aqueous electrolytes offer high ionic conductivity, are inexpensive, and are widely accepted. On the other hand, they get the drawback of having a limited voltage range and a low decomposing voltage of 1.233 V [61]. Different kinds of non-aqueous electrolytes have been created, with a cell voltage of up to 3.5 V [62]. On the other hand, the non-aqueous electrolytes have an electrical resistivity that is significantly greater than aqueous electrolytes, resulting in capacitors with higher internal resistance. A supercapacitor's power capabilities and applicability are limited by its high internal resistance [63]. The internal resistance of supercapacitors is caused by a lot of different things. This internal resistance is called equivalent series resistance (ESR).

IV. APPLICATIONS OF SUPERCAPACITORS

Supercapacitors are used in a variety of applications, from simple electrical devices like LEDs to military and medical technologies [64-66]. Because of their remarkable characteristics, supercapacitors are widely used in a variety of applications, including energy, transportation, electronics, aircraft, industry, medicine, and others [67]. Many industries are expected to grow, according to industry analysts. Supercapacitors' ever-improving performance leads to a steady increase in their applications. The energy storage industry has been dominated by rechargeable batteries over the past decade [68]. Demand for improved energy storage for a variety of applications, ranging from electronic portability to hybrid electric cars, is constantly rising. Performance optimization and cost reduction are critical in the energy storage business. Day-to-day applications involve goods that are simple to use. The freestyle (cordless) screwdriver is powered solely by supercapacitors made by Coleman Company Inc., and it lasts less time than one powered by a rechargeable battery. The disadvantage is that the runtime is half that of the battery model, despite the advantage of 90-second charging and charge retention [69]. As demonstrated in Figure 4, the schematic diagram of the hybrid energy storage vehicle propulsion system, According to Cameron, if the charging cycle is interrupted, there is little risk of damage to the components. In addition, in conjunction with Celadon, Maxwell Technologies has created items such as remote controls that use supercapacitors. The remote control was originally powered by two batteries, but supercapacitor functioning enabled rapid charging. According to Cresce et al. [70], the lifespan of a supercapacitor exceeds the lifetime of a remote capacitor. Supercapacitors are utilized in digital cameras to generate flashes. The portable speakers designed by Sam Beck with an embedded supercapacitor assembly are the most recent innovation [71]. Supercapacitors have previously been primarily employed for memory backup and

actuators. They are used in renewable and sustainable energy sources as stabilizers in power line systems based on wind and photovoltaics. Due to the supercapacitor's quick responsiveness to unpredictable weather fluctuations, hybrid supercapacitors provide brief energy bursts to wind turbines. The existence of hybrid supercapacitors with the ability to adjust blade position and safeguard a wind turbine in heavy winds addresses power cut scenarios. The large number of cycles, energy compliance with power density, and lack of maintenance work are further advantages of hybrid supercapacitors [72]. In 2004, the first supercapacitor bus was constructed. The world's first supercapacitor bus with a fast-charging station has been created in Shanghai's high-tech Park. In addition, in 2006, Shanghai's 11th became the world's first commercial supercapacitor bus line [73]. When a limited period of power supply is required in a security application, hybrid supercapacitors are employed. The hybrid supercapacitor has a similar purpose in security systems as the uninterrupted power supply (UPS) in computers. Hybrid supercapacitor energy devices are used in the Thames cable cars to help with lights and air-con. The entire assembly is charged fast, resulting in a 5 minute riding time [74]. In 2010, three Japanese businesses, Nippon-Chemi-Con, collaborated to produce eco-friendly street lighting in Japan using solar energy and supercapacitors as energy storage units. The assembly included LED lamps and solar boards to store solar energy during the day in supercapacitors (charging), while hybrid supercapacitors discharging escorts light up the LEDs at night. As a result, delivering a clean energy system that is more durable and long-lasting than conventional energy systems is challenging [75]. In the year 2019, the US created a new form of rechargeable supercapacitor. Different supercapacitor advancements and commercialization are taking place in practically all domains [76]. Supercapacitors can also be used in a range of biomedical applications, such as sweatbands for continuous monitoring and wireless contact lenses.

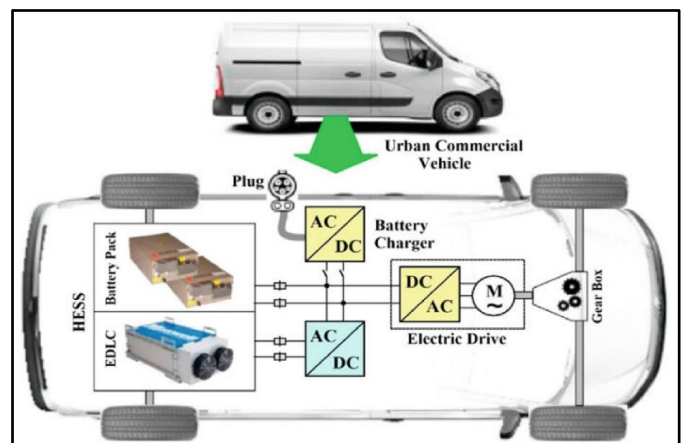


Figure 4: A supercapacitor is utilized in an urban commercial vehicle's hybrid energy storage system [77]

The market for supercapacitors in automotive applications is segmented into several characteristics, such as starting, stopping, electric assist, lighting, and hybrid driving. In the supercapacitor sector, hybrid buses and railways play a key role. It benefits from expanding consumer and operator demand, as well as increased vehicle supply at cheaper pricing. As demonstrated in Figure 5, the Tecate group has produced several supercapacitor devices for military purposes.



Figure 5: Supercapacitors manufactured by Tecate Group for various defensive applications [78]

V. ELECTRODES MATERIALS

An electrode is a solid electrical conductor that absorbs and then dissociates electrolyte ions. For high capacitance, the electrode material must have a wide surface area [79]. Two methods are used to store charges on the electrode material: electric double-layer generation and pseudocapacitive Faradaic reaction [80]. Some of the materials that can be used to manufacture electrodes used in supercapacitors, such as carbon materials derived from biomass, transition metal oxides, and conducting polymers.

VI. CONCLUSION

In conclusion, the scope of supercapacitors is expanding, and their applications are only limited by the users' imagination. Some applications require high specific power, such as GPS, phased array radar antennas, missiles, airbag exploit power, and avionics display instruments. The goal of this study is to professionally develop biomass-based carbon materials, transition metal oxides, and other related materials, and also electrodes for supercapacitors in the modern world. The advantages, problems, applications, and future prospects of supercapacitors are then discussed. As a result, we will present a comprehensive and detailed understanding of supercapacitor fundamentals, the latest development of supercapacitor electrode materials, and the design of innovative flexible devices in this research. This paper will be valuable to researchers and students in this field who want to understand more about the supercapacitor's recent

development and how to choose the right material for a high-performance supercapacitor.

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DECLARATIONS

Ethics, Consent to Participate, and Consent to publish declarations (Not applicable).

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