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A Study on Electrochemical Supercapacitors

Abstract

The reduction of fossil fuels and their destructive impacts on the environment has made researchers focus more on using clean and renewable energy sources. Various energy storage systems such as batteries, conventional capacitors, solar cells, and supercapacitors (SC) are being developed, and supercapacitors have received more attention in recent years. Based on energy storage mechanisms, electrochemical supercapacitors have a higher power density than batteries and solar cells. Also, they have a higher energy density than ordinary capacitors due to their unique energy storage mechanism. This paper focuses on electrochemical supercapacitors.

Keywords: *Energy Storage System, Electrochemical Capacitors, Electrode, Electrolyte.*

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Introduction

In recent years, one of the basic problems of our world is energy consumption and deterioration. A suitable storage source produces high energy in a short time and has high energy and power density. Among energy storage devices, electrochemical supercapacitors have a higher power density than batteries and solar cells and also have a higher energy density than ordinary capacitors due to their unique energy storage mechanism **[1].** Based on the energy storage mechanism, electrochemical supercapacitors are divided into two types: (i) Electrochemical Double-Layer Capacitors (EDLCs) (arising from the charge separation at electrode/electrolyte interfaces) and (ii) Pseudocapacitors, which store energy through reversible Faradaic reaction at the electrode surface.

Types of capacitors

Capacitors can be classified into three general categories:

(i) Electrostatic capacitors
(ii) Electrolytic capacitors
(iii) Electrochemical capacitors

Electrostatic capacitors

As shown in Fig. 1, these capacitors usually consist of two metal electrodes (parallel plates) separated by a dielectric. Dielectric is a non-conducting material that is placed between parallel plates. The operating voltage (V/m) of a capacitor depends on the strength of the dielectric material and is obtained from the following equation:

$$C = {}^{Q}/_{V} \qquad \textbf{1)(}$$

Dielectric strength is equal to the maximum electric field in the dielectric. For example, the air has a dielectric strength of about $3 \times 10^6\, {}^{V}/_{m}$. While the dielectric strength of paper is about $16 \times 10^6\, {}^{V}/_{\mathrm{m}}$. The dielectric increases the overall capacitance and operating voltage of the capacitor. Capacitance is measured in the Farads unit. It is defined as the total charge in coulombs on each electrode relative to the potential difference between the plates **[2].**

Electrolytic capacitors

The structure of an electrolytic capacitor is similar to an electrostatic capacitor, but it uses an active salt electrolyte in contact with metal electrodes. For example, aluminum electrolytic capacitors are made of two conducting aluminum electrodes (covered with an insulating oxide layer) and a paper impregnated with electrolyte **[3].** The oxide layer acts like a very thin dielectric, which leads to a high capacitance per unit volume compared to electrostatic capacitors.

Electrochemical capacitors

These capacitors also use an electrolyte solution but compared to electrostatic and electrolytic capacitors; it shows a higher capacity per unit volume due to the porous structure of their electrodes.

Advantages of supercapacitors over other energy storage systems

A unique energy storage mechanism exists in energy storage systems such as ordinary capacitors, solar cells, batteries, and supercapacitors. Their energy storage mechanism determines the charging and discharging behavior and their performance. In ordinary capacitors, electrostatic energy is stored as positive and negative charges on metal plates. In batteries, energy storage is done through chemical reactions between the electrode and the electrolyte **[4].** The storage process in solar cells is the result of the oxidation reaction. In supercapacitors, energy can be stored electrostatically by performing an oxidation-reduction reaction.

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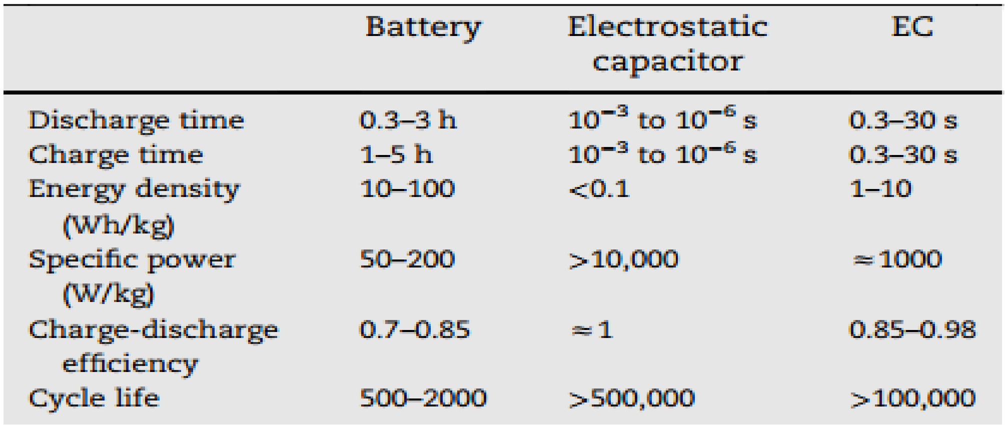
Table 1. A comparison of properties of batteries, electrostatic capacitors, and supercapacitors



	Battery	Electrostatic capacitor	EC
Discharge time	0.3–3 h	10^{-3} to 10^{-6} s	0.3–30 s
Charge time	1–5 h	10^{-3} to 10^{-6} s	0.3–30 s
Energy density (Wh/kg)	10–100	<0.1	1–10
Specific power (W/kg)	50–200	>10,000	≈1000
Charge-discharge efficiency	0.7–0.85	≈1	0.85–0.98
Cycle life	500–2000	>500,000	>100,000

The performance of an energy storage device is determined by two parameters: (i) Energy density, which is the amount of energy stored per unit of mass and is expressed as the following equation:

$$W = \frac{1}{2} C V^2 \qquad \textbf{(2)}$$

Where C is the specific capacitance and V is the voltage, and (ii) Power density, which is the amount of energy released per unit of mass and is expressed as the following equation:

$$P_{\max} = \frac{1}{4R_s} V_i^2 \qquad \textbf{(3)}$$

Where R_s is the Equivalent Resistance Series (ERS), and V_i is the primary voltage. Based on the energy and power density, the performance of the storage systems can be displayed based on the Ragone plot (Fig. 1). Batteries and solar cells can produce high energy density, although they have low power density. At the same time, ordinary capacitors have high power density and low energy. Due to the high surface area of electrodes in supercapacitors compared to ordinary capacitors, these capacitors have a higher energy density than ordinary capacitors. Supercapacitors have a higher power density than batteries and solar cells. Also, the change of chemical phase or composition in the electrodes of supercapacitors does not occur during the charging and discharging process. Thus, supercapacitors show high cycle stability and reversibility compared to batteries and solar cells. Also, supercapacitors are used in the temperature range between -30 and 60 ^{0}C, but batteries operate in a lower temperature range **[5].**

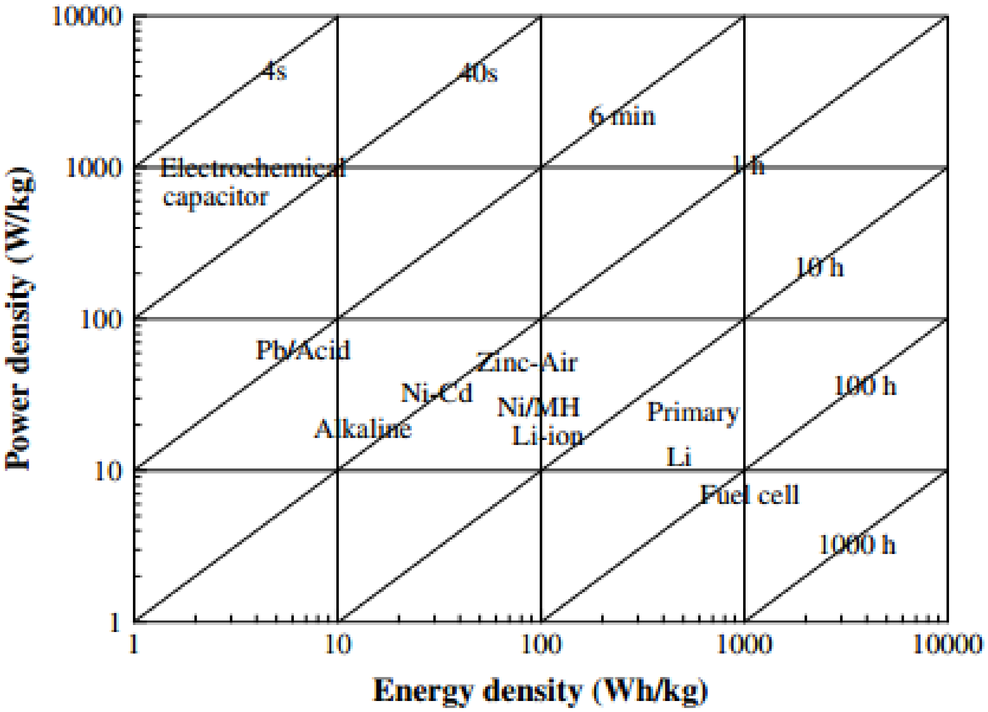


Fig. 1. A Ragone plot compares different energy storage systems **[6].**

A comparison of constant current discharge curves for batteries, ordinary capacitors, and supercapacitors is shown in Fig. 2. The voltage is constant for a period of time and therefore shows a horizontal region in the curve. A linear decrease in voltage with discharge time is observed in capacitors and supercapacitors. In general, ordinary capacitors show better charge and discharge behavior than supercapacitors. At constant current, there is a linear relationship between voltage and time for supercapacitors **[7].**

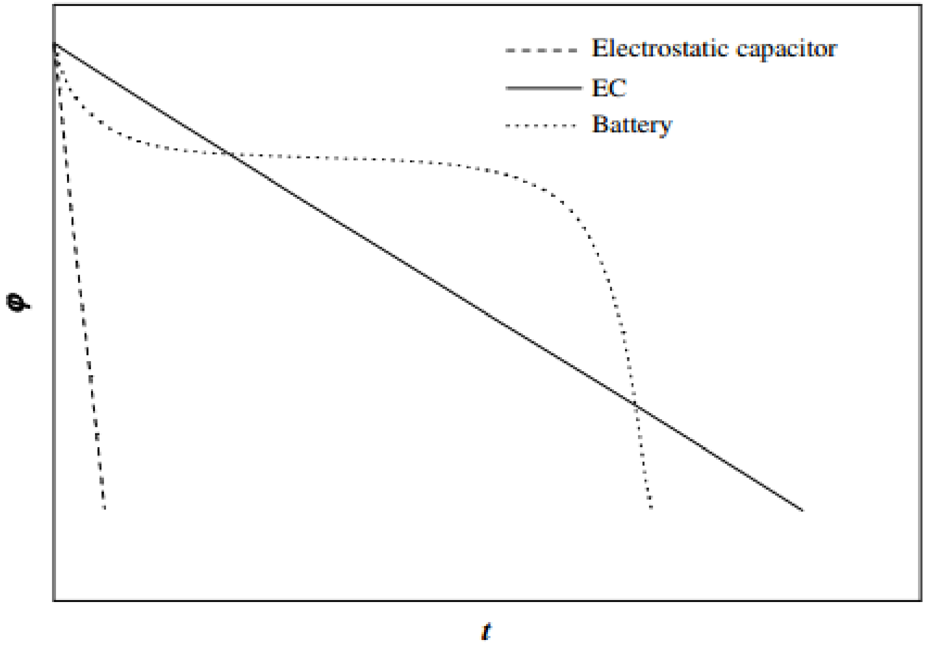


Fig. 2. Discharge behavior of batteries, electrostatic capacitors, and supercapacitors **[7]**.

The main factor limiting the use of supercapacitors in stores is their high cost, and another limitation is their low energy density.

Applications

The applications of supercapacitors are divided into three parts, including (i) energy discharge, (ii) main power sources, and (iii) alternating power sources. Supercapacitors are placed in parallel with a power source such as batteries to discharge energy. In case of a power outage, voltage drop, etc., supercapacitors can supply energy to the system. This advantage of supercapacitors is used for large stores, microcomputers, and clock systems. Due to the significant increase in energy density and power in recent research, supercapacitors can be used as energy sources in various applications such as industrial tools, transportation, and portable electronic devices. As an ideal energy source for electric vehicles, supercapacitors can produce high energy efficiency and power during energy loss due to braking **[8].** Although batteries and solar cells are also used as electric storage devices for electric vehicles, they are not capable of producing energy in a short period. Also, supercapacitors can be combined with batteries and solar cells for the above-mentioned applications **[9].**

Supercapacitors and energy storage mechanisms

Electrochemical capacitors (EDs) have been investigated as an attractive topic due to their applications in energy storage devices. They are often known as supercapacitors, electric double-layer capacitors (EDLCs), pseudocapacitors, strong capacitors, gold capacitors, and supercapacitors **[10].** The energy storage mechanism in these capacitors is based on forming an electric double-layer. Electrochemical double-layer capacitors are combined in single-cell assemblies (series or parallel) to produce high capacitance and suitable working voltage. Fig. 3 shows a model of the typical structure of a supercapacitor **[11]** **.**Depending on the charge storage mechanisms, supercapacitors are divided into three categories, including (i) electrochemical double-layer capacitors, (ii) faradic pseudocapacitors, and (iii) hybrid systems.

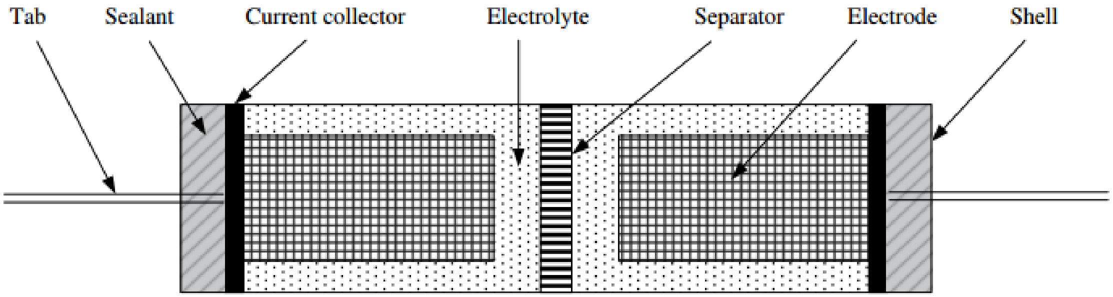


Fig. 3. A structural model of a supercapacitor **[12].**

Electrochemical double-layer capacitors

An electrochemical double-layer capacitor consists of two electrodes immersed in an electrolyte. A separator separates them. Electric charges are stored electrostatically at the electrode/electrolyte interface, which leads to the formation of an electrical double layer **[13].** The following equation calculates the capacitance of electrochemical double-layer capacitors:

$$C_{\mathrm{dl}} = \frac{\varepsilon_r \varepsilon_0 A}{d} \qquad \textbf{(4)}$$

Where ε_r is the dielectric constant in the electric double-layer, ε_0 is the vacuum permeability constant, A is the surface area of the electrode, and d is the thickness of the electric double-layer. The total capacitance can be calculated from the following equation:

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} \qquad \textbf{(5)}$$

In the above equation, C_1 and C_2 are the capacitor capacitance of the two electrodes. Here, the thickness of an electric double-layer is in the Angstrom range. It is somewhat less than the distance between the metal plates in ordinary capacitors, which is in the range of micrometers. When materials with a high surface area are selected as electrodes, the capacitance of the supercapacitors increases several times compared to ordinary capacitors. Also, this system does not have charge transfer at the interface in the energy storage process (non-faradic) and chemical change. Hence, high reversibility in the charge/discharge process along with long life is obtained for supercapacitors.

Pseudocapacitors

Energy storage in pseudocapacitors is based on performing rapid and reversible reactions on the electrode surface. Important processes responsible for pseudocapacitors are (i) Surface adsorption of ions from electrolytes, (ii) Redox reactions of electrolyte ions, and (iii) Doping and indoping of active Conducting Polymers (CP) in the electrode **[13].** The surface area of the electrode plays a vital role in cases (i) and (ii). While case (iii), which involves conducting polymers, is less dependent on the electrode surface and is a mass process. However, a high surface area with micro-pores increases the accessibility of ions to the electrode material. The capacitance of pseudocapacitors is expressed by the following equation:

$$C = \frac{Q_{tot}}{V_{tot}} \qquad \textbf{(6)}$$

Where, Q_{tot} is the total charge, and V_{tot} is the voltage change for an electrode charge or discharge. The capacitance of pseudocapacitors is 10-100 times higher than the carbon double-layer capacitor. A comparison of the capacitance of electrochemical double-layer capacitors and pseudocapacitors is shown in the table below **[7].**

Table 2. A comparison of the capacitance of electrochemical double-layer capacitors and pseudocapacitors **[7]**

Electrochemical double-layer capacitance	Pseudocapacitors capacitance	
non-faradic	Including faradic processes	1
20-50 μF/cm^2	2000 μF for single-mode processes and 200-500 μF for multi-mode processes	2
Capacitance is constant relative to potential (except at the point of zero charges).	The capacitance of RuO_2 is constant relative to potential and shows the maximum value for the single-mode process.	3
It shows mirror voltammograms.	It shows mirror voltammograms.	4

Types of electrodes used in supercapacitors

Based on the used electrodes, supercapacitors are divided into three categories: (i) High-surface area electrode, which is used in double-layer capacitors, (ii) Redox pseudocapacitors electrodes, and (iii) Composite electrodes. Fig. 4 shows the different electrodes used in each category.

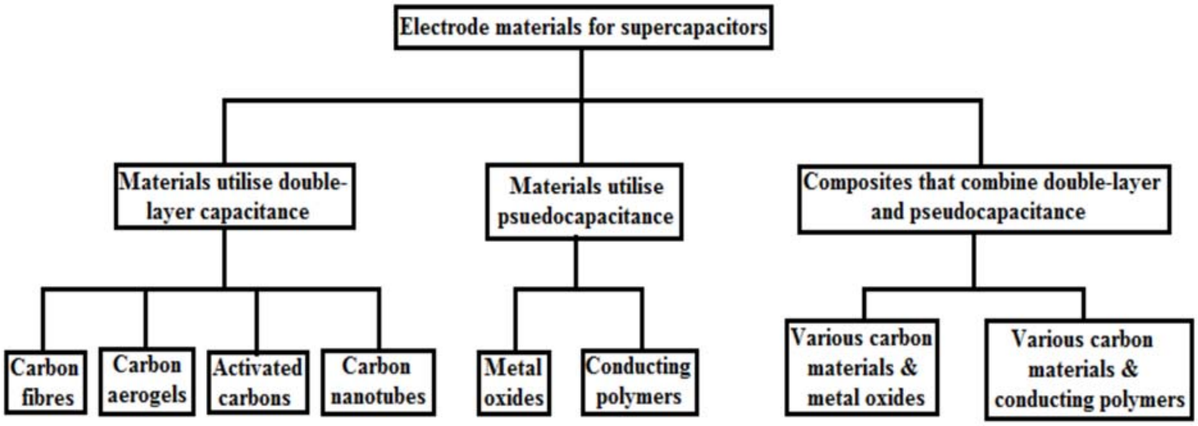


Fig. 4. Classification of supercapacitor electrode materials **[14]**.

High-surface area electrode material

Carbon materials in carbon blacks, carbon fibers, aerogels, activated carbons, and carbon nanotubes are used as high surface area electrodes in electrochemical capacitors. These compounds have suitable physical and chemical properties such as high conductivity, large surface area, high thermal stability, good heat resistance, easy processability, and compatibility in composite materials **[6].**

Carbon black

Carbon black is often used as a filling material for electrodes in batteries and supercapacitors. Carbon black is spherical with colloidal size. Carbon black is produced through the thermal decomposition of hydrocarbons in the gas phase. Carbon black has high conductivity, high pores, small particle size, and a chemically clean surface. The specific capacity of supercapacitors with these electrodes is about 250 F/g **[15].** Carbon black has low adhesive density. To increase the electrical resistance, a high binder concentration is needed to make stable electrodes.

Carbon fibers

Due to their high adsorption rate and capacity, activated carbon fibers are the preferred electrodes for supercapacitors. The manufacturing process and raw materials determine the quality of carbon fibers. Carbon fibers are produced from heat-resistant organic compounds such as cellulose, phenolic resins, and polyacrylonitrile. The diameter of carbon fibers is about 10 micrometers. The good accessibility of active sites is due to the many pores on the surface of the fiber. A high adsorption capacity and good adsorption rate have been observed in carbon fibers. Carbon fibers are woven into carbon clothes and used as electrodes **[16].**

Carbon aerogels

Carbon aerogels are produced through the thermal decomposition of organic aerogels, synthesis by the concentration of resoquinol and formaldehyde, followed by thermal decomposition **[17].** Carbon aerogels have good electrical resistance, a large surface area, high density, and uniform pores with a size of 2-50 nm. The surface area of aerogels can be increased through various activation methods such as electrochemical, thermal, and chemical vapor saturation **[18].** Carbon aerogels produced by resoquinol with formaldehyde and sodium carbonate as catalysts have a specific capacitance of about 110 farads/g **[19].**

Carbon nanotubes

Carbon nanotubes are produced from the catalytic decomposition of hydrocarbons. Based on the tube morphology at the nanoscale, carbon nanotubes are usually divided into (1) Single-Walled Nanotubes (SWNTs) and (2) Multi-Walled Nanotubes (MWNTs). The surface area of carbon tubes is less compared to activated carbons, and the specific capacitance of these electrodes is from 15 to 80 F/g. Figure 7 shows carbon nanotubes show ideal capacitive behavior in Cyclic Voltammetry (CV) **[20].** Further chemical activation with potassium hydroxide causes the capacitance of the nanotube to be twice as much as that of ordinary nanotubes.

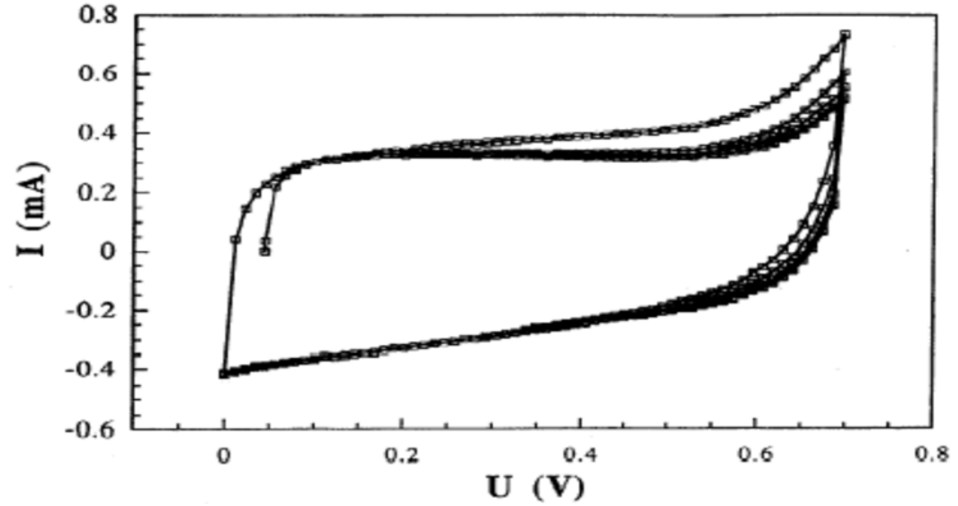
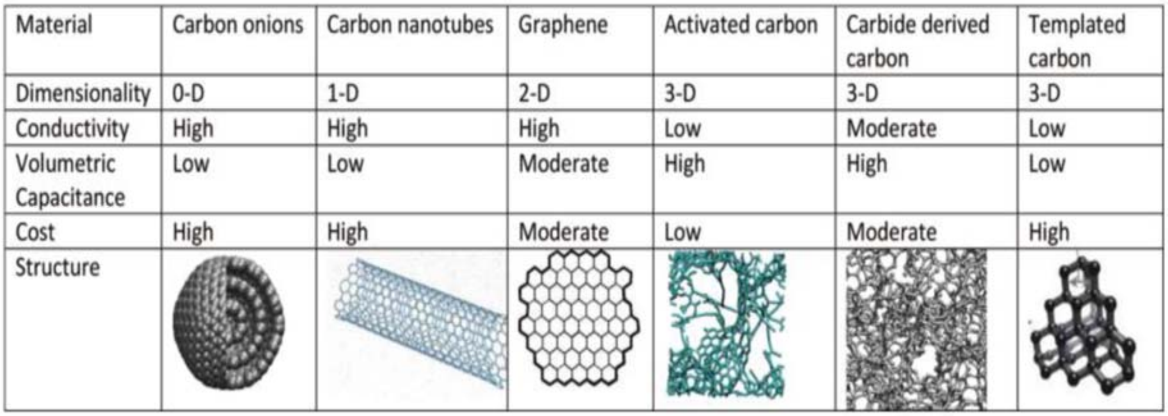


Fig. 7. Voltammetry characteristics of a carbon nanotube electrode obtained by acetylene decomposition at 700 °C with a scanning rate of 1 mV/s **[20]**.

They have good properties such as good electrical conductivity, thermal and chemical stability, and strength due to their unique porous structure and are suitable as electrodes for supercapacitors.



Material	Carbon onions	Carbon nanotubes	Graphene	Activated carbon	Carbide derived carbon	Templated carbon
Dimensionality	0-D	1-D	2-D	3-D	3-D	3-D
Conductivity	High	High	High	Low	Moderate	Low
Volumetric Capacitance	Low	Low	Moderate	High	High	Low
Cost	High	High	Moderate	Low	Moderate	High
Structure						

Fig. 8. Different carbon electrodes used in supercapacitors.

Pseudocapacitors electrodes

Reversible redox reactions occur on the surface of pseudocapacitor electrodes. Metal oxides and conducting polymers are two types of electrodes used in pseudocapacitors. The specific capacitance of these compounds is significantly higher than carbon electrodes. In the following, the types of electrodes used in these supercapacitors have been studied.

Metal oxides

Metal oxides such as MnO_2, RuO_2, NiO, and Co_3O_4 have been widely studied as electrodes for supercapacitors due to their specific capacitance in low resistance. The capacitive behavior of several metal oxides is discussed below.

Ruthenium oxide

A rapid and reversible charge transfer along with the electro-adsorption of protons on the surface leads to high capacitance ruthenium oxide formation in an acidic environment. The redox reaction that takes place on the surface of the electrode is expressed as follows **[6]:**

$$RuO_2 + xH^+ + xe^- \leftrightarrow RuO_{2-x}(OH)_x \quad \textbf{(7)}$$

Using ruthenium oxide as the electrode results in high power and energy density due to the low equivalent series resistance. RuO_2 provides high conductivity, electrochemical stability, and good cycling stability. Cyclic voltammetry of ruthenium oxide (as shown in Fig. 9) shows a mirror behavior that has the behavior of an ideal capacitor. The specific capacitance of hydrated ruthenium oxide in sulfuric acid is equal to 750 F/g, much higher than anhydrous ruthenium oxide. However, besides these advantages, the use of ruthenium oxide as an electrode is limited due to its high cost.

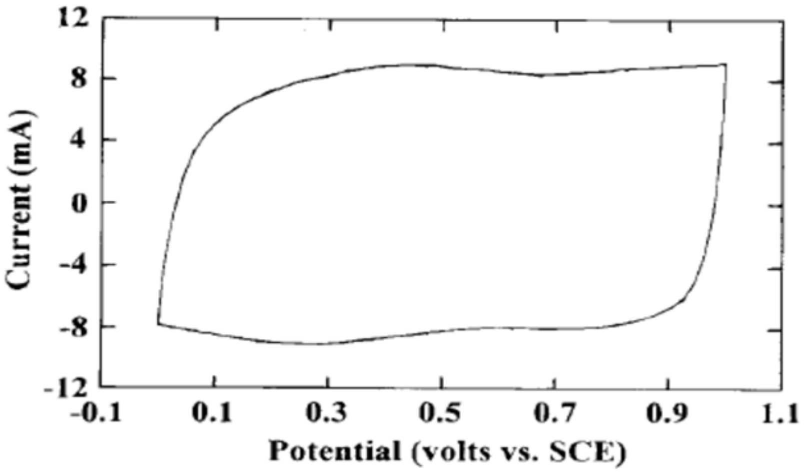


Fig. 9. Cyclic voltammetry of ruthenium oxide electrode.

Cobalt oxide

Cobalt oxide is used as an electrode in electrochemical capacitors. The energy storage mechanism is described as follows **[21]:**

$$Co_3O_4 + H_2O + OH^- \leftrightarrow 3CoOOH + e^- \tag{8}$$

The above mechanism changes at high temperatures due to the phase change of cobalt oxide. Cobalt oxide produces a capacitance value of about 164 F/g. Also, cobalt oxide shows capacitive behavior at negative potentials. These electrodes are used with other oxide materials as positive electrodes in systems with symmetrical electrodes **[22].**

Nickel oxide

Nickel oxides are used for electrode materials in supercapacitors by sol-gel technique. A specific capacitance of about 250 F/g has been obtained using Nickel oxides. Electrochemical deposition techniques have been recently developed to prepare nickel oxide films. These techniques are more controllable and cheaper than sol-gel techniques. The charge storage mechanism for nickel oxide is explained as follows:

$$NiO + OH^- \leftrightarrow NiOOH + e^- \tag{9}$$

The main disadvantages of nickel oxide films are (i) Low capacitance, (ii) Low voltage range, and (iii) Cyclic voltammetry, as shown in Fig. 10, which shows that the potential-current response is dependent on the potential, which is against to ideal capacitors.

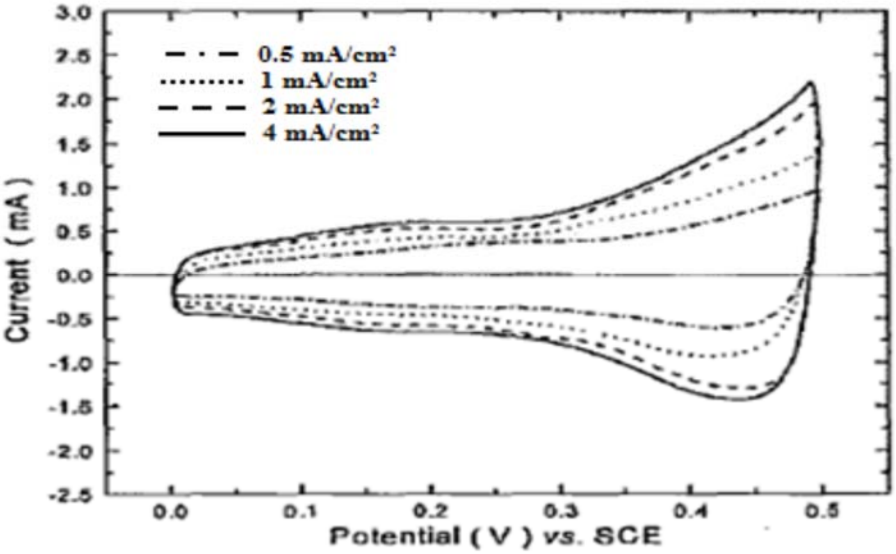


Fig. 10. Cyclic voltammetry of nickel oxide **[22].**

Manganese oxide

Compared to other metal oxides, manganese oxides are suitable electrode materials for electrochemical capacitors due to their low cost, suitable electrochemical, and Eco-friendly properties. Manganese oxide electrodes can be produced by electrochemical, deposition, or sol-gel techniques. The charge storage mechanism for manganese dioxide is expressed as follows **[23]:**

$$MnO_2 + xC^+ + yH^+ + (x+y)e^- \leftrightarrow MnOOC_xH_y \tag{10}$$

Adsorption of cations in the electrolyte and the addition of protons form the basis of the charge storage mechanism. Fig. 11 shows manganese oxides show ideal capacitive behavior in the cyclic voltammetry diagram.

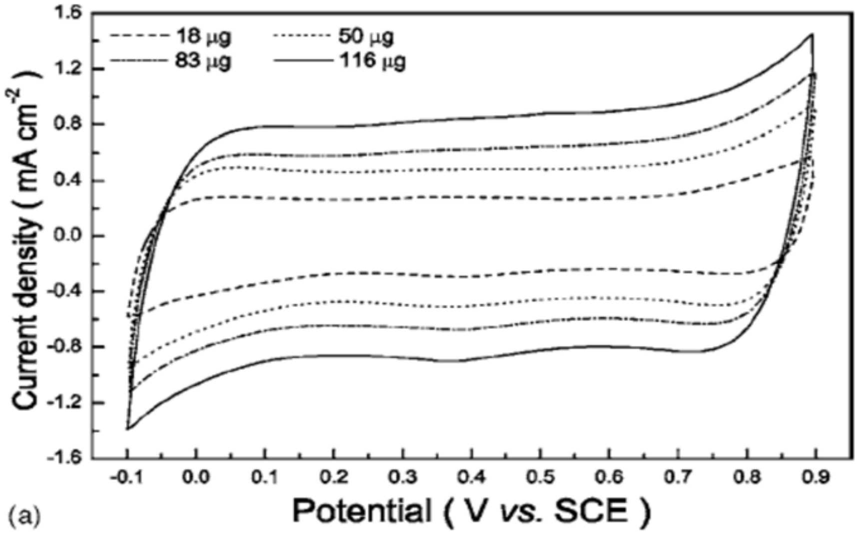


Fig. 11. Cyclic voltammetry of manganese oxide **[23]**

Conducting polymers

Conducting polymers such as polypyrrole, polyaniline, poly(3,4-ethylene dioxythiophene), polythiophene, and poly(p-phenylene vinylene) have been considered electrode materials in electrochemical capacitors. The presence of π-conjugated polymer chains increases electrical conductivity. These compounds provide high capacitance for charge storage, low equivalent series resistance, and high conductivity compared to carbon electrodes. These compounds are cheaper and show better environmental compatibility than metal oxide materials. Electric charge enters the polymer chain, and the ionic charge transfer into the polymer matrix causes charge separation. There are two charging processes: (i) p-doping and (ii) n-doping. P-type polymers are more useful than n-type polymers due to their better cyclic stability. The nature of impurity ions greatly influences the mechanical and electrochemical properties of the conducting polymer film **[25].** Other factors such as the nature of monomers, electrolytes, solution pH, and layer characteristics play an important role in the capacitance value of a conducting polymer film capacitor. Due to the destruction caused by excessive oxidation, the potential operating range of the conducting polymer electrode is limited.

Composite electrodes

Developing composite electrodes is used to use a mixture of suitable electrodes in one electrode. When large-area carbon electrodes are used as composites with redox pseudocapacitors electrodes in one electrode, the total capacitance increases significantly due to the composite of double-layer capacitors and pseudocapacitors. These electrodes are used in hybrid systems.

CNT-CP composite electrode

In the study of Shavo **[54],** the composite of carbon nanotube and conducting polymers resulted in high electrical resistance and reduced film degradation after different cycles. Carbon nanotube and polypyrrole (PPY) composite showed improved electrochemical performance. The electrochemical capacitance of CNT-PPY was six times higher than that of polypyrrole in organic electrolytes **[26].** Cyclic voltammetry in Fig. 12 showed better capacitance behavior for CNT-PPY composite than polypyrrole.

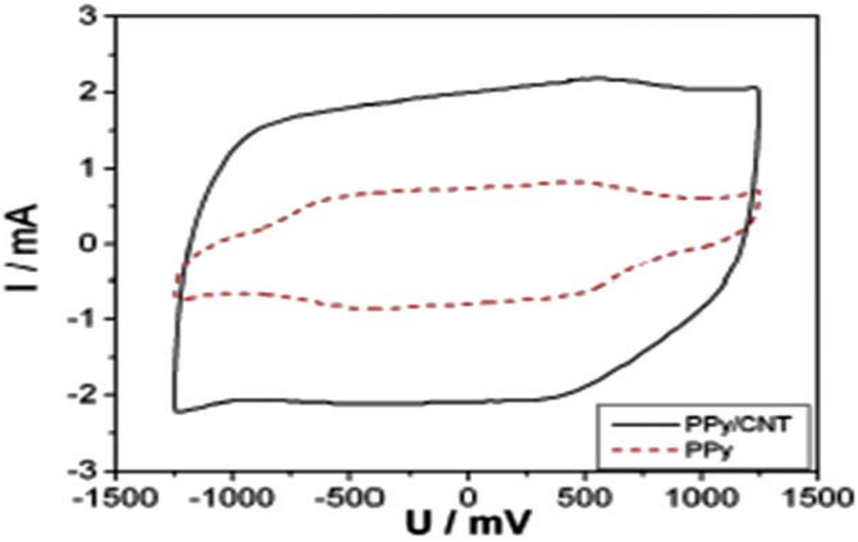
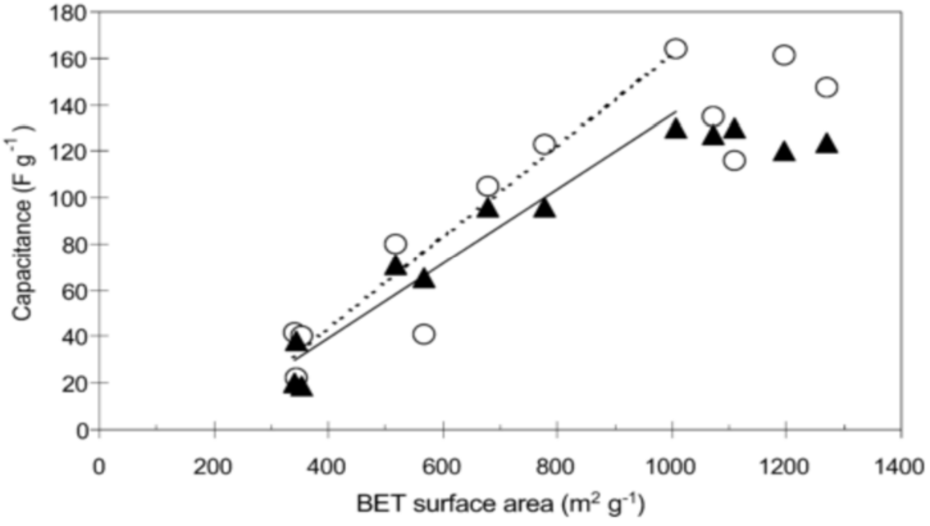


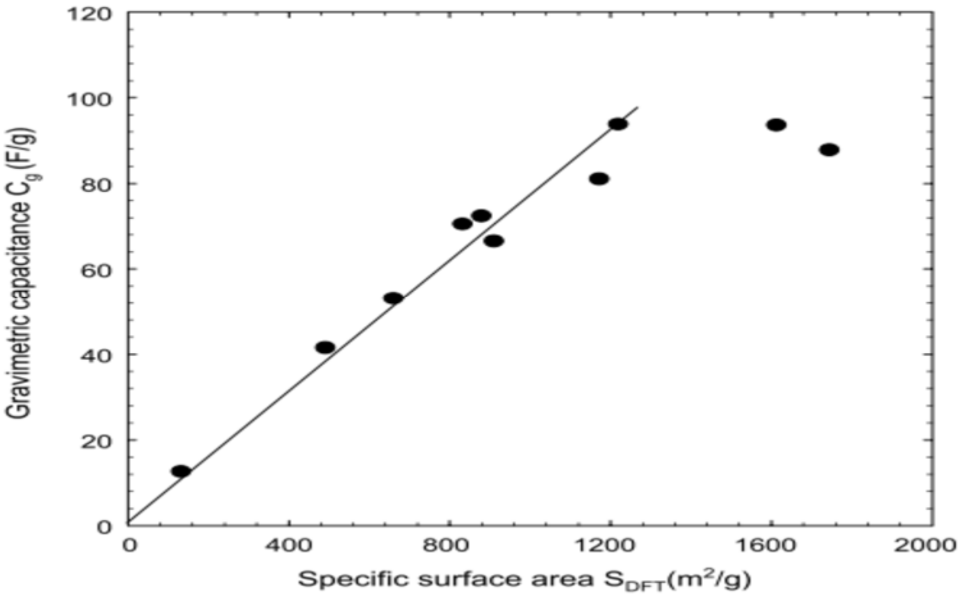
Fig. 12. Cyclic voltammetry of polypyrrole and CNT-PPY at a scanning rate of 20 mV/s **[26]**.

Effect of pore texture and ion size on capacitor capacitance performance

According to the equation $C = \varepsilon \, {}^{A}/_{D}$ The capacitance of carbon electrodes has a direct relationship with the surface area of the electrode. Several works have been done to relate the electrical double-layer capacitance to the DFT or BET surface area. The BET model based on the adsorption of a single layer of gas on a solid surface resulted in an unreliable surface area for carbons with micro-pores. For example, for pores smaller than 0.9 nm, the BET model underestimates the real surface area, while for sizes between 0.9 and 4 nm and above, it presents and provides the surface area with good accuracy **[27].** Therefore, the Dubinin-Radushkevich (DR) equation or Density-Functional Theory (DFT) are acceptable approximations. However, the specific surface area has been determined by both BET and DFT processes, and the specific capacitance of carbon electrodes does not show a linear relationship with the electrode surface area **[27].** As shown in Fig. 13, when the surface area is higher than $1200 m^2 g^{-1}$, the specific capacitance tends to have a constant value.



(a)



(b)

Fig. 13. (a) The specific capacitance of activated carbons in 1 M sulfuric acid (O) and 6 M potassium (▲) as a function of the BE surface area (b) The specific capacitance of carbon electrodes in 1 M $(C_2H_5)_4NBF_4$ in acetonitrile as a function of DFT surface area.

Electrolyte

The properties of electrolytes play a vital role in the electrochemical behavior of supercapacitors. Electrolyte resistance controls the power density of supercapacitors, and operation voltage controls the energy density of supercapacitors, which is also dependent on the breakdown voltage of the electrolyte. Three different types of electrolytes used in supercapacitors are (i) Aqueous, (ii) organic, and (iii) ionic.

Table 3. A comparison of aqueous and organic electrolytes **[28]**.

Aqueous electrolytes	Organic electrolytes
The cell voltage is about 1 V, which reduces the energy density.	The cell voltage is above 2 V, which leads to high energy density.
It results in low specific resistance and, therefore, high power density.	It has a higher specific resistance than aqueous solutions.
The purification and drying process is less .	During the production, the drying process produces hydrogen and oxygen gas; after the combined reactions, the charging process is carried out automatically.
Cheap	Relatively expensive

Aqueous electrolytes

Generally, alkaline and acidic electrolytes are used as aqueous electrolytes for electrochemical supercapacitors. The unique characteristics of acidic and alkaline electrolytes are the high conductivity and proton transfer mechanism of these electrolytes in electrochemical capacitors. In an aqueous electrolyte, a small proton with high mobility is chemisorbed by an oxidized ion. The high electrolyte concentration reduces the Equivalent Series Resistance (ESR) and improves conductivity. Concentrated sulfuric acid is used as an electrolyte for the ruthenium oxide electrode, which avoids the problem of electrolyte depletion during charging **[29].** The use of concentrated acids causes harmful environmental effects and increases electrode corrosion. Also, the voltage of a single cell in this condition is about 1 volt, which reduces the energy density. Dilute aqueous KCl electrolyte is used for manganese oxide electrodes in supercapacitors. NaCl has been widely used in supercapacitors. It is interesting to note that compared to acidic or alkaline environments, neutral aqueous electrolytes such as alkaline sulfates with a symmetrical carbon/carbon electrode can lead to a higher voltage **[30].** Also, a potential window of about 2 V was obtained with a carbon electrode at $0.5 mol L^{-1} Na_2SO_4$. The electrochemical analysis of seaweed carbons at $0.5 mol L^{-1} Na_2SO_4$ showed that the nature of the electrode material and the pH of the electrolyte affect the capacitance value and the potential window due to the presence of functional groups containing nitrogen in these carbons **[31].** Qu et al. **[32]** reported that the migration rate of hydrated ions in the electrolyte into the pores of the carbon electrode increases as follows:

$$Li^+ < Na^+ < K^+$$

The highest operating voltage (about 2.2 V) with high stability was obtained in Li_2SO_4 solution. Fic et al. suggested that the intense hydration of Li ions compared to K and Na ions is the reason for the voltage increase in the Li_2SO_4 solution **[33].**

Organic electrolytes

Acetonitrile or propylene carbonates are commonly used organic electrolytes that increase the operating voltage of the supercapacitor in the range of 2-2.5 V. Thus; a higher energy density is obtained in this case than in aqueous electrolytes. Tetraethylammonium salts are widely used in non-aqueous solvents due to their high solubility. The solubility of salts in organic solvents is relatively low. Compared to concentrated aqueous electrolytes, organic electrolytes show a higher specific resistance. Due to the large size of organic molecules, the electrode needs larger pores **[13].** Hence, the power density of supercapacitors is greatly reduced in these conditions. Tetraethylammonium salts are a suitable electrolyte due to their stability and high conductivity in organic solvents **[28].**

Ionic electrolytes

The ionic electrolyte is a combination of organic cations and various anions. These electrolytes can increase the potential range of supercapacitors. Unlike other electrolytes that dissolve salts in molecular solvents, an ionic liquid does not contain solvent molecules. At room temperature, ionic electrolytes exist as thermal and electrochemical stability liquids. They have low vapor pressure. Supercapacitors with ionic electrolytes have high energy density and power, increasing the operating voltage to 3.4 V **[28].** Commercial application of ionic electrolytes is limited due to the high cost. Ionic solvents used for supercapacitors electrolytes are imidazolium, pyrrolidinium, aliphatic ammonium salts with anions such as tetrafluoroborate, trifluoromethanesulfonate, bis(trifluoromethylsulfonyl)imide, bis(fluorosulfonyl)imide, and hexafluorophosphate **[34].**

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Conclusions

Global problems and issues urgently need research and development of energy systems with high efficiency and low cost. Hence, much research has been done on energy storage systems. A supercapacitor is one of the energy storage systems. The present paper conducted a relatively comprehensive review of supercapacitor technology (including its classification, construction, and applications). In the future, more research can be done on different parts of a supercapacitor to optimize them. For example, in addition to the main goals such as energy density or power density, electrode surface optimization for electrolyte penetration can be investigated as an important issue in carbon electrode supercapacitors. For a selected electrolyte, surface wetting properties and further optimization of the porous structure are very important. In addition to the research on electrodes, it is necessary to study ionic liquid electrolytes and new organic electrolytes (which have greater stability and higher temperature performance range than common organic electrolytes and aqueous electrolytes). Although the common applications of supercapacitors are mainly in automobiles, stations, and portable electronic industries, they also have special applications in the pharmaceutical, defense, and aerospace fields.

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Conflict of interest

None.

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Ethics statement

None

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