

# Review of Recent Advances of Supercapacitors Energy Storage Systems

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**Abstract** This paper presents a review of the recent advances of the supercapacitors energy storage systems. The recent development of the supercapacitors devices is presented and discussed. The need for highly dependable backup and emergency power is fueling growth in the energy storage and power transmission industries. One of the most advanced types of energy storage devices is the supercapacitor. At the electrode-electrolyte interface, these supercapacitors can store electrical charge in an electric double layer. Different materials are considered for creating the supercapacitors, such as graphene, carbon black, and charcoal. This paper focuses on the electrode material, rare earth and their composites-based electrode materials for supercapacitors, atomic layer deposition in the development of transition-metal-oxide and conducting polymer-based fibers for supercapacitors, and atomic layer deposition in the development of transition-metal-oxide and conducting polymer-based fibers for supercapacitors.

**Keywords:** *supercapacitors storage, electrode material, rare earth, atomic layer deposition, energy storage*

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## 1. Introduction

The supercapacitor, as a novel energy storage technology, has received of a lot of attention in recent years [1]. It offers several benefits, including high power densities, quick charge, and discharge times [2]. The supercapacitors are a fast-developing devices and widely used technology that can store and discharge energy extremely quickly and efficiently [2]. The supercapacitors are now used in various applications and are being investigated for an equally broad variety of future applications due to their unique advantages [2]. The supercapacitors are used to supplement a major power source that cannot regularly produce short bursts of energy, such as an internal combustion engine, fuel cell, or battery [2]. The supercapacitors, which are already a formidable alternative energy supply, have a bright future ahead of them [2]. The supercapacitors hold promise for storing electrical energy at high power densities, high charge rates, and high discharge rates for a variety of applications, including electric vehicles, hybrid-electric vehicles, industrial equipment, electrical grid load-leveling, and power tools, according to the specification [2].

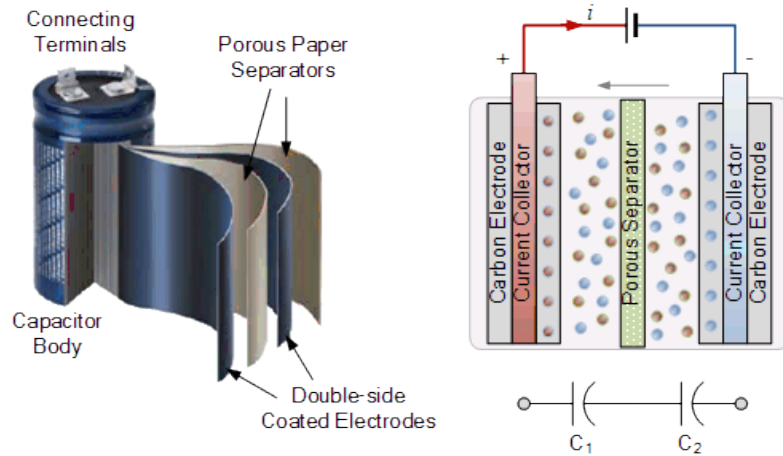
An enabling energy management strategy (EMS) is required in supercapacitors energy storage to assure efficient, safe, and dependable functioning of supercapacitors systems [3]. Based on standard control procedures, an energy management control approach for

bilateral supercapacitors energy storage devices is developed [3].

## 2. Supercapacitors Construction

The supercapacitors are a form of capacitor with a huge conducting plate, known as an electrode, with a big surface area ( $A$ ) and a very short distance ( $d$ ) between them [3]. Unlike traditional capacitors, which use a hard, dry dielectric such as Teflon, Polyethylene, or paper, a supercapacitor uses a liquid or wet electrolyte between its electrodes, making it more of an electrochemical device like an electrolytic capacitor [3]. Although the supercapacitor is an electrochemical device, the electrical energy it stores is not stored by chemical processes [3]. The supercapacitor is essentially an electrostatic device that stores its electrical energy in the form of an electric field between its two electrodes as shown in Figure 1.

Several materials including conductive activated carbon, carbon nanotubes, and carbon gels are used in the double-sided coated electrodes for the supercapacitor [4]. The electrodes are separated by a porous paper membrane called a separator, which enables positive ions to flow through while preventing bigger electrons. The liquid electrolyte is impregnated into both the paper separator and the carbon electrodes, with an aluminum foil sandwiched in between to function as a current collector and link them up [4].



**Figure 1.** Supercapacitors cell construction [3]

The carbon electrodes and the spacer's double-layer structure may be very thin, but when twisted together, their effective surface area reaches hundreds of square meters [4]. To improve the capacitance of the supercapacitor, the contact surface area should be increased [4].

The supercapacitors make excellent energy storage devices due to their high capacitance values of hundreds of farads, due to the very small distance ( $d$ ) or separation of their plates and the high surface area of the electrodes for formation on the surface of the layer of electrolytic ions forming a double layer, and because of the very small distance or separation of their plates. Its plates and the high surface area of the electrodes to form a layer of electrolytic ions on the surface of a layer of electrolytic ions, because this design basically makes two capacitors, one in each carbon electrode, the supercapacitor is sometimes known as a “double-layer capacitor”, because it effectively forms a capacitor in succession [4].

However, since the rated voltage of the super-capacitor cell is mostly limited by the electrolyte decomposition voltage, the voltage across the capacitor can only be very low [4]. Then, depending on the electrolyte used, a standard capacitor cell has an operating voltage of 1 to 3 volts, which may limit the amount of electrical energy that can be stored [4]. To store the charge at an acceptable voltage, supercapacitors must be connected in series [4]. The supercapacitors differ from electrostatic capacitors in that they have a lower terminal voltage [4]. To reach larger capacitance values, supercapacitor cells must be coupled in series or parallel to increase their rated final voltage to tens of volts [4].

The voltage of the supercapacitor value can be increased by connecting several capacitor cells in parallel [4]. Thus, the total voltage and total capacitance of an ultra-fast bank can be defined as in equation (1).

$$\begin{aligned} \text{Voltage, } V &= V_{\text{CELL}} \times N \\ \text{Capacitance, } C &= C_{\text{CELL}} \times \left[ \frac{M}{N} \right] \end{aligned} \quad (1)$$

Where,  $V_{\text{CELL}}$  denotes one cell's voltage and  $C_{\text{CELL}}$  denotes one cell's capacitance,  $M$  is the number of columns, while  $N$  is the number of rows [4]. Also, supercapacitors, like

batteries, it has a definite polarity, with the positive terminal indicated on the capacitor body [4].

## 2.1. Nanotechnology Based Supercapacitors

Nanotechnology research has enabled us to begin to explore the possibilities of in recent years, by offering materials with the requisite qualities for a broad range of industrial applications [5]. They are highly suited for applications ranging from efficient large-scale energy storage to extremely compact portable-wearable devices because to their high energy density, quick charging cycle, and broad working temperature range [5]. Various experts expect that supercapacitors will replace or supplement the battery and the fuel cell technologies in many fields of technology in the next years [5]. Commercial supercapacitors often use nanostructured carbon-based materials such as carbon nanotubes, porous activated carbons, or carbon aerogels as electrodes [5]. These materials are appropriate for use in the supercapacitors because they have a large surface area and very high conductivity [5]. However, there is a trade-off to be made in the electrode material design since smaller nanopores have a higher surface area but impede the passage of conducting ions, lowering conductivity [5]. As a result, the pore size must be chosen to fit the application of each the supercapacitor design [5].

## 3. Specification of Supercapacitors Storage

The specifications of the supercapacitors such as the device has a high capacitance of about 2 kF, supercapacitors bridge the gap between conventional capacitors and rechargeable batteries. They can store large amounts of energy; supercapacitors can store electricity through either electrostatic charge absorption-desorption and the charge time of the device is about 1-10 seconds [5].

The specifications of the supercapacitor modules manufactured by Maxwell Technologies [5] are shown in Table 1. Specifications of supercapacitor cells manufactured by Maxwell Technologies [5] are shown in Table 2.

**Table 1. Specifications of supercapacitor modules manufactured by Maxwell Technologies [5]**

Series	Capacitance range (F)	Rated voltage (V)	DC ESR (mΩ)	Max. energy (Wh)	Specific power (kW/kg)	Operating temperature	Application
Standard	3	2.7	70	0.003	8.9	−40 to 65 °C	Emergency lighting, security equipment
	50		16	0.0506	4.4		
	100		15	0.101	2.5		Smart meters, wireless transmitters
	360		3.2	0.36	3.8		Actuators, backup systems, UPS systems
XP	5	2.7	45	0.005	9.2	−40 to 85 °C	Smoke detectors, advanced metering, emergency lighting
	25		25	0.0253	5.1		
	50		16	0.0506	4.4		
Dura Blue	650–3000	2.7	0.29–0.80	0.66–3.04	5.8–6.8	−40 to 65 °C	Automotive subsystems, hybrid vehicles
	3400		0.23	3.66	7.4		Environments with high shock and vibrations
	3500	2.85	0.28	3.95	8.5		

**Table 2. Specifications of supercapacitor cells manufactured by Maxwell Technologies [5]**

Capacitance range (F)	Rated voltage (V)	DC ESR (mΩ)	No. of cells	Max. energy (Wh)	Specific power (kW/kg)	Application
1.5	5	130	–	0.0052	6.7	Actuators, emergency lighting, smoke detectors, UPS systems
2.5		85		0.0086	7.0	
58	16	22	6	2.1	2.2	Small UPS systems
500	16	2.1	6	18	2.7	Industrial equipment and transportation
9	24	139	–	0.72	1.2	Source of backup power for robots
165	48	6.3	18	53	3.3	Hybrid vehicles
94	75	13	32	73	2.1	Pitch control of wind turbines
63	125	18	48	140	1.7	Mining equipment, cranes, busses, electric vehicles

## 4. Supercapacitor Energy Storage

Capacitors and batteries are the most prevalent electrical energy storage technologies [6]. Charge separation stores energy in capacitors [6]. The energy is stored in a thin layer of dielectric material that is supported by metal plates that serve as the device's terminals in the simplest capacitors [6]. The voltage between the terminal plates is measured in volts [6]. The dielectric material's breakdown properties determine the capacitor's maximum voltage [6]. The CV determines the charge (Q) coulombs stored in the capacitor [6]. The dielectric capacitor's capacitance is determined by the dielectric constant (K), as well as the

dielectric material's thickness and geometric properties area (A) [6].

$$C_s = KA/th \quad (2)$$

Energy is stored chemically as active material in the electrodes of a battery [6]. By connecting a load across the battery's terminals, energy is released in electrical form, allowing the electrode materials to react electrochemically with the ions necessary in the reactions to be transmitted via the electrolyte in which the electrodes are submerged [6]. The VQ is the usable energy stored in the battery, where (V) is the cell voltage and (Q) is the electrical charge [6]. The voltage is determined by the chemical coupling between the active components [6]. For certain materials, the open-circuit voltage is near the voltage of the battery [6].

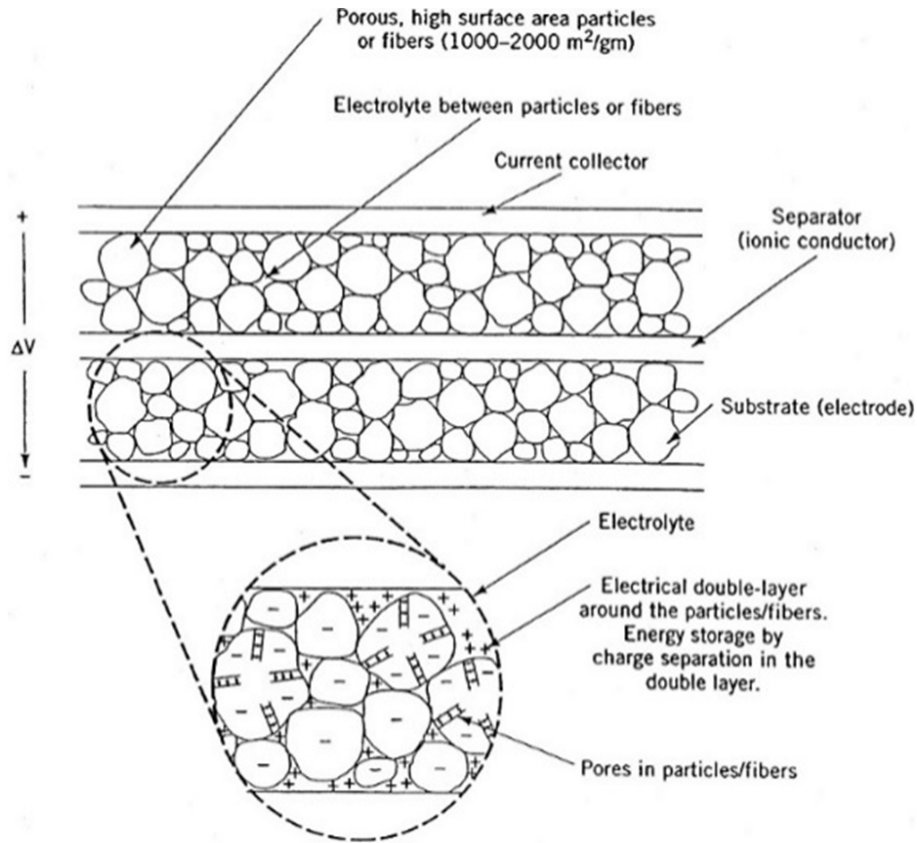


Figure 2. Schematic of a double layer ultracapacitor [6]

A supercapacitor, also known as an electrochemical capacitor, is a kind of electrical energy storage device that is built similarly to a battery [6]. It consists of two electrodes submerged in an electrolyte, separated by a separator [6]. The electrodes are made of a porous substance with a large surface area and nanometer-sized pores (nm) [6]. The electrode materials used in supercapacitors have a substantially larger surface area than those used in battery electrodes, ranging from 500 to 2000 m<sup>2</sup>/g [6].

At or near the interface between the solid electrode material and the electrolyte, charge is stored in micropores [6]. The charge and energy stored are calculated using the same formulas as the basic dielectric capacitor [6]. Calculating the capacitance of an supercapacitors, on the other hand, is far more complicated since it is dependent on complex events happening in the electrode's micropores [6]. It's easier to talk about energy storage processes in supercapacitors in terms of double-layer and pseudo-capacitance separately [6]. The physics and chemistry of these processes as they pertain to electrochemical capacitors are well discussed [6]. The mechanisms are briefly addressed in the following sections in terms of how they relate to the characteristics of the electrode materials and electrolyte [6].

#### 4.1. Double-layer Capacitors

Charge separation in the double-layer capacitor created at the interface between the solid electrode material surface and the liquid electrolyte in the electrodes' micropores stores energy [6]. Figure 2 shows a schematic of an supercapacitors [6]. Diffusion via the electrolyte

transports the ions displaced in generating the double-layers in the pores between the electrodes [6]. The electrochemical capacitor stores  $1/2 CV^2$  and  $CV$ , respectively, in energy and charge [6]. The capacitance is principally determined by the electrode material's surface area and pore size distribution. An electrode material's specific capacitance may be expressed as in equation (3).

$$C/g = (F/cm^2)_{act} * (cm^2/g) \quad (3)$$

The active region in the pores on which the double-layer is produced is referred to as the surface area [6]. The capacitance per unit of active area is calculated as follows:

$$F/cm^2_{act} = -K / \text{thickness of the double-layer}_{eff} \quad (4)$$

Table 3. The specific capacitance of selected electrode materials [6]

Material	Density g/cm <sup>3</sup> .	Electrolyte	F/g	F/cm <sup>3</sup>
Carbon cloth	0.35	KOH	200	70
		organic	100	35
Carbon black	1.0	KOH	95	95
Aerogel carbon	0.6	KOH	140	84
Particulate from SiC	0.7	KOH	175	126
		organic	100	72
Particulate from TiC	0.5	KOH	220	110
		organic	120	60
Anhydrous RuO <sub>2</sub>	2.7	H <sub>2</sub> SO <sub>4</sub>	150	405
Hydrous RuO <sub>2</sub>	2.0	H <sub>2</sub> SO <sub>4</sub>	650	1300
Doped conducting polymers	0.7	organic	450	315

The relationship between the electrolyte's dielectric constant ( $K_{eff}$ ) and the thickness of the double-layer

generated at the interface is complicated. In liquid electrolytes, the double-layer thickness is a fraction of a nanometer. It yields a high value of 15 to 30 mF/cm<sup>2</sup> for a given capacity resulting in a potential capacity of 150 to 300 mF/g of electrode material for a surface area of 1,000 m<sup>2</sup>/g as shown in Table 3 [6].

A significant portion of the surface area of most carbon materials lies in pores inaccessible to ions in the electrolyte, the measured specific capacitances of carbon materials used in supercapacitors are typically below these high values, which range from 75 to 175 F/g for water electrolytes and 40-100 pF/g for organic electrolytes [6]. This is particularly true in organic electrolytes, where ion sizes are substantially greater than in aqueous electrolytes [6]. For supercapacitors, porous carbons should have a substantial proportion of their pore volume in pores with a diameter of 1-5 nm. Materials having holes smaller than 1 nm. At discharge currents larger than 100 mA/cm<sup>2</sup>, there is a significant drop-off in capacitance, particularly when employing organic electrolytes [6]. Larger pore diameter materials may be discharged at current densities more than 500 mA/cm<sup>2</sup> with just little capacitance loss [6]. The electrolyte used determines the supercapacitor's cell voltage [6]. The cell voltage for aqueous electrolytes is about 1 V, whereas the cell voltage for organic electrolytes is 3-3.5 V [6].

#### 4.2. Electrochemical Capacitors Utilizing Pseudo-Capacitance

The charge is transported into the double-layer in a perfect double-layer capacitor, and there are no Faradaic interactions between the solid material and the electrolyte [6]. The capacitance (dQ/dV) is constant and voltage independent [6]. Most of the charge is transmitted at the surface or in the bulk near the surface of the solid electrode material in devices that use pseudo capacitance [6]. As a result, the interaction between the solid substance and the electrolyte in this scenario includes Faradaic events, which may be defined as charge transfer reactions in most cases [6]. The pseudo-capacitance ( $C = dQ/dV$ ) is the consequence of the charge transfer in

these processes being voltage dependent [6]. In the construction of the supercapacitors utilizing pseudo-capacitance, three kinds of electrochemical techniques have been used [6]. The surface adsorption of electrolyte ions, redox processes involving electrolyte ions, and doping and un-doping of the active conducting polymer material in the electrode are examples [6]. The first two processes are essentially surface mechanisms, and so are strongly reliant on the electrode material's surface area [6]. Although a relatively large surface area with micropores is required to distribute ions to and from the electrodes in a cell, the third process involving the conducting polymer material is more of a bulk process, and the specific capacitance of the material is much less dependent on its surface area [6]. To distribute and collect the electron current, the electrodes must have a high electronic conductivity in all instances [6]. The CV, which is commonly obtained via cyclic voltammetry, may be used to infer the charge transfer process [6]. The average capacitance ( $C_{av}$ ) is a useful metric for evaluating device attributes [6]. Considered equation (5)

$$C = Q_{tot} / V_{tot} \quad (5)$$

The total charge and voltage change for a charge or discharge of the electrode are ( $Q_{tot}$ ) and ( $V_{tot}$ ), respectively [6]. This allows the specific capacitance ( $C_{av}/g$ ) to be calculated [6].

#### 4.3. Hybrid Capacitors

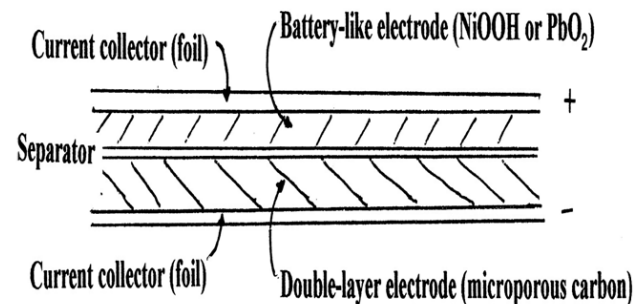


Figure 3. Schematic of a hybrid ultracapacitor [7]

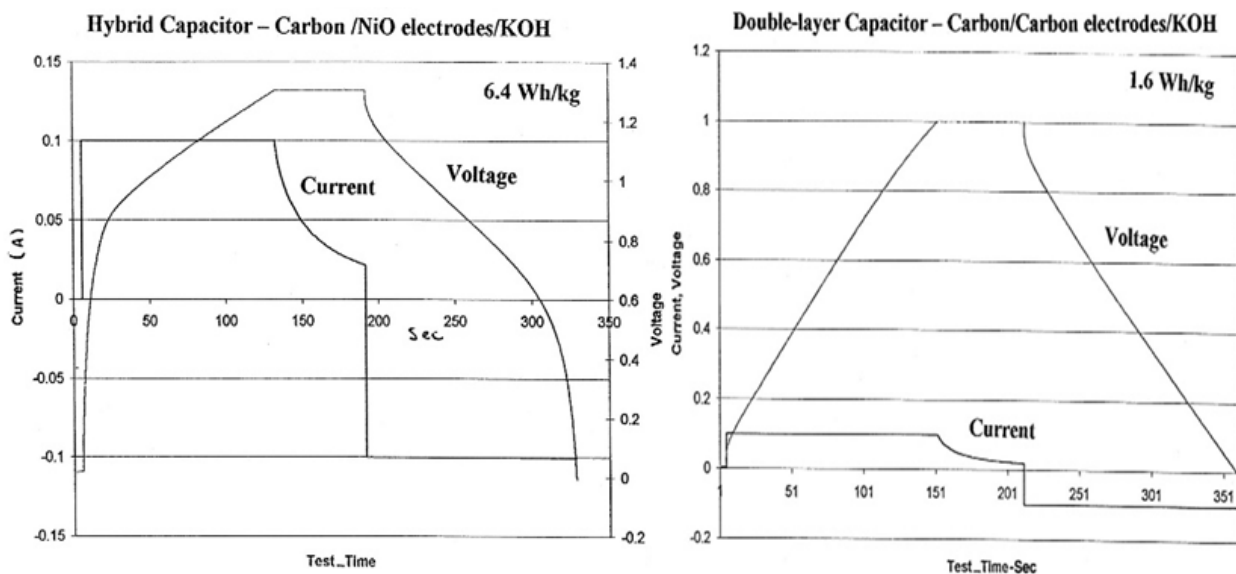


Figure 4. Charger / discharge characteristics of double-layer and hybrid ultracapacitors [8]

The supercapacitors can be made of one electrode of a double-layer carbon [7]. Figure 3 shows a hybrid capacitor with one electrode made of a high-capacitance material and the other of a low-capacitance material [7]. Nickel oxide has been employed as the pseudo-capacitance material in the positive electrode in most hybrid capacitors created to date [7]. These devices have a larger energy density than double-layer capacitors, but their charge/discharge behaviors are different, as shown in Figure 4 [8]. The voltage (V) vs. charge (Q) are far from perfect (nonlinear). Two non-similar mixed metal oxide or doped conducting polymer materials may also be used to make hybrid capacitors [8].

## 5. Supercapacitors Being Developed

The battery is the most popular electrical energy storage technology [8]. For most applications, batteries have been the technology of choice since they can store huge quantities of energy in a compact volume and weight while still providing enough power levels [8]. Most kinds of batteries have an issue with shelf and cycle life. In recent years, the power needs in a variety of applications have skyrocketed, far outstripping the capacity of standard-design batteries [8]. As a result, special high-power pulse batteries have been developed, frequently at the expense of energy density and cycle life [8]. As a replacement for pulse batteries, supercapacitors are being developed [8]. The supercapacitors must have significantly greater power and a much longer shelf and cycle life than batteries to be a viable option [8]. They

have a significantly lower energy density than batteries, and their low energy density is often the deciding factor in whether they can be used in a high-power application [8]. The balance between cost and performance is crucial in supercapacitors [8].

The sacrifice in energy density is required to get a large reduction in the time constant and thus a large increase in power capability [8].

Table 4 shows list of the properties of variety of supercapacitors and pulse batteries [8].

There are two methods for calculating the peak power density of the batteries [8]. The first and most common method is to calculate the power at the so-called matched impedance situation, in which one-half of the discharge's energy is in the form of electricity and the other half is in the form of heat [8].

The efficiency of the charger, discharge cycle is critical to the system efficiency in many situations where a considerable proportion of the energy is stored in the energy storage device before it is utilized by the system [8]. The energy storage device should only be used in situations that result in high charge and discharge efficiency [8].

As in common practice, the supercapacitors efficiency power density is matched to the batteries impedance power density [8]. Both kinds of devices' power capacity are mostly determined by their resistance, and knowing the resistance is crucial to establishing the maximal usable power capability. As a result, measurement is necessary [8].

When evaluating a device's high-power capacity, the resistance of the device in the pulsed mode of operation is crucial [8].

**Table 4. Comparison of the performance characteristics of various supercapacitors and high-power batteries [8]**

Type	Voltage V	A h	Weight kg	Resistance mV.	W h/kg	W/kg-max	
						95%	Matched
						Discharge	impedance
						efficiency	discharge
Maxwell supercapacitors 2700 F	3	2.25	0.85	0.5	4.0	593	5294
1000 F	3	0.83	0.39	1.5	3.1	430	3846
Panasonic 800 F	3	0.67	0.32	2.0	3.1	392	3505
2000 F	3	1.67	0.57	3.5	4.4	127	1128
Super farad 250 F	50	3.4	16	20	5.4	219	1953
Saft mfg. data Gen 2 144	3	0.12	0.030	24	6.0	350	3125
Gen 3 132 F	3	0.11	0.025	13	6.8	775	6923
Power Store 10F	3	0.0083	0.015	10	833	1680	15000
Batteries Panasonic NiHD	7.2	6.5	1.1	18	42	124	655
	12.0	98	17.2	8.7	68	46	240
Ovonic NiHD	13.2	88	17.0	10.6	70	46	245
	12.0	60	12.2	8.5	65	80	420
	12.0	20	5.2	11.0	46	120	628
	7.2	3.1	0.522	60	43	79	414
Varta NiHD mfg	1.2	4	0.18	3.5	29	109	571
	1.2	17	0.58	1.5	38	79	414
Sanyo Li-ion mfg	3.6	1.3	0.039	150	121	105	553
Hawker Pb-acid	2.1	36	2.67	0.83	27.0	95	498
	12	13	4.89	15	29.0	93	490
Optima Pb-acid mfg	6	15	3.2	4.4	28	121	635
Horizon Pb-acid	2.1	85	3.63	0.5	46	115	607
Bolder Pb-acid	2.1	1.05	0.083	5.7	25	442	2330

The long shelf and cycle life of the supercapacitors, in addition to their high-power capability, is another reason to consider them for a specific application [8]. This is particularly true with carbon electrode supercapacitors [8]. Most of them are secondary [8]. Due to self-discharge and corrosion effects, rechargeable batteries that have been kept on the shelf unused for several months may deteriorate significantly and become practically unusable after this period [8]. The supercapacitors will self-discharge to a low voltage over time [8]. They will, however, retain their capacitance and so be able to recharge to their previous state [8]. The supercapacitors have been shown to last for many years when left unused and in virtually perfect condition [8]. The deep cycling supercapacitors at high rates is possible [8]. With a relatively slight change in characteristics (10-20 % deterioration in capacitance and resistance) for 500,000-1,000,000 cycles, discharge periods of seconds are possible [8]. Even if the depth of discharge is maintained low 10–20%, this is feasible with batteries [8].

As a result, supercapacitors as pulse power devices have a higher power density, higher efficiency, and a longer shelf and cycle life than batteries [8]. The supercapacitors main drawback is their low energy density (Wh/kg and Wh/l) when compared to batteries, which limits its usage to applications where only tiny amounts of energy are needed before the supercapacitors may be recharged [8]. When compared to batteries, the supercapacitors may be recharged in seconds or fractions of seconds provided a source of energy at the appropriate high-power levels is available [8].

## 6. Designs of Supercapacitors-Based Energy Storage System

There are several design features of the supercapacitors-based energy storage system, such as component selection and rating [9]. A UC stack and a bidirectional DC/DC converter are usually included in a UC-based ESS [6]. Two switches and an inductive filter make up the bidirectional converter [9]. The coordinated functioning of two complementary systems [9]. Switches make it easier to use as a buck converter (during UC stack charging) and as a boost converter (during the discharging cycle). To begin, the design characteristics related with the UC-based ESS are provided for completeness' sake [9].

### 6.1. Design of Supercapacitors Stack

A basic RC model is used for the design and analysis of the UC stack. The intended amount of converter backup time is the key design parameter that dictates the value of capacitance in the UC stack (i.e., the duration that the UC stack is designed to discharge) [10]. The needed capacitance value for the UC stack may be computed mathematically using

(a) the required discharge duration ( $\Delta t$ ) [10].

(b) the UC stack's average current processed over the discharging time ( $I_{avg}$ ) [10].

(c) the voltage changes in the UC stack during discharge ( $\Delta V$ ) [10].

$$C_{uc} = \left( \frac{I_{avg}}{\Delta V} \right) \Delta t \quad (6)$$

According to the UCs, they are normally released at up to 50 % of their assessed value. 75 % of the energy stored in the UC has already been released at 50 percent of the rated value. The converter must be overrated to release the remaining energy, which is not cost-effective. Furthermore, difficulties associated to the initial charging process must be taken into consideration while entirely draining the UC stack [10]. As a result, it is preferable to set a lower limit on the voltage during discharge ( $V_{uc}$ , which is 50% of the rated value ( $V_{ucn}$ )) [10].

$$V_{uc} = \frac{V_{ucn}}{2} \quad (7)$$

The average current ( $I_{avg}$ ) is calculated by adding the highest and lowest currents handled by the UC stack together [10]. If  $P_o$  is the amount of power that the converter must process during discharge (i.e., converter rating), then the lowest ( $I_{min}$ ) and maximum ( $I_{max}$ ) current values correspond to a situation in which the stack voltage is at its rated value and 50% of its rated value, respectively [10].

$$I_{max} = \frac{P_o}{V_{uc}} = \frac{2P_o}{V_{ucn}}, I_{min} = \frac{P_o}{V_{ucn}} \quad (8)$$

As a result, the average current ( $I_{avg}$ ) may be calculated as follows:

$$I_{avg} = \frac{1}{2} \times [I_{max} + I_{min}] = \frac{3P_o}{V_{ucn}} \quad (9)$$

Using (1) and (3), the minimum value of stack capacitance ( $C_{uc}$ ) that will guarantee that the converter can handle the given power for a particular period can be calculated.

$$C_{uc} = \frac{3P_o \Delta t}{V_{ucn}} \quad (10)$$

If  $V_{ucc}$  is the voltage rating of the individual units of the UC stack (typically around 2.5 V), then the number of UC cells to be connected in series ( $n$ ) is given by (11) The variation of minimum stack capacitance as a function of processed power and desired discharge time that the discharge time of a UC stack of a given capacitance decreases with an increase in processing power [10].

$$n = \frac{V_{ucn}}{V_{ucc}} \quad (11)$$

The overall current rating of the UC stack and the current rating of individual UCs are commonly used to compute the number of parallel branches ( $p$ ) in the UC stack. The minimum capacitance required for individual UCs ( $C_{ucc}$ ) in a UC stack with ( $n$ ) series connected UCs and  $p$  parallel branches can be calculated as [10].

$$C_{ucc} = \frac{C_{uc, in} \cdot n}{p} \quad (12)$$

## 6.2. Design of Filter Inductance

The average inductor current and duty ratio determine the value of filter inductance [10]. Because the inductor is linked in series with the UC stack, the inductor and UC stack currents have the same minimum, maximum, and average ( $I_{L,avg}$ ) values (3) [10]. Only switch ( $sw$ ) is active during charging mode (CM), and the voltage across the inductor is equal to the difference between supply voltage ( $V_g$ ) and UC stack voltage, i.e.

$$V_g - DV_g = \left( \frac{\Delta i_L}{\Delta t} \right) \quad (13)$$

During the charging phase,  $L_c$  is the value of the filter inductance (14) may be expressed as, using a modest ripple approximation.

$$V_g - DV_g = \frac{(xI_{L,g})}{DT_s} \quad (14)$$

where  $x$  is the maximum permitted ripple (expressed as a percentage of average inductor current) and  $D$  represents the duty ratio [10]. The value of filter inductance may be calculated using (3) and (14).

$$L_c = (V_2 g T_s) / x P_o * \left( \frac{2D(1-D)}{3} \right). \quad (15)$$

The value of filter inductance is based on the operational duty ratio, according to Figure 5.2 depicts the usual fluctuation of inductance with duty ratio for three different converters [10]. The current ripple criteria will be fulfilled regardless of the operational duty ratio if the maximum value of inductance is chosen [10]. As a result, the value of the filter

$$L_c = \frac{1}{6} * \left( V_2 g \frac{T_s}{x P_o} \right) \quad (16)$$

inductor during charging mode may be calculated as the duty ratio at which  $dL_c/dD = 0$  [10].

The governing equation for the filter inductor during the discharging mode is

$$V_g = \left( \frac{\Delta i_L}{\Delta t} \right) = L_d \frac{xI_{L,s}}{DT_s} \quad (17)$$

In the discharging mode, the inductor current is given by

$$I_{L,s} = \frac{P_o}{V_{uc}} = \frac{P_o}{V(1-D)} \quad (18)$$

$$L_d = \frac{V_2 g T_s}{x P_o} * D(1-D)2 \quad (19)$$

The value of filter inductance may be calculated by substituting (13) for (12).

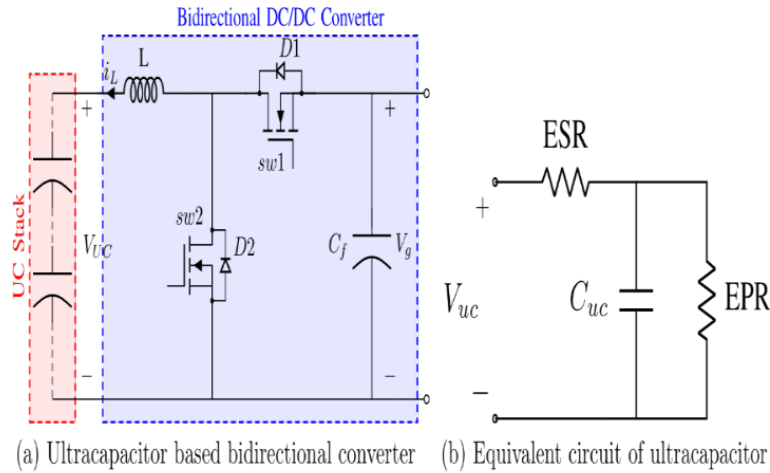


Figure 5.1. Bidirectional Converter and equivalent circuit [10]

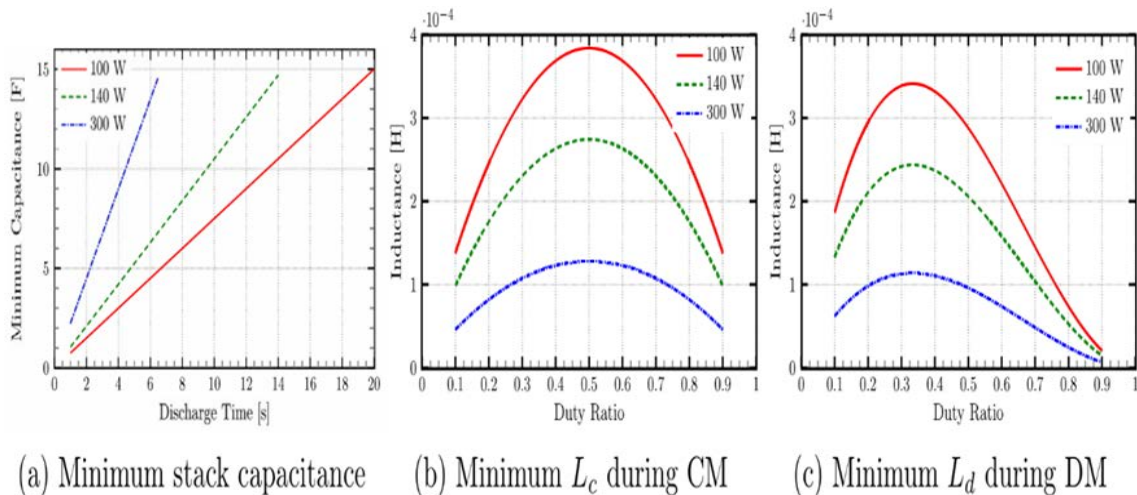


Figure 5.2. Variation of minimum stack capacitance and filter inductance [10]

Figure 5.1 shows the bidirectional Converter and equivalent circuit of filter inductance as a function of duty ratio in discharge mode [10]. Calculating the inductance corresponding to the duty ratio when  $dLd/dD = 0$  yields a unique inductor value [10].

$$L_d = \frac{4}{27} * \left( V 2g \frac{T_s}{xP_o} \right) \quad (20)$$

The value of filter inductance is determined to be  $L_{c, opt}$  (because  $L_{c, opt} > L_{d, opt}$ ) because the filter inductor must meet the ripple criteria for both charging and discharging modes [10].

$$L_f = L_c = \frac{1}{6} * V 2g \frac{T_s}{xP_o} \quad (21)$$

## 7. Supercapacitor's Sizing

The maximum and minimum voltages of the supercapacitor's module, the nominal capacitance, and the energy needs all play a role in supercapacitors selection [11]. The maximum current value of the DC/DC converter  $I_{c, max}$  determines the minimum voltage operation [11]. In typically, it is set at 40% or 50% of the maximum voltage, such that  $U_{c, min} > P_o / I_{c, max}$  is achieved [11].



Figure 6. BOOSTCAP BCAP0350 Supercapacitors from Maxwell [11]

The supercapacitors' maximum voltage should be less than the DC bus voltage, and the DC/DC converter gain should be less than or equal to 1 [11]. The energy stored in the vehicle in terms of kinetic energy. The fractions of energy to be shared among the wheels during braking are highly dependent on the initial state of the vehicle, road surface type and condition, and motor rotational speed [11].

Figure 6 shows the BOOSTCAP BCAP0350 Supercapacitors from Maxwell [11]. The fractions of

energy to be shared among the wheels are highly dependent on the initial state of the vehicle, road surface type and condition, and supercapacitors rotational speed [11]. Other losses, such as rolling resistance and air drag resistance, should be considered. The vehicle's deceleration is also aided by these resistance forces [11]. To size supercapacitors, an estimated energy calculus should be performed. According to the vehicle size as shown in Table 5, eighty-one percent of the total power shall be recovered by the front wheels and distributed between electronic and mechanical brakes in accordance with the ECE R13 standard while ensuring a maximum front/rear braking ratio [12]. In the worst-case scenario, the efficiency of the electrical/mechanical energy converters and transformers elements is estimated to be 90% [12]. Another assumption is that one-third of the energy available at the front wheel will be converted to electricity [11,12]. The energy collected by the UC and available to the front tire at a vehicle speed of 80 km/h is 81 kJ [12]. The maximum amount of energy that may be recovered from a starting voltage of  $U_{c, min}$ . A set of 120 Mx Boost Cap BCAP1200 P270 K04/5 ultra-capacitor cells will be employed in the researched application based on voltage and energy requirements [12] as shown in Figure 7.

Table 5. UC cell characteristics [12].

Product name	BCAP1200 P270 K04/5
Rated capacitance (F)	1200
Rated voltage (V)	2.7
ESR (mΩ)	0.58
Leakage current (mA)	2.7
Absolute maximum Current (A)	930
Max continuous current (A) at 15C	70
Max continuous current (A) at 40C	110
Weight (g)	260
Stored energy (Wh)	1.22
Emax (Wh/kg)	4.7
Pmax (W/kg)	12,000
Terminal	Threaded/weldable
Length (mm)	74
Diameter (mm)	60.4

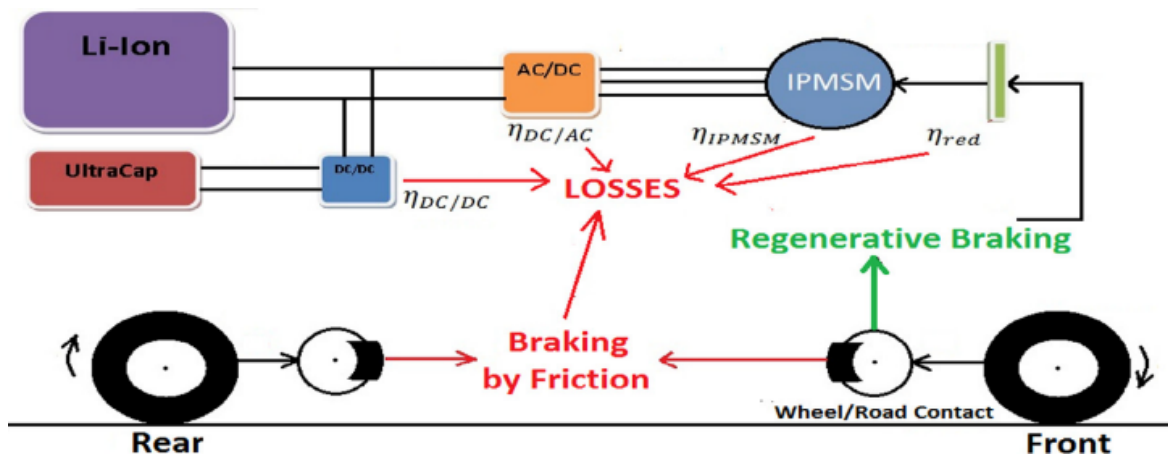


Figure 7. Power Flow from Wheel/Road Contact to the Energy Storage Elements [12]

According to the assumptions indicated above, DEC has a value of 392 kJ, which corresponds to a complete UC recovery during 4-5 braking actions [12].

The supercapacitors weigh 31.2 kg and have a total volume of 25.443 dm<sup>3</sup> [12]. Extra room for support, cabling, and electronic equipment for control and supervision should absolutely be considered [12]. The cost of the UC is calculated using the picture, which shows that the maximum amount of energy that can be stored in the UC set is 146 W/h [12]. The overall UC cost is estimated to be 4818 \$ at a rate of 33 \$/W/h [12]. The design of a flywheel energy storage system follows supercapacitors selection in the following section [12]. The findings of the chosen supercapacitors and FES are also discussed in terms of interpretations and analysis [12].

## 8. Classification of Supercapacitors

Supercapacitors may be split into three broad types based on current research and development trends: Electrochemical Double Layer Capacitor (EDLC), Pseudo capacitors, and hybrid capacitors [12]. Every class has its own set of characteristics and charge-storage mechanisms. Non-Faradaic, Faradaic, or a mix of both mechanisms are used to classify the processes [12]. Charges are transferred between the electrode and the electrolyte in the Faradaic process [12]. Oxidation and reduction reactions are examples of this process. The non-Faradaic method does not include any chemical reactions; rather, charges are spread on surfaces by a physical mechanism that does not form or break chemical bonds [12]. EDLC is the cheapest and most widely used supercapacitors of the three varieties [12]. Figure 8 shows the supercapacitors categorization in detail [12].

Researchers have been interested in enhancing the process of storing charge in supercapacitors over the last 10 years, thus they have conducted many studies employing various electrode materials and electrolytes

[13]. Most of them have resorted to hybrid capacitors since the electrode materials in them are composite and capable of providing a storage mechanism for their transport both physically and chemically [13]. The use of carbon-based materials is included by conducting polymer polymers or metal oxides in composite electrodes [13].

## 9. Application of Supercapacitors

Pagers, personal data assistance devices, and mobile phones are examples of common electronic uses [13]. To enhance the transmit burst in a digital phone system, the GSM phone will need a 200-Hz reaction time [13]. High power is more critical than energy density in these devices [13]. Supercapacitors employ aqueous electrolytes with substantially lower resistance to provide the appropriate frequency response [13]. Carbon electrodes must be thin and have big holes to achieve these frequencies [13].

Ion transport through the material at a high rate. The “electrification” of brakes, steering, air conditioning, and other subsystems to enhance the fuel economy and dependability of the 50-60 million passenger cars that roll off assembly lines throughout the globe each year [13].

Table 6. Applications of supercapacitors [13]

Market domain	Application
Automotive	Hybrid drives, board net stabilization, distributed power
Trains, trams	Regenerative braking, voltage stabilization
Buses	Regenerative braking
Aerospace	Electric actuators or latches
Pitch systems	Emergency power for windmill blades
Robotics	Peak and backup power
Telecom	Backup power

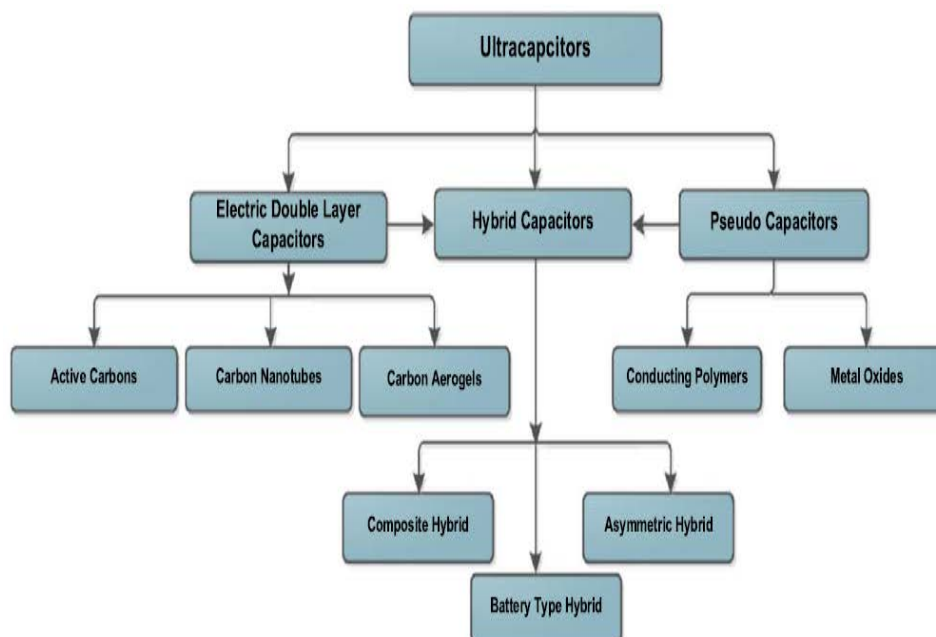
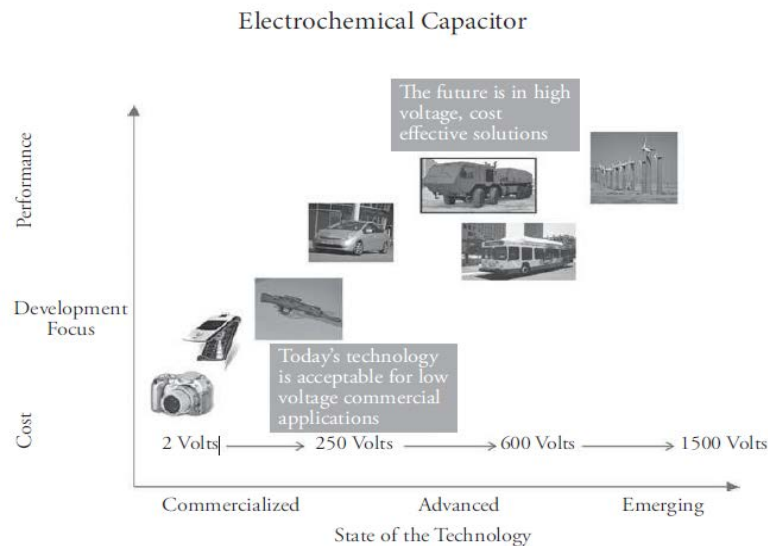


Figure 8. Classification of Supercapacitors [12]



**Figure 9.** Technology drivers for supercapacitors [13]

Figure 9 demonstrates how supercapacitors are being used in a variety of fields, including electronics, transportation, and grid systems, as well as the voltage range of capacitor banks [13].

## 10. Benefits and Limitations of Supercapacitors

In comparison to batteries, supercapacitors have several drawbacks and benefits, which are detailed below.

### 10.1. Advantages

Over hundreds of thousands of charge cycles, there is little degradation [14]. As a result, they will outlive the lifespan of most electronics, making them environmentally benign [14]. EDLCs can assist batteries by acting as a charge conditioner, storing energy from other sources, and then using that energy to charge batteries at a convenient time [14].

Over hundreds of thousands of charge cycles, there is little degradation [14]. As a result, they will outlive the lifespan of most electronics, making them environmentally benign [14]. EDLCs can assist batteries by acting as a charge conditioner, storing energy from other sources, and then using that energy to charge batteries at a convenient time [14]. Cycle cost is low, High-capacity output, Charge-discharge cycles are quick, Energy efficiency ranges from 95 to 98% (battery efficiency ranges from 70 to 80 percent) (A lead acid battery requires 30 % more energy than it stores.), Reversibility is excellent, charge and discharge rates are quite high, Internal resistance (ESR) is very low, resulting in a high cycle time, High efficiency (at least 95 %), as well as exceptionally low heating levels, Specific power is high. At 95 % efficiency, the specific power of electric double-layer capacitors may approach 6 KW/kg, Material toxicity is minimal, and there is no corrosive electrolyte, Simple charging methods-no need to check for full charge, and no risk of overcharging, the EDLC can provide energy for a limited period of time in various applications, lowering battery cycling duty and increasing battery life, the battery backup is excellent, battery severe discharge is

avoided, battery life is extended, one-fifth the weight of a battery, can even be used to replace batteries [14].

**Table 7.** Performance comparison of ultracapacitors and batteries [14]

Item	Ultracapacitor	Battery
Charging time	1–30 sec.	1–5 hours
Discharge time	0–30 sec.	0.3–3 hours
Energy density (Wh/kg)	5–15	20–150
Power density (W/kg)	2000–10,000	20–150
Charge/discharge efficiency	95%–98%	60%–80%
Recycle life	500,000–1,000,000	500–1000
Temperature range	–50–+70°C	–10–+40°C

### 10.2. Disadvantages

The amount of energy stored per unit weight is generally lower than that of an electrochemical battery (3 kW/kg–5 Wh/kg for an supercapacitors, though 85 Wh/kg was achieved in the lab as of 2010 compared to 30 kW/kg–40 Wh/kg for a lead acid battery), 100 kW/kg–250 Wh/kg for a lithium-ion battery, and about 1/1,000th the volumetric energy density of gasoline [14].

The highest dielectric absorption of any capacitor type, self-discharge rate is very high, much exceeding that of an electrochemical battery, low maximum voltage - larger voltages need series connections and voltage balancing, as the supercapacitors empties, the voltage across it lowers dramatically. Complex electronic control and switching equipment is required for effective energy storage and recovery, resulting in energy loss, when shorted, the capacitor's exceptionally low internal resistance allows for a very quick discharge, resulting in a spark danger comparable to that of any other capacitor of same voltage and capacitance [14].

## 11. Electrode Materials

K. Patel et. Al [15] reported an improved cycle stability with 98 % capacitance retention after 8000 cycles and a

volumetric energy density of 45.2 Wh/L [15].

In a typical experiment, a coating of PTH films on an activated carbon electrode resulted in a 50 % increase in the specific capacitance when compared to uncoated activated carbon electrodes [15]. Even after 5000 cycles, a retention rate of up to 90 % was found [15]. At 3 A/g current density in 1 M KCl, the original capacitance may be preserved up to 82 % after 1000 cycles. Even after 1000 cycles at a current density of 1 A/g, the composite displayed remarkable stability, retaining up to 92.4 % of its original value. At 1000 cycles, graphene as an EDLC material demonstrated a high retention capacity of more than 90% [15]. Compared to electrodes with 50% Nafion content, electrodes with 10% Nafion content offer roughly 50% reduced resistance to current flow in the Nafion electrolyte and Nafion/ Carbon layers [15]. Energy savings up to 30 % may be made by using the slowing or braking energy [15]. Researchers have recently begun to place a greater emphasis on clean and renewable energy because of energy scarcity and environmental damage caused by the continued use of nonrenewable fuels [15]. Shape memory alloys and piezoelectric materials may be used in combination with them [15]. Traditional electrolytic capacitors have a high dielectric strength and can withstand an infinite number of charge/discharge cycles [15]. Supercapacitors can hold ten to one hundred times more energy than normal capacitors [15]. Table 8 shows a comparison of the different attributes of supercapacitors against batteries [15]. Figure 10 shows the synthesizing rG<sub>0</sub> from graphene.

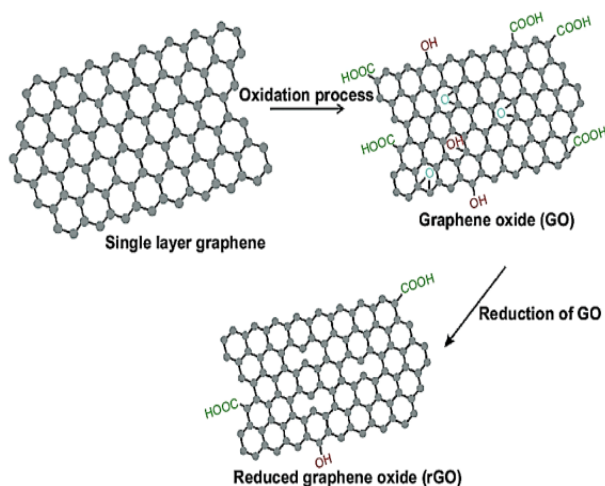


Figure 10. Synthesis of rGO from graphene [15]

Table 8. Compares capacitors to batteries and conventional capacitors [15]

Parameter	Battery	Supercapacitor	Conventional Capacitor
Specific-energy (Wh/kg)	10-100	1-10	<0.1
Specific-power (W/kg)	<1000	500-10,000	>10,000
Dis-charge time	0.3-3 h	a few s to > 1 min	$10^{-6}$ to $10^{-3}$ s
Charging time	1-5 h	a few s to > 1 min	$10^{-6}$ to $10^{-3}$ s
Charge and Discharge efficiency (%)	70-85	85-98	100
Cycle-Life	10,000	>500,000	Almost infinite

## 11.1. Rare Earths Based Electrode Materials

In General, research progress in rare earths and their composites-based electrode materials for supercapacitors the rare-earth metal oxides and hydroxides-based electrodes exhibit better electrochemical performances as shown in Table 9 and Table 10 rare-earth metal oxides/hydroxides have been composites with carbon to achieve better capacitances [16].

Table 9. Electrochemical performance of various rare-earth/metal oxide composites-based

Material	Electrolyte	$C_p$ ( $F g^{-1}$ )	Device	E.D (Wh $kg^{-1}$ )	PD (W $kg^{-1}$ )	Cyclic stability
MnO <sub>2</sub> /La <sub>2</sub> O <sub>3</sub>	1.0 M Na <sub>2</sub> SO <sub>4</sub>	245.4	Mn-La10 AC	25.8	0.3	-
CeO <sub>2</sub> /Fe <sub>2</sub> O <sub>3</sub>	6 M KOH	142.6	-	-	-	94.8%
CeO <sub>2</sub> @MnO <sub>2</sub>	1.0 M Na <sub>2</sub> SO <sub>4</sub>	255	CeO <sub>2</sub> @MnO <sub>2</sub>  AGO	27.5	500	82.2%
NiCo <sub>2</sub> O <sub>4</sub> /CeO <sub>2</sub>	3 M KOH + 0.1 M K <sub>4</sub> Fe(CN) <sub>6</sub>	2659	NiCo <sub>2</sub> O <sub>4</sub> /CeO <sub>2</sub>  AC	43.3	1550	99.6%
Pt <sub>10</sub> /NiCo <sub>2</sub> O <sub>4</sub>	2 M KOH	1635	Pt <sub>10</sub> /NiCo <sub>2</sub> O <sub>4</sub>   Pt <sub>10</sub> /NiCo <sub>2</sub> O <sub>4</sub>	6.6	150	-

Table 10. Electrochemical performance of various rare-earth oxides/hydroxides-based supercapacitors [16]

Material	Electrolyte	$C_p$ ( $F g^{-1}$ )	Device	E.D (Wh $kg^{-1}$ )	PD (W $kg^{-1}$ )	Cyclic stability
MnO <sub>2</sub> /La <sub>2</sub> O <sub>3</sub>	1.0 M Na <sub>2</sub> SO <sub>4</sub>	245.4	Mn-La10 AC	25.8	0.3	-
CeO <sub>2</sub> /Fe <sub>2</sub> O <sub>3</sub>	6 M KOH	142.6	-	-	-	94.8%
CeO <sub>2</sub> @MnO <sub>2</sub>	1.0 M Na <sub>2</sub> SO <sub>4</sub>	255	CeO <sub>2</sub> @MnO <sub>2</sub>  AGO	27.5	500	82.2%
NiCo <sub>2</sub> O <sub>4</sub> /CeO <sub>2</sub>	3 M KOH + 0.1 M K <sub>4</sub> Fe(CN) <sub>6</sub>	2659	NiCo <sub>2</sub> O <sub>4</sub> /CeO <sub>2</sub>  AC	43.3	1550	99.6%
Pt <sub>10</sub> /NiCo <sub>2</sub> O <sub>4</sub>	2 M KOH	1635	Pt <sub>10</sub> /NiCo <sub>2</sub> O <sub>4</sub>   Pt <sub>10</sub> /NiCo <sub>2</sub> O <sub>4</sub>	6.6	150	-

Models such as the Helmholtz model, the Gouy-Chapman model, and the Gouy-Chapman-Stern model may be used to explain the electrode charging behavior in an electrolytic solution under potential-static control, as illustrated in Figure 11.

## 11.2. Methods of Evaluation

Performance studies using single electrodes the working electrode was made by combining 80 wt% active electrode materials, 10 wt% conductive carbon, and 10 wt% polyvinylidene difluorides in 1-methyl-2pyrrolidinone (NMP) to make a homogenous paste, which was then coated on SS/Ni strips, Ni foam, or carbon paper, among other things. Using a three-electrode cell arrangement, the single electrode performance was measured using cyclic voltammetry, galvanostatic charge-discharge, and electrochemical AC-impedance after being dried at 80 C under vacuum for 12 hours [16].

Experiments with cyclic voltammetry the electrode material was determined using cyclic voltammetry (CV) [16]. CV is often performed in a certain potential range at various scan speeds. The current response of the working electrode was recorded after a potential waveform was applied to it [16]. The hypothesized charge storage mechanism of the electrode materials is depicted in Figure 2 based on the response (i.e., the form of the CV

curve) [16]. The non-Faradaic reaction-based charge storage mechanism was shown by the rectangular shape of the CV curve of the nitrogen-doped pomelo mesocarps-based nanosheet carbon electrode (N-PMNC) [16].

The CV curve of the  $\text{NiCo}_2\text{O}_4$  nanosheet on carbonized melamine foam electrode was non-rectangular, indicating a Faradaic reaction-based charge storage mechanism [16].

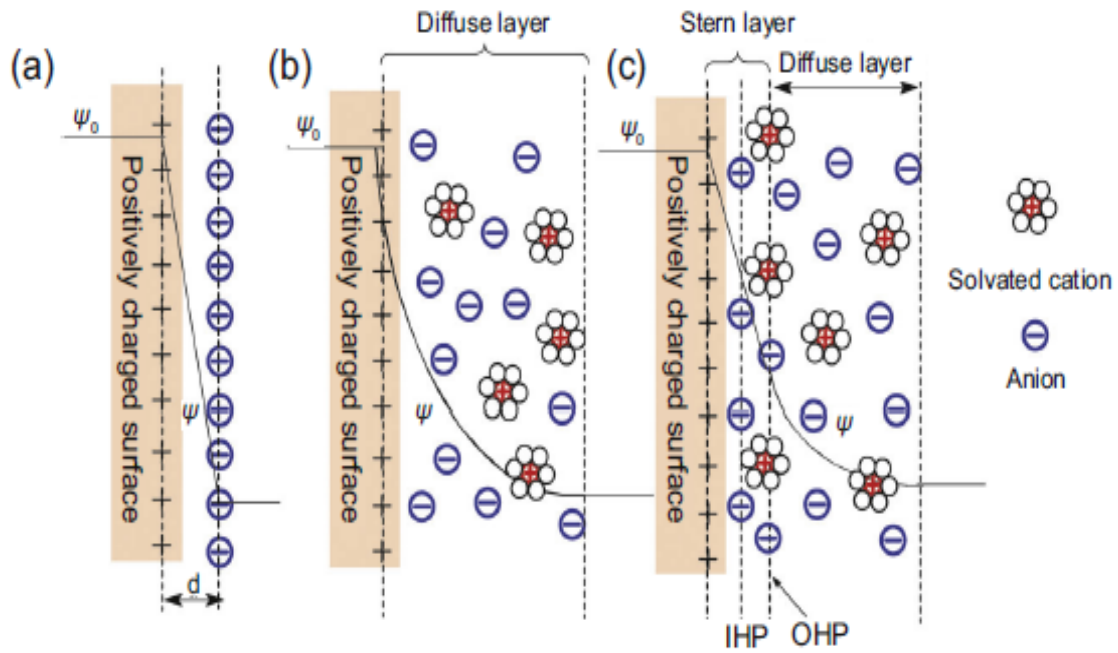


Figure 11. EDLCs models (a) Helmholtz model (b) Gouy-Chapman model (c) Stern model [16]

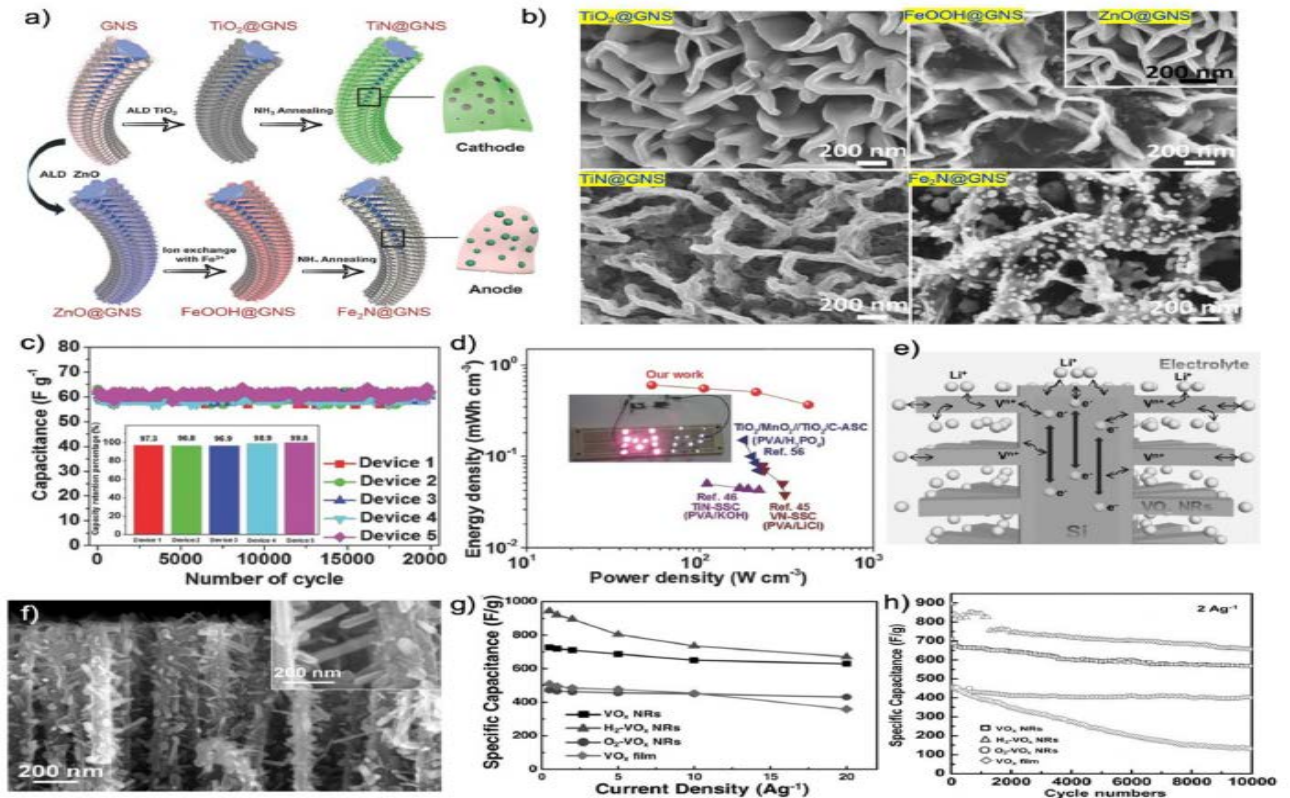


Figure 12. (a) Schematic and (b) SEM images illustration the preparation process and morphologies of TiN and  $\text{Fe}_2\text{N}$  on GNS. (c) cycling performance and (d) Ragone plot of corresponding SC device. (e) Schematic representation of  $\text{VO}_x$  NRs-Si NWs hierarchical structures used as SC electrode in  $\text{LiCl}$  electrolyte. (f) SEM cross-sectional view of as-synthesized  $\text{VO}_x$  NRs-Si NWs hierarchical structures; insets indicating the dimensions of the NR branches. (g) Specific capacitances of different  $\text{VO}_x$  NRs-Si electrodes compared to  $\text{VO}_x$  film-Si NWs under various current densities. (h) The specific capacitance values of various  $\text{VO}_x$ -Si electrodes along with the charge discharge process [17]

### 11.3. Atomic Layer Deposition in the Development

Figure 12 shows the preparation process and morphologies of TiN and Fe<sub>2</sub>N on GNS. A specific capacitance was achieved from such as-synthesized 3D NW architecture at a discharging current density of 0.5 Ag<sup>-1</sup>, which was 38.5% higher than that of Si NWs structure [17]. Although batteries have a high energy output (100-200 Wh/kg), they need more time to recharge, which results in low specific power performance [17]. As a result, supercapacitors are recognized as essential members of the energy storage family owing to their high specific power (500-10,000 W/kg) and satisfactory specific energy (1-10 Wh/kg) when compared to ordinary capacitors [17]. It's also worth noting that supercapacitors have a longer cycle lifespan and can be completely charged/discharged at a very quick pace [17]. Furthermore, the voltage windows are fully determined by the thermodynamic stability of the electrolytes [17]. Using an aqueous electrolyte with a low equivalent series resistance, a maximum voltage window of 1.0 V was attained (ESR) [17]. Although an organic electrolyte may work within a voltage range of 3.0-5.0 V, it is environmentally harmful and has a high ESR, which prevents it from obtaining high specific power [17]. As a result of its inexpensive cost, availability, and low toxicity, an aqueous electrolyte is often used in standard supercapacitors [17].

## 12. Conclusion

This review paper presented a clear highlight have about the recent development of supercapacitors with different electrode materials and configurations. Conducting polymers, carbon-based nanofillers, metal oxides, phosphides, sulfides, nitrides, and composites have displayed immense potential as supercapacitor electrode materials. The conducting polymer nanocomposite electrode material has been created by utilizing different TMOs (e.g.: Co<sub>3</sub>O<sub>4</sub>, V<sub>2</sub>O<sub>5</sub>), carbon materials (CNTs, Graphene, Activated Carbon, Cellulose). the rare-earth materials-based supercapacitors to understand the energy chemistry of rare earth materials. Rare-earth metal oxides and hydroxides-based electrodes exhibit better electrochemical performances, and hence they have been composited with carbon to achieve better capacitances. The evaluation methods for the electrode materials and device performances have also been discussed. However, still many challenges yet exist to be solved to control size, shape, etc. Supercapacitors have been recognized as appropriate storage devices for several applications, such as electronic gadgets, hybrid electric cars, and huge industrial equipment. Recent development in TMO, CP, and TMO/CP-based fibers has been highlighted and examined in this paper. Although TMO and CP-based Fibers have good electrochemical performance, these individual pseudo capacitor materials

have some limitations. Nano-advancements in ALD could lead to a new avenue of low-cost nanomanufacturing of novel SCs and LIBs devices. The future should see the development of more advanced ALD-based techniques for next-generation energy storage applications.

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