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Recent development of carbon based materials for energy storage devices

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ABSTRACT

The enormous demand of energy and depletion of fossil fuels has attracted an ample interest of scientist and researchers to develop materials with excellent electrochemical properties. Among these materials carbon based materials like carbon nanotubes (CNTs), graphene (GO and rGO), activated carbon (AC), and conducting polymers (CPs) have gained wide attention due to their remarkable thermal, electrical and mechanical properties. On this account, the present review article summarizes the history of ESDs and the basic function of various types of ESDs. Further, the various nanomaterials used in energy storage devices for the past few years have also been discussed in detail. In addition, the future trend in the development of highly efficient, cost-effective and renewable energy storage materials have also been highlighted.

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1. Introduction

With the rapid development of economy and escalating use of portable electronic/electronic vehicles, energy storage has become the most imperative topic worldwide and has attained an intensive attention of researchers and industrial developers. Energy can be stored in various forms like thermal, chemical, electrical and electrochemical energy [1]. Thermal energy provides cooling (air condition) or heating (geezers) using electricity. Wind and solar energy are the ubiquitous natural resources that provide electrical energy. Fossil fuels store energy as chemical form while in case of electrochemical energy storage, the electrical and chemical energies are interconvertible within a fraction of time [2]. Energy storage materials such as batteries, supercapacitor, solar cells, and fuel cell are heavily investigated as primary energy storage devices [3–6]. Their applications are increasing enormously growing from smart microbatteries to large-scale electric vehicles. Thus a high performance, smaller, lighter, versatile and more economically viable energy storage devices (ESD) are required in the future to fulfill the requirement. There are a variety of organic and inorganic or their nanocomposites are widely being used as a material for ESD. These materials include metal oxides, conducting polymers, graphene, CNTs, metal organic framework etc. [7–10] However, nanostructured materials play a critical role in the development of energy conversion and storage applications. They possess a characteristic dimensions with new properties and possibilities.

On this account, the present review article summarizes the history of ESDs and the basic function of various types of ESDs. Further, the various nanomaterials used in energy storage devices for the past few years have also been discussed in detail. In addition, the future trend in the development of highly efficient, cost-effective and renewable energy storage materials have also been highlighted.

2. History of energy storage devices and materials

There are number of energy storage devices have been developed so far like fuel cell, batteries, capacitors, solar cells etc. Among them, fuel cell was the first energy storage devices which can produce a large amount of energy, developed in the year 1839 by a British scientist William Grove [11]. National Aeronautics and Space Administration (NASA) introduced the first commercially used fuel cell in the year 1960, in which they used Grove's approach to generate electricity [11]. Afterward, number of modification have been made to improve its energy production ability. After that, researchers have focused on the storage of electrical energy and developed energy storage devices such as battery and capacitor (supercapacitor). The first battery (lead-acid) was developed by Gaston Plante

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in the year 1859. However, Emile Alphonse Faure was the first who commercially introduced lead-acid battery in the late nineteenth century (1880) after his invention of sticky plates [12]. In his development, he coated lead plates with a paste of lead powder and sulfuric acid, which helps in the storing of charges and improves the storage capacity of the battery. This process has been widely used by the other researchers and the improvement in storage capacity has been observed. For instance, Sellon has patented a process by using the Faure's process to make a battery, in this work they applied the same paste on a perforated plate and found that the resulted battery has a higher storage capacity than the Faure's battery [13]. Later on, in the year 1961 an electronic double layer capacitors (supercapacitors), were the first time established and patented by American Oil Company, Standard Oil of Ohio (SOHIO). Afterward, these devices have attracted great attention to the researchers and a remarkable improvement have been observed in the development of these devices. Another, tremendous improvement in the field of energy storage was the development of solar cell devices, which have brought a new revolution in energy storage application. The concept of solar cell was first introduced by Becquerel in the year 1839 and developed first solar cell devices [14]. To improve further storage ability and stability of these devices, researchers have explored number of materials like carbon-based materials, metal oxides, composite, and hybrids etc. which can be used in the energy storage application and have been discussed in proceeding sections.

3. Energy storage devices

In contrast to the growing demand of electricity and depletion of fossil fuel lead to the increase in development of various non-conventional energy storage devices. Among those batteries, supercapacitors (SCs), and fuel cells are the most significant energy storage devices [45]. These are discussed in the following subunits:

3.1. Batteries

Electrochemical batteries are considered as the most important device for energy storage. It produces electricity by releasing the potential energy stored in the chemicals of the battery. A traditional battery consists of two electrodes (cathode and anode), an electrolyte, and a separator (insulating and porous material) [15]. However, increasing demand of portable electronic devices has led to the drastic improvements in their performance. On this account, lithium ion batteries have gained considerable attention and have diverse applications. Fig. 1 represents a mechanism on which a conventional lithium ion batteries works. Here, the transport of lithium ions changes during charging and discharging process, i.e., the lithium ions transfer from anode to cathode during charging and vice-verse during discharging [16]. The pioneering work in 1991 by Sony Corporations has introduced a high performance Li-ion battery with high-voltage, and high-energy for portable electronic applications. Here, they have used a graphite material as a host anode structure in which lithium was accommodated. Since then, graphite has remained the choice as a host anode structure; while the blended cathode materials have implemented to further improve their performance.

3.2. Fuel cells

Fuel cells have become a ubiquitous material of 21st century for energy storage applications ranging from cell phones to

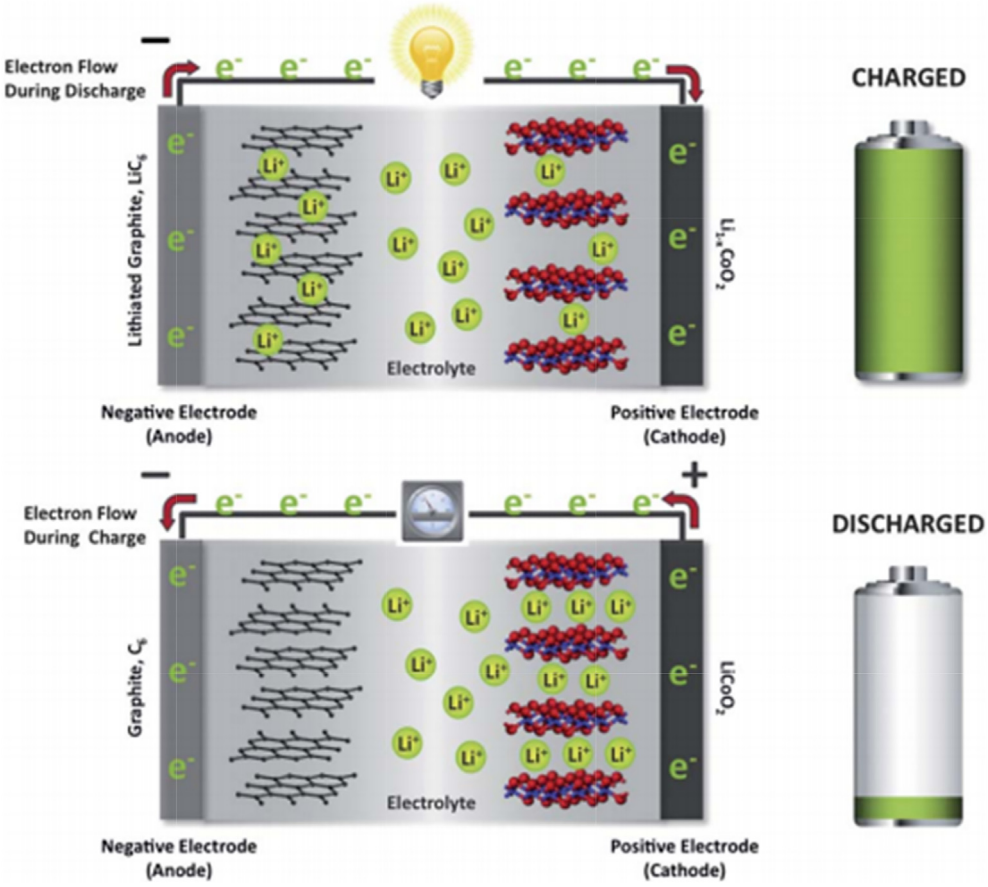


Fig. 1. Schematic representation for working principles of lithium ion batteries. Reproduced from Ref. [16] with permission from The Royal Society of Chemistry.

automobiles and power plants, due to their high efficiency, excellent load performance, low pollutant's emissions, and a wide range of size. Fuel cell is an electrochemical device that converts chemical energy directly into electrical energy [17]. In architecture, fuel cell also resembles with a battery i.e. consisting of two electrodes and an electrolyte. Nevertheless, different from battery, fuel cell does not require charging as the species consumed during the electrochemical reactions are continuously replaced. Fig. 2 illustrates the basic components of a fuel cell [18].

3.3. Supercapacitors

Supercapacitors (SCs) are also one of the most accessible and viable energy storage devices that have high power density and fast charge discharge capacity, which made them to stand alone as high potential and most demanded energy storage device compared to other devices. Recently, the thin and freestanding supercapacitor has covered a large area of consumer electronics, wearable, and portable electronics. Although in architecture point of view, these are very much similar with solid electrode batteries, it has thousands of times high power density, low maintenance, and long life cycle [19,20]. It consists of two electrode-containing electrolytes, which are separated by a separator [21]. The overall performance of a SC mainly governed by the type of electrodes, separator, current collector, and electrolytes (Fig. 3). While high power density (>10 Wh Kg^{-1}), long cycle life (100 times more than batteries), charge-discharge within seconds, low self-discharging are also the key parameters that evaluate the performance of SC [22]. SC stores charge in the form of capacitance and can be calculated by using Eq. (1). Power density, and maximum energy can be calculated according to the Eqs. (2) and (3).

$$C = i/m(dV/dt) \quad (1)$$

$$\text{Energy density} = (1/2) * CV^2 \quad (2)$$

$$\text{Maximum Power} = V_i^2/4mR_s \quad (3)$$

where, i is the current in amperes, m is either the mass, volume, or area, dV/dt is the change in voltage over the change in time in volts per second, V_i is the initial voltage of the device in volts, R_s is the equivalent series resistance in ohms, and V is the voltage of the SC in volts.

On the basis of charge storage mechanism, SC can be of two types (ii) electrochemical double layer capacitor and (ii) pseudocapacitor. In electrochemical double layer capacitor (EDLC), the storage of charge occur at electrode-electrolyte interface, while in pseudo capacitor charge is stored via Faradic reaction (charge transfer reaction between electrode and electrolytes) [23]. In case of EDLC, the specific capacitance of each electrode is equal to that of parallel plate capacitor.

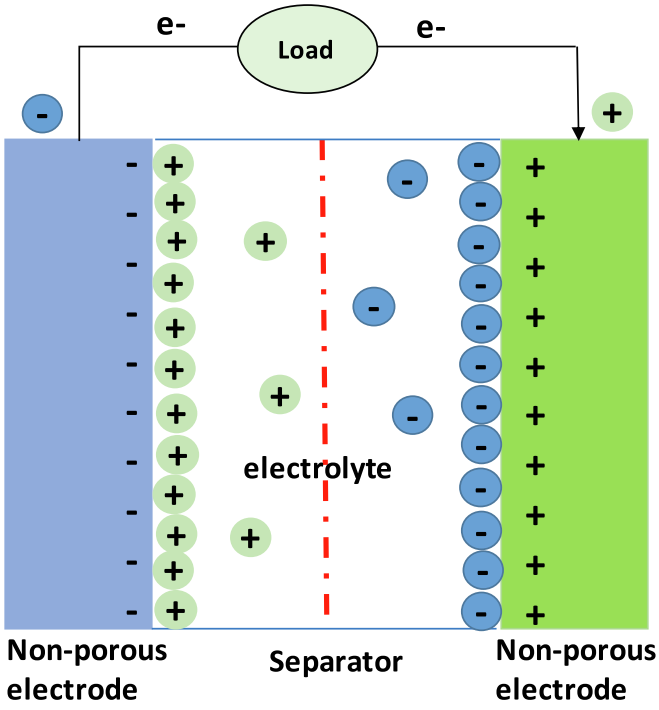


Fig. 3. Schematic diagram of two-cell supercapacitor.

4. Materials for energy storage

There are number of materials have been fabricated so far, which showed their potential in energy storage devices like carbon nanotubes (i.e. single walled and multiwalled), graphene, conducting polymers, metal oxides etc.

4.1. Carbon nanotubes (CNTs) based materials for energy storage

CNTs are one-dimensional nanostructures materials widely used and most attractive candidate for the application in energy storage. They possess excellent electrical, thermal, mechanical properties, high surface area, large surface-to-weight ratio, and good storage capacity [24]. Literature survey revealed that number of works have been reported on CNT based materials for their application in energy storage.

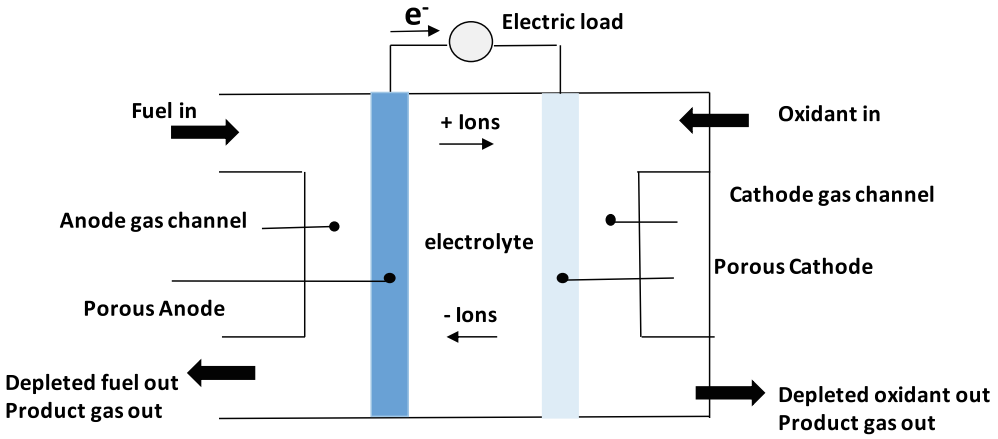


Fig. 2. Basic components of fuel cell.

4.1.1. CNT based materials in battery

For instance, He et al. [25] have synthesized Fe_3O_4/CNTs nanocomposite and studied its electrochemical behavior. The authors observed that the composite displayed excellent discharge capacity (656 mAh g^{-1}) and found to stable up to 145 cycle. The superb electrochemical performance of these materials may be attributed to the formation of conductive network within the composite. Wei and co-workers have fabricated MWCNT/S composite materials for their application in batteries. They showed that the synthesized materials exhibited excellent retention capacity of 96.5% for 100 cycles and found to be a potential cathodic material for Li-ion batteries. The superior electrochemical properties of the composite could be ascribed to the homogenous dispersion of MWCNT, which provides better ion transfer within the composite [26]. Afterward, Kim et al. [27] have prepared a core-shell nanowire using CNT and amorphous $FePO_4$ through solution mineralization process and investigated their electrochemical properties. They found that the composite exhibits superior specific capacity (1000 mA g^{-1}) and much higher rate capability compared to other reported composite. The authors also showed that the core-shell structure of the composite lead to the better transport of Li-ion, which improves the electroctrochemical properties and can be used as an environment friendly cathode material for Li-ion battery. Jian et al. [1] have synthesized CNT/RuO_2 core-shell composite by sol-gel approach and investigated its electrochemical performance. They observed that the composite displayed excellent efficiency (79%) with charge and discharge over potentials of 0.51 V and 0.21 V at a current of 100 mA g^{-1}. Xie and his coworkers [28] have developed an efficient electrode material by tin (Sn) and CNT using chemical vapour deposition method. The Sn/CNT nanopillar has been grown the surface of carbon paper and acted as a freestanding anode material for Na-ion battery application. The synthesized electrode showed an outstanding reversible capacity (887 mAh cm^{-2}) and exhibited excellent cyclability up to 100 cycles. Recently, Hong et al. [29] have formulated γ-Fe_2O_3/CNT composite for their application in the field of energy storage. The composite showed superior cycling capacity (1186.8 mAh g^{-1}) even after 400 cycles at a current of 200 mA g^{-1} along with excellent reversible capacity (518.5 mAh g^{-1}). These properties of γ-Fe_2O_3/CNT composite provide an extra edge to act as an anode material in Li-ion battery application.

4.1.2. CNT based materials in supercapacitor (SC)

Due to their exceptional chemical and thermal stability CNT have also been widely used in the supercapacitor (SC) application. Number of reports have been available which covers the synthesis of CNT based materials for application in SCs. For instance, Chen et al. [30] have reported the synthesis of CNT based PPy electrode and investigated their capacitive performance. This materials displayed superior electrochemical performance as compared to pristine conducting polymers and overcome the drawback associated with CP based SC i.e. fast capacitance decay. Authors showed that the fabricated electrode showed excellent stability, flexibility, long life and can be able to retain 95% capacitance even after 10,000 cycles. Later on, Sun et al. [31] have developed a composite material using PPy, CNT, and urethane for their application in stretchable yarn SC. The PPy@CNTs@urethane hybrid exhibit excellent capacitive performance and able to withstand around 80% even at high strain. This showed their potential in the field of an excellent SC. Gu et al. [32] have fabricated MnO_2/CNT and Fe_2O_3/CNT macro films for their application in SCs. The authors found that the said film is stretchable and displayed high capacitive performance as compared to pristine CNT, MnO_2 and Fe_2O_3. The excellent behavior is attributed to the synergistic effect of individual component. Yu et al. [33] have fabricated a stretchable film possessing excellent electrochemical performance, having specific capacitance of 1147.12 mF cm^{-2} at 10 mV s^{-1}. These materials can bear a strain (omnidirectional) of 200% that found to be twice the maximum strain bare by biaxially stretchable SCs based on CNT. This can be ascribed to the interficial bonding between CNT and the substrate molecule. Afterwards, Simotwo and co-workers [34] have prepared polyaniline (PANI) and polyaniline based CNT (PANI/CNT) nanofibers by electrospinning techniques. They showed that the synthesized materials can be a potential candidate for the application in SC electrode. The PANI/CNT hybrid electrode showed best performance (i.e. specific capacity of 385 F g^{-1}) as compared to that of pristine PANI (308 F g^{-1}). The interconnected network in PANI/CNT hybrid provides better electron transport to the active site leading to the best performance of hybrid electrode.

4.1.3. CNT based materials in solar cell

Choi et al. [35] have developed graphene-based multi-walled carbon nanotubes (GMWNTs) hybrid materials by chemical vapour deposition. The enhanced electrochemical properties lead to their application in photovoltaic devices. Hsieh et al. [36] have fabricated dye-sensitized solar cells (DSSCs) using CNT and graphene nanosheets (GNs). The enhancement in the performance of these materials may be ascribed to the additive effect of CNT and graphite, which provides excellent redox activity and charge-transfer. Li et al. have casted a CNT film on to the $CH_3NH_3PbI_3$ substrate to develop a perovskite solar cell. The CNT film provide a flexibility in the devices and increases the electron transport within the device. This results in the enhancement in electrochemical performance of these devices. Afterwards, Yan et al. [37] have introduced the CNT materials in the DSSC devices to improve their flexibility, mechanical integrity, and electrocatalytic activity. The increase in the electrocatalytic activity showed their potential in photovoltaic application.

4.2. Graphene based materials for energy storage

Graphene has emerged as a promising electrode material for the fabrication of energy storage devices owing to its superior electronic, thermal, and mechanical properties. The proceeding sections discussed the graphene based materials in different ESDs.

4.2.1. Graphene based materials in battery

In contrast to CNTs, graphene are robust electrode material because of strong inter-sheet Van der Waals force of attraction. Additionally, large surface area, microporosity, good electrical conductivity are the key features, which make them potential candidate for energy storage application. In this regard, Reddy and co-workers [38] have synthesized nitrogen doped graphene films by chemical vapour deposition technique and investigated its electrochemical properties. The composite film showed far superior capacitive behavior than virgin graphene film. The superior reversible discharge properties of the composite film can be due to the introduction of large number of defects on the surface of graphene that lead to the higher interaction between the N and graphene. These intercalation properties of the composite film led to their potential scope in the field of Li-batteries. Later on, Wu et al. [39] showed a comparative study by synthesizing nitrogen doped graphene and boron doped graphene material for Li-ion battery (LIB) application. They have synthesized the said materials by heat treatment process. The authors observed that the composite materials displayed outstanding specific capacity 199 mAh g^{-1} (N-doped graphene) and 235 mAh g^{-1} (B-doped graphene) at 25 A g^{-1} along with excellent rate capability and cyclability. It is worth to note that the composite materials showed fast charge and discharge with a short interval of time (i.e. 1 h to several 10 s). These properties of the composite could be beneficial for heavy duty LIBs. Wang et al. [40] have fabricated an anode material for Li-ion

battery application by using manganese oxide (Mn_3O_4) and reduced graphene oxide (rGO). The Mn_3O_4 nanoparticle has been grown the surface of rGO sheets. The excellent interaction between these moieties lead to the enhancement in various electrochemical properties like specific capacity, cyclability, and rate capability. They displayed outstanding specific capacity of 900 mAh g^{-1} and found to be a suitable candidate for battery application. Afterward, Sun and group [41] have synthesized a hybrid material of MoO_2 and graphene by solution phase process. The synthesized nanohybrid have been tested for LIB application and the authors found that the said material exhibits excellent reversible specific capacity (848.6 mAh g^{-1}) and clyclability (100% up to 70 cycle) at a current density of 500 mA g^{-1}. It is important to note that the synergistic properties of these two moieties lead to their superior specific capacity and charge storage ability. Moreover, this nanohybrid has been synthesized without using any seed crystal, templates and additives; therefore, it can be used in industrial scale. Yang et al. [42] have prepared a composite cathode material for lithium-sulfur (Li-S) battery application by using sulfur, porous carbon and graphene. The graphene acted as a matrix as well as conducting channel for Li-S battery while the porous carbon acted as a polysulfide reservoir to improve the vehicle effect. The authors noticed that the composite materials displayed superb electrochemical properties with high specific capacity and rate capability than the graphene-sulfur composite. The excellent properties of the porous carbon-S-graphene composite could be attributed to the homogeneous dispersion of S within the porous carbon and the better interaction between the porous carbon and graphene. This interaction provides a passage for fast electron transport between the moieties and hence, an increase in conductivity is observed which lead to their application in battery application. Wang et al. [43] have formulated a composite material by using graphene and sulfur by heating. They have explored their electrochemical properties and found that the materials showed enhanced performance in term of stability, cyclability and performance as compared to bare sulfur electrode. This may be due to the conducting coating of graphene lead to the better charge transport in the composite material leading to the increase in efficiency of the material. Further, Lavoie and co-workers [44] have designed high performance composite material for lithium ion battery using Mn_3O_4, graphene, and lithium carboxymethyl cellulose (LiCMC). The synthesized composite materials exhibits high specific capacity (700 mAh g^{-1}) and cyclability (>100 cycles). Wang et al. [45] have reported the synthesis of graphene coated polyethylene terephthalate (G-PET) film and studied their electrochemical performance. The authors found that these materials showed excellent performance having energy density of 452 Wh kg^{-1} along with retention of 96.8% after 30 cycles. They showed that this material may find their use as a low cost, high performance energy collector for lithium ion battery. Yuan et al. [46] have fabricated a graphene-nanocrystal composite (Ge/RGO/C) by using graphene and carbon coated germanium (Ge) nanocrystal. The authors have fabricated a sandwich structure of the composite by carbonization process. The said composite exhibited superior electrochemical performance and found suitable anode material for Li-ion battery as well as fuel cell application. It interesting to note that the said nanocomposite electrode may light many LED's, electric fan and other devices as well. Afterward, number of graphene based materials have been synthesized and investigated their electrochemical performance.

Abe et al. [47] have investigated the capacitive performance (positive, P/negative, N) of the $LiFePO_4$/graphite composite for their use in lithium-ion batteries. The authors found that the said material displayed excellent performance having charge-discharge cycles over 5000 times. The authors also reported that the lower N/P ratio the deeper would be the Li-ion intercalation for the negative electrode. The lower the N/P ratio higher will be the performance of the material but lower will be the overall capacity. The decrease in capacity may be due to aging by cycling. Zhang et al. [48] have reported the synthesis of $Na_3V_2(PO_4)_3$ incorporated graphene composite microsphere via spray drying process (Fig. 5). The electrochemical performance of the composite system has been studied and observed that the said material exhibited high specific capacity (115 mAh g^{-1} at 0.2 C), rate capability (44 mAh g^{-1} at 50 C), and cyclability (81% specific capacity retention even after 3000 cycle). The superior electrochemical properties of the composite may be attributed to the formation of highly conductive path, which provides better electron transport, hence an increase in electrochemical properties is observed. These materials may find their potential in the field of Na-ion batteries as a cathode.

Afterward, He et al. [49] have synthesized a composite material using tin oxide (SnO_2), nickel oxide (NiO), and rGO, which acted as an anode for Na-ion battery, as well as Li-ion battery application. The authors found that the NiO/SnO_2/rGO composite displayed excellent specific capacity of 800 mAh g^{-1} at a current density of 1000 mA g^{-1} along with superior cyclability (400 cycles). The excellent electrochemical properties of the composite may be ascribed to the homogeneous mixture of NiO and SnO_2 with rGO, which reduces the Li-ion diffusion path and increase the flow of electron that led to the enhancement in electrochemical properties. Yu et al. [50] have fabricated highly porous graphene nanoribbon foam by using chemical vapor deposition and Ar^+-plasma etching process for Al-ion battery application. The electrochemical properties of the said foam have been investigated and they found that the foam displayed excellent specific capacity of 123 mA h g^{-1} at current density of 5000 mA g^{-1}), along with superior cyclabilty (up to 10,000 cycles). The authors also noticed that the synthesized foam also exhibited high flexibility, surface area, superb mechanical property, and conductivity. Moreover, the fast charging (80 s) and slow discharge (3100 s) ability along with superb stability of the synthesized foam may open their wide scope in the field of Al-ion batteries.

4.2.2. Graphene based materials in supercapacitor

Le et al. [3] have synthesized a TiO_2/graphene composite for Sodium (Na)-ion capacitor by microwave assisted solvothermal approach. Literature revealed that the major drawback in the Na-ion capacitor is in their high capacitive performance. The authors found that the fabricated materials showed superior capacity (268 mAh g^{-1}) at a current density of 0.2C. After the cyclability over 18,000, the specific capacity of the said composite is found to be 126 mAh g^{-1} at 10 C. Therefore, it may considered as a potential candidate for Na-ion capacitor. A high performance three-dimensional (3D) composite materials have been formulated by Zuo and co-workers using SnO_2 and graphene (Fig. 4). The authors have tested their electrochemical properties and observed that the 3D composite material displayed outstanding reversible capacity of 720.8 mAh g^{-1} at a current density of 100 mA g^{-1}, even after 100 cycles. The outstanding electrochemical properties of the composite may be ascribed to the 3D structure of the composite and high surface area. The large surface area provides more space for interaction between the moieties resulting in the fast kinetics and better electron transport that led to their potential in battery application as well as in supercapacitor [51].

4.2.3. Graphene based materials in solar cell

Casaluci et al. [52] have prepared a dye-sensitized solar cell (DSSC) device using graphene ink by spray coating. The fabricated module can act as a counter electrode and may replace platinum. The said material exhibits high power conversion efficiency of ~3.5% and may find their potential in the field of photovoltaic devices. Wang et al. [53] have developed graphene based materials



Fig. 4. Schematic representation for the formulation of SnO_2/graphene oxide composite. Reprinted with permission from ref. [51]. Copyright (2018) American Chemical Society.

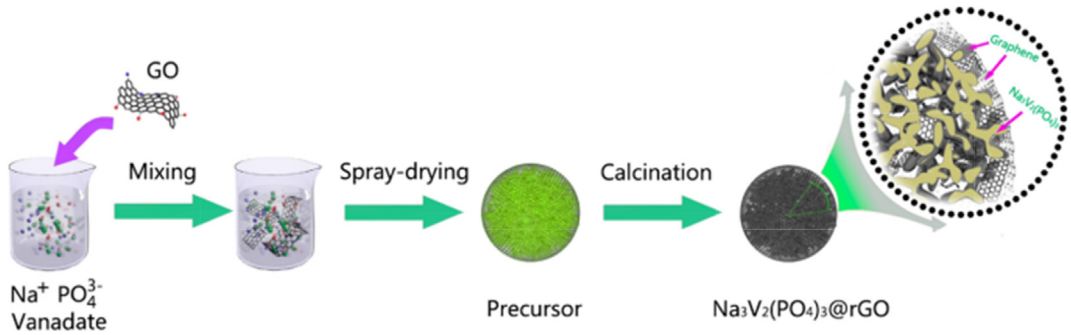


Fig. 5. Schematic representation for the formulation of $Na_3V_2(PO_4)_3$/rGO composite. Reprinted with permission from ref. [48]. Copyright (2018) American Chemical Society.

for DSSC devices and investigated their electrochemical performance. The authors found that the material can act as a cathode electrode having high conductivity and electrocatalytic activity. Han et al. [54] have formulated a composite material using reduced graphene oxide (rGO) and TiO_2 and studied their electrocatalytic activity. The rGO/TiO_2 hybrid material provide better charge transport and reduces the interfacial resistance that efficiently enhances the current density and power conversion efficiency. Further, Balamurugan et al. [55] have reported the synthesis of composite material using iron nitride (FeN) nanoparticles and nitrogen-doped graphene (NG). This composite material showed excellent power conversion efficiency of 9.93% and may find their application as DSSC devices. Cui et al. [56] have prepared a series of composite material and investigated their counter electrode. They have reported that among different composite, CoN_4/GN composite was found to be active and stable counter electrode, having superior power conversion efficiency. Recently, Lee et al. [57] have fabricated a paper based electrode by using graphene dot (GD) and PEDOT:PSS. They found that the GD/PEDOT:PSS electrode displayed improved electron transport, which further improves the efficiency of the fabricated cell 3-fold as compared to pristine paper electrode. Authors showed that the synthesized counter electrode may find their potential in the field of DSSC due to their excellent electrocatalytic activity and low cost.

4.3. Activated carbon based materials for energy storage

Apart from graphene, another excellent carbon based material is activated carbon (AC), which finds their potential in energy storage devices because of their excellent electrical conductivity and high surface area [58]. In order to improve its electrochemical properties the AC should have narrow pore size and high surface area. These properties of the AC have been further improved by the incorporation of other materials such as conducting polymer, metal oxides, and other carbon based materials. For this account, an efficient energy storage material have been fabricated by Fan et al. by using graphene, MnO_2, activated carbon nanofiber (ACN). The synthesized hybrid materials have been tested for supercapacitor application. They found that the composite materials exhibited brilliant specific capacitance (97%) after 1000 cycles and find a potential candidate for electrochemical supercapacitor application [58]. Later on, Wang et al. [59] have fabricated activated carbon cloth (ACC) for their application in solid-state supercapacitor. They displayed excellent electrochemical properties

having specific capacitance of 8.8 mFg^{-1} at a scan rate of 10 mV/s and found be much higher than that of normal carbon cloth. Further, the authors also demonstrated that the fabricated ACC also have high charging rate with retention of 50% capacitance. Therefore, this material found to be a best candidate for flexible and high performance capacitor. A porous, ultrahigh activated carbon based material have been synthesized by Zhang and group for Li-S battery application. The synthesized materials showed high surface area (3164 m^2 g^{-1}) and superior electrochemical properties with specific capacity of 1105 mA h g^{-1}. The fabricated material showed excellent retention capacity (up to 51%) after 800 cycle and found to be a potential cathode material for Li-S battery application. The excellent properties of the said composite is due to the high surface area and large pore volume that helps in the homogenous dispersion of sulfur into the AC, hence an increase in electrical behavior is observed [60]. Further, Luo et al. [61] have investigated electrochemical properties of CNT, graphene, graphite and activated carbon based materials for an efficient anode material for Na-ion batteries. Afterward, Li et al. [62] have incorporated nitrogen (N) into the AC and studied its electrochemical performance. They observed that the incorporation of N enhances the electrochemical properties especially an increase in energy density (230 W h kg^{-1}) is observed. The nitrogen doped activated carbon displayed high specific retention (76.3%) even after 8000 cycles. These properties of the synthesized composite material lead to their application in hybrid supercapacitor. Further, Barzegar et al. [63] have formulated an asymmetric capacitor by using activated pinecone carbon (APC). They displayed high surface area (808 m^2g^{-1}) and brilliant specific capacitance of 69 F g^{-1} at a current density of 0.5 A g^{-1} along with superior energy density (24.6 W h kg^{-1}), and find application in low cost, environment friendly carbon based capacitor. To further improve the electrochemical properties of AC, sulfur incorporated activated carbon composite have been prepared by Lee and co-workers. They showed that the electrochemical performance of the said composite increases with the incorporation of sulfur into the AC and can be used for Li-S battery application. The interaction between sulfur and AC increases, which reduces the distance between the layers and improves the Li-ion transport and storage ability of the composite. The authors found that the composite showed high specific capacity (1351 mA h g^{-1}) and the specific capacity is found to be decreases only up to certain limit (920 mA h g^{-1}) after 300 cycles [64]. Tai et al. [65] have prepared AC from graphite by high temperature annealing process using potassium hydroxide as a surface-etching agent. The fabricated AC exhibited high rate capability with superior reversible capacity (100 mAh g^{-1}), and cyclability (100 cycles) and may find its potential as a anodic material for potassium (K)-ion batteries. Recently, Yu et al. [66] have fabricated a flexible electrode using MXene ($Ti_3C_2T_x$) and AC by one-step chemical process (Fig. 6). The electrochemical capacitive performance of the synthesized material has been tested and it was observed that the composite electrode showed excellent capacitive behavior. The authors reported that the synthesized material displayed superior capacitance (126 F g^{-1}) at a current density of 0.1 A g^{-1} along with excellent charge retention ability (57.9%). The superb electrochemical properties of the composite may be due to the electrostatic interaction between MXene and AC, which provides excellent electron transport, as a result an increase in specific capacitance is observed. Here, MXene plays an important role and acted as a binder, conductive additive, and also provide flexible backbone to the electrode.

4.4. Conducting polymers based materials for energy storage

4.4.1. CP based materials in battery

Further, Wang and co-workers [67] have formulated a SnS_2/PANI hybrid and showed their potential in LIB application. They demonstrated that the hybrid material displayed superior reversible capacity and rate capability, which may be ascribed to the lamellar sandwich structure of SnS_2/PANI nanoplates. This sandwich structure facilitate fast transfer of electrons between the two moieties and inhibits the stacking of SnS_2 nanoplates as a result an increase in the capacity and cyclability is observed. Furthermore, the interaction between PANI and exfoliated SnS_2 offers short path length for Li^+ ion transport and further improves their charge-discharge ability. This induces the energy storage capacity, coulombic efficiency, and cyclability. Afterwards, Cao et al. [10] have fabricated the SnO_2/PPy hybrid composite and explored its electrochemical performance for energy storage. They demonstrated that the composite material showed outstanding specific capacity (646 mA h g^{-1}), along with superior retention ability (98%) even after 150 cycles. Authors revealed that PPy impedes the direct contact between the materials and electrolyte as a result a stable solid electrolyte interface (SEI) layer has formed, which plays important role to improve the stability as well as rate capability. Afterward, Parveen et al. [68] have fabricated polyaniline/titanium oxide/graphene (PANI/TiO_2/GN) composite and found that the synthesized composite exhibited excellent stability and cyclic ability i.e. 80% retention after 1000 cycle, which is found to much superior than the PANI/GN and pristine PANI. The superior

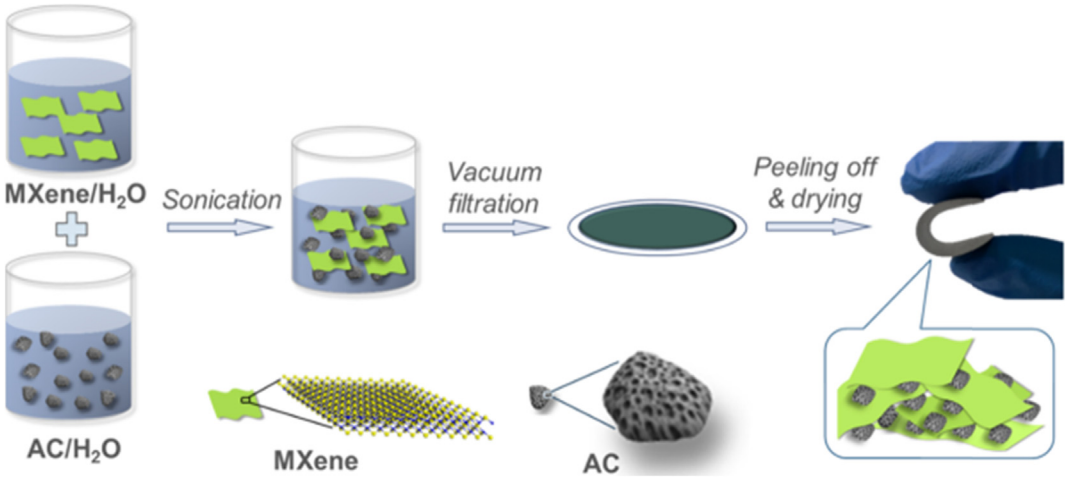


Fig. 6. Schematic diagram for the fabrication of MXene-bonded AC films. Reprinted with permission from ref. [66]. Copyright (2018) American Chemical Society.

electrochemical properties of the ternary composite mainly governed to the porous structure, which induces faster interaction between the electrode and electrolyte. The high surface area and faster electron transport lead to the enhancement in specific capacity of the composite.

4.4.2. CP based materials in supercapacitor

CP also finds their application in the field of supercapacitor. A number of work has been devoted on the CP based supercapacitor. For instance, Gao and co-workers [69] have prepared GO nanosheet/PANI nanowafer (GNS/PANI) hybrid material and explored their electrochemical properties. They found that the said hybrid material exhibited outstanding capacitance 329.5 F g^{-1} at a current density of 5 mVs^{-1}. They also showed that the said hybrid material also possessed superior life cycle. These properties of the hybrid make them a potential candidate for supercapacitor application. The excellent electrochemical properties of the hybrid composite may be due to their hierarchical structure, which enables fast electron transfer between the two moieties. Fan et al. [70] have fabricated a hybrid hollow sphere using polyaniline (PANI) and rGO by chemical polymerization approach. They showed that the hybrid electrode exhibited tremendous capacitance of 614 F g^{-1} at 1 A g^{-1} along with superior cyclability and stability. The outstanding electrochemical properties of the composite is mainly ascribed to the formation of conductive network between the moieties. The wrapping of rGO on the PANI surface induces the flow of electrons that facilitate the redox activity of PANI as a result an increase in electrochemical property is observed. Ye and co-workers [71] have formulated a hybrid graphene-PPy aerogel and investigated their capacitive performance. The synthesized aerogel displayed tremendous capacitance (253 F g^{-1}), stability, and excellent rate capability. The high surface area of PPy not only offer large space but also inhibit the restacking and aggregation of graphene sheets that facilitate the electron transfer process. These properties of the hybrid material make them efficient for high performance supercapacitor. A ternary hybrid material based on Polypyrrole (PPy), MnO_2, and carbon fiber (CF) have been fabricated by Tao et al. [72] for their application in supercapacitor. The authors demonstrated that the hybrid material showed excellent capacitance of 69.3 F cm^{-3} along with high energy density of 6.16×10^{-3} Wh cm^{-3}, and can be used as a new electrode material for energy storage devices. Wang et al. [73] have prepared mesoporous PANI/G hybrid and explored its electrochemical properties. They showed that the hybrid material possessed high capacitance (749 F g^{-1}) value at a current density of 0.5 A g^{-1}, which is found to be much higher in comparison to that of nascent PANI based electrode (315 F g^{-1}). This may be governed to the synergistic effect between PANI and graphene. In an another study, a flexible PANI/RGO/MWCNT ternary hybrid film have been formulated by reported by Fan and co-workers [74]. The composite film displayed superior capacitance and stability, and may acted as a excellent material for supercapacitor application. The MWCNT acted as a bridging element, which interconnects to the defects present in RGO leading to the formation of a conductive channel and enables fast transfer of electrons. Consequently, Jin et al. [75] have prepared a ternary hybrid material using graphene, SnO_2, and PANI and investigated its electrochemical performance. They showed that the synthesized composite materials exhibited outstanding capacitance of 913.4 F g^{-1} along with a good cyclic stability (1000 cycle), and rate capability. The homogeneous dispersion of graphene nanosheets enriches the mechanical strength and provides high stability to the hybrid composite. Liu et al. [76] have prepared hollow composite materials based on carbon microsphere and polypyrrole (PPy) via in-situ chemical oxidative polymerization. The coating (15 nm) of PPy onto the hollow carbon microsphere enhances the specific capacitance of 508 F g^{-1} at 1 A g^{-1}. This enhancement is mainly governed by the formation of thin coating of PPy on to the carbon microsphere resulting in the increase in electron transport.

4.4.3. CP based materials in solar cell

Cai et al. [77] reported the synthesis of composite material for their use in perovskite solar cell using poly(3-hexylthiophene) (P3HT) and bamboo structured carbon nanotubes (BCNs). The authors have investigated its electrochemical performance and found that the P3HT/BCNs composite material displayed superior electron transport and improves the efficiency of the material. The composite material showed efficient power conversion efficiency as compared of 8.3%, which is found to be much higher than that of virgin P3HT (3.6%). The addition of small amount of BCNs (1 wt%) considerably enhances the open circuit voltage (V_{oc}) and fill factor (FF). Li et al. [78] have fabricated conducting polymer based graphene electrode for their application in dye sensitized solar cell (DSSC). The different conducting polymer i.e. polyaniline (PANI), polypyrole (PPy), or poly(3,4-ethylenedioxythiophene) (PEDOT) have been used to prepared counter electrode (CE). These polymers have been intercalated with reduced graphene oxide (rGO) to formulate highly efficient electrode material for DSSCs. The authors found that among different counter electrode rGO/PPy electrode is showed excellent performance having maximum power conversion efficiency of 6.23% and found to be a potential candidate to fabricate efficient CE for DSSCs. Later on, Cogal and co-workers [79] reported the formulation of hybrid electrode using conducting polymer (i.e. PPy and P3HT) and multiwalled carbon nanotubes (MWCNT) for their use in DSSCs. The author found that the P3HT/MWCNT composite showed highest short circuit current densities of 5.61 mA/cm^2 as compared to PPy/MWCNT composite. The improved performance of P3HT/MWCNT composite is due to the excellent conducting properties of P3HT.

4.5. Fullerene materials for energy storage

Fullerene (C_{60}) is another important class of carbon in which carbon atoms are connected with single and double bond to form a closed mesh like structure [80]. Since, their discovery in 1985, they have gained enormous attention due to their chemical and thermal stability. The excellent conducting properties of these materials led to their use in energy storage devices. Arie et al. [81] have fabricated a fullerene-coated silicon thin film anode material for their use in secondary battery. They have coated the fullerene via plasma coating approach and found that the material exhibits excellent specific capacity i.e. >2000 mAh g^{-1}. The author found that the coating of fullerene helps in the improvement in conducting properties of the materials, which led to their use in battery application. Later on, Troshin and co-workers [82] have formulated fullerene (C_{70}) based materials for solar cell i.e. [70] fullerene, phenyl-C71-propionic acid propyl ester ([70]PCPP) and phenyl-C71-propionic acid butyl ester ([70]PCPB). It was found that the C_{70} molecule act as an better acceptor in comparison to that of photovolataic materials made up of C_{60} molecule and having 10% higher short circuit current density. These properties showed that these materials may find their application in the field of bulk heterojunction solar cells. Further, Yu et al. [83] have shown that grafting of C_{60} molecule on to graphene improves the efficiency of photovoltaic devices. These materials were used as an electron acceptor in poly-(3-hexylthiophene) based solar cell that enhances the efficiency of electron transport as well as overall performance of the solar cell having power conversion of ~1.22%. Zhang et al. [84] have prepared non-transition metal cluster (C_{60}) based cathode materials for their use in Mg-battery application. The specific capacity of this cathode was found to be 50 mAh g^{-1}. The enhanced performance of these materials was mainly due to

Table 1
Performance of various energy storage materials along with their application.

S. No.	Material	Application	Performance	Ref.
1	NiO/graphene	Li-ion battery	Discharge capacities of 759 and 104 mAh g^{-1} at 0.1 and 5 A g^{-1}	[87]
2	Polythiophene (PTh) infiltrated into TiO2 nanotubes (PTh-TNT)	Supercapacitors	specific capacitance (640 F g^{-1})	[88]
3	δ-MnO_2/holey reduced graphene oxide	Supercapacitors	specific capacitance (245 F g^{-1}), 64% capacitance retention	[89]
4	Thianthrene-functionalized polynorbornenes	Battery	Capacity of 66 mAh g^{-1} at an unprecedented high charge/ discharge potential of 4.1 V vs. Li/Li+	[90]
5	Ruthenium(II)-polypyridyl zirconium(IV) metal–organic frameworks	Solar cells	Maximum power conversion efficiency of 0.125%	[91]
6	Fe_3O_4/carbon nanotube composites	Li-ion batteries	Discharge capacity of 656 mAh g^{-1} and stable cyclic retention	[25]
7	CNT/PEDOT	Solar cells	Maximum power conversion efficiency of ~4.62%	[92]
8	TiO_2-Coated Carbon Nanotube-Silicon		Maximum power conversion efficiency of 15%	[93]
9	graphene/n-Si	Solar cell	Maximum power conversion efficiency of 8.6%	[94]
10	Zn-based MOF	Supercapacitors	Maximum specific capacitance of 251F g^{-1} in 1 M H_2SO_4 electrolyte	[95]
11	PANI/SWCNT composites	Supercapacitors	Specific power and specific energy values are 485 F g^{-1}, 228 W h kg^{-1} and 2250 W kg^{-1}	[96]
12	PANI-ZIF-67-CC)	Supercapacitors	Areal capacitance of 2146 mF cm^{-2} at 10 mV s^{-1}	[97]
13	Polyaniline (PAni) micro-rods polymer/n-Si	Solar cells	Current density of 14.72 mA cm^{-2}, having efficiency of 6.13%.	[98]
14	PPy-S/KB	Li-ion battery	Specific capacity of 823 mAh g^{-1} at 0.1C	[99]
15	PPy/Pb–$PbSO_4$	Supercapacitor	specific capacitances of 300–250 F g^{-1}	[100]
16	Activated carbon	Solar Cell	current density of 13.51 mA/cm^2 and power conversion efficiency (PCE) of 4.98%	[101]
17	N-Ni-CNF/ACF	Fuel Cell	maximum power density (~1850 mW/m^2	[102]
18	Polypyrrole-MnO_2	Li-S battery	Coulombic efficiency of ~98.6% and cyclability of 500.	[103]
19	MoS_2@CNT	Li-S battery	Specific capacity of 670 mA h g^{-1} stable up to 500 cycles at a current density of 1C	[104]
20	SnO_2@CSCNT	Solar Cell	Maximum power conversion efficiency of 14.3%	[105]
21	CNx/CNTs	Solar Cell	Maximum power conversion efficiency of 7.3%	[106]
22	Activated graphene nanoplatelets (aGNPs)	Solar Cell	Maximum power conversion efficiency of 7.7%	[107]
23	Fe–N–C/AC	Fuel Cell	Maximum power density was 4.7 ± 0.2 Wm^{-2}	[108]
24	Activated Carbon	Supercapacitor	specific capacitance (147 F g^{-1}), exhibit low resistivity (0.23 Ω) and fast frequency response (0.11 s)	[109]
25	AC/PANI	Supercapacitor	specific capacitance of 341 F g^{-1}	[110]

the presence of an extra electrons that delocalized on the entire C_{60} cluster and improving the efficiency of the said cathode. Noh et al. [85] have reported the synthesis of nitrogen doped fullerene (N-C_{60}), which acted as a catalysis for fuel cell and battery application. The authors have studied the density functional theory (DFT) calculations and ab-initio molecular dynamics (AIMD) to understand the design concept of this material. The authors found that the oxygen reduction reaction (ORR) and oxygen evolution reaction (OER) can be controlled by the varying N-content and the maximum result is obtained when the N-content is 10%. Recently, Friedl et al. [86] have reported the fullerene based novel liquid electrolytes system where fullerene and their derivatives acted as both anolyte and catholyte. These type of resources creates a revolution in the research field to establish a sustainable approach in the field of cheap and stable energy storage devices.

A detailed investigation of various materials pertaining to their application along with their performance has been provided in Table 1.

5. Future prospects and conclusion

A number of work have been reported on the development of energy storage materials and still lots of improvements need to done. Literature survey revealed that the two dimensional nanostructures materials have fabricated in enormous amount and very works have been reported on three dimensional materials. Therefore, future work should focus on the development of such type of materials. Further, literature also reveals that slight modification in the structure can improve the electrochemical properties. It was observed that the materials with high surface area and excellent conductivity enormously increases the specific capacity, cyclability and rate capability of material. Therefore, in future materials with high surface area and conductivity needs to be developed. The major challenge for the development of Li-ion rechargeable batteries, or any other battery is the knowledge of electrode-electrolyte interface in designing the new solid-solid or solid-liquid interfaces. Hence, the materials having good electrochemical properties are need to be used in the battery application. Recently, Moreover, new materials like metal-organic/inorganic framework also attracted great attention to the scientist and technologist but very scant articles have been reported on metal-organic framework. Further, literature reports that the various materials have been fabricated to replace the use of silicon in solar cell devices. But the efficiency of such materials is still poor. Therefore, the hybrid materials need to be developed in near future to enhance the power conversion efficiency of the synthesized materials. Similarly, in supercapacitor application, the materials showed excellent specific capacitance but their stability is a big challenge. So future development should focus on the development of such materials having high stability as well as excellent electrochemical properties. Overall, it can be concluded that the development of these materials will certainly enhance the energy storage capability and stability, which is also very necessary for ESDs.

In summary, the present review article highlights the history of ESDs and the basic function of various types of ESDs. Further, the

various nanomaterials used in energy storage devices for the past few years have also been discussed in detail. In addition, the future trend in the development of highly efficient, cost-effective and renewable energy storage materials have also been highlighted.

Declaration of Competing Interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.mset.2019.04.006.

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