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A review of flexible high-performance supercapacitors for the internet of things (IoT) and artificial intelligence (ai) applications

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Abstract: The Internet of Things (IoT) is a new area of modern technology today. Transportation, agriculture, healthcare, manufacturing, wearables, smart grid, energy-saving technologies, smart homes, smart management systems, and other fields of engineering, technology, and real-time management all have IoT applications. Moreover, artificial intelligence (AI) has broad applications in the car industry, surveillance, security, education, entertainment, gaming, e-commerce, portable gadgets, robotics, medicinal devices, etc. They require efficient energy to operate for an extended period. These devices necessitate offline and online energy storage devices that discharge for an extended period of time or require less time to charge advanced electrical energy storage devices such as supercapacitors. This review article reveals advanced energy storage devices such as supercapacitors and their applications in IoT and AI-based devices. A supercapacitor is an electrochemical capacitor that has high energy density and better performance efficiency.

1. Introduction

Supercapacitors, also known as ultracapacitors or electric double-layer capacitors (EDLCs), are energy storage devices that store and release electrical energy much more quickly than conventional batteries. Instead of a chemical process like batteries, they use a combination of electrostatic charges and electrochemical reactions to store energy in an electric field (Miller 2010). They can charge and discharge rapidly as a result, making them ideal for applications requiring high power bursts or quick charge times. Supercapacitors (SC) are divided into two types: electrochemical double-layer capacitors (EDLC) and pseudocapacitors (Conway and Pell 2003). It is further categorized based on applications, manufacturing, and materials. Electrolyte liquids are used to create electrodes with hydrophobic surfaces (Sharma et al. 2018). Surface chemistry is linked to the impact of ionic species. The electrode's surface morphology is studied for its electrochemical performance. Supercaps are a novel method of converting energy from chemical to electrical and vice versa. SC has the potential to be used as a replacement for batteries, which are constantly being developed but have a limited range of uses. In many instances, supercapacitors could be a much better solution (Wang et al. 2018). Batteries hold electrochemical energy through reversible chemical reactions of active masses but only meet a portion of the demand. In some instances, electrochemical batteries have a maximum charge/discharge cycle life of 400-500 cycles. The cause for this is that energy is lost due to heating during each cycle, limiting the cyclability of some batteries to several hundred cycles by convention. The supercapacitor has about 95% efficiency to exhibit charge/discharge operation because the heat loss from internal structures during each cycle is

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negligible in comparison with discharge and recharge time, which only lasts for several seconds or minutes (for short-circuit applications) or seconds or hours (for open circuit applications). The Internet of Things is a novel concept that refers to a network of physical objects embedded with software that interact via the internet (Fleisch 2010). IoT is classified into two types: remote-controlled and independent. When the remote-controlled kind of IoT fails to work properly, human intervention is required, but the autonomous type can control itself and execute based on preprogrammed rules (Kumar et al. 2019). The phrase IoT (Internet of Things) refers to a physical network that is linked to the internet, as well as software, sensors, actuators, and external peripherals. Physical things compose the communication network (Gatsis et al. 2017). The Internet is growing increasingly complicated and dynamic, pushing innovations and technical progress and opening up new options for organizations and consumers. There are a lot of internet-connected devices out there, and the number is only going to rise (Li et al. 2015). Statistical data reflecting the use of IoT over 75.44 billion devices by 2025 according to a Rangers report (Statista 2019). IoT plays an essential part in our lives by allowing humans and machines to communicate. In many ways, these technologies have already improved our lives. When it comes to the future of the Internet and technology, these two technologies are regarded as the next big thing (Lee et al. 2014). The latest applications of IoT (Internet of Things), AI (Artificial Intelligence), and ML (machine learning) in healthcare and biomedical instruments are exciting. This is mostly owing to their improved prediction, pattern recognition, and diagnostic analysis capabilities (Cao et al. 2004). IoT-based patient monitoring and diagnostic processes are being implemented in healthcare. It enhances the ability of healthcare organizations to provide high-quality services at a low cost and on time. Because of IoT and AI, electronics and telecommunications technologies are fast evolving. For AI applications, smartphones and, smart gadgets employ several types of smart sensors.

1.1 The novelty of the work

This article is a literature review. It is a synthesis of earlier research and investigation into the usage of supercapacitors in IoT and AI-based device applications. Because of their excellent performance, high energy density, high power density, high cycle rate, and extended life span, supercapacitors are also being investigated and evaluated for applications in a range of industries. A market study is also provided to assess current supercapacitor availability. A list of supercapacitor manufacturers, as well as critical specifications, was highlighted. All potential uses for which the supercapacitor could be useful have been examined.

1.2 The purpose of the study

The main purpose is to research more about energy sources and storage systems for IoT and artificial intelligence (AI) devices. Supercapacitors are currently required for modern devices that require steady, efficient energy to operate. As the Internet of Things and artificial intelligence technologies become more generally available, the market is increasingly utilizing them (Yoon and Lee 2018). The Internet of Things (IoT) technology is rapidly evolving. Traditional power sources and other electrical gadgets will be replaced, increasing the need for renewable energy sources. The usage of energy is an important part of the development of IoT and AI. Many research initiatives on energy management and power backup have been done in recent years to satisfy this need.

2. Supercapacitor technology

Capacitors accumulate charge on two parallel electrodes separated by a dielectric substance to store electrical energy. The capacity of a capacitor is the amount of charge stored per unit voltage applied across its plates (Sugimoto et al. 2006). The charge (q) and voltage (V) relationship determine whether a capacitor has an inductance or a resistance, which has other, sometimes confusing repercussions. Eq. (1) describes this relationship, where q is the charge stored in the capacitor, C is the capacitor value in Farads (f), and V is the capacitor voltage. A capacitor's capacitance value is supplied by the dielectric permittivity, the distance d between the capacitor electrodes, and the effective area of the electrodes composing device A, and it can be calculated using Eq. (2). The energy stored in a capacitor is a function of the device's capacitance and terminal voltage, and it may be computed using Eq. (3). Where E is the amount of energy stored in the capacitor, C is the capacitance value of the capacitor, and V is the capacitor terminal voltage.

$$\boldsymbol{q = CV} \tag{1}$$

$$\boldsymbol{C = \varepsilon \frac{A}{d}} \tag{2}$$

$$\mathbf{C} = \boldsymbol{\frac{1}{2} CV^2} \tag{3}$$

A standard DC capacitor is frequently employed as an energy storage device in a power circuit. Capacitor technology is progressing toward high-energy storage devices such as supercapacitors. When compared to older capacitors, it has a higher capacity and a lower ESR (Equivalent Series Resistance). The electrode and electrolyte structures of capacitors and supercapacitors differ slightly. Capacitance is measured using Eqs. (2 and 3).

2.1 Supercapacitor basic cell structure

The supercapacitor cell's basic construction consists of three critical elements: two electrodes, one separator, and electrolyte material. The electrodes are made of various conducting materials such as metal oxide, metal hydroxide, cobalt, and so on (Yadav et al. 2022). A membrane separates the conducting electrodes, which have large surface areas. As illustrated in Figure 1, an EDLC-type capacitor has a high capacitance and a large surface area. It describes the fundamental cell structure of a supercapacitor, which is made up of charged electrodes separated by a separator (Jiya et al. 2018).

2.2 Electrode, Electrolyte, and Separator

2.2.1 Electrode

An electrode is a critical functional component of a supercapacitor. Several metallic electrodes are employed in construction, and the specific capacitance varies depending on the materials. According to current research in the supercapacitor sector, the cobalt hydroxide electrode produces a high specific capacitance. High-capacitance electrodes for supercapacitors are made from cobalt-based metal oxides and hydroxides. Metal hydroxides have great electrical conductivity as well as excellent long-term stability. Supercapacitor electrodes are prepared using cobalt-based metal oxides and hydroxides. In supercapacitor applications, their great electrical conductivity and low chemical reactivity make them an extremely popular choice for electrodes. Higher energy and capacity ratios are often obtained with cobalt-based metal oxides or hydroxides than with other materials such as aluminum and copper hydroxides, nickel hydroxides, and so on (Gunjakar et al. 2018).

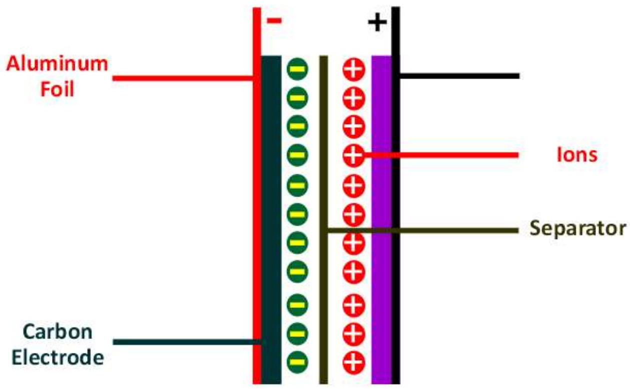

Figure 1 Double Layer Supercapacitor Basic Cell Structure (Reproduced under the creative commons license from Jiya et al. 2018).

2.2.2 Electrolytes

Traditional electrolytes are quaternary ammonium salts with a high electrochemical potential (pH) and, as a result, mildly alkaline solutions, limiting their usage in most commercial formulations. Organic electrolytes have a high dissociation voltage (above 2.5V). The electrolyte is in charge of moving charges (electrons) in aqueous, organic dissociation, and organometallic solutions. The movement of electrons causes the dissociation of organic, aqueous, and organometallic electrolytes. Electrolytes that dissociate in an aqueous solution are typically ionic, including cations and anions of varying sizes that may easily produce cations and anions in water. Organic electrolytes can also contain multivalent cations, including tetravalent cations. Salt, like organic electrolytes, has a difficult time dissolving molecules and forming inter-species in solution. Organic electrolytes have a larger energy density, greater conductivity, and comparable electrochemical stability.

2.2.3 Separator

The most significant component of EDLCs is the separator. They extract the electrolyte and separate the hydrogel economically. As a result, the separator constitutes a considerable component of the overall structure (Bose et al. 2012). The high-performance separators are used in supercapacitors with low voltage (1-10 V), high voltage (over 100 V), and high temperature. Paper, glass fiber, or ceramic separators can be used. The optimum efficiency level is necessary depending on the application. Separator performance can be assessed using a variety of methods, including calorimetry, capacity measurement, and eddy current investigation (Pell et al. 2004). An EDLC is a solid-electrode separation cell that separates ions based on their ability to conduct electricity using solid separators.

2.3 Supercapacitors Taxonomy

As indicated in Figure 2, supercapacitors are classified into three types: EDLC, Hybridge, and Pseudo capacitors. Super-

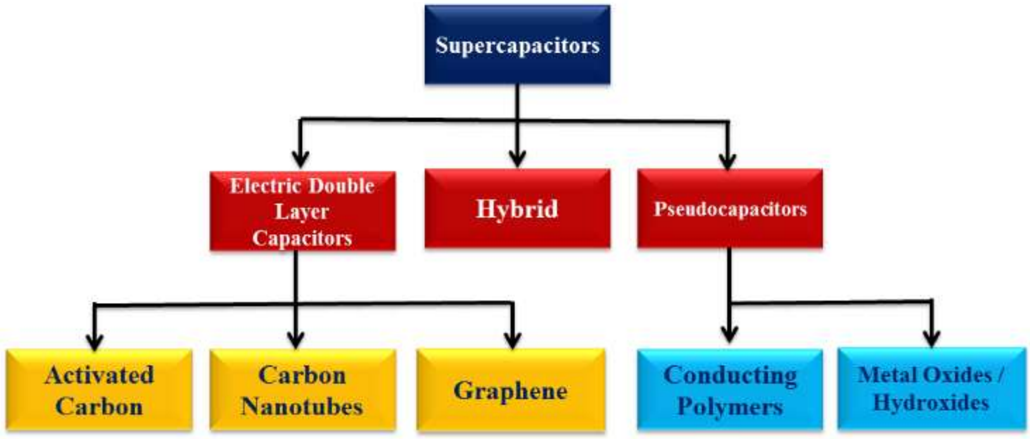

Figure 2 Supercapacitors Taxonomy (Reproduced under the creative commons license from Najib and Erdem 2019).

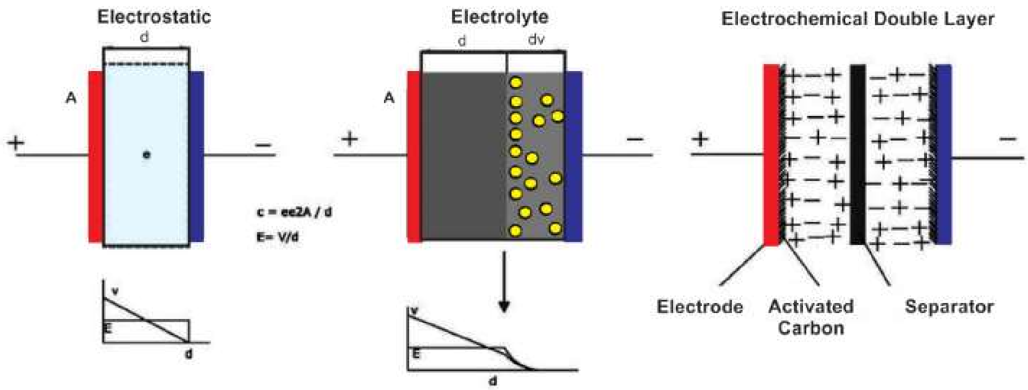

Figure 3 Schematic of Electrostatic capacitor, Electrolytic capacitor, and Electrical double-layered capacitor (Reproduced from Jayalakshmi and Balasubramanian 2008), copyright (2008), with permission from ESG).

-capacitors are classified based on their materials, production, electrodes, and applications. Activated carbon, carbon nanotubes, and graphene-based supercapacitors are the three forms of EDLC (Du and Pan 2006; Han et al. 2018)). On the other hand, Pseudocapacitors are two types of conducting polymers and metal oxide / hydroxide-based supercapacitors for enhanced energy storage devices (Chen et al. 2011). Figure 3 depicts the fundamentals of capacitors such as electrostatic capacitors, electrolyte capacitors, and electrical double-layer capacitors (Jayalakshmi and Balasubramanian 2008).

2.4 Electrochemical deposition technique

Supercapacitors can help with long-term energy storage in a variety of electrical systems. Over the last decade, the development of supercapacitors has been marked by rapid advancement, and as a result, several new materials have been introduced (Yu et al. 2013). The supercapacitor is one of the most creative energy storage technologies available today, receiving considerable interest from both industry and research. Supercapacitors are an innovative sort of electrochemical and electrical energy-saving technology. They charge and discharge quickly, have a higher energy density than batteries, and can be used to charge small electronic devices. Cobalt hydroxide thin films have been examined and studied for electrode manufacture and use in advanced electrical energy storage devices known as supercapacitors. The stabilities of supercapacitor factors such as electrolyte capacitance, electrode materials, structural features, and thicknesses are well understood. Electrochemical investigations on these characteristics are required for the development of appealing and efficient supercapacitor devices. The electrochemical deposition technique is shown in Figure 4. It is used to prepare the thin film and measure the electrochemical parameters by using three electrode methods. It consists of a Potentiostat interface to the working electrode (WE), reference electrode (RE), and counter electrode (CE).

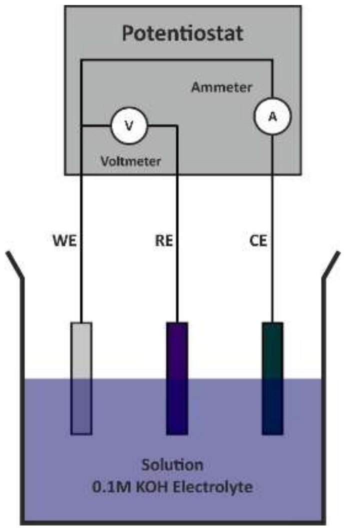

Figure 4 General diagram of electrochemical deposition to prepare thin film electrode for supercapacitor

2.5 Advanced energy storage devices

The most difficult challenge nowadays is to preserve renewable energy sources while controlling the rise in use. Solar and wind energy are the principal sources of renewable energy. SCs outperform batteries in several ways, including high energy density, superior energy density at low temperatures, excellent cycling durability, and fast charging rates (Dong et al. 2018). SCs, on the other hand, suffer from relatively sluggish charge/discharge rates because they are built from thousands of individual capacitors stacked in parallel. Due to their low capacity, these issues limit the practical implementation of SCs in consumer electronics applications (Yuan et al. 2017). Batteries, advanced batteries, and supercapacitors are examples of electrical energy storage devices with a high cyclic rate and lifespan (>1,000,000 cycles). These energy storage devices require little maintenance and are inexpensive (Song et al. 2005). Nippon Electric Company manufactures supercapacitors, while Pinnacle Research Institute manufactures ultracapacitors, for which General Electric submitted the first patent in 1957. Supercapacitors have recently been shown to have high specific capacitance and energy density (Cao et al. 2004). It is small in size, light in weight, and costly (Bose et. al 2012). Supercapacitors are a promising alternative to batteries due to their high performance and flat charging curve. When compared to alkaline batteries and fuel cells, supercapacitors have superior cycle stability and can charge faster (Winter e al. 2004).

Table 1 List of Supercapacitor Manufacturers (Reproduced from Sharma and Bhatti 2010, Copyright 2010, with permission from Elsevier).

	Devices	Voltage Range (V)	Capacitance (F)	Company	Country
1	BestCap	3.50-12.0	0.022-0.56	AVX	USA
2	BoostCap	2.5	1.60-2600	Maxwell	USA
9	Capacitor modules	12.0-52.0	100-8000	ESMA	Russia
11	Capattery	5.50-11.0	0.01-1.50	Evans	USA
5	Dynacap	2.50-6.80	0.033-100	ELNA	USA
4	EDLC	2.7	10.0-5000	NessCap	South Korea
3	GoldCap	2.30-5.50	0.10-2000	Panasonic	Japan
12	Kapower	12	1000	Kold Ban	USA
8	PowerStor	2.50-5.00	0.470-50.0	Copper	USA
6	Supercapa citor	3.50-12.	0 0.01-6.50	NEC	Japan
7	Supercapa citor	2.25-4.50	0.090-2.80	Cap-XX	Australia
10	Ultracapa citor	2.30-2.50	5.00-5000	EPCOS	USA

Table 2 General comparison between supercapacitor and battery (Reproduced under the creative commons license from Musolino et al. 2010).

No	Parameters	Supercapacitor	Battery
1	Energy density	Low	High
2	Power density	High	Low
3	Charge-discharge Cycle	10^5-10^6	500-1000
4	Self-discharge	Days to Week	Months
5	Lifetime	5-10 years	3-5 years
6	Cell Potential	1.2-3.8V	2.5-4.2V

Table 1 compares battery and supercapacitor technology and discusses how each type of device can be utilized to store electrical energy (Sharma and Bhatti 2010). A supercapacitor is an electrochemical power storage device (Kötz et al. 2000). Because they have no rate constraints, supercapacitors can be utilized as battery replacements. They outperform batteries in terms of cycling stability while providing a better energy density. Table 2 lists the critical supercapacitor and battery parameters. The supercapacitor has a high-power density but a poor energy density (Musolino et al. 2010).

2.6 Supercapacitors as a sustainable energy source

The main limitations of current lithium-ion battery technology include limited safety, sustainability, and recyclability, as well as a limited supply of starting materials (e.g. cobalt). The "hybrid supercapacitor" is a particularly promising battery-capacitor combination in the hunt for alternative electrochemical energy storage devices for use in e-mobility and for storing energy from renewable sources (Bello et al. 2013). It can store almost as much energy as traditional batteries and can be charged and discharged as quickly as a capacitor. In contrast to the latter, it can be charged and drained far more quickly and frequently: whereas a lithium-ion battery only accomplishes a few thousand charging cycles in its service life, a supercapacitor can handle about one million (Martínez-Casillas et al. 2019).

3. Role of Supercapacitor (SC) in Power Resource and Backup

Supercapacitors are a safe, dependable, and long-lasting energy source. They can be used to power sensors, water pumps, batteries, medical equipment, crop cultivation, and other systems. Several examples of Sc applications in various disciplines are provided below.

3.1 Real-Time Clocks (RTC)

A real-time clock is a device that records time and date as well as the correct date, time, and day. The RTC is typically on-chip or part of a chip with the processor. It can be used for a variety of purposes, including timing, system control, and the appropriate operation of other systems. Many electrical devices use batteries as a power source. Removing or replacing a battery temporarily might cause the device to lose power, resulting in decreased performance and productivity. However, with the introduction of replaceable batteries, long-term backup power has been obtained. You may then preserve your electronic investment and communicate with employees all around the world knowing that you have avoided the repercussions.

3.2 Emergency lighting, flashlights, Audio System, and Taxi Meter

Supercapacitors can power radio station memory and accumulated fare data in automobile audio systems. In taxi meters, SC acts as a power backup in the event of a power outage by powering emergency lighting. When the power goes out or fails for several hours, emergency lights (LEDs) are utilized to provide lighting. Supercapacitors are utilized to generate electricity for lighting and decorations at night events.

3.3 Hospital and medical instruments

Some numerous biomedical instruments and machines rely on a power supply. (DC). It also contains a backup power source to keep the instrument running during the diagnostic and operation processes. Electronic machines such as ECG, EEG, MRI, and others are required to display, process, and store data, as well as restore power to the work machine without interruption. Portable gadgets and handheld terminals also use supercapacitors.

3.4 Remote solar-powered installations

SC power supplies are appropriate backup power sources for mission-critical, dependable systems. SC has a long lifespan and is highly helpful for storing solar energy as electrical energy. It is then modified and transmitted to industrial uses. Based on supercapacitors, it is a more dependable and renewable energy source.

3.5 Electronics Gadgets

Tiny electronic gadgets are a market and lifestyle necessity. These electronic devices are portable, tiny in size, and have a long battery life. These power sources are the supercapacitors that allow users to do so. Electronic gadgets based on Sc, including digital watches, wireless headphones, wireless audio systems, flashlights, and so on.

3.6 Transportation and Automotive Industry

The transportation, automobile, and automotive industries are shifting away from fossil fuels and toward electricity. Vehicles that run on electricity include cars, buses, planes, and other modes of transportation. Solar systems and SC-based power supply storage are the primary sources of electricity. The opulent automobiles are entirely automated, with a comfy bake system that automatically opens and closes the doors.

3.7 Consumer electronics and home appliances

The wire is being phased out in most consumer devices and residential appliances. SC and modern electrical energy storage devices make it possible. Smartphones, toys, digital clocks, laptops, tabs, minicomputers, smart watches, personal digital assistance, and other consumer gadgets include power supply sources. Because of SC, these gadgets are inexpensive, dependable, and have long-lasting battery backups.

3.8 Uninterrupted power supply (UPS)

The use of supercapacitors in UPS provides ultra-high-power density, dependability, and ease of integration. SC is used in UPS to deliver and sustain continuous power supply to electronic equipment such as computers, televisions, printers, scanners, and so on. UPS is required offices, organizations, and businesses to work online 24 hours a day, seven days a week to ensure client satisfaction.

3.9 Other applications

Supercapacitors are now employed in almost every industry, including banking, airports, transportation, control towers, communication networks, IT parks, textile industries, agriculture, and many more. It bridges the gap between traditional power supplies and battery-powered systems. It also replaces bulk energy storage and expensive devices with an efficient energy source.

4. Major Applications of IoT and AI

IoT and AI refer to a system of technical devices that use network connectivity to connect items or sensor networks, this infrastructure that may gather and exchange data (for example, weather reports) across an existing network. The basic idea behind IoT is to allow different types of devices to coexist peacefully by sharing data, decreasing manual duties, boosting efficacy at a low cost, and increasing productivity.

4.1 Smart City, Transportation, and GPS

The implications of smart cities are substantial because they are a large component of the IT sector. Smart homes, smart offices, and smart cities based on IoT and AI are concepts for living in a better environment in which all items are connected to the internet and can communicate with one another. The owner can control the household equipment from within the premises. IoT is also being used to guide citizens in smart transportation and traffic control. It is possible to ship and deliver products on time with IoT. It allows the user to keep track of their orders from numerous places. The global positioning system (GPS) is extremely beneficial for travelers and mapping.

4.2 Computerized Maintenance Management

The growth of physical assets, as well as their technological state, has resulted in a shift in how they are handled. Sensors, control systems, application software, and the internet all employ Enterprise Asset Management (EAM) and Computerized Maintenance Management Systems (CMMS). These solutions improve administration for both users and service providers. These tools are used in malls, canteens, service centers, retail, and warehouses.

4.3 Healthcare Sector and Wearable Devices

Patient monitoring systems based on IoT and AI are now used in healthcare facilities and hospitals. The doctor diagnoses the patients, and the computer generates reports. Furthermore, IoT and AI-based systems continuously monitor critical parameters.

4.4 Smart Grid and Energy Storage

IoT and AI monitor the electrical supply, storage, and distribution networks. IoT offers electricity management solutions to utilities and manufacturers. Communication with users and service providers is simple. It also aids in locating the fault and correcting it at that node. IoT allows the controller to be updated on the status of on-grid and off-grid conditions. Power backup is provided by supercapacitors and advanced electrical energy storage devices. Nowadays, electrical energy providers generate electricity from natural resources such as windmills, solar panels, and so on.

4.5 Smart Water Supply Management System

Water supply distribution and management systems based on the Internet of Things (IoT) are being implemented in a number of cities. It is one of the IoT applications that deal with a good water management system to control drinking water waste. IoT has enabled businesses to collect, process, and analyze data in order to give higher value to their customers. This enables the organization to comprehend its consumers' actions and, as a result, develop a relationship built on trust and mutual gain. Similarly, IoT has enabled water businesses to monitor data linked to their customers' use patterns. Water consumption may now be tracked online or via mobile applications. These web pages (mobile applications) are accessible via smartphones and tablets.

4.6 Agriculture and Greenhouses

The adoption of IoT helps farmers to automate farm procedures. Wearables are intelligent devices, and sensors play an important role in environmental monitoring, managing and automating operations, and saving energy (Dubal et al. 2018). The agricultural industry is the world's fifth-largest industrial sector by GDP. The global agriculture sector employs over one billion people and is critical to millions of people's food security. However, due to a variety of factors such as climate change, rising demand for natural resources, and rising population, agricultural activity has been proposed as one of the answers to alleviate stress on natural resources and thus boost productivity. Greenhouses are built to create a controlled environment (environmental parameters) in order to maximize crop yield.

5. Conclusions

Supercapacitors are the electrical energy storage technologies of the future. It is utilized in a variety of industries, including electric vehicles, portable devices, wearable gadgets, household appliances, consumer electronics, robotics, automotive electronics, artificial intelligence, and IoT devices. To function properly, IoT and AI-based gadgets required a power source and energy backup. It is achievable because supercapacitors give a constant supply to the system for an extended period of time. IoT has substantial applications in healthcare, agriculture, metrology, transportation, home appliances, consumer electronics, and other fields. Supercapacitors are versatile and can be used in a variety of applications. Supercapacitors provide power to linked devices that run on low voltage and cannot generate energy on their own. The supercapacitor is essential for supplying energy.

Authors' contributions

SN has done the literature review work and summarized the supercapacitor technology and its applications in IoT devices. AV did a comparative study of all types of electrical energy storage devices. UP has supervised and contributed in manuscript writing. AB, KM, and MB have contributed to paper writing and proofreading. All authors read and approved the final manuscript.

Disclosures

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