Chapter

# Piezoelectric-Driven Self-Powered Supercapacitor for Wearable Device Applications

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## Abstract

Supercapacitors are the most promising energy storage devices that bridge the gap between capacitors and batteries. They can reach energy density close to the batteries and power density to the conventional capacitors. Several kinds of research have been carried out in the field of supercapacitors for the development of promising electrode and electrolyte materials as well as device fabrications to breakthrough in energy storage systems with diverse applications in electronics. They have a broad range of applications as they can deliver a huge power within a very short time. The applications of supercapacitors in several sectors like consumer and portable electronics, transportation and vehicles, power backup, biomedical, military, aerospace, etc.

**Keywords:** Piezoelectric, Self-powered, Supercapacitor, Energy harvesting

## 1. Introduction

### 1.1 Supercapacitor as next generation energy storage device

The continuous development of smart electronic devices and industrial high-power devices has made a strong requirement of high-performance electrochemical energy storage devices. Out of various electrochemical energy storage devices available in the market. Lithium-ion batteries (LIBs) and supercapacitors (SCs) find a considerable application. However, SC device offers a wide variety of benefits in the electronic devices. Some of the benefits related to the SC device are it offers low-cost material E.g., Activated Carbon (AC), lightweight and long durability cell performance for the smart and portable electronic devices. In the past few decades, the rapid growth in the advancements in the development of portable electronic systems has stimulated the research interest among researchers to design and develop innovative electrical energy storage devices with maximum energy density and power density. SCs or supercapacitors are electrochemical energy storage device that store electrical charges via electrochemical and electrostatic charge storage mechanism takes place at the surface of the electrode. SCs hold high energy performance as compared to common dielectric capacitors and hence SCs are extensively utilized not only for powering several portable electronic devices but also plug-in hybrid electric vehicles.

SCs showed outstanding potential as an energy storage device as compared to LIB systems because of their high-power density, super-longer cycle life, and longer cyclic stability. SCs are already being used worldwide in various applications ranging from automotive, renewable energy to consumer electronics and even employed in the bio-medical field of application. SCs are steadily paving the way for hybrid power storage applications, such as complimentary batteries, especially in two-wheeler applications. Various market reports estimate the global demand for SCs to grow tremendously, primarily driven by different consumer electronics and automotive applications, to provide backup power. SCs provide the necessary power backup required for the smooth functioning of applications such as video calling, high-quality image output which is captured during the night-time using cameras, wireless communications, and global positioning system (GPS) navigation, etc.

As per the IDTech Ex report, the global supercapacitor market is expected to reach US$ 8.3 billion by 2025. The market is projected to grow at a compound annual growth rate (CAGR) of 30 percent till 2025 as depicted in **Figure 1**. Consumer electronics and automotive will be the highest revenue-generating segments during this period. Although the supercapacitor market is at a nascent stage, ample emerging growth opportunities are available for the future. Highlighting features such as regenerative braking and easy application in hybrid electric vehicles (EVs) are making supercapacitors the best-suited device in automotive applications. Increasing demand for renewable energy generation has been observed in countries across Europe, Asia, and the USA, which would further fuel the supercapacitor market growth.

Interestingly, the supercapacitors market in India is projected to grow at a compound annual growth rate (CAGR) of around 16% during the year between 2012 and 2022 on the account of a huge demand for supercapacitors from the consumer electronics segment (**Figure 1**). Supercapacitors are used in several devices in the consumer electronics category such as smartphones, laptops, TVs, cameras, lighting appliances, GPS devices, etc. Moreover, the evolution of supercapacitors as a sustainable energy storage solution, growth of the electric vehicles market, and increasing capacities of supercapacitors resulting in their application in the wind and solar power sectors is anticipated to boost demand for supercapacitors in India during the next five years.

According to 'Supercapacitor Market Landscape Study' prepared by the Electronic Industries Association of India (ELCINA), an apex industry association supporting the electronics and IT hardware manufacturing industry, by 2020, the

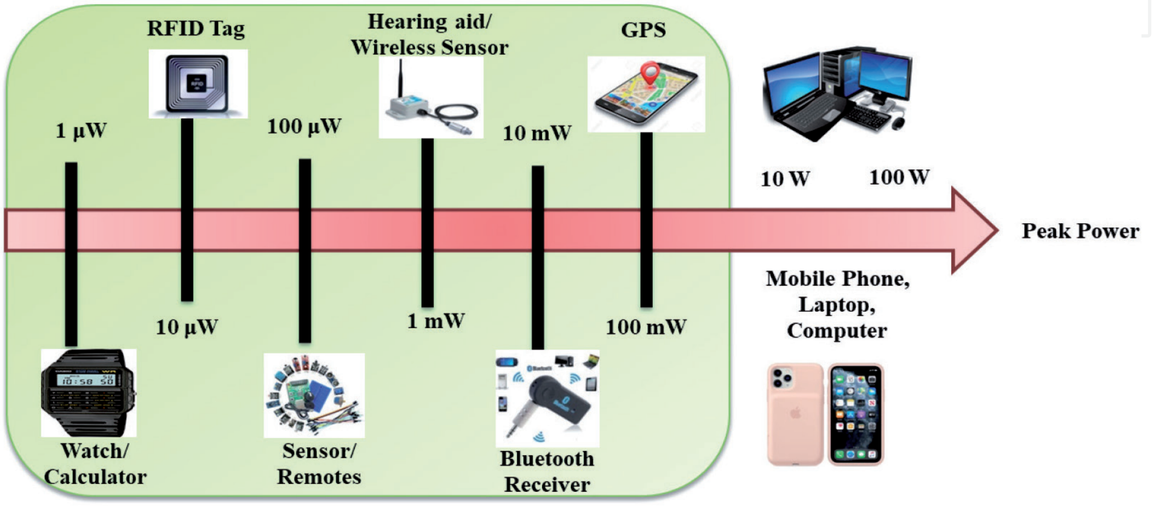


**Figure 1.**
*Schematic diagram of energy harvesting various power range.*

overall market opportunity for supercapacitors in India will be approximately 1 billion units, with major demand from consumer electronics, EVs, renewable energy, railway, and defense, etc. Supercapacitor technology has not yet been commercialized in the Indian market, and supercapacitors are not yet common in use. Only a handful of companies and research laboratories are working on their manufacturing in the lab proto-type level. However, considering growing concerns of environmental issues, global warming, air pollution, green energy as well as government initiatives "Make in India" in which India becoming a global manufacturing hub, the Indian market is poised for an explosive demand for supercapacitors in various sectors due to their diverse applications.

### 1.2 Supercapacitor developers

The requirement for the SC device is increasing day by day. So there is a potential opportunity for the SC developers in the market. Recently, the number of manufactures and developers for the SC device is increasing rapidly. The two categories of SCs device is available in the market. i.e. aqueous and non-aqueous-based SC. However, the non-aqueous-based SC developers have occupied the majority of the market. The main reason is organic electrolyte offers high operating voltage. So it offers high energy density without sacrificing its power density. The solvent mostly used in organic SCs is acetonitrile (ACN) and propylene carbonate (PC). The two solvents ACN and PC are responsible for the high voltage operation of the SC device. However, currently, 50% of the SC manufacturer's available in the market offers non-toxic and non-combustible electrolyte with unique performance and quality. Based on the Electrochemical energy storage requirements the application of SC varies. The various available SC manufacturers and developers will be discussed in detail in the following sections.

In general, SC manufacturers offer to build the device in a cylindrical or prismatic design. In cylindrical manufacturing, electrode cells are deposited onto a sheet and wound like a jelly roll into a cylinder. A casing maintains the capacitor's shape. Cylindrical designs are more common, but more prismatic designs are evolving so that EDLC based supercapacitors can substitute for LIBs in consumer electronics. Most established companies in the SC area are based in Japan, however many startups are located in the USA and Europe.

### 1.3 Global supercapacitor and supercapacitor manufacturers

Maxwell technologies are the United States of America (USA) based SC company/manufacture. The company was founded in the year of 1965. But now, Maxwell Technologies is one of the leading supercapacitor manufacturers in the global supercapacitor market with is having huge customers around the globe through its device performance. Maxwell's supercapacitors are rapidly evolving and increasingly used technology that can charge and discharge energy quickly and efficiently. Maxwell technology Supercapacitors supplement the main source of energy, that cannot usually cause rapid explosions, such as a combustion engine, battery, or fuel cell. The horizon of the future looks bright for supercapacitors, that are readily distinguished as a potential alternative energy source. The various products of Maxwell technology offer for commercial applications, including high voltage capacitors, microelectronic components, and systems, telecommunication equipment as environmentally safe backup power supplies.

Second, Murata Manufacturing is a Japan-based supercapacitor company that was laid in the year of 1944. Murata is also involved in the design and development of Supercapacitor for the global market. Murata is mainly involved in the manufacture of lower farad capacitors, and sales of electronic parts, including components for supercapacitors and piezoelectric products. Nanoramic Laboratories, formerly known as FastCAP Systems, is a USA-based SC manufacture that specializes in nanocarbon materials and high operating temperature SC. FastCAP Supercapacitors, specializes in harsh environment energy storage systems, producing supercapacitors capable of operating in temperatures up to 150°C and under conditions of high shock and vibration.

To find a replacement for the Lithium-ion batteries in small scale, Paper Battery Company (PBC Tech), is the manufacturers for the ultrathin supercapacitors as replacements for lithium batteries. The PBC tech's SC offers ultrathin supercapacitors of 1 Farad. Also, the company targets the consumer electronics, wearables, and wireless sensor markets.

On the other hand, Skeleton Technologies is the SC manufacture from Estonia who manufactures and develops EDLCs with high energy and power density. The company serves many applications to the market includes transportation, automotive, industrial, and renewable energy markets. Also, skeleton technology SC offers high-end carbon and adsorption materials to the energy storage application. Like the same, Yunasko is a Ukraine based SC manufacture laid in the year of 2010, who develops prismatic type EDLCs capacitor to the market. Its R&D facility is located in Ukraine. Yunasko EDLC cells are manufactured in special prismatic encasements made from multi-layered laminated aluminum foil. Depending on the number of cells connected in series, the module can handle the voltage range from 2.7 V (single-cell) up to 750 V (large assemblies of cells).

## 2. Energy harvesting for self-powered wearable device applications

Piezoelectric harvesting has proven to be a new solution to replace lead acid batteries and lithium-ion batteries in remote power supply applications. Unfortunately, low energy efficiency is shown in **Figure 1** to make effective use of energy enhancement in daily life. The Power Electric perspective was introduced after reviewing the current research literature on piezoelectric energy harvesting focusing on low frequency vibration mechanics from circuit design. Piezoelectric energy can be used for low power generation due to its high energy storage capacity. The energy harvester to convert stored crop energy includes electrical energy and renewable energy. The reason for choosing piezoelectric is the high energy storage capacity as shown in **Figure 2**. In piezoelectric energy harvesting, the piezoelectric sensor is used as a harvesting vibrational material and the supercapacitor storage element [1–4].

Recent advances in super-low electronic microcontrollers have produced Device that provide unprecedented integration with the amount of energy used. These chip systems have powerful energy-saving schemes, such as shutting down idle work. In fact, these devices require very little power to use, so most sensors are wireless because they run easily on batteries. Unfortunately, the batteries need to be replaced regularly, which is very expensive to produce and the most difficult maintenance [5–7]. The sensory atmosphere is an effective wireless energy solution for harvesting the surrounding mechanical, thermal, solar and electro-magnetic forces in **Figure 2**.

Analog devices provide ICs with high power for super-low power generation applications. Power management products that convert energy from vibratory (piezoelectric), photovoltaic (solar) and thermal (TEC, TEG, thermopiles, thermocouples) provide high-performance conversion to source controlled voltage and charge batteries, supercapacitors and storage devices. Booster converters operate on

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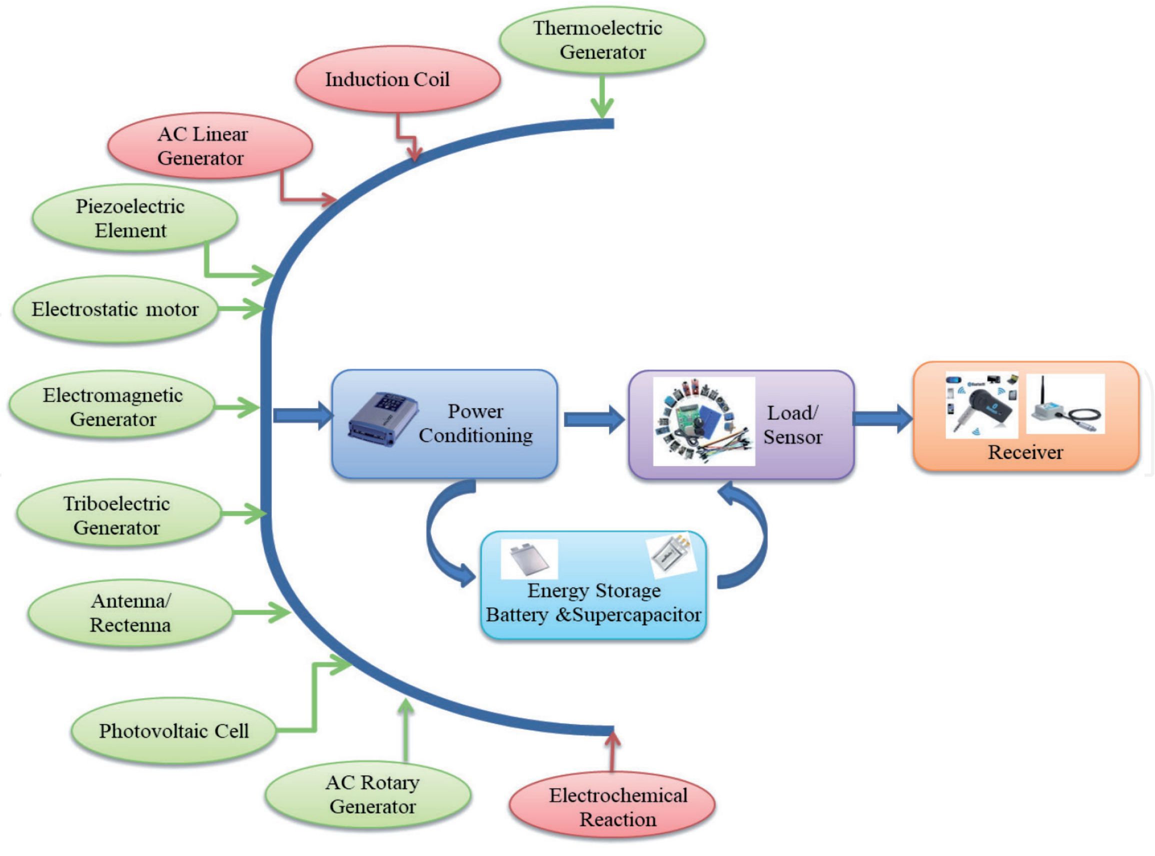


**Figure 2.**
*Schematic diagram of ambient energy source and energy harvesting technologies.*

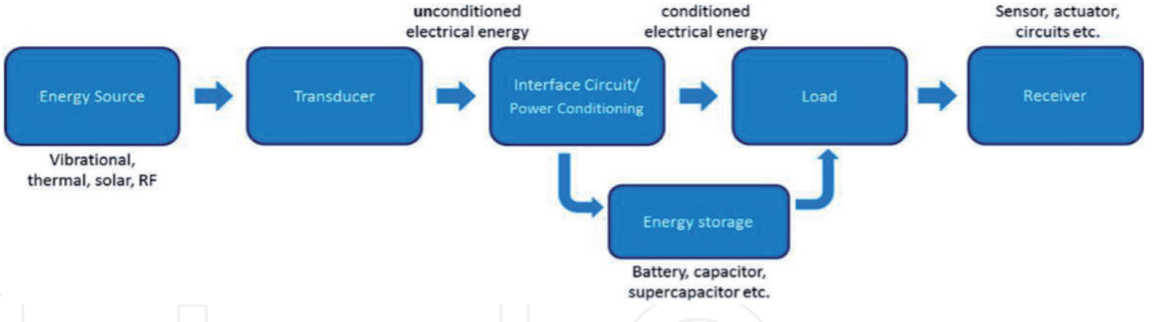


**Figure 3.**
*Block diagram of energy harvesting system.*

small 20 mV high capacity battery chargers, expanding the possibilities of automation and industrial control, wireless sensors, navigation, applications and portable electronics [8–10]. Current low power controllers, app amps, comparators, voltage monitors, ADCs, DACs and low power storage devices provide additional blocks for standalone systems as shown in **Figure 3**.

The renewable energy environment is very energy efficient, so energy harvesters are a good source of energy for IoT applications, eliminating the need to replace and dispose of batteries. However, low-power harvesters are often unable to provide the high capacity needed to collect and transfer data. This article shows you how to use a supercapacitor mounted on an energy harvester to provide the maximum power needed using a small piezoelectric strip as a case study. A standard power supply consists of a power harvester that connects a large charging circuit directly to the supercapacitor with a direct load. The high C and low ESR of the supercapacitor keep the electrical energy constant for the load while breaking its high power [11–14].

Over the past decade, flexible electronics, wearable electronics, and portable devices have become of great importance in various fields such as mobility, consumer technology, biomedical, sports, clean and natural energy. Therefore, since high power consumption is required, these electronics require smart energy storage devices. In various energy storage systems, supercapacitors are an important device that can deliver high power in a very short time with new energy storage methods. Supercapacitors are a good energy saving device that closes the gap between electrolytic capacitors and batteries. Compared to traditional electrolytic capacitors, the supercapacitor can use batteries and power supplies near the power supply. Much research has been done in the field of supercapacitors in the manufacture of fine electrodes and electrolyte materials and in the development of energy-efficient electronic storage systems. Initially, supercapacitors were produced from high-carbon materials by forming a double-layer structure. They have excellent power with very high discharge rates and long cycle life. However, over time many types of pseudo supercapacitor gain interest due to the high energy levels obtained from their faradaic process as a result of the surface redox reaction. Recently, hybrids of two building materials have been improved using the low energy content of carbon material and poor performance, as well as the interaction of the two components to overcome the surface area of pseudo supercapacitors Therefore, it is possible to achieve efficiency between capacitors and conventional batteries by improving power and maximum power. In the first stage, supercapacitors were traditionally used as hybrid electric vehicles as well as alternative energy-saving devices in batteries or fuel cells. Since then, this attractive electrical device has slowly evolved into a backup power provider with batteries and fuel cells. Nowadays, supercapacitors occupy applications in many fields such as wearable electronics, flexible electronics, portable electronics, electric vehicle transportation, electric power storage, biomedical, military and aerospace. This paper details the multiple uses of supercapacitors, their real-time application in modern technology and the end of convenience trends [15–24].

## 3. Methodology

Ambient power sources include light, temperature variation, vibration beam, RF signal signals or other sources that can generate electricity through a transducer. For example, small solar panels have been using hand-held electronic devices for years and can produce 100 mW / cm2 in direct sunlight and 100 μW /cm2 in indirect light. See beck devices convert thermal energy into electrical energy, where the temperature gradient is obtained. Energy sources vary according to body temperature, with earth producing 10 μW/cm$^2$ for a fire stack capable of producing 10 mW/cm$^2$. Piezoelectric elements can produce up to 100 μW/cm$^2$ depending on their size and formulation and are shown in **Figure 4**. RF energy is collected by the harvesting antenna and emits 100 pW/cm$^2$.

Piezoelectric Transducer Application **Figure 4** illustrates the piezoelectric system that, when plugged into an air transmission, produces 100 μwatts of power at 3.3 V. The deviation of the piezoelectric element is 0.5 cm at a frequency of 50 Hz. Harvesting of mechanical energy in human motion is an attractive way to obtain clean and stable electrical energy. Piezoelectricity is the electrical energy generated by mechanical pressure (e.g. walking, running). When pressure is applied to an object, there is a negative charge on the elongated side and a positive charge on the suppressed crystal piezoelectric side. When

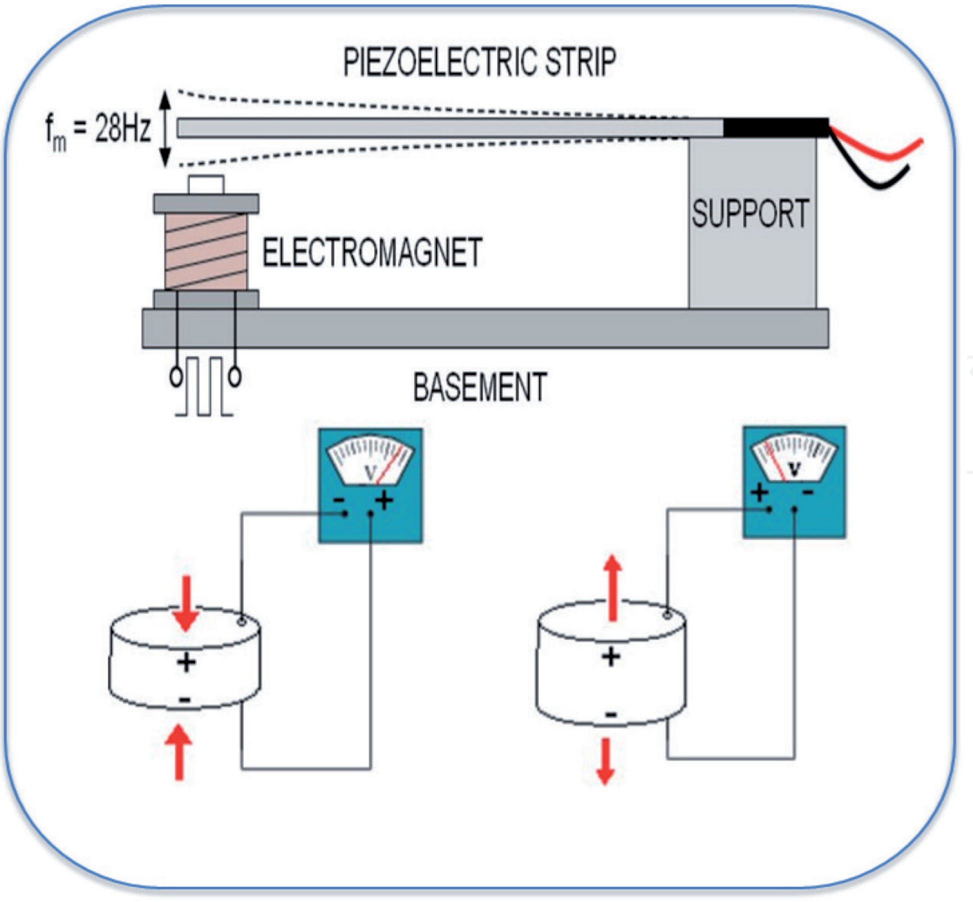


**Figure 4.**
*Block diagram of principle of piezoelectric materials.*

pressure is applied, electrical energy flows through the whole. Widely used resources: solar power, triboelectric nano generator power and piezoelectric power. This study focuses on piezoelectricity because it relies on mechanical stresses to obtain electrical energy and some resources are not always reliable. Compared to the three nano generators for maximum energy storage capacity, piezoelectric has more energy saving properties than other energy generation methods.

Piezoelectric sensors should be placed on the two main parts of the shoe where high pressure will occur. A piezoelectric generator is installed inside the shoe insole. The shoe has two points, where the pressure is very strong and the heel and toe, and the piezoelectric sensor wing are the exact location shown in **Figure 5**. The piezoelectric array arrangement fixes the shoe insole. One sensor can produce 3–5 volts in a constant pressure application, in which case four sensors are connected in parallel, which increases the probability of obtaining the highest gains. It is more advantageous to use piezo polymeric materials than piezoelectric materials when it comes to using sensors, as polymer films can be easily made in different sizes. However piezo ceramic sensor was used in this work because it is available for sale at low cost.

The design includes series-connected piezoelectric generator units. The front panel features piezoelectric generators with a straight forward arrangement and a rear panel with circular rotation. The acquisition and charging side collects intermittent or continuous power input from the piezoelectric generator and charges its power properly in the supercapacitor bank. During the charging process, the supercapacitor voltage is constantly monitored. When it reaches 5.2 V, it can power the module's output rectifier and charging circuit.

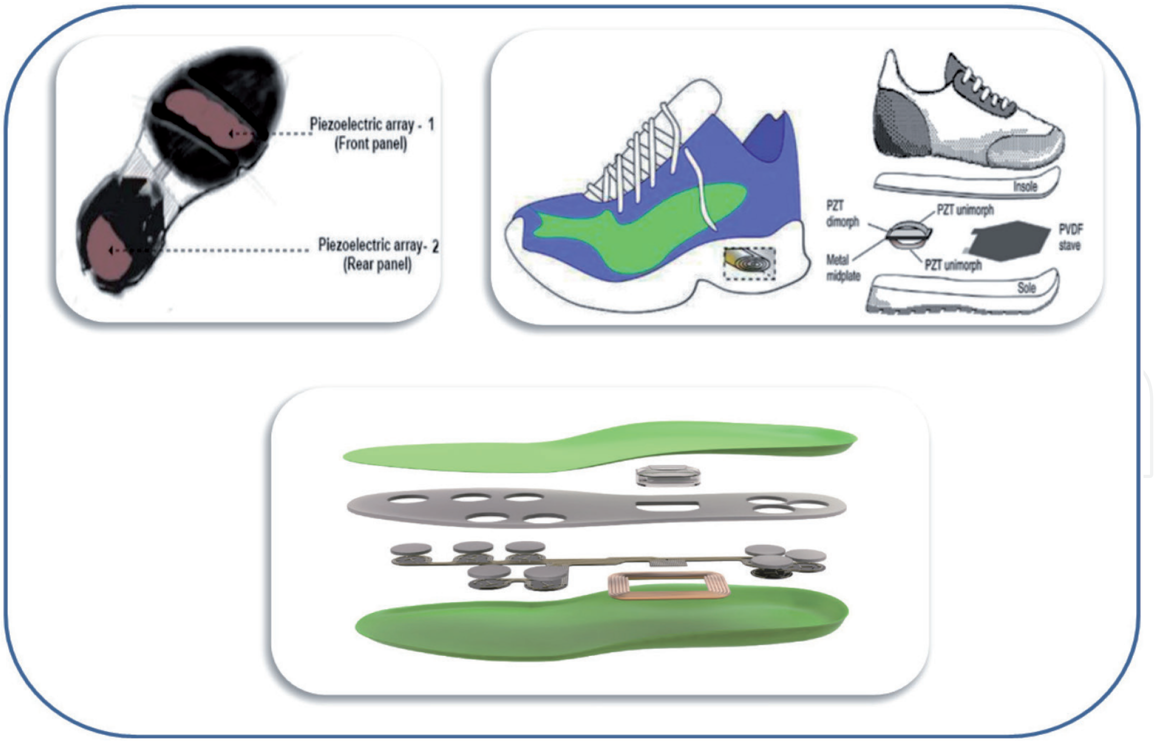


**Figure 5.**
*Arrangement of piezoelectric generator inside a shoe insole.*

The piezoelectric generator is mounted on the shoe. As a person moves, pressure builds up on the ground and this pressure can be converted into electrical energy and used to charge the supercapacitor. This energy storage system uses biomedical sensor applications.

There are many studies that successfully explore power augmentation in laboratories, but the overall efficiency of the underlying systems is limited to the trade-off between the capacities of each system. For example, some researchers pay full attention to increasing the productivity of a piezoelectric source, while dissipating the controller's energy reduces the useful energy stored in the energy buffer. The functional cycle of a supercapacitor with a high-performance life cycle is investigated based on a systematic analysis of piezoelectric power generation from a power management perspective.

## 4. Results

Successful design of complete wireless systems requires energy-saving microcontrollers and transducers used from low-power electronic applications. Since both are now readily available, the active power conversion product capable of changing the output of the transducer is active energy. The LTC3588–1 shown in **Figure 6** is a complete power generation solution designed for high impedance sources such as piezoelectric transducers. It features a full bridge rectifier and a highly efficient buck converter of low damage bridge rectifier that transfers power from the device to the output at a controlled capacity capable of supporting loads up to 100 mA. The LTC3588–1 is available in a 10-lead MSE package with 3 mm × 3 mm DFN.

**Figure** 7 shows the power generation system with the methods of harvester, transducer and power condition circuit that converts this stored electrical energy into a controlled power supply. The transgender may also need a

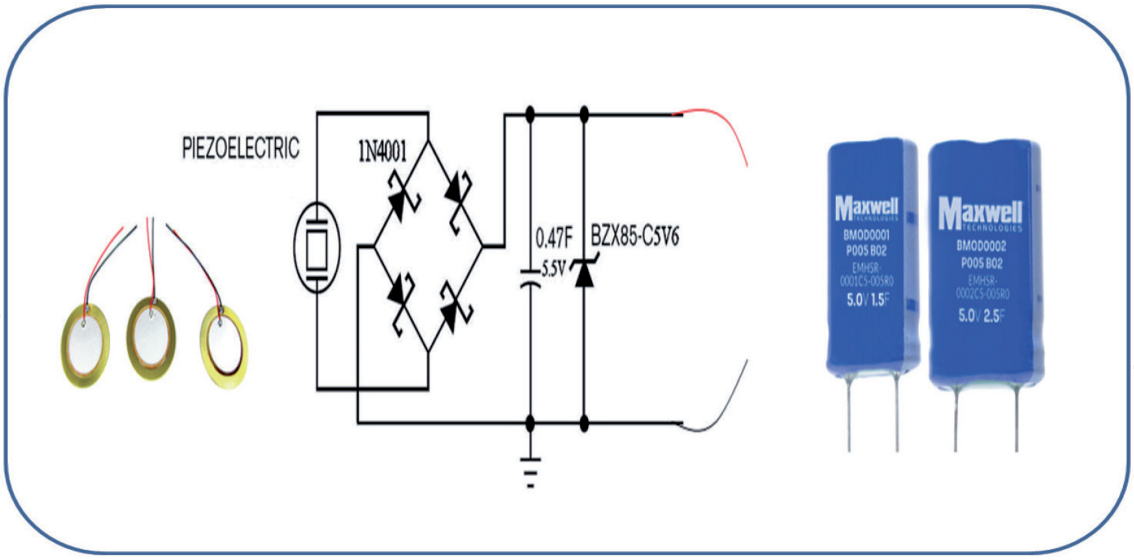


**Figure 6.**
*Simple circuit diagram of piezoelectric-driven charging supercapacitor.*

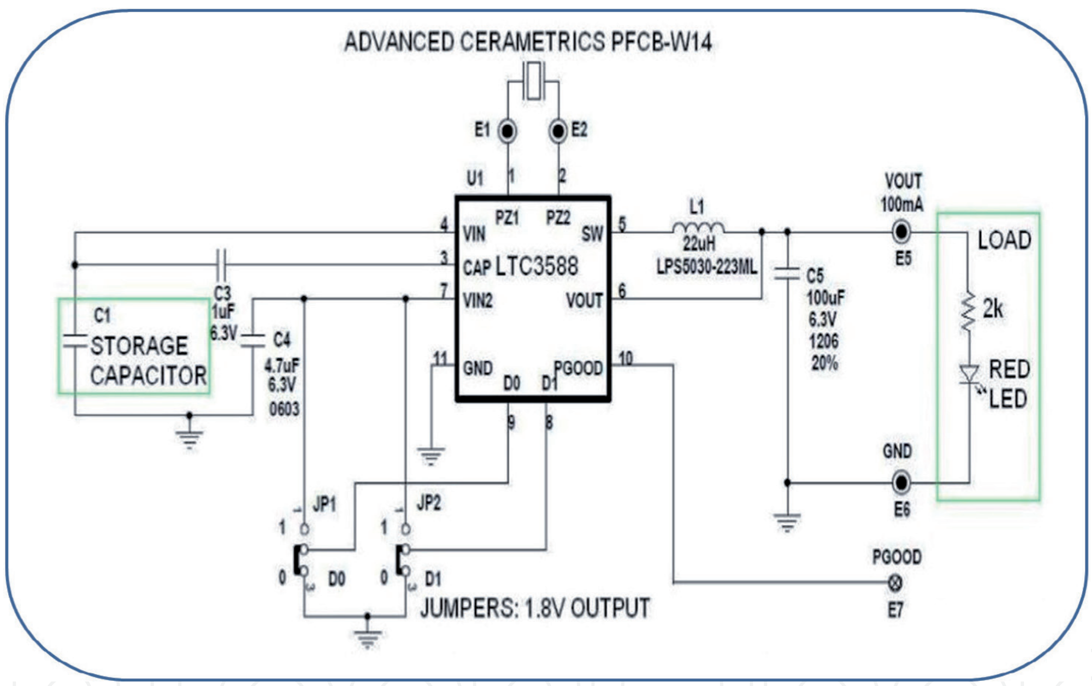


**Figure 7.**
*Simulink model of piezoelectric-driven supercapacitor for charging and discharging.*

controllable power supply network between the power transducer and the power storage element to block the power supply or to adjust the AC signal in the case of a piezoelectric device. Operating Example LTC3588–1 The output power of the transducer must exceed the minimum power limit, which increases the specific power limit set at the input pins D0 and D1. To transmit high power, the power transducer must have a double open circuit voltage and a short-circuit current of input voltage, which is twice the required input shown in **Figure 6**. These requirements must be kept to a minimum uninterruptible power supply capacity.

The piezoelectric generator, which is the constant current charge level of the supercapacitor, can be obtained by exposing the working cycle of the buck regulator using software used for pulse width modulation. The test results confirm the electrical circuit model of the piezoelectric generator, the presence of a constant current charged supercapacitor, and the simple control of the circuit designed as shown in **Figures 8** and **9**.

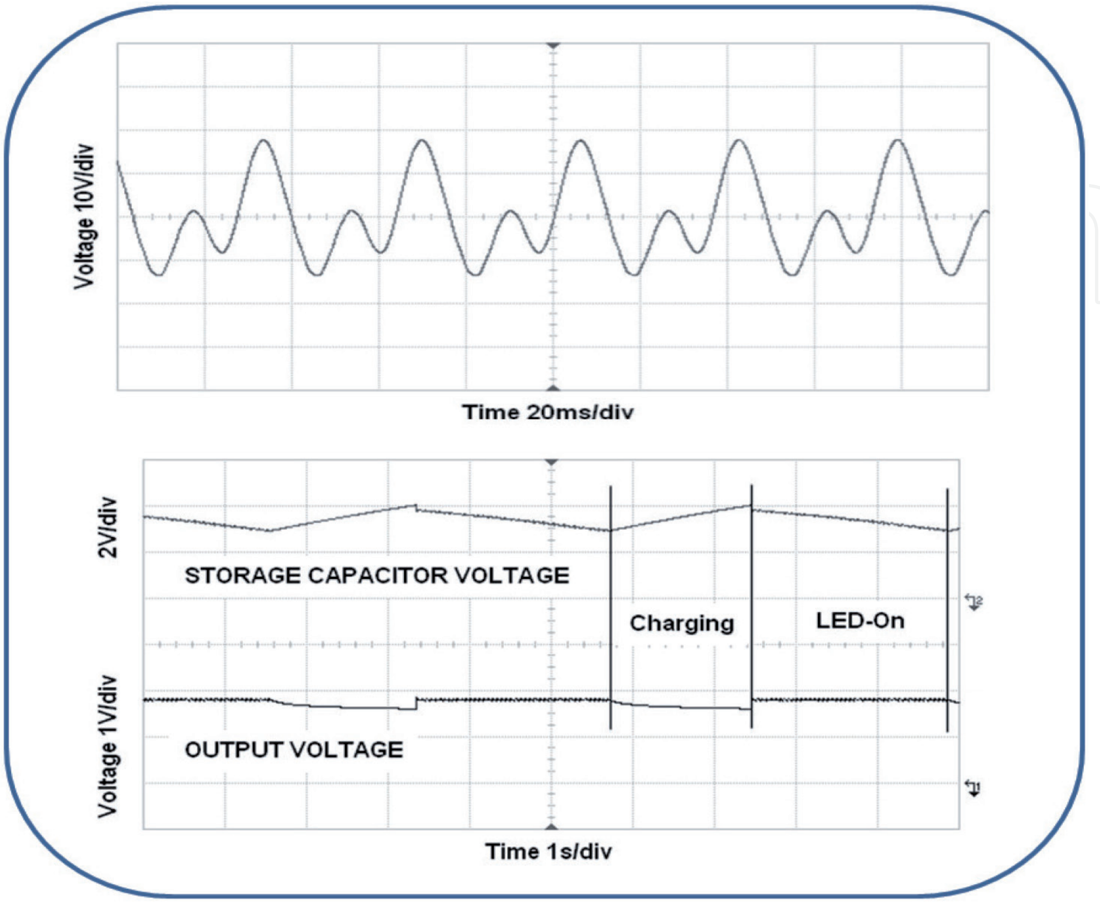


**Figure 8.**
*Piezoelectric driven supercapacitor charging and discharging characteristics.*

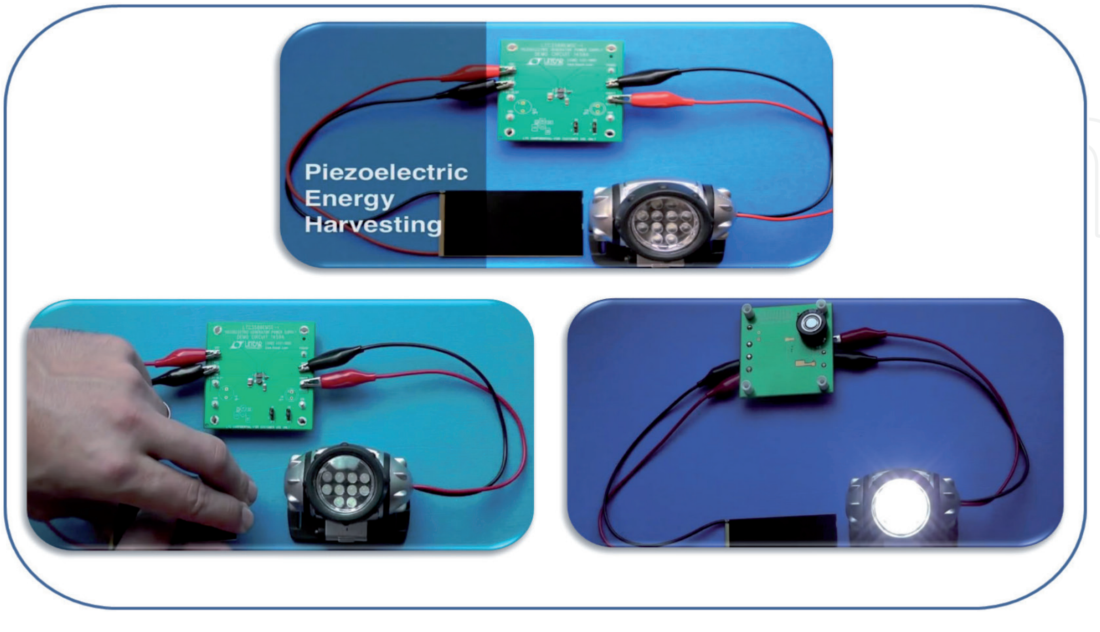


**Figure 9.**
*Hardware implementation of piezoelectric driven charging and discharging supercapacitor for LED flash application.*

## 5. Wearable electronics

Wearable electronic devices represent a paradigm shift in consumer electronics, body sensing, synthetic skins and wearable devices. Since all of these electronics devices require electricity to operate, portable electrical systems are an integral part of portable devices. In fact, the electrodes and other components in these electronics devices must be flexible and comfortable for the user. Presented here is a critical review of devices designed for power conversion and storage applications for use on portable devices. The main focus is on the development of solar cells, triboelectric generators, piezoelectric generators, Li-ion batteries and supercapacitors for the wearable device applications shown in **Figure 10**. These devices must be attached to the fabric., Interaction takes place. Limited to devices made with fiber and ribbon. Some major challenges and future guidelines will also be followed [24–27].

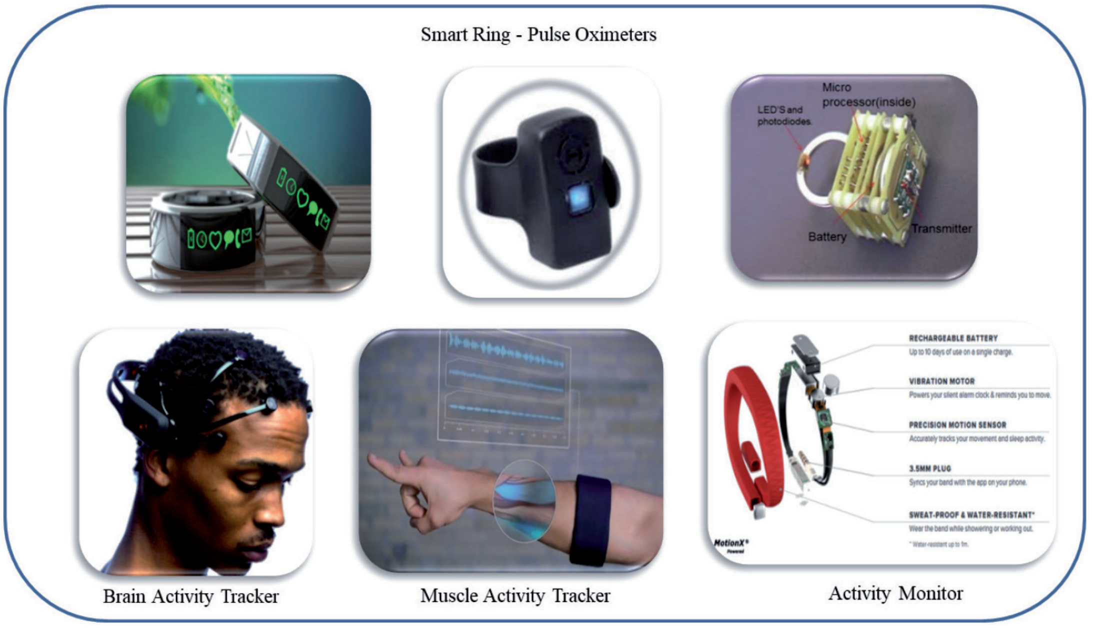


**Figure 10.**
*Application of wearable electronics.*

## 6. Flexible electronics

Solid state flexible supercapacitors have many applications that are flexible and wearable for current and future generations. Flexible supercapacitors can be easily connected to wearable clothing and serve as a power supply for various electronic devices such as mobile phones. The energy generated by piezoelectric generators can be stored in a large storage device and used to charge cell phones. An example is a supercapacitor-powered t-shirt called a "sound charge" that can generate electricity under the pressure of sound waves. The T-shirt tested at the Glastonbury event produced enough power to recharge two basic phones over the weekend. Activated carbon screen-printed, woven and woven with carbon fiber-based supercapacitor electrodes, fitted with a long-sleeved T-shirt, as shown in **Figure 11** [28–32].

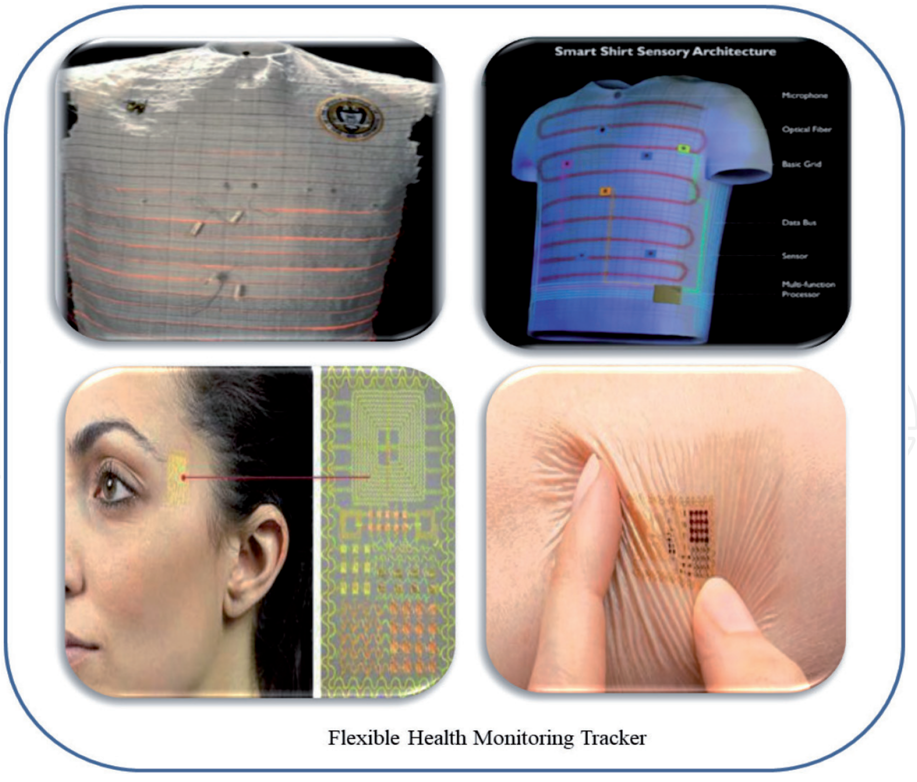


**Figure 11.**
*Application of flexible electronics.*

## 7. Implantable healthcare

Piezoelectric charged supercapacitors are widely used in many fitted healthcare systems where microwatts up to milliwatts are required. These supercapacitors are used for cardiac pacemakers, insulin pumps, and health care systems. Continuous glucose monitoring (CGM) systems monitor glucose levels throughout the day. CGM users inserted a small sensor wire under their skin using an automated device. This attachment has a CGM sensor housing so that the sensor can measure glucose readings in the fluid day and night. A small, reusable transmitter leads to the sensor and sends real-time readings to the receiver wirelessly, allowing the user to view the data. For some systems, a smart compatible device with a CGM application acts as a

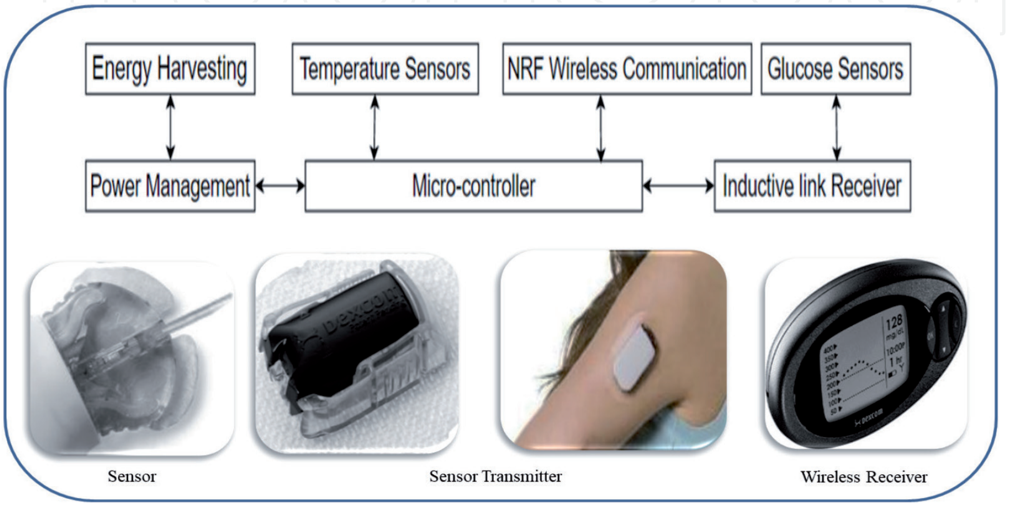


**Figure 12.**
*Continuous glucose monitoring (CGM) sensor, receiver and transmitter.*

display device. A convenient receiver or smart device reflects current glucose levels, as well as historical trends in levels. The compatible CGM receiver and/or smart device can be set to send alerts to the user when the glucose limit is reached [33–39].

With the advancement of technology in the wireless network and microelectromechanical system, smart sensors designed to be set up in remote locations, such as pull-sensing health sensors and medical sensors implanted in the human body, have lost a CGM (continuous glucose monitor) device. It provides "real time" glucose reading and trends in glucose levels. The glucose level reads under the skin every 1–5 minutes (10–15 min delay). This suggests that high and low glucose monitors turn on alarms and inform diabetes management practice. Finding a battery replacing sensor is expensive and costly every time. In embedded cases, access is impossible and devastating. With the advent of energy-efficient harvesting technology, the lifespan of those sensors can be significantly extended or replaced by their own batteries, as shown in **Figures 12**, **13** and **14** [40–45].

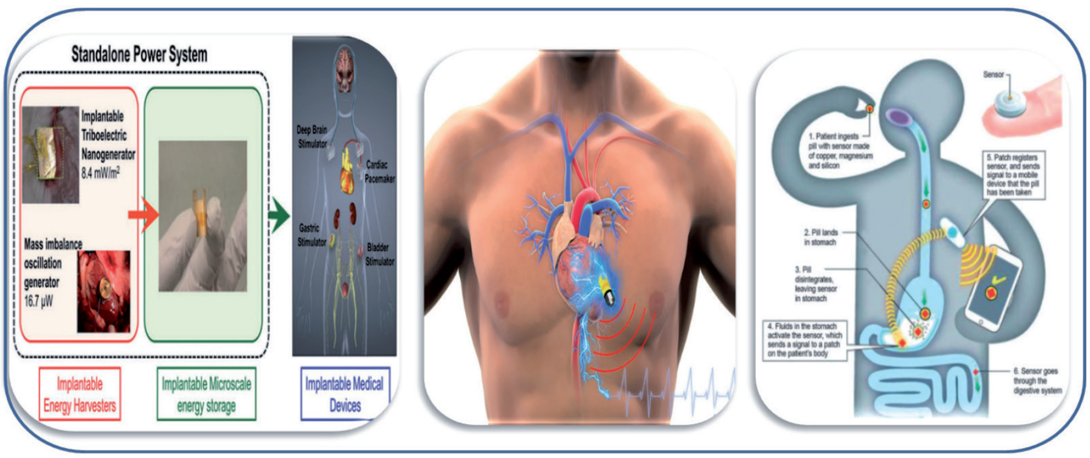


**Figure 13.**
*Bio-medical sensor application for supercapacitor.*

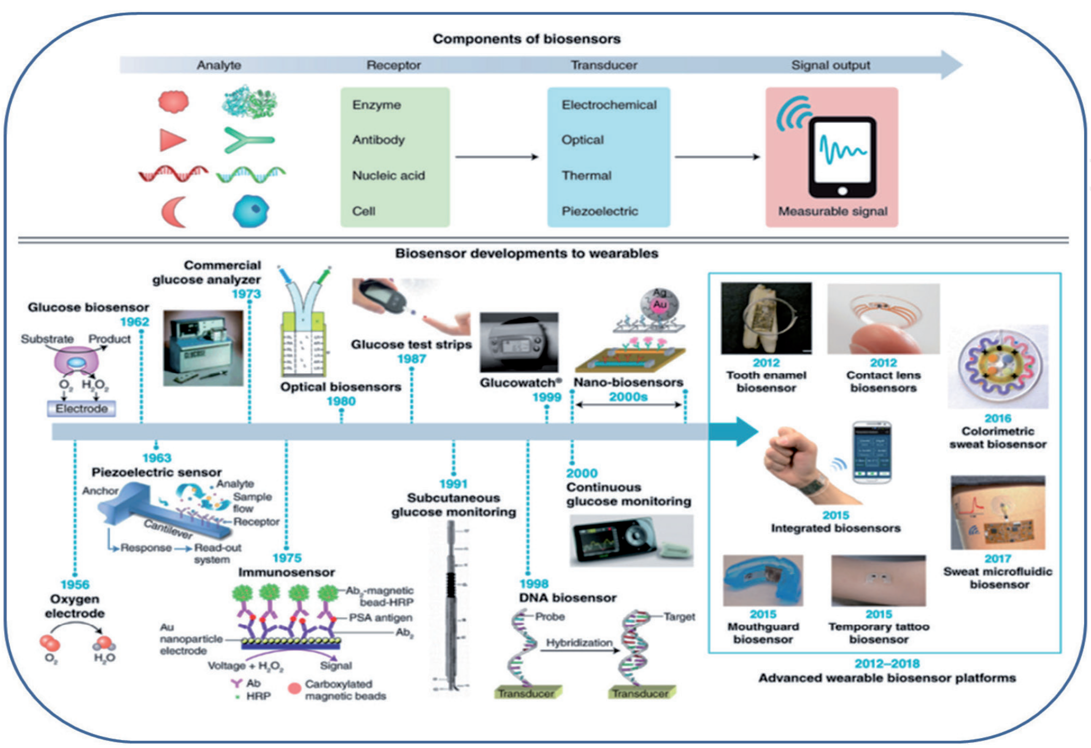


**Figure 14.**
*Application of portable electronics and medical equipment.*

## 8. Portable electronics

Nowadays, we cannot imagine a world without portable electronics like smartphones, smartwatch, laptops, cameras, and much more, making our daily life more modern to accomplish various new tasks. However, these smart electronics need power with energy-saving systems. Supercapacitors play an important role as an energy storage system as well as batteries. Hybrid devices with battery-supercapacitor hybrids are the best choices for current and future electronic power supply devices. This combination enables lightweight battery devices to be integrated into small portable electronic gadgets such as the clock, sensors, cell phone and headset shown in **Figure 15**.

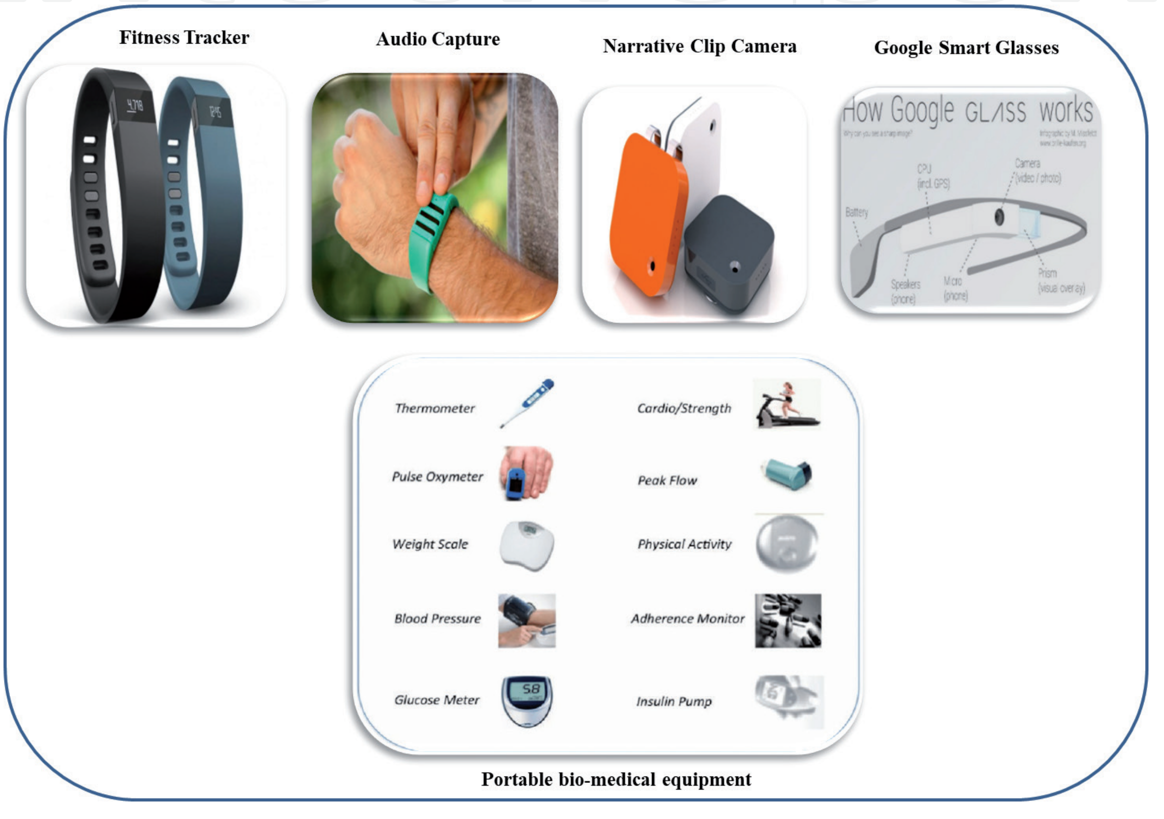


**Figure 15.**
*Application of Portable Electronics.*

## 9. Summary and outlook

Supercapacitors are unique energy storage systems between batteries and electrolytic capacitors based on their electrical performance. These can supply power as capacitors and bring the energy density closer to the battery. Research is not limited to the development of electrode materials and electrolytes and other materials. Many new promising supercapacitor devices are also designed for portable and wearable electronics. Made with the best development sandwiches, planers, wires, fibers, cables and more wearable and flexible supercapacitors. Research has been advanced on supercapacitors such as piezoelectric, shape-memory, thermal management systems and to extend working applications. In flexible electronics. Therefore, supercapacitors have evolved from composite applications to energy storage systems to portable and wearable electronics, smart clothing, automotive, energy-saving systems, implantable medical devices, and emerging technologies such as military and aerospace craft applications.

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