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Review

Supercapacitor-Assisted Energy Harvesting Systems

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Abstract: Energy harvesting from energy sources is a rapidly developing cost-effective and sustainable technique for powering low-energy consumption devices such as wireless sensor networks, RFID, IoT devices, and wearable electronics. Although these devices consume very low average power, they require peak power bursts during the collection and transmission of data. These requirements are satisfied by the use of energy-storage devices such as batteries or supercapacitors (SCs). Batteries offer significantly higher energy density but are subject to regular replacement, thermal runaway risk, and environmental concerns. On the other hand, SCs provide over a million-fold increase in capacitance compared to a traditional capacitor of the same volume. They are considered as the energy-storing devices that bridge the gap between conventional capacitors and batteries. They also offer fast charging times, a long lifecycle, and low equivalent series resistance (ESR). Most importantly, they are capable of handling the high transient currents produced by energy harvesters and provide a stable power source for external loads. This study encompasses a brief exploration of the three fundamental SC types. Then, the discussion delves into the integration of SCs into energy harvesting applications. The collective knowledge presented aims to guide future research endeavors fostering the development of novel energy harvesting systems using SCs.

Keywords: energy harvesting; energy storage; power management; supercapacitors

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1. Introduction

Over the past few years, there has been a growing focus on energy harvesting comprising a series of methodologies aimed at harnessing energy from various sources within the local environment, including but not limited to motion, temperature differentials, luminosity, electromagnetic radiation, and chemical energy. The power generated from these sources is typically very low, as depicted in Figure 1 [1,2]. Different techniques are used to convert the harvested energy into electrical form such as turbines, photovoltaic (PV) cells, thermoelectric generators (TEGs), antennas, solar panels, photodiodes, and piezoelectric sensors applicable to self-sustaining devices considering costs, energy usage, and ecological footprint [3]. As modern electronic functions have steadily diminishing power requirements (as shown in Figure 1) [4], the feasibility of energy harvesting becomes increasingly apparent and is increasingly employed to energize small-scale devices such as IoT sensors and portable electronics [5]. Also, the growing interest in harvesting biomechanical energy from human movements to power wearable and portable electronic devices has been fueled by the rapid development of wearable electronics [6].

The main stages of a conventional energy harvesting system are depicted in Figure 2 [7,8]. The energy from the source is converted to electricity by the energy harvester and then the converter changes this voltage or current to appropriate levels for charging the storage element which is, ideally, a rechargeable battery or an SC. The controller manages the energy storage and load demand. The final stage is the load where the harvested energy is utilized [7]. In optimized systems, the extracted energy is maximized by using maximum power point tracking (MPPT) along with maintaining high transduction efficiency [9].

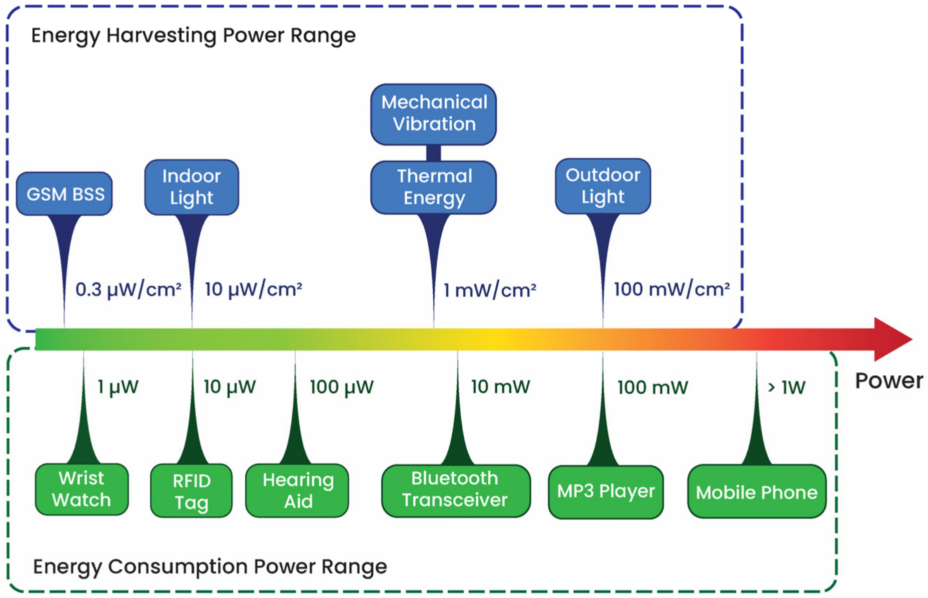


Figure 1. Power generation from energy sources and power demand from loads [1,2].

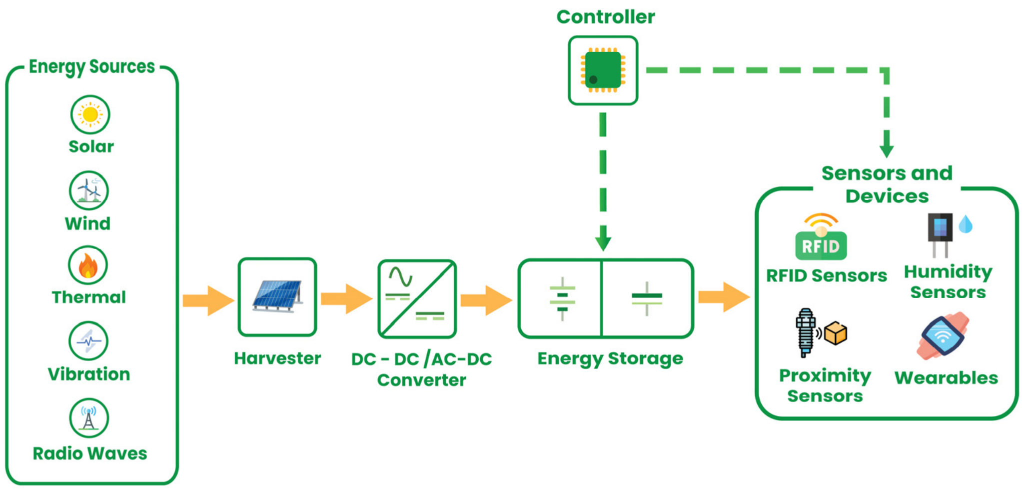
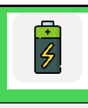


Figure 2. The main stages of an energy harvesting system. Adapted from [7,8].

2. Supercapacitors and Their Basic Types

By using electrodes with a greater surface area and thinner dielectric materials, SCs can provide capacitances that are one million times greater than conventional capacitors. Thus, SCs are considered energy storing devices that bridge the gap between conventional capacitors and batteries and which suit the ever-increasing demand for reliable power in industrial, energy, and computing applications. Table 1 compares the major differences between capacitors, SCs, and batteries, and Figure 3 depicts the Ragone plot of various energy storage devices [10]. SCs are governed by the same fundamental equations applicable to conventional capacitors [11].

Table 1. Comparison of characteristics of supercapacitors versus batteries and conventional capacitors [11].

Characteristics	Capacitors 	Supercapacitors 	Batteries 
Power density (W/kg)	>10^6	60,000	<3000
Energy density (Wh/kg)	<0.1	1 to 73	10 to 250
Equivalent series resistance	Typically, in mΩ range	Typically, in mΩ range	Fractional Ω to few Ω
Charge time (s)	10^{-3} to 10^{-6}	0.3 to 60	3600 to 18,000
Discharge time (s)	10^{-3} to 10^{-6}	0.1 to 1800	600 to 10,800
Lifetime cycles	10^6	50,000 to 1,100,000	500 to 18,000
Typical lifetime (years)	30	30	5–20
Operating temperature range (°C)	−40 to +125	−40 to +70	−20 to +65

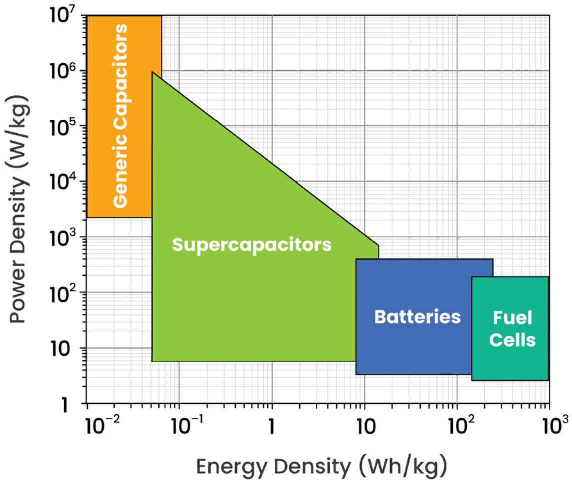


Figure 3. Ragone plot of various energy-storing technologies [10].

Moreover, SCs have attractive features compared to batteries such as long lifetime cycles and low ESR. Also, the ESR of SCs remains almost constant during the charging and discharging processes and their charging and discharging limits are not critical, which means they use less complex charging circuitry. Unlike batteries, they pose zero thermal runaway risk over a wide range of temperatures. They are also environmentally friendly as they do not contain heavy metals [11–13]. They are employed in various applications such as regenerative braking in electric vehicles, portable electronic devices, uninterruptible power supplies, smart grids, energy harvesting, backup power for data centers, telecommunications, and nonconventional DC–DC converters [11,14–19].

Figure 4 displays the structure of three basic SC families: symmetrical electric double-layer capacitors (EDLCs), hybrid capacitors, and pseudocapacitors [11]. EDLCs are composed of two carbon-based electrodes with a dielectric separating them, as shown in Figure 4a. As the potential difference is applied across the electrodes, the charges in the material move to electrodes of opposite potentials [20]. The electrical double layer formed adjacent to a large-area electrode and an electrolyte is effectively used; hence the name EDLC. Their larger area plates and shorter distances between plates can provide a higher effective capacitance [15].

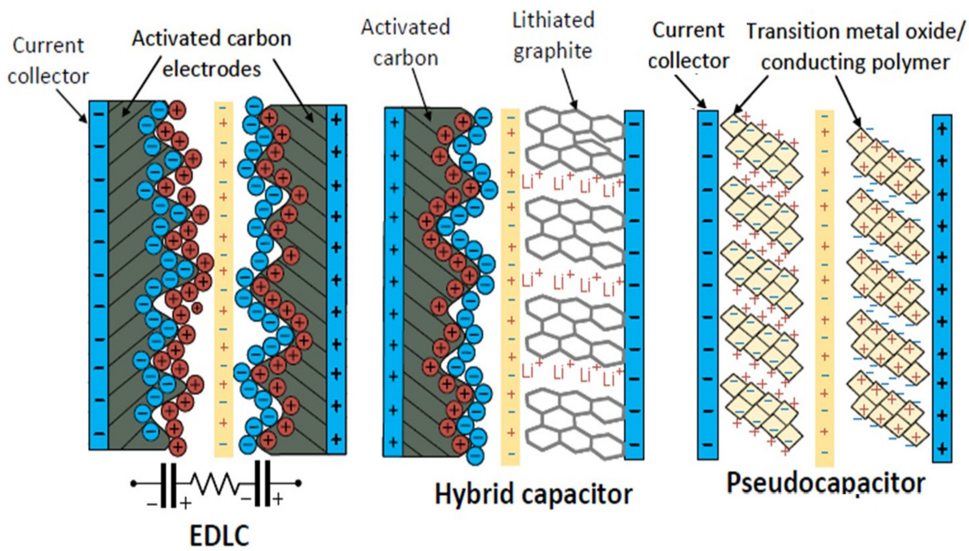


Figure 4. Electro-chemistry of three commercial SC families: (**a**) Electric double-layer capacitor, (**b**) hybrid capacitor, (**c**) pseudocapacitor [11].

Hybrid SCs merge the chemistry of a battery with the physics of an SC in a single structure, as shown in Figure 4b. Due to their higher specific energy compared to EDLCs and good power density, there has been an increasingly strong demand for these devices in recent years [20]. In hybrid SCs, one electrode is activated carbon, and the other is like an electrode in Li-ion batteries. These SCs can provide reliable ride-through or backup power in applications, such as data storage systems, servers, utility meters, and controllers for automated systems [20].

The third type (Figure 4c) is the battery capacitor, based on the concept of pseudocapacitance. Although these SCs have an energy density comparable to lead–acid batteries, they suffer from a relatively low power density and lack of cycling stability compared to EDLCs [21].

3. Advantages of Supercapacitors in Energy Harvesting

Isolated sensors strategically deployed in remote or challenging terrains are amalgamated to establish low-power wireless sensor networks, forming the foundation for diverse industrial, medical, and commercial applications [3]. With the aid of energy harvesting sources, cost-effective power solutions can power these devices. Such autonomous systems have a low power output, which is insufficient for wireless networks. To address this issue, a small rechargeable battery or SC is used as an energy buffer and supplies the necessary power bursts during the transmission of data. These energy storage devices charge at low average power but are capable of releasing power bursts on demand [22]. They also act as a backup energy storage for periods when the primary energy source is unavailable such as at night with solar energy harvesting systems or when RF fields are absent with RF harvesters [23].

Rechargeable batteries have drawbacks in energy harvesting systems such as limited cycle life, cold intolerance, critical charging rates and environmental concerns. They need periodic replacement, and it is an expensive and complex task to manage and maintain batteries in a large-scale sensor network [24,25].

Because SCs serve as a link between traditional capacitors and rechargeable batteries, they possess performance features that are ideal for energy harvesting applications. Because wireless sensor networks often operate with a low-duty cycle and require high peak power to intermittently collect and send data while consuming very little average power, they are suitable for being powered by an SC. The energy harvester can either directly charge the

SC or provide power to a power management IC that charges the SC at a minimal rate. The SC then delivers the necessary peak power for the sensor to perform data collection and transmission [16]. This approach reduces the overall cost of the system and eliminates the need for costly battery replacements providing maintenance-free operation.

Moreover, SCs demonstrate excellent performance when paired with a dependable and efficient energy harvesting method like wireless charging. Typically, AC power is accessible to energize a wireless charger loop, ensuring the circuit remains operational in close proximity. Acting as a rectifier filter, the SC delivers a charged output and can temporarily take over when AC power is unavailable [4]. Moreover, energy efficiency and superior energy predictability are other significant characteristics of SCs over batteries which make them suitable for solar-based energy harvesting systems [26].

Furthermore, EDLCs store energy electrostatically across a broad working voltage range, constrained solely by the electrochemical stability of the electrolyte, whereas batteries store energy at specific cell voltages determined by the electrode Faradaic processes. This flexible characteristic of EDLCs allows them to be applied in energy harvesters that function at low voltages [27].

The battery charger usually functions as a DC–DC converter, operating as a load that takes constant power from the energy source. Therefore, it is logical to extract this power at the most optimal point by utilizing MPPT. On the other hand, unlike a battery, an SC does not require charging at a constant voltage. Instead, it achieves the most efficient charging by drawing the maximum current that the source can provide [22].

In addition, SCs serve as substitutes for batteries in certain applications and can complement them in hybrid setups. In some applications where an SC's energy storage is insufficient, a battery can be utilized [22]. In cases where the ambient energy source (for example, the sun), has intermittent availability, such as during the night or rainy days with cloudy skies, the device needs to store energy not only for delivering power at peak levels but also to sustain the application over an extended period. Also, in applications where the required peak power surpasses the battery's capacity (for example, during GSM calls), the battery can charge the SC at a lower rate during the rest of the time, and the high-power bursts are delivered by the SC during peak demands. This mechanism prevents the battery from undergoing deep cycling, ultimately prolonging its lifespan [22].

4. Applications of Supercapacitors in Energy Harvesting

Ambient and external energy sources include a wide range of renewable energy sources such as solar radiation, wind currents, vibrations, and thermal differences. As depicted in Figure 5, several technologies are applied to harvest the ambient energy and provide sustainable power for different applications from small-scale sensors to larger infrastructure systems [28]. Each energy harvesting technique has its own set of advantages and disadvantages, which are compared in Table 2 [29–32]. In these techniques, due to their versatility and superior performance, SCs play a vital role in optimizing the efficiency and effectiveness of energy harvesting technologies by effectively managing the variability of energy sources. Table 3 lists the stored energy ranges of three fundamental SC types in different energy harvesting applications [29–31].

There are mainly three challenges in energy harvesting: (a) efficiency and energy density; (b) sustainability and materials; (c) integration and scalability. These technological limitations and the need for continuous innovation in these areas as well present further obstacles. Realization of proper and eco-friendly energy storage devices such as supercapacitors [12,13] and application-driven customizable designs are extremely desirable for long-term stability; hence, interdisciplinary research and work is necessary to address these gray areas [29–31].

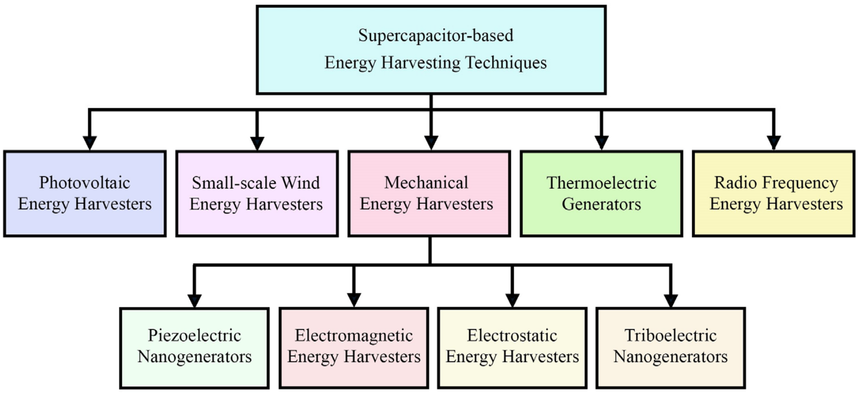


Figure 5. Supercapacitor-based energy harvesting methods.

Table 2. Comparison of advantages and disadvantages of different energy harvesting methods.

Energy Harvesting Technique	Advantages	Disadvantages
Photovoltaic	High energy availability and good energy conversion efficiency	Intermittent supply
	Environmentally friendly	Space requirement
	Scalability	Requirement for maintenance and cleaning
Small-scale wind	High power potential	Intermittent and fluctuating supply
	Scalability	Regular maintenance required
Mechanical	Ubiquitous sources	Intermittent nature
	Compact size	Complexity of energy conversion
Thermal	Continuous supply	Low conversion efficiency
	Easy to install	Material degradation at high temperatures
Radio frequency	Minimal maintenance	Interference issues
	Ubiquitous availability	Distance limitation

Table 3. Supercapacitor types and their typical energy storage ranges in energy harvesting.

Supercapacitor Type	Typical Stored Energy Range (J)				
	Photovoltaic	Small-Scale Wind	Mechanical	Thermal	Radio Frequency
Electric Double-Layer Capacitors	200–400	20–50	20–50	50–100	10–30
Hybrid Supercapacitors	500–1000	100–200	100–200	200–400	50–100
Pseudocapacitors	300–600	50–100	50–100	100–200	30–50

4.1. Supercapacitor-Based Mechanical Energy Harvesting

Mechanical energy harvesting, through the utilization of motion and vibrations, presents a highly promising approach to generating electricity. Three primary converters facilitate the transformation of mechanical energy into electrical energy: piezoelectric devices, electromagnetic devices, and electrostatic devices [33]. In addition, triboelectric energy harvesters have recently emerged as one of the most straightforward and economical methods for capturing mechanical energy [34].

Piezoelectric energy harvesters (PENGs) utilize the piezoelectric effect, wherein strain in a material results in structural deformation, leading to an imbalance in charge and the generation of voltage [35]. They typically operate at high frequencies (>1 kHz) and offer the benefits of self-sufficiency, a relatively high voltage output, small dimensions, and a strong electromechanical coupling factor, making them useful in many energy harvesting applications including architecture, biomechanics, and human motion [36]. Because the output power of PENGs entirely depends on the input vibrational energy, it becomes intermittent if the mechanical energy is not constant and this poses a significant challenge for electronic devices that require a continuous power supply [37]. To mitigate this effect, SCs are applied as energy buffers in PENG-based energy harvesting systems.

Electromagnetic energy harvesters, EEHs, operate based on Faraday's law of electromagnetic induction, where the movement of a magnet through a coil results in the generation of electric current [36,38]. They are distinguished from other types of vibrational harvesters by their capacity to harness kinetic energy within a relatively narrow bandwidth around their resonant frequency [36]. They have the advantages of a simple structure, long life, large output current, and low resonance frequency [39].

In electrostatic energy harvesters, the energy is harvested using an electrostatic transducer that works by a force creating a change in capacitance which induces a voltage [36]. They consist of two plates separated by air, vacuum, or other dielectric material. There are two types of electrostatic generators: electret-free and electret-based. The former utilizes conversion cycles involving charging and discharging of the capacitor, whereas the latter employs electrets to directly convert mechanical power into electricity [40]. These generators facilitate the development of cost-effective devices as they do not require magnets or potentially expensive piezoelectric materials [40]. Nevertheless, they are unable to supply power directly to the IoT and wearable devices without using an energy storage device because of their low average power [41]. SCs have garnered significant interest in recent years in electrostatic energy harvesting due to their exceptional power density, extended cycle life, and notably rapid charge/discharge rate.

The triboelectric nanogenerator (TENG) is another mechanical energy harvesting method which has multiple advantages such as eco-friendliness, affordability, effectiveness, and an extensive array of material options, rendering it appropriate for a multitude of self-powered electronic devices. It operates by harnessing the combined effects of contact electrification and electrostatic induction [42]. When two dissimilar materials with varying electron affinities come into contact, they exchange electrons, resulting in opposite charges on their surfaces. The repetitive contact–separation or sliding motion of these materials generates an alternating current output. SCs emerge as ideal contenders for storing the energy harnessed by TENGs. This is primarily due to the numerous advantages offered by SCs, including higher peak current, minimal leakage currents, affordability, and commendable reversibility [34]. Therefore, the increasing need for sustainable and effective energy generation and storage solutions has increased interest in combining triboelectric nanogenerators (TENGs) with SCs.

The typical SC-based mechanical energy harvesting system is depicted in Figure 6. It consists of five major components: the mechanical energy harvester, SCs, a rectifier circuit, a controller, and a load. The acquired mechanical energy is converted to AC followed by rectification. The stored energy is utilized based on the load demand with the use of a switching circuit and a controller. Table 4 summarizes several applications of mechanical energy harvesting methods that utilize SC as energy storage.

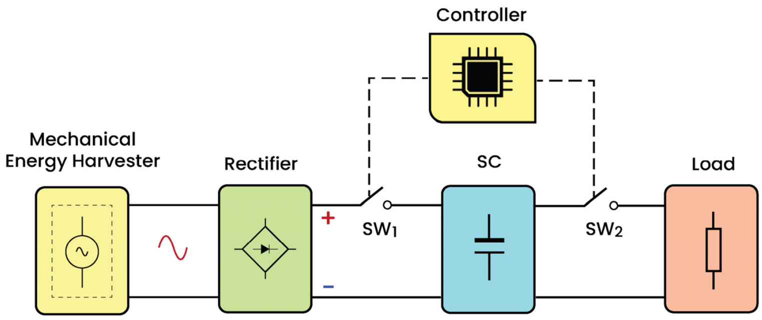


Figure 6. A typical application example of supercapacitors in mechanical energy harvesting.

Table 4. Different applications of supercapacitors in mechanical energy harvesting.

Converter Type	Study	Hardware	Applications	Role of Supercapacitors
Piezoelectric	Energy harvesting and storage with ceramic piezoelectric transducers coupled with an ionic liquid-based supercapacitor [27]	Integrated piezoelectric unit, ionic liquid-based micro-SC, and a bridge rectifier	Wearable electronics	To reduce the charge times and overall system volume
	Piezoelectric-driven self-powered supercapacitor for wearable device applications [43]	LTC3588-1 (from Analog Devices, Wilmington, NC, USA) based circuit designs which combine a low-loss full-wave bridge rectifier with a high-efficiency buck converter	Wearable electronics	Energy storage element with low leakage current
	Analysis of batteries or supercapacitor as energy storage device for a sound energy harvester system [44]	Q220-A4-503YB (from https://piezo.com/, Woburn, MA, USA) piezoelectric energy transducer, 0.22 F SC, voltage multiplier, voltage regulator	Low-power electronic devices, LEDs	More efficient energy storage device due to their better charging and discharging characteristics
	Self-charging piezo-supercapacitor: one-step mechanical energy conversion and storage [37]	Fabricated piezoelectric driven self-charging SC	Portable electronic devices	To harvest sporadic mechanical energy, convert it to electrical energy, and simultaneously store energy
Electromagnetic	A portable high-efficiency electromagnetic energy harvesting system using supercapacitors for renewable energy applications in railroads [45]	Mechanical transmission system, regulating circuit, SCs	Safety facilities/standby power supplies for rail-side equipment	To permit the storage of energy from rapidly changing transient currents and act as a steady power supply for external loads
	Maximum power transfer tracking for ultralow-power electromagnetic energy harvesters [46]	Rectifier, boost rectifier, voltage regulators, controller with MPTT, SCs	Resistive loads	The low output power and large storage capacitance of SCs enable the MPTT control to rely solely on output current measurement.
	Ultralow power, fully autonomous boost rectifier for electromagnetic energy harvesters [47]	Full-wave boost rectifier, SC	Wireless sensor nodes	Energy storage element which is fed by a boost rectifier
Electrostatic	A flexible all-solid-state micro supercapacitor and its application in electrostatic energy management system [32]	Flexible micro-SC, rectifier, buck-boost converter, low-dropout regulator, controller	Wearable electronics	Flexible energy storage element

Table 4. *Cont.*

Converter Type	Study	Hardware	Applications	Role of Supercapacitors
Triboelectric	Wearable self-charging power textile based on flexible yarn supercapacitors and fabric nanogenerators [48]	Rectifier, SC, circuit to switch between the SC and the load	Wearable electronics	Lightweight energy storage element
	Triboelectric nanogenerator/supercapacitor in-one self-powered textile based on PTFE yarn wrapped PDMS/MnO_2NW hybrid elastomer [6]	Rectifier, SC, circuit to switch between the SC and the load	Wearable electronics and versatile pressure sensing	Energy storage element with high volumetric energy density and excellent cyclic stability

4.2. Supercapacitor-Based Photovoltaic Energy Harvesting

Solar energy is considered to be the most auspicious and inexhaustible source of energy where the radiant light emitted by the sun can be harnessed and transformed into usable energy. The typical power architecture of SC-based PV energy harvesters can be divided into two basic methods: (1) direct charging when the SC voltage is higher than the open-circuit voltage of the PV array, and (2) using a boost converter with MPPT when the open-circuit voltage of the PV array is higher than the SC voltage.

Figure 7 depicts a straightforward charging system designed for method (1) [22] where I_{PV}, D_{INT}, R_P, and R_S represent the solar PV current, and diode array due to the recombination, equivalent parasitic shunt resistance, and equivalent parasitic series resistance, respectively. The diode (D_B) serves to block the SC from discharging in reverse through the solar-cell array when it is dark [22]. In Figure 7's circuit, the SC, starting at 0 V, initially pulls a short-circuit current from the solar-cell array. As the supercapacitor charges, the current diminishes, influenced by the solar-cell array's voltage/current behavior. Despite this, the SC consistently draws the maximum current available to charge at the fastest rate possible. If the open-circuit voltage of the energy source exceeds the rated voltage of the SC, it is necessary to employ overvoltage protection for the SC using a shunt regulator. A shunt regulator is a cost-effective and straightforward strategy for safeguarding against overvoltage. An example shunt regulator is provided in [22]. Once the SC is fully charged, the dissipation of any excess energy becomes inconsequential. The output load (R_L) is driven when the SC has a sufficient charge for the load demand by closing the switch (SW).

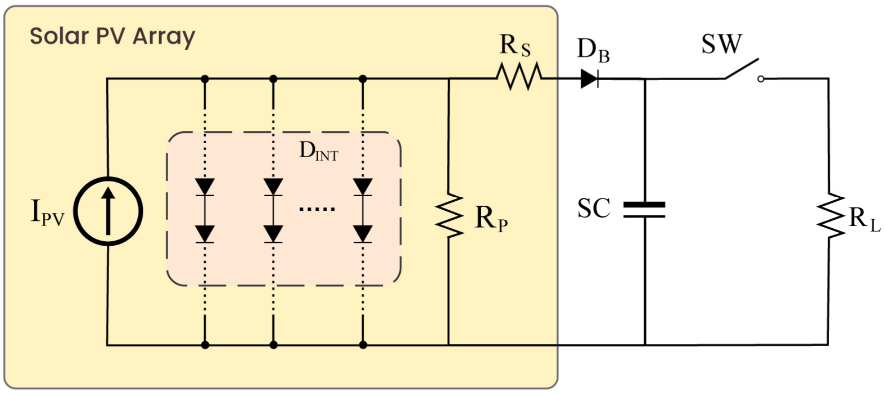


Figure 7. The simplified approach to direct charge the supercapacitor using solar cells. Adapted from [22].

A similar study is performed by utilizing a small solar cell in which the SC is charged using an energy harvester to meet the peak power requirements [49]. The energy harvester provides a modest amount of power to charge the SC, which, in turn, delivers intermittent or irregular bursts of power to gather and transmit data in IoT applications. The major drawback of method (1) is that it has low efficiency as it does not have an MPPT system.

In method (2), the efficiency is maximized by using a boost converter with MPPT. An example schematic of a practical circuit designed using this approach is demonstrated in [49]. An integrated circuit (BQ25504 from Texas Instruments, Dallas, TX, USA) is used which adjusts the input current to keep the solar cell operating at its optimal power point, while also ensuring that the SC is charged even when the light level decreases. This approach is achieved by maintaining the solar cell voltage below the SC charge voltage.

4.3. Supercapacitor-Based Small-Scale Wind Energy Harvesting

Over the past few decades, wind energy has emerged as a rapidly growing source of renewable energy [1]. Small-scale wind energy harvesting systems have become an increasingly popular source of energy for homes, buildings, businesses, and communities. These systems have numerous advantages over large-scale wind energy systems, such as space efficiency and low cost [50]. These systems are designed based on wind turbines and wind-induced vibration technologies [50]. Table 5 shows a few application examples developed by several research teams using SCs in wind energy harvesting. These methods relate to Figure 6 where the harvester can be either a small wind turbine or a vibrational energy harvester.

Table 5. Examples of recent SC-based wind energy harvesting applications.

Study	Hardware	Applications	Role of Supercapacitors
Wind energy harvesting system powered wireless sensor networks for structural health monitoring [51]	Wind turbine, rectifier, DC–DC boost converter, SCs as energy storage	Sensors, wireless modules	Alternative energy storage device which eliminates the complication of replacing the batteries at regular intervals results in the developing a sustainable power management system for wireless sensor nodes
Instantaneous charging and discharging cycle analysis of a novel supercapacitor-based energy harvesting circuit [52]	Vertical axis turbine, battery–SC combined energy storage, rectifier, DC–DC boost converter, Arduino-based controller	Low-power electronic devices with improved charging efficiency in the energy storage	Supportive energy storage unit which increases the longevity of the battery pack in use.
Wind energy harvesting for autonomous wireless sensor networks [53]	Wind turbine, rectifier, DC–DC converter, SCs as energy storage	Wireless sensor networks	Energy storage device

In order to cater to applications that must have an uninterrupted power supply throughout their operational lifespan, it is advantageous to integrate solar power with an alternative power source, such as wind, which offers complementary availability [53]. The research in [53] introduces multiple solar/wind (hybrid) SC-based harvesters, utilizing pre-existing open-source designs of solar-only harvesters. This work unveils the potential of using hybrid harvesters to reduce downtime significantly, in contrast to systems relying solely on solar or wind power [53].

4.4. Supercapacitor-Based Thermoelectric Energy Harvesting

TEGs have become a focal point in energy harvesting methods due to their ability to transform temperature differences into electrical energy. They present a viable option for powering devices without the need for batteries, as they can harness temperature variations in the surroundings to create a consistent and sustainable power source. This characteristic renders TEGs highly suitable for a range of applications, including industrial environments, transportation systems, and even utilizing the heat generated by the human body [25].

TEGs are comprised of multiple pairs of thermocouples placed between ceramic plates, totaling in the tens or hundreds, which are interconnected in series electrically and in parallel thermally [54]. They offer advantages such as no moving parts, a longer service life and silent operation [54]. However, in many cases, the electrical output generated from thermoelectricity typically remains at the millivolt level, making it unsuitable for direct use and challenging to store [55]. Table 6 highlights a few applications of SCs in TEG-based energy harvesting, whereas Figure 8 shows a typical application using commercial power management ICs such as ADP5090 (from Analog Devices, Wilmington, NC, USA), LTC 3108 (from Analog Devices, Wilmington, NC, USA), and BQ25504 (Texas Instruments, Dallas, TX, USA).

Table 6. Examples of recent SC-based thermoelectric harvesting applications.

Study	Hardware	Applications	Role of Supercapacitors
Powering a low-power wireless sensor in a harsh industrial environment: energy recovery with a thermoelectric generator and storage on supercapacitors [54]	Eureca TEG1-30-30-8.5/200 TEG module, commercial energy harvesting IC (The BQ25504 (Texas Instruments, Dallas, TX, USA), SC storage, TPS610995 (Texas Instruments, Dallas, TX, USA) boost converter and TPS71533 (Texas Instruments, Dallas, TX, USA) low-dropout regulator	Battery-free autonomous power supply, wireless sensor networks	Battery-free energy storage that operates at temperatures of up to 80 °C
High-efficient energy harvesting architecture for self-powered thermal-monitoring wireless sensor node based on a single thermoelectric generator [3]	Thermoelectric generator, DC–DC boost converter with MPPT, 30 mF SC energy storage, microcontroller	Wireless sensor nodes	Energy storage module
Wearable thermoelectric power generators combined with flexible supercapacitor for low-power human diagnosis devices [56]	Wearable thermoelectric generator, flexible SC	Low-power human diagnosis devices, sensor nodes	Flexible energy storage element to realize the combination of renewable energy and wearable devices.
A laterally designed all-in-one energy device using a thermoelectric generator-coupled micro supercapacitor [57]	A thermoelectric generator-coupled micro SC	Self-powered electronic devices	All-in-one energy devices with space efficacy
Carbon nanotube-based thermoelectric generator and graphite nanoparticle-based supercapacitor for smart wearable sensors [58]	Nanoparticle-based thermoelectric generator and SC, DC–DC boost converter	Self-powered wearable sensors	Stabilize the voltage output of the TEG and power out the loads under different conditions

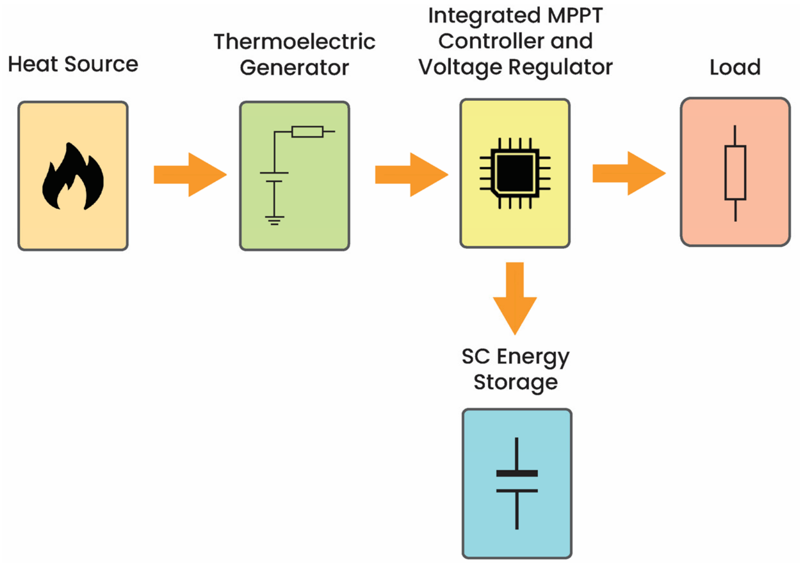


Figure 8. SC-based thermoelectric generator application example.

4.5. *Supercapacitor-Based RF Energy Harvesting*

Radiofrequency energy harvesting (RFEH) is a method used to convert energy from an electromagnetic (EM) field into electrical energy [59]. There is a plentiful supply of RFEH available from various sources in the surroundings, such as nearby mobile phones, Wi-Fi networks, wireless local area networks, broadcast television signals, and FM/AM radio signals. Contrary to other techniques for energy harvesting, RFEH possesses numerous benefits, including the capability to regulate and guarantee consistent transmission of energy over long distances, as well as providing stable and predictable energy outputs [60]. The concept of RFEH has undergone significant advancements over the past two decades, particularly in terms of the signals utilized. Recently, there has been a shift towards exploring the industrial, scientific, and medical (ISM) band at 2.45 GHz as well as GSM frequencies at 900 MHz and 1800 MHz, due to the widespread proliferation of WiFi, 3G, and 4G systems worldwide in recent years [61].

In order to transform an RF signal into DC voltage, the development of a Rectenna circuit is essential, which is displayed in Figure 9 [61]. A matching network is used between the antenna and the diode to achieve optimal power transfer. The diode is connected to a low-pass filter, which consists of a capacitor and a resistor [61]. Several studies have demonstrated the applicability of SCs in RF energy harvesting, as listed in Table 7.

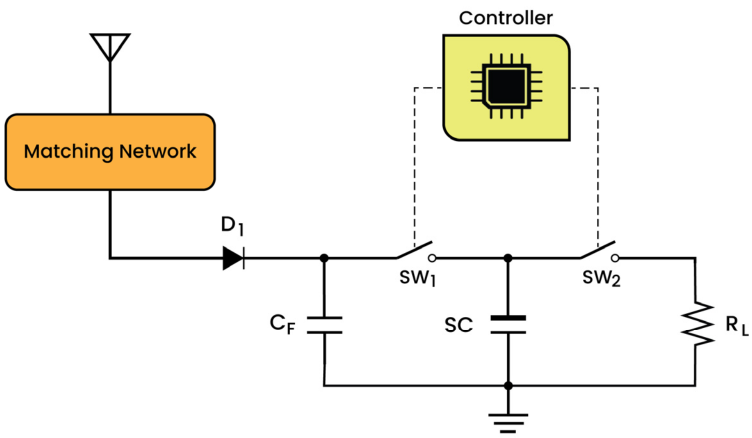


Figure 9. The rectenna circuit. Adapted from [61].

Table 7. Examples of recent SC-based RF energy harvesting applications.

Study	Frequency Range	Hardware	Applications	Role of Supercapacitors
Radiofrequency energy harvesting and storing in supercapacitors for wearable sensors [62]	Digital terrestrial television frequency (DTT) band: 750–758 MHz	SCs, N-stage Dickson voltage multiplier PCBs	Low-power electronic devices	Energy storage device which can cope with the receiver energy fluctuations
Ultralow power RF energy harvesting system using a supercapacitor as an energy reservoir for an IoT node [61]	2.45 GHz	RF-to-DC converter, a storage SC, and a DC–DC boost converter.	IoT sensor nodes	Energy reservoir
Performance of printable supercapacitors in an RF energy harvesting circuit [23]	13.56 MHz	Printed loop antenna and half-wave organic diode rectifier, pair of SCs (0.45 F and 0.21 F), voltage regulator	Sensors and small indicator display	Printable supercapacitors as energy storage devices
Radio-frequency energy harvesting for wearable sensors [63]	GSM 900/1800 MHz cellular and 700 MHz DTT	Rectenna, buck-boost converter, SC energy storage and Arduino-based controller	Wearable biomedical sensors	Battery-free energy storage for low maintenance and precise estimation of remaining energy

5. Limitations of Supercapacitors in Energy Harvesting

SCs, despite their high potential for energy harvesting applications, do have certain limitations that must be taken into account in the design process.

- The low voltage of a single-cell supercapacitor (typically 2.7 V to 5.5 V) is one major constraint in energy harvesting applications, particularly in scenarios involving systems demanding higher voltage levels. SCs generally come with a maximum voltage rating; exceeding it will lead to damage or malfunction. This constraint may impede their efficiency in energy harvesting setups that rely on higher voltages for optimal functionality. A cascade of serial-connected SCs is a promising solution to expand the voltage range [23]. Nevertheless, voltage balancing circuits are essential in cascaded SC systems due to the tolerance and changes in the capacitance caused by the production or ageing [64].
- Energy density constraint presents a hurdle in some energy harvesting scenarios where optimizing energy storage capacity is essential. The use of hybrid SCs is one solution to increase energy density. As discussed in Section 2, these SCs integrate the benefits of both SCs and batteries, providing a greater energy density compared to conventional SCs alone. Recent studies reveal that the unique blend of electrode materials/composites and electrolytes, coupled with their manufacturing design significantly boosts the energy density of the SCs and also their electrochemical efficiency [65,66].
- Comparatively higher self-discharge rates were observed in SCs as opposed to batteries. Overcoming this obstruction is crucial for maximizing the efficiency and reliability of SCs in energy harvesting applications. Recently, numerous studies have been published aiming to address this drawback using a range of innovative approaches such as the use of enhanced electrolytes and applying a blocking layer with an insulating material on the electrode surface [67].
- The extent of temperature sensitivity further constrains the potential applicability of SCs in certain energy-harvesting contexts. Elevated temperatures can hasten deterioration, whereas lower temperatures can impact capacitance and raise internal resistance, both of which can have a negative effect on overall performance [68]. The

use of thermal management systems such as active and passive cooling methods can effectively control the temperature of SCs and mitigate the decline in performance caused by high temperatures [69]. Encapsulating SCs in materials with high thermal conductivity or with insulation properties can help protect them from temperature fluctuations and maintain their performance [68].

- SCs can be a more expensive option than batteries for energy harvesting systems as the cost per kWh of SCs is higher than for Li-ion batteries [70]. Even so, the advantage is seen in long-term cost savings as the Li-ion batteries have close to 1000 lifetime cycles compared to the SCs which have 15,000 to 1,000,000 lifetime cycles [71]. In addition, research continues to enhance the materials and refine the manufacturing processes in order to minimize the costs associated with manufacturing of SCs [72].

Despite the limitations of SCs in energy harvesting applications, continuous research and development in materials science, device engineering, and system integration are actively working towards overcoming these challenges. Through these innovations, SCs have the potential to enhance their efficiency, reliability, and versatility as integral components in energy harvesting systems, thereby contributing to the progress of sustainable energy solutions.

6. Conclusions

The unique properties of SCs: high power density, rapid charge/discharge cycles, and a long lifecycle make them ideal candidates for complementing and enhancing the efficiency of energy harvesting systems. The collective insights provided in this review comparing several SC-based energy harvesting approaches illustrate the potential of providing stable, efficient, and scalable storage solutions as a substitute for traditional battery energy storage approaches. Moreover, this review serves as a comprehensive guide to future research endeavors in SC storage applications, highlighting key areas of SC characteristics that contribute to a more energy-efficient and environmentally friendly future.

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References

1. Donovan, J. New Applications for Energy Harvesting. 2024. Available online: https://www.mouser.com/applications/energy-harvesting-new-applications/ (accessed on 10 April 2024).
2. Dostal, F. New Advances in Energy Harvesting Power Conversion. *Analog. Dialogue* **2015**, *49*, 1–3.
3. Álvarez-Carulla, A.; Saiz-Vela, A.; Puig-Vidal, M.; López-Sánchez, J.; Colomer-Farrarons, J.; Miribel-Català, P.L. High-efficient energy harvesting architecture for self-powered thermal-monitoring wireless sensor node based on a single thermoelectric generator. *Sci. Rep.* **2023**, *13*, 1637. [CrossRef] [PubMed]
4. Gabay, J. Supercapacitor Options for Energy-Harvesting Systems. 2013. Available online: https://www.digikey.com/en/articles/supercapacitor-options-for-energy-harvesting-systems (accessed on 13 April 2024).
5. Mehta, P.; Gaur, A.; Kumar, C.; Nella, A.; Bhowmick, A.; Rajagopal, M. Energy Harvesting Techniques and Trends in Electronic Applications. In *Energy Harvesting Trends for Low Power Compact Electronic Devices*; Nella, A., Bhowmick, A., Kumar, C., Rajagopal, M., Eds.; Springer International Publishing: Cham, Switzerland, 2023; pp. 205–220. [CrossRef]
6. Mao, Y.; Li, Y.; Xie, J.; Liu, H.; Guo, C.; Hu, W. Triboelectric nanogenerator/supercapacitor in-one self-powered textile based on PTFE yarn wrapped PDMS/MnO_2NW hybrid elastomer. *Nano Energy* **2021**, *84*, 105918. [CrossRef]
7. Nexperia. *Designing an Energy Harvesting System Using the NEH2000BY PMIC*; Nexperia: Nijmegen, The Netherlands, 2023.
8. Kalnoskas, A. What's New in Electrolytic Capacitors and Supercapacitors for Energy Harvesting. Available online: https://www.powerelectronictips.com/whats-new-in-electrolytic-capacitors-and-supercapacitors-for-energy-harvesting/ (accessed on 1 May 2024).
9. Zhang, H.; Ma, T. Adaptive energy harvesting from low-level ambient vibrations. *Appl. Mater. Today* **2023**, *34*, 101911. [CrossRef]
10. Lamedica, R.; Ruvio, A.; Tobia, M.; Buffarini, G.G.; Carones, N. A Preliminary Techno-Economic Comparison between DC Electrification and Trains with On-Board Energy Storage Systems. *Energies* **2020**, *13*, 6702. [CrossRef]

11. Subasinghage, K.; Gunawardane, K.; Padmawansa, N.; Kularatna, N.; Moradian, M. Modern Supercapacitors Technologies and Their Applicability in Mature Electrical Engineering Applications. *Energies* **2022**, *15*, 7752. [CrossRef]
12. Biswas, S.; Chowdhury, A. Organic Supercapacitors as the Next Generation Energy Storage Device: Emergence, Opportunity, and Challenges. *ChemPhysChem* **2023**, *24*, e202200567. [CrossRef] [PubMed]
13. Migliorini, L.; Santaniello, T.; Borghi, F.; Saettone, P.; Comes Franchini, M.C.; Generali, G.; Milani, P. Eco-Friendly Supercapacitors Based on Biodegradable Poly(3-Hydroxy-Butyrate) and Ionic Liquids. *Nanomaterials* **2020**, *10*, 2062. [CrossRef]
14. Gunawardane, K.; Bandara, N.; Subasinghage, K.; Kularatna, N. Extending the Input Voltage Range of Solar PV Inverters with Supercapacitor Energy Circulation. *Electronics* **2021**, *10*, 88. [CrossRef]
15. Kularatna, N.; Subasinghage, K.; Gunawardane, K.; Jayananda, D.; Ariyarathna, T. Supercapacitor-Assisted Techniques and Supercapacitor-Assisted Loss Management Concept: New Design Approaches to Change the Roadmap of Power Conversion Systems. *Electronics* **2021**, *10*, 1697. [CrossRef]
16. Subasinghage, K.; Gunawardane, K.; Lie, T.; Kularatna, N. Design of an efficiency improved dual-output DC-DC converter utilizing a supercapacitor circulation technique. In Proceedings of the 2016 IEEE 2nd Annual Southern Power Electronics Conference (SPEC), Auckland, New Zealand, 5–8 December 2016; pp. 1–6.
17. Subasinghage, K.; Gunawardane, K.; Kularatna, N.; Lie, T.T. Extending the Supercapacitor-Assisted Low-Dropout Regulator (SCALDO) Technique to a Split-Rail DC–DC Converter Application. *IEEE Access* **2019**, *7*, 124034–124047. [CrossRef]
18. Subasinghage, K.; Gunawardane, K.; Kularatna, N.; Lie, T.T. Selection of the Stable Range of the Equivalent Series Resistance (ESR) of the Output Capacitor for a SCALDO Regulator. In Proceedings of the 2018 IEEE 27th International Symposium on Industrial Electronics (ISIE), Cairns, Australia, 13–15 June 2018; pp. 1359–1364.
19. Subasinghage, K. Advanced Analysis of Supercapacitor-Assisted Low-Dropout (SCALDO) Regulator. Ph.D. Thesis, Electrical and Electronic Engineering, Auckland University of Technology, Auckland, New Zealand, 2019.
20. Eaton. *Eaton's HS Hybrid Supercapacitors Combine Proprietary Materials to Achieve Greater Energy Density and Cycle Lifetimes*; Eaton: Cleveland, OH, USA, 2021.
21. Zhou, L.; Li, C.; Liu, X.; Zhu, Y.; Wu, Y.; van Ree, T. 7—Metal oxides in supercapacitors. In *Metal Oxides in Energy Technologies*; Wu, Y., Ed.; Elsevier: Amsterdam, The Netherlands, 2018; pp. 169–203. [CrossRef]
22. Mars, P. Coupling a supercapacitor with a small energy harvesting source. *EDN-Electron. Des. News* **2012**, *57*, 39.
23. Lehtimäki, S.; Li, M.; Salomaa, J.; Pörhönen, J.; Kalanti, A.; Tuukkanen, S.; Heljo, P.; Halonen, K.; Lupo, D. Performance of printable supercapacitors in an RF energy harvesting circuit. *Int. J. Electr. Power Energy Syst.* **2014**, *58*, 42–46. [CrossRef]
24. Mathúna, C.Ó.; O'Donnell, T.; Martinez-Catala, R.V.; Rohan, J.; O'Flynn, B. Energy scavenging for long-term deployable wireless sensor networks. *Talanta* **2008**, *75*, 613–623. [CrossRef] [PubMed]
25. Puluckul, P.P.; Singh, R.K.; Weyn, M. TEGBed: A thermal energy harvesting testbed for batteryless internet of things. *Internet Things* **2024**, *25*, 101060. [CrossRef]
26. Hassanalieragh, M.; Soyata, T.; Nadeau, A.; Sharma, G. Solar-supercapacitor harvesting system design for energy-aware applications. In Proceedings of the 2014 27th IEEE International System-on-Chip Conference (SOCC), Las Vegas, NV, USA, 2–5 September 2014; pp. 280–285.
27. Selleri, G.; Poli, F.; Neri, R.; Gasperini, L.; Gualandi, C.; Soavi, F.; Fabiani, D. Energy harvesting and storage with ceramic piezoelectric transducers coupled with an ionic liquid-based supercapacitor. *J. Energy Storage* **2023**, *60*, 106660. [CrossRef]
28. Elahi, H.; Eugeni, M.; Gaudenzi, P. Chapter 3—Energy harvesting. In *Piezoelectric Aeroelastic Energy Harvesting*; Elahi, H., Eugeni, M., Gaudenzi, P., Eds.; Elsevier: Amsterdam, The Netherlands, 2022; pp. 41–59. [CrossRef]
29. Miller, J.R.; Simon, P. Materials science: Electrochemical capacitors for energy management. *Science* **2008**, *321*, 651–652. [CrossRef]
30. Conway, B.E. Transition from "Supercapacitor" to "Battery" Behavior in Electrochemical Energy Storage. *J. Electrochem. Soc.* **1991**, *138*, 1539. [CrossRef]
31. Lu, W.; Qu, L.; Henry, K.; Dai, L. High performance electrochemical capacitors from aligned carbon nanotube electrodes and ionic liquid electrolytes. *J. Power Sources* **2009**, *189*, 1270–1277. [CrossRef]
32. Paradiso, J.A.; Starner, T. Energy scavenging for mobile and wireless electronics. *IEEE Pervasive Comput.* **2005**, *4*, 18–27. [CrossRef]
33. Boisseau, S.; Despesse, G.; Seddik, B.A. Electrostatic Conversion for Vibration Energy Harvesting. In *Small-Scale Energy Harvesting*; Mickael, L., Ed.; IntechOpen: Rijeka, Croatia, 2012; Chapter 5. [CrossRef]
34. Feng, X.; Zhang, Y.; Kang, L.; Wang, L.; Duan, C.; Yin, K.; Pang, J.; Wang, K. Integrated energy storage system based on triboelectric nanogenerator in electronic devices. *Front. Chem. Sci. Eng.* **2021**, *15*, 238–250. [CrossRef]
35. Das, K.K.; Basu, B.; Maiti, P.; Dubey, A.K. Piezoelectric nanogenerators for self-powered wearable and implantable bioelectronic devices. *Acta Biomater.* **2023**, *171*, 85–113. [CrossRef] [PubMed]
36. Muscat, A.; Bhattacharya, S.; Zhu, Y. Electromagnetic Vibrational Energy Harvesters: A Review. *Sensors* **2022**, *22*, 5555. [CrossRef]
37. Mondal, S.; Thakur, S.; Maiti, S.; Bhattacharjee, S.; Chattopadhyay, K.K. Self-Charging Piezo-Supercapacitor: One-Step Mechanical Energy Conversion and Storage. *ACS Appl. Mater. Interfaces* **2023**, *15*, 8446–8461. [CrossRef] [PubMed]
38. Cepnik, C.; Lausecker, R.; Wallrabe, U. Review on Electrodynamic Energy Harvesters—A Classification Approach. *Micromachines* **2013**, *4*, 168–196. [CrossRef]
39. Li, Y.; Li, J.; Liu, Z.; Hu, H.; Hu, J.; Wang, J.; He, Z. Theoretical and experimental investigation of magnet and coil arrays optimization for power density improvement in electromagnetic vibration energy harvesters. *Energy Convers. Manag.* **2023**, *293*, 117411. [CrossRef]

40. Kim, S.; Chou, P.H. Energy Harvesting with Supercapacitor-Based Energy Storage. In *Smart Sensors and Systems*; Lin, Y.-L., Kyung, C.-M., Yasuura, H., Liu, Y., Eds.; Springer International Publishing: Cham, Switzerland, 2015; pp. 215–241. [CrossRef]
41. Liu, X.; Chen, S.; Pu, J.; Wang, X. A Flexible All-Solid-State Micro Supercapacitor and Its Application in Electrostatic Energy Management System. *J. Microelectromech. Syst.* **2016**, *25*, 929–936. [CrossRef]
42. Dong, J.; Huang, S.; Luo, J.; Zhao, J.; Fan, F.R.; Tian, Z.-Q. Supercapacitor-Inspired Triboelectric Nanogenerator Based on Electrostatic Double Layer. *Nano Energy* **2022**, *95*, 106971. [CrossRef]
43. Ammaiyappan, A.B.S.; Seyezhai, R. Piezoelectric-Driven Self-Powered Supercapacitor for Wearable Device Applications. In *Supercapacitors for the Next Generation*; Daisuke, T., Aneeya Kumar, S., Eds.; IntechOpen: Rijeka, Croatia, 2022; Chapter 12. [CrossRef]
44. Liew, H.F.; Rahim, R.A.; Isa, M.; Ismail, B.; Hassan, S.I.S. Analysis of batteries or supercapacitor as energy storage device for a sound energy harvester system. *IEEJ Trans. Electr. Electron. Eng.* **2018**, *13*, 1699–1708. [CrossRef]
45. Zhang, X.; Zhang, Z.; Pan, H.; Salman, W.; Yuan, Y.; Liu, Y. A portable high-efficiency electromagnetic energy harvesting system using supercapacitors for renewable energy applications in railroads. *Energy Convers. Manag.* **2016**, *118*, 287–294. [CrossRef]
46. Szarka, G.D.; Burrow, S.G.; Proynov, P.P.; Stark, B.H. Maximum Power Transfer Tracking for Ultralow-Power Electromagnetic Energy Harvesters. *IEEE Trans. Power Electron.* **2014**, *29*, 201–212. [CrossRef]
47. Szarka, G.D.; Burrow, S.G.; Stark, B.H. Ultralow Power, Fully Autonomous Boost Rectifier for Electromagnetic Energy Harvesters. *IEEE Trans. Power Electron.* **2013**, *28*, 3353–3362. [CrossRef]
48. Pu, X.; Li, L.; Liu, M.; Jiang, C.; Du, C.; Zhao, Z.; Hu, W.; Wang, Z.L. Wearable Self-Charging Power Textile Based on Flexible Yarn Supercapacitors and Fabric Nanogenerators. *Adv. Mater.* **2016**, *28*, 98–105. [CrossRef]
49. Mars, P. Using Supercapacitors in Energy Harvesting. 2017. Available online: https://www.powersystemsdesign.com/using-supercapacitors-in-energy-harvesting/31 (accessed on 14 April 2024).
50. Calautit, K.; Johnstone, C. State-of-the-art review of micro to small-scale wind energy harvesting technologies for building integration. *Energy Convers. Manag. X* **2023**, *20*, 100457. [CrossRef]
51. Sathiendran, R.K.; Sekaran, R.R.; Chandar, B.; Prasad, B.S.A.G. Wind energy harvesting system powered wireless sensor networks for Structural Health Monitoring. In Proceedings of the 2014 International Conference on Circuits, Power and Computing Technologies [ICCPCT-2014], Nagercoil, India, 20–21 March 2014; pp. 523–526.
52. Khan, M.D.S.A.; Kuni, S.K.; Rajkumar, R.; Syed, A.; Hawladar, M.; Rahman, M.M. Instantaneous charging & discharging cycle analysis of a novel supercapacitor based energy harvesting circuit. *AIP Conf. Proc.* **2017**, *1919*, 020046. [CrossRef]
53. Habibzadeh, M.; Hassanalieragh, M.; Ishikawa, A.; Soyata, T.; Sharma, G. Hybrid Solar-Wind Energy Harvesting for Embedded Applications: Supercapacitor-Based System Architectures and Design Tradeoffs. *IEEE Circuits Syst. Mag.* **2017**, *17*, 29–63. [CrossRef]
54. Boitier, V.; Estibals, B.; Seguier, L. Powering a Low Power Wireless Sensor in a Harsh Industrial Environment: Energy Recovery with a Thermoelectric Generator and Storage on Supercapacitors. *Energy Power Eng.* **2023**, *15*, 372–398. [CrossRef]
55. Yang, X.; Tian, Y.; Wu, B.; Jia, W.; Hou, C.; Zhang, Q.; Li, Y.; Wang, H. High-Performance Ionic Thermoelectric Supercapacitor for Integrated Energy Conversion-Storage. *Energy Environ. Mater.* **2022**, *5*, 954–961. [CrossRef]
56. Deng, F.; Qiu, H.; Chen, J.; Wang, L.; Wang, B. Wearable Thermoelectric Power Generators Combined With Flexible Supercapacitor for Low-Power Human Diagnosis Devices. *IEEE Trans. Ind. Electron.* **2017**, *64*, 1477–1485. [CrossRef]
57. Yang, K.; Cho, K.; Yang, S.; Park, Y.; Kim, S. A laterally designed all-in-one energy device using a thermoelectric generator-coupled micro supercapacitor. *Nano Energy* **2019**, *60*, 667–672. [CrossRef]
58. Gunawardana, B.R. Carbon Nano tube based Thermoelectric generator and Graphite Nanoparticle based supercapacitor for smart wearable sensors. In Proceedings of the 2023 IEEE International Students' Conference on Electrical, Electronics and Computer Science (SCEECS), Bhopal, India, 18–19 February 2023; pp. 1–3.
59. Serdijn, W.A.; Mansano, A.L.R.; Stoopman, M. Chapter 4.2—Introduction to RF Energy Harvesting. In *Wearable Sensors*; Sazonov, E., Neuman, M.R., Eds.; Academic Press: Oxford, UK, 2014; pp. 299–322. [CrossRef]
60. Ibrahim, H.H.; Singh, M.J.; Al-Bawri, S.S.; Ibrahim, S.K.; Islam, M.T.; Alzamil, A.; Islam, M.S. Radio Frequency Energy Harvesting Technologies: A Comprehensive Review on Designing, Methodologies, and Potential Applications. *Sensors* **2022**, *22*, 4144. [CrossRef] [PubMed]
61. Grante, F.; Abib, G.; Muller, M.; Samama, N. Ultra Low Power RF energy harvesting system using a super capacitor as an energy reservoir for an IoT Node. In Proceedings of the WINSYS 2022: 19th International Conference on Wireless Networks and Mobile Systems, Lisbon, France, 11 July 2022; pp. 15–21.
62. Luís, M.; Borges, F.J.V. Radio frequency energy harvesting and storing in supercapacitors for wearable sensors. In *Wearable Technologies and Wireless Body Sensor Networks for Healthcare*; IET: London, UK, 2019; pp. 457–543. [CrossRef]
63. Borges, L.M.; Chávez-Santiago, R.; Barroca, N.; Velez, F.J.; Balasingham, I. Radio-frequency energy harvesting for wearable sensors. *Healthc. Technol. Lett.* **2015**, *2*, 22–27. [CrossRef]
64. Kalbitz, R. *Keep the Balance–Balancing of Supercapacitors*; Würth Elektronik eiSos GmbH & Co.: Waldenburg, Germany, 2021. Available online: https://www.we-online.com/components/media/o671684v410%20ANP090a_EN.pdf (accessed on 12 May 2024).
65. Pathak, M.; Bhatt, D.; Bhatt, R.C.; Bohra, B.S.; Tatrari, G.; Rana, S.; Arya, M.C.; Sahoo, N.G. High Energy Density Supercapacitors: An Overview of Efficient Electrode Materials, Electrolytes, Design, and Fabrication. *Chem. Rec.* **2024**, *24*, e202300236. [CrossRef] [PubMed]

66. Redondo, E.; Fevre, L.W.L.; Fields, R.; Todd, R.; Forsyth, A.J.; Dryfe, R.A.W. Enhancing supercapacitor energy density by mass-balancing of graphene composite electrodes. *Electrochim. Acta* **2020**, *360*, 136957. [CrossRef]
67. Shang, W.; Yu, W.; Xiao, X.; Ma, Y.; He, Y.; Zhao, Z.; Tan, P. Insight into the self-discharge suppression of electrochemical capacitors: Progress and challenges. *Adv. Powder Mater.* **2023**, *2*, 100075. [CrossRef]
68. Zhou, W.; Liu, Z.; Chen, W.; Sun, X.; Luo, M.; Zhang, X.; Li, C.; An, Y.; Song, S.; Wang, K.; et al. A Review on Thermal Behaviors and Thermal Management Systems for Supercapacitors. *Batteries* **2023**, *9*, 128. [CrossRef]
69. He, X.; Zhang, X. A comprehensive review of supercapacitors: Properties, electrodes, electrolytes and thermal management systems based on phase change materials. *J. Energy Storage* **2022**, *56*, 106023. [CrossRef]
70. Roy, P.K.S.; Karayaka, H.B.; He, J.; Yu, Y.H. Economic Comparison between Battery and Supercapacitor for Hourly Dispatching Wave Energy Converter Power. In Proceedings of the 2020 52nd North American Power Symposium (NAPS), Tempe, AZ, USA, 11–13 April 2021; pp. 1–6.
71. Sirimanne, D.C.U.; Kularatna, N.; Arawwawala, N. Electrical Performance of Current Commercial Supercapacitors and Their Future Applications. *Electronics* **2023**, *12*, 2465. [CrossRef]
72. Shi, C.; Zhao, Q.; Li, H.; Liao, Z.-M.; Yu, D. Low cost and flexible mesh-based supercapacitors for promising large-area flexible/wearable energy storage. *Nano Energy* **2014**, *6*, 82–91. [CrossRef]