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Low power energy harvesting systems: State of the art and future challenges

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Abstract

Recent works on self-charging power technologies mainly focused on the low energy harvesting component, while its integration with the energy storage system was usually not further evaluated or discussed. This was addressed in the present work by providing a comprehensive state-of-the-art review on different types of energy storage used for self-sufficient or self-sustainable power units to meet the power demands of low power devices such as wearable devices, wireless sensor networks, portable electronics, and LED lights within the range of 4.8 milliwatts to 13 watts. The paper presents the relevant scientific studies and recent developments on incorporating low energy harvesting with energy storage and power management systems. Recent advances on seven types of low energy harvesting technologies or transducers and eight types of micro/small-scale energy storage systems from farads to amps were examined to assess the integrated design's overall efficiency. The study focused on the design, distribution management networks, efficiency, compatibility with other components, costs, and environmental impact of self-sustainable power unit. To effectively assess the most suitable energy storage for the self-charging power unit, assessing its technical characteristics, economical, and environmental impact is discussed. Finally, the review identified the challenges and further research that must be carried out to achieve a more sustainable and stable integrated technology, moving from the proof of concept or laboratory to actual applications.

Highlights

- There is a lack of literature evaluating both/combined low energy harvesting and storage
- Recent advances on seven types of low energy harvesting technologies were examined
- Eight types of micro/small-scale energy storage systems for energy harvesting were examined
- Assessment of integrated design of low power energy harvesting, energy storage, and power management
- Techno-economic analysis, environmental impacts of low energy storage were discussed

Keywords: Low Energy Harvesting Systems; Energy Storage System; Power Management; Self-Sustainable Technologies; Transducer

Number of words: 9,675

ABBREVIATION AND NOMENCLATURE

EHS	Energy Harvesting System
ESS	Energy Storage System
WSN	Wireless Sensor Network
MEMS	Micro Electro Mechanical Systems
PMFC	Plant Microbial Fuel Cells
kWh	Kilowatt-hour
MFC	Microbial Fuel Cell
PCM	Phase Change materials
kW	Kilowatt
kWh	Kilowatt per hour
μW	Microwatt
Hz	Hertz
mAh	Milliamp Hour
μA	Microampere
MPPT	Maximum Power Point Tracking
RF	Radiofrequency
ms	Milliseconds
CAES	Compressed Air Energy Storage
MOSFET	Metal oxide semiconductor field effect transistor
SEM	Scanning Electron Microscopy
FEP	Fluorinated Ethylene Propylene
TES	Thermal Energy Storage
μ	Micro
RF	Radiofrequency
ms	Milliseconds
mF	Microfarad
F	Farad
PZT	Lead Zirconate Titanate (piezoelectric ceramic material)
NIMH	Nickel metal hydride
mW	Milliwatt
W	Watt
V	Volt
Wh/kg	Watt-hours per kilogram
Wh/L	Watt-hours per litre
Ah/g	Ampere hour per gram
$mAh\ g^{-1}$	Milliampere hours per gram
TES	Thermal Energy Storage
Li-ion	Lithium-ion
RMS	Root Mean Square
SIB	Sodium-ion battery
PMS	Power Management System
mW/cm^2	Milliwatt per cubic centimetre per second
dBm	Decibels
CWMC	Cockcroft-Walton Voltage Multiplier

1. Introduction

Rapid growth and production of small devices such as micro-electromechanical systems, wireless sensor networks, portable electronics, and other technologies connected via the Internet of Things (IoT) have resulted in high cost and consumption of energy [1]. This trend is still projected to grow as the demand for connected technologies such as wireless sensors, processors, wearables, smart home, health monitors, and connected technology in agriculture continues to increase [2]. The report by [2] projected that by the end of the year 2020, there would be 20 billion IoT connected technologies. This challenge has motivated engineers and researchers to develop sustainable and highly efficient low energy harvesting technologies [1]. Low energy harvesting systems have been a promising solution for the rapid developments in smart and IoT technologies that require a continuous supply of power [3]. This technology is also highly beneficial in places where conventional power sources are not accessible; it eradicates the need for running wires to end applications [4]. However, the main concern with this system is its intermittent nature of energy source, and hence the power generated by energy harvesters is not continuous and sometimes limited. For an uninterrupted power supply, energy storage and power management systems are needed to improve the efficiency of low energy harvesters and capture maximum power [5].

The main challenge for wireless sensor networks, wearable technologies, and portable electronics are batteries. Batteries are insufficient in providing enough energy for long term applications, which lead to inconvenient frequent charging or replacement. With the pursuit of the greater energy density of energy storage systems, an alternative strategy that has been drawing much attention from the research community is self-sustainable technology, which incorporates low energy harvesting, energy storage, and power management technologies [6]. Many studies [5-9] have demonstrated different solutions to increase output power and provide a continuous supply of energy, such as efficient charge boosting techniques to meet the power and continuous demands. Cheng et al. [5] highlighted the use of charge boosting to extract more charge from triboelectric nanogenerators (TENG) to enhance performance. Zhao et al. [6] focused on optimizing the storage materials of nanogenerator-based self charging devices.

Several recently published review papers, including [4, 7-14] have focused on the low energy harvesting or transducer such as triboelectric nanogenerators [5-6] and piezoelectric energy harvesters [7-8,11] rather than the energy storage system, as shown in Table 1. Li et al. [8] focused on low energy harvesting transducer’s overall efficiency, while the topic of energy storage was not further examined. Similarly, [15-18] reviewed the different energy harvesting devices for wireless sensor network systems. While the review paper [12] evaluated electromagnetic and piezoelectric acoustic energy harvesting system in terms of feasibility at a low-level frequency range. Likewise, Priya et al. [11] mainly focused on the performance of energy harvesting transducer. Adu-Manu et al. [12] reviewed low energy harvesting for environmental monitoring wireless sensor networks. Pozo et al. [4] reviewed different low energy harvesting systems focusing on their operation, efficiency, and maturity of state of art, without any detailed information about the storage devices. While Khalid et al. [14] discussed the recent challenges and progress of human movement energy harvester. The study focused on evaluating the performance of piezoelectric, electromagnetic, and triboelectric in harvesting biomechanical energy from human motion. Particular focus was given to strategies such as ultrathin flexible single-electrode, double pendulum system, core-shell structure, liquid metal electrode, air-cushion mechanism, and sprung eccentric rotor. The study also reviewed the different human biomechanical motions such as finger movement, walking, running, typewriting, and even minute displacements inside the human body, which possess an abundant amount of wasted energy that can be harvested.

On the other hand, Pandey et al. [7] focused more on improving the technique used for impedance matching and the design of a power management circuit for optimized piezoelectric energy harvesting to charge Li-ion batteries. Similarly, Newell and Duffy [13] concentrated more on the voltage step-up energy management strategies, such as the challenges with a cold start and maximum power point tracking (MPPT). The present review aims to fill the unexplored gap in self-sufficient technologies by evaluating different integrated designs of low powered energy harvesting systems with energy storage and power management system. Studies such as [17-18] evaluated hybrid energy harvesters with storage but focused more on the energy harvester and power management. The work [19] proposed the integration of triboelectric with a keyboard to power an electronic thermometer. Although the study specified that a supercapacitor was employed, its integration and performance were not detailed. A triboelectric energy harvester was also used in the studies of [20-21]. It was suggested that it could be incorporated with storage and power management system for better performance, but no further details were given.

To the author's knowledge, there has been no comprehensive review paper on self-sustainable technology that specifically focuses on the design of the energy storage system for micro-scale energy harvesting systems. Therefore, detailed technical analysis and evaluation of each micro-scale energy harvester, energy storage, and power management systems will be carried out. Particular focus will be given to studies that attempted to solve the impedance mismatch issue, which is one of the main barriers of self-sustainable technologies [22-28].

Table 1: The emphasis of relevant review papers published between 2014 to 2021.

[Ref]	Components			Types of Analyses			Application
	Transducer	Power Management	Storage	Technical	Economic	Environmental	
[16]	✓	✗	✗	✓	✓	✓	Wireless Sensor Networks
[8]	✓	✗	✗	✓	✓	✗	Wearable Electronics
[10]	✓	✗	✗	✓	✗	✗	Wireless Sensor Networks

[11]	☑	☑	✗	☑	☑	✗	Wireless Sensor Networks
[7]	☑	☑	✗	☑	✗	✗	Recharging Battery
[13]	☑	☑	✗	☑	☑	✗	Wireless Sensor Networks
[12]	☑	✗	✗	☑	☑	✗	Wireless Sensor Networks
[14]	☑	✗	✗	☑	☑	✗	Wearable Electronics
[4]	☑	✗	✗	☑	☑	☑	Low Power Electronic Devices
[17]	☑	☑	✗	☑	☑	☑	Supercapacitor energy storage
[18]	☑	☑	✗	☑	✗	✗	Supercapacitor energy storage
[19]	☑	☑	✗	☑	☑	☑	Wearable Device
[20]	☑	✗	✗	☑	☑	☑	Wearable Device
[21]	☑	✗	✗	☑	☑	☑	Wireless Sensor Networks

Low energy harvesting and energy storage systems are certainly both important components for the development of self-sustainable technologies. However, in this study, the focus is on energy storage technologies used for micro/small-scale devices since low energy harvesting systems have been examined extensively for many years, and this technology cannot consistently work alone effectively [29-32]. There is still further improvement needed for it to be widely adopted. This review examined recent developments on different types of energy storage used for self-sufficient or self-sustainable technologies to meet the power demands of low power devices within the range of 4.81 milliwatts to 13 watts. The study assessed and compared different types of energy storage systems such as electrochemical, electrical, thermal, and mechanical energy storage. Also, the technical, economic analysis, environmental impacts, advantages, and disadvantages were evaluated to know which energy storage devices are most suitable, efficient, cost-effective, and environmentally friendly for integrated design of self-sustainable technology. The research on small-scale energy storage systems used for self-sustainable technology identified the challenges and further research that must be carried out to achieve a more sustainable and stable integrated technology, moving from the proof of concept or laboratory to actual applications. Furthermore, the study evaluated how integrated designs of the self-charging power system can fulfil the needs of IoT and portable electronic devices in terms of power supply as it is a bottleneck for the micro/small scale technologies.

2. Low Energy Harvesting and Energy Storage Systems

This section discussed the current developments, benefits, and limitations of low energy harvesting and energy storage systems. Figure 1 shows the concept of energy/electricity production and storage solutions reviewed in this study. The most used energy sources for micro/small-scale devices include solar, wind, wave, human motion, and vibration. To enhance renewable energy systems' performance and efficiency, different technologies, including transducer and energy storage, are usually integrated into one device [33].

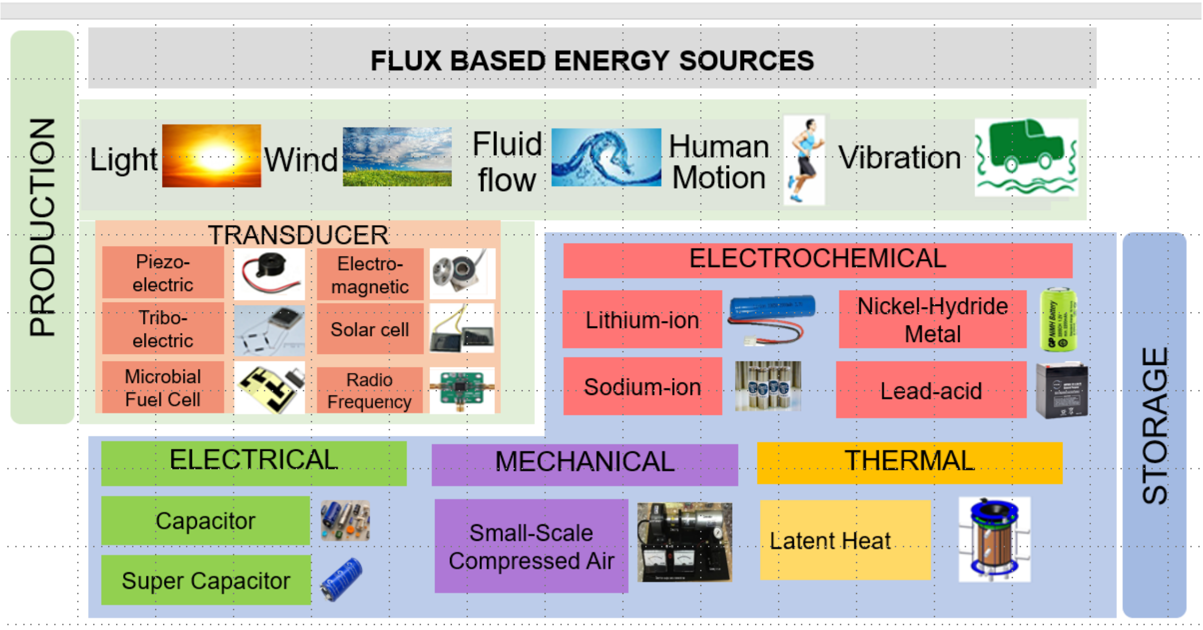


Figure 1: Concept of low energy/electricity generation and storage solutions.

2.1. Low Energy Harvesting Devices

Harvesting energy from the environment is an attractive alternative to battery-operated systems, particularly for low-power, long-term and self-sustaining devices. Moreover, using the power near the source can eliminate the requirement for long cables and transmission losses [34]. A few of its applications are for powering wireless sensor networks, wearable devices, charging mobile phones, lighting LED, and cloud-based data transfer systems [35]. However, there are several challenges when assessing and selecting an optimum low energy harvesting technology for specific applications [36].

Studies [37-39] have shown the capabilities of low energy harvesting systems such as piezoelectric, electromagnetic, electrostatic, and triboelectric transducers in providing electrical power ranging from a few tens to hundreds of μW. However, challenges still exist, such as materials development, matching with the ambient vibration frequencies, which may differ depending on the time, usage location, scalability, mass production, and energy conversion rate [37-39]. The main concern is whether energy harvesting systems can produce enough power considering the energy sources' intermittency. Also, the implementation costs and production of low energy harvesting systems are important challenges that hamper technology development [40]. Therefore, more research is necessary to improve technology adoption [41].

The enhancement of the performance of self-sustainable technologies is an important challenge. According to Luo et al. [42], the significance of selecting the suitable battery or supercapacitor energy storage system must not be underestimated. The capacities and impedances of energy storage system must match the pulsed output of the energy harvesting device. In Luo et al. [21] study, a triboelectric nanogenerator integrated with an energy storage system to supply power to commercial wireless sensors and other smart connected technologies was examined. Another design of self-sustainable technology was introduced in Luo et al. [43] study. The system consists of a flexible self-charging power film (SCPF) that operates either as a self-powered information input matrix or power generator integrated with an energy storage unit. The system can harvest mechanical energy from finger movements based on the coupling between the interaction of electrification and the effects of electrostatic induction whilst storing the harvested energy. With Luo et al. [36], a strategy of using a cost effective and simple laser engraving approach was implemented for flexible self-charging micro-supercapacitor power unit (SCMPU). The SCMPU was incorporated with a triboelectric-nanogenerator and electrochemical storage system into a single device. Results have shown significant benefits, including high durability and self-charging capability. The laser-induced graphene (LIG) showed a 0.8 W/m^2 peak power density at a loading resistance of 20 MΩ. The micro-supercapacitors (MSCs) showed a ~10.29 mF/cm2 high capacitance at the current density of 0.01 mA/cm^2.

Table 2 shows the comparison of different transducers that are commonly utilized for low energy harvesting systems. The advantages and disadvantages of each technology are summarized. This will help recognize the key factors that can be improved. The technologies mentioned in Table 2 are the most used type of transducers found in research works and applied in the industry or available in the market. Based on existing research, piezoelectric, triboelectric, and thermoelectric energy generators are easily combined with other technologies due to the size and compactness [34, 44-46]. These energy harvesting systems are usually integrated into existing technologies such as wireless networks and low powered electronic devices through producing usable power from movement, vibration, and waste heat [47]. Piezoelectric and triboelectric energy generators are usually integrated into microelectromechanical systems, wireless sensor networks, and other low powered electronic devices [48-49]. While others use thermoelectric energy systems for wearable devices and sensors for health monitoring [50].

Since the piezoelectric energy generators have the greatest density and output, and more flexibility in terms of incorporating into existing devices, piezoelectric materials are well applied and investigated both theoretically and experimentally [51-56]. While triboelectric energy generators also have their own benefits, such as highly efficient energy harvesting at low-frequency sources [34, 45-47]. While the thermoelectric energy generator is known for its high reliability, scalability, and compact size [47, 57].

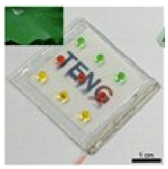
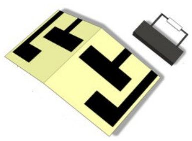
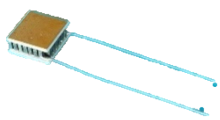
There are limited studies on their lifespan; the study [58] indicated that a PZT ceramic (lead zirconate titanate), which generated 8.4 mW had a lifespan of 20 years. Whereas for the triboelectric, it is expected to be 2 years based on the research of [59]. While thermoelectric energy harvesters that are made of inorganic materials with various dimensions have 5 years lifespan.

The impedance mismatch between energy harvesting devices and energy storage devices is extremely important to the self-charging power system. The internal resistance of each energy harvesting systems varies according to their design, components, and environmental conditions. A piezoelectric harvester internal resistance was investigated in [60]. The internal resistance was measured in different frequencies through the impedance meter. The result of the experiment revealed that the internal resistances of piezoelectric energy harvesters have a frequency dependent property. It also mentioned that the internal resistance of this energy harvester depends on the number of cycles of input sinusoidal wave. While for the electromagnetic harvester, Hendijanizadeh et al. [61] installed an intelligent control device to switch between cubic and linear load resistance to optimise the power output of the electromagnetic energy harvester in different frequencies and amplitude excitations condition in the actual environmental state. The result of the study showed that the internal resistance of the electromagnetic plays a significant role in choosing the maximum load resistance for the energy harvesting system and it must be recognized in the control technique design.

To assess the internal resistance of triboelectric, a test was conducted in the study of [62] at a particular cyclic load with 100 N force with various external resistance with up to 142MΩ. The findings demonstrated that the current curves and voltages intersect at R = 58 MΩ optimal resistance.With microbial fuel cell (MFC) energy harvester, the fixed external resistance is not always matching the energy harvester's internal resistance and recapture the optimal power output in microbial fuell cell working condition due to internal resistance of the energy harvester which always depends on changes in MFC operations and operational parameters including pH, temperature, and substrate concentration.

An AM-RF energy harvester was examined in [63]. The energy harvester operates as power sources, hence, this behaves an energy source in series with the internal resistance. It was stated in the study that the load resistance should match with the internal resistance of the system to measure the optimal power provided by the AM energy harvester, this is in agreement with the maximum transfer of power theorem. In the study [64], it demonstrated that at the time when the thermoelectric generator is connected electrically in cycles, the overall internal resistance is proportional to their number. This means that even if a great number of thermoelectric increases, the voltage supplied from the thermoelectric generator's effect on the internal resistance is still undesirable. The PV modules in the research [65] stated that the effectiveness of to generate electric energy is identified through parasitic internal impedance, which contains series of parallel resistance. The increase in the internal resistance means that there is a reduction in the output quality systematically.

Table 2: Comparison of different transducers used for micro/small-scale technologies.

Ref.	Technologies		Advantages	Disadvantages
[34, 44, 66-67-69]	Piezoelectric		Compact and simple structure; high output; high configuration compatibility; easy to scale down to the nanoscale	High cost for high energy output; brittle material; easy fatigue and crack; coupling coefficient linked to material properties
[34, 44-46, 68]	Triboelectric		High conversion efficiency, simple fabrication, low cost	Impedance mismatch; low durability; low current at high voltage;
[34, 44]	Electromagnetic		Small size; does not require smart materials; high durability and long life; high output currents	Low voltage output; low efficiency in low frequencies; Size is often larger than piezoelectric and triboelectric nanogenerator; inevitable coil losses; complicated to miniaturized
[70-73]	Microbial Fuel Cell		Flexibility, higher efficiency; low cost; simple maintenance; direct conversion of organic substrate to electricity	Low power density; low capacitance; limited surface area of the electrode; activation losses; bacterial metabolic losses
[34, 74]	Radiofrequency		Portable; low installation cost; easy to install; prolong the lifetime of electronics and WSNs; long effective energy transfer distance	Low power density; low efficiency; ultra-low output power
[47, 57]	Thermoelectric		Wide applicability; easily combined with other technologies; simple maintenance; no additional power sources; performance output highly scalable; small space requirement; does not need maintenance for longer periods	High cost per unit; low efficiency; uneven temperature distribution on the plate may lead to inefficiencies; low energy conversion efficiency rate; requires relatively constant heat source; structure failure of thermoelectric at high temperatures

[29]	Small photovoltaic cells		High energy output; works well for long periods with no maintenance	Can only harvest with the presence of light

2.2. Micro or Small-Scale Technologies

Energy storage system (ESS) plays an important role in the future of energy technologies, particulary on electrical devices, as it can enhance the distribution management networks, improve efficiency, and lower costs [75]. Energy storage systems such as capacitors and supercapacitors are usually applied for reactive power compensation in distribution channels [76]. The goal of energy storage devices is to reduce energy and power losses and maintain improved voltage regulation for load buses and enhance the security system. The level of compensation supplied to the storage devices, which are installed in the distribution channel, varies on the size, location, and kinds of energy storage system integrated with the energy harvesters [77]. The energy can be stored in different forms, including chemical, electrical, thermal and mechanical [78]. The scalability, cost, and size of this system mainly rely on the form of the stored energy. According to [78], a few types of energy storage are more suitable for micro/small scale devices. For instance, chemical batteries are more appropriate for small-scale technologies. ESS systems have different operational parameters and designs, which creates constraints to when each is suitable to use. These systems have their benefits and limitations that are ideal in different applications and situations.

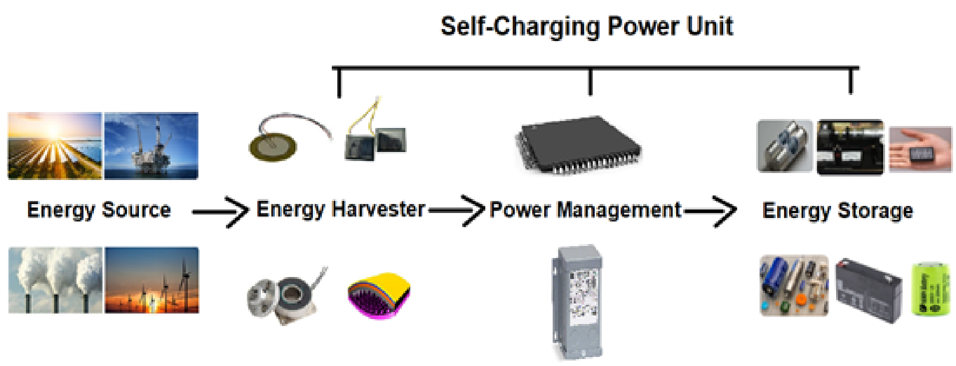
Although the conventional EES systems are already well known, this field's growth is still fast and vast [79]. According to Sabihuddin et al. [33], storage devices can be compared based on 14 parameters such as efficiency, specific power, power density, specific energy, energy density, cycle life, lifespan, scale, self-discharge rate, application, power and energy capital cost, technical maturity, and environmental impact. It was also suggested that a combined database analysis of energy storage and production devices should be developed.

Chemical energy storage strategies remain the most studied and developed field [33]. Most conventional electrochemical batteries have high performance and showed to be highly suitable for small-scale technologies. Li-ion batteries have demonstrated not only to have great power and energy efficiency but also an exceptional life cycle. However, Li-ion batteries are expensive with charging and safety problems, and the scarcity of lithium reserves limits their applications. The abundance of materials and long-life span has demonstrated great potential for a storage solution. However, these technologies experienced high self-discharge rates and suffered from poor performance. Most conventional batteries also suffer from reduced capacities and life with high discharge rates, overcharging or complete discharge, and improper storage environments [33].

Currently, capacitor and supercapacitor are competing with batteries and observe to be widely used for small-scale applications. It can easily be integrated into different types of systems, deliver electrical energy in a short time, and provide long shelf life [80]. Capacitors are easier to use and suitable storage for powering portable electronics, sensors, wearable devices, and others. However, if the application requires higher energy density and a long lifespan, then capacitor storage would not be feasible. As an alternative supercapacitor; secondary batteries; and thermal energy storage can be employed [33]. The major concern with a small-scale energy storage system is its image on creating environmental issues from toxic remains [81]. In general, energy storage technologies are environmentally inert waste at the time of operation, but negative impacts are observed through construction and decommissioning. Users must understand accurate information on batteries' recycling; hence a proper recycling channel must be operated [81].

2.3. Power Management

The incorporation of low energy harvesting, energy storage and power management system can take advantage of its potential and provide an optimal solution for high efficiency and energy savings through the statistical circulation of load durations. One of the most important technical issues encountered by the self-sustainable technology is to store harvested energy into an energy storage device efficiently. Since energy harvester technologies have naturally high impedance, the design usually experiences great impedance mismatch mainly when the energy sources are at low frequency [82]. Also, each incorporated system's actual deployment rarely achieves its optimal performance when the self-charging power unit is out of the ideal operating conditions [83]. Figure 2a shows the concept of a self-sustainable technology incorporated with energy harvesting, power management, and energy storage system. Figure 2b demonstrates the energy management cycle for low energy harvesting systems.



(a)

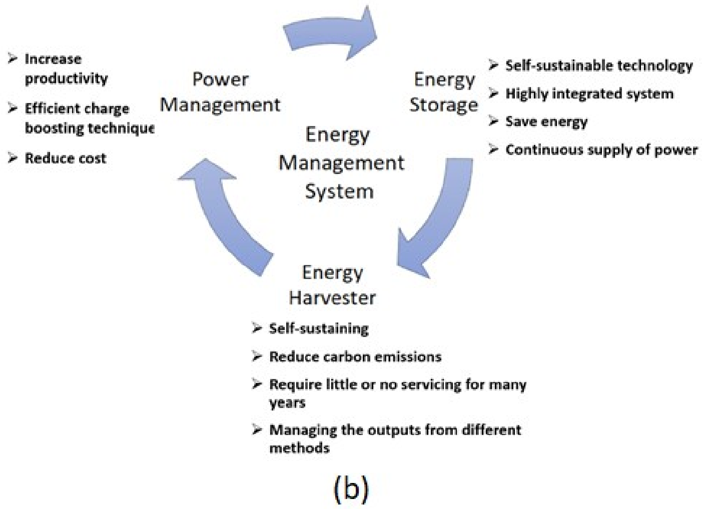


Figure 2. (a) A self-charging power unit incorporated with energy harvesters, power management, and energy storage, (b) energy management for low energy harvesting systems Cheng [5].

3. Recent Advances on Energy Storage for Self-Sustainable Technologies

This section examined the different energy storage types incorporated with low energy harvesting and power management systems for self-sustainable technology used in micro/small electronics including wireless sensor networks, cloud-based data transfer, wearable electronics, portable electronics, and LED lights. The energy storage technologies are classified into electromechanical, electrical, thermal, and mechanical. It is sequenced from the early studies to recent developments to overview how the technology has progressed over the last few years.

3.1. Electrochemical energy storage

Batteries were the first energy storage systems to be integrated with low energy harvesting technologies [84-86], and the most used power storage system in conventional portable electronic devices [87].

3.1.1. Lead-acid battery

Lead-acid battery accounts for the highest battery market share worldwide [33]. It has also been extensively utilized for recharging the battery and powering small scale technologies [88-89]. It is known for its fast charging and discharging process. However, it has a short life cycle and provides low energy density [90]. Ashwathi et al. [91] investigated a lead-acid battery incorporated with a piezoelectric energy harvesting system. To prevent lead-acid from overcharging, a high cut-off voltage was employed. While a low-cut, off relay was applied to prevent the battery from deep discharge. For the relay to work, a relay driver circuit was applied, which performs as a current amplifier. The output voltage was stored in 2 lead-acid batteries with 6 V, 5 Ah attached in series. This design was chosen due to its cost, maintenance requirement, and long life. Also, another application was performed for powering AC load of 3-13 W bulb, the DC voltage of 12 V transformed into 12 V AC through producing 50 Hz using resistor, inductor, and capacitor network.

The design was improved in [92] by incorporating a control technique of power management to design a lead-acid battery with a piezoelectric transducer and rectifier. An efficient control technique was conducted for the voltage, including a mode control technique to regulate the DC-to-DC buck converter and ensure a smooth DC voltage output. This can later be utilized to charge the lead-acid battery for future low power operations. Moreover, the study confirmed that the technology could charge the lead-acid battery with 40 V stable output rectified voltage by allowing a linear increase with state of charge (SoC) from 0-18 per cent after 4 seconds lead-acid is completely charged.

A better result was observed in the study of [93] with another configured design and application method. The study showed that the force applied to piezoelectric crystals could be transformed into electrical energy and store the voltage into the lead-acid battery. An inverter was used to convert 12V to the 230V AC voltage. Later, the 230 V AC was used to activate the loads. A microcontroller was used to demonstrate the battery charge when the foot was placed on the piezoelectric energy harvester.

As observed in this study, only a few recent studies for lead-acid battery were incorporated with low energy harvesting and power management systems. This shows that recent developments are more concentrated on advancing other types of energy storage systems that are more environmentally friendly with long term cycles and cost-effective technologies.

3.1.2. Lithium-ion batteries (LIB)

In the last few decades, Li-ion batteries have been recognized as the powerhouse for digital electronic innovations in modern mobile technology. It is usually used in electronics such as smartphones and laptops [94]. Pu et al. [84] have examined the first flexible self-sustainable technology by incorporating a triboelectric nano-generator and li-ion battery, simultaneously capturing and store ambient mechanical energy. The study improved the study [95] by adding a power management system into the integrated design of lithium-ion and low energy harvesting system. The system consists of lithium-ion with a smart solar energy harvesting system and MPPT circuit. A monitoring device was employed for charging the lithium battery that improved the performance of the system. The experiment showed that the technology could provide a continuous power supply with 5V output voltage via a universal serial bus interface. This self-sustainable technology technique can prevent numerous charge-discharge cycle; therefore, the lithium-ion battery lifetime can be prolonged. The experiment also showed that technology could turn on the power supply automatically.

As the development of the self-sustainable technology progressed, different components are being introduced and integrated into the technology to improve its efficiency, high configuration compatibility, and great output. Since piezoelectric transducers are known for these capabilities, a lithium-ion battery configuration and a piezoelectric stack energy harvester were proposed in [96]. The purpose of the study was to match the parameters of a piezoelectric stack transducer with lithium-ion for supplying power to LED lamps. The piezoelectric stack transducer has shown great characteristics such as high electric capacitance with a considerable impact on the device's harvested electric energy flow. The study proposed a modelled dynamic of the battery, and the input battery impedance was observed when charging at 12 mA steady current, which demonstrated that the impedance relies on the actual state of charges. The recommended models' excellent characteristics are their ability to discharge and charge simultaneously at each state of the battery charge.

Gao et al. [86] have improved the design of [84] by embedding flexible lithium-ion into a triboelectric transducer but in a more advanced configuration and technique for simultaneously capturing wind energy and storing it into chemical energy. This system comprises of a reliable lithium-ion battery, two Cu electrodes, and FEP film. The triboelectric transducer's operation was based on the effective combination of electrostatic and triboelectrification induction in periodical contact of Cu foils and FEP film. The developed design can provide a 135 V output voltage and 12 μA output current, which can be used to efficiently charge from 1.5 V to 3.5 V with the assistance of a rectifier and transformer to plug the triboelectric nanogenerator. The results have proven that the design can efficiently harvest and store energy for self-sustainable technologies.

It has been observed in this study that lithium-ion battery integrated with a piezoelectric or triboelectric generator and power management have provided great results with efficiently harvesting and storing energy for self-sustainable technologies. The design and method prolonged the life cycle with higher power performance.

3.1.3. Nickel metal hydride (NiMH) battery

NiMH battery storage is the best alternative for Li-ion batteries [97]. It utilizes negative electrodes which use hydrogen-absorbing alloy and positive electrodes of nickel oxyhydroxide. NiMH batteries are used in daily consumer electronics, including portable electronic devices and cameras [98]. However, only two studies found in the recent literature used NiMH battery for a self-sustainable technology.

A nickel-metal hydride battery integrated with a piezoelectric low energy harvesting system was used to harvest energy from ambient vibration and store captured energy in the battery [99]. The study's findings have demonstrated that the energy harvesting system charged 550 mAh batteries to a maximum voltage in less than 7 hours driven by an ambient vibration corresponding to the generator output of 2 roots mean square voltage. The harvesting system could not charge the 2200 mAh batteries at a maximum voltage of 1.2 V. It is due to the low output current of the system. It also showed that this technology could charge the standard low capacity battery with 40 and 80 mAh.

Sodano et al. [97] proposed an improved design of a nickel-metal hydride battery charging circuit with a full-wave rectifier. The integrated design has more functions, including supplying power to WSNs and portable electronic devices. Figure 3 shows the time needed to charge different batteries using a piezoelectric energy harvester. A typical charge cycle of NiMH battery was 80 mAh. The results can further provide guidelines on selecting the optimal piezoelectric system and assessing the level of time needed for it to recharge a NiMH battery storage. The simplicity of the circuit enables it to be built very efficiently and no additional materials can lead to power dissipation.

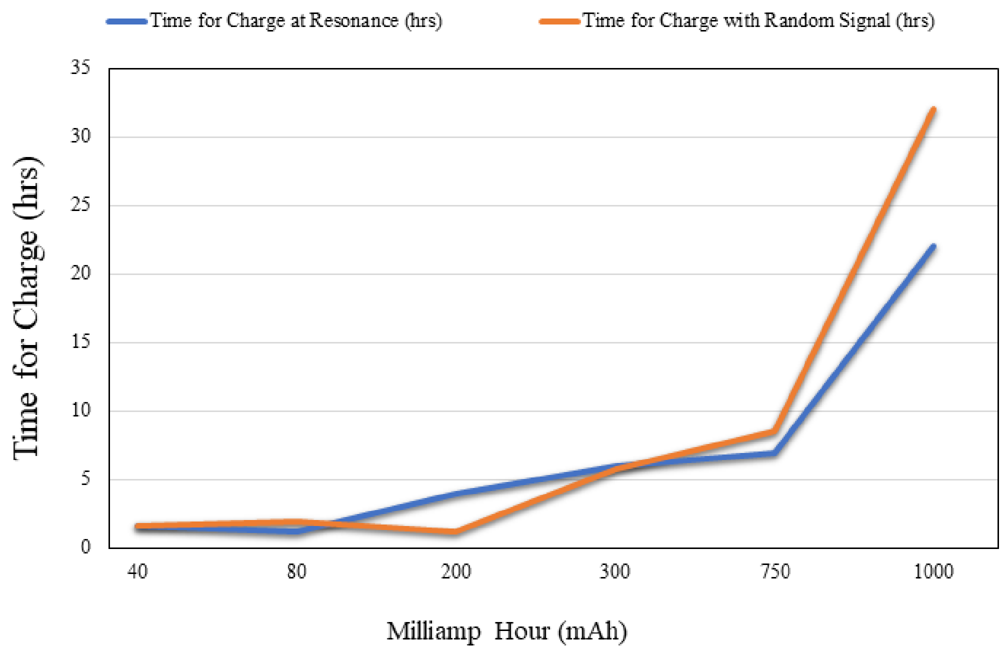


Figure 3: Time needed to charge different nickel-metal hydride batteries size using piezoelectric [97].

Based on the examination of this study, it is very rare to see these combined nickel hydride metal batteries with energy harvesting and power management systems in the literature, and the only available studies are not very recent. The reason may be because researches are switching to more environmentally friendly components for the self-sustainable technology.

3.1.4. Sodium-ion battery (SIB)

Due to the relative abundance of the sodium elements and numerous minerals compared to lithium, scholars started to show interest in a sodium-ion battery to develop a more sustainable technology [100]. Also, it demonstrated a promising performance to achieve the high demands of electrical energy systems. This type of battery is already commercialized for stationary use and consumer electronics [100-101]. However, their main disadvantages are its high operating temperature of up to 300°C, which minimizes the cells' round-trip energy efficiency and causes safety hazards [101]. According to Mahlia et al. [102], this harmful hazard problem can lead to the battery potentially blowing up when interacted with air.

Hou et al. [87] proposed a durable solid-state SIB with safe and stable performance for effectively storing pulsed energy captured through the triboelectric nanogenerator. The SIB showed a high 1000 cycles in cycling performance with an 85 per cent capacity retention at a high charge and discharge current density of 48 mA g-1. The results showed 62.3 per cent energy generation efficiency when charged by the triboelectric nanogenerator system. The incorporation of all-solid-state SIBs and triboelectric nanogenerators demonstrated promising performance for offering more steady-state power output for self-powered technologies.

The design was improved in [69] by integrating an elastic film and sodium-ion battery that represents wide-ranging mechanical energy harnessing efficiency and excellent flexibility and self-charging capability, which is necessary for the advancement of future electrochemical power devices for soft wearable electronics. It can be charged to 0.65 V through palm patting under 300 s, but also showed self-charging features even with quasi-static pressing. It is noticed that the sodium-ion can deliver 64 milliampere hours per gram (mAh g^{-1}) 64 mAh g^{-1} after fifty cycles. The capacities of the sodium-ion battery were examined at several current densities. High reversibility was observed when the current density reverts to 11.7 mA g^{-1}, the sodium ion battery can regain 72 mAh g^{-1}.

It is well recognized that these types of batteries are cost-effective, so researchers are now considering moving from li-ion to SIBs to offer an inexpensive option that is less prone to supply risks and resources. However, studies on sodium-ion batteries integrated with low energy harvesting systems are still not widely available in the literature [103].

3.2. Electrical Energy Storage

Currently, these devices are competing with batteries and observe to be widely used for small-scale applications as it can easily be integrated into different types of systems, deliver electrical energy in a short period time, and provide long shelf life [80]. Electrical energy storage is considered a reinforcing technology for solving issues with impedance mismatch for distribution networks wherein energy is stored in a particular state and transformed into electrical energy. Capacitor and supercapacitor are an example of these systems [36].

3.2.1. Capacitor

During the early studies, the capacitor was placed as a fit-and-forget solution. As time progressed, researches have focused more on switchable capacitors that allow active management of network losses [98]. With the advances in energy harvesting, using inexpensive and easy to process low-profile transducers incorporated with energy storage has attracted significant attention [105].

Zi et al. [105] proposed a triboelectric nanogenerator transducer integrated with a more efficient design of capacitor with random-pulsed output power. To effectively power small scale devices by capturing mechanical energy utilizing nano-generators, energy storage is necessary to deliver a stable and regulated electric output usually achieved through a direct connection among the two elements using a rectifier. The study focused on designing a charging cycle that can optimize the capacitor's efficiency by adjusting the flow charge in the device observed on the triboelectric nanogenerator by installing a motion sensor. The theoretical and experimental analysis demonstrated that the proposed design could enhance the maximum efficiency of energy storage with up to fifty per cent and boost the saturation voltage. This demonstrates that the proposed technology can successfully store the energy generated from nanogenerators using ambient mechanical energy to power implantable, wearable, and portable electronics.

Wearable devices have also emerged to an innovative kind of human to computer interaction with the fast advancement of information and communication technology [17]. A wearable triboelectric energy harvesting device with a capacitor was proposed and tested in [106]. The configured design was intended to power wearable sensors and electronics with ultra-low-cost material. Findings revealed that the wearable triboelectric device could generate energy with more than 70 V output voltage, which can power fifty-two LEDs simultaneously with a 9×9 cm^2 area. Moreover, it can produce 4.81 mW at maximum power from hand-clapping under 4 Hz. Several capacitors were chosen to examine for charging under various frequencies. Results have demonstrated that a capacitor with a capacity of 47 μF can capture a maximum power of around 4.8113mW, from 4 Hz movements. The study noted that capacitors with higher capacitance increase gradually and more stable.

Chung et al. [107] have enhanced the early design of [105] by adding a metal to metal contact for current amplification to the triboelectric nanogenerators transducer with a capacitor under manual input to improve its efficiency. Figure 4a shows the capacitor's design incorporated with a capacitor incorporated with a triboelectric nanogenerator (CI-TENG) rolled inside a cylinder case. Figure 4b demonstrates the movement of the sheet composite when contracted and released through external input. The operation of open-circuit voltage and closed-circuit current is demonstrated in Figure 4c. This system can produce 156 V open-circuit voltage and 4.3 mA closed-circuit current for one device. It can charge the capacitor three times faster as compared to a traditional triboelectric nanogenerator.

The design has proven its potential to produce a considerable amount of power and an ultimate power source for wearable and portable devices.

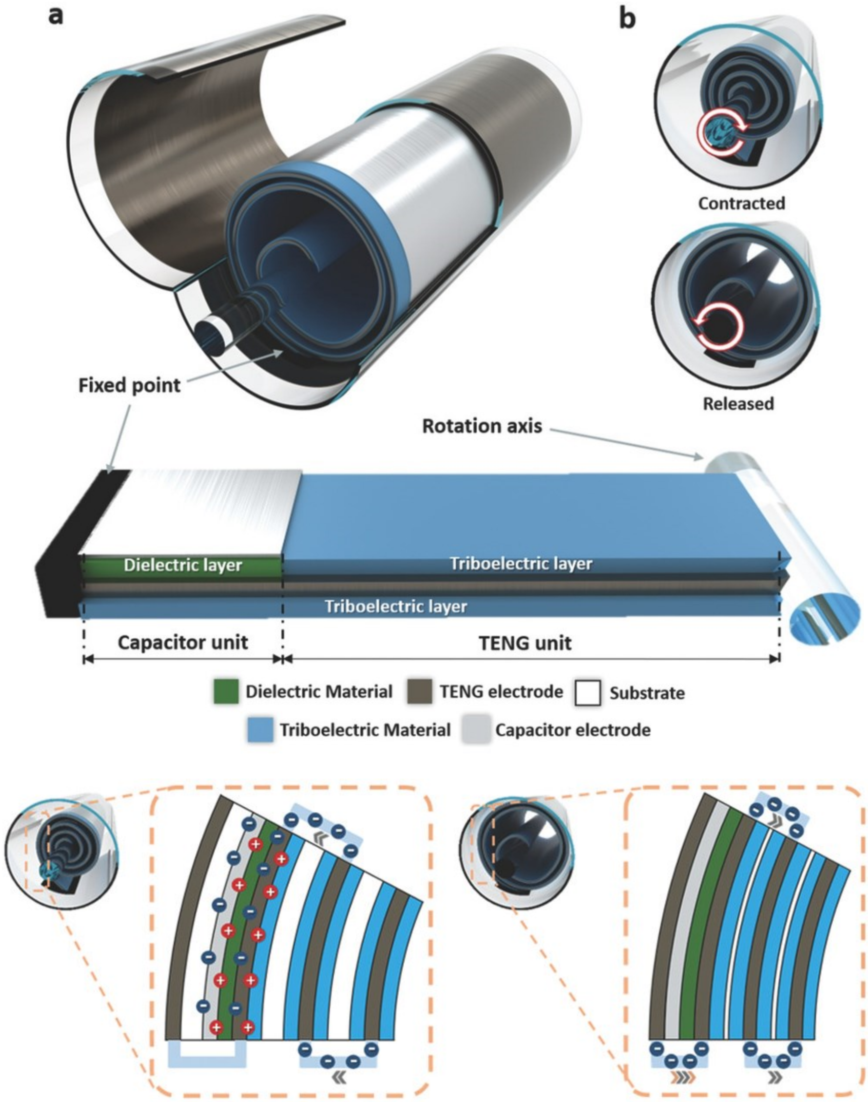


Figure 4: (a) Schematic design of a capacitor incorporated with triboelectric nanogenerator. (b) The movement of the sheet material at the time of contraction and release. (c) operating mechanism [107].

Lan et al. [108] introduced a different integrated design of capacitor and kinetic-powered wearable sensors to detect and track human movements. The capacitor's main benefit with sensing features is that it prevents sampling the movement signal at the time of the activity detection period, which can significantly save the wearable system's power use. The challenge encountered with these capacitors is usually non-linear energy accumulators, which result in high fluctuations in charging rates at various times varying on the current charge rate of a capacitor. This issue was resolved by combining the capacitor's parameters and its harvesting circuits that enable it to work on charging roughly linear cycles. The design of kinetic powered shoe sole was investigated through conducting experiments with ten different subjects. Results demonstrated that the capacitor with sensing features could identify five different daily activities with 95 per cent accuracy, whereas using 73 per cent less power than traditional movement signals with activity detection [108].

Advances on self-charging power designs also include radio frequency integrated with a capacitor. Radiofrequency is another emerging low energy harvesting technology due to its self-sustainable strategy. It can offer limitless energy supply and install in remote areas to power micro/small scale technologies [109]. In the study [63], an amplitude modulated (AM) broadcast radio frequency with a capacitor was developed for low powered, portable calculators placed 2.5 km apart from the device. The highest radio frequency power generated was reached through 10 capacitors with full-wave 6 stage Cockcroft–Walton voltage multiplier (CWMC) based on BAT85 diodes with efficiency up to 90.6%. This means that the output resistance of the system greatly varies on stage capacitors. The device efficiency was measured by evaluating the highest power distributed into the load through its output resistance. The device with an output resistance of 1.5 milliohms (MΩ) distributes the highest power of 62 μW into the calculator. Even though the power rate appeared to be low, it was still capable of powering a portable calculator, weather monitoring stations, and LEDs. This study showed that the capacitors integrated with low power internet connection sharing eradicate the demand for batteries, eliminating the challenges towards developing networks, including the Internet of Things, smart cities, and smart skins. Figure 5 shows the proposed structure of AM broadcast radio frequency for energy harvesting integrated with capacitor and Cockroft-Walton multiplier [63].

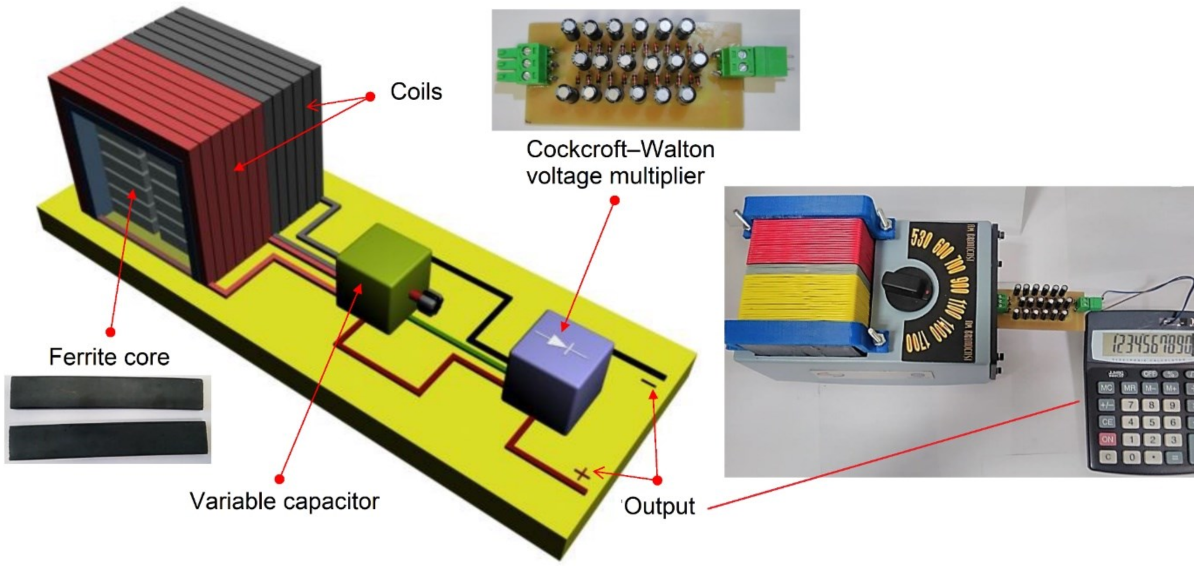


Figure 5: Structure of the energy harvesting system with a variable capacitor. Reproduced with permission from [63].

Another design of radiofrequency harvesting device incorporated with the capacitor was investigated in [11076] to improve the output performance. The configuration of the system includes radio frequency with an Archimedean spiral antenna and Cockcroft-Walton multiplier circuit. The antenna showed that it could function from 350 MHz to 16 GHz with an excellent presentation. The frequency displacement in the circuit was modified to consider the various parasitic components of the printed circuit board and modules. When the input power was dBm, the produced circuit demonstrated a modified 30 per cent efficiency. The capacitor had more than 1.25V charge, which is sufficient to operate a temperature sensor.

With modern innovation, a smaller radiofrequency energy harvester incorporated with capacitor energy storage and circuits for powering WSN was proposed in the study [111]. The recommended integrated circuit includes a low dropout voltage regulator, RF DC rectifier, charge control circuit, and over-voltage protection circuit. For the direct radiofrequency current, a 6-stage Dickson multiplier was applied to enhance the radiofrequency signal received to direct current voltage through utilizing MOSFET with a low-threshold voltage. The charging current was increased a few times by applying the current mirror for a stable and fast charge with the recommended charge control circuit. Findings proved that this system configuration's optimal power conversion efficiency was 40.56 per cent for 1.5 V output voltage, the input power of −6 dBm, and a load of 30 kΩ.

Recently, microbial fuel cells (MFCs) are also drawing significant attention due to their potential in producing renewable energy from organic matter [25]. The integration of an energy harvesting system and plant MFC produces a maintenance-free replacement to hazardous batteries. On the other hand, there are also a few major difficulties with the system, including low-energy supply, dynamic charging rates, and power supply. To further examine MFC's potential for efficient low energy technologies, Sung et al. [111] proposed a new design of MFC integrated with energy harvesting circuits, capacitor, and power management system. A single power management system (PMS) is attached to a parallel-connected MFC or single MFC with boosted voltage from 0.2-3.3V, many single PMS are then attached in series which improved to 6.6V when using 2 PMS. When one MFC provides low power to the PMS in series, the capacitor's voltage reversal happens in the series-connected PMS, not in MFC. However, the influences of this reversal are compensated through the advantages of protecting the MFC from breakdown. This method can be useful for using MFC and PMS as a power source in electronic systems' actual applications.

Many works have been conducted on capacitor's integrated design with high-temperature dielectric ceramics, radiofrequency, microbial fuel cells, or low-profile transducer. The efficiency of each proposed design showed great potential in terms of charging and output voltage. These designs have demonstrated great potential in applications of wearable electronics, wireless sensor networks, implantable devices, and weather monitoring stations and LEDs. Moreover, its low cost, high capacity, and portability improve the overall value of the technology. Impedance mismatch is the most common concern of this technology.

3.2.2. Supercapacitor

Recent innovations have turned supercapacitors a safer and viable charging alternative [70]. Also, these storages have drawn much attention in the energy storage field, primarily due to their long life cycle, low maintenance cost, fast charging capabilities, and high power density [112].

In the past decade, a global drive towards waste management, and researchers are taking advantage of by-products in different ways by using it for energy storage and harvesting materials [113]. There are many various forms of organic and inorganic waste resources that exist in the environment, which resulted in pollution, degradation of ecosystems and human quality life [114]. The capability of the supercapacitors with peptide materials is still lagging behind its inorganic counterparts. The long term cycling steadiness is an issue, specifically with alkaline or acidic electrolyte, due to catalyzed hydrolysis of the peptide bond [112-11685]. To improve peptide supercapacitors' capability, [117-120] introduced a novel atomic layer deposition (ALD) to cover the peptide structure with a conformal coating of Co_9S_8 to handle a Co_9S_8 nanoparticles core/shell structure.

In the last few years, there has been growing interest [121] on the topic of self-powered environmental sensors incorporated with supercapacitor to monitor and examine environmental situations for safety purposes. Zhu et al. [121] designed a self-powered wireless smart sensor node (SSN). The system diagram is demonstrated in Figure 6a. Figure 6b shows the configuration and components, including supercapacitor, sensors, power conditioning unit, and radiofrequency transmitter. A supercapacitor with 0.55F utilized 4.5V to offer suitable charging time. It could store 5.57J maximum energy if the input voltage were directly connected to the supercapacitor. When the regulator attempted to work before achieving the required voltage of 0.9V, this resulted in a regulator dropping its current from the supercapacitor at a level that improved with utilized voltage. Thus, the voltage of supercapacitor stops increasing further than 0.5V, which requires increasing at 0.9V for the regulator's assured performance. To resolve this issue, a cold start circuit which comprises of low-power voltage detector and MOSFET was proposed. The results demonstrated that the regulator could effectively switch on and deliver 3.3V when the supercapacitor attained to 2V.

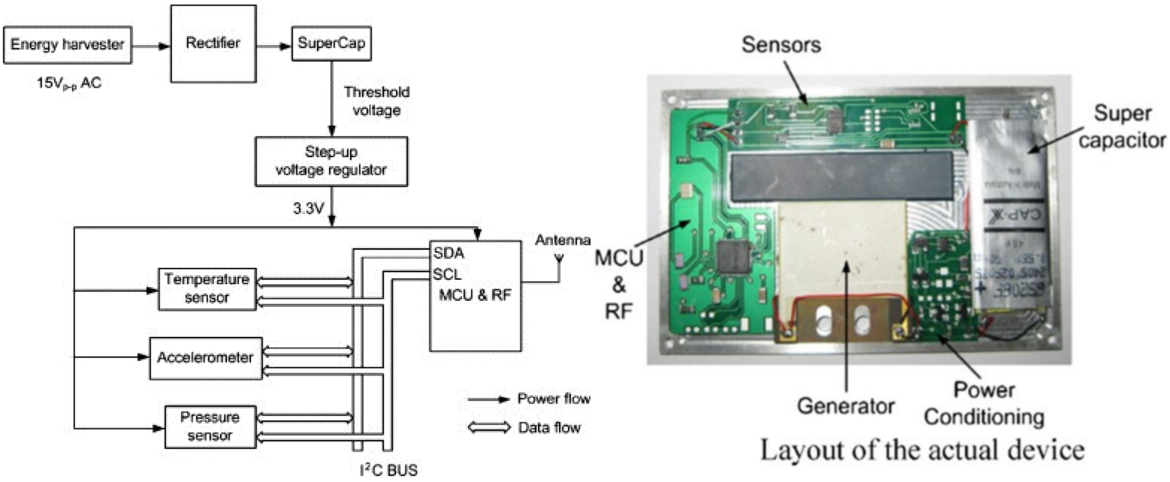


Figure 6: Self-powered wireless smart sensor network (a) system diagram (b) arrangement of the actual device integrated with sensors, supercapacitor, power conditioning, generator, microcontroller, and radiofrequency transmitter [121].

Studies [122] aim to develop lightweight, flexible full electrode elements to enhance energy storage performance for applications including implantable medical devices, portable and wearable electronics, smart clothing, and electronic skins. Dubal et al. [122] reviewed the current developments on the different cathode and anode elements and innovative cell designs of a flexible supercapacitor. The current study found that flexible, supported novel electro-active elements with controlled structural design showed great potential towards significant improvement in the electrochemical performance with its cycling stability, power densities, and high energy density.

Microbial fuel cell technologies have recently shown great promising features in converting organic substrates in wastewater into electricity using a bioelectrochemical [123]. In the study [71], a plant micro fuel cell energy harvesting device was incorporated with supercapacitor energy storage, as demonstrated in Figure 7. The design was suggested for the application of automatic self-powered WSN and cloud-based transfer service. The PM circuit is incorporated with output voltage (V_{OUT}) Select Pin 1 (V_{S1}) connected to Auxiliary low voltage input (V_{AUX}) and V_{OUT} Select Pin 2 (V_{S2}) to ground (GND), delivering a controlled VOUT of 3.3V to the wireless sensor network. This circuit was developed to generate and regulate energy for long term applications. Results showed that the technology achieved a maximum power of 0.71 V, and power density of 3.5mW/cm, and a current density of 5 mA/cm. Also, the phase change microbial fuel integrated with energy harvester enabled an autonomous real-time data processing of the internet of things from powered wireless sensor devices.

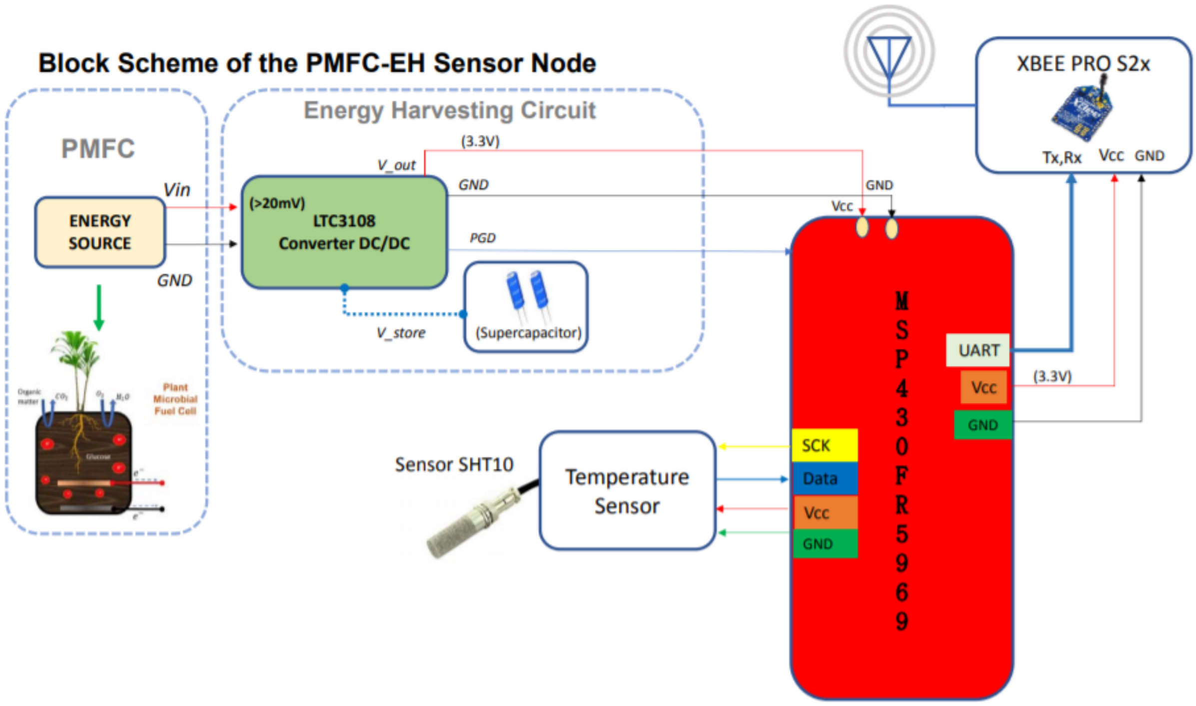


Figure 7: Conceptual plant micro fuel cell (MFC) energy harvesting system for IoT applications. Reproduced with permission from [71].

Another configuration of MFC was proposed in the work of [25]. The proposed design includes an ultra-low power energy harvester for MFCs, and it was intended to use for wide-range wireless communication and environmental sensing. To capture useable energy from micro fuel cells, an energy harvesting system is required, which can store energy in a supercapacitor and improve the microbial fuel cell output voltage. Results showed that the minimum requirement for input power from a micro fuel cell to ultra-low-power energy harvester for charging the supercapacitor to 3.3V was merely 2.09 microwatt (µW), and this is less compared to any other input power recorded for any energy harvesting system up to date [25].

As observed in this subsection, many studies focused on the improvement of inexpensive materials for supercapacitors and took advantage of high-performance electrode materials of a supercapacitor using waste materials as a precursor. The supercapacitors have very adjustable features of materials, which makes them an excellent option for a wide scale of applications with great power demand. This technology's main drawbacks are its requirement for series connections to achieve high voltages and low energy density compared to the electrochemical energy storage systems.

3.2.3. Thermal energy storage (TES)

TES systems enable users to store energy generated in the heat or cold state for later applications. These systems have been a great contributor to energy efficiency in large-scale applications for decades [124]. Recently, there has been increasing attention to energy storage for small scale applications [125].

Nakagawa and Suzuki [126] proposed a highly efficient thermoelectric transducer component for sensing and detecting the sewer water level monitoring system. However, this study used a maintenance hole cover as the source of heat with PCM. To improve the temperature variation around the thermoelectric transducer, a PCM was employed as latent thermal energy storage for storing heat via a thermoelectric generator from the maintenance hole cover. Figure 8a shows the structure of the thermoelectric generator with phase change material. Figure 8b demonstrates the actual installation of thermoelectric equipped to the maintenance hole cover. Figure 8c illustrates the amount of electricity produced daily. With 50.4 Joules per day, the standard level of power produced by using paraffin-based latent heat is six times higher than natural air-conditioning, which is 7.8 Joules per day. The power produced was sufficient to power the wireless sensor unit, which has reached 38 Joules per day while working at sensing and transmission intervals of once every 5 minutes.

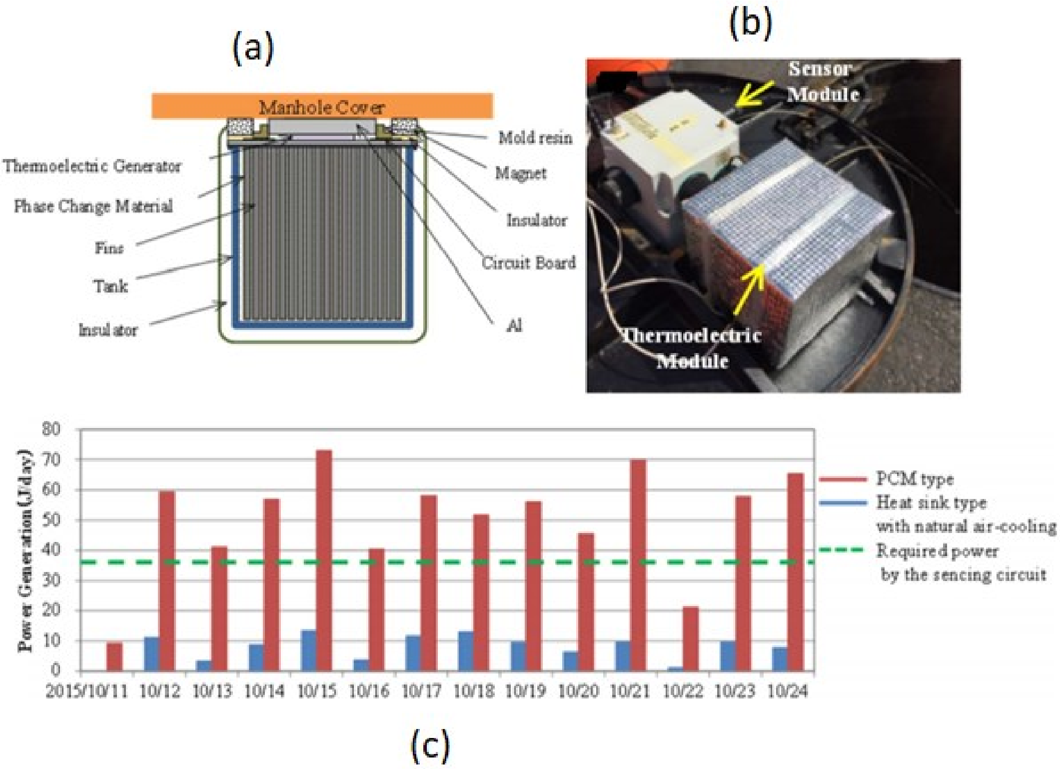


Figure 8: (a). The thermoelectric unit configuration with phase change material, (b) phase change material with the thermoelectric system placed in a manhole cover, (c). The power produced per day and comparison between natural air-cooling and heat storage [126]

Similar work was studied in [127]; however, the design was improved to provide a more efficient and higher output for thermoelectric transducer integrated with sensible and latent heat energy storage to power sensors for monitoring the water level and regulate the power production target required for radio transmission and sensing to 38 Joules per day. To produce power, it is highly efficient to position the thermal heat storage on the thermoelectric generator's cold side. The experiments' results demonstrated the difference between the experimental and simulated data to be within 20 per cent for latent heat and sensible heat energy storage devices. According to the simulated results, the average power produced was roughly 58.5 Joules per day, which is higher than the expected value of 38 Joules per day.

PCM has also shown a promising performance to satisfy and meet the increasing demands of smart thermal energy management and portable thermal energy technologies [128]. The latent heat storage system is characterized as energy storage components with excellent performance for several innovative residential and industrial use. However, shape-instability and low thermal conductivity in the phase change process transition were the major challenges of these materials [128]. Yadav and Sahoo [125] proposed a system that comprises of thermal energy storage with lauric phase change and proven its significant development in exergy and energy efficiency for lauric acid phase change material having 0.4-kilogram mass, which grew by 57.5-68 per cent compared with stearic acid phase change material thermal energy storage system incorporated with a diesel engine. This study indicated that lauric acid phase change materials could be utilized as thermal heat energy storage for exhaust heat recovery from machines at high temperatures and as an alternative for green devices [125].

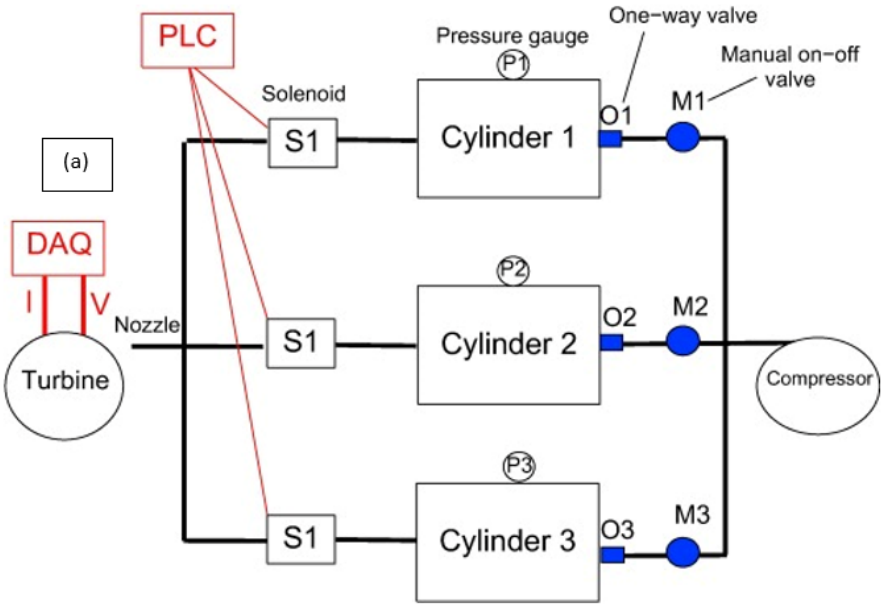
This study demonstrated the efficiency of latent heat thermal energy storage technology with the phase change material and proved to produce a continuous supply of voltage. Also, the study confirmed that the proposed design could be utilized in low power applications, including sensors and monitoring systems. The main limitation of this technology is low thermal conductivity in the transition of the phase change process.

3.2.4. Mechanical energy storage

This type of energy storage technology utilizes gravitational forces to store energy [129]. It is usually used for large-scale applications, for instance, grid support or back up power that requires high power for a short period [130]. A compressed air energy storage technology (CAES) is an example of this technology. It is well known for promising features of high efficiency, long service life, and at the same time protecting the environment [131]. This study is focused on small-scale CAES used in rural off-grid areas [132].

Researchers [130-134] have been interested in the CAES system due to its potential to increase round trip efficiency and long-life cycle by operating in polygeneration mode, which minimizes pollution and energy costs and simultaneously mitigate the relatively low efficiency of this technology. [132] investigated a small-scale CAES system by developing a 400L storage tank, and round-trip efficiency as measured by performing various charging and discharging testing. Results have demonstrated that the compressor works with almost 62 per cent average efficiency, although the efficiency rating was 85 per cent, as a result of part-load operation at the charging time. While the charging efficiency showed only 32.3 per cent and the remaining 67.7 per cent was converted to heat energy, and with the process of storing and using the energy before thermal expansion, it can significantly boost the round-trip efficiency.

Alami et al. [133] proposed a smaller form of micro-CAES as compared to early studies. The study presented modular CAES technology's structure and testing working at low pressure and intended for wind energy applications, specifically in remote areas. Figure 9a demonstrates the system diagram of a micro-CAES, while a small micro CAES technology prototype is shown in Fig 9b. The device's capabilities were assessed by regulating the discharge from the modular systems that could simply be integrated into almost any capacity needed. The study results demonstrated that even when regulating the application to the low-pressure area of the device ability (without surpassing 5 bars), the overall maximum efficiency achieved 97.6 per cent and 95.6 per cent for the highest mechanical efficiency. The low-pressure working condition can store compressed air without temperature increase and offer operation flexibility by regulating different modules affixed and working cycles. The system also has minimal capital and operational costs and easier to install and use, with off-the-shelf parts [102].



(b)

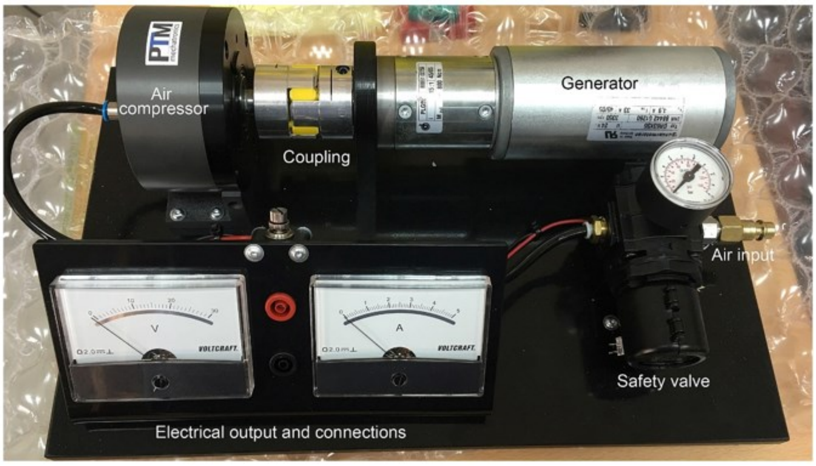


Figure 9: (a) System diagram of a micro-CAES (b) Prototype of micro-CAES [133]

As observed in this study, there are limited recent studies on micro CAES, which causes a great challenge for researchers to assess the device's potential. The disadvantage of this technology is that it needs high-pressure devices.

4. Assessment of Integrated Design of Low Energy Harvesting, Energy Storage, and Power Management

This assessment is based on recently available studies on the fully integrated self-sustainable technology self-charging power unit, which comprises low energy harvesting, energy storage, and power management systems. Figure 10a demonstrates the different designs of self-sustainable technology. Previous works showed that the technology could simultaneously capture energy using transducers and store energy into the energy storage systems. As shown in Figure 10a, the majority of the applications were for self-powered sensor networks, followed by LED/bulb light, electronic devices, and wearable technologies. The researches with the same configured components were not mentioned twice from the summary in Figure 10a.

Figure 10b demonstrates the different types of transducers with power values between 0.27 $mW/cm^2$to 13.6 mW/cm^2, while bulb requires more, roughly 3-13 W. While for energy storage, eight different types were used such as a capacitor, super capacitor, li-ion, sodium-ion, nickel-metal hydride, lead-acid battery, micro-CAES, and latent heat energy storage. As demonstrated in Figure 10b, the capacitor's nominal capacity ranges between 0.22 µF to 100 µF under different conditions for microscale applications. While supercapacitors have a greater nominal capacity of around 0.22 F to 100 F. For electrochemical energy storage systems such as lead-acid, li-ion, sodium-ion, and NiMH have a nominal capacity ranges between 80 to 550 mAh for lower density and 0.15 Ah/g to 2 Ah/g used for higher energy density. While for a micro CAES to store 360 Wh, it requires a size of 18 m^3 storage reservoir.

As shown in Figure 10b, the power management components and systems typically used in the studied researches are buck converter, regulator, microcontroller, full-wave Cockroft Walton multiplier, and MPT. These systems have proven to resolve issues on impedance mismatch, efficient charge boosting technique, increase productivity, power management circuits that monitor, charge, and maintain energy storage performance. In [82], a power management circuit has achieved 90 per cent efficiency and 60 per cent overall efficiency, which is an excellent enhancement as compared to directly charging.

It has been observed that there is a lack of recent literature that focused on both the energy harvesting system and energy storage. Existing studies have shown more detailed information about the low energy harvesting or transducer than the energy storage system, which results in uncertainties about the technical data and certain limitations when these systems are combined. More studies must be conducted on integrated technologies to further investigate how these devices can efficiently and effectively work together. Information about the efficiency of integrated design is very vague and limited. Furthermore, the performance, design, and strategy of configured low energy systems and energy storage are difficult to assess because of limited sources of data. The energy storage role is usually not detailed based on the reviewed research on combined low energy harvesting transducer and power management systems.

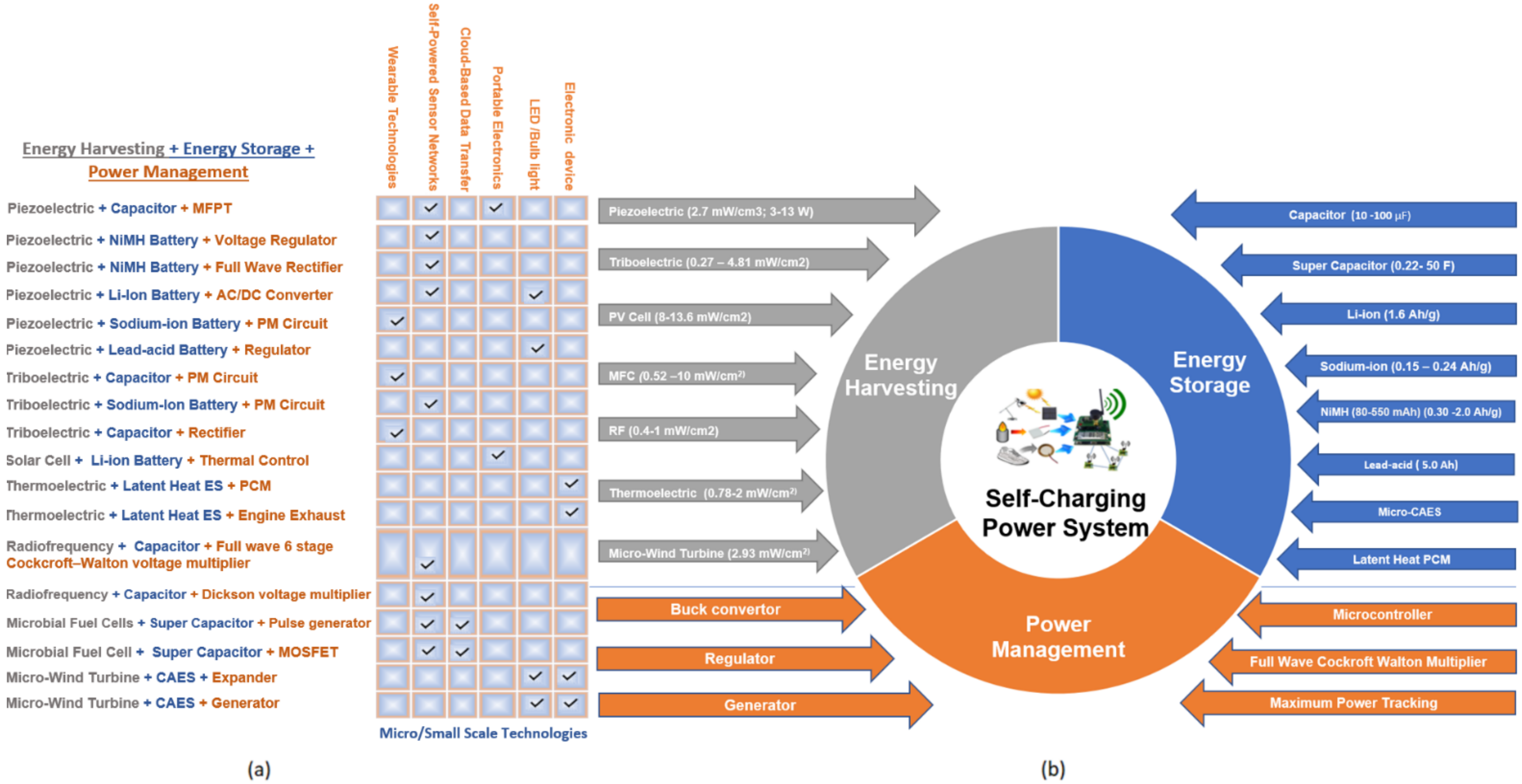


Figure 10: Summary of studies on low energy harvesting system incorporated with energy harvesting transducer, power management, and energy storage [25, 69-70, 75, 87, 92-93, 96-97, 100, 105, 106, 104, 112, 121-122, 126-128, 132-133]

Figure 11 demonstrates the focus or priority of recent studies on the developments of self-sustainable technologies. Since there is a lack of recent literature in the field of the self- self-sustainable technology that provided detailed information about the full system, only 30 recent research studies were assessed. Other available studies do not provide detailed information about the full system, it is either one of energy storage system or low energy harvesting was the focus of the research. According to the reviewed studies, the majority were focused on compatibility, low carbon emission, simple structure, low cost, and efficiency/distribution networks of the technology. While only 17% of the researches were focused on efficient distribution management networks. The technology readiness was not discussed from all reviewed studies on the self-sustainable technology. Reasons may be because self-sustainable technologies are still at an exploratory stage and need more improvement.

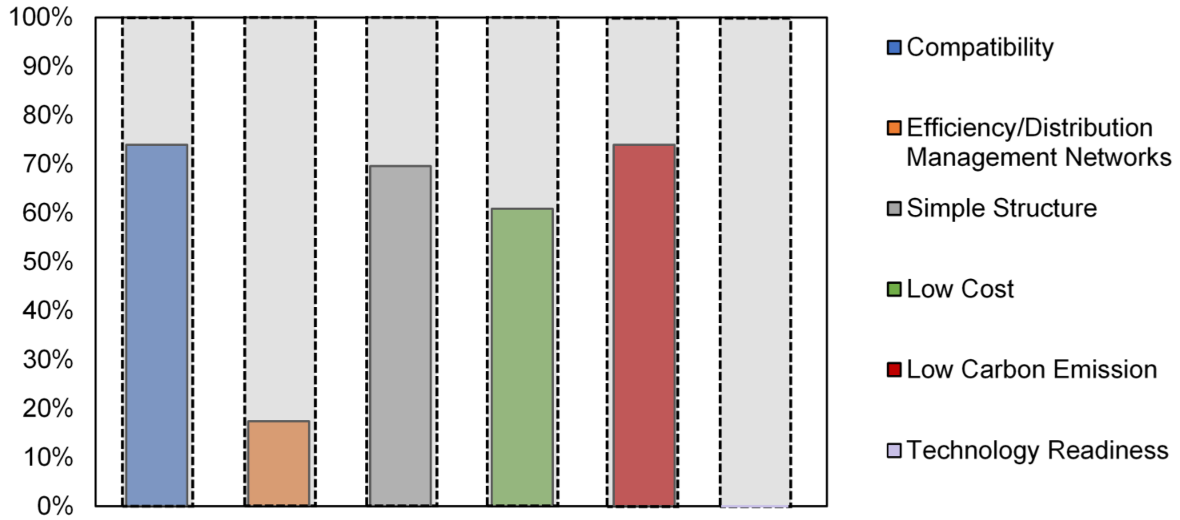


Figure 11: Priority of reviewed studies (% of studies) on integrated design of low energy harvesting, energy storage and power management technologies

In this study, different research methods were used for examining the performance and efficiency of a self-sustainable technology. There are 30 reviewed studies on self-sustainable technology topics that provided clear results and discussions about the fully integrated design. As shown in Figure 12, most studies have relied on theoretical and lab experiment research methods to investigate the performance of different integrated designs of low energy harvesting, energy storage, and power management technologies. Lab experiments employed transmission electron microscope, scanning electron microscopy and high-resolution x-ray diffraction to examine the material properties of proposed integrated self-sustainable technologies. While simulation has also been used with a combination of either laboratory experiments or field testing for validation. On the other hand, little research was carried out for field testing due to the high cost and difficult setup. More field testing is needed to validate novel ideas' viability by conducting more realistic and standardized tests.

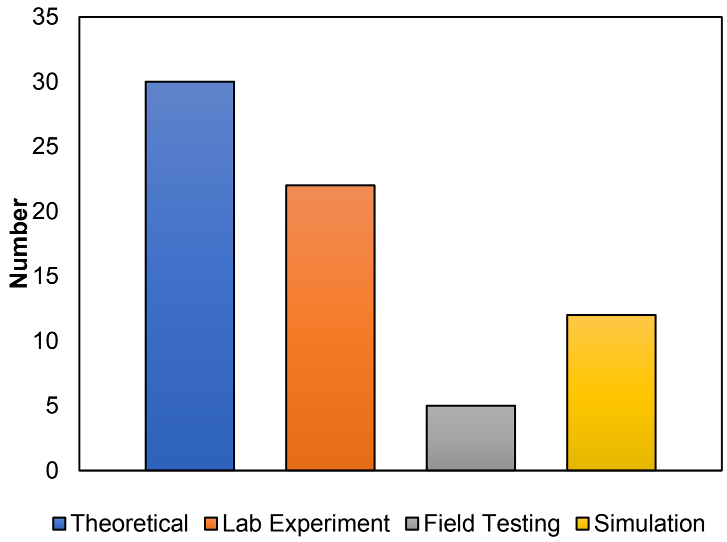


Figure 12: Number of the reviewed studies which employed the different research methods for the self-sustainable technology

Figure 13 summarized the key issues and challenges experienced with developing the self-sustainable technology in the existing studies. The power or energy loss has been the top challenges encountered, mostly due to ineffective integrated circuits and components. There has also been a technical challenge with efficiently storing energy harvested from electric energy to an energy storage system; this creates low battery current leakage [82]. Also, since energy harvesting technologies have naturally high impedance, this design usually experiences a great impedance mismatch, mainly when the energy sources are at low frequency. The lifespan of batteries has been one of the concerns for many years, so researchers have focused on finding different ways to store energy with a greater life span to avoid constant replacements. Also, their disposal creates another problem. High capital cost appears to be one reason for the delay in the commercialization of self-sustainable technology . Furthermore, when low energy harvesting's output performance is highly boosted, it creates nearly 300 mA short circuit current [135].

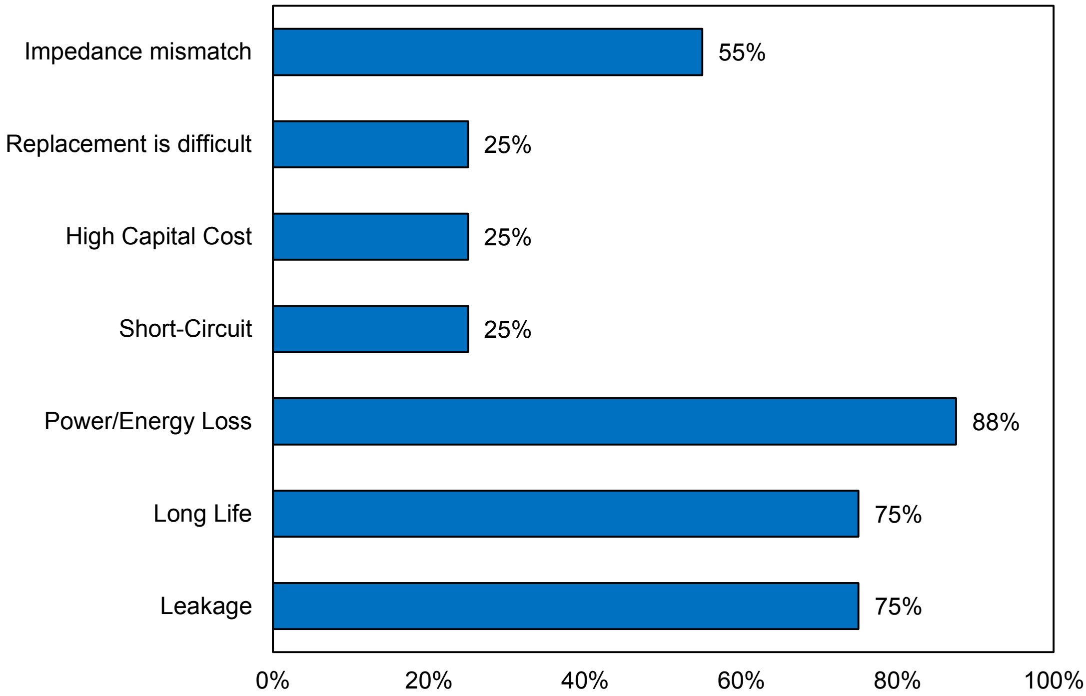


Figure 13 Percentage of the reviewed studies which observed the key issues and challenges on the advancement of a self-sustainable technology

5. Technical Characteristics of Energy Storage Technologies

Advancements in renewable energy have been the driving force for the continuous development of energy storage technologies [33]. The selection of energy storage devices is primarily influenced by the technical characteristics of the technologies [36]. When investigating any energy storage systems' technical potential, the common factors that are mainly considered are the energy density, power density, self-discharge, lifetime, discharge durations, and response time [136]. Table 3 shows each technical features of different available energy storage systems used for micro/small-scale devices. The relative advantages and disadvantages of different energy storage technologies used for low power devices are shown in Table 4.

Table 3: Technical features of reviewed energy storage systems

ES Technology	Energy Density (Wh/L)	Power Density (W/L)	Specific energy (Wh/kg)	Daily Self-Discharge (%)	Efficiency (%)	Lifetime (years)	Discharge time	Response Time	Reference
Capacitor	0.05; 2–10	15–4,500	0.05-5	40	75-90	5; 1-10	milliseconds-60 minutes	<milliseconds	[33, 36]
Super Capacitor	1–35	15–4,500	0.07–85.60	0.46–40	65–99	5–20	milliseconds-60 minutes	<milliseconds	[33, 36, 99, 131]
Micro-CAES	30–60	-	-	-	41-75	25–40	1 to 12 h	5–15 min	[69, 83, 131]
Li-ion	75–250	150–315	-	0.1-0.3	65-75	5-15	minute to hour	<seconds	[36, 69, 83],
NiMH	38.90	7.80	30-90	0.30	50-80	2-15	second to hour	seconds	[33]
Lead acid	30–50	75–300	-	0.1–0.3	75-90	3–15	second to hour	<seconds	[69, 83]
	50-90	10-700	20-50	0.0333-0.3	70-90	5-15	second to hour	minutes	[131]
TES	80-120	-	-	0.50	75.00–90.00	10-20	1 to 8 hours	-	[33, 83]

As detailed in Table 3, Li-ion has a higher energy density compared to standard batteries. Energy density depends on the brand, even though it has the same energy storage system [36]. TES, lead acid, NiMH, and micro-CAES have a medium energy density. A low energy density is observed for capacitor and supercapacitor but has high power density, which is apt for power quality with fast responses and large discharge currents. The highest specific energy is NiMH and for the lowest is capacitor. The capacitor and supercapacitor reached the highest percentage (up to 40 percent). These systems can only be used for limited cycle intervals in several hours.

Lead acid, TES, capacitor, and supercapacitor have an excellent efficiency of around 65-99 per cent, while CAES demonstrated the least efficient among all the energy storage system mentioned. However, micro compressed air energy storage has demonstrated a longer life span as compared to others. Capacitor and supercapacitor showed the fastest discharge duration and response time, but the compressed air energy storage needs more time (1 to 12 hrs) for discharge and 5-15 minutes with the response time.

Table 4 shows the relative advantages and disadvantages of different energy storage technologies used with low energy harvesting devices. This evaluates each strength and weaknesses, which can serve as a guideline for further advancement of energy storage technologies. Also, it can assess which type of energy storage technologies are suitable and can easily be integrated and with a low energy harvesting system.

Table 4: Advantages and disadvantages of the reviewed small-scale energy storage technologies

Reference	Type of Energy Storage	Advantages	Disadvantages
[132-134]	➢ Capacitor ➢ Supercapacitor	✓ Fast response time ✓ Fast charge time ✓ Can charge or discharge several times with little loss and minimal maintenance	✗ Advanced materials used are expensive to manufacture ✗ High energy dissipation ✗ Low energy density
[132-134]	➢ Micro-Scale Compressed Air	✓ Fast discharging times ✓ High energy density ✓ High storage capacity ✓ No dependence on geographic locations ✓ Long storage capabilities	✗ Low efficiency
[133-136]	➢ Lead-acid	✓ Mature technology ✓ Compact and economical ✓ Can easily be integrated with little effect on neighboring architecture ✓ High sustainability compared to other batteries ✓ High potential for recycling ✓ Fast response time	✗ Minimal working life before replacement (roughly 1200–1800 cycles) ✗ Slow response times ✗ Less specific energy
[133-135]	➢ Lithium-ion	✓ Matured technology ✓ Fast response time	✗ Can be harmful when at full discharged ✗ Sensitive voltage operating range
[137-138]	➢ Nickel-Metal Hydride	✓ Fewer toxic metals ✓ Few periodic exercise cycles are needed	✗ Considerably less discharge current ✗ Produces more heat while charging ✗ Only 500 charges/discharge cycles
[139-140]	➢ Sodium-ion	✓ Long battery life ✓ High power density ✓ Low cost ✓ Earth-abundant materials ✓ High efficiency with more than 90%	✗ High operating temperatures ✗ Less mature technology
[141-142]	➢ Thermal Heat	✓ High energy density ✓ Low volume/weight of material	✗ Minimal thermal conductivity ✗ Minimal discharge and charge times ✗ Limited operating temperature

6. Economic Analysis and Environmental Impacts of Energy Storage Technologies

Table 5 summarized the current developments in the energy storage system from economic and environmental perspectives. These analyses can be useful for further developing energy storage components for the integrated design of self-sustainable technology.

Table 5: Economic analysis and environmental impact of the energy storage system

Technology	Power ($/kW)	Energy ($/kW h)	Life cycle	Capital Cost kWh-per cycle	Technology Maturity	Influence on environment	Reference
Capacitor	200-400	500-1000	-	-	Commercial	Very Low	[33,75]

Super Capacitor	110-440	330-4430	10^4-10^6	2-20	Commercial	Very Low	[33, 75]
Micro-CAES	440-1280	11-130	5 x 10^3 - 2 x 10^4	2-4	Commercial	Low	[33, 75]
Li-ion	220-1990	16-110	700-3000	-	Mature	High	[33, 75]
NiMH	7.80-588	38.90-300	300-3000	-	Mature	High	[33]
Lead-acid	55-330	22-110	200-650	≈50	Mature	High	[33, 75]
Latent Heat TES	200–300	3-88.73	-	-	Commercial	Low	[33]

6.1. Capital Cost

The capital cost of the energy storage component is an important matter to consider in developing a self-sustainable technology. Since it is difficult to find detailed information about the capital cost of these systems, all mentioned figures are gathered from the review of Sabihuddin [33] and Nguyen [75] for small-scale energy storage technologies. As shown in Table 5, the costs are demonstrated in power ($/kW), energy ($/kW h), and capital cost kWh-per cycle [75]. The per-cycle cost is the cost per unit energy divided by the life cycle; this measures the cost of ES in charge or discharge use cycle [75]. The capacitor and supercapacitor are suitable for a short duration and high-power density applications. However, both are costly in terms of energy storage capacity. CAES is in the low range in terms of capital cost.

It is important to note that the capital cost of energy storage technologies could be considerably different from the calculations mentioned in Table 5. Reasons may be because of the different size of the system, time of production, and breakthroughs in systems. Therefore, this summary must be viewed as an exploratory analysis.

6.2. Technology Maturity

When evaluating the maturity of an energy storage device, a technology maturity model is represented by evaluating the technology readiness level (TRL) and market's stage of development for each energy storage system [75]. According to the analyzed research papers, most energy storage systems are ranked similarly, and their level of maturity is almost identical to the work of [148]. The technology maturity of each device is shown in Table 5. Lead-acid, lithium-ion, NiMH batteries are the matured energy storage systems. Therefore, the deployment of these technologies is expected to experience a few difficulties with application and operation. These systems are followed by a capacitor, super capacitor, latent heat TES and micro-CAES, which have reached their growth and currently commercializing. While sodium-ion energy storage technology is less experienced globally and can potentially face difficulties during operation [33, 75].

6.3. Environmental Impact

In recent years, the energy storage sector has been aiming to achieve an efficient shift to a low-carbon future. The influences of energy storage system on the environment are compared in Table 5. It is noticeable that all batteries mentioned below remain to have a strong influence on the environment in toxicity. This has been an issue for such a long time, but it is still unresolved. Batteries have been widely used in various applications, but few were examined in terms of possible environmental effects for the overall life cycle. However, several research types have been conducted to improve efficiency in several methods [149]. Due to their rapid growth and production, many batteries of various sizes, types are manufactured worldwide, which resulted in several public health and environmental issues [149]. However, other forms of energy storage systems have a low environmental impact, such as micro CAES and latent heat TES, since these systems do not contain toxic chemicals. The capacitor and supercapacitor have a very low impact on the environment [33].

7. Conclusion

In this study, different configurations of low energy harvesting, energy storage, and power management systems have proven to offer continuous, direct current output driven by low frequency from harvested energy in random frequency and amplitude. This is efficient for the sustainable operation of self-powered sensor networks, cloud-based transfer service, portable electronics, LED light, and other low power electronic device. The self-sustainable technology is a paradigm shift for a limitless energy source that cannot be obtained with only low energy harvesting systems. Moreover, the self-sustainable technology is highly beneficial for micro/small device applications positioned in remote areas and simultaneously provides great power and energy density with low-cost materials and lower series resistance.

Although improvements are achieved with the development of incorporated low energy harvesting and energy storage systems, there are still a few issues that need to be considered. These issues include (i) The impedance mismatch between a single power system must be addressed. A mismatch of the impedance can lead to significant current leakage, which can greatly influence the hybrid systems' final output power. The capacities and impedances must meet the output power of low energy harvesting technology for high conversion efficiency. Furthermore, there are also challenges with easiness, safety, and cost to incorporate these systems. (ii) The power or energy densities of the incorporated systems are usually low, and their efficiency decreases with the increasing working time. Also, the life-cycle cost is still high for energy storage devices. (iii) No single energy storage technology meets the overall demands of an ideal ESS, which have high efficiency, low costs, long lifetime, high density, mature and environmentally friendly all in one system. Each of the available energy storage devices is suitable for a specific application range. CAES and thermal energy storage are suitable for energy management implementations. While capacitors, supercapacitors, and batteries are more suitable for a short duration and power quality. Also, batteries are a more promising system for power distribution. (iv) The self-sustainable technology rarely achieves its optimal performance when it is out of the ideal operating conditions (v) High implementation and production cost of low energy harvesting technologies are also the significant challenges that hamper the development of the technology.

This study's main challenge is the lack of recent literature that focused on both low energy harvesting and energy storage system. The majority of the research available on low energy harvesting systems incorporated with energy storage is either focused on one of these topics and not integrated into one single device. Existing studies have also shown more detailed information about the low energy harvesting or transducer than the energy storage system, which results in uncertainties about the technical data and certain limitations when these systems are combined. The role of the energy storage is usually not detailed more according to reviewed researches on integrated design. There are only 30 papers that provided detailed information about the whole self-sustainable technology. It was also found that several types of research opted to focus more on large-scale energy systems, particularly power networks on power grids, power shaving, and level of support from the government.

8. Recommendations for Future Works

Further investigation should be carried out on integrated designs of low energy harvesting, energy storage, and power management system to investigate whether these devices can efficiently and effectively work together. Available information about the efficiency of integrated design is limited. Also, there were only a few available studies for energy storage that investigated small-scale energy storage applications, while most studies were focused on either medium or large-scale systems. Therefore, there is also a need for a detailed examination of small-scale energy storage devices to examine the best-suited energy storage for the self-sustainable technology for a particular application and situation. On the other hand, little research was carried out for field testing due to the high cost and difficult setup location. More field testing is needed to validate novel ideas' viability by conducting more realistic and standardized tests. To promote the use of self-sustainable technologies, governing bodies should step in by imposing rules and regulations within the market to highlight its benefits. Lastly, detailed cost-benefit analysis and environmental impacts must be considered when designing the optimal self-sustainable technology.

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Reference

[1] Zhou C, Yang Y., Sun N, Wen Z, Cheng P, Xie, X, Shao H., Shen Q, Chen X, Liu YJ, Wang, Z.L, Sun X. Flexible self-charging power units for portable electronics based on folded carbon paper. Nano Research 2018;11:4313-4322.

[2] KPMG International Cooperative 2020. Static Reports for Internet of Things connected technologies, https://advisory.kpmg.us/content/dam/advisory/en/pdfs/connected-devices-leaving-you-exposed.pdf; 2020 [assessed on 1 April 2020].

[3] Kamalinejad P, Mahapatra C, Sheng, Z, Mirabbasi, S, Leung, VCM, Guan YL Wireless energy harvesting for Internet of Things. IEEE Communications Magazine 2015;53(6):102-108.

[4] Pozo B, Garate JI., Araujo JÁ, Ferreiro S. Energy Harvesting Technologies and Equivalent Electronic Structural Models—Review. Electronics 2019;8*:*486.

[5] Cheng X, Tang W, Song Y, Chen H, Zhang H, Wang ZL. Power management and effective energy storage of pulsed output from triboelectric nanogenerator. Nano Energy 2019; 61:517-532.

[6] Zhao, K., Wang, Y., Han, L. Wang Y, Luo X, Zhang, Z, Yang Y. Nanogenerator-Based Self-Charging Energy Storage Devices. Nano-Micro Letters 2019;11(1):19.

[7] Pandey S, Zalke J, Nandanwar R, Verma A. Design and Analysis of Piezoelectric Energy Harvesting Circuit for Rechargeable Ultra - Low Weight Lithium-Ion Batteries. Journal of Engineering Science and Technology Review 2018;11:77-83.

[8] Li H, Tian CM, Deng ZD. Energy harvesting from low frequency applications using piezoelectric materials. Applied physics reviews 2014;1:041301.

[9] Akinyele D, Rayudu R. Review of energy storage technologies for sustainable power networks. Sustainable Energy Technologies and Assessment 2014;8:74–91.

[10] Khan FU, Khattak MU. Contributed Review: Recent developments in acoustic energy harvesting for autonomous wireless sensor nodes applications. The Review of Scientific Instruments 2016;87(2): 021501.

[11] Priya SJ, Song HC, Zhou Y, Varghese R, Chopra A, Kim SG., Kanno I, Wu L, Ha D, Ryu, J, Polcawich R. A Review on Piezoelectric Energy Harvesting: Materials, Methods, and Circuits, Energy Harvesting and Systems. Walter de Gruyter GmbH 2017*;*4:021501.

[12] Adu-Manu KS., Adam N, Tapparello C, Ayatollahi H, Heinzelman WB. Energy-Harvesting Wireless Sensor Networks (EH-WSNs): A Review. ACM Transactions on Sensor Networks (TOSN) 2018;14:1-50.

[13] Newell D, Duffy M., Review of Power Conversion and Energy Management for Low-Power, Low-Voltage Energy Harvesting Powered Wireless Sensors. IEEE Transactions on Power Electronics 2019; 34(10):9794-9805.

[14] Khalid S, Raouf I, Khan A, Kim N, Kim H, S. A Review of Human-Powered Energy Harvesting for Smart Electronics: Recent Progress and Challenges. International Journal of Precision Engineering and Manufacturing-Green Technology 2019;6:821-851.

[15] Akbari S. Energy harvesting for wireless sensor networks review. Federated Conference on Computer Science and Information Systems 2014:987-992.
[16] Zhou G, Huang L, Li W, Zhu Z. Harvesting Ambient Environmental Energy for Wireless Sensor Networks: A Survey. Journal of Sensors 2014:1-20.
[17] Lee J, Kim D, Ryoo HY, Shin BS. Sustainable Wearables: Wearable Technology for Enhancing the Quality of Human Life. Sustainability 2016;8:466.
[18] 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 and Systems Magazine 2017;17(4):29-63.
[19] Liu Y, Wang L, Zhao L, Yu X, Zi Y. Recent progress on flexible nanogenerators toward self-powered systems. InfoMat 2020;2(2).
[20] Gu Y, Hou T, Chen P, Cao J, Pan C, Hu W, Yang B, Pu X, Wang Z. Self-powered electronic paper with energy supplies and information inputs solely from mechanical motions; Photonics Research 2020;8:1496-1505.
[21] Luo, J, Wang, ZL. Recent progress of triboelectric nanogenerators: From fundamental theory to practical applications. EcoMat 2020;2:e12059.
[22] Yang C, Lai Y, Kim J. A piezoelectric brace for passive suppression of structural vibration and energy harvesting. Smart Materials Structures 2017; 26:085005.
[23] Zhu Y, Yang B., Liu J, Wang X, Wang L. Chen X. Yang C. A flexible and biocompatible triboelectric nanogenerator with tunable internal resistance for powering wearable devices. Science Reports 2016;6:22233.
[24] Ambrożkiewicz B, Litak G, Wolszczak P. Modelling of Electromagnetic Energy Harvester with Rotational Pendulum Using Mechanical Vibrations to Scavenge Electrical Energy. Applied Sciences 2020;10:671.
[25] Yamashita, T., Hayashi, T., Iwasaki, H., Awatsu, M., Hiroshi Yokoyama, Ultra-low-power energy harvester for microbial fuel cells and its application to environmental sensing and long-range wireless data transmission. Journal of Power Sources 2019;430:1-11.
[26] Liu Q, Si T, Xu X, Liang F, Wang L, Pan S. Electromagnetic radiation at 900 MHz induces sperm apoptosis through bcl-2, bax and caspase-3 signaling pathways in rats. Reproductive Health 2015;12(65).
[27] Leicht J, Heilmann P, Hehn T, Li X, Maurath D, Moranz C, Thewes M, Scholl G, Manoli Y. Thermoelectric energy harvesting system for demonstrating autonomous operation of a wireless sensor node enabled by a multipurpose interface. Journal of Physics: Conference Series, Volume 476, The 13th International Conference on Micro and Nanotechnology for Power Generation and Energy Conversion Applications (PowerMEMS 2013) London, UK.

[28] Hamzah Y, Sulistyo A, Agustina R, Wati Lazuardi Umar, Widyaningrum Indrasari. Determination of internal parasitic of photovoltaic polycrystalline silicon Hooray MCP-12 under direct sunlight using the Lambert-W function; AIP Conference Proceedings 2019;2169:030003.
[29] Ostfeld E, Arias AC. Flexible photovoltaic power systems: integration opportunities, challenges, and advances. Flexible and Printed Electronics 2017;2(1):013001.
[30] Jaksik J. Moore HJ, Trad T, Okoli, OI. Uddin, MJ. Nanostructured functional materials for advanced three-dimensional (3D) solar cells. Solar Energy Materials Solar Cells 2017;167:121-132.
[31] Lee Y, B, Han JK, Noothongkaew S, Kim SK, Song W, Myung S, Lee SS, Lim J, Bu SD, An, KS. Toward arbitrary-direction energy harvesting through flexible piezoelectric nanogenerators using perovskite PbTiO3 nanotube arrays. Advanced Materials 2017;29(6):1604500.
[32] Lin Z, Chen J, Li X, Zhou Z, Meng K, Wei W., Yang J, Wang, ZL. Triboelectric nanogenerator enabled body sensor Network for self-powered human heart-rate monitoring. American Chemical Society Nano 2017,11:8830-8837.
[33] Sabihuddin S, Kiprakis AE, Mueller MA. Numerical and Graphical Review of Energy Storage Technologies. Energies 2015;8:172-216.
[34] Tang X, Wang X, Cattley R, Gu F, Ball AD. Energy Harvesting Technologies for Achieving Self-Powered Wireless Sensor Networks in Machine Condition Monitoring: A Review. Sensors (Basel) 2018;23;18(12):4113.
[35] Thong NA. For partial fulfillment of the Degree of Master of Engineering Department of Electrical and Computer Engineering National University of Singapore. Application of Supercapacitor in Electrical Energy Storage System 2011.
[36] Luo J, Fan F, Jiang T, Wang Z, Tang W, Zhang C, Liu M, Cao G, Wang Z. Integration of micro-supercapacitors with triboelectric nanogenerators for a flexible self-charging power unit. Nano Research 2015;8:3934-3943.
[37] Aktakka EE, Najafi K. A micro inertial energy harvesting platform with self-supplied power management circuit for autonomous wireless sensor nodes. IEEE Journal of Solid-State Circuits 2014; 49(9):2017-2029.
[38] Sano C, Mitsuya H, Ono S, Miwa K, Toshiyoshi H, Fujita H. Triboelectric energy harvesting with surface-charge-fixed polymer based on ionic liquid. Science and Technology of Advanced Materials 2018;19(1):317-323.
[39] Suzuki Y. Recent progress in MEMS electret generator for energy harvesting. IEEJ Transactions on Electrical and Electronic Engineering 2011;6:101-111.
[40] Digital Transformation Monitor 2017. Energy harvesting to power the rise of the Internet of Things. https://ec.europa.eu/growth/toolsdatabases/dem/monitor/sites/default/files/DTM_Energy%20harvesting%20v1_0.pdf; 2020 [Accessed 01 March 2020].
[41] Logothetis I, Vassiliadis S, Siores E. Triboelectric effect in energy harvesting. IOP Conference Series: Materials Science and Engineering 2017;254(4):1-7.

[42] Luo J, Wang Z, Recent advances in triboelectric nanogenerator based self-charging power systems, Energy Storage Materials 2019;23:617-628.

[43] Luo J, Tang W, Fan F, Liu C, Pang Y, Cao G, Wang Z. Transparent and Flexible Self-Charging Power Film and Its Application in a Sliding Unlock System in Touchpad Technology ACS Nano 2016;10(8):8078-8086.

[44] Fang L, Hassan S, Abd Rahim R, Abdul Malek, M. A Study of Vibration Energy Harvester Asian Research Publishing Network (ARPN) Journal of Engineering and Applied Sciences 2016;11(8).

[45] Invernizzi, F, Dulio S, Patrini M., Guizzetti G., Mustarelli, P. Energy harvesting from human motion: Materials and P. Energy harvesting from human motion: Materials and techniques. Chemical Society Reviews 2016;45(20):5455–5473.

[46] Wang ZL, Chen J, Lin L. Progress in triboelectric nanogenerators as a new energy technology and self-powered sensors. Energy and Environmental Science 2015;8:2250-2282.

[47] Kalagobe T. Energy recovery system for cryprocurrency mining activities using a GPU rig. Thesis for Mechanical Engineering, 2019.

[48] Nechibyute A, Chawanda A, Luhanga P. Piezoelectric Energy Harvesting Devices; An Alternative Energy Source for Wireless Sensors. Smart Materials Research 2012;853481:13.

[49] Ha M, Park J, Lee Y, Ko H. Triboelectric generators and sensors for self-powered wearable electronics. ACS Nano. 2015;9(4):3421-3427.

[50] Wen D, Deng H, Liu X, Li G, Zhang X, Zhang X. Wearable multi-sensing double-chain thermoelectric generator. Microsystems & Nanoengineering 2020;6(68).

[51] Abdelkefi A, Nayfeh A, Hajj M. Modeling and analysis of piezoaeroelastic energy harvesters. Nonlinear Dynamics 2012;67:925–939.

[52] Hasanyan A, Hasanyan D, Energy Harvesting Performance of Dynamic Bimorph Thermopiezoelectric Benders with Arbitrary Support Location. Journal of Thermal Stresses 2015;38:1411-1429.

[53] Harne Theoretical investigations of energy harvesting efficiency from structural vibrations using piezoelectric and electromagnetic oscillators. Journal of the Acoustical Society of America 2012; 132(1):162-172.

[54] Fakhzan M; Muthalif A. Vibration based energy harvesting using piezoelectric material. Mechatronics (ICOM)2011 4th International Conference;1-7.

[55] Baghdasaryan G, Hasanyan Armanj, Hasanyan D. Dynamic bimorph thermo-piezoelectric benders with arbitrary support location. part i: application to energy harvesting-analytical derivations.. Mechanics - Proceedings of National Academy of Sciences of Armenia 2016;69:25-38.

[56] Andosca R, McDonald T, Genova V, Rosenberg S, Keating J, Benedixen C, Wu J. Experimental and theoretical studies on MEMS piezoelectric vibrational energy harvesters with mass loading. Sensors and Actuators A: Physical 2012;178:76–87.

[57] Datta A, Sangle A, Hardingham N, Cooper C, Kraan M, Ritchie D, Narayan V, Kar-Narayan S. Structure and Thermoelectric Properties of $Bi_{2-x}Sb_xTe_3$ Nanowires Grown in Flexible Nanoporous Polycarbonate Templates. Materials (Basel) 2017;10(5):553.
[58] Moussa R. The Effect of Street Bumps on Energy Generation and Reduction of the Global Carbon Emissions. WSEAS Transactions on Environment and Development 2019;15:430-437.
[59] Ahmed A, Hassan I, Ibn-Mohammed T, Mostafa H, Reaney I, Koh L, Zu J, Wang Z. Environmental life cycle assessment and techno-economic analysis of triboelectric nanogenerators. Energy & Environmental Science 2017;10:653-671.
[60] Shimose S, Makihara K, Minesugi K, Onoda J. Assessment of Electrical Influence of Multiple Piezoelectric Transducers' Connection on Actual Satellite Vibration Supression. Smart Materials Research 2011;2011;6886289:8.
[61] Hendijanizadeh M, Elliot S, Ghandchi-Tehrani M. The effect of internal resistance on an energy harvester with cubic resistance load. Conference: The 22nd International Congress on Sound and Vibration (ICSV22) 2015.
[62] Ibrahim A, Jain M, Salman E, Willing R, Towfighian S. A Smart Knee Implant Using Triboelectric Energy Harvesters. Smart Materials and Structures 2019;28(2).
[63] Leon-Gil JA, Cortes-Loredo A, Fabian-Mijangos A, Martinez-Flores JJ, Tovar-Padilla M, Cardona-Castro MA, Morales-Sánchez A., Alvarez-Quintana J. Medium and Short Wave RF Energy Harvester for Powering Wireless Sensor Networks. Sensors 2018;18(3):768.
[64] Jaziri N, Boughamoura A, Müller J, Mezghani B, Tounsi F, Ismail M. A comprehensive review of Thermoelectric Generators: Technologies and common applications, Energy Reports 2020;6(7):264-287.
[65] Hamzah Y, Sulistyo A, Agustina R, Wati Lazuardi Umar, Widyaningrum Indrasari. Determination of internal parasitic of photovoltaic polycrystalline silicon Hooray MCP-12 under direct sunlight using the Lambert-W function; AIP Conference Proceedings 2019; 2169:030003.
[66] Ramos A, Pinto AL, Fonseca I, Ferreira C. System for micro generation and energy storage, state of the art - Example of the piezoelectric effect. 51st International Universities Power Engineering Conference (UPEC) 2016.
[67] Zhao H, Yu J, Ling J. Finite element analysis of Cymbal piezoelectric transducers for harvesting energy from asphalt pavement. Journal of the Ceramic Society of Japan 2010;118:909-915.
[68] Wang Y, Yang Y, Wang ZL. Triboelectric nanogenerators as flexible power sources. Nature Partner Journals Flexible Electronics 2017;1(1):10.
[69] Zhou D, Xue L, Wang L, Wang N, Lau W, Cao Z. Self-chargeable sodium-ion battery for soft electronics. Nano Energy 2019;61:435-441.
[70] Osorio de la Rosa E, Vázquez Castillo J, Carmona Campos M, Barbosa Pool GR, Becerra Nuñez G, Castillo Atoche A, Ortegón Aguilar J. Plant Microbial Fuel Cells Based Energy Harvester System for Self-powered IoT Applications. Sensors 2019;19(6):1378.

[71] Chaturvedi, Venkatesh & Verma, Pradeep. Microbial fuel cell: A green approach for the utilization of waste for the generation of bioelectricity. Bioresources and Bioprocessing 2016;3.

[72] Chouler J, Cruz-Izquierdo A, Rengaraj S, Scott J, Lorenzo M. A screen-printed paper microbial fuel cell biosensor for detection of toxic compounds in water. Biosensors and Bioelectronics 2018; 102:49-56.

[73] Kenneth S, Thorne RJ, Cameron PJ. An investigation of anode and cathode materials in photomicrobial fuel cells Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 2016;374.

[74] Roy S, Rahman A, Helal M, Kaiser S, Chowdhury Z. Low cost RF based online patient monitoring using web and mobile applications. Conference: 2016 International Conference on Informatics, Electronics and Vision (ICIEV) 2016:869-874.

[75] Nguyen T, Martin V, Malmquist A, Silva C. A review on technology maturity of small-scale energy storage technologies. Renewable Energy and Environment Sustainability 2017;2:36.

[76] Sambaiah K, Jayabarathi T. Loss minimization techniques for optimal operation and planning of distribution systems: A review of different methodologies. International Transactions on Electrical Energy Systems 2020;30:e12230.

[77] Neelima S, Subramanyam P. Optimal Capacitor Placement in Distribution Networks Using Genetic Algorithm: A Dimension Reducing Approach for Different Load Levels. Journal of Theoretical and Applied Information Technology 2012.

[78] Novakovic B, Nasiri A. Introduction to electrical energy systems. In: Rashid MH, editor. Electric renewable energy systems. Academic Press; 2016, pp 1–20.

[79] Gustavsson J. Energy Storage Technology Comparison: A knowledge guide to simplify selection of energy storage technology. KTH, School of Industrial Engineering and Management (ITM), Energy Technology 2016.

[80] Huang S, Xianglin Z, Samrat S, Yufeng Z. Challenges and opportunities for supercapacitors. APL Materials 2019;7(10):100901.

[81] Kokkotis P, Psomopoulos C, Ioannidis GC, Kaminaris SD. Small Scale Energy Storage Systems. A Short Review in their Potential Environmental Impact. Fresenius Environmental Bulletin 2017; 26:5658-5665.

[82] Niu, S., Wang, X., Yi, F., Zhou, Y. Wang, Z. A universal self-charging system driven by random biomechanical energy for sustainable operation of mobile electronics. Nature Communications 2015; 6:8975.

[83] Yun, S., Zhang, Y., Xu, Q., Liu, J., Qin, Y. Recent advance in new-generation integrated devices for energy harvesting and storage. Nano Energy 2019;60:600-619.

[84] Pu X, Li L, Song H, Du C, Zhao Z, Jiang C, Cao G, Hu W, Wang ZL. A Self- Charging Power Unit by Integration of a Textile Triboelectric Nanogenerator and a Flexible Lithium- Ion Battery for Wearable Electronics. Advanced Materials 2015;27:2472-2478.

[85] Nan X, Zhang C, Liu C, Liu M, Wang Z, Cao G. Highly Efficient Storage of Pulse Energy Produced by Triboelectric Nanogenerator in Li3V2(PO4)3/C Cathode Li-Ion Batteries. ACS applied materials & interfaces 2015;8(1):862-870.
[86] Gao T, Zhao K, Liu X, Yang Y. Implanting a solid Li-ion battery into a triboelectric nanogenerator for simultaneously scavenging and storing wind energy. Nano Energy 2017;41:210-216.
[87] Hou HD, Xu QK, Pang YK, Li L, Wang JL, Zhang C, Sun CW. Efficient Storing Energy Harvested by Triboelectric Nanogenerators Using a Safe and Durable All- Solid- State Sodium- Ion Battery. Advanced Science 2017;4(8):1700072.
[88] Abdin Z, Khalilpour KR. Chapter 4 - Single and Polystorage Technologies for Renewable-Based Hybrid Energy Systems. In: Khalilpour KR, editor. Polygeneration with Polystorage for Chemical and Energy Hubs, Academic Press 2019;77-131.
[89] Hesse HC, Schimpe M, Kucevic D, Jossen A. Lithium-Ion Battery Storage for the Grid—A Review of Stationary Battery Storage System Design Tailored for Applications in Modern Power Grids. Energies 2017;10:2107.
[90] Baumann MJ, Peters JF, Weil M, Grunwald A. CO2 Footprint and Life Cycle Costs 693 of Electrochemical Energy Storage for Stationary Grid Applications. Energy Technology 2017;5(7):1071-1083.
[91] Ashwathi A, Brindha M, Esther R, Veena B. Micro Energy Harvesting Using Piezoelectric Material. International Research Journal of Engineering and Technology (IRJET) 2017;4(5):2395-0072.
[92] Bouzelata Y, Kurt E, Uzun, Y, Chenni R. Mitigation of high harmonicity and design of a battery charger for a new piezoelectric wind energy harvester. Sensors and Actuators A: Physical 2018:273:72-83.
[93] Rathod V, Shubhada J, Daundkar N. Mahajan A, Chaple A. Power Generation using Piezoelectric Material. International Research Journal of Engineering and Technology (IRJET) 2018;5(2).
[94] Deng D. Li-ion batteries: basics, progress, and challenges. Energy Science and Engineering 2015;3(5):385-418.
[95] Li Y, Shi R. An intelligent solar energy-harvesting system for wireless sensor networks. EURASIP Journal on Wireless Communications and Networking 2015;179.
[96] Shevtsov S, Chang SH. Modeling of vibration energy harvesting system with power PZT stack loaded on Li-Ion battery. International Journal of Hydrogen Energy 2016;41(29):12618-12625.
[97] Sodano H, Par, G, Leo D, Inman D. Electric power harvesting using piezoelectric materials. Center for Intelligent Material Systems and Structures. Virginia Polytechnic Institute and State University Blacksburg, USA, 2013.
[98] Qazi S. Chapter 2 - Fundamentals of Standalone Photovoltaic Systems, Standalone Photovoltaic (PV) Systems for Disaster Relief and Remote Areas, Elsevier; 2017:31-82.

[99] Akande R, Nechibvute A, Luhanga PVC. Energy harvester device for charging capacitors and low capacity NiMH batteries. Material Science 2010;6(1):0974-7486.
[100] Kundu, D., Talaie, E., Duffort, V., Nazar, L., F. The Emerging Chemistry of Sodium Ion Batteries for Electrochemical Energy Storage. Angewandte Chemie International Edition 2015;54(11):3431-3448.
[101] Ellis, BL, Nazar, LF. Sodium and sodium-ion energy storage batteries. Current Opinion in Solid State and Materials Science 2012;16(4):168-177.
[102] Mahlia T, Saktisahdan T, Jannifar A, Hasan M, Matseelar H. A review of available methods and development on energy storage; technology update. Renewable and Sustainable Energy Reviews 2014; 33:532-545.
[103] Nayak P, Yang L, Brehm W, Adelhelm P. From lithium-ion to sodium-ion batteries: A materials perspective. Angewandte Chemie (International ed. in English) 2017;57:102-120.
[104] Greenwood DM, Sarantakos I, Davison P, Patsios C, Ahmad A, Black M. Enhancing the Understanding of Distribution Network Losses. In: 25th International Conference & Exhibition on Electricity Distribution (CIRED), Madrid, Spain: AIM. 2019.
[105] Zi Y, Wang J, Wang S, Li S, Wen Z, Guo H, Wang Z. Effective energy storage from a triboelectric nanogenerator. Nature Communications 2016;7(1):10987.
[106] Li X, Sun Y. WearETE: A Scalable Wearable E-Textile Triboelectric Energy Harvesting System for Human Motion Scavenging. Sensors 2017;17(11):2649.
[107] Chung J, Yong H, Moon H, Choi S, Bhatia D, Choi D, Kim D, Lee S. Capacitor-Integrated Triboelectric Nanogenerator Based on Metal-Metal Contact for Current Amplification. Advanced Energy Materials 2018:1703024.
[108] Lan G, Ma D, Xu W, Hassan M., Hu W. Capacitor Based Activity Sensing for Kinetic Powered Wearable IoTs. ACM Transactions on Internet of Thing 2018;1(1).
[109] Saeed W, Shoaib N, Cheema HM., Khan MU. RF Energy Harvesting for Ubiquitous, Zero Power Wireless Sensors. International Journal of Antennas and Propagation, 2018:1-16.
[110] Alex-Amor A, Palomares-Caballero Á, Fernández-González JM, Padilla P, Marcos D, Sierra-Castañer M, Esteban J. RF Energy Harvesting System Based on an Archimedean Spiral Antenna for Low-Power Sensor Applications. Sensors 2019;19:1318.
[111] Sung GM, Chung CK, Lai YJ, Syu JY. Small-Area Radiofrequency-Energy-Harvesting Integrated Circuits for Powering Wireless Sensor Networks. Sensors 2019;19:1754.
[112] Yu A, Chen Z, Maric R, Zhang L, Zhang J, Yan, J. Electrochemical supercapacitors for energy storage and delivery: Advanced materials, technologies and applications. Applied Energy 2015;153:1-2.
[113] Bhada- Tata P, Hoornweg DA. What a waste?: A global review of solid state waste management World bank Group, Washington DC, USA. Reports, Case Studies & Assessments, 2012 [accessed 01 March 2020].

[114] Colherinhas G, Malaspina T, Fileti EE. Storing Energy in Biodegradable Electrochemical Supercapacitors. ACS Omega 2018;3:13869-13875.
[115] Gong C, Sun S, Zhang Y, Sun L, Wei G. Hierarchical nanomaterials *via* biomolecular self-assembly and bioinspiration for energy and environmental applications. Nanoscale 2019;11:4147-4182.
[116] Zhang J, Wu X, Gan Z, Zhu X, Jin Y. Unidirectionally aligned diphenylalanine nanotube/microtube arrays with excellent supercapacitive performance. Nano Research 2014;7:929–937.
[117] Xiong W, Guo Q, Guo Z, Li H, Zhao R, Chen Q, Liu Z, Wang X. Atomic layer deposition of nickel carbide for supercapacitors and electrocatalytic hydrogen evolution. Journal of Materials Chemistry 2018;6: 4297-4304.
[118] Xiong W, Guo Z, Li H, Zhao R, Wang X. Rational Bottom-Up Engineering of Electrocatalysts by Atomic Layer Deposition: A Case Study of $Fe_xCo_{1-x}S_y$-Based Catalysts for Electrochemical Hydrogen Evolution. ACS Energy Letter 2017;2:2778-2785.
[119] Li H, Shao Y, Su Y, Gao Y, Wang X. Vapor-Phase Atomic Layer Deposition of Nickel Sulfide and Its Application for Efficient Oxygen-Evolution Electrocatalysis. Chemistry of Materials 2016; 28:1155-1164.
[120] Li H, Gao Y, Shao Y, Su Y, Wang X. Vapor-Phase Atomic Layer Deposition of Co_9S_8 and Its Application for Supercapacitors. Nano Letters 2015;15:6689-6695.
[121] Zhu D, Beeby SP, Tudor MJ, Harris NR. A credit card sized self-powered smart sensor node. Sensors and Actuators A: Physical 2011;169:317-325,
[122] Dubal D, Chodankar N, Kim DH, Gómez-Romero P. Towards flexible solid-state supercapacitors for smart and wearable electronics. Chemical Society Reviews 2018;47:2065-2129.
[123] Li H, Tian C, M, Deng ZD. Energy harvesting from low frequency applications using piezoelectric materials. Applied physics reviews 2014;1(4):041301.
[124] Weiss L, Moore A, Hays A, Eboda F, Borquist E. Operational enhancements for small scale thermal energy storage devices. Microsystem Technologies 2018;24(18):2617-2625.
[125] Yadav C, Sahoo R. Energetic and exergetic investigation on lauric and stearic acid phase- change material–based thermal energy storage system integrated with engine exhaust. Heat Transfer-Asian Research 2019;48(3):1093-1108.
[126] Nakagawa K, Suzuki T. A High-efficiency Thermoelectric Module with Phase Change Material for IoT Power Supply. Procedia Engineering 2016;168:1630-1633.
[127] Nakagawa Kan, Suzuki TA. Highly Efficient Thermoelectric Module with Heat Storage Utilizing Sensible Heat for IoT Power Supply. Journal of Electronic Materials 2018;48:1939-1950.
[128] Allahbakhsh A, Arjmand M. Graphene-based phase change composites for energy harvesting and storage: State of the art and future prospects. Carbon 2019;148:441-480.
[129] Energy Storage Association. Why Energy Storage Technologies. https://energystorage.org/why-energy-storage/technologies/mechanical-energy-storage/; 2020 [accessed 1 May 2020].

[130] Amiryar ME, Pullen KR. A Review of Flywheel Energy Storage System Technologies and Their Applications. Applied Science 2017;7:286.
[131] Chen L, Zheng T, Mei S. Xue X, Liu B, Lu Q. Review and prospect of compressed air energy storage system. Journal of Modern Power Systems and Clean Energy 2016;4; 529–541.
[132] Venkataramani G, Ramakrishnan E, Sharma MR, Bhaskaran AH, Dash PK, Ramalingam V, Wang J. Experimental investigation on small capacity compressed air energy storage towards efficient utilization of renewable sources. Journal of Energy Storage 2018;20:364-370.
[133] Alami A, Aokal K, Abed J, Alhemyari M. Low pressure, modular compressed air energy storage (CAES) system for wind energy storage applications. Renewable Energy 2017;106;201-211.
[134] Chen S, Arabkoohsar A, Zhu T, Nielse, MP. Development of a micro-compressed air energy storage system model based on experiments. Energy 2020;197:117152.
[135] Song Y, Cheng X, Chen H, Huang J, Chen X, Han M, Su Z, Meng B, Song Z, Zhang HX. Integrated Self-Charging Power Unit with Flexible Supercapacitor and Triboelectric Nanogenerator. Journal of Materials Chemistry A 2016;4:14298-14306.
[136] Gallo AB, Simões-Moreira JR, Costa HKM, Santos MM, Moutinho Dos Santos E. Energy storage in the energy transition context: A technology review. Renewable and Sustainable Energy Reviews 2016;65:800-822.
[137] World Energy Resources, World Energy Council, London, Full Report. https://www.worldenergy.org/assets/images/imported/2016/10/World-Energy-Resources-Full-report-2016.10.03.pdf; 2016. [assessed on 01 April 2020].
[138] Díaz-González F, Sumper A, Gomis-Bellmunt O, Villafáfila-Robles R. A review of energy storage technologies for wind power applications. Renewable and Sustainable Energy Reviews 2012;16:2154-2171.
[139] Lourenssen K, Williams J, Ahmadpour F, Clemmer R, Tasnim S. Vanadium redox flow batteries: A comprehensive review. Journal of Energy Storage 2019;25:100844.
[140] Maya GJ, Davidson A, Monahov B. Lead batteries for utility energy storage: a review. Journal of Energy Storage 2018;15:145-157.
[141] Lang X, Li Y, Ca, K, Li L, Zhang Q, Wu H. Preparation of bipolar lead-carbon electrode and study on its electrochemical performance. International Journal of Ionics The Science and Technology of Ionic Motion 2018:935–941.
[142] Swarnakar A, Choubey S. Hazardous chemical present in Batteries and their impact on Environment and Humans. In: Conference, Raipur 2014.
[143] Young KH, Yasuoka S. Capacity Degradation Mechanisms in Nickel/Metal Hydride Batteries. Batteries 2016;2(1):3.
[144] Gao DW. Energy Storage for Sustainable Microgrid, Academic Press: 2015, p. 152.
[145] Vaalma C, Buchholz D, Weil M, Passerini S. A cost and resource analysis of sodium-ion batteries. Nature Reviews Materials 2018;3(4):18013.

[146] Tatsidjodoung P, Le Pierrès N, Luo L. A review of potential materials for thermal energy storage in building applications. Renewable and Sustainable Energy Reviews 2013;18:327–349.
[147] Agyenim F, Hewitt N, Eames P, Smyth M. A review of materials, heat transfer and phase change problem formulation for latent heat thermal energy storage systems (LHTESS). Renewable and Sustainable Energy Reviews 2010;14:615–628.
[148] Leffler O, Mansour N, Energy Storage – A Global Overview and Technological Comparison, Bachelor thesis, KTH School of Industrial Engineering and Management 2016.
[149] Kousksou T, Bruel P, Jamil A, El Rhafiki T, Zeraouli Y, Energy storage: Applications and challenges. Solar Energy Materials and Solar Cells 2014;120(Part A):59–80.