Applications of Sustainable Hybrid Energy Harvesting

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Contributor: Hamna Shaukat , Ahsan Ali , Shaukat Ali , Wael A. Altabey , Mohammad Noori , Sallam A. Kouritem

The potential usage of self-powered wireless sensor (WSN) systems has drawn a lot of attention to sustainable energy harvesting. Hybrid energy harvesting involves collecting energy from multiple sources and converting it into electrical energy using various transduction mechanisms. By properly integrating different energy conversion technologies, hybridization can significantly increase power outputs and improve space utilization efficiency.

energy harvesting | hybrid energy harvesters | sustainable energy harvesting | energy conversion

1. Introduction

Using sustainable/renewable energy sources, such as light, wind, heat, waves, rotation, or vibration, becomes a viable and effective solution to the world's energy crisis [1][2][3][4]. Environmental energy-harvesting methods have been the subject of numerous studies and efforts over the past years. These energy sources provide electricity for household and industrial use, thus addressing local power shortages. Because of the challenge of connecting electrical cables with various sensors, powering wireless sensor node systems is a concern [5][6][7]. However, a source of power without the self-powering ability limits the sustainable functioning of wireless sensor systems. It creates difficulties for the users due to the low capacity of batteries [8][9][10]. Although the operating times of wireless sensor systems can be increased by using an ultralow power system and a high-capacity battery, they cannot ensure the system will run without interruption for a long period of time [11]. Thus, one of the innovative aspects proposed for a sustainable future society is an energy-harvesting system which transforms waste environmental energy into electrical energy [12][13][14]. Such energy harvesters provide sustainable power solutions by collecting ambient sustainable/renewable energy sources and converting them into electrical energy using a variety of transduction mechanisms [10][15][16][17], including thermoelectric, photovoltaic, pyroelectric, electromagnetic, piezoelectric, triboelectric, and other mechanisms. The development of self-charging electronics and self-powering wireless sensor systems has gained considerable interest in research on sustainable and renewable energy harvesters [18][19][20][21].

There are always both artificial and natural energies present, including wind, solar, wave, machine vibration, heat, and automobile noise energies. As a result, solar, thermal, and mechanical energy-harvesting devices can coexist and continuously produce energy, as illustrated in **Figure 1** [22]. To date, energy harvesters have typically been made to utilize a single source of energy. For example, photovoltaic harvesters were created to harvest light energy; to harvest thermal gradients, pyroelectric and thermoelectric harvesters were specifically created; and for harvesting kinetic energy, piezoelectric, triboelectric, electrostatic, and electromagnetic harvesters are especially helpful. A single energy harvester cannot always meet the power needs of electronic devices because its energy generation depends on the accessibility of the energy source. The environment is filled with kinetic energy from human activities, wind flows, structural and machine vibration, water waves, etc. Yet, because humans require rest, wind or water waves might not always be always present, and a machine might not run continuously, kinetic energy might be insufficient and fluctuating. Kinetic energy harvesters will not work in these situations. Thermal energy harvesters would likewise experience similar circumstances when dealing with unpredictably changing temperature gradients. Hybrid energy harvesting is gaining popularity as a response to the problem of energy deficiency among single energy harvesters.

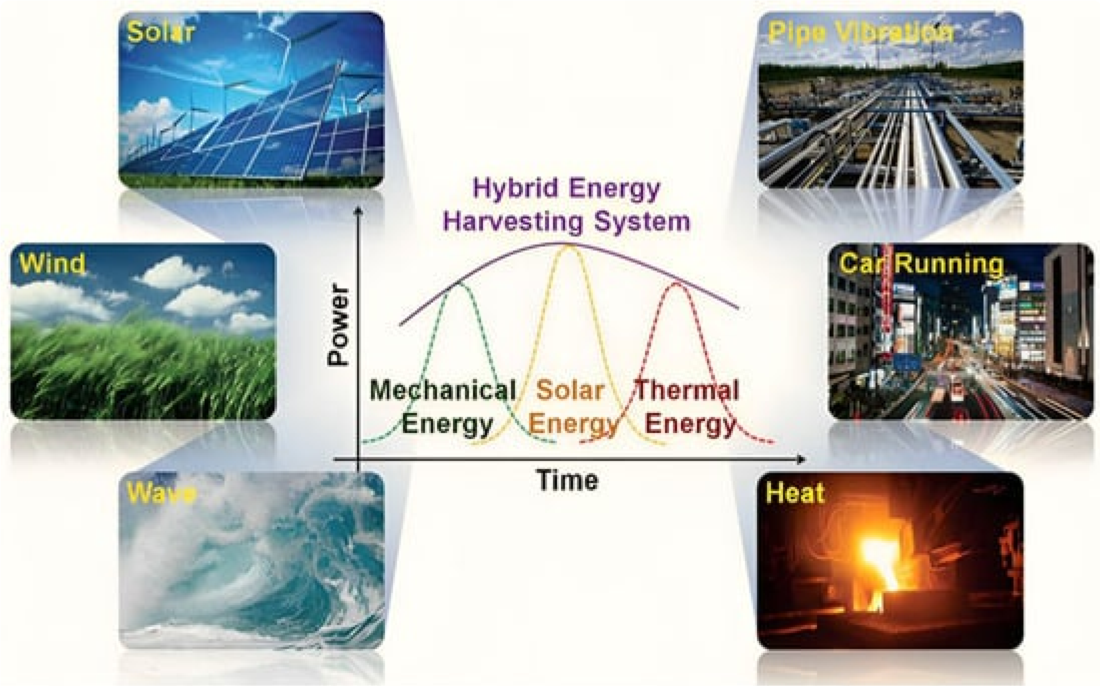

Figure 1. Diagram of a hybrid energy harvesting that uses both artificial and natural energies [22].

Research on hybrid energy harvesters has experienced a tremendous increase in recent years, which has resulted in significant developments in the field. A critical analysis of the existing literature identifies several trends and patterns that help to explain hybrid energy harvesting and its uses. To increase power output and boost energy efficiency, numerous studies have concentrated on investigating various combinations of sources of energy and transduction mechanisms. For instance, studies have demonstrated the advantages of integrating electromagnetic and piezoelectric energy harvesters along with the synergistic effects attained by combining electromagnetic, triboelectric, and piezoelectric energy harvesters. Comparing these hybrid systems to single-source energy harvesters, they have shown to be more capable of producing power. In addition, a deeper examination of the literature reveals the gaps and significant areas for hybrid energy harvesting.

Additionally, a comparison of the existing studies demonstrated variability in the efficiency, reliability, and performance of various hybrid energy-harvesting systems. These differences result from the use of differed materials, configurations, design, optimization techniques and energy management approaches. The elements that lead to greater performance and efficiency can be easily identified by critically analyzing and comparing these studies, thereby paving the path for further advances in hybrid energy-harvesting systems. Although hybrid energy-harvesting research has advanced significantly, there are still possibilities to expand the understanding of its uses and fill the existing gaps. Yet, this cutting-edge technology still has several significant gaps. First, maintaining compatibility and seamless integration between the various energy sources is a challenging task that calls for advanced power control and management systems.

2. Hybrid Energy Harvesting

Hybrid energy harvesting integrates multiple energy conversion mechanisms into one design. The hybrid energy harvesters show the integration of different harvester types to achieve synergistic effects that enhance the overall energy output. They are not just a simple combination but are designed for optimal interaction between the integrated components. The integration aims to capitalize on coupling effects during operation, thereby significantly boosting the energy output. It is essential to carefully design these systems to remove any negative impacts or interference that might potentially reduce the overall energy-harvesting efficiency. Due to the coupling effect and high performance of the hybrid energy-harvesting systems, they have drawn considerable attention as a potential candidate for sustainable/renewable energy harvesting. Examples of hybrid energy harvesters (HEHs) include a combination of mechanical and photovoltaic energy harvesters [23][24][25][26][27][28], mechanical and thermal energy harvesters [29][30][31][32][33], thermal and photovoltaic energy harvesters [34][35][36], and combinations of other energy harvesters [37][38][39][40][41].

2.1. Piezoelectric–Electromagnetic Hybrid Energy Harvesters

Piezoelectric and electromagnetic processes are frequently utilized to produce electricity from kinetic energy. These processes are integrated in the HEHs to increase the system power density and the potential to generate more energy [42][43][44][45][46][47][48][49][50]. One of the goals of these solutions is to improve the electrical dampening and match it with the mechanical one to increase the efficiency of energy conversion in the HESs. Xia et al. created a novel approach for the piezoelectric–electromagnetic (PE-EM) harvesters by altering the axial magnetic force, as illustrated in **Figure 2**a [51]. The results showed a broad operating frequency range of about 25.5–62 Hz. In response to this, in the cantilever harvester, Xu et al. [52] added another magnetic oscillator in between the coils and tip magnet, as shown in **Figure 2**b. Power control circuits are a challenge for hybrid energy harvesting. Output in the form of alternating currents is common for the harvesters utilizing piezoelectric and electromagnetic technologies. It is necessary to convert this alternating current into a more stable form through rectification, storing the energy and stabilizing the voltage to accumulate the charges collected in a single storage unit. Piezoelectric energy harvesters (PEHs) often have high output impedance due to their low capacitance and operating frequency. Conversely, the electromagnetic harvester yields high output current and low voltage due to its lower impedance in the coil. The distinct variations in output characteristics between PEHs and electromagnetic energy harvesters pose considerable challenges when designing an effective interface for hybrid harvesters. A practical approach involves designing separate rectification and storage components for piezoelectric and electromagnetic harvesters and operating them concurrently, as illustrated in **Figure 2**c [53].

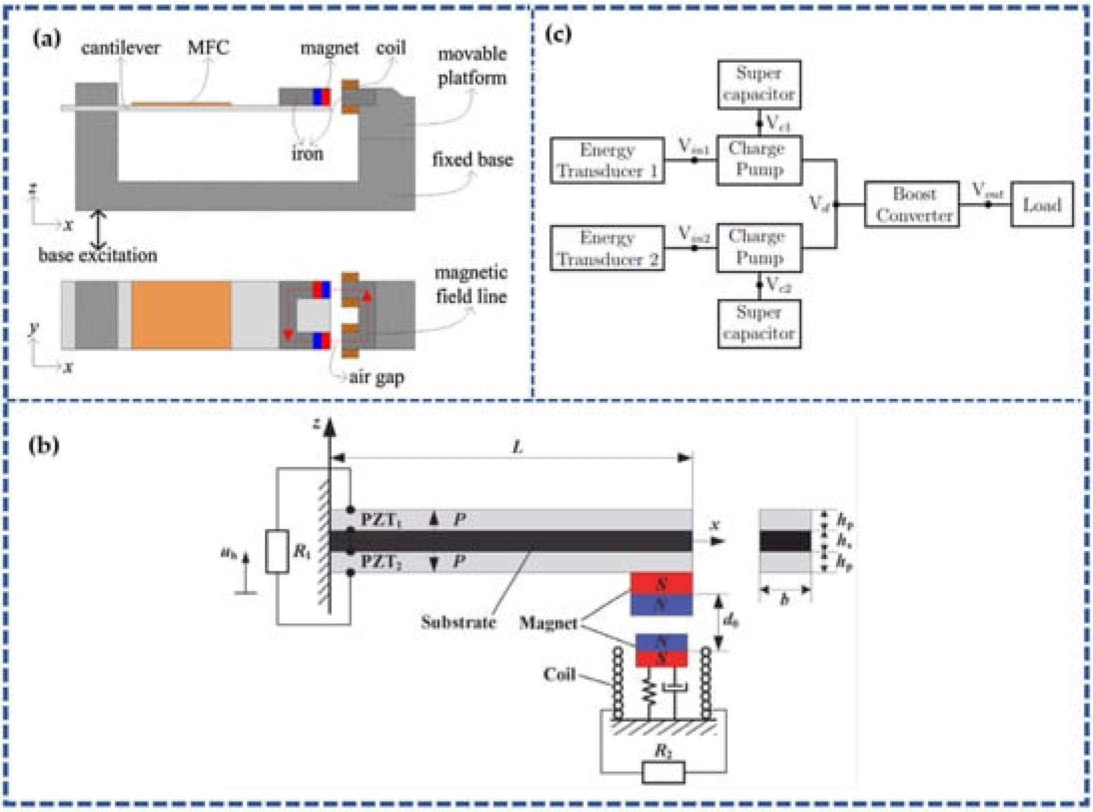

Figure 2. Schematic diagram of PE-EM hybrid energy harvester proposed by (**a**) Xia et al. [51]; (**b**) Xu et al. [52]; (**c**) proposed power management circuit for controlling power in hybrid PE-EM systems [53].

2.2. Piezoelectric–Triboelectric Hybrid Energy Harvesters

The piezoelectric effect and the triboelectric effect are mechanisms for converting mechanical energy into electrical energy through the fundamental concept of displacement current. When two triboelectric materials come into contact or separate from one another under the influence of an external force, electrons are transferred, and the triboelectric nanogenerator (TENG) creates a potential difference over the surfaces of the materials due to the flow of current. In contrast, the piezoelectric energy harvester creates an internal electrical potential across the piezoelectric material. When a stress is applied on the piezoelectric material, this stress causes a displacement of electric charges within a material, resulting in an electrical potential and subsequent electrical current. Hence, these two effects exhibit certain similar operational properties in responding to mechanical vibration, compression, and deflection, which may be further incorporated as the hybrid energy-harvesting system for increasing the energy output. Recent revolutionary studies have demonstrated that piezoelectric and triboelectric phenomena can coexist in a particular function material and interact, opening a new path to improve the performance of hybrid piezoelectric–triboelectric (PE-TE) devices.

2.3. Electromagnetic–Triboelectric Hybrid Energy Harvesters

To benefit from electromagnetic and triboelectric energy harvesters, several researchers tried to integrate TENG and electromagnetic energy harvesters (EMEHs) into one hybrid device. The EMEH and TENG, however, are unable to effectively exchange power processing circuits. To harvest wind energy, Wang et al. [54] created a hybrid wind energy harvester that combines both EMEH and TENG. When the central oscillating FEP film is oscillating vertically by the wind flow, it contacts both the upper and lower electrodes, causing an electron flow in the TENG component. Additionally, the varying distance between the oscillating magnets on the central film and coils on the upper and lower bases enables the EMEH component to produce output voltage or current simultaneously. A water wave energy-harvesting system comprising the EMEH and TENG components was proposed by Wang et al. [55]. A series of aluminum (Al) rolling rods and polytetrafluoroethylene (PTFE) film covered with the copper inter-digital electrodes make up the TENG component. Four steel rods were placed between the top and bottom magnet arrays in the EMEH component to direct the copper coil motion. The hybrid generator simultaneously enables a simultaneous increase in the operating frequency range and maximizes the energy conversion efficiency at a low frequency below 1.8 Hz.

2.4. Piezoelectric–Electromagnetic–Triboelectric Hybrid Energy Harvesters

Researchers are looking at the possibilities of triple hybrid energy-harvesting technologies based on dual hybrid systems combining PE-TE, EM-TE, and PE-EM mechanisms. Combining the piezoelectric–electromagnetic–triboelectric (PE-EM-TE) harvesting systems into one device may be a potential way to further enhance the output performance. A hybridized PE-EM-TE generator using a central magnet floating structure with increased vibrational sensitivity was described by et al. [56]. The peak power (below 20 Hz), produced by the bottom EMEH was 38 mW, and that from the top EMEH was 36 mW. The peak power produced by the bottom PEH was 105 mW and that from the top PEH was 122 mW. Compared with these components, TENG produced a negligible peak power of about 78 μW.

2.5. Various Hybrid Energy-Harvesting Systems

In most situations, energy sources like heat, vibrations, and light coexist; however, some of these may only be partially accessible or available. Consider humans as an illustrative example. People will move a lot when they are traveling or exercising but not much when they are at rest. An alternative would be to use other sources of energy, such as light or thermal energy. Hence, researchers are looking into hybrid energy-harvesting methods that combine different sources of energy into one device to provide a resilient and sustainable power supply [57][58][59]. To harvest different sources of energy, Gambier et al. created an HEH comprising layers of flexible solar panels, thin film batteries, a thermoelectric generator and piezoceramic [60]. A combined power management circuit-equipped hybrid harvester from thermal and indoor light energy was presented by Tan and Panda [57].

A PE-EM hybrid energy harvester combines high energy conversion efficiency by capturing both mechanical vibrations and electromagnetic induction, but there are design complexities and challenges in power management. PE-TE offers versatility by harvesting energy from two different sources. However, it faces challenges related to material compatibility and potential losses due to friction. EM-TE is prone to mechanical wear and tear due to its operating mechanism. PE-EM-TE has superior energy-harvesting capabilities through multiple mechanisms, yet the design complexity and system optimization present significant drawbacks.

3. Applications of Sustainable Hybrid Energy Harvesting

3.1. Smart Transportation

The latest trends in transportation, particularly in the automobile sector, are automated vehicles and electrification. To meet the demands of digitalization and automation, electronics and sensors will be incorporated into the structures on a significantly bigger scale. A more reliable and effective power supply can be achieved by utilizing various forms of energy sources. Many different energy sources can be used to power vehicles, including trains, cars, ferries, airplanes, and buses. Utilizing integrated multi-mode vibrations and mechanical non-linearity, a broadband vibration-based energy harvester was designed for the self-powered monitoring systems of the underground trains by Fu et al. [61]. The idea of harnessing wind energy through the aerodynamic losses on the highways has been covered by numerous recent patents globally [62]. The GPS and accelerometer are the main signal sources in the current systems, which quickly consume the device's battery [63]. Hybrid energy-harvesting technologies may be capable of providing transportation vehicles with self-powered sensing capabilities for event detection and condition monitoring.

3.2. Infrastructure Health Monitoring

There is widespread agreement regarding the significance of managing and monitoring the condition of civil infrastructures, such as water management, power and communication infrastructure, roads, buildings, bridges, railways, tunnels, environmental monitoring, and agricultural facilities. Energy harvesting is the potential method that helps to generate clean, renewable energy and increase the sustainability of infrastructures. An energy generator, storage device, and electrical circuit are the three main parts of energy-harvesting systems. The energy generator transforms thermal, mechanical, and solar energy from the environment into electrical energy. The resulting voltage is then increased and regulated by the electrical circuit to assist in making it suitable for a variety of applications. The energy that has been captured is then saved for subsequent use in supercapacitors or rechargeable batteries. The amount of energy produced by an energy-harvesting system might vary greatly depending upon the principle underlying the harvesting technology used. The amount of energy produced overall depends on various factors, including the availability and intensity of the environmental energy source and the effectiveness of the conversion process. By using HEHs, it significantly increases the output performance by converting the mechanical energy into electrical using multiple transduction mechanisms [64]. To monitor the health of an infrastructure, a high proportion of WSNs are arranged, which enables continuous detection that may eventually save lives as well as minimize downtime and economic losses. As the infrastructural systems are generally located outdoors, a variety of renewable energy sources, including solar, wind, rain, and radio-frequency energy, are readily available instead of traditional batteries and wire power supplies.

3.3. Marine Monitoring and Development

Different countries and research groups are paying more attention to marine monitoring and development. The power supply, and more particularly the carrying battery's capacity, has a significant role in limiting the functional life of the marine equipment. It has been recognized that the ocean contains a significant quantity of renewable energy, including wind energy, solar energy, water wave energy, tidal energy, temperature gradient energy, salinity gradient energy, and water flow energy [65][66]. The blue-energy-harvesting technique that is based on the different transduction mechanisms has drawn the attention of many researchers in recent years. These methods were discovered to be a potential source for self-charging batteries or self-powered sensors in marine monitoring and development systems [67][68]. For the sustainable growth of society, blue energy, which is obtained from the ocean waves, is a significant and promising renewable energy source. Both TENGs and EMGs are recognized as potential methods for harnessing blue energy.

3.4. Human Healthcare Monitoring

The advancement of implantable and wearable electronic devices can help professionals intervene in chronic illnesses as soon as possible. The sustainable supply of power is one of the major constraints. A human body may have a variety of energy sources available, such as muscle contraction, human motion, body heat, cardiac and lung motions, blood pulsation, etc. Several energy-harvesting designs have been proposed for replenishing batteries and ultimately developing self-powered implantable or wearable electronic devices to harvest the human body energies [69][70][71][72]. Zhu et al. [73] developed self-functional socks that provide self-powered monitoring and the sensing of different physiological signals, like contact force, sweat level gait, etc. They did this by utilizing the hybrid PE-TE energy harvester phenomena from human walking. With a frequency of 2 Hz and a load resistance of 59.7 MΩ, an output power of 1.71 mW is obtained. All the described conversion methods have advantages at various sources or areas of the human body. For instance, the mechanical energy that is provided by the footsteps is considerable, making this suitable for TE and EM [74][75][76]. For applications involving the upper body and the skin, TEG and PV would be preferable [77][78][79]. However, the sources of energy from the human body generally occur in low-frequency or low-grade and in random form compared to the other applications. Designing efficient strategies to provide enough energy for monitoring and sensing in a limited environment is more challenging. Hybrid systems that use a variety of energy sources or conversion mechanisms could offer a way to address this challenge. Due to the ability to produce a huge amount of data that is important for healthcare, the impact of PE-TE hybrid nanogenerators (HBNGs) has recently come under study. This PE-TE HBNG measures the changes and diverse movements in the human body, including respiration, muscular contractions, and blood circulation. They can be used in various healthcare settings to power non-invasive sensors, enabling continuous patient monitoring without limiting the patient's comfort or range of motion.

3.5. Aerospace Engineering

To improve passenger safety, decrease operational downtime, and save maintenance costs, it is essential to continuously monitor the operational conditions and structural integrity of spacecraft and aircraft [80][81]. For those distributed WSNs monitoring the operating condition, energy harvesting could offer reliable energy sources. Many energy sources are also available in spacecraft and aircraft, particularly vibration, temperature difference, and solar. A thorough analysis of the technology and energy sources for energy harvesting in aerospace applications is provided by Le et al. with a focus on thermal and vibration sources [82]. The main cause of interior vibration is the propulsion system. In both the propeller-driven aircraft and the helicopters, the amplitude and frequency range are greatly affected by the blade passage frequency and rotor speed. Common jet engine vibrations seem to have a frequency range of about 20–500 Hz. Engines, gear trains, and hydraulic systems all produce heat when used as a thermal source. Another way sensors located on the fuselage might be energized is by the temperature gradient between the fuselage and the cabin. Using the temperature gradient in the fuselage, Kiziroglou et al. developed a temperature gradient for a TEG utilizing the heat mass [83].

3.6. Industry Condition Monitoring

It is widely acknowledged that condition monitoring is essential for modern manufacturing and production processes particularly for smart industries (Industry 4.0; fourth technological revolution in the future). Since companies and industries cannot afford any unplanned downtime due to equipment failure; vibration, voltage, temperature, current, and other machine data are all fed to condition monitoring systems, which enables the early detection and evaluation of machine and system faults in real time. In addition, these equipment condition insights enhance productivity, expediting the transformation toward Industry 4.0. WSNs are suitable for implementing real-time condition monitoring because of their low power requirements and high flexibility. To supply power to sensor nodes, hybrid energy-harvesting systems gather unused energy through machines or the surrounding environment, minimizing the high cost and process of recharging or changing the batteries, particularly in remote or unreachable conditions [84].

3.7. Water Purification

The potential of hybrid energy-harvesting systems to address the issue of obtaining reliable sources of energy for water purification has also attracted attention. Researchers are investigating how to sustain point-of-use (POU) water treatment technology using various energy sources like solar, thermal, and mechanical energy. Hybrid energy harvesters provide a constant and sustainable energy supply for water purification by integrating various energy conversion approaches. Various hybrid energy harvesters have been investigated for the water purification system: these are solar and triboelectric, solar, and piezoelectric, thermal-induced triboelectric, thermal-assisted piezoelectric, and thermal and photovoltaic hybrid energy harvesters. These hybrid energy harvesters have the potential to effectively harvest many energy sources simultaneously, making them reliable, affordable, and energy-efficient water-purifying solutions. They offer self-powered disinfection of microorganisms and degradation of pollutants, facilitating the purity of drinking water in areas with minimal access to electricity and sanitary facilities. Hybrid energy harvesters that are used for water purification become even more crucial during time of worldwide epidemics like COVID-19. To ensure continuous operation, hybrid energy harvesters, which combine solar and other energy sources, can efficiently harvest solar energy during the day and convert it to piezoelectric or triboelectric energy harvesting in changeable weather conditions or at night. The use of hybrid energy-harvesting devices for water purification presents a promising option for self-sufficient, sustainable water treatment.

4. Challenges of Hybrid Energy Harvesters

The effective utilization of different energy sources within a single device offers a chance to sustain the power provision durability. Researchers have diligently explored this approach across various applications and energy sources. However, the integration of a hybrid energy-harvesting system presents different challenges as well that need to be addressed. The foremost challenge revolves around optimizing the synergy among various conversion mechanisms to enhance the overall system efficiency while maintaining a compact design. Additionally, the creation of power management circuits capable of efficiently handling the varied types of generated power is crucial.

As the research on the hybrid energy harvester is still early, conducting quantitative analyses or directly comparing various solutions proves challenging. PE-EM hybrid energy harvesters are primarily designed for vibration energy harvesting. However, there are some instances where they are utilized for harvesting human motion [85][86], airflow [87][88], and acoustic energy sources. On the other hand, PE-TE hybrid systems involving applying external forces to deformable laminated structures, achieving deformation of the piezoelectric material (e.g., PVDF) and contact-separation of the triboelectric materials (e.g., Al, Au, Cu, PDMS, PTFE) [89]. The piezoelectric part generally yields higher output power than the triboelectric part with the same dimensional area, while the triboelectric part primarily contributes to higher output voltage. Some studies have achieved the PE-TE dual effect through composite material synthesis like PDMS mixed with piezoelectric nanoparticles or nanofibers [90]. In triple-hybrid energy-harvesting systems, the output power is typically mainly contributed by one or two energy conversion effects. This suggests that certain energy conversion effects may not provide sufficient energy to the hybrid device but could enhance the capacitor charging efficiency or act as a self-powered sensing unit. Attaining significant energy contribution from three types of energy conversion effects in one hybrid energy-harvesting system remains challenging.

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