



Review

Evolution of Micro-Nano Energy Harvesting Technology—Scavenging Energy from Diverse Sources towards Self-Sustained Micro/Nano Systems

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Abstract: Facing the energy consumption of a huge number of distributed wireless Internet of Things (IoT) sensor nodes, scavenging energy from the ambient environment to power these devices is considered to be a promising method. Moreover, abundant energy sources of various types are widely distributed in the surrounding environment, which can be converted into electrical energy by micro-nano energy harvesters based on different mechanisms. In this review paper, we briefly introduce the development of different energy harvesters according to the classification of target energy sources, including microscale and nanoscale energy harvesters for vibrational energy sources, microscale energy harvesters for non-vibrational energy sources, and micro-nano energy harvesters for hybrid energy sources. Furthermore, the current advances and future prospects of the applications of micro-nano energy harvesters in event-based IoT systems and self-sustained systems are discussed.

Keywords: energy harvester; triboelectric; piezoelectric; thermoelectric; pyroelectric; event-based IoT; self-sustained; self-powered



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1. Introduction

The development of the Internet of Things (IoT), together with wireless data transmission techniques, has ushered in the new 5G and big data era, in which portable electronics and wearable electronics are experiencing rapid advancement [1–3]. As a result, the proliferation of distributed IoT sensor nodes, which merge with our body and living environment, are redefining the conventional means by which we engage with the world [4–12]. For example, accelerometers and gyroscopes are integrated into smartphones and watches to provide information related to human motion and healthcare [13–18], tactile and pressure sensors are embedded in gloves, socks and mats to recognize human gestures and motions to build human-machine interfaces [19–25], and humidity and gas sensors are placed both in wearable and portable devices to furnish us with information related to environmental factors and give timely warnings of danger [26–32]. Furthermore, there are microphones for human voice recognition [33–36], to mention just a few.

With the large-scale deployment of distributed IoT sensor nodes, energy supply has become an important issue. Wiring each sensor node individually to an external energy source has proven to be neither feasible nor economical due to the nature of the distributed arrangement and the wireless data transmission of the sensor nodes. For this reason, built-in chemical batteries designed to meet the energy consumption requirements of the IoT sensor nodes is the most commonly used method at present. However, apart from environmental concerns, chemical batteries also have a limited service life. Replacing or recharging chemical batteries for massive sensor nodes frequently will bring great economic costs.

Fortunately, there are various kinds of abundant energy in our surrounding environment, such as human kinetic energy, wind energy, thermal energy, solar energy, etc., which can be converted into electrical energy through electrostatic, electromagnetic, piezoelectric, thermoelectric, pyroelectric, triboelectric, and photovoltaic effects, and their hybrid architectures that work in phases to power the distributed wireless sensor nodes [37–39], as shown in Figure 1. Meanwhile, energy harvesters, as core components that can be integrated into sensor nodes to realize energy conversion, have been a focus of the scientific literature for years [40]. Remarkable advances have been made in improving their energy output in different scenarios. On the one hand, the rapid development of microelectromechanical system (MEMS) technology since the middle of the last century has not only enabled the emergence of a series of miniaturized sensors, which are widely applied in environmental monitoring, healthcare and industrial automation [41–46], etc., but also spawned a batch of miniaturized energy harvesters, such as MEMS electrostatic, electromagnetic, thermoelectric, and piezoelectric energy harvesters [47–51]. These MEMS or microscale energy harvesters have the advantages of small size and the easy mass fabrication and integration into wearable and portable devices. On the other hand, the triboelectric nanogenerator (TENG), as a representative of nanoscale energy harvesters, was first proposed by Prof. Z. L. Wang's group based on contact electrification and electrostatic induction in 2012 [52]. Since then, the study of TENG has garnered considerable attention worldwide, with a multitude of research efforts directed towards various facets of this technology, spanning from energy density, structural advancements, stability, biocompatibility, surface modification, circuitry design, to holistic system integration [53–58]. TENG stands out not only as a promising power supply for wearable and implantable electronic devices through harvesting biomechanical energy, owing to its broad material choices, low cost, simple fabrication process, large output at low frequencies, versatile operation modes, high scalability, and compatibility with wearable and implantable devices, but also as an auxiliary energy unit to increase the energy efficiency in harvesting mechanical energy from various energy sources [59–65]. Although the energy output of micro-nano energy harvesters is not as high as that of traditional large-scale energy harvesters, they are still a promising technology for powering distributed IoT sensor nodes with low power consumption. First, the small size of micro-nano energy harvesters allows them to be directly integrated with IoT sensor nodes. In addition, micro-nano energy harvesters can convert various ambient fragmentary energies into electrical energy to support the operation of IoT sensor nodes. Furthermore, the low fabrication cost of micro-nano energy harvesters enables them to be potentially mass-produced to meet the energy needs of massive IoT sensor nodes [66–69].

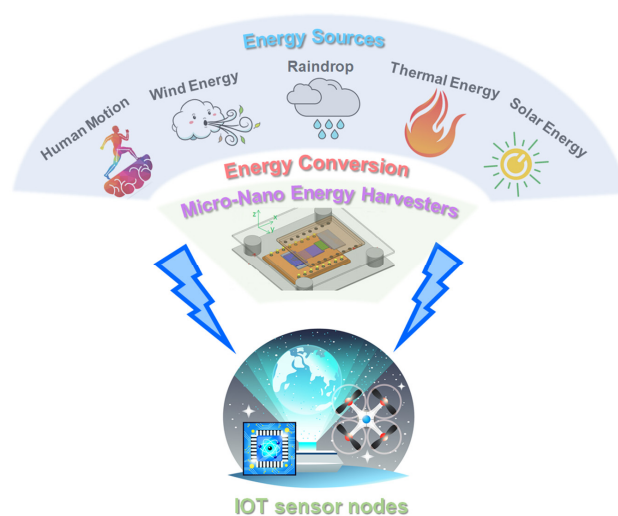


Figure 1. Overview of diverse energy sources which can be harvested to enable self-sustained systems through different energy conversion mechanisms. Reproduced with permission of [70], copyright 2012 IOP Publishing.

In general, micro-nano energy harvesters with different mechanisms and structures are suitable for different types of energy sources. By classifying energy sources into vibrational energy sources, including human kinetic energy and environmental kinetic energy, and non-vibrational energy sources, we will give an overview of the research progress of micro-nano energy harvesters for each of the above-mentioned types of energy sources. This review starts by introducing the vibration-based microscale energy harvesters and nanoscale energy harvesters with different optimization techniques and design considerations. Next, non-vibrational energy source-based micro-nano energy harvesters are presented. Following that, micro-nano energy harvesters with hybrid energy sources are described. Thereafter, the applications of micro-nano energy harvesters in event-based IoT systems and the research status of the self-sustained systems using micro-nano energy harvesters are introduced and discussed. Lastly, we will review the future development trend of the micro-nano energy harvesters.

2. Energy Harvesting from Vibrational Sources

Among diverse energy sources, vibration-type or kinetic energy sources have attracted extensive attention from researchers because of their widespread existence in the environment, and the advantages of easily being captured and converted into electrical energy [71–73]. Vibration-type energy sources usually exist in the form of human kinetic energy, such as daily walking, handshaking and exercise, and kinetic energy in the environment, such as wind energy and mechanical equipment vibration [73–75]. To harvest energy from these vibration sources, various technologies have emerged which can be divided into microscale energy harvesting technologies and nanoscale energy harvesting technologies, according to their feature size [72,76].

2.1. Energy Harvesting from Human Kinetic Energy

2.1.1. Microscale Energy Harvesting Technologies

Microscale energy harvesting technologies refer to these technologies that use microfabrication to prepare energy harvesters to convert vibrational energy into electrical energy [77–79]. These energy harvesters possess the advantages of small size and low cost, making them ideal candidates for mass fabrication and integration into various wearable devices, in order to harvest human kinetic energy to provide an energy supply [80,81]. Electrostatic [82], electromagnetic [83,84], and piezoelectric [85,86] effects are the three main mechanisms adopted by these microscale energy harvesters to realize energy conversion. Among them, electrostatic energy harvesters are the most competitive in terms of their energy density and compatibility with IC. Figure 2a shows a typical parallel-plate-type electrostatic energy harvester developed by Guo et al. [87]. Two capacitor electrode plates are arranged in parallel and are biased by an external voltage source, and one of the electrode plates is suspended to act as a proof mass simultaneously. When there is ambient vibration, the proof mass will vibrate along with the vibration source and change the gap between the two electrode plates, resulting in a variation in capacitance, thereby generating an electric current. To avoid the “pull-in” effect, small stoppers are added to the bottom electrode plate. In addition, a comprehensive model is proposed to optimize the design of the energy harvester, including the stoppers’ height, the two electrode plates’ gap, and the electret layer’s surface potential. Experimental results prove that this model provides a feasible optimization route for the electrostatic energy harvesters, with broad bandwidth, decent power output, and the avoidance of the “pull-in” effect. Except for being arranged in parallel along the vertical direction, the capacitor electrode plates of the electrostatic energy harvesters can also be arranged on the same plane for harvesting the energy of plane vibration. As shown in Figure 2b, Yang et al. presented an in-plane rotary comb-based electrostatic energy harvester [88]. The capacitor electrodes are designed as both fixed combs and movable combs, and arranged rotational overlappingly to collect energy from ambient planar vibrations with arbitrary motion directions, wherein the moveable combs are integrated with the proof mass composed of a center ring mass, a middle grid mass, and

an outer ring frame mass. Meanwhile, the “pull-in” effect between the fixed and moveable combs is prevented by introducing ladder springs and stoppers. During operation, both the gap and overlapping area between the combs change with external vibrations, which increase the electric energy output by the energy harvester to a certain extent. Experimental results reveal that the maximum output power for excitation vibrations of 2.5 g reaches $0.35 \mu\text{W}$ when the loading resistance matched the parasitic, and the energy harvester operates at its resonant frequency. Furthermore, to obtain higher power output under the external vibration of smaller acceleration, the energy harvester is further vacuum packaged to reduce the influence of air damping, and the maximum energy output of $0.39 \mu\text{W}$ at 0.25 g is achieved.

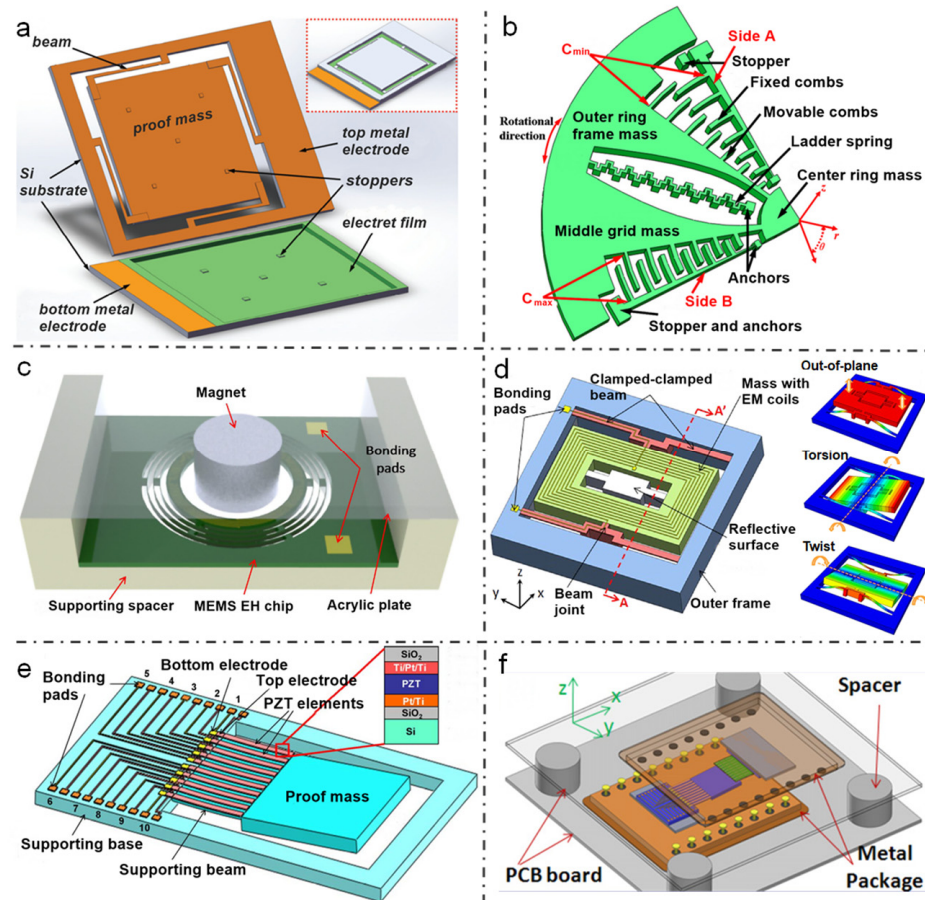


Figure 2. Microscale energy harvesters based on different operational mechanisms. (a) Parallel-plate type electrostatic energy harvester. Reproduced with permission of [87], copyright 2020 Elsevier; (b) In-plane rotary comb type electrostatic energy harvester. Reproduced with permission of [88], copyright IOP 2010 Publishing. (c) Multi-frequency vibration-based electromagnetic energy harvester. Reproduced with permission of [89], copyright 2013 Elsevier. (d) Electromagnetic energy harvester with ultra-wide bandwidth. Reproduced with permission of [90], copyright 2014 AIP Publishing. (e) Wideband piezoelectric energy harvester for low-frequency vibration sources. Reproduced with permission of [91], copyright 2011 IEEE. (f) Impact-based piezoelectric energy harvester with a wide operating bandwidth. Reproduced with permission of [70], copyright 2012 IOP Publishing.

The energy conversion of the electromagnetic energy harvesters relies on electromagnetic induction, which occurs when an electrical conductor cuts through stationary magnetic field lines, or a magnetic field changes. As sketched in Figure 2c, Liu et al. designed and fabricated a multi-frequency vibration-based electromagnetic energy harvester consisting of a fixed cylinder magnet and movable coils integrated into a circular suspension structure [89]. To harvest energy from vibrations with multiple frequencies and directions, the circular suspension structure composed of a circular mass and circular

rings is designed in a more flexible form, which enables the energy harvester to easily operate in multiple vibration modes. In addition, according to the simulation result of the magnetic field of the cylinder magnet, the distance between the magnet and the circular suspension structure is optimized to be zero in order to achieve a larger magnetic flux change and a higher energy output. With an input acceleration of 1 g, the maximum output power densities are 0.157, 0.014 and 0.117 $\mu\text{W}/\text{cm}^3$ when the energy harvester operates at out-of-plane, torsion and in-plane vibration modes, respectively. Traditional linear vibration-based energy harvesters usually possess a narrow operating bandwidth, which makes their output power drop dramatically under off-resonance conditions. To overcome this, Liu et al. further proposed an ultra-wide bandwidth electromagnetic energy harvester by leveraging a hybrid frequency broadening mechanism [90], as shown in Figure 2d. The hybrid frequency broadening behavior is realized both by the duffing stiffening of the clamped-clamped beam and the multi-frequency harvesting mechanism. As observed from the experimental results, the broad operating bandwidth of the energy harvester is from 62.9 Hz to 383.7 Hz, with an input acceleration of 1 g.

Unlike electrostatic and electromagnetic energy harvesters, which use the relative displacement of the built-in structure to achieve energy conversion, piezoelectric energy harvesters utilize the strain change of the piezoelectric layer to convert external vibrations into voltage output through the piezoelectric effect, which makes their configurations relatively simple. Figure 2e presents a cantilever-type piezoelectric energy harvester composed of a silicon beam with 10 lead zirconate titanate (PZT) thin film elements parallel-arranged on top and a large silicon-proof mass [91]. To widen the operation frequency bandwidth, the whole energy harvester chip is assembled onto a metal carrier with a limited spacer. Both experimental and simulation results demonstrate that the energy harvester generates the maximum power output when the PZT elements are connected in parallel. Meanwhile, the output power steadily increases from 19.4 nW to 51.3 nW within the operating frequency range from 30 Hz to 47 Hz at 1 g. Similar to other types of energy harvesters, the frequency-widened-bandwidth mechanism is also the research focus of piezoelectric energy harvesters. Figure 2f illustrates another work from Liu et al., an impact-based piezoelectric energy harvester with a wide operating bandwidth [70]. A high-frequency PZT cantilever and a low-frequency PZT cantilever are integrated into the energy harvester and arranged face-to-face above a metal package base with a pre-determined space, where the low-frequency PZT cantilever has an additional proof mass attached to the end. The frequency-widened bandwidth of the energy harvester is induced by two mechanical stoppers, in which the high-frequency cantilever acts as the top stopper, and the metal package base acts as the bottom stopper. When the forced vibrating proof mass impacts with the top and bottom stoppers, the impact will retard the vibration amplitude but broaden the operating frequency bandwidth of the low-frequency PZT cantilever. Meanwhile, the high-frequency PZT cantilever will be excited and oscillated at its higher resonant frequency (a frequency-up-conversion mechanism) due to the impact effect, and the output electric energy together with the low-frequency PZT cantilever.

2.1.2. Nanoscale Energy Harvesting Technologies

Scavenging kinetic energy from human motions is one of the most promising solutions to power wearable sensors. However, the effectiveness and output performance of previously designed microscale energy harvesters has been limited by the low frequency, large deformation, and strain range typically associated with biomechanical energy sources. As a consequence, it has become imperative to develop novel energy harvesting techniques that can overcome these limitations, while also possessing the desirable qualities of wearability, stretchability, durability, washability, and the ability to be mass-produced [92]. In comparison to other energy scavenging devices, nanoscale triboelectric generators (TENG) provide several advantages, such as flexibility in material selection, low cost, ease of fabrication, high output at low frequencies, versatility in operation modes, scalability, as well as compatibility with wearable and implantable electronic devices [93–95]. As depicted

in Figure 3a, Dong et al. introduced an electronically conductive fabric (e-textile) relying on a triboelectric energy harvester incorporating a three-dimensional, five-directional woven (3DB-TENG) architecture [96]. This inventive construction aims to transcend the shortcomings of diminished power output and inferior sensing capacities inherent in existing e-textiles. The 3DB-TENG demonstrates remarkable pliability, form adjustability, structural robustness, repetitive washability, and excellent mechanical durability. The 3DB arrangement enables heightened compression resistance, increased energy generation, refined pressure responsiveness, and a superior vibrational power collection capability. The productivity of the 3DB-TENG was evaluated under a compressive force of 20 N, revealing a relatively constant open-circuit potential, a short-circuit charge exchange (70 V and 25 nC, respectively), and a progressively ascending short-circuit current (from 0.16 to 0.7 μA) as the frequency rose from 1 to 5 Hz. In contrast to earlier triboelectric generator textiles, the 3DB-TENG yields almost twice the electrical output, signifying that the unique 3D interlaced architecture with supplementary contact-separation regions effectively boosts the overall energy generation. Jiang et al. proposed a flexible, washable, and ultra-slim skin-mimicking triboelectric generator (SI-TENG) for capturing human kinetic energy while simultaneously functioning as an extremely sensitive self-sufficient tactile detector (Figure 3b) [97]. The SI-TENG consists of a pliable composite electrode, formed by intertwining silver nanowires (AgNWs) with thermoplastic polyurethane (TPU) nanofiber matrices. The architectural design and material choice have been meticulously refined for extensibility, extreme thinness, and reduced mass, rendering the SI-TENG appropriate for unobtrusive adhesion to the human epidermis. The SI-TENG can attain an open-circuit potential of 95 V, a short-circuit current of 0.3 μA , and an energy concentration of 6 mW m^{-2} . Moreover, the SI-TENG's performance remained unaltered without degradation after 40,000 cycles of tapping experiments, with an applied force of 5 kPa at a frequency of 1 Hz, illustrating its endurance. The SI-TENG offers immense potential for utilization in human-machine communication, safety systems, and next-generation wearable devices, either as an autonomous sensory mechanism or an energy provider. He et al. present a fabric-based triboelectric nanogenerator (TENG) as an optimal approach for collecting low-frequency and irregular surplus energy from bodily movements and for energizing self-reliant systems [98]. They proposed a straightforward and comprehensive tactic to enhance the triboelectric output by integrating a narrow-gap triboelectric generator fabric with a high-voltage diode and a fabric-based switch (Figure 3c). The closed-loop current of the diode-augmented fabric-based triboelectric generator (D-T-TENG) can be magnified 25 times, enabling the direct excitation of rat muscular and neural tissue. The charging circuit of the D-T-TENG has been optimized by incorporating a traditional bulk converter to further accelerate the charging pace. As a result, the D-T-TENG can charge a 27 μF capacitor to 3.8 V after 35 bending cycles at the highest degree, which is nearly five times the charged voltage attained by the solitary T-TENG. Simultaneously, the D-T-TENG has been demonstrated to be a valuable energy source for wearable detectors by powering Bluetooth sensors integrated into garments for humidity and temperature monitoring, which can function for 1 s after each discharge and collect environmental moisture and temperature information. The proposed D-T-TENG presents a promising approach for a self-sustaining wearable textile-based nano-energy nano-system (NENS) for future healthcare applications and wearable sensor networks on everyday attire, as it presents innumerable possibilities for distributed energy sources across the entire body. Yang et al. suggested a rucksack design for capturing wasted energy from human motion based on a triboelectric generator (Figure 3d) [99]. The rucksack was designed with two elastomers that uncouple the motion of the cargo and the human body, reducing the vertical oscillation of the load by 28.75%, and the vertical force on the wearer by 21.08%. Under typical walking conditions, the mechanical-to-electric energy conversion efficiency of the rucksack is calculated to be 14.02%. The electricity generated by the rucksack is extracted through three current channels using a multilayered configuration. The output current theoretically increases with the number of layers, with three layers of interdigital transducer (IDT) electrodes being adopted for optimal carrying comfort and

weight. The generated electricity from the three layers was measured to be 58 μA and 1.3 kV for the top layer, 60 μA and 1.5 kV for the middle layer, and 15 μA and 1.2 kV for the bottom layer. This proposed rucksack design has the potential to be a power source for small-scale wearable and portable electronics, GPS systems, and other self-powered health monitoring sensors, while simultaneously serving as an aid to enable the carrying of heavier loads compared to conventional backpacks.

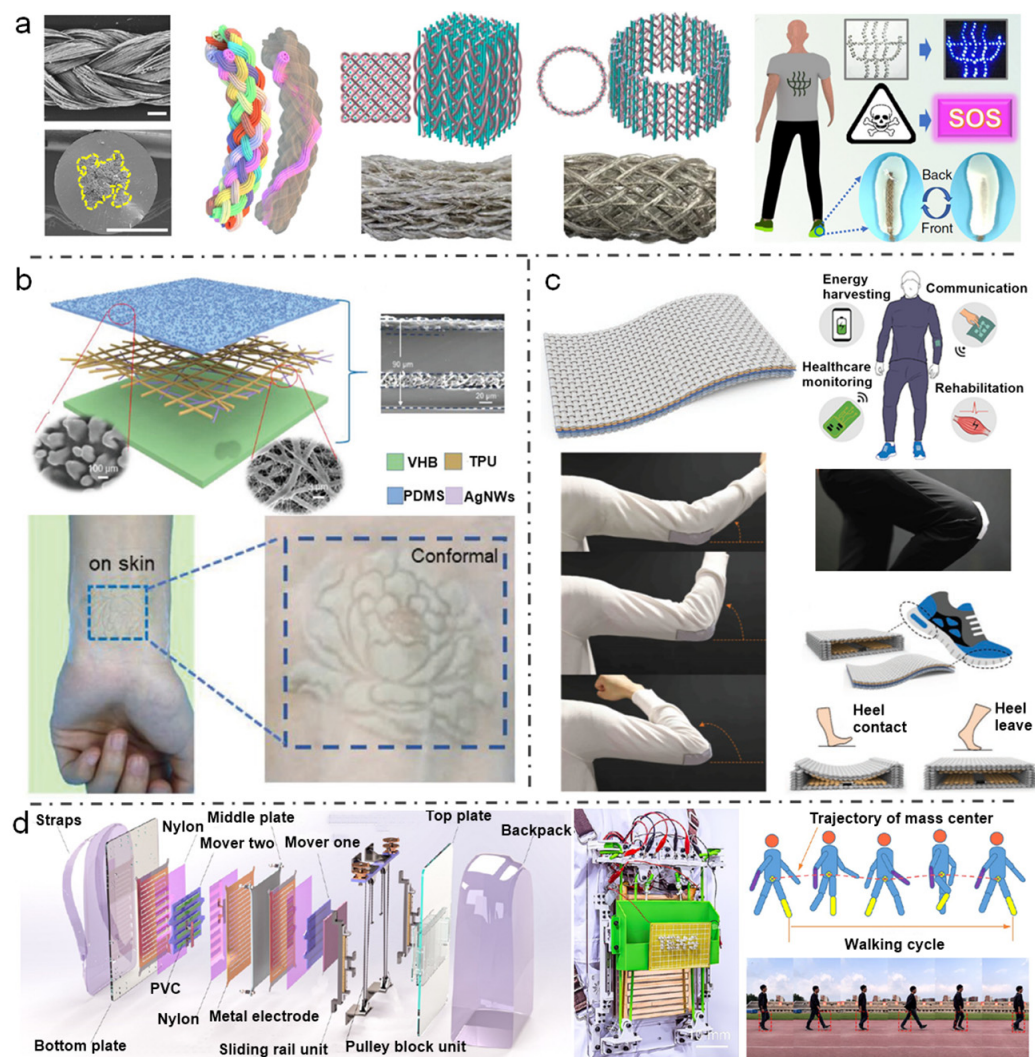


Figure 3. Triboelectric-based biomechanical energy harvesters. (a) Electronic textile-based TENG with a three-dimensional, five-directional braided structure to achieve high output power. Reproduced with permission of [96], copyright 2020 Springer Nature. (b) Stretchable, washable, and ultrathin skin-inspired TENG to harvest human motion energy with tactile sensing capabilities. Reproduced with permission of [97], copyright 2020 John Wiley and Sons. (c) Narrow-gap TENG textile with a high-voltage diode and a textile-based switch for highly efficient biomechanical energy harvesting. Reproduced with permission of [98], copyright 2019 John Wiley and Sons. (d) Backpack designed for the harvesting of wasted energy from human motion based on TENG with kilo-volt output. Reproduced with permission of [99], copyright 2021 American Chemical Society.

2.2. Energy Harvesting from Kinetic Energy in the Environment

Except for the kinetic energy of human motion, there is also abundant kinetic energy in the surrounding environment, which can be harvested by the microscale and nanoscale energy harvesting technologies described above to power autonomous sensors [100–104]. Firstly, the wind is an abundant and often a very convenient source of energy that is

freely available. To efficiently scavenge wind energy, Chen et al. proposed a hybrid piezoelectric and triboelectric-based energy harvester, as illustrated in Figure 4a [105]. A polyethylene terephthalate (PET) flapping blade, a polyvinylidene fluoride (PVDF) cantilever, two outer frames, and friction films of aluminum and polydimethylsiloxane (PDMS) constitute the main structure of the energy harvester. The outer frames that serve as the bluff body are specifically designed in a spindle shape to enhance the vortex shedding effect. When a cut-in wind flows past the spindle-shaped outer frames, vortices will be created above and below the flapping blade, causing the flapping blade to oscillate upward and downward. Correspondingly, the PVDF cantilever connected to the flapping blade will be forced to vibrate and contact the inner surfaces of the two outer frames. During this period, the vibration of the PVDF cantilever will output voltage through the piezoelectric effect of the d_{31} mode. Meanwhile, the contact between the Al films and the pyramid structure PDMS films will also generate voltage due to the triboelectrification effect and electrostatic induction. With optimized load resistances, the maximum power outputs of the piezoelectric and triboelectric parts are recorded as 112 and 76 μW at a wind speed of 10 m/s, respectively. In addition to the direct form of flowing wind, wind energy can also exist in other indirect forms, such as moving tree branches in a forest. Figure 4b shows a novel multilayered cylindrical TENG (MC-TENG) hanging on tree branches, developed by Pang et al., which is designed to harvest the kinetic energy of moving tree branches for powering wireless sensors of a fire alarm system [106]. The proposed MC-TENG mainly consists of two sleeve cylinders, including a top fixed hanging sleeve and a mass block bonded bottom core sleeve, and works in a sliding mode. Furthermore, a highly stretchable rubber band is adopted to connect the top and bottom sleeves to form a spring-mass vibration structure. To realize the contact triboelectrification and electrostatic induction, a thin layer of Cu film is coated on the surface (both the inside and the outside surface) of the two sleeve cylinders to serve as the triboelectric material and the electrode, while a layer of polytetrafluoroethylene (PTFE) is bonded onto the bottom sleeve (surface of Cu electrode layer) to work as the electrification contact material. In the case of increasing the surface charge density of the PTFE film through the corona charging method, the maximum average power of 1.2 mW is achieved by the MC-TENG at a low frequency of 1.25 Hz.

Raindrop energy is another abundant renewable energy in the environment, but there was a lack of effective energy harvesting methods until the emergence of TENGs [107–113]. To deal with the complex structure and low output power density of current droplet-based TENGs (DEGs), Li et al. demonstrated a rain droplet-based electricity generator with a simple open structure (SCE-DEG), mainly an upper electrode, a layer of PTFE film, a lower electrode, and a load, as depicted in Figure 4c [114]. The SCE-DEGs can be arranged and connected in parallel to harvest large-scale raindrop energy in sloping buildings. When dripped water droplets continuously collide with and detach from the PTFE film, a large amount of charge will accumulate on the film surface until it reaches a saturation state, and then an alternating voltage will be outputted from the upper electrode due to the self-capacitance effect. Compared with other DEGs, the simplified SCE-DEG does not need to connect the upper electrode to the lower electrode, which is more convenient for large-scale popularization. Moreover, the SCE-DEG possesses a significantly higher instantaneous peak output power of 765 W/m^2 . Similar to raindrop energy, there is also water wave energy, known as a blue energy, which utilizes water as the energy carrier [115–119]. Based on the liquid-solid contact triboelectric mechanism, Liu et al. introduced a flexible and bendable thin film blue energy harvester, as depicted in Figure 4d [120]. Different from the dielectric electrode TENGs with a single electrode mode, a novel external U structure electrode (including a bar electrode and a U-shape electrode) is designed for the energy harvester to minimize the shielding effect from water, thereby improving the output power. During the interaction with water waves, the dielectric film of the harvester will form an electrical double layer (EDL) and accumulate charges, and the accumulated charges will flow to the external circuit through the designed electrodes.

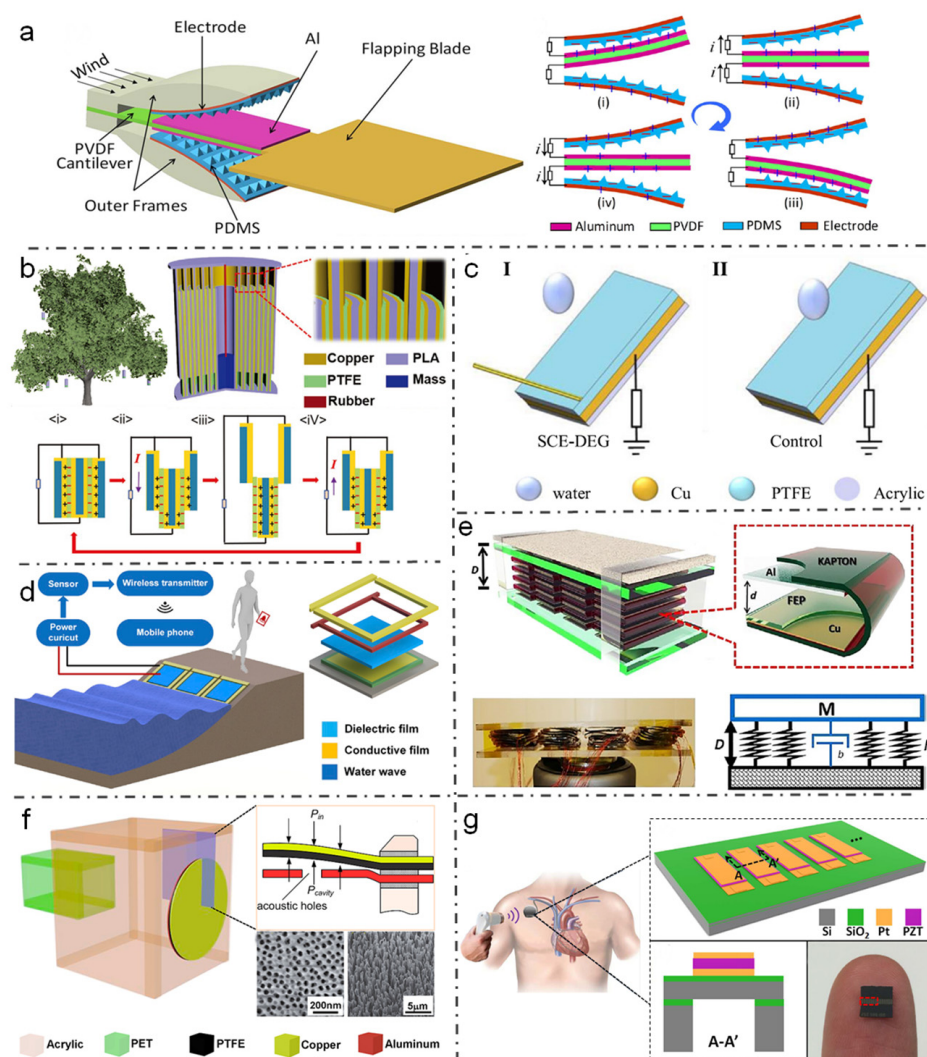


Figure 4. Harvesting environmental kinetic energy with different kinds of energy harvesters. (a) Hybrid flapping-blade wind energy harvester. Reproduced with permission of [105], copyright 2016 IEEE. (b) Multilayered cylindrical TENG for harvesting the kinetic energy of shaking tree branches. Reproduced with permission of [106], copyright 2020 John Wiley and Sons. (c) Droplet-based electricity generator with a simple open structure. Reproduced with permission of [114], copyright 2022 Elsevier. (d) A thin film blue energy harvester with a flexible and bendable structure. Reproduced with permission of [120], copyright 2019 Elsevier. (e) An elastic multiunit TENG for harvesting the vibration energy of a bicycle. Reproduced with permission of [121], copyright 2017 American Chemical Society. (f) An organic film nanogenerator for acoustic energy harvesting. Reproduced with permission of [122], copyright 2014 American Chemical Society. (g) A MEMS-based piezoelectric ultrasonic energy harvester (PUEH) with a wide operation bandwidth. Reproduced with permission of [123], copyright 2016 Springer Nature.

Vibration energy in the environment is also produced by man-made equipment, such as the vibration of moving vehicles and mechanical equipment [124–126]. Although human-induced vibration energies are abundant in the ambient environment, their oscillation frequencies are generally low and uncertain. Aiming at this type of vibration energy, Wang et al. designed a zigzag-shaped elastic multiunit TENG with a wide operation frequency range [121]. Figure 4e shows the detailed structure of the device, whereby the zigzag-shaped structure is formed by a Kapton thin film, and the triboelectric layers are composed of an aluminum thin film and a copper-deposited fluorinated ethylene propylene (FEP) film. In the meantime, micropores and nanowires are fabricated on

the surface of the triboelectric layers to obtain an enhanced triboelectric charge density. Furthermore, two acrylic plates are placed both at the top and bottom of the nanogenerator to construct the mass-spring-damper structure. The prepared energy harvesting system is mounted on a bicycle to harvest its vibration energy, and the harvested energy can charge a 1 mF electrolytic capacitor from 1 to 2.3 V and power the temperature and humidity sensors. Acoustic waves are another type of human-induced vibration energy which is abundantly available in our daily life [127–129]. As presented in Figure 4f, Yang et al. used a PFET thin film and a holey aluminum film electrode (under straining conditions) to develop a triboelectrification-based nanogenerator for harvesting acoustic energy with low frequencies [122]. The nanogenerator is shaped as a Helmholtz cavity with a size-tunable narrow neck to enhance its sensitivity to acoustic waves. When there are acoustic waves in the ambient environment, the acoustic pressure will cause the PTFE film and aluminum film to separate and contact repeatedly, and electric energy will be generated due to triboelectric transduction. According to the experimental measurement, the maximum electric power density of the nanogenerator reaches 60.2 mW m^{-2} , which is sufficient to light 17 commercial light-emitting diodes (LEDs). For those high-frequency sound waves, that is, ultrasonic waves, Shi et al. utilized piezoelectric micromachined ultrasonic transducers (pMUTs) to prepare a broadband piezoelectric ultrasonic energy harvester (PUEH) for the first time [123]. The PUEH is made by miniaturized PZT film with a high piezoelectric coefficient, and possesses two overlapped resonant modes, which gives it an extra wide operation bandwidth, as displayed in Figure 4g. Thanks to the miniature size and high efficiency, the developed PUEH can be implanted into the human body to collect external ultrasonic energy to power the implanted biomedical devices.

3. Energy Harvesting from Non-Vibrational Sources

Corresponding to the vibration-type energy sources, there are also non-vibration energy sources that are widely present in the natural environment, represented by thermal energy and solar energy [130–137]. Harvesters for this type of energy source have a relatively compact structure because they do not require components designed to sense external vibrations. Figure 5a shows a CMOS MEMS-based thermoelectric power generator developed by Xie et al., which is designed to convert waste heat into electrical power [138]. Since the energy conversion of the thermoelectric power generators mainly depends on the Seebeck effect, a thermopile is formed in the proposed generator by electrically connecting phosphorus and boron heavily doped polysilicon thin films. Meanwhile, to optimize the heat flux in the generator, thermal legs are embedded between the top and bottom cavities, and a heat-sink layer is coated on the cold side to effectively disperse the heat. With the temperature difference across the generator reaching 5 K, the open-circuit voltage and output power of the devices are 16.7 V and 1.3 μW , respectively. Organic-based flexible thermoelectric power generators show outstanding potential for use on the human body to convert body heat into electrical energy, but their output power is too low to meet the power supply requirements for wearable devices [139,140]. In this regard, Kim et al. demonstrated an inorganic-based flexible and lightweight thermoelectric power generator with an unprecedentedly large output power density [141]. The flexible generator is realized by screen printing inorganic material-based (n-type Bi_2Te_3 film and p-type Sb_2Te_3 film) thermocouples on a glass fabric-based textile (Figure 5b). Under 120 cycles of repeated bending, the generator has no obvious performance change. Another mechanism to achieve the conversion of thermal energy into electrical energy is the pyroelectric effect, which originates from the spontaneous polarization change inside pyroelectric materials caused by the ambient temperature change [132]. Owing to the flexibility and excellent pyroelectric properties, PVDF was selected by Jeon et al. to fabricate a pyroelectric generator, as presented in Figure 5c [142]. In addition, tosylate-doped poly (3,4-ethylene dioxythiophene) (PEDOT: Tos), instead of metal and other organic materials, is introduced and optimally prepared as a high-performance thermal radiation adsorption electrode for the pyroelectric generator to improve the thermal conversion. The experimental results show that the

pyroelectric conversion efficiency of the generators is increased by an order of magnitude due to the PEDOT: Tos electrode, and a significant voltage output is observed when a finger is approaching.

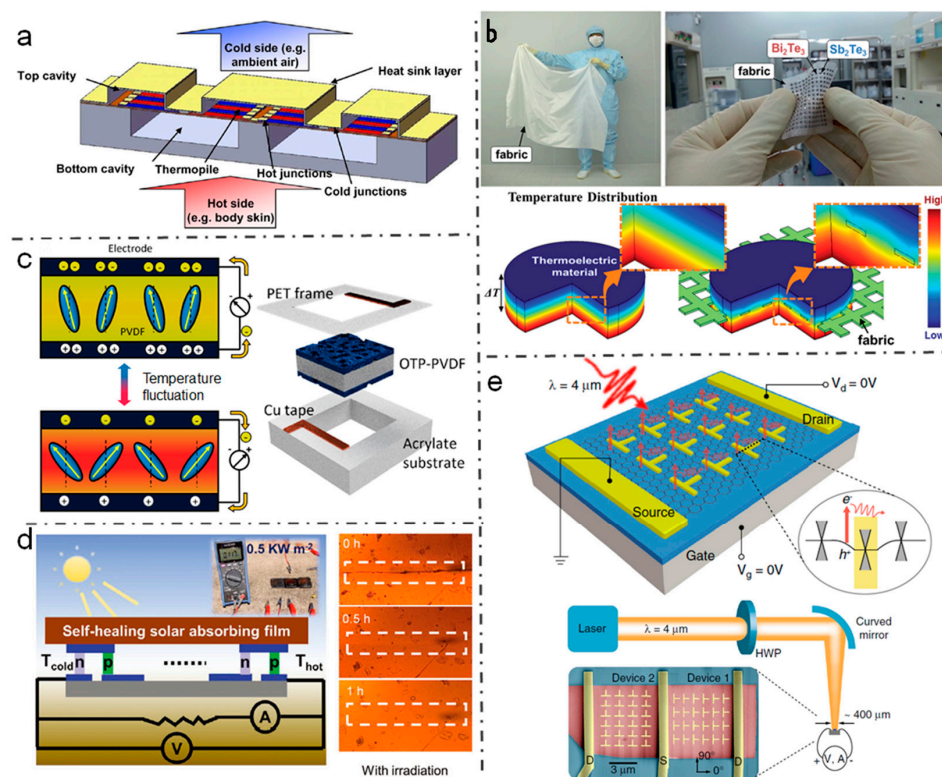


Figure 5. Harvesting non-vibrational energy. (a) CMOS MEMS-based thermoelectric power generator. Reproduced with permission of [138], copyright 2010 IEEE. (b) Glass-fabric-based wearable thermoelectric power generator. Reproduced with permission of [141], copyright 2014 Royal Society of Chemistry. (c) PVDF pyroelectric generator. Reproduced with permission of [142], copyright 2022 Elsevier. (d) Flexible organic-inorganic-composited solar thermoelectric generator. Reproduced with permission of [137], copyright 2022 Wiley. (e) Metasurface-mediated graphene mid-infrared harvester. Reproduced with permission of [143], copyright 2020 Springer Nature.

Clean and renewable solar energy is one of the indispensable energy sources in today's society. To make full use of solar energy, light harvesters with wide absorption bands (especially covering the near-infrared light regions) are the pursuit of researchers. As shown in Figure 5d, Sun et al. exhibited a diradical-featured organic small-molecule derivative-based (CR-DPA-T) ultra-broadband and highly efficient solar energy harvester [137]. The CR-DPA-T powder can provide a wide light absorption band from 300 to 2000 nm, which benefits from its radical characteristics and strong intermolecular π - π interactions. Meanwhile, the CR-DPA-T powder exhibits excellent performance in photothermal conversion, and the conversion efficiency reaches 79.5% under an 808 nm laser irradiation. To construct a flexible solar energy harvester, the CR-DPA-T is incorporated into a flexible self-healing poly (dimethylsiloxane) (H-PDMS) film to serve as the solar absorber, and the Ecoflex and Ecoflex/aluminum nitride mixture are functionalized as the insulation layer and bottom sheet, respectively. The heat obtained by the absorption of solar energy by the H-PDMS/CR-DPA-T film will be converted into electrical energy through the thermopiles underneath. An open-circuit voltage of 192 mV and a maximum power density of 1.86 W m^{-2} is achieved by the energy harvester under a 5 kW m^{-2} solar irradiation. Except for the wideband harvesters, light harvesters for specific wavelength bands are also being investigated. Figure 5e presents a metasurface-mediated graphene mid-infrared harvester [143], proposed by Wei et al. The device consists of a heavily p-doped silicon chip with a thermal

SiO₂ layer, patterned graphene flakes, and non-centrosymmetric metallic nanoantennas. Under uniform mid-infrared illumination, the hot photocarriers in graphene will gain momentum and produce a shift current with the assistance of the non-centrosymmetric metallic nanoantennas.

4. Hybrid Energy Harvesters

Early energy harvesters (EHs) have mainly been tailored to focus on a single energy source, such as piezoelectric, electromagnetic, and triboelectric generators for mechanical energy acquisition, solar cells for light harvesting, and thermoelectric or pyroelectric generators for thermal energy conversion. However, in many practical applications, the output power of a single-source energy harvester may not be sufficient to fulfill the requirements of the sensor network, as the energy source can be intermittent or unstable. For instance, biomechanical energy is available only during motion, thermoelectric/pyroelectric harvesters require a steady temperature gradient/fluctuation, and solar cells produce power under favorable light conditions, which decrease substantially in darkness [144–147]. In these situations, the energy input from a single source to the harvester may be inadequate to power sensors or other electronic components. To overcome this issue, hybrid energy harvesters have been designed to collect multiple forms of energy sources simultaneously, with structural integration being the dominant approach [148–152]. The hybrid energy harvester's output power is considerably improved when one or more energy sources are unstable or weakened, compared to earlier harvesters with a dedicated conversion mechanism. Chen et al. fabricated a micro-cable power fabric for the simultaneous extraction of energy from ambient sunlight and mechanical movements (Figure 6a) [153]. This material comprises lightweight polymer fibers woven into micro cables through a shuttle-flying technique, using fiber-based TENGs to create a smart fabric. With a thickness of 320 μm , the fabric can be integrated into various garments, curtains, and tents. Under ambient sunlight and mechanical stimuli, such as human motion and wind, the fabric can charge a 2 mF commercial capacitor to 2 V within 1 min. It can also power an electronic watch continuously, directly charge a mobile device, and facilitate water-splitting reactions. The produced fabric is lightweight, flexible, foldable, sustainable, and constructed from cost-effective polymer fibers. It boasts a highly adaptable, breathable, easily transportable and storable structure, making it suitable for mass production. Consequently, the proposed hybrid textile can be utilized not only for self-powered electronics, but also for large-scale power generation. Li et al. outlined a hybrid energy-harvesting system (HEHS) that concurrently collects biomechanical and biochemical energy [154]. The HEHS consists of a triboelectric generator and a glucose fuel cell integrated on a flexible PET substrate. Both the triboelectric generator and glucose fuel cell are connected in parallel, and their electrical outputs can be successfully combined, demonstrating the viability of using a triboelectric generator and a glucose fuel cell to harvest multiple energies simultaneously. The triboelectric generator and glucose fuel cell individually generated output currents of 0.3 and 0.9 μA , respectively, which can be combined to approximately 1.2 μA after integration. Moreover, the HEHS exhibited a quicker charging rate for a commercial capacitor compared to either the triboelectric generator or glucose fuel cell individually, validating its enhanced efficiency as a hybrid system for energy harvesting. Additionally, it was demonstrated that the HEHS can power a commercial calculator and green light-emitting diode pattern. Seo et al. engineered a combined thermo-triboelectric generator (HThTG), employing systematic optimization techniques in frequency feature-size variable contexts (Figure 6c) [155]. The mechanism functions by using body heat to transfer electrons from n-type and holes from p-type bismuth telluride to the cold side during surface interaction. Through linking the p-type and n-type bismuth telluride, the electric current can be extracted from thermoelectric apparatuses. Moreover, triboelectric power is generated upon contact between human skin and PDMS layers. The thermoelectric voltage exhibits three unique regions based on the heat source's frequency and duration: the mounting, saturation, and cooling phases. The device's saturation region depends on the touch input frequency. The mounting phase's du-

ration is impacted by surrounding thermal resistance factors, such as PDMS layer size and compactness. At lower tapping frequencies, the thermoelectric output offsets shortcomings. A power density of $3.27 \mu\text{W cm}^{-3}$ is attained at a driving frequency of 2.5 Hz, producing meaningful microwatts within a frequency scope of 0.5 Hz to 2.5 Hz. In addition, Xu et al. presented a versatile, hybrid all-in-one energy solution (AoPS) for environmental energy collection (Figure 6d) [156]. The AoPS merges efficient spherical triboelectric generators and photovoltaic cells, enabling the simultaneous capture of energies like wind, rain, and sunlight. The spherical TENG components, equipped with packaged designs, effectively gather fluid energy, while force and fluid dynamics are assessed through experimentation and finite element method (FEM) computations. An almost constant direct current and a higher average power of 5.63 mW are achievable for four triboelectric generator modules, which are further supplemented by solar cells. The demonstrated applications encompass self-sustaining soil moisture regulation, forest fire deterrence, and pipeline surveillance. This research introduces an environmental energy solution that smoothly integrates into diverse environments, offering electrical supply for all-climate electronic devices and laying a solid groundwork for the IoT age.

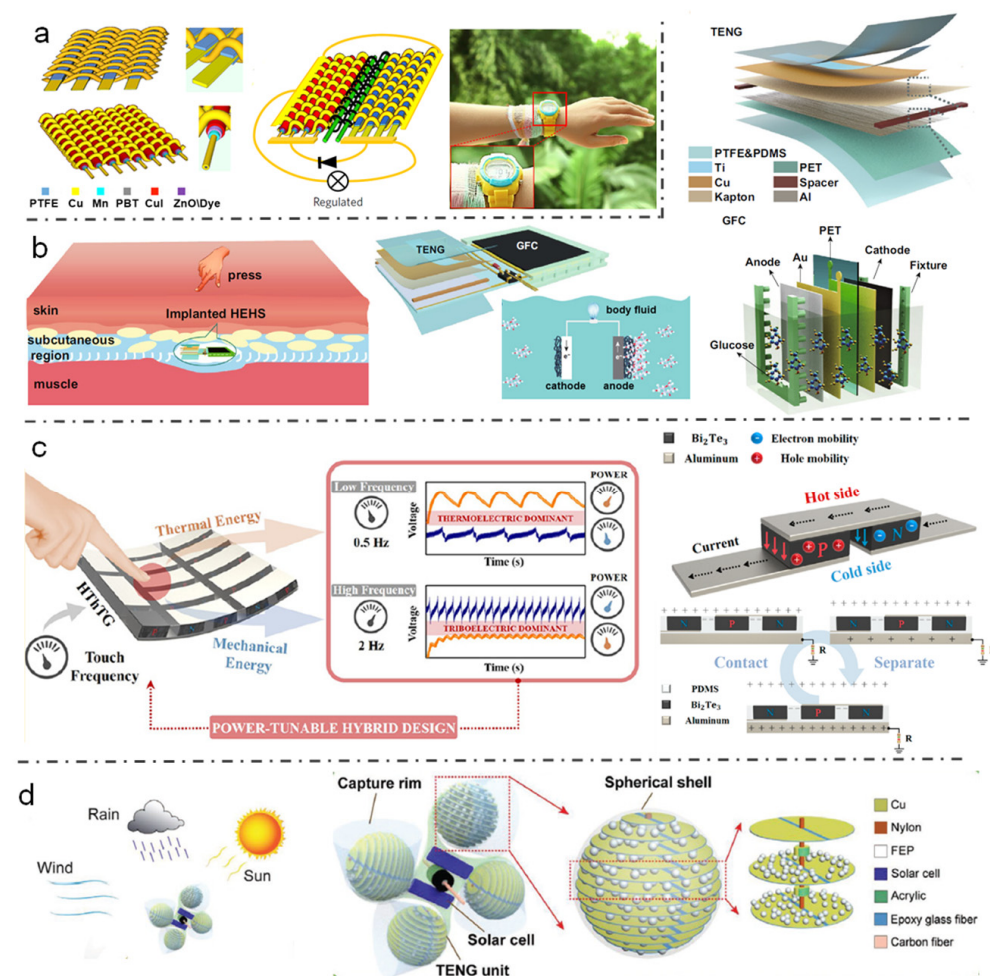


Figure 6. Energy harvesters with hybrid energy sources. (a) Micro-cable power textile for harvesting solar and biomechanical energy. Reproduced with permission of [153], copyright 2016 Springer Nature. (b) Hybrid energy-harvesting system for harvesting biomechanical and biochemical energy. Reproduced with permission of [154], copyright 2019 Springer Science & Business Media. (c) Hybrid thermotriboelectric generator for harvesting biomechanical and thermal energy. Reproduced with permission of [155], copyright 2019 American Chemical Society. (d) Hybrid all-in-one system for harvesting solar, wind, and raindrop energy. Reproduced with permission of [156], copyright 2020 Wiley.

5. Application of Micro-Nano Energy Harvesters in Event-Based IoT Systems

Event-based IoT systems or wake-up IoT systems are considered to be an effective strategy to reduce the power consumption of various IoT sensor systems and prolong their lifespan [157,158]. In event-based IoT systems, the micro-nano energy harvesters can not only collect the surrounding energy to support the operation of the IoT systems during the dormant period, but also utilize the energy of the measured signal (meet the pre-defined threshold) to trigger a wakeup event and output the signal [159]. As displayed in Figure 7a, Wang et al. leveraged a novel hybrid piezoelectric generator and TENG to form an autonomous wireless sensor node for information acquisition and status detection of machines during operation [160]. The piezoelectric generator is functioned by a hinged-hinged mounted PZT bimorph and two T-shaped copper-proof masses bonded to it. To make the resonant frequency of the PZT bimorph tunable, a bolt together with a nut is mounted on one side of the polymethyl methacrylate (PMMA) made cube package to produce an axial force. Two TENGs, consisting of a nickel fabric electrode material and an Eco flex (with a pyramidal synaptic array structure) negative triboelectric material, are placed on both sides of the piezoelectric generator to serve as the stoppers. By colliding with the piezoelectric generator, the TENGs can increase the operating bandwidth of the piezoelectric generator due to the frequency-up-conversion mechanism, and they can also generate voltage signals by themselves through electrostatic induction. Embedding the hybrid piezoelectric generator and TENG into the autonomous wireless sensor node, the TENGs will convert the irregular vibration incidents of the machines, e.g., a train, into sine voltage signals, and the piezoelectric generator will harvest the vibration energy to power the Arduino nano and the RF transceiver. By doing so, the signal related to the abnormal operating status of the machines can be sent out wirelessly by Zigbee. Similarly, Zhang et al. reported an autonomous wireless vibration frequency monitoring system (AWFMS) powered by a broadband vibration energy harvester [161]. As shown in Figure 7b, the AWFMS mainly consists of two vibrational TENGs, a power management module (PMM), a signal processing module (SPM), a microcontroller unit (MCU), and a transmitter. As the core component of the AWFMS, the TENGs are prepared by Cu films, acrylic plates, and FEP films. The Cu film attached to the top acrylic plate is separated to form two nanogenerators, in which one with a large part Cu film (P-TENG) is aiming for vibration energy harvesting and the other one with a small part Cu film (S-TENG) is used for abnormal vibration frequency sensing. To realize the integrated functions of a power source and a sensor, the P-TENG and S-TENG work simultaneously in the AWFMS. The output voltage obtained by P-TENG scavenging vibration energy of mechanical equipment is converted into a 2.5 V stable direct current voltage with the assistance of the PMM, and is used to power the MCU. The output signal of the S-TENG related to the abnormal operation of the mechanical equipment is acquired and processed by the MCU, and is transmitted wirelessly to the cloud platform by the Narrow Band IoT technology.

To make the energy output by the micro-nano energy harvesters high enough to power or trigger the event-based IoT systems, an efficient energy-management strategy is critical. To this end, Wang et al. reported an ultrahigh voltage energy-management system to effectively boost the energy utilization of TENGs, as presented in Figure 7c. The established system includes two key components, a simple and tunable automatic spark switch triggered by 7540 V voltage and a matched induction transformer with standard design procedure [162]. The automatic spark switch is designed as a plate-to-plate structure to maximize the voltage output from the TENG through the spark discharge effect, and processes the features of extremely low leakage current and applicability in full-range voltage. Furthermore, the induction transformer is developed by a new standard design procedure to match with random electrostatic energy. With this energy-management system, an ultrahigh charge output of 660 μC , an average power of 1.102 mW, and a peak power density of 11.13 kW m^{-2} at 3 Hz are achieved, which greatly promotes the practical applications of the TENGs.

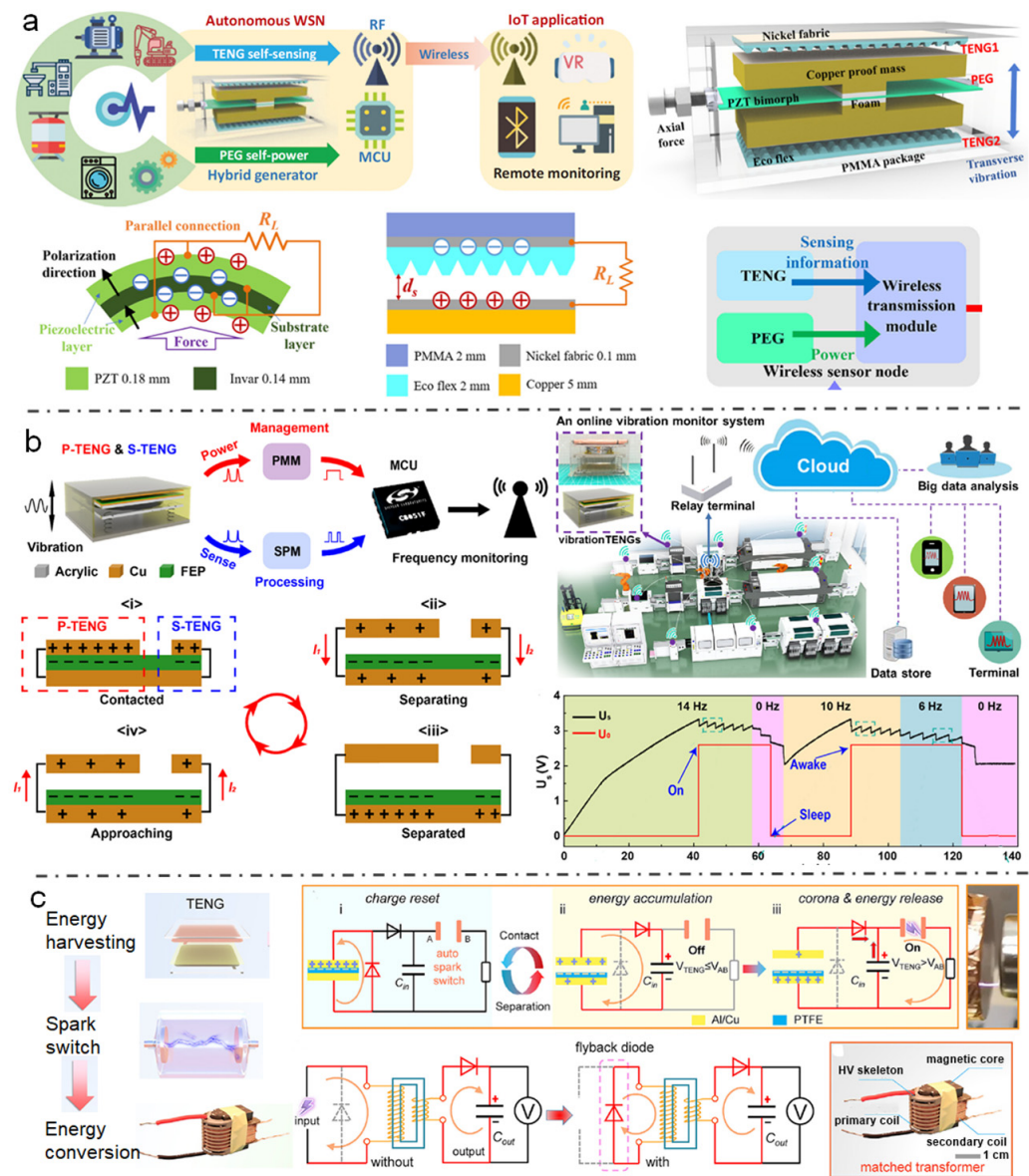


Figure 7. Micro-nano energy harvesters-enabled event-based IoT systems. (a) A hybrid piezoelectric generator and TENG-based autonomous wireless sensor node. Reproduced with permission of [160], copyright 2021 Elsevier. (b) An autonomous wireless vibration frequency monitoring system powered by two TENGs-based broadband vibration energy harvesters. Reproduced with permission of [161], copyright 2022 Elsevier. (c) An ultrahigh voltage energy-management system for TENG. Reproduced with permission of [162], copyright 2021 Elsevier.

6. Realization of Self-Sustained Systems

Harvesting ambient energy to meet the power consumption demand of IoT sensor nodes, thus forming self-sustained systems without relying on batteries or an external power supply, is the ultimate goal of the development of micro-nano energy harvesters [163,164]. Although the ultimate goal is still far from being reached, researchers have made considerable progress [165]. Micro-nano energy harvesters usually serve as both power sources and sensors in self-sustained systems to keep the systems in a state of continuous operation. As illustrated in Figure 8a, Chen et al. demonstrated an integrated self-powered real-time pedometer system by integrating a TENG, a data acquisition and processing (DAQP) module, an analog front-end (AFE) circuit, a mini electromagnetic generator, a supercapacitor, and a mobile phone APP [166]. The TENG is designed in a porous structure to achieve the contact-separation operation mode, and serves as a pressure sensor to convert the

users' footsteps into electrical signals. The footsteps-related electrical signals are then acquired and regulated by the DAQP module and AFE circuit, and transmitted to the mobile phone APP through a Bluetooth SoC. Meanwhile, the operation of the entire integrated pedometer system is powered by the combination of the electromagnetic generator and the supercapacitor.

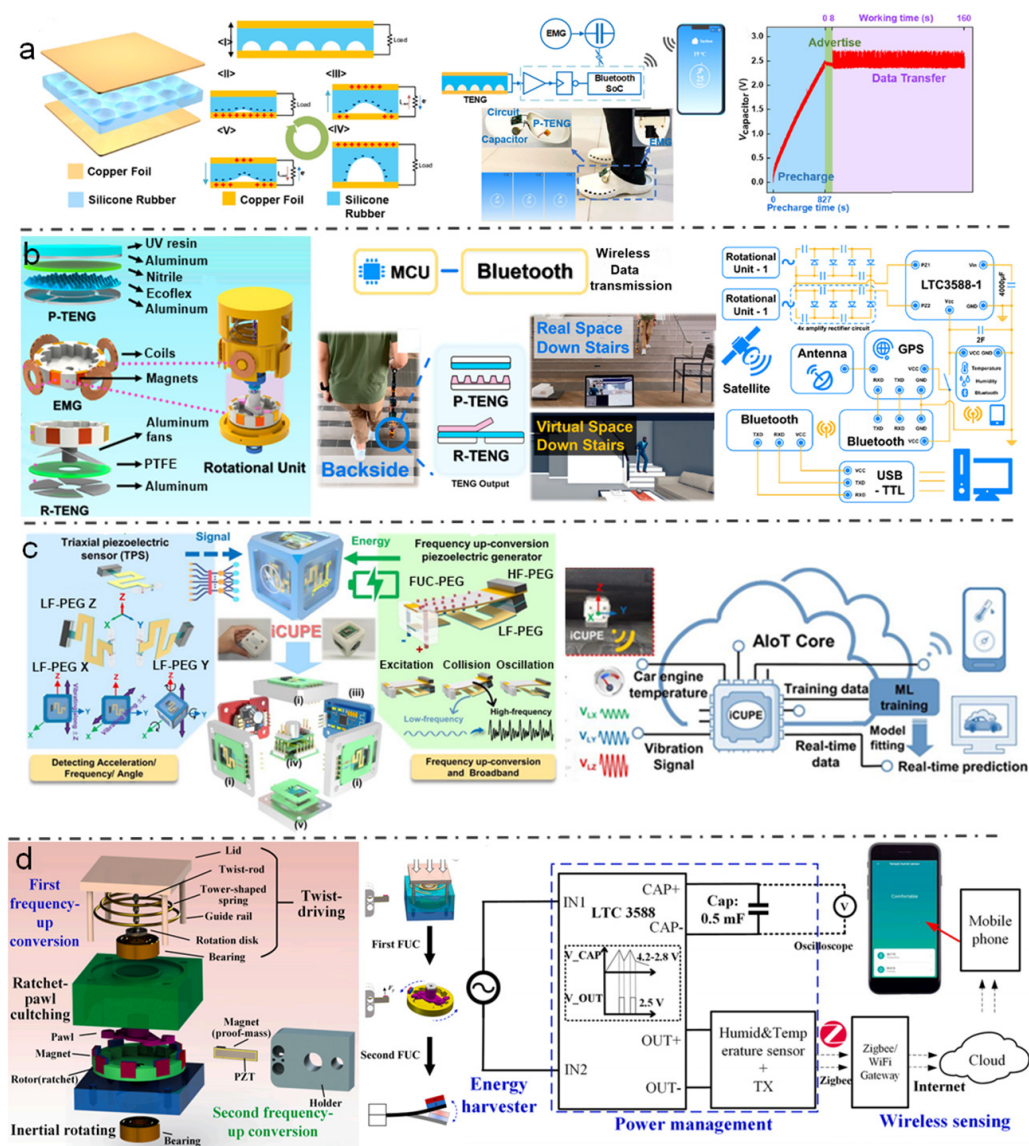


Figure 8. Micro-nano energy harvesters-based self-sustained systems. (a) A self-powered real-time pedometer system. Reproduced with permission of [166], copyright 2021 American Chemical Society. (b) An AI-enhanced walking stick as a comprehensive, real-time monitoring platform for aged individuals and individuals with disabilities. Reproduced with permission of [167], copyright 2021 American Chemical Society. (c) A self-powered piezoelectric Artificial Intelligence of Things node. Reproduced with permission of [168], copyright 2023 American Chemical Society. (d) A self-powered humidity-temperature sensing system based on a vibration energy harvester with a double frequency-up conversion mechanism. Reproduced with permission of [169], copyright 2023 Elsevier.

In a similar vein, Guo et al. introduced an AI-augmented walking stick as an all-encompassing, real-time monitoring platform tailored specifically for elderly individuals and people with disabilities [167], as shown in Figure 8b. The device consists of two modular units: a hybrid unit and a rotational unit, both crucial to the device's functionality. The hybrid unit integrates a top press triboelectric generator (P-TENG) with five separate

electrodes, a rotational triboelectric generator (R-TENG), and a rotational electromagnetic energy generator (EMG). The P-TENG and R-TENG can achieve contact point sensing and contact speed sensing, respectively. Moreover, the application of artificial intelligence in data analysis allows for advanced features such as disability assessment, motion differentiation, user identification, and gait irregularity detection. The rotational unit, however, contains only an EMG, focusing on supplying power to a wireless sensing system. The incorporation of a pawl-ratchet mechanism allows the unit to convert the slow linear movement of a walking stick into a rapid rotation of the inner ratchet. The ratchet can also sustain rotation through inertia, facilitating continuous output and eliminating the need for stimulus frequencies. The rotational unit's maximum peak power is 55.1 mW under a load resistance of 100 Ohm, and the average output power is 27.5 mW under a 1 Hz driving frequency, which remains at 6.3 mW when the frequency drops below 0.1 Hz, making it a dependable power source for a self-sustaining IoT system. The entire system comprises two rotational units, a power management circuit (LTC-3588), a GPS location sensor, environmental humidity and temperature sensors, and a wireless module. The power management circuit is in charge of rectifying and amplifying the voltage produced by the two rotational units to charge a 4000 μ F small capacitor, which then releases energy to charge a 2 F supercapacitor, acting as the main energy storage unit for the system. The self-sustaining IoT system enables the comprehensive monitoring of users by tracking their current motion status and location, and sending out an alert in the event of accidents, offering a holistic caregiving solution.

Moreover, Huang et al. presented the design and characterization of a self-powered piezoelectric Artificial Intelligence of Things (AIoT) node, called iCUPE, which aims to be used in smart mining, factory automation, industry 4.0, transportation and smart city applications. As depicted schematically in Figure 8c, the iCUPE features a three-dimensional (3D) hexahedron modular design with six replaceable sensing and functional modules located at six faces. This includes a temperature and humidity sensing module, a Bluetooth module, a core data processing module, and a frequency up-conversion piezoelectric generator (FUC-PEG) module. The FUC-PEG module is designed to broaden the operational frequency range of the iCUPE by integrating a low-frequency piezoelectric generator (LF-PEG) with a thick-film high-frequency piezoelectric generator (HF-PEG). The FUC-PEG is able to convert low-frequency excitations to high-frequency self-oscillations, and can generate an open-circuit voltage of 48 V at low-frequency conditions. The output performance of the FUC-PEG is affected by the acceleration magnitude of the external excitation and the gap distance between LF-PEG and HF-PEG, and it is also capable of generating peak power under various conditions. This modular design ensures both the robustness of the system and the great compatibility towards different scenarios, and hence, fulfills various requirements of the AIoT ready smart city. In addition to the design and characterization of the self-powered piezoelectric AIoT node, they also demonstrate the system-level work that integrates the iCUPE into smart city applications. The iCUPE is capable of not only acting as a vibrational energy harvester to support the operation of IoT sensor nodes, but also as a piezoelectric self-powered sensor for detecting the vibration parameters associated with vehicle driving conditions and equipment operation conditions in a smart city, such as intelligent mines and smart transportation. The proposed iCUPE can sense the surrounding vibration signals without an additional power supply, thus providing preliminary sensing information, such as frequency and acceleration. The sensing data can be analyzed by machine learning techniques, and the implementation of multiple sensing channels can substantially improve the intelligence of the entire system by the collaborative processing of the fused data, thus enabling the capability of artificial intelligence techniques. The iCUPE is designed to be highly compatible and robust to different scenarios, making it a versatile and powerful tool for AIoT ready smart city applications.

Micro-nano energy harvesters can also be used simply as a power source to power various sensors in self-sustained systems. Figure 8d displays a self-powered humidity-temperature sensing system based on a vibration energy harvester for ultra-low frequency

vibration sources [169], which was proposed by Luo et al. To deal with the poor energy conversion efficiency because of the frequency mismatch between the vibration sources and the resonant vibration energy harvesters, the energy harvester is designed with a double frequency-up conversion (FUC) mechanism. As shown in the figure, the double FUC mechanism of the energy harvester is realized by two main components, an inertial rotary structure and a Pb-based PZT beam. The inertial rotary structure, consisting of a twist-driving structure and an inertial rotor structure, works as the first FUC part to directly collect energy from vibration sources, while the Pb-based PZT beam with a mounted magnet-proof mass serves as the second FUC part. During operation, the ultra-low frequency of a few sub-hertz of the vibration sources can be up-converted to tens of hertz by the first FUC part, and further converted to hundreds of Hertz through the second FUC part. Thanks to the high-frequency conversion ratio, an average output power of 75 μ W can be obtained by the energy harvester under the excitation of a 0.2 Hz vibration source. To demonstrate the promising application prospects, the energy harvester is embedded into a wireless sensor node to continuously power a humidity-temperature sensor.

7. Conclusions and Outlook

Currently, micro-nano energy harvesters with different mechanisms are investigated to scavenge energy from diverse sources to power distributed wireless IoT sensor nodes in order to prolong their lifetimes. This review outlines the current state of the art in micro-nano energy harvesters, aiming for different kinds of energy sources. For vibrational energy sources, including human kinetic energy and kinetic energy existing in the environment, energy harvesters based on electrostatic, electromagnetic, piezoelectric, and triboelectric effects are introduced, respectively. For nonvibrational energy sources, thermal energy and solar energy, thermoelectric, pyroelectric and photovoltaic effects-based energy harvesters are described accordingly. Furthermore, hybrid energy harvesters, which are designed to scavenge energy from multiple types of sources, are also discussed due to their relatively high output power. Finally, the applications of the micro-nano energy harvesters in event-based IoT systems and self-sustained systems are briefly enumerated.

Although remarkable progress has been made in developing micro-nano energy harvesters towards self-sustained systems, there are still some technical gaps that exist with regard to their final implementation. First of all, the energy output from the current micro-nano energy harvesters still cannot meet the power consumption requirements of all IoT sensor nodes, such as image sensors and gas sensors, whose power consumption reaches from 150 mW to 800 mW [170]. In addition to improving the output power of the micro-nano energy harvesters by selecting new functional materials and optimizing the device structure, possible solutions can also be to use energy storage units and power management modules. Energy storage units such as supercapacitors and rechargeable batteries can superimpose the generated energy from the micro-nano energy harvesters to the required value of the IoT sensor nodes [171], while the power management modules help to improve the energy utilization efficiency of the IoT sensor nodes [172,173]. Secondly, the environmental adaptability of micro-nano energy harvesters in harsh environments such as high temperature, high humidity, high pressure, and complex deformation needs to be improved further. Taking TENGs as an example, their energy collection efficiency drops dramatically in high-temperature and high-humidity environments [174–180]. Looking forward, using particular materials, such as stable temperature and water-proof materials to prepare TENGs would be an effective way to solve the adaptability problem of micro-nano energy harvesters in harsh environments [181,182]. Lastly, the micro-nano energy harvesters have not been able to achieve system integration with energy management modules. Given this, it is also necessary to further develop new micro-nano manufacturing technologies to achieve the mass production and system integration of the energy harvesters, thereby reducing the footprint of the IoT sensor nodes.

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