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Topical Review

Technology evolution from micro-scale energy harvesters to nanogenerators

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Abstract

Since the end of the last century, energy harvesting technologies have obtained prominent development as the sustainable power supplies for billions of wireless sensor nodes distributed in both the city and remote areas. Microelectromechanical system (MEMS) energy harvesters based on the energy transferring mechanisms of electrostatic effect, electromagnetic induction, and piezoelectric effect were first proposed to scavenge the vibrational energy from the ambient environment. Thereafter, the piezoelectric nanogenerator and triboelectric nanogenerator emerged as promising techniques to harvest diversified mechanical energy for addressing the energy consumption of flourishing wearable devices. Targeting for a more efficient system, multiple strategies for improving the output performance of individual energy harvesters as well as hybridized energy harvesters are extensively investigated. Merging the well-developed energy harvesters with energy storage, wireless data transmission, and other functional units, self-sustainable systems have been realized. Shortly, with the evolving AI technologies, we can foresee that the AI-assisted self-sustainable systems will also be achieved and play a vital role in the future 5 G era. In this review, we systematically introduce the evolution of energy harvesting techniques in the 5 G and IoT era, with detailed operation principles, structural designs, enhancement strategies, self-sustainable and AI-assisted system development, and our perspectives.

Keywords: energy harvesting, triboelectric nanogenerator (TENG), self-sustainable system, self-powered sensor, artificial intelligence (AI)

(Some figures may appear in colour only in the online journal)

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1. Introduction

In the past few decades, we have witnessed the enormous development of microelectromechanical system (MEMS) technology and the extensive range of applications for various miniature sensors it promoted [1]. The power consumption of a sensor has been decreased to μW range while the number of sensor nodes distributed in our cities keeps increasing till billions [2–4]. Since the invention in 1799 by A Volta, batteries have provided the primary practical choice as the electricity source for portable devices [5]. However, they also have certain drawbacks when integrated with the miniature sensors, such as the limited lifespan that needs to be replaced or recharged frequently, high contamination to the environment, biological incompatibility, and low power density that makes their capacity too small when scaling to the millimeter dimension [6, 7]. These drawbacks mentioned above greatly hinder their applicability for the widely distributed small-scale sensor nodes, especially for sensors applied in a harsh environment like high buildings, bridges, or vehicles [8]. To find an alternative choice to batteries, MEMS-based energy harvesters have widely investigated as sustainable power sources by converting various types of available ambient energies into electricity, such as mechanical [9–11], thermal [12–20], light [21–27], etc. In 2000, the 1st International Conference on Micro and Nanotechnology for Power Generation and Energy Conversion Applications (PowerMEMS) was held in Sendai, Japan, to promote the technologies in this area. Since 2004, special issues of PowerMEMS conferences with opportune research advancements have been published in J Micromech. Microeng. Along this evolutional trip of energy harvesting technologies, we have spectated the flourishing of the extensive applications they have brought (figures 1(A) and (B) [28–36]).

Among the abovementioned energy sources, vibration as a universal form of mechanical energy is ubiquitous and abundant in various surrounding environments. Thus MEMS-based vibration energy harvesters (VEHs) able to transfer mechanical vibration energy from the ambient environment to electricity have been proposed as the green, sustainable, and miniaturized power supply for such sensors [37]. MEMS-based VEHs are typically designed based on three main principles: electromagnetic [38–40], electrostatic [41–43], and piezoelectric [44–47]. The first concept of a MEMS VEH and its theoretical model was proposed by Professor Williams and Professor Yates from the University of Sheffield in 1996 [48], which is based on the electromagnetic induction discovered by Michael Faraday in 1831: when applied external vibration, the coil and magnet will have relative displacement and a voltage proportional to the time rate of change of the magnetic flux will be induced into the coil. There are mainly two categories of designs for MEMS-based electromagnetic vibrational energy harvesters (EM-VEHs), with fixed coils and moving magnet [49–51] or fixed magnet and moving coils [52–54], and some typical designs are shown in figure 1(C), (i) [39, 55–57]. Generally, the EM-VEHs advantage in easy fabrication, mature choices for magnet materials, no pull-in effect, and large output current [58, 59]. Moreover, to improve their output performance, several effective approaches have been widely investigated by researchers, such as broadening the operational bandwidth [60], overcoming the limited number of coil turns [61, 62], and improving the compatibility with the MEMS system [63–65]. On the other hand, the first MEMS-based electrostatic vibrational energy harvester (E-VEH) and the corresponding energy conversion cycle model was proposed by Professor Chandrakasan from MIT [66]. E-VEHs contain a charged capacitor that can generate electric energy when applied external vibrations through the capacitance variation, with several designs shown in figure 1(C), (ii) [66–69]. Electret materials, including silicon dioxide, Teflon, Parylene, and CYTOP, which can store charges stably, are utilized as the external bias to charge the capacitor continuously [68–71]. The typical designs for E-VEHs include in-plane overlapping, in-plane gap-closing, and out-of-plane gap-closing [72]. Compared to EM-VEHs, E-VEHs mostly advantage in the compatibility with the MEMS fabrication process and can be easily integrated with CMOS devices as an on-chip power source [73, 74]. And to further improve their output performance, researches include broadening bandwidth [75–77], optimizing parameters to increase the maximum capacitance variation [78, 79], exploring electret materials with higher surface charge density and stability [80, 81], and avoiding the pull-in effect have been performed [82, 83]. Besides, another type of widely investigated MEMS-based energy harvesters is piezoelectric vibration energy harvesters (P-VEHs), based on the materials with piezoelectric effect firstly reported by Professor J Curie and P Curie in 1880. Two MEMS-based P-VEHs designed at an early time are shown in figure 1(C), (iii) [45, 84]. When applied external mechanical strain or stress, piezoelectric materials can generate electric charges due to the induction of polarized electric dipole moment [85, 86]. And due to the unique material property, piezoelectric devices are also widely used in other MEMS-based sensing and actuation applications [87, 88], such as pressure sensor [89–91], force sensor [92–94], accelerometer [95–97], ultrasound transducers [98–100], etc. Compared with EM-VEHs and E-VEHs, P-VEHs have higher energy density in small scale, simpler structure, and inherent reciprocal conversion capability [101–103]. For P-VEHs, the operation modes (d_{31} mode and d_{33} mode) and structure configurations play a leading role in their output performance, and multiple structure designs to fully leverage the piezoelectric effect are one of the main improvements directions [104]. Other directions include broadening bandwidth [105–107], frequency up-conversion [108–110], optimizing electrode design [111, 112], and exploring piezoelectric materials with higher piezoelectric coupling coefficients [113, 114].

With the further development of the internet of things (IoT) and wireless data transmission technique, we are now entering the new 5 G era, in which portable electronics are going through a much more explosive advancement [115–117]. The linkage between wireless sensors is no more limited to buildings, machines, or vehicles but extended to ourselves [118–120]. The flourishing of wearable and implantable sensors merging with our bodies to record our temperature, respiration rate, blood pressure, and pulse changes the traditional ways

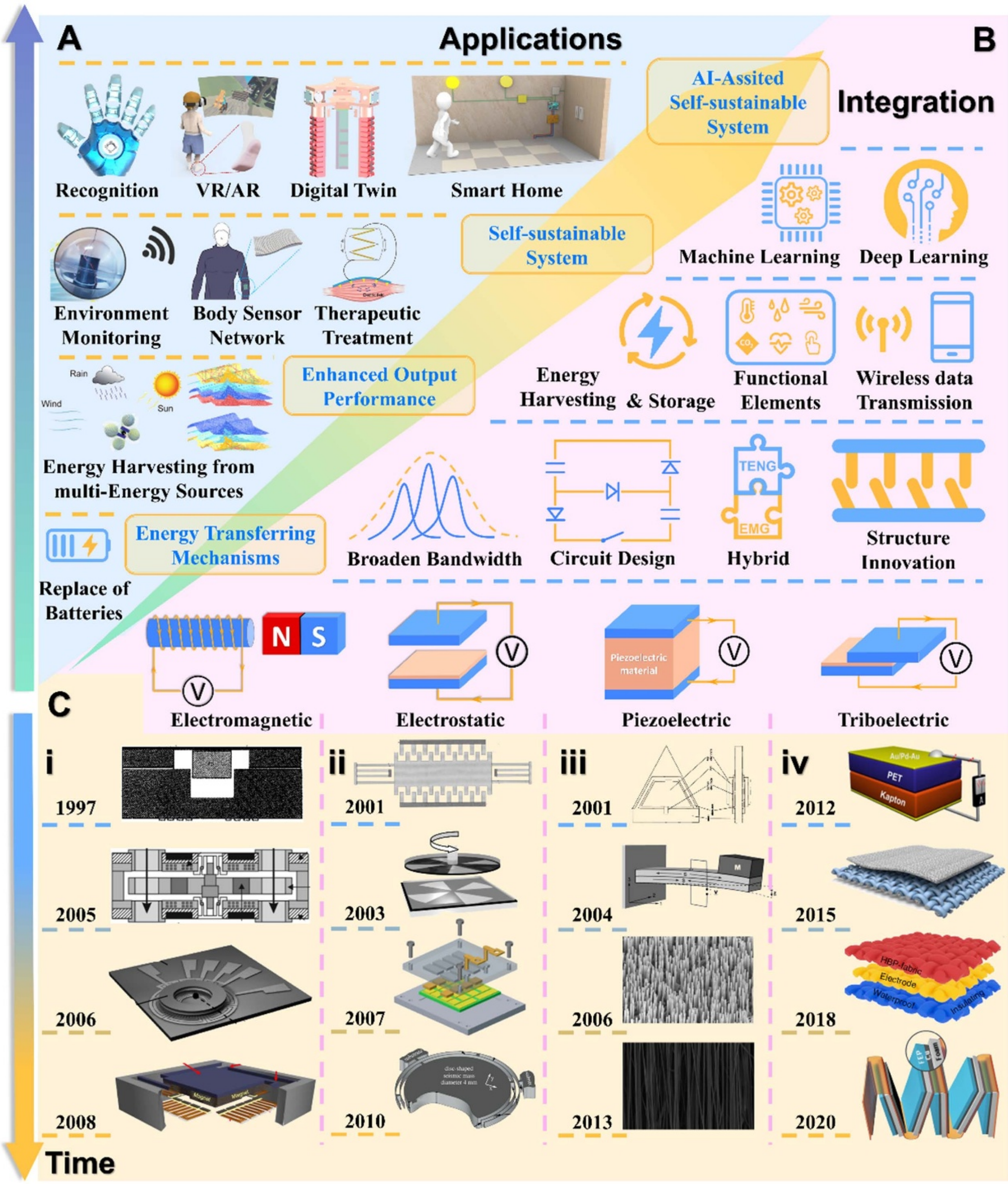


Figure 1. The evolution of energy harvesting technologies. (A) Flourishing applications with the development of energy harvesting technologies. Reproduced from [28]. CC BY 4.0. Reproduced from [29]. CC BY 4.0. Reproduced from [30]. CC BY 4.0. Reproduced from [31]. CC BY 4.0. Reproduced from [32]. CC BY 4.0. Reproduced from [33]. CC BY 4.0. [34] John Wiley & Sons. © 2020 Wiley-VCH GmbH. Reproduced with permission from [35]. CC BY-NC 4.0. [36] John Wiley & Sons. © 2020 Wiley-VCH GmbH. (B) Technology evolution. (C) Typical devices for each energy transferring mechanism: (i) electromagnetic. © [2005] IEEE. Reprinted, with permission, from [39]. © [2001] IEEE. Reprinted, with permission, from [55]. © [2008] IEEE. Reprinted, with permission, from [56]. Reproduced from [57]. © IOP Publishing Ltd. All rights reserved, (ii) electrostatic © [2001] IEEE. Reprinted, with permission, from [66]. Reproduced from [67]. © IOP Publishing Ltd. All rights reserved. Reproduced from [68]. © IOP Publishing Ltd. All rights reserved. © [2003] IEEE. Reprinted, with permission, from [69], (iii) piezoelectric. Reproduced from [45]. © IOP Publishing Ltd. All rights reserved. © [2001] IEEE. Reprinted, with permission, from [84]. Reprinted from [123], Copyright (2009), with permission from Elsevier. Adapted by permission from Springer Nature Customer Service Centre GmbH: Nat. Commun Nature [131]. (2013), and (iv) triboelectric. Reprinted from [132], Copyright (2012), with permission from Elsevier. Reprinted with permission from [136]. Copyright (2015) American Chemical Society. Reproduced from [137]. CC BY 4.0. Reproduced from [138] with permission of The Royal Society of Chemistry.

we interact with the world [121]. To power these wearable sensors, one of the most promising solutions is to scavenge the biomechanical energy from human motions. Nevertheless, due to the generally low frequency (below several hertz) and large deformation and strain range, previously designed MEMS-based VEHs show less effectiveness and lower output performance. Novel energy harvesting techniques with higher wearability, stretchability, durability, washability, and mass production ability are required to fulfill the new requirement [122]. Bearing this proposal, the first piezoelectric nanogenerator (PENG) was reported in 2006 based on piezoelectric ZnO nanowires (NWs) by Professor Z L Wang's group, as shown in figure 1(C), (iii) [123], which can generate electric power with tiny physical motions and work in an extensive frequency range [124]. Since then, a large number of PENGs have been designed based on two main approaches: layer stacking and yarn intersection for on-body electricity generation [125–127]. And PENGs have shown great potential as a compelling approach as the power supply for wearable devices in inflexibility and durability [128–131]. Further, in 2012, a triboelectric nanogenerator (TENG) that uses contact electrification and electrostatic induction was also proposed by Professor Z L Wang's group [132]. Compared to other energy scavenging devices, TENG advantages in broad material choices, low cost, simple fabrication process, large output in low frequency, versatile operation modes, high scalability, and wearable and implantable compatibility [133–135], with some representative devices shown in figure 1(C), (iv) [132, 136–138]. TENG stands out not only as a promising power supply in harvesting biomechanical energy for wearable and implantable electronic devices, but also as an auxiliary energy unit to increase the energy efficiency for energy harvesters aiming at scavenging mechanical energy from various energy sources, including vibrational energy, wind energy, and ocean energy [139–141]. In the past decade, TENG has received intensive efforts globally in a large number of aspects, including but not limited to energy density, structure innovation, stability, biocompatibility, surface treatment, circuit design, and systematic integration [142–144].

Together with the development in the energy harvesting techniques from the original energy transferring mechanisms, energy enhancement strategies have also been deeply explored to increase energy efficiency. To harvest mechanical energy in the ambient environment, which is generally in an extensive frequency range, broad bandwidth is always one of the most significant research directions achieved through frequency up-conversion, multi-DOF system, and nonlinearity system [145–148]. Circuit designs also play an essential role in the advancement of output performance, including but not limited to an energy management unit to charge devices more efficiently [149, 150], a bennet doubler combined with switches to increase the current density [151, 152], and regulator design to generate a stable direct current (DC) output [153, 154]. Besides, single energy transferring mechanism has its specific advantages but inevitably also shows its imperfection at the same time. Therefore, hybridized energy harvesters with the combination of multiple energy transferring mechanisms have also been massively reported to better leverage the characteristics of each principle [31, 155, 156]. Moreover, the energy output is further increased through efficiently scavenging energy from various sources [36, 157, 158].

Based on the advancement of energy harvesting technologies, the self-sustainable functional system became realizable with the further integration of power management circuits, energy storage units, functional devices like multiple sensors, and wireless data transmission units. Over the past few years, a large number of researches toward self-sustainable systems in environment monitoring, body sensor network, and therapeutic treatment have been reported, such as gas sensing [159, 160], temperature sensing [161], humidity sensing [34], healthcare monitoring [28], vehicle monitoring [162], and neural stimulation [163, 164]. Recently, the burst of artificial intelligence (AI) technology has further enriched the functions and applications of sensing systems. The conventional manually analyzing method for sensory data naturally can only extract shallow features [165–167]. With the help of machine learning and deep learning to learn high-level features of the raw data, various information collected by sensors can now work in a more complicated and synergetic way [168, 169]. In-edge techniques including human-machine interface, gesture recognition, smart home, digital twin, and virtual and augmented reality become available with the combination of sensing systems and AI technology [30, 32, 33, 35]. Although the currently proposed AI-assisted systems are based on self-powered sensors with external power supply for other functional units, we believe the AI-assisted self-sustainable system will be vigorously developed with the ongoing improvement of energy harvesting technologies.

This review focus on the evolution progress of micro-scale vibrational energy harvesters to nanogenerators towards a self-sustainable functional system and, finally, the AI-assisted self-sustainable system. Firstly, we provide a brief overview of the MEMS-based VEHs and PENGs, followed by a detailed introduction of TENGs. Then, we discuss the broad applications of TENGs in the energy harvesting design for both biomechanical energy and mechanical energy, as well as the energy enhancement strategies for them. In the next section, self-sustainable systems enabled by the advancement of energy harvesting techniques are presented. Moreover, we summarize the recently reported work of AI-assisted systems with self-powered sensors. Based on the above information, we finally provide the conclusion and perspective at the end of this review.

2. MEMS-based vibrational energy harvesters and piezoelectric nanogenerators

Typically, there are three types of MEMS-based VEHs, based on electrostatic effect, electromagnetic induction, and piezoelectric effect. The MEMS EM-VEHs normally consist of a seismic mass made by magnetic materials and a coil, and the current can be induced through their relative movement based on Faraday's Law, as demonstrated in figure 2(A), (i). The first actual MEMS EM-VEH was reported and measured by Professor Shearwood and Professor Yates in 1997, which achieved a maximum RMS output power of 0.3 μW under the resonant frequency of 4.4 kHz [170]. Figure 2(A), (ii) shows a MEMS EM-VEH with multiple vibration modes [53]. A permanent magnet is fixed on a supporting beam and attached to a MEMS chip with a movable circular mass. The center mass is suspended by a circular spring to enable both in-plane and out-of-plane vibrations. And the center mass also served as the movable coils with three diamond-shaped Al coils deposited on it. This EM-VEH was characterized by three different vibration modes, with the direction along the z-axis,

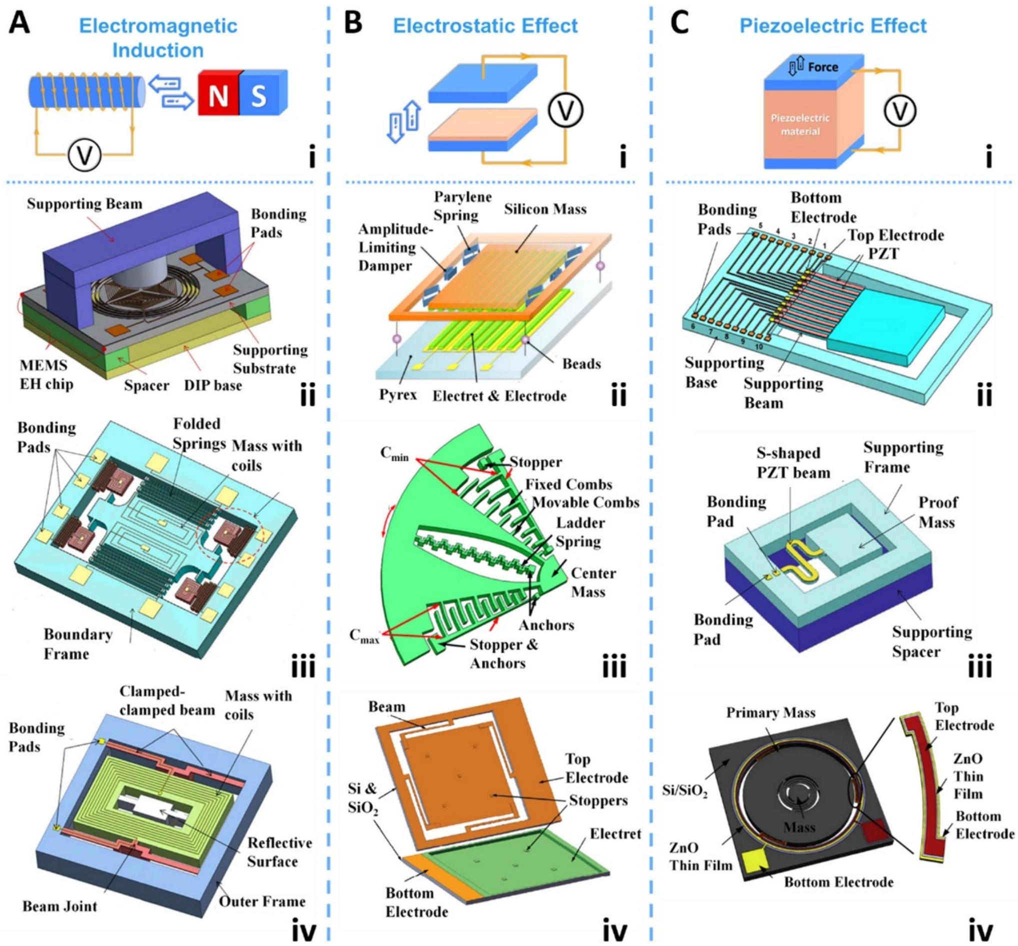


Figure 2. Working principle and typical devices proposed recently for (A) MEMS-based EM-VEHs. Reproduced from [53]. © IOP Publishing Ltd. All rights reserved. Reprinted with permission from [54]. Copyright (2014), AIP Publishing LLC. © [2014] IEEE. Reprinted, with permission, from [134], (B) MEMS-based E-VEHs Reproduced from [173]. © IOP Publishing Ltd. All rights reserved. Reproduced from [174]. © IOP Publishing Ltd. All rights reserved. © [2016] IEEE. Reprinted, with permission, from [175], (C) MEMS-based P-VEHs © [2012] IEEE. Reprinted, with permission, from [105]. Eprinted by permission from Springer Nature Customer Service Centre GmbH: Microsyst. Technol. Springer [179] (2012). Reprinted from [185], Copyright (2019), with permission from Elsevier.

and 60° and 150° with respect to the x-axis, with the overall power density of 0.444 μW cm^{-3}, 0.242 μW cm^{-3}, and 0.125 μW cm^{-3}. Based on a new design to further increase the circular mass area and to apply the softening of the circular spring-mass system, an EM-VEH with a wide frequency range was also proposed. Figure 2(A), (iii) shows an EM-VEH with broad frequency enabled by four small mass-spring structures fixed on the frame around the center mass [171]. When the external excitation reaches a certain level, the center mass will engage with the small mass-spring structures, thus induce the spring stiffening effect. A maximum normalized resonance offset with the value of 78.7% has been achieved in this work under the acceleration of 3 g, with the peak power density of 56 nW cm^{-3}. Another MEMS EM-VEH with wide operation bandwidth is shown in figure 2(A), (iv) [54]. Through balancing of structure parameters of the two clamped-clamped beams on each side, three different vibration modes, including out-of-plane mode, torsion mode, and twist mode, can have original resonant frequency close to each other. Further combined with the spring softening mechanism, the vibration mode with lower frequency would be able to engage with neighboring vibration mode with higher frequency, thus enable the frequency broadening phenomenon and achieve an ultra-wide operation bandwidth. Under the acceleration of 1 g, the resonance frequency can be extended from its original 62.9 Hz to 383.7 Hz.

MEMS E-VEHs mainly consist of a structure with variable capacitance under external excitations and a pre-charged electret layer to provide the voltage bias continuously, as depicted in figure 2(B), (i). Considering the relative moving direction between the movable and static combs, E-VEHs can be divided into three main types, namely the in-plane overlapping, in-plane gap closing, and out-of-plane gap-closing [58, 72]. As shown in figure 2(B), (ii). In 2010, Professor Y Suzuki's group at the University of Tokyo designed an E-VEH with an in-plane overlapping structure based on an electret material named CYTOP, which has an extremely high surface charge density compared to previously applied conventional polymer electret materials like Teflon AF [172, 173]. With a novel electrostatic levitation method to avoid the stiction, a maximum output power of 1 μW has been achieved with an active area of 11.6 $\times$ 10.2 mm^2 under 63 Hz and 2 g acceleration. To increase the capacitance variation and the output power, another E-VEH with the in-plane overlapping structure was designed as shown in figure 2(B), (iii) by Professor B Yang and Professor C Lee in 2010 [174]. With the rotary comb and ladder spring structure, maximum capacitance variation of 8 pF for one set of fixed combs is achieved under a resonant frequency of 110 Hz and acceleration of 2.5 g at 1 atm with the device volume of 39.4 mm^3, and the maximum output power of 0.39 μW has been obtained. Figure 2(B), (iv) shows an E-VEH with the out-of-plane gap-closing structure put forward by Professor F Wang's group in SUSTech [175]. A pre-charged CYTOP layer was also applied to provide the bias, and stoppers were added on the bottom plate to achieve a broad bandwidth. The maximum power output of 4.04 μW has been achieved under the acceleration of 1 g and frequency of 155.8 Hz, and average output power of 2.22 μW has been obtained under random vibrations with 1 g acceleration and 160 $\pm$ 12.5 Hz frequency range.

MEMS P-VEHs are based on the piezoelectric effect, which was firstly reported by J Curie and P Curie in 1880 [176]. This effect describes a phenomenon that certain solid materials are able to generate electric charges if undergoing an external mechanical strain or stress due to the induction of polarized electric dipole moment, as demonstrated in figure 2(C), (i). Start from the 1960s, the ferroelectric lead zirconate titanate [PZT or $Pb(Zr_{1-x}Ti_x)O_3$] is the material with the widest utilization in P-VEH for its high piezoelectric coefficient, compatible with MEMS fabrication process and low cost [177]. A MEMS P-VEH with PZT thin film using d_{33} piezoelectric mode was proposed by Professor J Y Park's group in 2010 [178]. A $PbTiO_3$ layer was applied as an interlayer to further increase the piezoelectric property of the PZT thin film, and interdigital shaped Pt electrodes were deposited on the PZT thin film to collect the voltage output of d_{33} mode, which is more sensitive to the external vibration compared to d_{11} mode. The maximum output of 1.1 μW has been achieved for this work under the acceleration of 0.39 g and the resonant frequency of 528 Hz. And the corresponding normalized power density reaches 7.3 mW cm^{-3} g^{-2}. To harvest the mechanical energy from vibration sources in the environment more sufficiently, a MEMS P-VEH with low resonant frequency and wide bandwidth was designed as shown in figure 2(C), (ii) [105]. Due to the amplitude limitation tuned by a spacer mounted on the backside of the P-VEH, an operation frequency bandwidth of 17 Hz was measured, and the corresponding normalized frequency bandwidth reaches 0.47. After that, a MEMS P-VEH with further lower resonant frequency and driven acceleration was designed based on an S-shaped spring, as shown in figure 2(C), (iii) [179]. At the driven acceleration of 0.06 g, maximum normalized power of 0.31 μW g^{-2} has been achieved. And the nonlinear phenomenon can be induced with larger driven acceleration by a mechanical stopper to broaden the bandwidth, and the threshold acceleration can be tuned by varying the distance of this stopper. Through replacing the mechanical stopper with another P-VEH with a much higher resonant frequency as a frequency-up-conversion stopper, the low-frequency vibration can be converted to self-oscillation at the high resonant frequency and further improve the efficiency and operation bandwidth. Besides PZT, other new materials like single-crystal piezoelectric ceramic lead magnesium niobate—lead zirconate titanate (PMN-PZT) [180] and lead-free materials like barium titanate ($BaTiO_3$) [181], aluminum nitride (AlN) [182], and zinc oxide (ZnO) [183] have also been utilized to piezoelectric energy harvesters. Compared with PZT, lead-free piezoelectric materials are more environmentally friendly. While among them, P-VEHs based on ZnO thin film also advantages in the simple fabrication process for no requirement for poling or post-annealing [184]. A P-VEH based on ZnO thin film is shown in figure 2(C), (iv) [185]. The proposed P-VEH is composed of two sub-systems, with one inner system consisted of a small circular mass with high resonant frequency and one outer system facilitating the low resonance. As shown in the figure, ZnO thin film is deposited and patterned on the top of the outer arc beams for harvesting vibrational energy, with a thickness of 3 mm. Two resonant peaks and the maximum power normalized power density of 1.75 $\times$ 10^{-7} W cm^{-3} g^{-2} are successfully achieved.

In 2006, the first piezoelectric nanogenerator (PENG) was proposed by Professor Z L Wang's group based on ZnO nanowires (NWs) [124]. And the vertically and laterally aligned ZnO NWs with the help of polymethyl methacrylate (PMMA) to achieve a synchronized charging and discharging process for better output performance were further designed by Professor Z L Wang's group in 2010, as shown in figure 3(A), (i) [186, 187]. In 2012, Professor Y Park's group integrated ZnO NWs with a charged dielectric film on a textile substrate for the actual applications in wearable devices, as shown in figure 3(A), (ii) [188]. This PENG with a textile substrate is able to provide an output current of 2.5 μA and an output voltage of 8 V. Figure 3(A), (iii) shows another typical PENG design fabricated with PDMS and $BaTiO_3$ nanopillars (NPs) by Professor Z Li's group [189]. The mixture of PDMS elastomer and $BaTiO_3$ NPs are prepared and molded to a rectangular sheet. And the Cr layer and Al layer are deposited by magnetron sputtering onto the upper and lower surfaces as two electrode layers. Also In 2015, Professor S Kim's group constructed a stable PENG fiber based on polyvinylidene fluoride-cotrifluoroethylene (PVDF-TrFE) shown in figure 3(A), (iv) [190]. Sheets wrapped by carbon nanotubes (CNTs) and silver-coated nylon were applied as the outer electrode and inner electrode, respectively. This PENG fiber can not only generate a power density over 50 μW cm^{-3} but also are with high flexibility, stretchability, and stability. Recently, PENGs also have received great development and exploration in output performance and applications. Based on a new piezoelectric material Sm-PMN-PT, a PENG with a three-dimensional intercalation electrode to increase the output power density was designed, as shown in figure 3(B) [191]. Previously, the interdigital electrode design with two-dimensional was widely applied in piezoelectric energy harvesters, while this design has the limitation of the requirement to balance the strip width

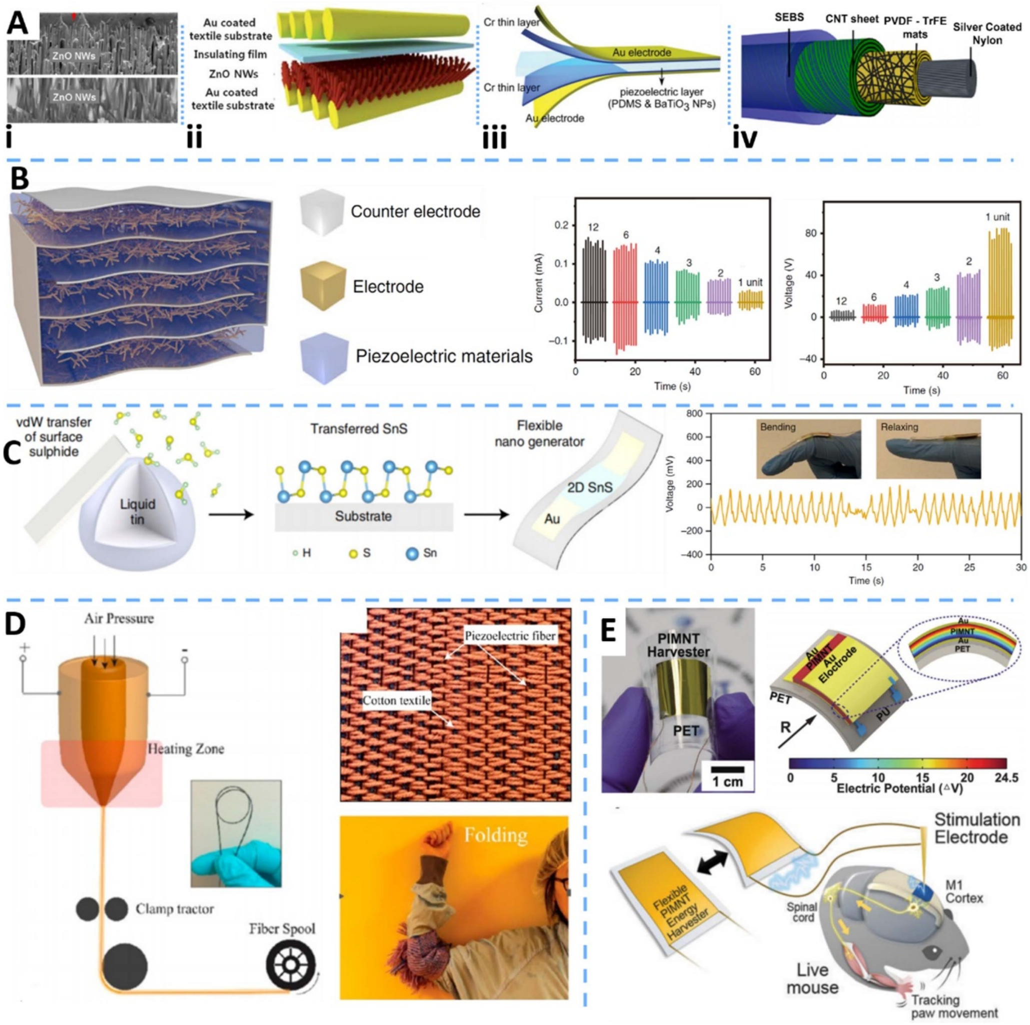


Figure 3. Piezoelectric nanogenerator: (A) typical devices. Reprinted with permission from [186]. Copyright (2012) American Chemical Society. Reproduced from [188] with permission of The Royal Society of Chemistry. [189] John Wiley & Sons. © 2015 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. [190] John Wiley & Sons. © 2015 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, (B)–(E) Recently development and applications: (B) A PENG with three-dimensional intercalation electrode. Reproduced from [191]. CC BY 4.0, (C) A PENG with liquid metal-based synthesis of SnS monolayer Reproduced from [192]. CC BY 4.0, (D) PENG fibers for wearable textile Reprinted with permission from [193]. Copyright (2017) American Chemical Society, (E) Flexible PENG for deep brain stimulation Reproduced from [194] with permission of The Royal Society of Chemistry.

for either low output current density or poor stain uniformity [112]. The PENG is divided into multiple stackable units sandwiched by a pair of well-matched electrodes. The structure becomes similar to a capacitor and ensures the electric field is evenly distributed, making the materials can be fully polarized even the thickness of the electrode layer is very thin. To fabricate this 3D PENG, each stackable piezoelectric thin film is firstly fabricated separately with an average thickness of 110 μm. And the 3D PENG is realized through the stacking of multiple single units. All the Al/PDMS electrodes on the right side and left side are connected together, respectively. The maximum output current of 329 μA has been achieved for this PENG with an effective area of 1.2 cm^2 stacked with six units. Except for conventional piezoelectric ceramic thin-films, two-dimensional (2D) materials also provide viable avenues in this field for their ability to withstand large strains and potential of large piezoelectricity. The tin monosulphide (SnS), as one of the group IV mono-chalcogenides, has been envisioned theoretically to have excellent piezoelectricity. However, its applications have been greatly hindered by the difficulty in the fabrication for large-scale surface coverage. Through the proposed synthesis process via the van der Waals exfoliation technique as shown in figure 3(C), a large scale and highly crystalline semiconducting monolayer SnS was successfully achieved [192]. This monolayer shows a promising piezoelectric coefficient of about 26.1 pm V^{-1} and was further applied to fabricate a PENG. Attributing to the large d_{11} value, a high energy conversion efficiency is realized, with a large average peak voltage output around 150 mV at only 0.7% strain. And its suitability for low-frequency motion energy harvesting and wearable applications was also demonstrated. Thanks to the flexibility of PENGs, they can also be weaved seamlessly into fabrics for fabricating multifunctional wearable devices. Based on the fiber drawing process, piezoelectric fibers can be obtained and further be weaved into a cotton textile, as shown in figure 3(D) [193]. The fabricated CNT/PVDF microstructured fibers show great durability with high piezoelectric output, with up to 6 V under 26 000 operation cycles. And the textile can be worn as cloth with good wearable comfort. In a 90° bend-release action of the elbow, the piezoelectric textile is able to generate the output with ∼10 V in open-circuit voltage and 5–15 nA in short-circuit current. Furthermore, the PENGs can also serve as a promising platform for self-powered medical devices. Figure 3(E) shows a flexible PENG with an indium modified crystalline $Pb(In_{1/2}Nb_{1/2})O_3$–$Pb(Mg_{1/3}Nb_{2/3})O_3$–$PbTiO_3$ (PIMNT) thin film encapsulated by a plastic substrate [194]. Cr/Au layers serve as the top and bottom electrodes deposited by sputtering. Due to the high piezoelectric charge coefficient d_{33} of up to ∼2700 pC N^{-1}, an extremely high current of 0.57 mA can be achieved with slight bending. And the generated current is enough to meet the requirement of inducing forearm movements in mice.

3. Transducing mechanisms for triboelectric nanogenerators

While PENGs do have advantages in power density, flexibility, and have been developed for a long time, the drawbacks of piezoelectric materials also limit their applicatioons, such as difficult fabrication process and high pollution caused by lead. Since Professor Z L Wang's group inventing the TENG in 2012 [132], it has become a promising energy harvester due to the advantages of low-cost, easy fabrication, and high conversion efficiency [140, 141, 195–197]. The TENG can convert mechanical energy into electrical energy based on the coupling of the triboelectric and electrostatic effects, which also provides effective means for studying triboelectrification and overturns conventional understanding of electrostatic effect being harmful in both daily life and industrial manufacturing. In the past years of research works focusing on materials' selection and improvement [198–200], structures' design and optimization [201–204], and management circuits' application and optimization [150, 205–207], the TENG has been utilized in harvesting distributed and low-frequency mechanical energy such as wind energy [208–210], blue energy [211–213], and biomechanical energy [143, 214, 215], further successfully powering electronics like LED arrays, thermometers, and wireless sensors.

In figure 4(A), Xu *et al* have proposed an electron-cloud-potential-well model for explaining contact-electrification (CE) or triboelectrification (TE), which is based on real-time quantitative measurements with a TENG worked under high temperatures [216]. The electron clouds of material A and material B are overlapped due to the 'screening' between the two materials introduced in physical contact, and then electron could hop from the atom of material A to the atom of material B by asymmetric double-well potential. After the separation of materials A and B, most of the electrons transferred to material B will be kept due to the energy barrier. Therefore, the contact electrification occurs with the positively charged material A and negatively charged material B. The transition probability of electron transfer as a function of the interatomic distance has been calculated to support the electron-cloud-potential-well model [217, 218]. Besides basic disclosure of triboelectrification in solid-solid interface [219–223] and liquid-solid interface [224–229], adjustable properties like temperature [230], UV light irradiation [231], the atmosphere [232], surface curvature [233], functional groups [234, 235] have been proved as influence factors for surface charge accumulation, which indicate effective strategies of preparing high-output TENG.

Generally, kinds of TENGs are divided into four main working modes as shown in figure 4(B): vertical contact separation mode (VCSTENG), contact-sliding mode (CSTENG), single electrode mode (SETENG), and free-standing triboelectric layer mode (FSTENG) [236–238]. As the most basic structure, the VCSTENG utilizes relative movements perpendicular to the interface between a pair of electrodes, where polymer electrodes are deposited with conductive electrodes. A representative example is illustrated in figure 4(C): Wang *et al* proposed an arch-shaped VCSTENG consisting of a multi-layer polymer electrode and a single-layer metal electrode [239]. The separation distance in the VCSTENG can be achieved by arches and other internal structural supports [240–244] or external support like springs and sponges [245–248]. During the contact-separation processes, the potential changes between the two electrodes vary with changing distance, and external current flows are generated to keep charge balance. In contrast, the CSTENG utilizes relative displacement parallel to the contact interface, and a representative device reported by Wang *et al* has illustrated in figure 4(D) [249]. The reciprocating sliding of two contacted electrodes leads to electric flowing to keep charge balance. Similarly, this model can be applied in devices of cylindrical rotation [250, 251] and disc rotation [252, 253]. In figure 4(E), a representative SETENG has proposed by Chen *et al*, constructing a single polymer layer deposited with a metal layer on the bottom [254]. The working principle of SETENG is similar to VCSTENG, and electric flows are generated due to changing distance between the external object and the electrode. Typically, this mode is most useful for harvesting mechanical energy from moving objects and relieving the problem of wires and is widely applied in achieving tactile sensing [255–258]. As for the FSTENG reported by Wang *et al* and shown in figure 4(F), a freestanding object is forced to move along a similar plane with other stationary electrodes. And electric flows between electrodes are generated as charge balance changes with moving objects. The electrodes in the FSTENG can be designed into a series of electrodes for harvesting mechanical energy in rotating [259–261] and sliding [262–264].

To sum up, the TENG is a wide-ranging technology for various kinds of mechanical energy and has presented promising applications in environment monitoring [265, 266], human-machine interface [133, 169], smart home [168], and healthcare [267, 268]. Benefit from plentiful material's selections and versatile structures, the TENG shows the potential of harvesting renewable energies eco-friendly and efficiently.

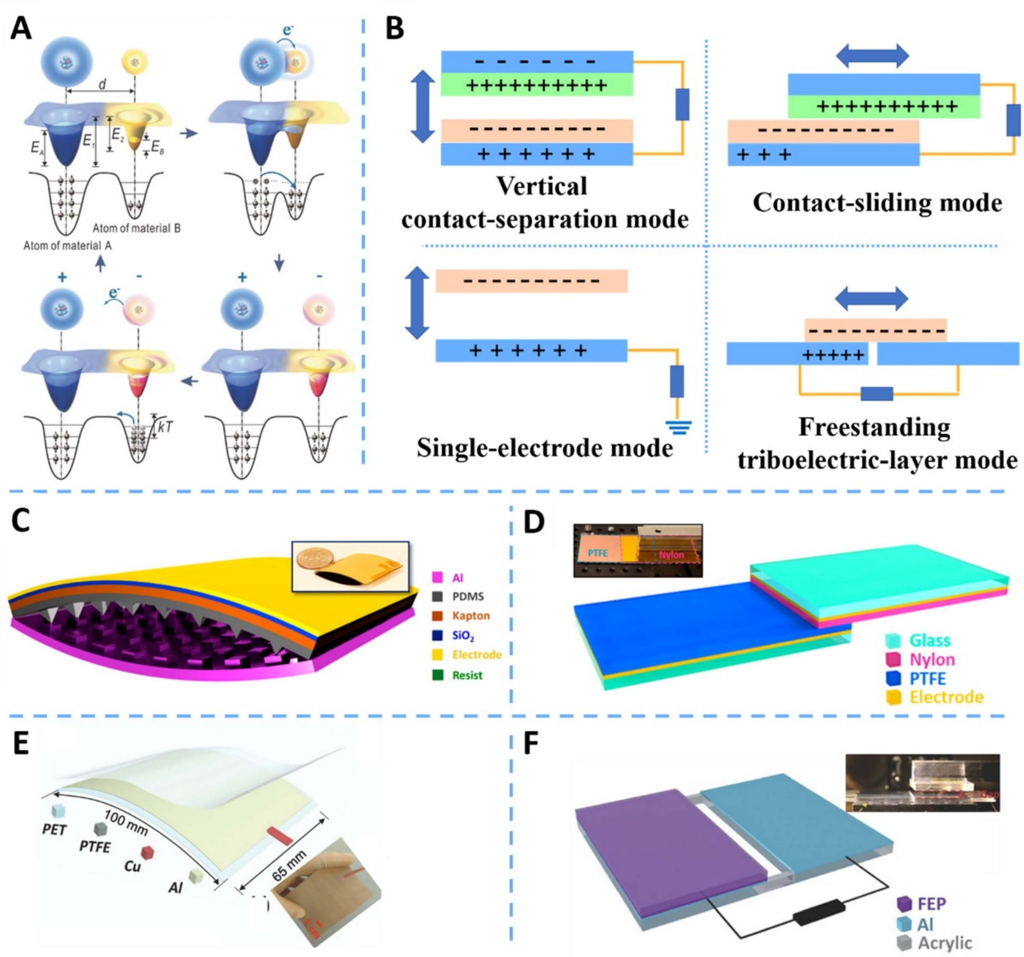


Figure 4. Triboelectric nanogenerator: principles & representative devices. (A) The overlapped electron-cloud model proposed for explaining contact-electrification. [216] John Wiley & Sons. © 2018 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (B) Schematic of four main working modes of the TENG. Typical TENG devices with: (C) vertical contact separation mode. Reprinted with permission from [239]. Copyright (2012) American Chemical Society, (D) contact-sliding mode. Reprinted with permission from [249]. Copyright (2013) American Chemical Society, (E) single electrode mode. [254] John Wiley & Sons. © 2016 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, and (F) free-standing triboelectric layer mode. [271] John Wiley & Sons. © 2014 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

4. Human motion-based TENG devices

With the gradually completed development of triboelectric principles and charge generating modes [132, 196, 236, 238, 239, 249, 269–271], the TENG included energy harvesters and self-powered sensors have been boomed focus on the energy source varied from the natural environment [162, 204, 211, 272–275] to human body motion [116, 133, 135, 276–279]. To push forward the revolution of TENG, especially under the healthcare and physical signals detection framework, there are plenty of studies providing various approaches for the future realization of self-sustainable power supply and sensors for wearable electronics. Apart from rigid mechanical components based on TENG for human body motion monitoring and healthcare applications, e.g. exoskeleton auxiliary structures [30, 35, 280–283], many flexible materials and devices are envisioned to be a great promising solution to fulfill the aim of energy harvesting and sensing from a human body, including stretchable rubber-based TENG [284–286], woven fabric-based TENG [287–289], textile-based TENG [28, 33, 290, 291] and electronic skin-based TENG [163, 292–294].

Wang *et al* propose a stretchable and shape-adaptable single-electrode triboelectric nanogenerator for harvesting human motion energy, as shown in figure 5(A). The innovative point of the rubber-based TENG mainly uses liquid-based electrodes, which are composed of potassium iodide and glycerol (KI-Gly) liquid electrolyte. By filling the liquid-based electrode in the silicone rubber mold, the TENG exhibits its excellent stretchability and multiple deformability. Thanks to these good properties, the liquid-based single electrode TENG demonstrates stable output performances. That is, operating under 250% tension stretching for 10 000 cycles of repeated contact-separation motion, the TENG remains original state without deterioration. Besides, the output achieves high performance with an open-circuit voltage of 300 V, short-circuit current density of 17.5 mA m^{-2}, and maximum

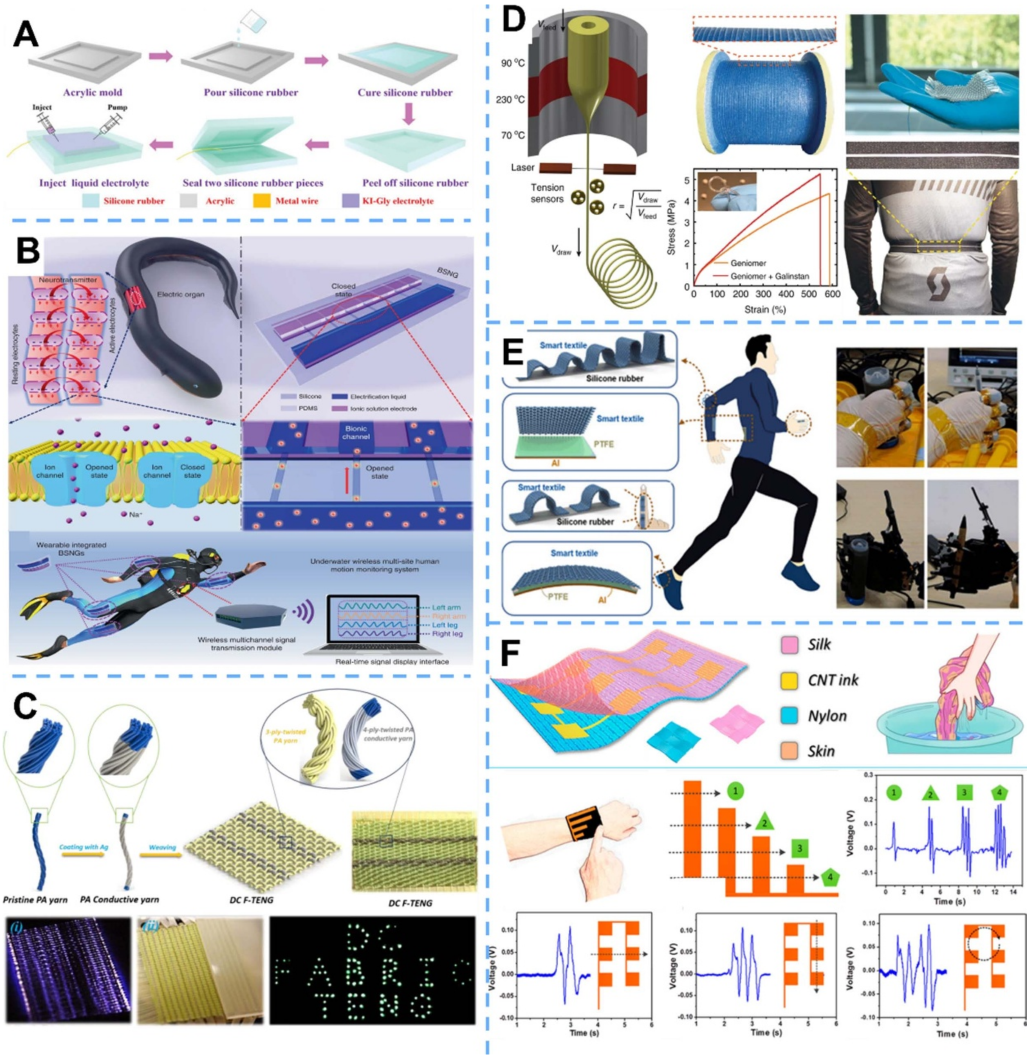


Figure 5. Various wearable triboelectric nanogenerators for a wide range of sensing applications. (A) Fabrication process of a stretchable and shape-adaptable triboelectric nanogenerator based on biocompatible liquid electrolyte. Reproduced with permission from [295]. CC BY-NC 4.0. (B) A bionic stretchable nanogenerator for underwater motion sensing. Reproduced from [300]. CC BY 4.0. (C) Schematic illustration and fabrication process of a triboelectric fabric nanogenerator for harvesting biomotion. Reprinted with permission from [305]. Copyright (2020) American Chemical Society. (D) Demonstration of super-elastic liquid metal fibers and textiles based on the triboelectric mechanism with self-powered breathing monitoring and gesture sensing capabilities. Reproduced from [306]. CC BY 4.0. (E) Schematic diagram of a smart textile based on TENG for monitoring daily activities of humans and photographs for robotic hand control. Reprinted from [312], Copyright (2019), with permission from Elsevier. (F) Self-powered triboelectric electronic textiles for intelligent Human-Machine Interaction [256].

output power of 2.0 W m^{-2}. The stretchable TENG configures different body joints for human biomechanical energy collecting, such as arm shaking, human walking, and hand tapping. For practical employment, multiple commercial electronics can be completely powered to achieve human body monitoring and health conditions assessment [295]. To propel the development and application of the stretchable rubber-based TENG on human body energy harvesting and sensing, more scenarios of different activities are included [296–299]. Zou *et al* present a bionic stretchable triboelectric nanogenerator applied to harvest energy and sense signals from underwater human motions. The inspiration comes from an electric eel. By mimicking the structure of ion channels on the cytomembrane of electrocyte and using polydimethylsiloxane (PDMS) and silicone for manufacturing a mechanical control channel under the stress-mismatch principle, a flexible, stretchable, and mechanical responsible TENG is designed to use in wet and dry environments, especially perfectly suit for underwater employment, as shown in figure 5(B). For the stretchability, it shows excellent tensile fatigue resistance, which operates by a linear motor under 50% strain for over 50 000 cycles. Based on the novel bionic structure and excellent performance, it can provide two unique working modes, which allows the TENG to generate over 170 V open-circuit voltage in dry conditions and over 10 V in liquid conditions. In this way, the bionic stretchable nanogenerator can accomplish a human body motion sensor and a promising alternative power source for wearable electronics in any surroundings [300].

In addition to the stretchable rubber-based wearable TENG for human motion sensing and kinetic harvesting, woven fabric-based nanogenerators have emerged as great potential and comfortable candidates to achieve healthcare monitoring and disease pre-diagnosis in daily life [301–304]. In figure 5(C), Chen *et al* report a TENG intelligently take advantage of the annoying and harmful electrostatic breakdown phenomenon of clothes to directly acquire DC output to store and power wearable electronics. Compared to the normal traditional fabric TENGs with an alternating current (AC) output, the DC fabric TENG handle without rectifier bridge demonstrates great convenience and high efficiency in practice. With its high output performance, a size of 1.5 cm $\times$ 3.5 cm DC fabric TENG sliding at 2 Hz can easily flicker 416 serially connected light-emitting diodes (LEDs) or 115 LEDs marked as letters 'DC FABRIC TENG'. A sliding cycle can light up these LEDs for one time, which demonstrates the high efficiency of the power generation. Furthermore, by weaving yarn supercapacitors into the TENG, a lightweight, flexible, wearable, low coast, and high-efficiency power supply is fulfilled to harvest human motion energy from daily activities [305]. Owing to the high output and power storage of the woven fabric-based TENG, it can act as a health-monitoring electronics supply for multiple signals acquisition. Furthermore, we have seen the functionalities on direct body motion tracking and self-sustained wearable systems. As shown in figure 5(D), Dong *et al* use superelastic liquid metal to fabric a scalable and stretchable triboelectric fiber with a micro-textured surface and several electrodes integration. With the process of thermal drawing, the superelastic TENG accomplishes almost the same efficiencies as planar systems. This kind of fibers displays high sustain strains under repeated large deformations (up to 560%), good electrical output performance (up to 490 V, 175 nC), and deformable machine-washable. In the long run, the triboelectric fabric fibers can not only act as the energy harvester but also can achieve multi-functional smart textiles, including breathing monitoring and gesture sensing capabilities [306].

Moving forward, a suit of wearable textile-based cloth is taking into account two characteristics of the wearing comfort and practical monitoring healthcare applications. Wide sorts of applications are included to measure the physical motions and signs and symptoms of humans, along with the ambient environment for healthy living conditions, which can broadly apply to the patients and elderly people for daily monitoring and rehabilitation training [307–311]. He *et al* develops a triboelectric nanosensor on textile with a simple dip-coating method to achieve multiple functionalities, including energy harvesting, physical sensing, and gas sensing. Using the dip-coating method with coating solutions of poly (3,4-ethylene dioxythiophene) polystyrene sulfonate (PEDOT: PSS) with polytetrafluoroethylene (PTFE) pairing, the TENG can obtain high output performance (a maximum output power density of 2 W m^{-2} under 2 Hz foot stepping) and low matched impedance (as low as 14 MΩ). This TENG tactfully leverages a height-varying multi-arch structure to achieve hand gestures monitoring for interpreting American Sign Language and robotic hand feedback controlling. In addition, the arch structure with the PEDOT: PSS coated textile realizes a large strain sensing range from 10% to 160%, which helps to adapt different human/robot fingers and detect multiple angle bending. Not only for applying to gesture monitoring but the PEDOT: PSS coated textile would also benefit the CO_2 concentration detection of the human ambient environment. Moving forward, the smart textile can be integrated with wearable suits to realize great potential as both energy harvesters and various functional self-powered sensors for multiple healthcare applications [312].

Beyond smart textile for real clothes using, the electronic skin (e-skin) is highly interesting for the advantages of high flexibility, stretchability, sensitivity, stability, which has gained wide attention in human-machine interactions and AI [31, 313–316]. Peng *et al* present a self-powered electronic skin, using all-nanofiber triboelectric nanogenerators and a sandwiching fabrication to attain a breathable, biodegradable, antibacterial, and conformality wearable nanogenerator and nanosensor. The sandwiching fabrication method employs polylactic-co-glycolic acid (PLGA) and polyvinyl alcohol (PVA) as upper and lower layers, with inserting silver nanowire (Ag NW), a sandwich-like micro-to-nano hierarchical porous structure is manufactured. Furthermore, the properties of antibacterial and biodegradable capability change with the variation of the concentration of Ag NW, PVA, and PLGA. Thanks to this novel structure, the e-skin not only acquires a high specific surface area for contact electrification but also attains numerous capillary channels for thermal-moisture transfer. This kind of e-skin is used on a human body to achieve physiological signal sensing and joint movement detecting, realizing real-time and whole-body movements and signals monitoring, which provides a super practicable hospital equipment-carried around with multi functionalities [317]. As depicted in figure 5(F), a self-powered washable electronic textile (E-textiles) is fabricated to apply in the aspects of touch/sensing performance and human-machine interfacing by Cao *et al* Owing to the interaction of the CNTs and fabrics, the E-textiles demonstrates great advantages in air permeability, satisfactory washability, and even mass fabrication. The excellent stability would hold great application prospects for future wearable suits and medical aids [256].

5. TENG-based hybrid energy generators

Considering that most IoT devices are adopted in the environment or human relative applications where exhibit abundant mechanical energy, various generators with mechanical energy harvesting ability will be most desirable. In this regard, TENG technology, due to its superior advantages of high output performance, simple fabrication, low cost, versatile operation modes, wide material availability, and implantable compatibility [116, 143, 208, 318], has been extensively explored for mechanical energy harvesting. Benefitted from the above merits, integrating TENG with other transducer mechanisms yields a promising research direction for hybridized mechanical energy harvesters. Furthermore, TENG-based

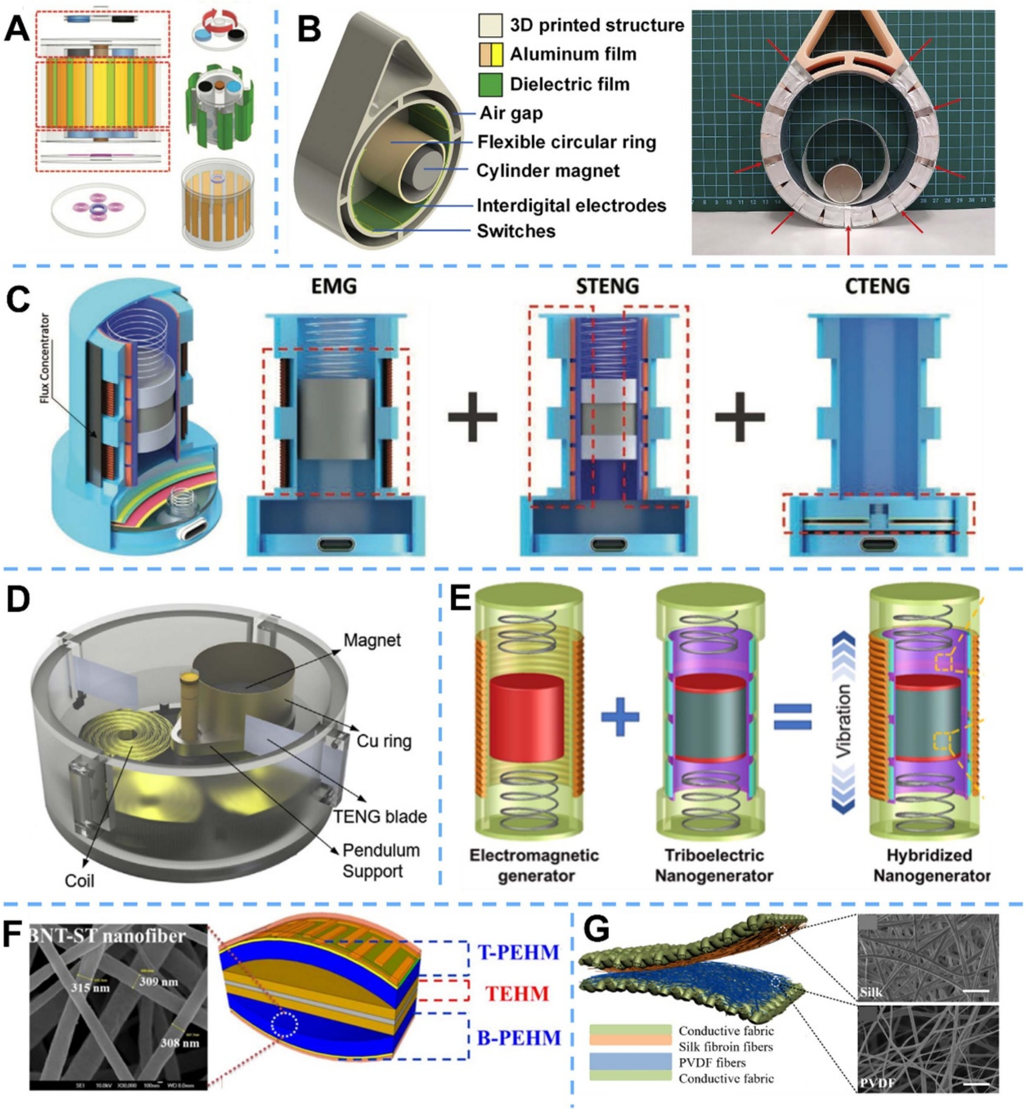


Figure 6. Hybridized mechanical energy harvesters. (A) an easily assembled electromagnetic-triboelectric hybrid nanogenerator. [322] John Wiley & Sons. © 2019 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (B) A hybridized TENG and EMG blue energy harvester based on a pendulum structure. Reprinted from [204], Copyright (2020), with permission from Elsevier. (C) A universal self-chargeable power module. [34] John Wiley & Sons. © 2020 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (D) A rotational pendulum triboelectric-electromagnetic hybrid generator. Reprinted from [281], Copyright (2019), with permission from Elsevier. (E) A highly miniaturized freestanding kinetic-impact-based hybridized nanogenerator. Reprinted from [280], Copyright (2020), with permission from Elsevier. (F) All-in-one piezo-triboelectric energy harvester module based on piezoceramic nanofibers. Reprinted with permission from [331]. Copyright (2020) American Chemical Society. (G) An all-fiber hybrid piezoelectric-enhanced TENG. Reprinted from [332], Copyright (2018), with permission from Elsevier.

hybrid energy harvesters integrated with power management circuitry, energy storage units, and functional components, a variety of systems with self-sustainability can be achieved for broad applications [311, 319–321].

As illustrated in figure 6(A), an easily assembled electromagnetic-triboelectric hybrid nanogenerator (EANG) was proposed by Zhong *et al* for collecting energies from multiple sources [322]. The proposed system consists of a cylindrical stator with multiple attached electrodes and a cylindrical rotator with several FEP films mounted on the outer surface. When the top driver of the device is driven to rotate by wind or water flow, the rotator will spin due to the magnetic coupling force, resulting in the contact-separation motion between the FEP film blades and the fixed Cu electrodes for triboelectric output generation. Meanwhile, the magnets in the bottom of the rotator will induce electromagnetic output in the copper coils fixed underneath the lower stator. With a rotating speed of 500 rpm, the maximum output power of the TENG and the electromagnetic generator (EMG) could reach 1.05 mW and 58.3 mW, respectively. The combined output power is sufficient to directly power various sensors, such as humidity sensors, thermometers, etc, indicating that the practical issues of sustainable power supply can be solved by such an HMEH strategy for the smart home.

The energy in the ocean area is one of the most promising renewable clean energy resources for large-scale practical applications. Conventional blue energy harvesters are mostly based on the EMG, while the optimal operating frequency of EMG is higher than 50 Hz. Not all water motions are suitable to be harvested by EMG, especially for those rectilinear motions that operate below 10 Hz. TENGs are capable of scavenging low-frequency (<5 Hz) mechanical energy with the advantages of low cost, high voltage, and simple fabrication. Moreover, the energy conversion efficiency of TENG can be further improved by integrating with EMG to form a hybridized system [211, 323–325]. As shown in figure 6(B), a hybridized blue energy harvester was designed based on a pendulum structure containing an interdigital electrodes-TENG, a switches-TENG, and an EMG [204]. The outputs of TENGs are enhanced by an optimized flexible circular ring supporting a rolling magnet. With a novel designed hybridized circuit, the output power can reach 95.4 mW at a load of 100 Ω. After the management circuit, a lithium battery of 200 mAh can be charged from 3.07 V to 3.35 V by this blue energy harvester with six hours of water wave impaction. The proposed device integrated with a solar cell panel and a Bluetooth low energy sensor can establish an all-weather IoT platform, which shows the potentials of battery-free IoT in ocean areas. In figure 6(C), a universal self-chargeable power module (USPM) is presented that can efficiently harvest ocean wave blue energy, human bio-mechanical energy, and vehicle vibration energy [34]. The proposed high-performance power module is comprised of a hybrid energy harvester, including one contact separation TENG, one sliding TENG, and one EMG, and a power management circuit. By implementing a multiple spring-based mechanical coupling design, the hybrid EMG and TENG system show high performance despite miniaturization under low acceleration ($\leqslant 1$ g) and low frequency ($\leqslant$6 Hz) vibration. The electromagnetic performance is further optimized by using a soft magnetic material-based flux concentrator, while electrospun nanofibers enhance the triboelectric performance. The USPM is a compactly designed device including a power management circuit, a battery charging circuit, built-in rechargeable storage, and a USB-C outlet, providing a DC power of a maximum 34.11 mW. It demonstrates the capability of harvesting blue energy and powering a wireless water health monitoring system using a PANI/LIG/PDMS-based pH sensor. Similar hybrid generators for vibrations were also reported [326, 327]. Figure 6(D) shows a rotational pendulum based TENG-EMG hybrid system, including a pendulum rotor, coils, TENG blades, and a cylindrical frame [281]. The unrestricted rotational movement of the pendulum enables the hybrid generator with wide applicability to low-frequency (<5 Hz) and irregular vibration. When the pendulum rotor rotates, the magnetic flux across each coil will change and generate the electromagnetic output. Besides, the Cu ring settled on the rotor will also contact with the PTFE intermittently during rotating for generating the triboelectric output. Based on the above configuration optimization, the maximum power density of the TENG and EMG can reach 3.25 W m^{-2} and 79.9 W m^{-2}, respectively, with a water wave frequency of 2 Hz and an amplitude of 14 cm. Combining these two elements, the proposed hybridized system is successfully demonstrated to integrate a buoy for utilizing the energy from waves, which shows the potential to directly drive various IoT sensors. In addition, the HMEH based on EMG and TENG also can be used to collect the energy from human motions. As shown in figure 6(E), a highly miniaturized freestanding kinetic-impact-based hybridized energy harvester for various human-induced vibrations was reported [280]. The rational integration of EMG and TENG into a common mechanical system can improve the power generation capability of the hybrid generator under the same mechanical input. For the testing using shaker at 5 Hz, the EMG and the TENG can produce a maximum power of 102.12 mW and 171.13 μW, respectively. For different body-worn positions of the hybrid generator under walking and slow running activities, a storage capacitor can be effectively charged up to various voltage levels according to the motion-induced accelerations. Moreover, two digital temperature-humidity meters and an array of commercial LEDs are simultaneously powered by the random vibrations of human motions. With the aid of a customized power management circuit, the output can be used to power modern electronics like smartphones, smartwatches, and wireless temperature sensors.

Except for integrating TENG with EMG to harvest mechanical energy directly from the living environment, another common method of TENG combining with PENG has triggered intensive research in the past decade [187, 328–330]. For instance, figure 6(F) shows a piezo-triboelectric hybrid energy harvester module (HEHM) [331]. The proposed all-in-one HEHM, as a green energy source for wearable devices, comprising a top-piezoelectric energy harvester module (T-PEHM) layer, a bottom-PEHM (B-PEHM) layer, and a triboelectric energy harvester module (TEHM) layer with an arch shape was characterized based on flexible piezoceramic nanofibers. The output performance of the T-PEHM and B-PEHM layers fabricated with an interdigitated electrode (IDE) was optimized by employing a z-axis array arrangement of the single modules. As shown in the figure of full-contact state, the piezoceramic nanofibers were stressed due to the sufficient displacement and pressing force, which can generate maximum piezoelectric energy. Meanwhile, the PEHM with IDE will show the d33 operating mode, which generates a higher voltage than the piezoelectric module with top and bottom electrode d31 operation mode. Based on this hybrid mechanism, the all-in-one HEHM could generate a maximum voltage of 253 V and a maximum power of 3.8 mW, which can charge a 0.1 μF capacitor to 25 V within 40 s. Moreover, figure 6(G) shows a textile-based triboelectric-piezoelectric nanogenerator (TPNG) with a multi-layer structure for collecting the mechanical energy from human motions [332]. Silk fibroin nanofibers and PVDF nanofibers were electrospun on the two conductive fabrics as TENG and PENG parts, respectively. The two parts were combined together to form a cloth-shape device, which has great mechanical flexibility as well as desirable wearing comfort. This process leads to the accordant working state of the TENG part and PENG part, which would induce the same potential direction and get the higher electric output. Therefore, TPNG achieved an outstanding maximum output performance with 500 V output voltage, 12 mA current, and 0.31 mW cm^{-2} power density through the well-collaborative work between TENG and PENG. Finally, a wearable self-powered real-time microsystem based on TPNG was demonstrated for fall-alert detection. The micro-cantilever is actuated by the instantaneous output of TPNG as a switch to sending the emergency message to a remote terminal for falling down detection.

Through the above works referred to TENG-based hybrid energy generators, mechanical stimulus either in types of rotations or vibrations are efficiently converted into electric power. In table 1, different energy harvesting units among hybrid devices are illustrated, resulting in TENG possessing relatively less weight ratio and volume ratio than EMG [34, 280, 281, 322, 326, 327]. Although EMG has relatively high output power and power density when compared with TENG, TENG has good advantages in energy harvesting with low frequency and broad operational bandwidth. Besides, it can also improve the capacitor charging performance for the hybridized system. Apart from the structure hybridization with other energy generators, TENG can also serve as a functional part through the material hybridization with piezoelectric materials to improve the output performance [331, 332]. Overall, TENG can contribute enhancement for hybrid energy generators in energy harvesting.

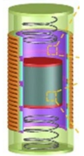
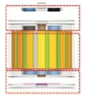
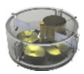
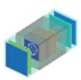
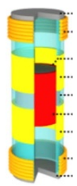
6. Output enhancement strategies for TENGs

As an emerging technology, TENG can effectively harvest varied environmental low-frequency mechanical energy. However, there is still a distance for commercial use of TENG due to the insufficient function modes and output performance. It is of great significance to enhance the output performance of the TENG and push forward the commercial process of TENG devices [333–335]. In addition to hybridized with EMG and PENG mentioned in the previous section, another approach for improving output performance of TENG is to utilize an optimum contact structure, effective circuit design, upgraded power management, etc [336–338].

First of all, TENG can be implemented by increasing the efficiency of contact electrification to enhance the surface charge density of TENG. For instance, figure 7(A) shows a high-efficiency bioinspired photoelectric electromechanical integrated nanogenerator by comprehensively utilizing solar energy and tidal energy, and a bioinspired photoelectric-electromechanical integrated TENG (Pem-iTENG) [339]. A composite membrane is constructed by a layer-by-layer self-assembly method of planting a type-II P-N heterojunction (TiO_2/PANI) on the surface of bionic cilia. Pem-iTENG accumulates numerous negative charges in the PDMS film due to the excess photogenerated electrons from photocatalysis and the triboelectric negative charges from contact electrification. Pem-iTENG shows the maximal output power density (17.23 mW cm^{-2}), open-circuit voltage (124.2 V), and the short-circuit current density (221.6 μA cm^{-2}) under the action of tidal waves and sunlight. More importantly, by referring to the method of evaluating power conversion efficiency in solar cells, Pem-iTENG exhibits a high energy conversion efficiency of 16.72%. Moreover, figure 7(B) shows a type of 'self-matched' tribo-piezoelectric nanogenerators (TPNG) with enhanced output based on the augmented triboelectric output [340]. The surface charge of TPNG is generated by PVDF that modifies the surface potential of the PET layer to match the electron-transfer direction of the spider silk during triboelectrification. Thus, the enhanced difference in potential wells depths between the spider silk and the PET/PVDF can significantly increase the number of transferred electrons and thereby boost the energy output. After encapsulating the device in a silk-based package, it can be implanted in the chest of a Sprague-Dawley rat for heartbeat energy harvesting and monitoring. Next, an outstanding improvement of TPNG can obtain a maximum instantaneous power density of 4016 mW m^{-2}. A large-scale and continuous roll-to-roll manufacturing process indicates that the 'self-matched' TPNG has great potential to approach the 'green' and the human-friendly intelligent IoT era. Figure 7(C) presents a microstructure-designed direct-current TENG (MDC-TENG) with a rationally patterned electrode structure to realize the miniaturized sliding block structure at the same time [341]. By tailoring the electrode structure, the surface charge density of MDC-TENG with the size of 1 cm $\times$ 5 cm can be improved to 5.4 mC m^{-2}. As a demonstration, the MDC-TENG can charge a commercial capacitor of 660 μF to around 0.05 V in 4.5 s. These excellent performances represent potential applications of the MDC-TENG in mechanical energy harvesting and motion vector sensing. Especially, its advantages of miniaturization and simple external circuit resulted from DC output provide a solution strategy for TENGs to be applied in small electronic device systems or MEMS as an energy supply resource or self-powered sensor.

Bennet doubler is a method of the charge pump for the continuous doubling of a small initial charge through a sequence of operations with three plates [342, 343]. Leveraging from this mechanism, figure 7(D) shows a self-sustained conditioning system that makes TENG work at high voltages for high-energy conversion [152]. The proposed system utilizes an unstable Bennet doubler combined with a high-voltage MEMS plasma switch in a 2-stage circuit. The hysteresis of the high-voltage MEMS plasma switch is controllable by topological design, and the actuation of the switch combines the principles of micro-discharge and electrostatic pulling, without the aid of power-consuming control electronic circuits. The harvested energy per cycle over time is improved by two orders of magnitude compared to the case using only a full-wave rectifier, and by 34 times compared to another case using a full-wave rectifier and a full-hysteresis switch in a 2-stage conditioning system, respectively. A maximum output current for a stable output DC voltage of 3.3 V is obtained with a 330 kΩ resistive load. Thus the practical available average power is 30 μW, corresponding to an energy per mechanical cycle of 6 μJ as the excitation frequency of the TENG is 5 Hz. The employment of the high-voltage MEMS plasma switch in the conditioning circuits can significantly push forward the practical and commercial applications of the energy harvesters by largely improving the system performance. Similarly, based on the Bennet doubler mechanism, figure 7(E) presents an out-of-plane design to achieve high-performance TENG [151]. The electrodes B

Table 1. Comparisons of different energy harvesting units among hybrid energy generator.

Ref.	Device	Output power	Weight	Volume	Power density	Capacitor charging performance
[34]		TENGs: 18.9 mW and 1.7 mW EMG: 717 mW	TENGs: 7.5 g and 1.2 g EMG: Magnet with spring (50 g) and Coil (43 g) Others: 20 g	N/A	TENGs: 2.36 mW g^{-1}, and 1.42 mW g^{-1}. EMG: 7.55 mW g^{-1}.	Charging a capacitor of 220 μF. TENG: 2.5 V within 20 s. EMG: 12.5 V within 20 s. Hybrid: 15 V within 20 s.
[280]		TENG: 171.13 μW EMG: 102.12 mW	TENG: 1 g EMG: Magnet with springs (26 g), Coil with casing (41 g)	N/A	TENG: 0.17 mW g^{-1} EMG: 1.52 mW/g	Charging a capacitor of 560 μF. TENG: 0.5 V within 20 s. EMG: 6.5 V within 20 s. Hybrid: 7 V within 20 s.
[322]		TENG: 1.05 mW EMG: 58.3 mW	N/A	TENG: 113.33 cm^3 EMG: 69.08 cm^3	N/A	Charging a capacitor of 22 μF. TENG: 0.75 V within 5 s. EMG: 2.28 V within 5 s. Hybrid: 2.8 V within 5 s.
[281]		TENG: 0.65 mW EMG: 265 mW	N/A	TENG: 0.04 cm^3 EMG: 158.28 cm^3	TENG: 4.1 μW cm^{-3} EMG: 1.67 mW/cm^3	Charging a capacitor of 22 μF. TENG: 2 V within 20 s. EMG: 3 V within 20 s. Hybrid: 3.8 V within 20 s.
[326]		TENGs: 1.20 mW and 1.21 mW EMG: 142.42 mW	TENG: 3 g EMG: Magnet with spring (50 g), coil stack and case (35 g)	N/A	N/A	Charging a capacitor of 2200 μF. TENG: 0.7 V within 120 s. EMG: 6.7 V within 20 s. Hybrid: 7.5 V within 120 s.
[327]		N/A	TENG: 4.6 g EMG: Magnets (9 g), and Coil stack (8.6 g) Case: 9.1 g Oscillator: 13.3 g	N/A	TENG: 130 W kg^{-1} m^3 EMG: 128 W kg^{-1} m^3	N/A

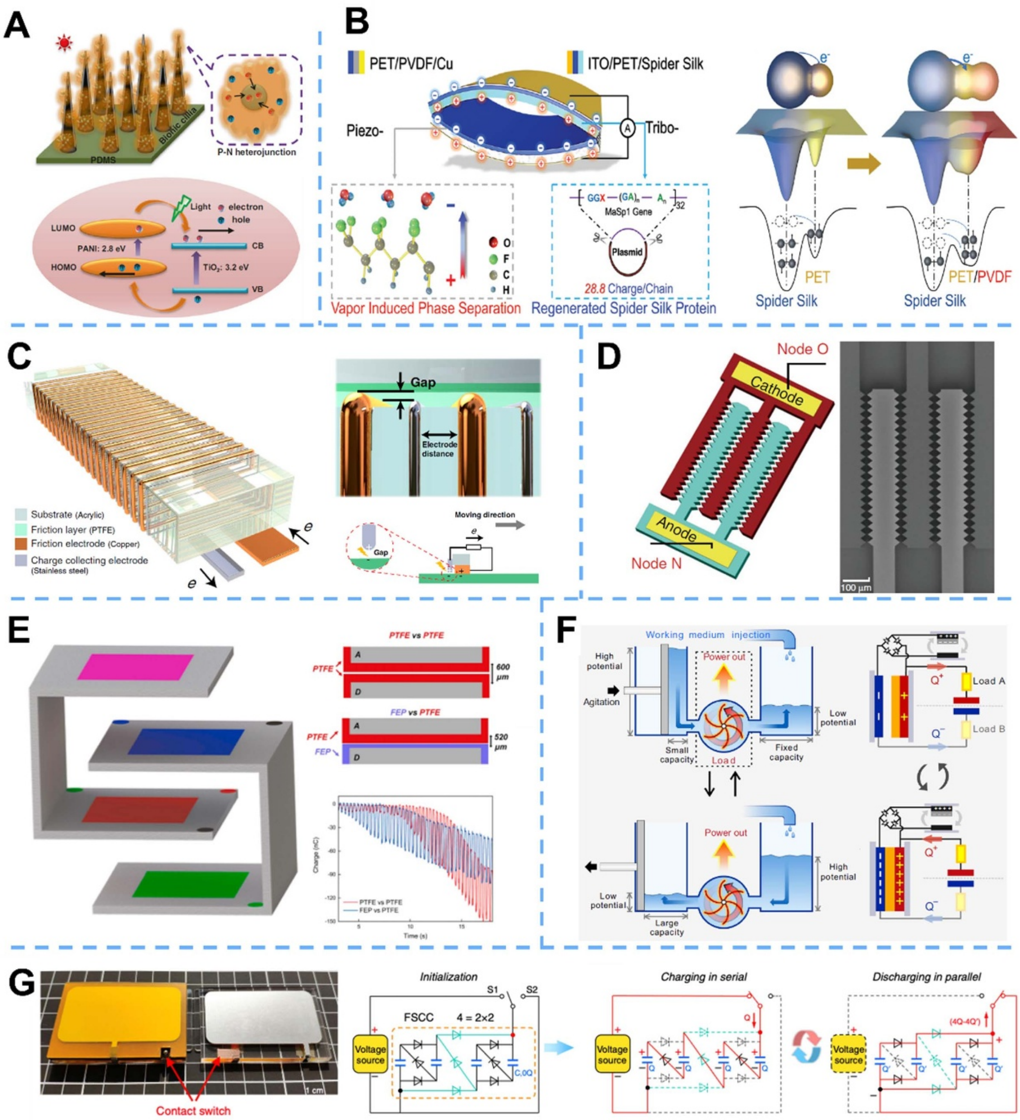


Figure 7. Output enhancement for TENGs. (A) A high-efficiency bioinspired photoelectric-electromechanical integrated nanogenerator. Reproduced from [339]. CC BY 4.0. (B) A type of 'self-matched' tribo-piezoelectric nanogenerator. [340] John Wiley & Sons. [2020]. (C) The rationally patterned electrode of direct-current TENG for ultrahigh effective surface charge density. Reproduced from [341]. CC BY 4.0. (D) A self-sustained conditioning system that allows the TENG to work at high-voltages for high-energy conversion without power-consuming electronics. Reproduced from [152]. CC BY 4.0. (E) Out-of-plane design of the Bennet doubler-based Programmed-TENGs. Reprinted from [151], Copyright (2020), with permission from Elsevier. (F) A high-performance triboelectric nanogenerator based on charge shuttling. Reproduced from [296]. CC BY 4.0. (G) Switched-capacitor-convertors based on the fractal design for output power management of TENG. Reproduced from [348]. CC BY 4.0.

and D are arranged on the left part, while electrodes A and C are arranged on the right part of the designed structure. There are two different dielectric combination groups for comparing the output performance, i.e. PTFE vs. PTFE with 600 μm thickness and FEP vs. PTFE with 520 μm thickness. Since the friction material is the same for the PTFE vs. PTFE group, the voltage increases slower than that of the FEP vs. PTFE group. However, due to a thicker dielectric layer, the PTFE vs. PTFE group shows a higher maximum voltage. The maximum voltage is 1400 V and 1150 V for the PTFE vs. PTFE and the FEP vs. PTFE group, respectively. Both two groups reach the maximum peak power at around 200 MΩ with 3.3 and 2.5 mW, respectively.

Charge improvement from material modifications is finite, while vacuum strategy limits applications of TENGs. Therefore, more effective methods are desired to overcome air breakdown for broad applications of TENG [318, 344, 345]. Figure 7(F) proposes a high-performance TENG based on the shuttling of charges [296]. The charge shuttling TENG consists of a pump TENG, a main TENG, and a buffer capacitor. The electrodes of the main TENG and the buffer capacitor form two conduction domains, presenting a quasi-symmetrical structure with a Q^+ side and a Q^- side. The capacitance of the main TENG changes upon contacts and separations, while that of the buffer capacitor remains constant, inducing voltage differences between them. The charges shuttled between the main TENG and the buffer capacitor in a quasi-symmetrical way will be generated electricity on the two loads. When the main TENG changes to the contact state, the capacitance of the main TENG grows, causing the voltage on it to descend. Therefore, charges return from the buffer capacitor to the main TENG via the loads. Consequently, an ultrahigh projected charge density of 1.85 mC m^{-2} is obtained in the ambient conditions. Based on this mechanism, an integrated device for water wave energy harvesting shows the feasibility of the charge shuttling TENG as a fundamental device to be applied in complex structures for various practical applications.

In addition, the output charge can be multiplied by setting capacitors charged in serial and discharged in parallel connection with a switch [346, 347]. However, the high output impedance and switching loss largely reduce the switched-capacitor converter (SCC)'s power efficiency due to the imperfect topology and transistors. Fractal-design-based switched-capacitor-convertors (FSCC) provides significant guidance for the development of power management toward multi-functional output in numerous applications [348]. As shown in figure 7(G), an FSCC with characteristics including high conversion efficiency, minimum output impedance, and electrostatic voltage applicability was proposed, in which a rough or piecemeal geometric shape can be divided into several parts and each part is reduced and has the self-similar property. Considering the low charges in TENG, large switching loss and zero gate voltage drain current of MOSFET, and super-low leakage current of rectifier diode, the SCC composed of rectifier diodes and capacitors are designed to convert the electrostatic voltage of TENG. By integrating the FSCC power management system on a printing circuit board (PCB), over 67 times charge boosting, 14.3 A m^{-2} current density, and 954 W m^{-2} power density can be reached by a common TENG under a pulse output for driving electric devices like a buzzer. Under constant output mode, over 94% of total energy transfer efficiency is realized with an output power density of 37.09 mW m^{-2}, and mobile electric devices like digital vernier caliper and temperature hygrometer can be driven continuously by the TENG with the FSCC power management system.

7. Self-sustainable systems and applications

The ultimate goal of the energy harvesters is the establishment of self-sustainable systems or systems with a prolonged battery lifetime by making use of the waste energy from the ambient environment, e.g. biomechanical energy associated with human body motions. We have witnessed the flourishing of various self-sustainable systems targeting diversified applications, which integrate the developed energy harvesters with other functional components, such as power management circuits, energy storage units, sensing units, etc [159, 349–354]. For instance, figure 8(A) presents a self-sustainable wireless sensing node (WSN) for IoT applications, where a TENG textile is integrated with a coil through a mechanical switch [307]. By controlling the mechanical switch, the triboelectric charges can be instantaneously discharged, and an oscillating signal will then be formed in this RLC circuit. A near-by coil can receive this oscillating signal directly through inductive coupling, with a transmission range up to 1 m. The resonant frequency, which serves as the sensing parameter, contains the information regarding the capacitance of the TENG itself or a single-pixel of the sensor. The resonant frequency-based sensing is highly stable over environmental interferences such as humidity and transmission distance compared to the conventional sensing with the signal amplitude. For practical demonstration, a wireless electronic scale and a mat-based human-machine interface for 2D/3D control are realized. Targeting for vibrational energy harvesting, figure 8(B) depicts a self-sustainable autonomous WSN based on a triboelectric and piezoelectric hybrid energy harvester [162]. The device consists of a hinged-hinged PZT bimorph and T-shaped proof masses where the contact-separation TENGs are located. A broadband characteristic has been achieved with the impact of TENG, and a tunable frequency is demonstrated by adjusting the axial force. Due to the large output from the PENG and the good sensing capability of the TENG, the WSN is constructed with the PENG as the power source and the TENG as the acceleration sensor. With the low-power setting, the PENG can sustainably power an Arduino nano and RF transmitter that can send the triboelectric signal out by Zigbee. Under this configuration, the authors demonstrated train status monitoring in a virtual-reality environment, showing its great prospect for self-sustainable WSN in the harsh environment. Generally, the harvested energy from the energy harvester is stored in an energy storage unit to power up sensing units, through which way more self-sustained sensing functionalities can be realized. In figure 8(C), a narrow-gap TENG textile has been developed to harvest various kinds of biomechanical energy, and a facile strategy to boost up the current output of such flexible TENGs was proposed as well [28]. An instantaneous discharging has been achieved by integrating a diode and a mechanical switch, contributing to 25 times higher current output and a stable output waveform over different pressing/releasing speeds. The soft, flexible, and thin characteristics of the TENG textile ensure a moderate output under various operation conditions even when it is randomly scrunched. The TENG textile can be put inside a shoe, harvesting biomechanical energy from foot motions, which can be stored in a capacitor and then be used to power up a Bluetooth module for humidity and temperature sensing. In a similar systematic configuration, a self-powered wireless indoor positioning system is constructed by a magneto-mechano-triboelectric nanogenerator (MMTEG), a power management unit, and an IoT Bluetooth beacon [355]. The MMTEG that converts a gentle magnetic field into electricity can generate an open-circuit voltage and short-circuit current of 708 V and 277 μA under an AC magnetic field of 7 Oe, which is high enough to enable the continuous operation of the IoT beacon. When a user approaches the target beacon, the IoT device can transmit a wireless signal with its location information to a smart pad and then to the main monitoring computer through wireless internet service. Apart from biomechanical energy, ocean wave blue energy is also an abundant energy source worthy of being reused [204, 212, 323]. For instance, a USPM for both automobile vibrational energy and blue energy

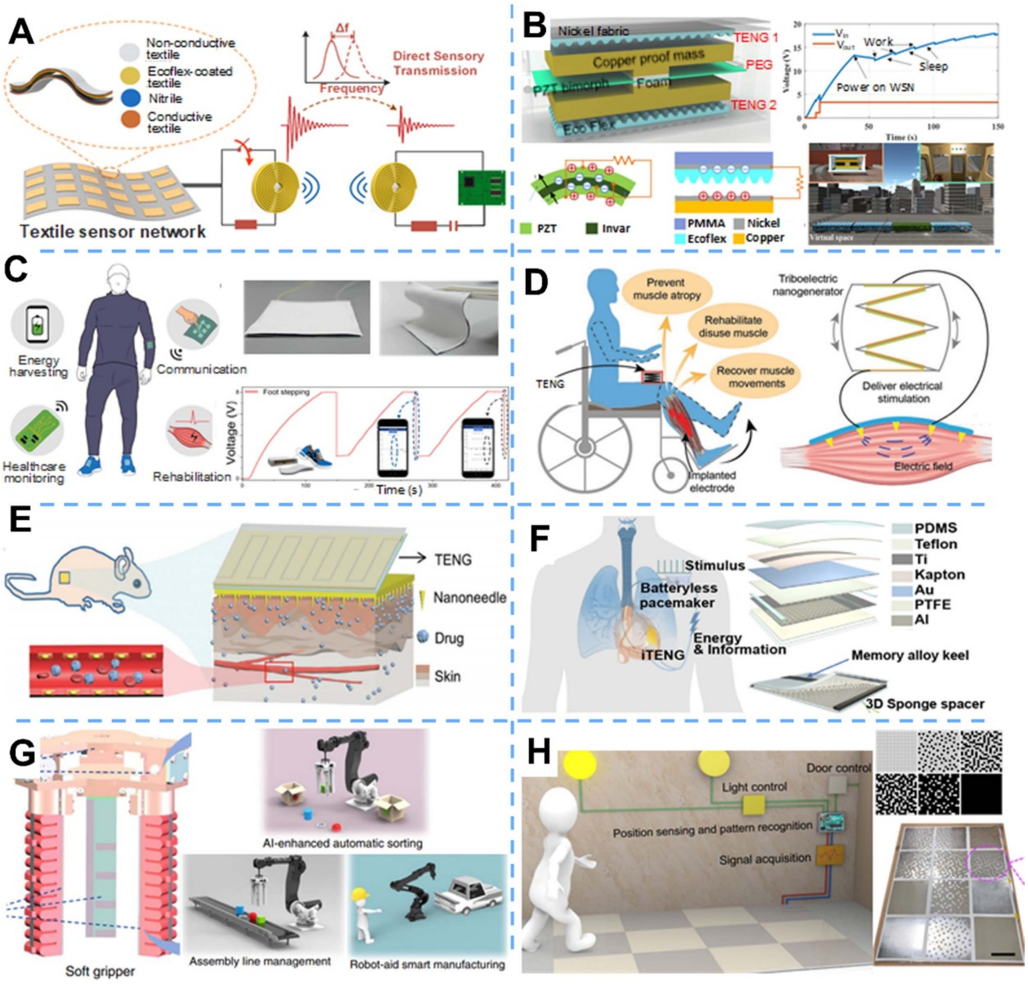


Figure 8. Self-sustainable systems and applications. (A) A self-sustainable WSN for IoT applications. Reprinted from [307], Copyright (2020), with permission from Elsevier. (B) A self-sustainable autonomous WSN based on a triboelectric and piezoelectric hybrid energy harvester. Reprinted from [162], Copyright (2021), with permission from Elsevier. (C) A narrow-gap TENG textile constructed a self-powered system for temperature and humidity sensing. Reproduced from [28]. CC BY 4.0. (D) Self-powered TENG system for direct muscle stimulation. Reproduced from [29]. CC BY 4.0. (E) Self-powered intracellular drug delivery driven by a TENG. Reprinted from [362], Copyright (2019), with permission from Elsevier. (F) A SPM based on an implantable TENG. Reproduced from [363]. CC BY 4.0. (G) A smart soft-robotic gripper system aiming at digital twin applications. Reproduced from [30]. CC BY 4.0. (H) A scalable floor monitoring system with deep learning-enabled smart mats. Reproduced from [32]. CC BY 4.0.

scavenging has been reported, containing an EMG and a triboelectric generator in a multiple-spring mechanical coupling configuration [34]. The UPSM is in a compact design where a power management circuit, an energy storage unit, and a USB-C outlet are integrated together. A self-powered wireless water PH monitoring system was demonstrated with the UPSM converting simulated wave energy into electric power. A mobile application displaying the wirelessly received PH value was also developed, demonstrating a complete and user-friendly wireless sensing system with a self-sustainable characteristic.

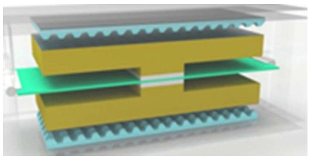
Moving from the outside of the body to the inside, implanted energy harvesters scavenging energy from muscle stretching, biofluid/blood flowing, and sonic waves penetrated deep tissues have been developed for the prolonged operation of implanted devices [356–358]. Compared to wearable electronics, implanted electronics suffer from a much higher cost of substitution and management of the conventional batteries, which is desperately in need of self-sustainable systems. Due to the ubiquitous existence of the biomechanical energy around us, we have seen various self-sustainable implantable systems combining mechanical energy harvesters with implanted devices. For example, neural interfaces are evolving towards self-powered systems by integrating with energy harvesters such as TENGs [164, 359–361]. In figure 8(D), the direct muscle stimulation for future muscle function loss treatment has been demonstrated, with the aid of a stacked-layer TENG and a multi-channel epimysial electrode [29]. The stacked TENG is specially designed to achieve a large current, enabling the effective stimulation of the muscle tissue. On top of that, an optimal electrode configuration is also obtained by mapping tests, further improving the TENG stimulation efficiency. Interestingly, it is found that stimulation with a TENG pulse generates a more stable output force than conventional square waves, possibly due to the avoided motoneuron recruitment synchronization. The high-voltage output of the TENG would also benefit the drug delivery systems. In figure 8(E), a TENG-driven electroporation system for intracellular drug delivery is developed, with minimal cell damage both *in vitro* and *in vivo* [362]. In this system, biomechanical energy-driven TENGs with different structures were fabricated for either *in vitro* or *in vivo* electroporation, with the assistance of a nanoneedle array electrode. The TENG voltage pulse triggers the increase of plasma membrane potential and the permeability of the membrane, while the nanoneedle array enhances the localized electrical field at the nanoneedle-cell interface and molecular influx cooperatively. This integrated system achieves efficient delivery of exogenous materials into various types of cells with a delivery efficiency of up to 90%, showing a great prospect for self-tuning drug delivery. Moving forward, implantable energy harvesters can be integrated with implanted functional units to form fully implanted self-sustainable systems. Figure 8(F) shows a self-powered implantable symbiotic pacemaker (SPM), which consists of an implanted TENG, a power management unit, and a pacemaker unit [363]. The TENG device is entirely packaged by Teflon and PDMS to enhance the stability and avoid liquid damage to it. Owing to the discrepancy between the TENG output and power consumption of the pacemaker unit, the electricity was firstly stored in the capacitor of the PMU; the switch of the PMU was then turned on by a magnet functioning as a wireless passive trigger. Through this way, the pacemaker unit could be driven to produce electrical pacing pulses and control cardiac contraction rate. With the ceaseless investigation on the energy harvesters, we wish to see the prosperous future development of self-sustainable systems both for wearable and implantable applications.

Generally, the data analysis of conventional sensing systems relies on manual or simple feature extraction, which would limit the full potential of the sensors. In recent years, AI has become more popular and capable thanks to advanced algorithms, increased data volumes, and improved computing power/storage. In particular, machine learning-based data analytics have received immense attention from a broad discipline of research areas, which offers brand new possibilities for novel applications with superior capabilities in solving complicated tasks [364–370]. Targeting for digital twin applications, figure 8(G) presents a smart soft-robotic gripper system based on triboelectric sensors in two configurations for gripper continuous bending motion sensing and tactile information capturing [30]. The tactile TENG (T-TENG) with patterned electrodes can detect sliding, contact position, and gripping mode of the gripper, while the length TENG (L-TENG) measures the bending angle, enabling comprehensive monitoring of the gripper system. With the aid of machine learning to process the multi-parameter inputs, the gripper can recognize various objects with 97.1% accuracy and 98.1% with sensor channels from 6 to 15. A digital twin model is established to simulate the robotic manipulation and real-time object recognition in the duplicate VR environment. Since machine learning assisted data analytics offer a possibility to extract the full sensory information from sensors, the requirement on the amount and density of the sensors would be highly reduced. For example, Shi *et al* proposed a deep learning-enabled floor monitoring system with scalable triboelectric mats, which are differentiated by unique 'identity' electrode patterns fabricated with a low-cost and highly scalable screen printing technique (figure 8(H)) [32]. Each pattern offers a specific electrode coverage rate, which affects the amplitude of the triboelectric output signal. With a specific arrangement of the triboelectric mats in an array, the electrodes of them can be parallelly connected to minimize the output channels to reduce the system complexity and computational cost. Position/trajectory tracking and activity monitoring can be readily achieved directly from the sensory output thanks to the specially designed 'identity' electrode patterns. A deep learning-assisted data analytic enables the recognition and differentiation of different users from their distinctive gaits, through which a smart home environment has been demonstrated with auto-controlled door access granted only to the valid users. The average prediction accuracy can reach 96% for a 10-person CNN model with 1000 data samples. This smart floor technology may lay the foundation of future smart building/home by providing a video-privacy-protected and highly secured recognition method.

8. Conclusion

With the rapid development of MEMS technology as well as the wireless data transmission technology, the new 5 G era we are entering into has shed light on the requirement for a wireless sensor network consisted of billions of smart sensors and IoT devices widely distributed in both the city and remote areas. For the massive amount of these sensors and the harsh environment that some of them are applied in, the traditional batteries are no longer the most proper choice due to their drawbacks, including the high contamination, low lifespan, and low energy density. To explore a sustainable and green power supply for these wireless sensor nodes, energy scavenging devices that are capable to continuously transfer mechanical energy from the ambient environment to electricity have been designed and developed. At first, to harvest the vibrational mechanical energy and power the sensors applied in high buildings, bridges, or vehicles, MEMS-based VEHs have been well investigated with three primary energy transferring mechanisms, including electrostatic, piezoelectric, and electromagnetic. Moreover, with the flourishing wearable electronics, the new requirement for a sustainable power supply with the characteristics including flexible, bendable, durable, stretchable, and able to scavenge the human motions with very low frequency or large deformation has been put forward. In this regard, the PENG and TENG have been correspondingly designed to harvest biomechanical energy. Simultaneously, strategies to further improve their output performance, including the broadening operational bandwidth, design of power management circuits, and hybridized energy harvesters, have been studied. On top of that, the self-sustainable system becomes realizable when further integrating the well-developed energy harvesters with functional units, energy storage units, and wireless data

Table 2. Promising devices in various application scenarios.

Ref.	Device	Energy Sources	Output Performance	Applications
[28]		**Biomechanical Energy** (Human Motion)	Charging a 27 μF capacitor under 0.67 Hz through: Hand pressing (40 s to 8 V) Foot stepping (40 s to 4 V) Elbow bending (40 s to 3 V) Knee bending (40 s to 2.5 V)	• Direct muscle stimulation • Direct nerve stimulation • Self-powered wireless communication board • Self-sustained Blue-tooth sensing
[363]		**Biomechanical Energy** (Cardiac Pacing)	0.495 μJ for each cardiac cycle	• Energy supply for long-term implantable devices • Self-powered pacemaker • Cardiovascular events identification • Direct electrical stimulation for cell and tissue
[162]		**Mechanical Energy** (Vehicle Vibration)	Output power of 6.5 mW under 1 g and 25 Hz	• Self-sustained autonomous wireless monitoring
[34]		**Mechanical Energy** (Automobile Vibration) **Biomechanical Energy** (Human Motion) **Blue Energy** (Ocean Wave)	Charging 240 LED lights (100 mW) for 190 s after 10 s gentle hand shaking. 37 V open-circuit voltage under 2 Hz ocean wave. 40 V open-circuit voltage when driving on the unpaved road.	• Power supply for wearable devices: earbud, smartphone smart band • Self-powered wireless water PH monitoring system • Self-powered in-car wireless environment monitoring system
[36]		**Environmental Energy** (Wind, Rain Drop, and Sun Light)	Charging a 220 μF capacitor to 3.5 V in 170s in a wind speed of 7.3 m s^{-1}. Charging a 220 μF capacitor to 2.1 V in 274 s with rain drops. Short-circuit current of 24.3 μA from the sun light.	• Power source for wireless monitoring system in various outdoor environments

transmission units. Furthermore, with the help of machine learning technology, AI-assisted systems have been designed for broader and more cutting-edge applications, including VR/AR, HMI, healthcare, and smart home.

Table 2 has listed the five representative energy harvesters as the energy supply for various application scenarios. With the advantages of flexibility and low operation frequency, TENG and PENG become the promising energy supply for wearable and implantable devices, and can also serve as the self-powered sensor in healthcare monitoring. P-VEH and EM-VEH, for their high output power and energy density, are always the essential part in hybridized energy harvesters for a self-sustained system with high power consumption. At the same time, low-frequency and broad-bandwidth design are also the overriding part for energy harvesters to ensure the stability of high output when applied in the realistic environment. Furthermore, scavenging more available energy sources, like the radiant energy from the sun light, is also the viable method for the application in various outdoor environments.

Despite the viable progress in developing energy harvesters, several challenges still remained to be solved on the road toward the future AI-assisted self-sustainable system. First and foremost, the output performance of the current energy harvesters should be further improved to power such a functional system with higher power consumption compared to conventional wireless sensor nodes. Potential research directions include broadening operational bandwidth through multi-DOF system, spring nonlinearity and stopper effect, exploring new materials like the electret materials for E-VEHs, the piezoelectric materials for P-VEHs and PENG and materials with a higher potential difference for TENG, structural and electrodes design innovation, and the design of power management circuit. Besides, the hybridized energy harvesters also worth to be more thoroughly studied for their potential in scavenging various energy sources in the environment to significantly improve the output power. Apart from the hybridization in the structural domain, more compact designs rooted in their fundamental principles should be taken into consideration for the further enhancement to each other, rather than just simply combine each part. Except for the energy generation unit, an energy storage unit with superior stabilities is the prerequisite of self-sustainable systems for long-term operation, which worths equal significance in future research. Besides the technology evolution in energy harvesting, the decrease of the power consumption of AI functional units should be studied parallelly, such as the application of AI-chips to decrease the power required for large data transmission and processing through directly training the input signals on that chip. In this regard, the bright future of the 5 G era will be greatly beneficial by the realization of AI-assisted self-sustainable systems in diverse application areas.

Data availability statement

No new data were created or analysed in this study.

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Conflict of interest

The authors declare no conflict of interest.

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