

Review

Hybrid Energy-Harvesting Systems Based on Triboelectric Nanogenerators

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SUMMARY

Energy harvesting plays an important role in developing power-independent electronics such as wearables, implantable devices, monitoring networks, and robotics. The triboelectric nanogenerator (TENG), a novel promising energy-harvesting technology, has attracted increasing attention across a broad range of applications from self-powered sensing to implantable medical devices to blue energy. However, a comprehensive review associated with the TENG-based hybrid energy system is lacking. Here, we systematically summarize the recent advances in the TENG-based hybrid energy-harvesting system with a focus on the concept designs and significant applications of the hybrid devices in various fields. The major hybridization designs through unique combinations of electromagnetic nanogenerators (NGs), piezoelectric NGs, solar cells, and thermo-/pyroelectric NGs with TENGs are discussed in detail for self-charging power units, self-powered biomedical systems, wearable electronics, environment-monitoring systems, and blue energy-harvesting facilities. We finally discuss the major challenges and perspectives for the future development of hybrid energy-harvesting systems.

INTRODUCTION

Compatible portable power sources are essential to driving a variety of smart internet-of-things (IoT) devices such as wearables,^{1–4} implanted devices,⁵ soft robotics,^{6,7} and smart packages.^{8,9} In this aspect, energy harvesters or generators play a key role in harvesting ambient environmental energies such as vibration,^{10,11} human motion,¹² wind,¹³ water wave,^{14–16} solar,^{17–19} and waste heat²⁰ to power the IoT devices and/or generate electricity in a scalable way.^{21–23} The energy generated by these harvesters can be stored in rechargeable batteries or supercapacitors and be used to supply energy for the operation of electronics when needed.^{24–29} Triboelectric nanogenerators (TENGs), as a fundamentally new invention based on the conjugation of triboelectric effect and electrostatic induction, have been extensively explored to harvest mechanical energy in the environment. TENGs have the attractive advantages of low fabrication cost, high energy-conversion efficiency, ease of fabrication, and being lightweight and environment-friendly.^{30–34} While TENGs can generate high output voltage, the low output current under normal excitations limits their applications and sustainability. To address this issue, researchers have made efforts to combine the TENGs with other types of energy-harvesting mechanisms to build hybrid energy-harvesting systems that can harvest energy from multiple sources in the surrounding environment.^{35–41} In fact, the first hybrid nanogenerator was demonstrated by Wang's group in 2009 for simultaneously harvesting

Progress and Potential

Triboelectric nanogenerators (TENGs) have been utilized to harvest various forms of mechanical energy from the environment as a sustainable power supply. However, TENGs usually generate high output voltages but low output currents, limiting their potential uses. Hybrid energy harvesters based on TENGs provide a promising method to effectively use the environmental conditions for energy harvesting by combining two or more working mechanisms, generating high currents by harvesting all types of available energy to meet the needs of distributed energy units. Significant progress has been made in improving the performance of TENG-based hybrid energy-harvesting systems via new concepts, designs, and integration methods. It is expected that TENG-based hybrid power systems will have significant development with the rapid advances in materials science and manufacturing technologies, and that the critical challenges will be addressed for practical applications.

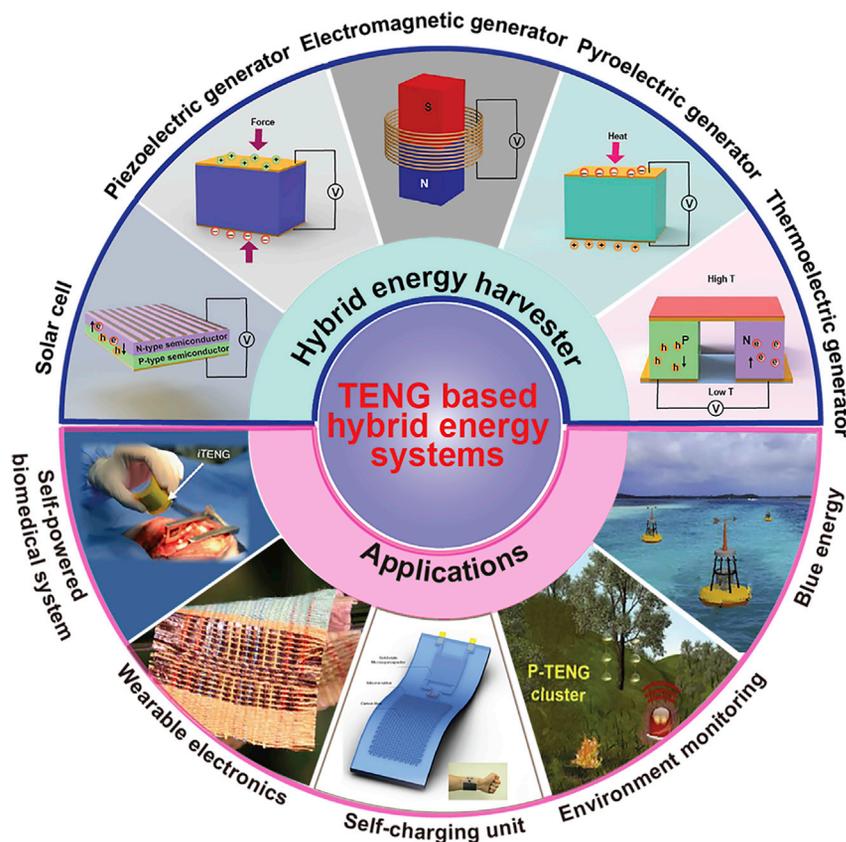


Figure 1. Outline Illustration of the Review of Hybrid Energy-Harvesting Systems via Triboelectric Nanogenerators

The hybrid energy harvesters are integrating triboelectric nanogenerators (TENGs) with other major energy-harvesting techniques, including electromagnetic generator, piezoelectric generator, thermoelectric generator, pyroelectric generator, and solar cell. They can be used for a variety of applications such as self-charging power system, self-powered biomedical system, wearable electronics, environment monitoring, and wave energy harvesting.

mechanical and solar energy.^{42–44} This concept has now been expanded to many different types of energy harvesters to acquire any type of energy that is available anywhere and at any time. Since their invention in 2012, TENGs have been extensively developed and several reviews have been conducted to summarize the advances of stand-alone TENG^{45–48} and specific hybrid TENGs,³⁷ providing useful references for the working principles and designs for interested researchers. However, there is no comprehensive review for the progress in the applications of advanced TENG-based hybrid energy systems.

In this review, we summarize the recent progress in developing TENG-based hybrid energy-harvesting systems with a focus on the concept designs of the novel devices and their applications in different fields (Figure 1). The paper is organized as follows. First, the proposed types and designs of hybrid energy harvesters are presented, including the combination of TENGs with electromagnetic generators (EMGs), piezoelectric generators, thermoelectric generators, pyroelectric generators, and solar cells, respectively. The discussions are mainly on their working principles, structural designs, and comparisons with classical mechanical energy-harvesting technologies. The working mechanism and electrical characteristics of different

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Table 1. Comparison of the Major Energy-Harvesting Technologies

	Energy-Harvesting Technology					
	TENG	EMG	PENG	Solar Cell	TEG	PyNG
Working mechanism	triboelectrification and electrostatic induction	electromagnetic induction	piezoelectric effect	photovoltaic effect	Seebeck effect	pyroelectric effect
Open-circuit voltage	high	low	medium	low	low	medium
Short-circuit current	low	high	low	high	medium	low
Output power	low	high	low	high	medium	low
Power characteristic	AC	AC	AC	DC	DC	AC
Internal impedance	MΩ	Ω	kΩ	Ω	Ω	kΩ

energy-harvesting technologies are compared in Table 1. The promising applications of the TENG-based hybrid energy systems are then summarized and highlighted in self-powered electronics, biomedical systems, wearable electronics, environment-monitoring systems, and ocean energy-harvesting facilities. Finally, the conclusion and perspectives for the future development of the TENG-based hybrid energy systems are discussed.

TYPES AND DESIGNS OF HYBRID ENERGY-HARVESTING SYSTEMS VIA TRIBOELECTRIC NANOGENERATORS

Hybrid Electromagnetic and Triboelectric Nanogenerators

The EMG is the main technology for converting mechanical energy into electricity.^{49,50} The EMG is based on Faraday’s law of electromagnetic induction whereby an induced electrodynamic potential is produced via relative motion between the magnet and the coil (Figure 2A).⁵¹ It has high conversion efficiency at high-frequency ranges and has high durability for long-term operations. However, TENG is based on the coupling of triboelectrification and electrostatic induction during the periodic relative contact-separation and/or sliding motion of the surfaces of two materials (Figure 2A). For the rotating EMGs with two magnets and coils of wires, its peak value of output voltage is expressed as: $E_m = n \cdot B \cdot S \cdot \omega$, where B denotes the magnetic flux density, n is the turns of coils, S is the area of the coil, and ω is the rotational angular velocity of the coil. For a disk-shaped rotating TENG, the absolute value of the output current is expressed as $|I| = \frac{n}{\pi} \cdot \sigma \cdot S \cdot \omega$, where n is the number of segments of the disk, σ is the triboelectric charge density of the friction surface, S is the friction area of the disk (half the area of the whole circle), and ω is the rotational angular velocity of the top metal. The electrodynamic potential of an EMG and the short-circuit current of a TENG depend on four major variables: the intrinsic properties of the materials, device size, device structure, and input mechanical energy.⁵¹

To maximize the output powers, different matching impedances are needed for EMG and TENG (Figure 2B), indicating that the EMG can be considered as a voltage source with low internal resistance while the TENG is mostly recognized as a current source with high internal resistance.⁵¹ In a recent study, Zi and coworkers systematically compared the output performance of EMG and TENG at low-frequency motions. They found that the power density of EMG is proportional to the square root of the frequency while that of TENG is proportional to the frequency.⁵² Therefore, at a low-frequency range, the output power of TENG was higher than that of EMG (Figure 2C). It is demonstrated that a TENG can light up a light-emitting diode (LED) easily at low frequencies, while an EMG has to run at a much higher frequency to light an LED (Figure 2D). Zhao et al. studied the effects of motion amplitude on

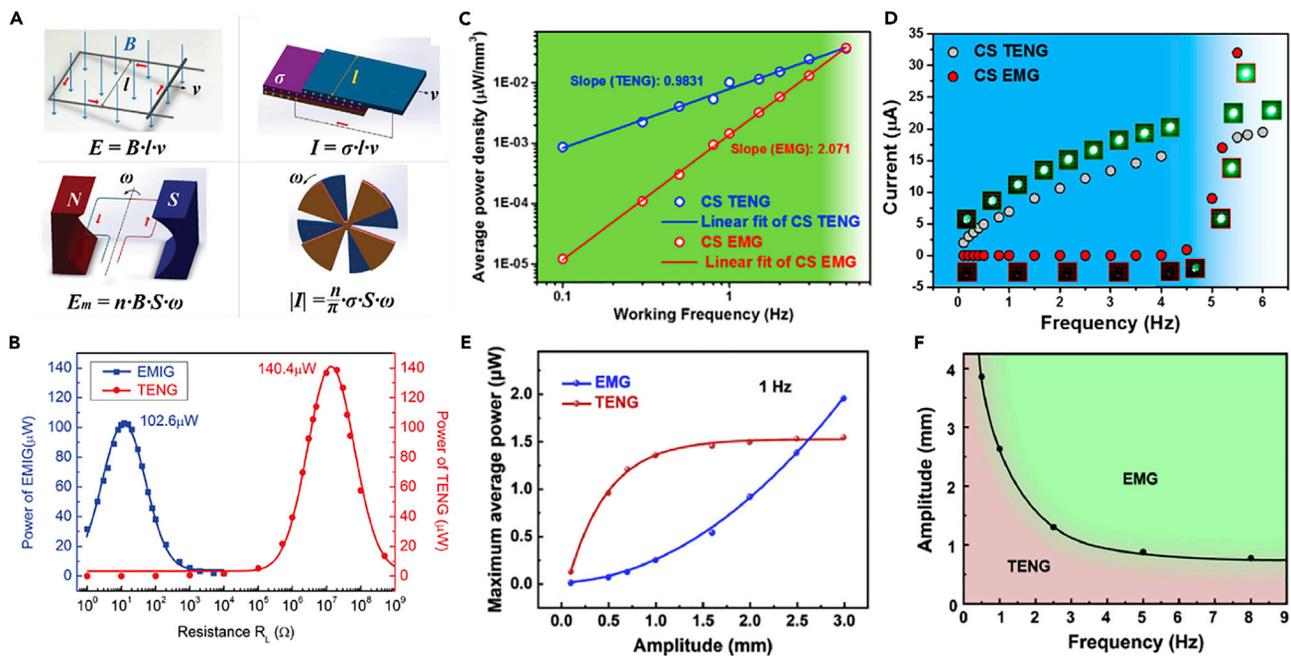


Figure 2. Comparison of Working Mechanism and Output Performance of TENGs and EMGs

(A) Schematic illustrations for the working mechanisms of TENG (right) and electromagnetic generator (EMG) (left).

(B) Output power of the rotating DC-TENG and DC-EMG as a function of load resistance. Reproduced with permission from Zhang et al.⁵¹ Copyright 2014, Wiley-VCH.

(C) The variation of the average output power density of the TENG and the EMG with the working frequency.

(D) The electric currents generated by TENG and EMG versus excitation frequency. The brightness of each green LED indicates the power intensity generated by the harvesters. Reproduced with permission from Zi et al.⁵² Copyright 2016, American Chemical Society.

(E) The effect of the excitation amplitude on the maximum average output power of TENG and EMG.

(F) Amplitudes in crossover points of both maximum average output power characteristic curves at different frequencies. Reproduced with permission from Zhao et al.⁵³ Copyright 2019, Elsevier.

EMG and TENG⁵³ and reported that a TENG had a larger maximum average output power than that of an EMG when using small amplitude less than 2.5 mm at 1 Hz (Figure 2E). Figure 2F summarizes the amplitudes in crossover points at different frequencies, where the maximum average output power characteristic curves of the TENG and EMG intersect one another, showing that the TENG has a dominant scope over the EMG at low-frequency and small-amplitude ranges. Considering that the TENG and EMG possess opposite electrical properties (TENG has high output voltage but low output current while EMG has low output voltage but high output current), it is interesting to combine TENG and EMG to take advantage of their complementary output characteristics and increase the efficiency of mechanical energy harvesters.

In 2016, Zhao et al. proposed a fully packed hybrid generator (Figure 3A),⁵⁴ which is composed of a rolling TENG and an EMG. Thanks to the low friction achieved through a rolling structural design, the proposed TENGs exhibited excellent electrical output stability and mechanical durability (Figure 3B). The experimental results indicated that the rolling TENG had better output performance than EMG in low-frequency range (<1.8 Hz). Thus, the proposed hybrid generator used a sustainable approach to effectively harvest mechanical energy at a broad frequency range. The rotating structure has also been used in TENGs and EMGs for harvesting wind and water wave energy. For example, Guo et al. demonstrated a rotation-based triboelectric-electromagnetic hybrid nanogenerator (NG) to harvest

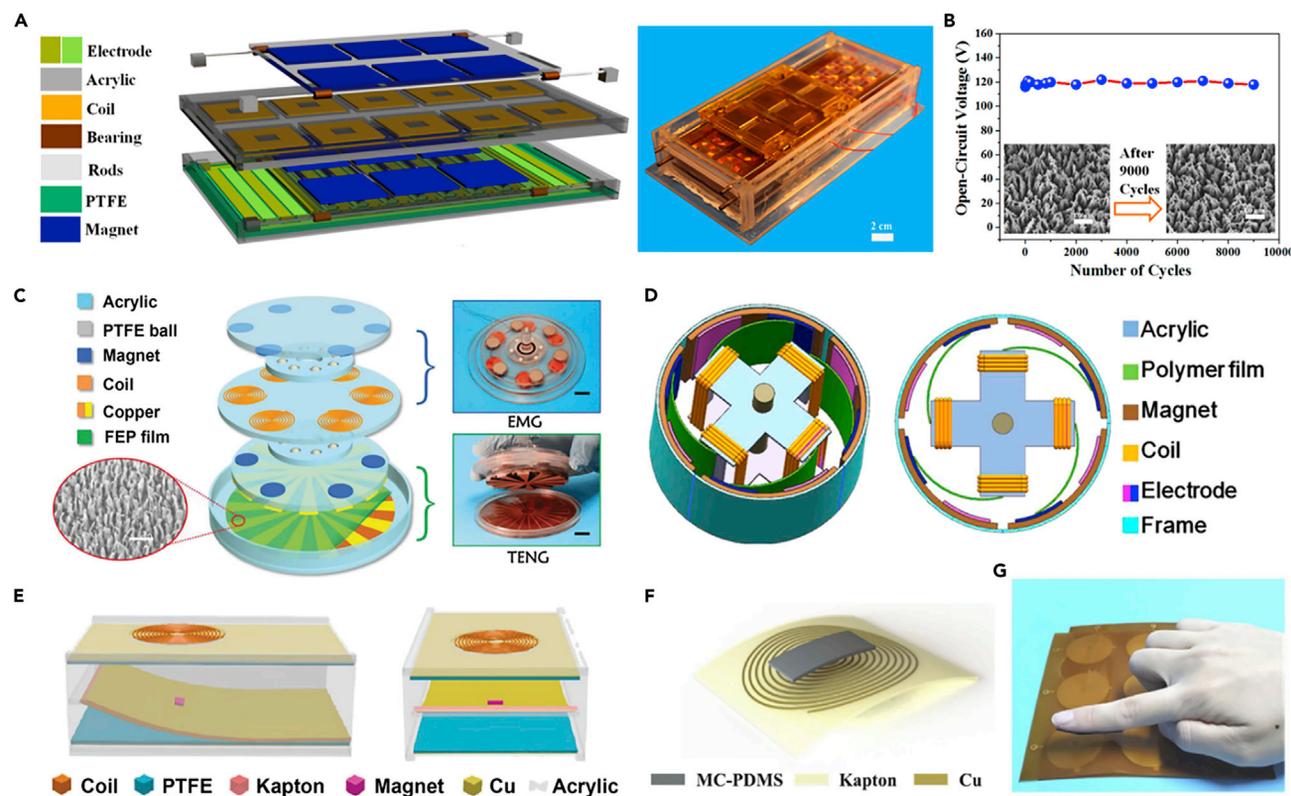


Figure 3. Hybrid Electromagnetic-Triboelectric NGs

(A) Structural design of a fully packed hybrid energy harvester consisting of a rolling TENG and an EMG.

(B) Robustness and stability demonstration of the TENG shown in (A). Reproduced with permission from Wang et al.⁵⁴ Copyright 2016, American Chemical Society.

(C) Schematic illustrations and photographs of a triboelectric-electromagnetic hybrid NG by combining the TENG and EMG. Reproduced with permission from Guo et al.⁵⁵ Copyright 2015, Wiley-VCH.

(D) Schematic illustration of an ultralow-friction triboelectric-electromagnetic hybrid NG. Reproduced with permission from Wang et al.⁵⁶ Copyright 2018, American Chemical Society.

(E) Schematic diagram of a hybrid electromagnetic-triboelectric NG for harvesting airflow energy. Reproduced with permission from Wang et al.⁵⁷ Copyright 2015, American Chemical Society.

(F) Schematic of a flexible hybrid energy harvester.

(G) Application of the hybrid energy harvesters in (F) as a 3D trajectory sensor. Reproduced with permission from Wan et al.⁵⁸ Copyright 2020, Elsevier.

mechanical energy (Figure 3C).⁵⁵ The rotational sliding freestanding-triboelectric-layer mode TENG was packed fully isolated, whereby a noncontact magnetic force transferred the external mechanical energy to the TENG. Meanwhile, the rotational EMG was fabricated by integrating these magnets and metal coils into the stator. By using transformers and full-wave rectifiers, the hybrid NG obtained a 2.3 mA short-circuit current and 5 V open-circuit voltage at a rotational speed of 1,600 rpm. In sliding-type TENGs for harvesting rotational energy, the large friction force between the two frictional layers limits the rotation of the rotator and thereby decreases the energy collection efficiency of the TENG. To solve this problem, Wang et al. designed an ultralow-friction hybrid NG consisting of a rotary-blade-based TENG and a rotary EMG (Figure 3D).⁵⁶ The highly flexible dielectric film was used as the freestanding triboelectric layer, which significantly reduced the friction force (~ 0.03 N) so that the TENG could be actuated by a low external force. This type of hybrid NG can power humidity or temperature sensors or can be used for detecting wind speed.

The aforementioned rotation-based hybrid generators can generate high output power; however, their applications are limited by their complex structures and large volumes, which are not suitable for powering wearable electronics. To solve this problem, Wang et al. developed a hybrid EMG-TENG (Figure 3E, 6.7 cm × 4.5 cm × 2 cm in size and 42.3 g in weight) to harvest airflow energy.⁵⁷ The flexible hybrid device on a Kapton film was utilized to power four temperature sensors and a wireless temperature sensor. Recently, Wan et al. proposed a flexible hybrid EMG-TENG based on NdFeB microparticles, polydimethylsiloxane (PDMS), and multiwalled carbon nanotube (MWCNT) (Figure 3F),⁵⁸ which could be attached on cloth surface or human body to harvest mechanical energy from human motions. Based on this hybrid EMG-TENG, they also designed a novel self-powered trajectory sensing system (Figure 3G), which was able to detect the trajectory and height information in a three-dimensional (3D) space.

Hybrid Piezoelectric and Triboelectric Nanogenerators

Piezoelectricity is another widely used technology to convert mechanical energy into electricity, based on a piezoelectric effect. A typical piezoelectric nanogenerator (PENG) consists of several layers, including a top electrode, a bottom electrode, and an insulator piezoelectric material layer, such as lead zirconate titanate (PZT),⁵⁹ BaTiO₃,⁶⁰ ZnO,⁶¹ and poly(vinylidene fluoride) (PVDF) and its copolymers.^{62–64} When an external force is applied to a PENG, the center of the cations and anions are relatively displaced, resulting in a piezoelectric potential difference between the ends that can drive the electrons to flow through the external circuit (Figure 4A).⁶⁵ Given that a few reviews on the piezoelectric materials and energy harvesters have already been published,^{66–68} we do not review these related studies in this article.

The PENGs and TENGs have similar output characteristics, resistances, and working frequency ranges.⁶⁹ It has been demonstrated that a combination of the PENG and the TENG will be promising to enhance the energy-conversion efficiency from the environment.^{74–76} For example, Chen et al. reported a hybrid NG with a wavy structure (Figure 4B)⁶⁹ in which the wave-shaped supporting structure was formed by sandwiching a piezoelectric film made of poly(vinylidene fluoride-co-trifluoroethylene) (P(VDF-TrFE)) nanofibers between Kapton films. Owing to the all-in-one design, the device generated power from both triboelectric and piezoelectric transducers in a single pressing-releasing cycle (Figure 4C). Guo et al. also utilized electrospun silk fibroin and PVDF nanofibers on conductive fabrics as triboelectric layers (Figure 4D) to make flexible, breathable, and wearable hybrid NGs.⁷⁰ The output power density of the hybrid NG reached up to 310 μW cm⁻² due to the large surface area of electrospun electrification materials and the ability of silk fibroin to lose electrons. The textile-based hybrid generator had good flexibility and air permeability and could be easily sewn onto human cloth for harvesting biomechanical energy. Using P(VDF-TrFE) as the piezoelectric layer, Al:ZnO (AZO) as transparent electrodes, and PDMS with microstructures as the triboelectric layer, Wang et al. developed a flexible and transparent single-friction-surface triboelectric-piezoelectric hybrid generator (Figures 4E and 4F),⁷¹ which could be attached to the human skin to serve as an energy harvester and an active sensor capable of detecting small skin motions.

Piezoelectric inorganics are also explored for developing PENGs due to their superior piezoelectric effects compared with organic PVDF and its copolymers. For instance, Li et al. reported a flexible hybrid triboelectric/piezoelectric NG based on multilayered nanocomposite materials (Figure 4G).⁷² In their design, the top electrification layer consisted of PDMS matrix and polytetrafluoroethylene (PTFE)

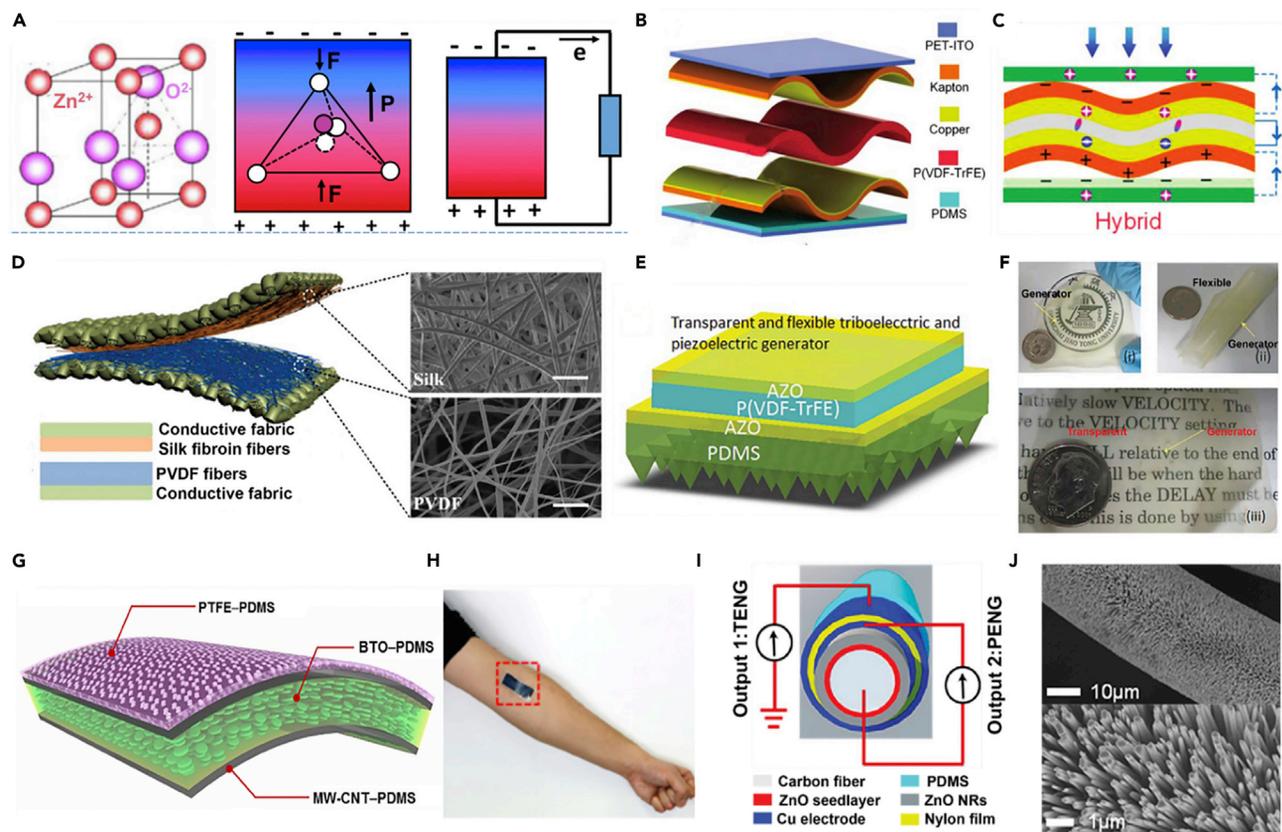


Figure 4. Hybrid Piezoelectric-Triboelectric NGs

- (A) Schematic diagram of material ZnO with wurtzite-structure and its working principle in a piezoelectric nanogenerator (PENG). Reproduced with permission from Sun et al.⁶⁵ Copyright 2019, Elsevier.
- (B) Schematic diagram of a hybrid piezoelectric-triboelectric NG with wavy structures.
- (C) The working principle of the hybrid NG in (B). Reproduced with permission from Chen et al.⁶⁹ Copyright 2017, Royal Society of Chemistry.
- (D) Schematic diagram of an all-fiber hybrid NG made of silk fibroin fibers and PVDF fibers on conductive fabrics. Reproduced with permission from Guo et al.⁷⁰ Copyright 2018, Elsevier.
- (E and F) Schematic illustration and photographs of a transparent and biocompatible hybrid NG. Reproduced with permission from Wang et al.⁷¹ Copyright 2017, Royal Society of Chemistry.
- (G) Schematic diagram of a flexible multilayered hybrid NG.
- (H) The hybrid NG is attached on skin surface to harvest motion energy. Reproduced with permission from Li et al.⁷² Copyright 2017, Springer.
- (I) Schematic diagram of a 3D fiber-based hybrid NG.
- (J) SEM images of ZnO nanowires around carbon fiber. Reproduced with permission from Li et al.⁷³ Copyright 2014, American Chemical Society.

nanoparticles. $\text{Bi}_4\text{Ti}_3\text{O}_{12}$ nanoplates were uniformly dispersed in the PDMS matrix to fabricate the piezoelectric layer. A 2.5 cm \times 2.5 cm hybrid device had an output voltage of 280 V and a maximum current of 25 μA , indicating its superiority to the previously reported hybrid NGs (Figure 4H). The ZnO nanowire-based PENGs have also been invented for specific applications.⁶¹ For example, Li et al. developed a fully integrated fiber-based hybrid nanogenerator (FHNG) composed of TENG and PENG.⁷³ The ZnO nanorods (NRs)-based PENG was positioned in the core and covered coaxially by the TENG to form a core/shell structure (Figure 4I). By a hydrothermal growth approach, ZnO NRs were uniformly grown on the carbon fibers with a length of 10 μm (Figure 4J). The outer PDMS film and the Cu electrode together made a single-electrode TENG. The maximum output power density of the TENG and PENG was 42.6 mW m^{-2} and 10.2 mW m^{-2} , respectively. The FHNG could be integrated into cloth for energy harvesting and self-powered strain-sensing purposes.

Hybrid Solar Cell and Triboelectric Nanogenerators

Solar cells convert sunlight to electricity via a photovoltaic effect and have been extensively studied due to the high potential of solar energy as a renewable energy source.^{17,77,78} The main drawback of solar cells is the high dependency of the energy generation on daily light and weather conditions.⁷⁹ Therefore, combining solar cells with TENGs will enable the harvesters to be effective even when no sunlight appears and thus achieve sustainable energy harvesting. For example, the recent work by Liu et al. reported an energy-harvesting system combining a solar cell with a TENG (Figure 5A). The hybrid device was able to harvest energy from both the sunlight and the dynamics of raindrops.⁸⁰ In their design, a poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) film with digital video disk pattern (Figure 5B) was used as a functional electrode for Si/organic heterojunction solar cell and TENG. In comparison with Si/planar PEDOT:PSS, the Si/imprinted PEDOT:PSS solar cell showed a higher light-harvesting ratio, short-circuit current density, and power-conversion efficiency of 13.6%. A single-electrode-mode TENG with an imprinted PDMS as a triboelectric layer on the solar cell was built to collect the raindrop energy. The imprinted microstructure efficiently increased the contact area between the TENG and water drops, and thus significantly improved the output performance of the TENG, achieving an open-circuit voltage peak of ~ 2.14 V and a short-circuit current peak of ~ 33.0 nA. This hybrid energy-harvesting system demonstrated a promising approach to collect energy from the environment in different weather conditions.

IoT to monitor or manage natural resources and the services of civil infrastructures in our cities require considerable energy sources for long-term continuous detection. It will be helpful to develop transformative technologies to power the sensor networks by harvesting energy from the surrounding environment. Wang et al. presented a hybrid NG by combining a solar cell and a TENG capable of harvesting wind and solar energy simultaneously (Figure 5C).⁸¹ Three Si-based solar cells were fixed on the top of a TENG composed of the middle Kapton/Cu/fluorinated ethylene propylene (FEP) vibration films, and another two Cu electrodes were fixed on the top and bottom of an acrylic substrate. Airflow could induce high-frequency vibrations of the middle films, resulting in contact and separation between the middle film with the top/bottom Cu films. The output power of the TENG and the solar cell reached up to 26 mW and 8 mW with a loading resistance of 1 M Ω and 600 Ω , respectively. Four parallel connected devices were demonstrated on the roof of a house model for implementation of self-powering functionalities in a smart city, such as illumination and temperature-humidity monitoring (Figure 5D).

Compared with crystalline silicon,⁸⁴ organic solar cells (OSCs) are relatively low-cost, lightweight, mechanically flexible, and easily fabricable to serve as wearable power supplies. Thus, much work has been carried out to fabricate flexible hybrid OSC-TENG devices. As shown in Figure 5E, Fang et al. proposed a flexible and semi-transparent hybrid NG cell by integrating an OSC and a TENG into a thin film.⁸² The top TENG was composed of a thin FEP film and AgNWs/polyimide (PI) electrode, which had high transparency and generated little impact on the photoconversion efficiency of the OSC. The solution-processed OSC was fabricated by coating multiple organic functional layers on the bottom electrode of AgNWs/PI. The flexible hybrid NG cell could harvest both solar and mechanical energy to power wearable devices (Figure 5F). Additionally, researchers utilized an inexpensive dye-sensitized solar cell (DSSC)⁸⁵ to develop hybrid NGs. For example, Wen et al. designed a whole textile-based energy-harvesting system through the integration

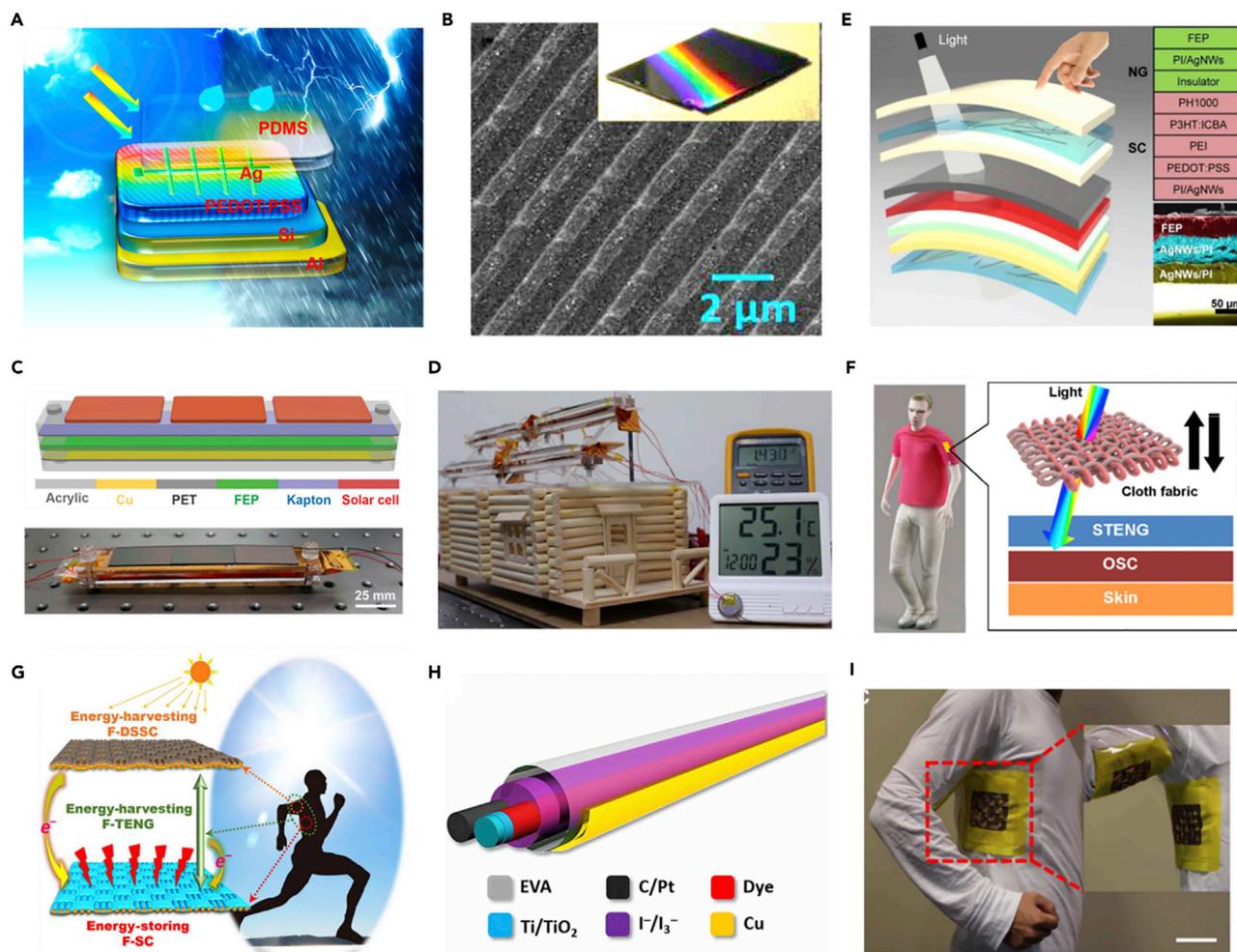


Figure 5. Hybrid Photovoltaic-Triboelectric NGs

(A) Schematic illustration of a hybrid NG cell consisting of a solar cell and a TENG.

(B) SEM image of the imprinted PEDOT:PSS on a Si substrate. Inset is the optical photo of the macroscale surface. Reproduced with permission from Liu et al.⁸⁰ Copyright 2018, American Chemical Society.

(C) Schematic diagram and photograph of a hybrid NG made of solar cell and TENG.

(D) Demonstration of a temperature-humidity sensor powered by four integrated hybrid NGs fixed on the roof of a house model. Reproduced with permission from Wang et al.⁸¹ Copyright 2016, American Chemical Society.

(E) Exploded view for the structure design of a flexible hybrid NG cell.

(F) Schematic diagram of the working mechanism of the hybrid NG in (E) covered by cloth as a wearable power source. Reproduced with permission from Fang et al.⁸² Copyright 2015, Elsevier.

(G) Schematic illustration of a self-powered textile that combines a dye-sensitized solar cell, a TENG fabric, and a fabric-shaped supercapacitor.

(H) Schematic diagram of the single fiber-shaped dye-sensitized solar cell.

(I) Photograph of the self-charging power textile to harvest sunlight energy and mechanical energy of human motions to power wearable electronics. Reproduced with permission from Wen et al.⁸³ Copyright 2016, the American Association for the Advancement of Science.

of fabric-based TENGs, fiber-shaped DSSCs (F-DSSCs), and fiber-shaped supercapacitors (Figure 5G).⁸³ The F-DSSC was assembled with N719 dye-sensitized TiO₂ nanotube arrays on a Ti wire as the photoanode, Pt-coated carbon fiber as the counter electrode, and I⁻/I₃⁻-based electrolyte sealed by a Cu-coated ethyl vinyl acetate tube (Figure 5H). Thanks to the all-fiber-based shape of each device, the hybrid energy-harvesting system can be woven into electronic textiles for smart clothes (Figure 5I), capable of harvesting sunlight energy and mechanical energy of human motions to sustainably power mobile or wearable electronics.

Hybrid Thermo-/Pyroelectric and Triboelectric Nanogenerators

Thermal energy can be considered to be a useful energy source in the environment for energy harvesting in many applications such as cooking, powering wearable electronics, and space exploration.⁸⁶ A hybrid NG that can harvest both thermal and mechanical energy is desired for specific situations where both the mechanical vibration and temperature difference exist. A thermoelectric generator (TEG) based on the Seebeck effect converts thermal energy directly into electricity, which is solid-state, simply operated, environmentally friendly, reliable, and safe.^{86–88} As illustrated in Figure 6A, a TEG module is composed of units of n-type and p-type semiconducting materials connected electrically in series and thermally in parallel. When there is temperature difference between the two semiconducting materials, a direct electric current will appear in the circuit. The figure of merit ZT is the standard measurement of a material's thermoelectric performance, which is expressed as $ZT = \frac{\alpha^2 T}{\sigma \kappa}$, where α is the Seebeck coefficient, σ is the electrical conductivity, T is the mean operating temperature, and κ is thermal conductivity. Improving thermoelectric performance requires novel materials with high electrical conductivity but low thermal conductivity.

As shown in Figure 6B, Yang et al. for the first time demonstrated a hybrid energy cell consisting of a TENG and a TEG,⁸⁹ in which a polyamide and perfluoroalkoxy (PFA) polymer film-based TENG and a Bi_2Te_3 -based TEG were fabricated at the top and bottom for harvesting mechanical and thermal energy, respectively. They demonstrated a self-powered electrolytic water system (Figure 6C) either to store the harvested energy into Li-ion batteries or to decompose water to generate H_2 . The continuous contact-separation or sliding friction between the two triboelectric layers of TENGs in energy harvesting produces considerable heat, thereby limiting the TENG's energy-harvesting performance. Recently, Wu et al. designed a triboelectric-thermoelectric hybrid nanogenerator (T-TENG) to harvest energy from both mechanical and thermal sources.⁹⁰ As shown in Figure 6D, the T-TENG was composed of a two-dimensional disk-structured rotary TENG (r-TENG) with a thermoelectric nanogenerator (TMENG) inserted between the electrodes and the substrate. The rotor and the stator of the r-TENG had a high-speed relative rotation inducing electrons to flow between the electrodes. At the same time, the heat energy produced by the friction was transferred to the TMENG and converted into electricity (Figure 6E). Compared with the r-TENG, the T-TENG exhibited a higher short-circuit and could light an LED with stronger illumination intensity (Figure 6F).

A pyroelectric nanogenerator (PyNG) based on the pyroelectric effect is another major type of device converting thermal energy into electricity,^{93–95} typically formed by a sandwiched structure composed of a top metal layer, a middle pyroelectric layer, and a bottom electrode (Figure 6G). Different from TEG, PyNG requires continuous temperature changes⁹⁶ rather than a temperature gradient, which induces spontaneous polarization change to create a flow of charge. The short-circuit current I is described as $I = pA \frac{dT}{dt}$, where p is the pyroelectric coefficient, A is the surface area of pyroelectric material, and dT/dt is the rate of temperature change. Thus, the optimization of the device structure and the pyroelectric coefficient are the key factors for enhancing the output performance of PyNG.⁹⁶

Low-grade wasted heat is widely available in industrial processes and is typically discarded due to the limitations in the recovery technology. Recently, Jiang et al. developed a hybrid triboelectric/pyroelectric nanogenerator (T-PyNG) to harvest both the thermal and kinetic energy of the thermal fluids originating from the spray nozzles of hyperboloid cooling towers (Figure 6H).⁹¹ When the droplets with either lower or

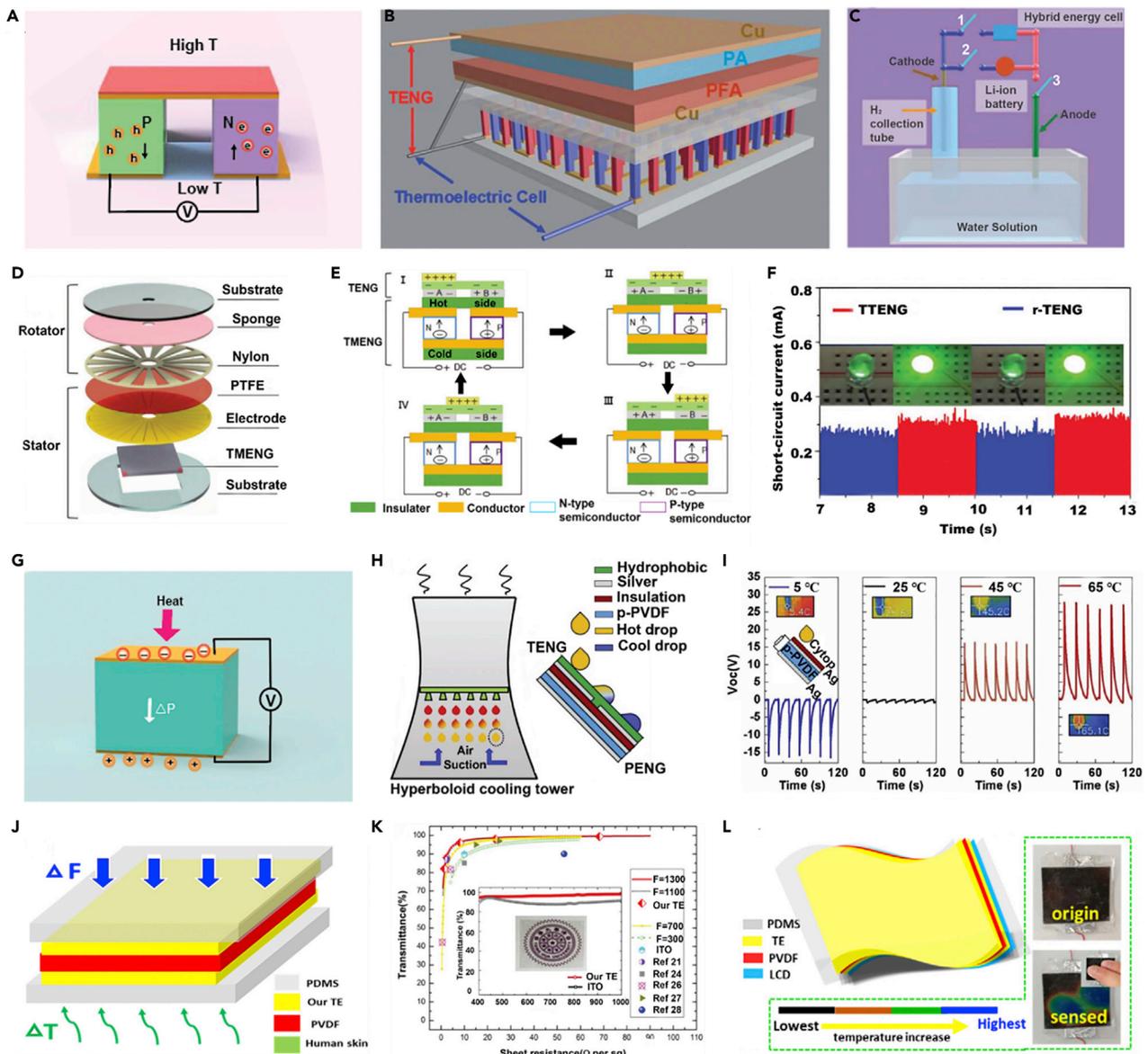


Figure 6. Hybrid Thermo-/Pyroelectric-Triboelectric NGs

(A) Schematic diagram and working principle of a thermoelectric generator.

(B) Schematic view of a hybrid NG composed of a TENG and a thermoelectric cell.

(C) Schematic diagram of a self-powered water splitting system for H₂ generation. Reproduced with permission from Yang et al.⁸⁹ Copyright 2013, Royal Society of Chemistry.

(D and E) Schematic diagrams of the structure design (D) and the working principle (E) of a hybrid triboelectric-thermoelectric NG.

(F) Comparison of the output currents from a hybrid NG and a TENG. The green-light LED visually indicates the generated power. Reproduced with permission from Wu et al.⁹⁰ Copyright 2018, Wiley-VCH.

(G) Schematic diagram for the working principle of a pyroelectric generator.

(H) Schematic illustration of a hybrid pyroelectric-triboelectric NG for harvesting energy from low-grade waste fluids.

(I) Output voltage of the hybrid NG in (H) for different droplet temperatures. Reproduced with permission from Jiang et al.⁹¹ Copyright 2018, Elsevier.

(J) Schematic diagram of a flexible transparent tribo-piezo-pyroelectric hybrid NG.

(K) Transmittance and conductivity measurements of the highly transparent and conductive electrodes.

(L) Schematic diagram of a smart device composed of an LCD and hybrid NG for temperature sensing. Reproduced with permission from Sun et al.⁹² Copyright 2018, Elsevier.

higher temperatures contacted the PyNG device, voltage signals were generated as a result of the temperature difference (Figure 6I). The power density peak of the T-PyNG could reach $2.6 \mu\text{W cm}^{-2}$ being able to power up to 28 LEDs. To harvest both mechanical and thermal energy from human activities, Sun et al. designed a transparent, flexible, and biocompatible triboelectric-piezoelectric-pyroelectric hybrid NG (Figure 6J).⁹² Inspired by the unique structure of leaf venation, silver nanowire electrodes were fabricated through a green and cost-effective approach.⁹² The electrode exhibited an ultra-high transmission up to 99% (at $68.2 \Omega \text{ sq}^{-1}$ sheet resistance) and the sheet resistance was as low as $1.4 \Omega \text{ sq}^{-1}$ (with 82% transmission), superior to other transparent electrodes reported in the literature (Figure 6K). The hybrid NG can also be used as a self-powered sensor to monitor various human physiological signals, including breath rate, heartbeat pulse, and swallow behavior. A self-powered user interactive smart device was also developed by integrating the hybrid NG with a thin thermochromic liquid crystal (LCD) film (Figure 6L), which has the potential application as a visualized thermometer for medical diagnostics.⁹²

Hybrid Energy Cells with Multiple Working Mechanisms

Compared with the bihybrid energy harvesters, hybrid energy harvesters with three or more working mechanisms demonstrated even better robustness, adaptability, and energy-conversion efficiency for specific applications. For instance, Shao et al. developed a multifunctional hybrid power unit composed of three types of energy devices: a contact-separate mode TENG, an EMG, and a solar cell (Figure 7A).⁹⁷ In their design, noncontact attractive force between the top and bottom magnets made the two triboelectric layers of TENG contact and separate constantly to harvest mechanical energy by the TENG and EMG. On the other hand, through integrating a solar cell on the top surface of the device, the hybrid unit could also harvest solar energy with sunlight, enabling the hybrid device to work under all weather conditions. In another work, Wang et al. reported a rotation-based hybrid NG by combining a TENG, an EMG, and a TEG to simultaneously harvest mechanical and thermal energies in one process (Figure 7B).⁹⁸ With efficient power-management circuits integrated, the hybrid NG could generate a constant output voltage of 5 V and a pulsed output current of ~ 160 mA. Thanks to the high output power and rotational structure, the hybrid NG was able to be easily installed in a commercial bicycle to charge a smartphone (Figure 7C).

It should be noted that most hybrid NGs stack individual energy harvesters together in a simple way, which hinders the massive production, miniaturization, and integration of the complex devices. To address this issue, Ji et al. developed a hybrid NG based on ferroelectric barium titanate (BaTiO_3) (Figure 7D) by combining pyro-tribo-piezo-photoelectric effects in one structure with only two electrodes.⁹⁹ The ferroelectric BaTiO_3 could harvest both mechanical energy and thermal energy, and with a direct band gap of 3.3 eV, the BaTiO_3 could also harvest solar energy under light source. Compared with traditional hybrid NGs, this new multieffect coupled NG has the merits of low cost, simple structure, and small volume, which represents a new trend of all-in-one multiple energy harvesting and a significant step toward miniaturized and integrated hybrid energy harvesters. Furthermore, a highly transparent and flexible hybrid NG with one device structure was recently proposed by Wang et al. (Figure 7E).¹⁰⁰ A PVDF nanowires-PDMS composite film served as the triboelectric layer while a polarized PVDF film acted as both the piezoelectric and pyroelectric layers, which could individually or simultaneously harvest both mechanical and thermal energies. In comparison with TENG-PENGs or PyNGs, it was found that the developed hybrid NG exhibited a much better charging performance for a $10 \mu\text{F}$ capacitor.¹⁰⁰

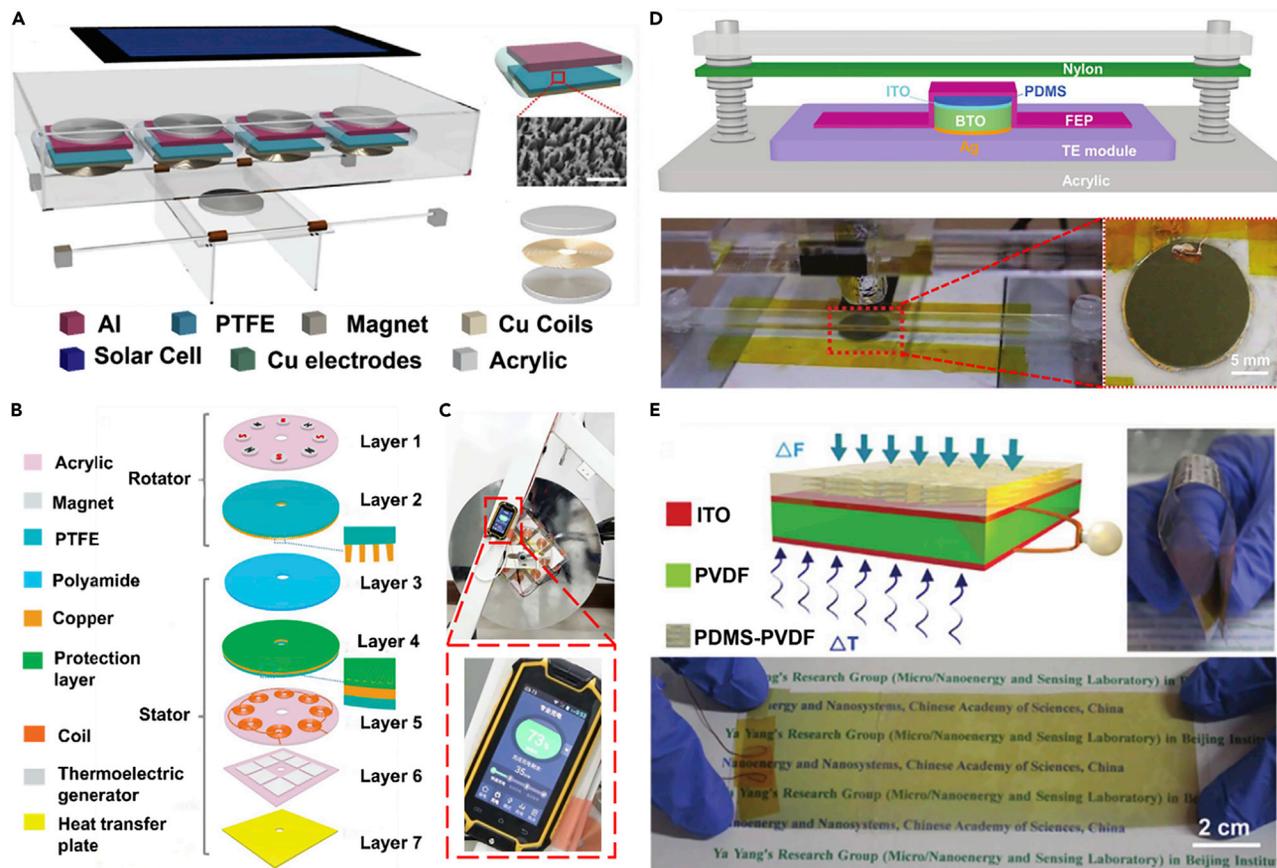


Figure 7. Hybrid Energy Cells with Multiple Working Mechanisms

(A) Schematic diagram of a hybrid power unit composed of TENGs, EMGs, and a solar cell. Reproduced with permission from Shao et al.⁹⁷ Copyright 2017, Elsevier.

(B) Schematic diagram of a hybrid NG composed of a TENG, an EMG, and a TEG.

(C) Photographs of the hybrid NG installed on a bicycle for charging a cell phone. Reproduced with permission from Wang et al.⁹⁸ Copyright 2016, Elsevier.

(D) Schematic diagram and photograph of one-structure-based multi-effects coupled NG, which can simultaneously harvest thermal, solar, and mechanical energies. Reproduced with permission from Ji et al.⁹⁹ Copyright 2018, Wiley-VCH.

(E) Schematic diagram and photograph of a transparent, flexible, and hybrid NG for harvesting mechanical and thermal energies by triboelectric-piezoelectric-pyroelectric effects. Reproduced with permission from Wang et al.¹⁰⁰ Copyright 2016, Wiley-VCH.

APPLICATIONS OF TENG-BASED HYBRID ENERGY HARVESTERS

Self-Charging Power System

The TENG suffers from its irregular pulsed output and low current output, which limits its being used alone to drive most of the available electronic devices.¹⁰¹ An effective solution is to integrate the TENG with an energy-storage device such as capacitors, supercapacitors (SCs), or batteries to form a self-charging power unit as a reliable energy supply.^{45,102–105} However, the TENGs, EMGs, PENGs, and PyNGs discussed above are generating alternative current (AC) output, which are not able to directly charge an energy-storage unit (e.g., battery) usually requiring a direct current (DC) input. A simple and popular approach is to add a rectifier that can convert AC to DC between energy harvesters and energy-storage units. For example, Luo et al. developed a flexible self-charging micro-supercapacitor power unit by integrating a TENG, a micro-supercapacitors (MSCs) array, and a rectifier into a single device (Figure 8A).¹⁰⁶ They utilized a simple laser-engraving technique to fabricate porous graphene-based electrodes on a polyimide substrate. The

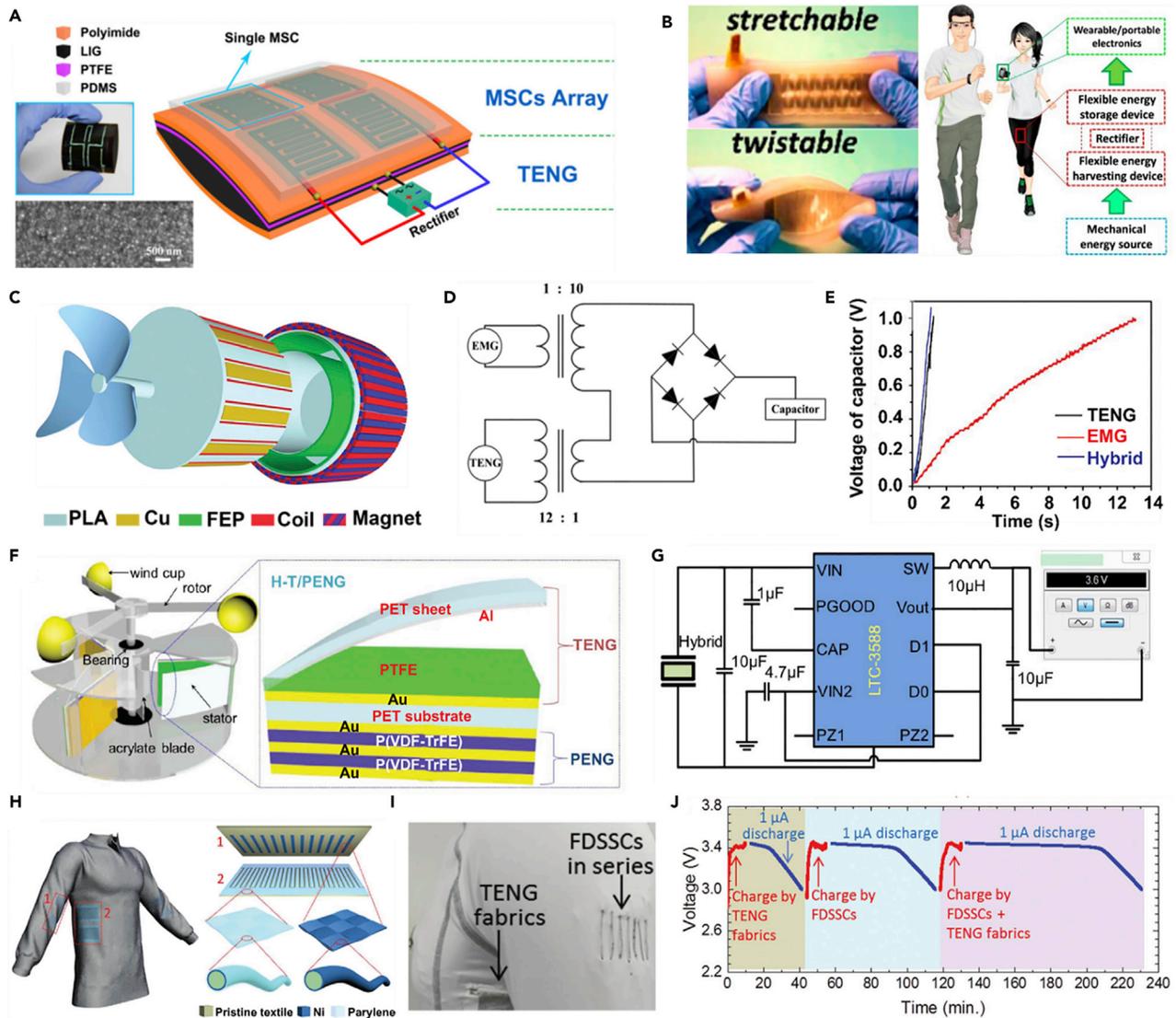


Figure 8. Self-Charging Power Units Based on Hybrid Energy-Harvesting Systems

- (A) Schematic diagram and photograph of a flexible self-charging power unit consisting of microsupercapacitors (MSCs) and a TENG. Reproduced with permission from Luo et al.¹⁰⁶ Copyright 2015, Springer.
- (B) Schematic illustration of the working principle and the photography of an all-in-one shape-adaptive self-charging power system. Reproduced with permission from Guo et al.¹⁰⁷ Copyright 2016, American Chemical Society.
- (C) Schematic illustration of a rotating-sleeve hybrid NG composed of a TENG and an EMG.
- (D) Circuit diagram of a power management system based on two transformers.
- (E) Charging plots of the hybrid NG with TENG and EMG. Reproduced with permission from Cao et al.¹⁰⁸ Copyright 2017, American Chemical Society.
- (F) Schematic diagram of a hybrid TENG-PENG device.
- (G) Electrical circuit diagram of a commercial power management module (LTC3588). Reproduced with permission from Zhao et al.¹⁰⁹ Copyright 2019, Elsevier.
- (H) Schematic illustration of a grating-structured TENG fabric.
- (I) Photograph of a hybrid power-textile integrated by the TENG fabric and fiber-shaped dye-sensitized solar cell.
- (J) Charge/discharge curves of a Li-ion battery using the hybrid NG. Reproduced with permission from Pu et al.¹¹⁰ Copyright 2016, Wiley-VCH.

capacitance of MSC can reach 10.29 mF cm^{-2} at a current density of 0.01 mA cm^{-2} with the array being able to be charged up to 3 V in 117 min by the TENG, demonstrating its capability as a self-charging system. Guo et al. invented an all-in-one shape-adaptive self-charging power unit (SCPU) composed of a kirigami paper-based SC, an all-flexible silicone rubber based TENG, and a rectifier (Figure 8B).¹⁰⁷

Their SCs exhibited excellent stretchability (up to 215%) and mechanical durability (2,000 stretching/relaxation cycles). The ultra-stretchable and shape-adaptive TENG used Ag nanowires and silicone rubber as the electrode and the triboelectric layer, respectively. The as-fabricated SCPU is stretchable, bendable, twistable, and capable of continuously powering an electric watch by hand flap, which provides a potential platform for self-powered wearables.

As discussed above, TENG has high output voltage, low current, and high impedance, while EMG exhibits opposite electrical characteristics of high current, low voltage, and low impedance. This difference makes the synergistic integration of TENG and EMG a little difficult in the same circuit. To solve this problem, Cao et al. proposed a rotating sleeve hybrid NG consisting of a TENG and an EMG and achieved impedance matching through commercial transformers (Figure 8C).¹⁰⁸ As shown in Figure 8D, a TENG and an EMG were connected with a step-down transformer and a step-up transformer, which adjusted their impedances to the same level. The hybrid NG with transformers showed a faster charging rate than that of an independent TENG or EMG (Figure 8E). However, it is noted that the transformer in this design requires to be operated at a high frequency, so that it is only suitable for a hybrid NG with a rotational structure. Since a TENG has similar output characteristics and matched impedance with a PENG, some commercial power-management modules used for PENGs are applied to build TENG-PENG-based hybrid NGs. In a recent study, Zhao et al. developed a hybrid TENG-PENG device for efficiently harvesting mechanical rotation energy (Figure 8F).¹⁰⁹ By integrating with an energy-managing circuit (Figure 8G), the system generated a stable and constant output voltage of 3.6 V, which could directly power commercial electronics or charge energy-storage units.

Owing to the high energy density and constant voltage output, the self-charging power systems based on batteries and hybrid NGs are regarded as a promising power source for portable or wearable electronics. Pu et al. integrated a fabric TENG, a fiber-shaped dye-sensitized solar cell (FDSSC), and a Li-ion battery (LIB) to form a self-charging power system (Figure 8H).¹¹⁰ The FDSSC was assembled with a Ti wire coated by a mesoporous TiO₂ layer as the photoanode, a twisted Pt wire as the counter electrode, and the electrolyte sealed by a transparent PTFE tube. Several FDSSCs connected in series could be sewn on cloth and integrated with a rectified TENG fabric in parallel as the complementary power device for harvesting energy from sunlight and human motions (Figure 8I). The grating-structured TENG fabric was demonstrated on a sleeve underneath the arm to harvest the energy from arm swings during walking or running. It was shown that the hybrid NG could charge an LIB with commercial LiFePO₄ as cathode and Li metal as anode in 10 min, and the fully charged LIB could provide a constant voltage of 3.4 V with a DC current of 1 μ A for 98 min (Figure 8J).

Self-Powered Biomedical Systems

The increasing needs for customized healthcare and real-time health monitoring in biomedical engineering raise significant challenges in providing continuous and long-term power supplies for electronic devices such as wearable and implantable devices.^{111–113} Many ongoing researches are attempting to find better solutions for sustainable long-term operations of the devices by either lowering the energy consumption or harvesting more energy to power them. Recently, Zou et al. presented a pulse sensor based on a self-arched hybrid NG composed of a TENG and a PENG (Figure 9A).¹¹⁴ In their design, the morphology of the self-arched structure was easily regulated by adjusting the mass ratio of Ecoflex and PDMS. A thin

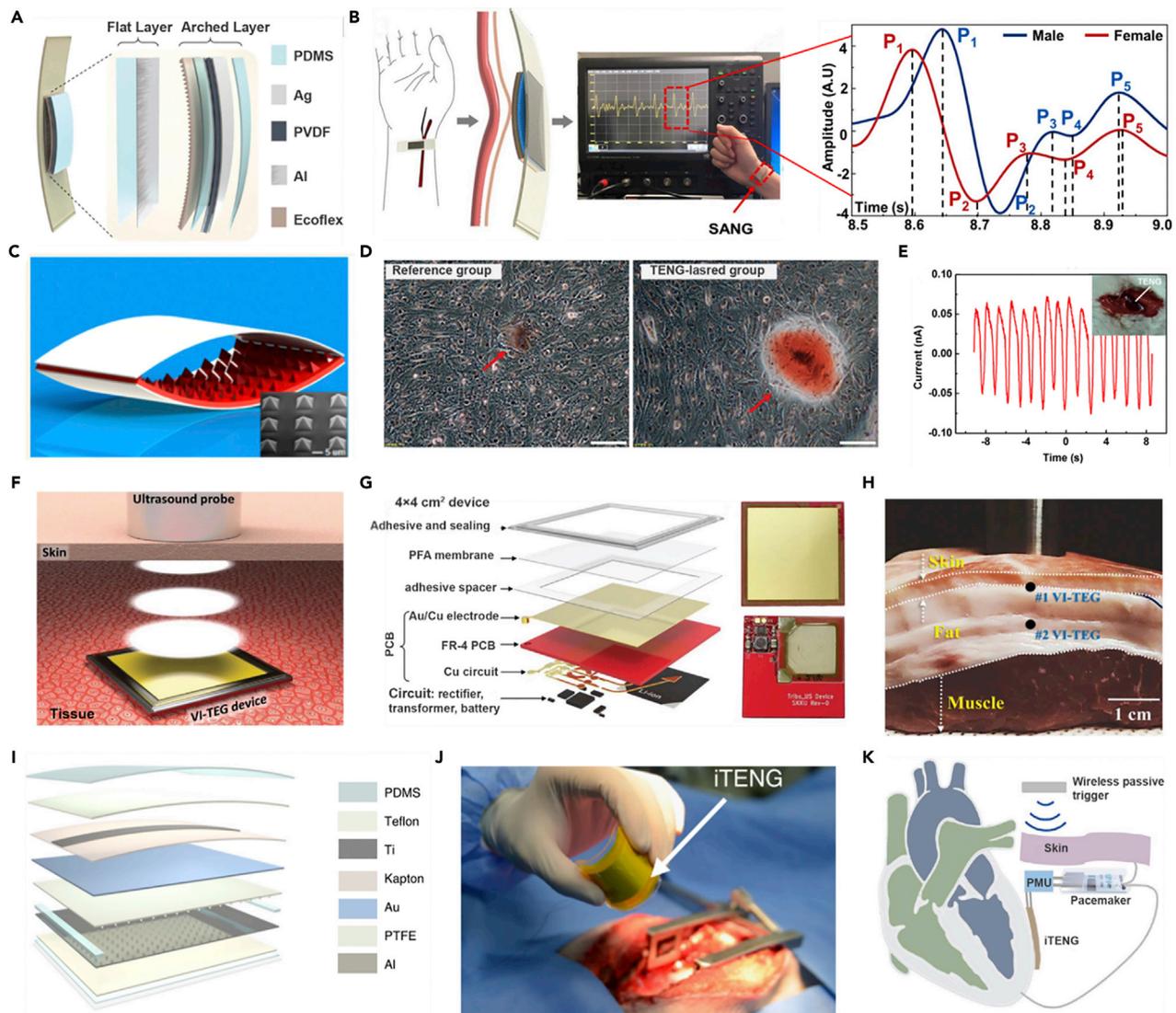


Figure 9. Self-Powered Biomedical Systems by Hybrid Energy-Harvesting Systems

- (A) Schematic diagram of a self-arched hybrid NG for self-powered pressure sensing.
- (B) Demonstration of the device for detecting pulse signals of radial artery when attached on the wrist. Reproduced with permission from Zou et al.¹¹⁴ Copyright 2020, Elsevier.
- (C) Schematic diagram of a flexible arch-shaped TENG with a pyramid array patterned triboelectric layer.
- (D) Mineral deposition images of the TENG-lased irradiation group and the reference group. The mineral deposition area (stained by Alizarin red S) represent the bone formation.
- (E) Output current of the implanted TENG in the body of a rat. Reproduced with permission from Tang et al.¹¹⁵ Copyright 2015, American Chemical Society.
- (F) Schematic illustration of the implantable TENG beneath skin to harvest ultrasound energy.
- (G) Exploded view and photograph of the implantable device.
- (H) Image of the implanted TENG under the porcine tissue. Reproduced with permission from Hichet et al.¹¹⁶ Copyright 2019, the American Association for the Advancement of Science.
- (I) Schematic diagram of an implantable TENG-based self-powered pacemaker system.
- (J) Photograph of the surgery to implant the self-powered device into animal's body.
- (K) Illustration of implant pacemaker system turned on by wireless passive trigger. Reproduced with permission from Ouyang et al.¹¹⁷ Copyright 2019, Springer Nature Group.

PVDF film was added to the arched layer to improve the signal-to-noise ratio of the device. The hybrid NG was attached to the wrist for real-time monitoring pulse waveform of the radial artery (Figure 9B). Additionally, it was able to effectively convert

the pulse signal into the electrical signal to identify the condition of human physiology.

In another study, Tang et al. demonstrated a self-powered low-level laser cure system (SPLC) composed of a TENG, a capacitor, and an infrared laser excitation unit for osteogenesis.¹¹⁵ The TENG design was based on a pyramid array patterned PDMS film and an indium-tin oxide film (Figure 9C), achieving a short-circuit current of about 30 μA , an open-circuit voltage of 115 V, and a transferred charge of 70 nC. The optical images in Figure 9D show that the area of mineral deposition in TENG-lasered group was significantly larger than that in the reference group, which demonstrated that the SPLC had a positive effect on bone remodeling. The system could also be driven by human motions or even breathing of a mouse (Figure 9E), indicating its great potential in portable or implantable biomedical systems.

Implanted medical devices, such as neurological stimulators and pacemakers, are generally powered by external batteries that may need to be replaced through additional surgery, resulting in high risk as well as extra cost and pain. To solve this issue, Hinchet et al. developed a high-frequency vibrating and implantable triboelectric generator (VI-TEG) for harvesting ultrasound energy *in vivo* (Figure 9F).¹¹⁶ The VI-TEG included a PFA membrane and an Au/Cu electrode with an air gap of 80 μm , and was implanted underneath the skin. A rectifier, a transformer, voltage regulator, and battery were integrated with a flexible printed circuit board attached to the backside of the VI-TEG (Figure 9G). When the VI-TEG was triggered by 20-kHz ultrasound, it generated a root-mean-square (RMS) voltage of 9.71 V, an RMS current of 427 mA, and a power density of 5.2 W m^{-2} . To simulate more accurate clinical conditions, the VI-TEG was installed in porcine tissue where it could generate a power of 98.6 μW , capable of fully charging an LIB with a capacity of 700 μAh (Figure 9H).

Apart from external mechanical stimuli, TENGs can also convert the mechanical energy of human body muscles to electrical energy to power implanted medical devices. For example, Ouyang et al. presented an implanted symbiotic pacemaker based on an implantable TENG (iTENG) to harvest biomechanical energy (Figure 9I).¹¹⁷ The output performance of iTENG was evaluated *in vivo* by placing the device between the heart and pericardium of a large animal model (Figure 9J). It was demonstrated that the open-circuit voltage of iTENG reached 65.2 V and the harvested energy from each cardiac motion cycle was 0.495 μJ , which could be stored in a capacitor to power a pacemaker after the magnet placed outside the body turned on the reed switch (Figure 9K).

Self-Powered Wearable Electronics

Wearable electronics have great potential in many applications such as health monitoring,^{118,119} soft robotics,¹²⁰ and man-machine interactions.^{121,122} To achieve a reliable power supply for these devices, new energy-harvesting techniques such as hybrid TENG-based energy harvesters have been investigated over the past few years.^{123–127} For example, Zhu et al. developed a self-powered and self-functional sock by integrating a TENG and PZT piezoelectric chips (Figure 10A).¹²⁵ The sock could generate an output power of 1.71 mW at a jumping frequency of 2 Hz. Thus, the hybrid sock can be adopted for walking pattern recognition and motion tracking of individuals for healthcare and smart home use (Figure 10B). In another work, Chen et al. developed an all-solid hybrid power textile based on lightweight polymer fibers for capturing solar and mechanical energy (Figure 10C),¹²⁶ capable of stably powering an electronic watch and directly charging a cell phone when exposed to sunlight (Figure 10D).

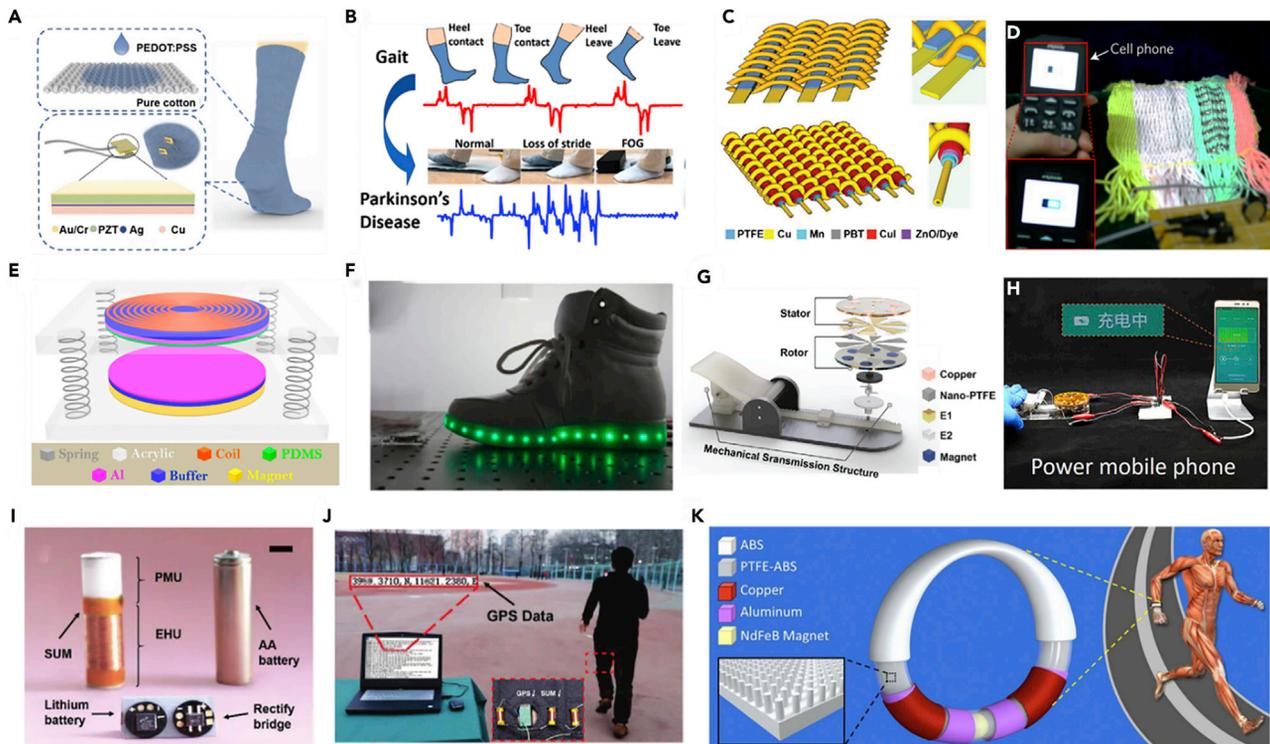


Figure 10. Self-Powered Wearables Driven by Hybrid Energy-Harvesting Systems

(A) Schematic diagram of a PEDOT:PSS-based TENG sock with integrated force sensors.

(B) Demonstration of the capability of a simple fabricated device in monitoring indoor activities. Reproduced with permission from Zhu et al.¹²⁵ Copyright 2015, American Chemical Society.

(C) Schematic illustration of a hybrid power textile based on TENG and solar cell.

(D) Demonstration of the power textile to directly charge a cell phone. Reproduced with permission from Chen et al.¹²⁶ Copyright 2016, Springer Nature Group.

(E) Schematic illustration of a hybrid NG with TENG and EMG.

(F) The LEDs bonded on a shoe can be lightened when walking. Reproduced with permission from Zhang et al.¹²⁷ Copyright 2015, American Chemical Society.

(G) Schematic diagram of the structure of a hybrid EMG-TENG nanogenerator in shoes.

(H) Demonstration of the hybrid NG for charging a mobile phone. Reproduced with permission from Jiang et al.¹²⁸ Copyright 2020, Wiley-VCH.

(I) Photography of a battery-like self-charge universal module compared with an AA commercial battery. The module consists of piezoelectric generator, TENG, electromagnetic generator, and a power management unit.

(J) Demonstration of the module for powering a GPS. Reproduced with permission from Tan et al.¹²⁹ Copyright 2019, Wiley-VCH.

(K) Schematic diagram of the curve-shaped wearable hybrid electromagnetic-triboelectric NG worn on a wrist for harvesting human kinetic energy. Reproduced with permission from Maharjan et al.¹³⁰ Copyright 2018, Elsevier.

Recently, much research has been focusing on harvesting walking energy by integrating the harvesters into shoes to power wearable sensors and electronics.¹³¹ For example, Zhang et al. developed a hybrid EMG-TENG (Figure 10E) mounted in a shoe heel for capturing biomechanical energy to power on-shoe LEDs during walking or jumping (Figure 10F).¹²⁷ Furthermore, the hybrid NG can charge an LIB and power a smart wireless pedometer. For example, Jiang et al. demonstrated a novel wearable rotating hybrid nanogenerator (WRNG) that was composed of a noncontact free-rotating TENG and an EMG.¹²⁸ As shown in Figure 10G, the WRNG could effectively convert the human body's potential energy into the rotational kinetic energy of a rotor through a unique mechanical transmission structure. The WRNG could then generate output energy of 14.68 mJ in one compression-releasing cycle, which is enough to power certain wearable electronics, such as a GPS sensor, a temperature sensor, and a mobile phone (Figure 10H). Chen et al.

also proposed a hybrid TENG-EMG harvester with a maximum power density of 6.79 W m^{-2} .¹³² By integrating such a hybrid NG, a radiofrequency identification (RFID) tag, and a transistor-controlled power-management module, a self-powered active RFID tag for smart shoes was developed, being able to work autonomously, sustainably, and omnidirectionally in an ultra-large area of up to tens of meters.

In addition to the footstrike energy, vibrations and touches from human body motions are another important biomechanical energy source. Tan et al. introduced a battery-like self-charge universal module (SUM)¹²⁹ consisting of a hybrid generator (TENG, EMG, and PENG) and a power-management unit (energy management circuit and battery) (Figure 10I). The new SUM had the same shape and size as a standard AA battery that can be easily applied to electrical appliances. The output power density of the SUM reached 2 mW g^{-1} at low-frequency ranges (5 Hz). After jogging for 10 min, the SUM could harvest sufficient energy to charge a battery between 2.5 and 3.2 V, and continuously power a GPS sensor for 0.5 h (Figure 10J). To develop a wrist-wearable energy harvester for harvesting kinetic energy from arm-swinging motion, Maharjan et al. utilized 3D printing to fabricate a hybrid electromagnetic TENG (Figure 10K).¹³⁰ The proposed device was small and light, and suitable to be worn on the wrist. They demonstrated a self-powered heart-rate sensing system that could harvest energy from arm-swinging motion and stabilized the electricity for detecting the heart pulse.

Self-Powered Environment Monitoring

A self-powered wireless sensor network based on TENGs has been considered as an effective solution for monitoring environmental conditions and raising the alarm for natural disasters.^{133,134} Due to the constraints in different scenarios, a hybrid energy-harvesting system that is capable of capturing different energy sources in the environment will significantly enhance the reliability of the monitoring or alarm systems. For example, Qian and Jing developed a wind-driven hybrid energy harvester (WH-EH) composed of a TENG, an EMG, and a solar cell (Figure 11A) for multiple-purpose detection,¹³⁵ which exhibited a peak output power of 2.13 mW by TENG under a load resistance of $3 \text{ M}\Omega$ and a peak output power of 0.34 mW by the EMG under a load resistance of 10Ω . The WH-EH was able to be integrated with a vibration sensor for earthquake detection (Figure 11B) and a wireless transceiver for natural disaster alarm reporting (Figure 11C). Recently, our group also developed a multilayered cylindrical TENG (MC-TENG) to harvest kinetic energy of moving tree branches in a forest (Figure 11D) to power a forest fire alarm system.¹⁰⁴ The MC-TENG prototype demonstrated high output performance and could capture the kinetic motions of tree branches in an arbitrary direction at low-frequency ranges. This self-powered forest fire alarm system can also be used for environmental monitoring in natural resource management.

In a recent work, Zhang et al. developed a self-powered active wireless traffic volume sensor to measure traffic-flow characteristics in real time (Figure 11E).¹³⁶ The designed harvester consisted of a bottom hybrid energy harvester (TENG and EMG) and a top blade, which converted the ambient wind flow to the mechanical rotational motion. At a rotation rate of 1,000 rpm, the hybrid NG generated an output power of 17.5 mW with a loading resistance of 700Ω . The hybrid nanogenerator was demonstrated to harvest energy from the wind flow induced by the moving vehicles so as to continuously power a wireless transmitter that can trigger a counter to monitor traffic volume, which could be potentially used for intelligent traffic systems. Xi et al. also demonstrated a self-powered intelligent buoy system (SIBS) that harvested water wave energy for ocean monitoring (Figure 11F).¹³⁴ A high-output multilayered

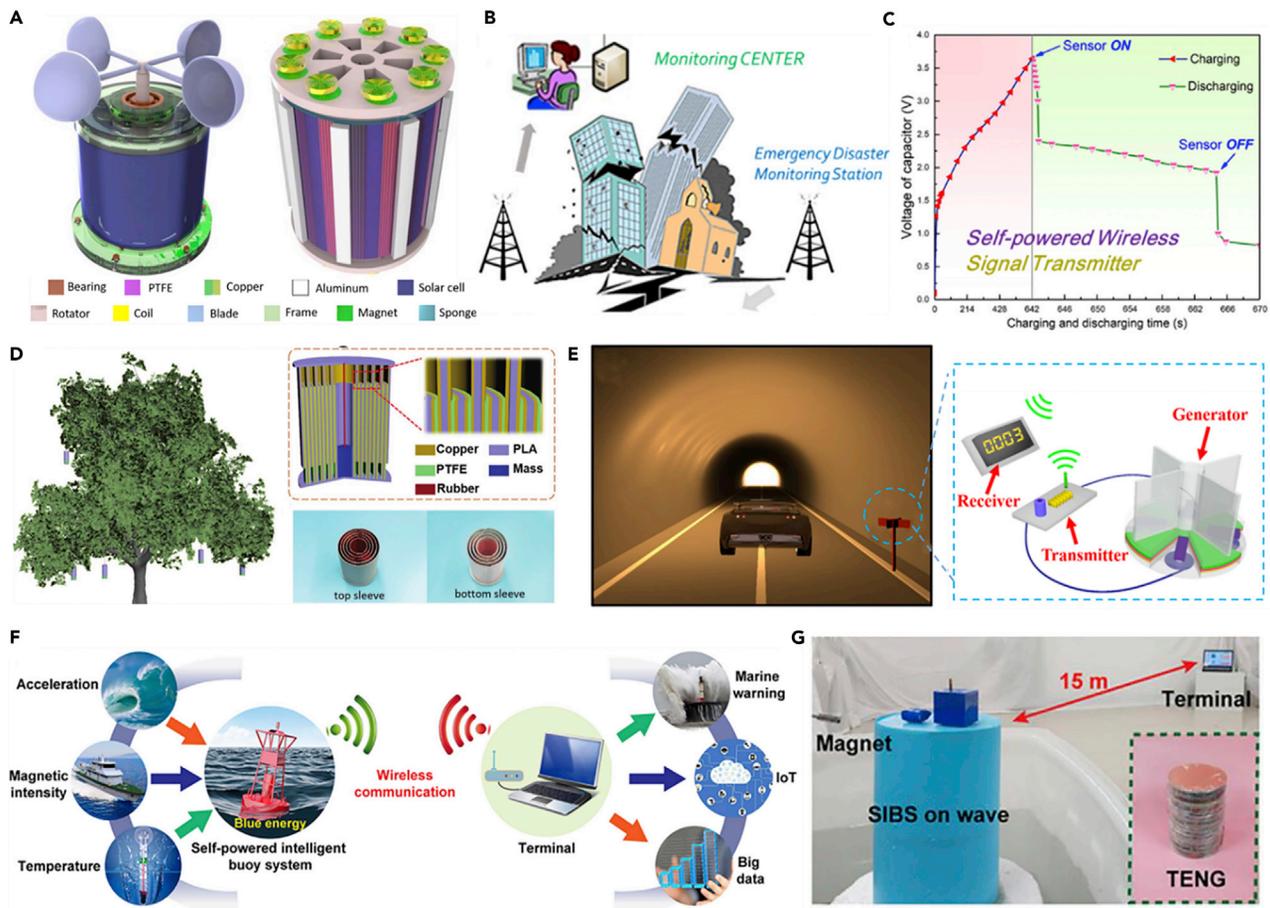


Figure 11. Environment Monitoring Enabled by Hybrid Energy-Harvesting Systems

(A) Structural design of a wind-driven hybrid generator by combing TENGs, EMGs and solar cells.

(B) Schematic illustration of a self-powered earthquake monitoring system enabled by TENGs that can harvest vibration energy.

(C) Charge/discharge curve of a capacitor connected for powering a wireless transmitter. Reproduced with permission from Qian and Jing.¹³⁵ Copyright 2018, Elsevier.

(D) Schematic illustration of a multilayered cylindrical TENG (MC-TENG) for harvesting the kinetic energy of tree branches for powering forest fire alarming systems. Reproduced with permission from Pang et al.¹⁰⁴ Copyright 2020, Wiley-VCH.

(E) Schematic diagram of a self-powered wireless traffic volume system made of rotational TENGs. Reproduced with permission from Zhang et al.¹³⁶ Copyright 2016, American Chemical Society.

(F) Schematic diagram of a self-powered intelligent buoy system for monitoring ocean environment by harvesting the ocean wave energy.

(G) Photograph of a self-powered intelligent buoy system for detecting simulated ocean environment and transferring data in a range of 15 m via wireless transmission. Reproduced with permission from Xi et al.¹³⁴ Copyright 2019, Elsevier.

TENG was designed to provide an average output power density of 13.2 mW m^{-2} . With a power-management module, a steady and continuous DC voltage of 2.5 V was generated to power a microprogrammed control unit, several microsensors, and a transmitter. At a wave frequency of 2 Hz, the SIBS was demonstrated to detect the acceleration, magnetic intensity, and temperature of the ocean wave and transfer these data in a range of 15 m with the rate of 19 bytes per 30 s via wireless transmission (Figure 11G).

Efficient Blue Energy Harvesting

Ocean wave energy is one of the most desirable sustainable energy sources with low dependency on environmental conditions.^{137–139} However, it is challenging and inefficient to harvest wave energy by traditional EMGs due to the low-frequency

features of ocean waves (<2 Hz). TENG, as a new mechanical energy harvester, has unique advantages in harvesting low-frequency wave energy.⁵² In 2013, Lin et al. for the first time developed a liquid-solid contact electrification TENG for water wave energy harvesting.¹⁴⁰ Since then, various TENGs with different structural designs have been proposed for wave energy harvesting, including wavy-electrode structure,¹⁴¹ rolling spherical structure,¹⁴² duck-shaped structure,¹⁴³ and air-driven membrane structure.¹⁴⁴ Recently, to improve the conversion efficiency and boost the harvested energy over a broad frequency range, hybrid NGs have been increasingly developed and tested for harvesting low-frequency random water wave energy.^{145–148} For example, Wen et al. reported a hybrid NG made of a spiral-interdigitated-electrode TENG and a wrap-around EMG (Figure 12A).¹⁴⁷ Their device could capture the tidal, ocean current, and wave energy under either a fluctuation mode or a rotation mode. As shown in Figure 12B, the designed hybrid NGs were integrated into an energy-harvesting floating panel that could simultaneously harvest solar, wind, and blue energy. Later, Wang et al. developed a cubic structured hybrid NG based on a TENG and an EMG with an optimized inner topological structure,¹⁴⁸ which could effectively harvest ocean wave energy (Figure 12C). The complementary output from the TENG and EMG improved the energy-conversion efficiency over a broad range of operational frequencies. Under a wave frequency of 1 Hz, the packed hybrid NG could power a temperature sensor or light up dozens of LEDs.

Another interesting design by Chen et al. demonstrated a chaotic pendulum triboelectric-electromagnetic hybrid NG for harvesting wave energy (Figure 12D).¹⁴⁹ Under normal wave excitation, the TENG and EMG of the hybrid NG would generate a maximum output power of 15.21 μW and 1.23 mW, respectively, being able to light up ~ 100 LEDs, power a wireless sensing node, and detect the remote transmission of marine environmental condition (Figure 12E). In addition, Hou et al. reported a rotational pendulum triboelectric-electromagnetic hybrid generator (RPHG),¹⁵⁰ which could harvest the irregular low-frequency multidirectional vibration energy of ocean waves. As shown in Figure 12F, the disk-shaped rotor magnets were used as a pendulum rotor that could rotate easily around the central shaft via a small external excitation force. By optimizing the structure, the TENG and EMG obtained a maximum power density of 3.25 W m^{-2} and 79.9 W m^{-2} , respectively. The RPHG was demonstrated to harvest human mechanical energy and water wave energy fixed on the human body and an in-house developed buoy, respectively. In a recent study, Feng et al. developed a hybrid TENG-EMG energy harvester based on honeycomb-like three electrodes for ocean wave energy harvesting.¹⁵³ The hybrid NGs could harvest kinetic energy and potential energy of ocean waves in multiangle range because of the innovative design of the electrode structure. Two basic units packaged into a cylinder acrylic shell were demonstrated to harvest ocean wave energy and power tens of LEDs.

Spherical hybrid NGs with low weight, high buoyancy, and low resistance to the water wave motions have also been designed for harvesting wave energy. For example, Wu et al. developed a spherical hybrid NG based on a magnetic sphere for capturing water wave energy (Figure 12G).¹⁵¹ The magnetic sphere could freely roll inside through water wave actuation, and the open-circuit voltage was produced by the two coils based on the electromagnetic induction effect. At the same time, a triboelectric mover embedded in a magnetic cylinder was driven by a magnetic sphere sliding between the two electrodes in a Tai Chi shape (Figure 12H). A self-powered wireless water-temperature alarm system was developed by integrating the hybrid generator, an SC, a control circuit, and a temperature switch, which demonstrated the ability of the hybrid generator to harvest water

Table 2. Comparison of the Different Types of TENG-Based Hybrid Energy-Harvesting Systems

Hybrid Type	Pros	Cons
TENG + EMG	high output voltage, current, and power; wide-frequency bandwidth; high energy-conversion efficiency; weather independent	large impedance mismatch; high weight and large volume; structure complexity; rigid magnet structure, loose integration
TENG + PENG	high output voltage; similar internal impedance; simple structure; low weight; flexible and wearable; easy manufacturing; tight integration; wide-frequency bandwidth; weather independent	low output current and power; not easy for large-scale applications; environmental conditions interference; high impedance
TENG + solar cell	high output voltage and power; DC power output; flexible and wearable; long lifetime; cost effective	weather and configuration dependent; need large area deployment; toxic chemicals used in production process
TENG + TEG	DC power output; long service lifetime; good stability; wide compatibility	low energy-conversion efficiency; rigid structure; constant heat source required; loose integration, limited applications
TENG + PyNG	flexible structure; similar internal impedance; simple structures; low weight; tight integration	low output current; low energy-conversion efficiency

SUMMARY AND PERSPECTIVES

The hybrid energy harvesters based on TENGs provide a promising approach to effectively use the environmental conditions for energy harvesting by combining two or more working mechanisms, aiming at harvesting various forms of energy wherever it is available to meet the needs of distributed energy units. Significant progress has been made in improving the performance of TENG-based hybrid energy-harvesting systems by introducing new concepts, designs, and integration methods. In this review, we have systematically summarized the working principles, structural designs, performances, and applications of the TENG-based hybrid energy-harvesting systems. The hybrid systems can independently or collaboratively harvest energy from one or more kinds of sources under different conditions, which improves the energy-conversion efficiency and widens its potential applications. The pros and cons of the different TENG-based hybrid energy devices are summarized in [Table 2](#). It is expected that TENG-based hybrid power systems will have significant development with the rapid advances in materials science and manufacturing technologies, and that critical challenges will be addressed for practical applications.

Most consumer wearable electronics have power consumption at the level of microwatts to milliwatts, far above the output power generated by current hybrid energy harvesters. Therefore, the performance of TENG-based hybrid energy systems needs to be improved so as to power multifunctional wearable electronics. The output power of TENG is proportional to the square of the surface charge density. Future research needs to invent and improve new methods and technologies for achieving maximized performance, such as creating micro-/nanostructures, chemically modifying the friction surface, and modulating bulk friction materials.¹⁵⁴ Moreover, highly efficient power-management circuits are necessary in the TENG-based hybrid systems for maximizing the output power harvester. As discussed in this review, different types of harvesters have different properties such as matched resistance, working frequency, and polarity, which could lead to more challenges in the integration process and become a bottleneck for the application of TENGs.¹⁵⁵ For example, the impedance of EMG is quite small ($\sim\Omega$), while that of TENG is at the level of $M\Omega$. TENGs and EMGs generate AC output whereas solar cells and

TEGs generate DC output. Furthermore, TENGs have the characteristics of high voltage and pulsed output, which are not applicable to direct battery charging as energy-storage unit that are usually required for stable DC input. Therefore, it is essential to design a more effective power-management circuit for improving the energy-conversion and storage efficiency of hybrid power systems. In addition to improving their power density, miniaturization of the current devices is also important for certain applications such as implantable devices.

Critically, most current hybrid NGs are fabricated by simply stacking different energy harvesters together with a complex device structure, constraining the device dimension for certain applications such as implantable and wearable devices. Therefore, significant work needs to be done to optimize structural design and realize the unique integration and miniaturization such as the all-in-one structure. Additionally, the development of multifunctional materials that can combine multiple effects within one single material or structure will be a promising approach for coupling-effect energy-harvesting devices. In particular, multimodal designs for wave energy harvesting are highly desired for boosting the efficiency in generating enough electricity for potential large-scale grid-level applications. It is also challenging but promising to investigate the fluid-structure interactions of individual and network hybrid TENGs to optimize their performance under real ocean environments using numerical and experimental methods.

Furthermore, device stability and durability are critical factors in the development of hybrid systems which determine the potential of practical applications and service life as well as fabrication and operation costs. Polymers have been widely used for many TENG-based devices, which may be sensitive to sunlight, temperature, and humidity, and degradable under certain conditions, resulting in a limited service life. This is desirable in cases such as short-term medical treatment/monitoring but should be avoided in long-term applications such as forest fire alarm systems. The materials abrasion of triboelectric layers, especially the designed surfaces with nano-/microstructures, is inevitable in long-term operations. It is necessary to explore high-performance but durable materials for the triboelectric layers. For instance, when used to power implanted neurological stimulators and cardiac devices, high stability and durability of the power devices are favored because frequent surgical replacement may be risky and causes extra physical and mental stress to patients. In addition, advanced encapsulation materials and techniques protecting hybrid systems need extra attention in terms of compatibility and integration requirements in their deployment. Textile-based hybrid energy-harvesting systems will be promising in developing a variety of wearable applications. This has the potential to develop compact deformable self-powered electronic systems with scalable approaches such as weaving and coating. In this field, the washability and durability of the devices still need to be improved. Further studies of these key challenges in materials development, structural design, manufacturing methods, and system integration could lead to a broader range of applications of hybrid energy-harvesting systems in self-powered wearables, medical devices, environmental monitoring, and large-scale energy harvesting.

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AUTHOR CONTRIBUTIONS

Conceptualization, C.C. and Y.P.; Investigation, Y.P. and Y.C.; Writing – Original Draft, Y.P. and C.C.; Writing – Review & Editing, Y.C., M.D., Y.F., Z.L.W., and C.C.; Supervision, C.C.

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