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Review

Recent Progress in Hybridized Nanogenerators for Energy Scavenging

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SUMMARY

As the world's demand for alternative energy increases, the development of green energy harvesters becomes ever more important. As a result, the creation of triboelectric (TENG), piezoelectric (PENG), and pyroelectric nanogenerators, electromagnetic generators (EMG), solar cells, and electrochemical cells is attracting interest in an effort to convert mechanical, thermal, magnetic, solar, and chemical energy into electricity. In order to take advantage of the ambient energies from our surrounding environment, the design of hybridized generator units that can simultaneously scavenge energy in a variety of forms continues to develop. These systems are being considered to satisfy the energy needs of a range of electronic devices and adapt to a variety of working environments. This review demonstrates the latest progress in hybridized nanogenerators in accordance with their structure, operating principle, and applications. These studies demonstrate new approaches to developing hybrid techniques and novel assemblies for efficiently harvesting environmental energy from a number of sources.

INTRODUCTION

With the rapid growth in social concerns regarding worldwide energy needs and the consequences of global climate change, the use of renewable and green energy sources is becoming increasingly more significant. In addition, there is need for a reduced reliance on the use of batteries that provide power to electronic items and the Internet of Things. As a result, nanogenerators (Wang, 2017) are being considered to harvest many forms of energy surrounding us in our daily life. These include vibrational energy (Quan and Yang, 2016), human body motion (Zhang et al., 2018a, 2019a, 2019c), mechanical triggering of tire rotation (Zhao et al., 2017b), wind flow energy(Chen et al., 2018a, 2018b; Jiang et al., 2017, 2018), solar energy(Ji et al., 2018), blue energy (Gao et al., 2020), thermoelectric energy (Yang et al., 2012a, 2012c, 2012d), and so on (Ji et al., 2019; Yang et al., 2012b). However, the mode of operation and the operating conditions of any harvesting device is one of the most significant factors that influence the output performance of nanogenerators. Currently, there is a drive to achieve the goal of self-supplied operation of electronic devices to reduce their reliance on power cables or batteries. However, achieving this goal remains challenging to provide sufficient levels of continuous power.

Hybridized nanogenerators (Zhang et al., 2017, 2019b) are of interest in this context as they aim to combine several diverse nanogenerators into a single unit, which can utilize numerous energy sources individually or simultaneously, enabling the use of any available ambient forms of energy at any time. On the other hand, there is an increase in the total electric power generated by carefully integrating two or more forms of harvesters that can harvest various kinds of energy from surrounding. Such devices can be used in a variety of situations, such as wearable products (Lee et al., 2014), self-powered sensors (Zhang et al., 2014b), charging Li-ion batteries (Gao et al., 2017; Zhao et al., 2017c), and charging supercapacitors (Zhao et al., 2017a).

Here we summarize latest advancements in the development of hybridized nanogenerators. The review begins with an introduction of the key theoretical background and energy generation mechanisms, such as the electromagnetic, triboelectric, and piezoelectric effects. After introducing the fundamentals of nanogenerators, the wide variety of hybridized nanogenerators are then introduced. The range of applications of hybridized nanogenerators are then described in detail, including self-powered transducer and wearable devices. Finally, we summarize the present status of hybridized nanogenerators and highlight key issues and their vision for the future.

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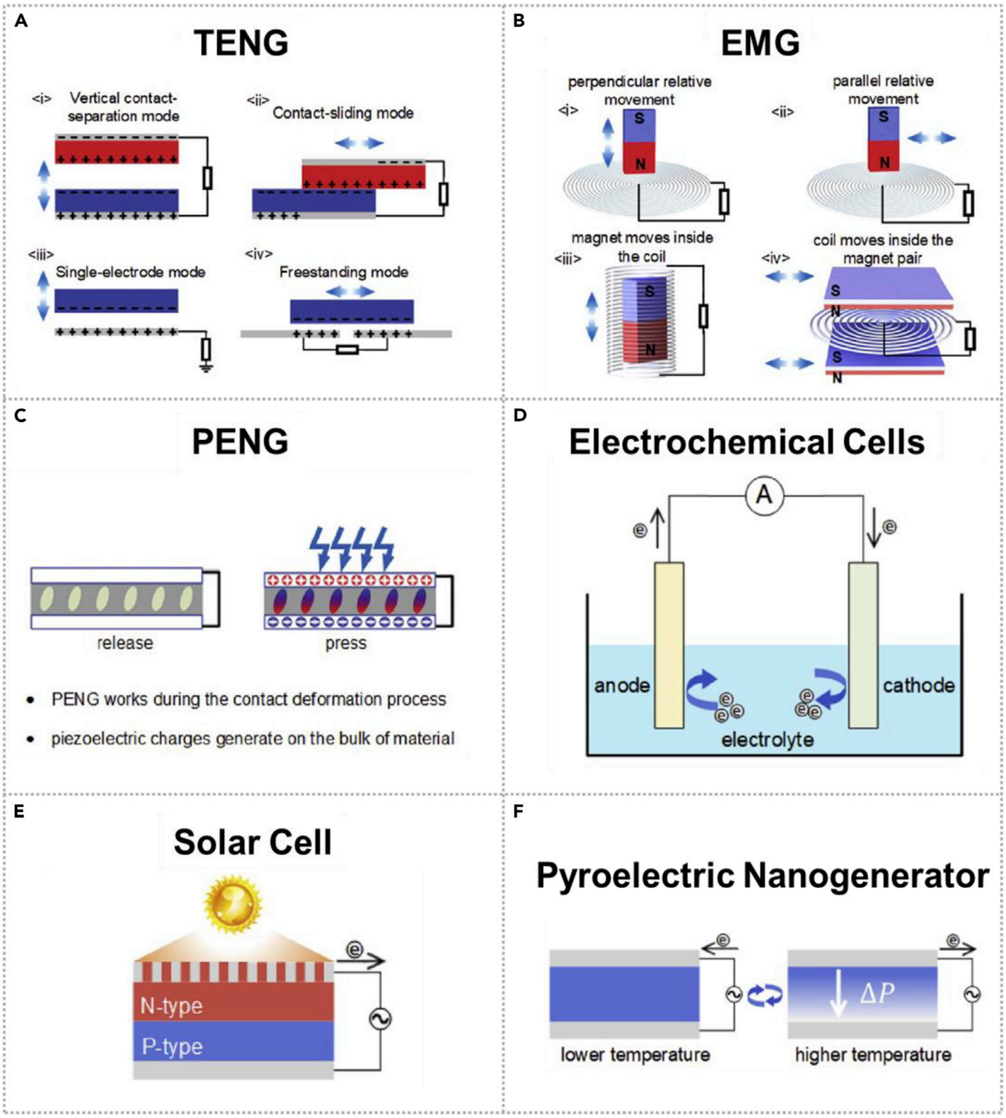

Figure 1. Schematic of Different Types of Nanogenerators

(A) Triboelectric nanogenerator (TENG) working modes.

(B) Electromagnetic generator (EMG) working modes.

(C) Piezoelectric nanogenerator (PENG) working modes.

(D) Principle diagram of electrochemical cell.

(E) Principle diagram of solar cell.

(F) Principle diagram of pyroelectric nanogenerator. Reproduced with permission, from Chen et al. (2020b), Copyright 2020, Elsevier.

THE FUNDAMENTALS OF NANOGENERATORS

Obtaining energy that is present in our daily life is an intriguing method to satisfy the energy needs of the Internet of Things (Wang et al., 2016a), which are built on low-power electronics. It provides users with many potential ways to drive electronic devices. In recent years, several techniques and mechanisms have been exploited by a number of researchers, such as the photovoltaic effect, triboelectric effect (Fan et al., 2012; Gao et al., 2019; Olsen et al., 2019; Zhao et al., 2019), biochemical reactions, and piezoelectric effect. This wide range of techniques can be used to collect the surrounding energy in several ways, ranging from mechanical energy (Zhang et al., 2014c), light change, the difference of temperature, to the variation in magnetic fields. Figure 1 compares and summarizes the basic technologies to harvest environmental energy

(Chen et al., 2020b; Zhang et al., 2018b), which include triboelectric nanogenerators (TENG), electromagnetic generators (EMGs), piezoelectric nanogenerators (PENGs), electrochemical cells, solar cells, and pyroelectric nanogenerators.

The basic principle of triboelectric nanogenerators (Gao et al., 2018; Liu et al., 2018a) is the coupling of triboelectrification and electrostatic induction between the surfaces of two different friction materials during periodic contact/separation, as illustrated in Figure 1A. In addition, Figure 1A presents the TENG's four fundamental working modes (Wang et al., 2015a; Yang et al., 2014).

An electromagnetic generator (EMG) (Zhang et al., 2014a) is a common and efficient method for electricity production in modern society, which is based on Faraday's law of electromagnetic induction. An induction of an electromotive force is obtained as a result of a change in magnetic flux during the motion between the magnet and the coil. Figure 1B presents the electromagnetic generator's rudimentary working modes.

The direct piezoelectric effect is the fundamental mechanism for the operation of piezoelectric nanogenerators (PENG) (Qin et al., 2008; Wang and Song, 2006). Many materials exhibit the piezoelectric effects; these include piezoelectric ZnO nanowires (Wang and Song, 2006), ferroelectric lead zirconate titanate (PZT) ceramics (Chen et al., 2010; Park et al., 2013), ferroelectric polyvinylidene fluoride (PVDF) (Chen et al., 2017), and its copolymers. As Figure 1C shows, when a deformation is induced by a mechanical force applied to the material surface, the piezoelectric material will generate negative and positive charges on opposing surfaces owing to a change in polarization. When the mechanical force is removed the charge is no longer present since the polarization returns to its original state. However, if the piezoelectric is connected to an electrical load, the charges can be collected to generate power during this process.

The solar cell is the typical light energy harvester (Lee et al., 2012), whose mode of operation is based on the photovoltaic effect (Hara et al., 2004). When a solar cell is illuminated by the sun, electron-hole pairs can be excited by the absorbed light in a semiconductor, as illustrated in Figure 1E. When attracted by a p-n junction electric field, the electron-hole pairs can separate and be transmitted, thus generating a photocurrent. As shown in Figures 1D and 1F, there are other types of nanogenerators (Liu et al., 2017), such as electrochemical cells (Wang and Yang, 2019) and pyroelectric nanogenerators (Zhao et al., 2020).

It can be easily seen that the range of sources of power in Figure 1 are only available in certain circumstances. For example, the solar cell only can be used with sunlight and the wind energy can only be obtained with wind. In the last few years, a variety of hybridized nanogenerators have been exploited, concentrating on structural designs to optimize the scavenged energy by harvesting a range of energy sources from the ambient environment (Wu et al., 2014). Such hybrid systems have the potential to provide a more continuous source of power, and potentially at a higher level. The classification of hybridized nanogenerators is now discussed.

THE CLASSIFICATION OF HYBRIDIZED NANOGENERATORS

Mechanical Energy Harvesting Systems

Hybridized Electromagnetic-Triboelectric Nanogenerator

The triboelectric and electromagnetic effect can both collect mechanical energy (Wu et al., 2015), such as wind energy, water wave energy, and rotational energy (Zhong et al., 2015). By combining a TENG and EMG (Zhang et al., 2016b) in a single device, a composite mechanical energy collection technique can increase the total output of the device significantly. The fundamental mode of operation of a TENG is a constant contact/separation to realize the constant transfer of charge, whereas Faraday's law of electromagnetic induction is the basic principle of EMG, as shown in Figures 2A and Figure 2B. To scavenge air-flow energy, Wang et al. developed a hybridized triboelectric-electromagnetic (TENG-EMG) device, shown in Figure 2C, which included two TENGs and two EMGs. When the air flow blows, the magnet on the Kapton film vibrates to change the flux through the copper coil. Meanwhile, the vibration of the Kapton film can drive the TENG to develop power. The hybridized TENG-EMG was based on a cubic structure with a weight of 42.3 g and dimensions of 6.7 cm × 4.5 cm×2 cm. The hybridized triboelectric-electromagnetic nanogenerator was used to charge a 3,300-μF capacitor, which was able to continuously drive four self-driven temperature transducers to implement a temperature sensor network, when subjected to an air flow velocity of 18 m/s (Wang et al., 2015b). In 2016, a self-powered wireless traffic transducer was reported by Zhang et al. The sensor included a TENG and an EMG. The structure of the equipment is based on rotating disk, which is

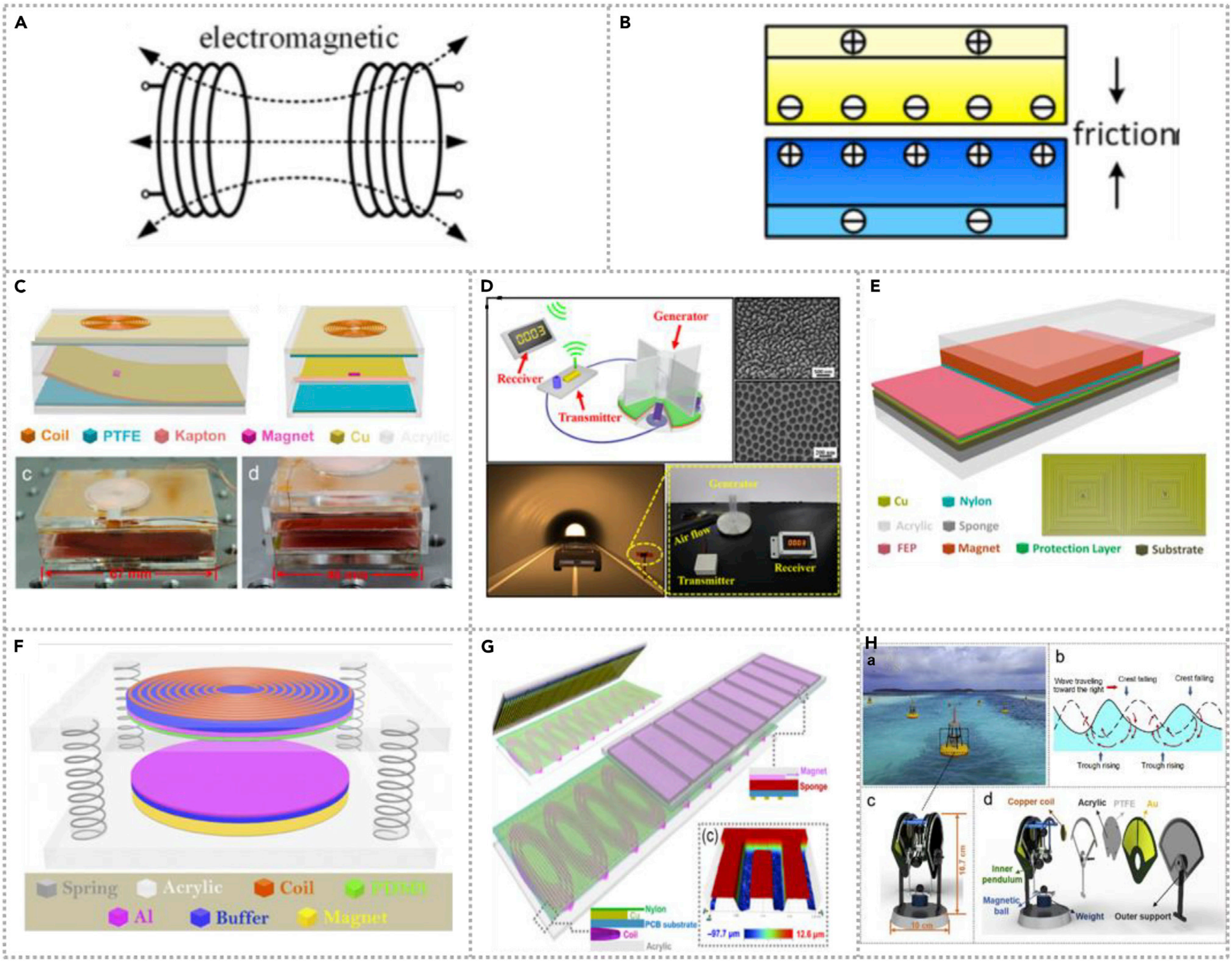

Figure 2. Hybridized Electromagnetic-Triboelectric Nanogenerators' Structures and Basic Working Modes

(A) Schematic of electromagnetic effect. Reproduced with permission, from Zhang et al. (2018b), Copyright 2018, Elsevier. (B) Schematic of triboelectric effect. Reproduced with permission, from Zhang et al. (2018b), Copyright 2018, Elsevier.

(C) Schematic of hybridized nanogenerator to scavenge air-flow energy. Reproduced with permission, from Wang et al. (2015b), Copyright 2015, American Chemical Society.

(D) Structural design of self-driven wireless traffic transducer system. Reproduced with permission, from Zhang et al. (2016a), Copyright 2016, American Chemical Society.

(E) Diagram of a shared-electrode-based hybridized harvester. Adopted with permission, from Quan et al. (2016), Copyright 2016, American Chemical Society.

(F) A spring-structured hybridized nanogenerator to harvest biomechanical energy. Reproduced with permission, from Zhang et al. (2015), Copyright 2015, American Chemical Society.

(G) A linear-grating hybridized nanogenerator to harvest energy generated by sliding. Reproduced with permission, from Zhang and Yang (2016), Copyright 2016, Tsinghua University Press and Springer-Verlag Berlin Heidelberg.

(H)A chaotic-pendulum-based hybridized triboelectric-electromagnetic nanogenerator to scavenge wave energy. Reproduced with permission, from Chen et al. (2020a), Copyright 2019, Elsevier.

shown in Figure 2D. This hybridized nanogenerator can generate 17.5 mW of output power, amounting to a 55.7 W/m^3 volume power density with a load resistance of 700Ω (Zhang et al., 2016a). Quan et al. developed a hybridized EMG-TENG that could harvest mechanical motion and exploited a shared-electrode, which is illustrated in Figure 2E. By using power management circuits to connect the two devices in parallel, the product can be used to power acceleration sensor systems (Quan et al., 2016). In 2015, Zhang et al. recorded a spring-structured hybridized EMG-TENG (Figure 2F) that was able to harvest human motion energy through walking. The main configuration of the device is a double-layered acrylic substrate, which was supported by four springs at four corners. During walking, the distance between the magnet and the copper coil varies as the spring deforms, and the EMG generates electricity because of the flux change in the coil. Meanwhile, collisions between PDMS and the aluminum electrodes activate the TENG by the triboelectric effect. The hybridized nanogenerator can produce power densities up to 5.1 W/m^2 by the TENG and 3.6 W/m^2 by the EMG (Zhang et al., 2015). In 2016, Zhang et al. illustrated a hybridized EMG-TENG that used a linear grating, which could scavenge mechanical energy form by sliding motions. Two main components are contained in the device: a multilayered slider and a multilayered stator, which are shown in Figure 2G. The relative slippage between the stator and slider leads to charge transfer. Accordingly, it is possible to understand the hybridized nanogenerator's working principle from the electromagnetic induction and triboelectrification. When the acceleration reached 20 m/s^2, the hybridized nanogenerator can generate a combination of 102.8 mW by the TENG and 103.3 mW by the EMG (Zhang and Yang, 2016). Chen et al. illustrated a hybridized EMG-TENG on the basic of a chaotic pendulum structure (Figure 2H). The movement of the pendulum with a weight and magnet ball can drive the device to obtain electricity from both triboelectrification and electromagnetic induction. This hybridized nanogenerator design combines the advantages of the high electromechanical conversion efficiency of the chaotic pendulum and its low operating frequency. The EMG power output is equivalent to 1.23 mW, whereas the TENG's maximum output power is up to 15.21 μW, and the mechanism is inspired by the water waves (Chen et al., 2020a).

Hybridized Piezoelectric-Triboelectric Nanogenerator

The piezoelectric effect is highly sensitive to external stimulus and can be easily integrated at a micro- and nano-scale. Although the conversion efficiency of materials such as ZnO is low, ferroelectric materials such a lead zirconate titanate can exhibit higher conversion efficiencies. Both the piezoelectric and triboelectric effects are able to generate power from continuous external slapping and other mechanical motion, as shown in Figure 3A and Figure 2B. Singh et al. reported a hybridized PENG-TENG based on flexible ZnO-PVDF/PTFE (Figure 3B). They observed that the addition of zinc oxide can improve both the piezoelectric properties of PVDF and the triboelectric properties. The output power of a hybrid nanogenerator based on flexible ZnO-PVDF/PTFE is ∼2.5 times higher than hybridized nanogenerator based on pure PVDF (Singh and Khare, 2018). To achieve improved performance from nanogenerators, Shi et al. developed a hybridized piezoelectric-triboelectric nanogenerator (PTNG) and a packaged self-powered system based on the PTNG. The working mode of a PTNG is contact-separation of a multi-layered structure, as illustrated in Figure 3C. This hybridized nanogenerator was able to generate up to 60 V and 1 μA, and the connectors were one of the most significant part of the PSNGS; therefore, several designs of the connectors were discussed to achieve a broader field of applications (Shi et al., 2016). To achieve a good performance at high temperature, Sun et al. reported a soft hybridized PENG-TENG (Figure 3D) on the basis of piezoelectric ceramic particles. This device exhibited good temperature stability at a temperature of 200°C and can generate an output power of 560 nA and 150 V (Sun et al., 2020). Chen et al. analyzed the basic principle of contact-mode hybridized generator (Figure 3E) from the transfer of charge, current, voltage, and average output power from hybridized nanogenerator's material properties, structural parameters, and operational conditions. Their work provides researchers with the fundamental principles to progress the development of new hybrid systems (Chen et al., 2017a).

Hybridized Electromagnetic-Piezoelectric-Triboelectric Nanogenerator

In the development of triboelectric-electromagnetic and piezoelectric-triboelectric hybridized nanogenerators, there are a range of reported hybridized EMG-TENG-PENG devices to scavenge mechanical energy. As the operating conditions in which they are used to produce electricity are similar, all three types of energy can be harvested and utilized simultaneously in the same movement. Deng et al. demonstrated a self-powered insole plantar mapping system based on the pressure generated from feet, as presented in Figure 4A. The device was composed of a hybridized TENG-EMG to provide electricity and a PENG to detect the movement of the foot as a pressure sensor. The electrical charge generated can be converted to a signal that can be detected by a smart phone by Bluetooth. The application of the device provides a new way to realize the design of sports shoes and provides information of sport/exercise biomechanics (Deng et al., 2018). Du et al. reported on a hybridized EMG-TENG-PENG to scavenge mechanical vibrational energy, as shown in Figure 4B. By combining the system with transformers and rectifiers, the maximum output power density is up to 100 W/m^3. It can also be converted to direct current via a power management circuit (Du et al., 2018). In 2018, He et al. reported on a hybridized EMG-TENG-PENG that contained a TENG, two EMGs, and two PENGs. Its core component is a magnetic suspension structure,

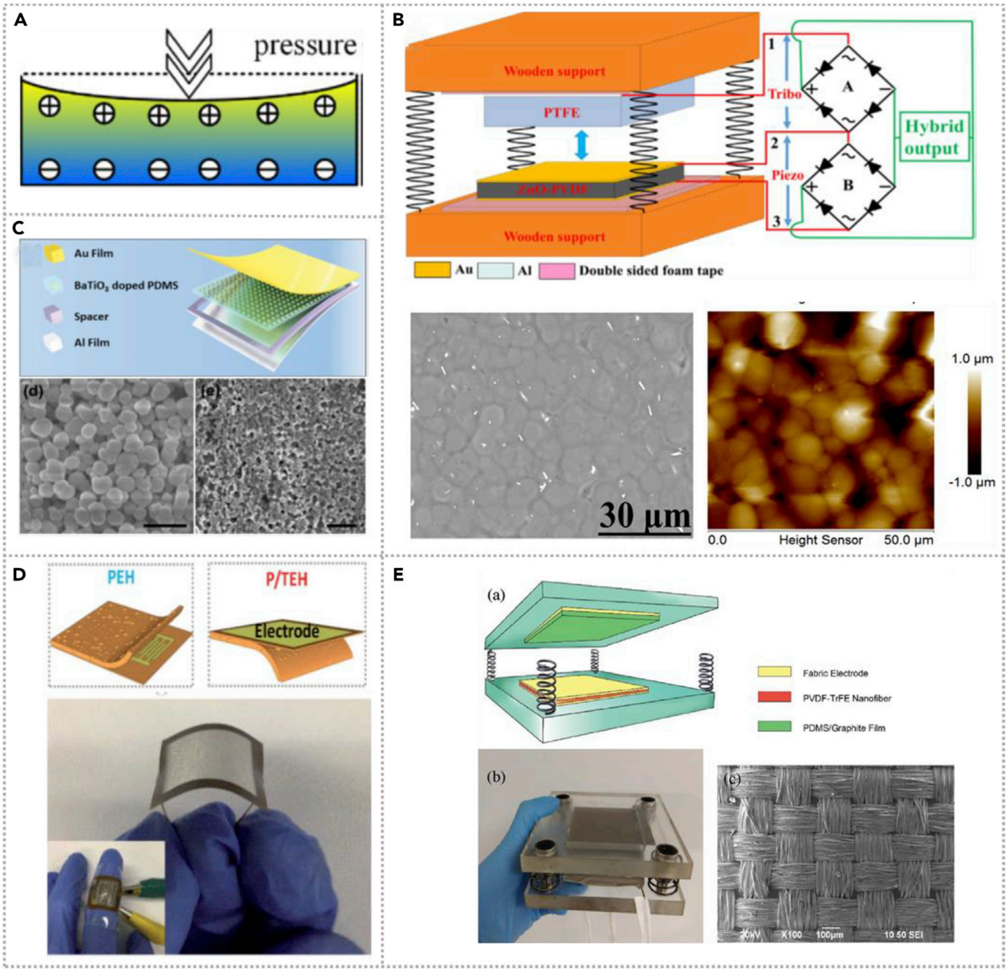

Figure 3. Hybridized Piezoelectric-Triboelectric Nanogenerators' Structures and Basic Working Modes

(A) Schematic of piezoelectric effect. Reproduced with permission, from Zhang et al. (2018b), Copyright 2018, Elsevier.

(B) A spring-based hybridized piezoelectric-triboelectric nanogenerator, along with electrical connections. Reproduced with permission, from Singh and Khare (2018), Copyright 2018, Elsevier.

(C) Structural design of multi-layered piezoelectric and triboelectric hybrid nanogenerator. Reproduced with permission, from Shi et al. (2016), Copyright 2015, WILEY-VCH.

(D) Schematic and image of soft hybrid piezo-/tribo-electric energy harvester. Reproduced with permission, from Sun et al. (2020), Copyright 2020, The Royal Society of Chemistry.

(E) Structural design of a piezoelectric and triboelectric hybrid nanogenerator. Reproduced with permission, from Chen et al. (2017a), Copyright 2016, WILEY-VCH.

as illustrated in Figure 4C. The device is based on a columnar structure with an upper and lower symmetry. The magnet that is located in the middle of the device oscillates up and down to change the magnetic flux of the coil and collides with the lead zirconate titanate (PZT) piezoelectric plate to generate a current due to the direct piezoelectric effect. This structure serves to collect energy from small vibrations, such as small impacts or a smoothly running car. The TENG, EMG$_1$, EMG$_2$ and PENG$_1$, PENG$_2$ can generate a power density of 78.4 µW, 36 mW, 38.4 and 122 mW, 105 mW, respectively (He et al., 2018). To harvest energy during walking, Rodrigues et al. combined a TENG, EMG, and PENG in a stratified structure device that can be embedded within shoes. The device includes a TENG that is an optimized parallel plate structure, an EMG and a PENG. The structure and image of this hybridized nanogenerator is presented in Figure 4D. One of the most significant parts is the sponge between the triboelectric nanogenerator and electromagnetic nanogenerator, which allows the distance between the magnet and planar coil change regularly during walking. They also studied the energy storage when using a range of capacitors and found that the

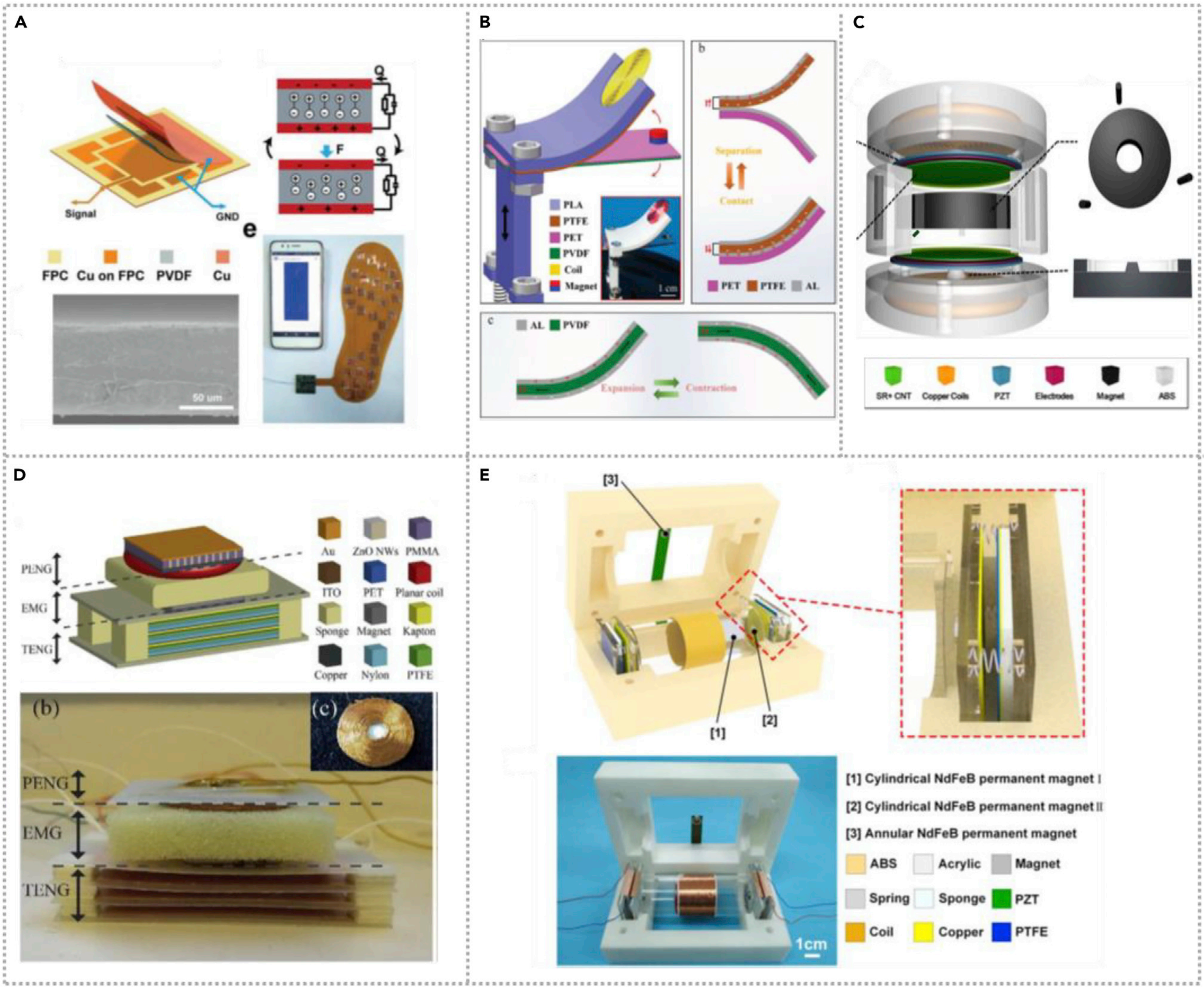

Figure 4. Hybridized Electromagnetic-Piezoelectric-Triboelectric Nanogenerators' Structures and Basic Working Modes

(A) Schematic of a plantar pressure transducer system for foot pressure distribution monitoring. Reproduced with permission, from Deng et al. (2018), Copyright 2018, WILEY-VCH.

(B) Basic structure and operation principle of hybridized nanogenerator. Reproduced with permission, from Du et al. (2018), Copyright 2018, WILEY-VCH.

(C) Structure of a triboelectric-piezoelectric-electromagnetic hybrid nanogenerator. Reproduced with permission, from He et al. (2018), Copyright 2017, Elsevier Ltd.

(D) Schematic and photograph of hybrid generator for power-generating footwear. Reproduced with permission, from Rodrigues et al. (2019), Copyright 2019, Elsevier Ltd.

(E) Structural design of hybrid energy harvester and enlarged illustration. Reprinted with permission, from Ma et al. (2019), Copyright 2019, WILEY-VCH.

larger load capacitances took more time to achieve their saturation voltage compared with the smaller load capacitances (Rodrigues et al., 2019). In 2019, Ma et al. reported a hybridized triboelectric-electromagnetic-piezoelectric nanogenerator on the basic of a permanent and movable magnet to scavenge rotational motion energy. The structure and image are shown in Figure 4E, where the device has two TENGs, an EMG, and a PENG. Magnet I has three important roles in the device. The first is to set up a repulsive force between itself and Magnet II; then the flux in the copper coil can circularly change, which can induce energy by Faraday electromagnetic induction. Finally, the force between the permanent magnet and Magnet I can generate power by the piezoelectric effect by making the piezoelectric cantilever bend. On this basis, a single motion cycle can generate three power modes, which improves the energy collection efficiency and realizes higher energy conversion (Ma et al., 2019).

Solar and Mechanical Energy Harvesting System

The working environment of electronic devices and the available energy sources for harvesting are likely to change with time. As a result, it is of considerable interest to harvest a variety of energy sources to extend their working life. Solar cell is an important and promising way to harvest green energy that can constantly draw energy from the sun. Although solar cells benefit from good performance, low cost, and large-scale production, their output is easily affected by weather or light intensity. In order to overcome the solar cells' weather-dependent nature, the hybridization of solar cells with a TENG or EMG is necessary to continuously obtain energy from the environment. A transparent and flexible polymer material constitutes the TENG, which can be utilized as a part of triboelectric nanogenerator and also acts as a protective coating for solar cells. Ren et al. reported a new-style pliable and self-cleaning hybridized energy collection system (Figure 5B) that included an autonomous single-electrode triboelectric nanogenerator and a soft organic solar cell. The device can also be attached to a garment so that when the wearer swings their shoulders, the TENG will obtain energy from the resulting mechanical motion. Meanwhile, it is able to harvest energy from sunlight by the solar cell in an outdoor environment (Ren et al., 2020). Liu et al. created an energy harvester (Figure 5C) consisting of a solar cell and a triboelectric nanogenerator to scavenge energy from water droplets and sunlight. The solar cell was based on heterojunction silicon (Si) and shared a cooperative function electrode of a poly (3,4-ethylenedioxythiophene):poly (styrenesulfonate) layer with the TENG.

This combination is expected to be an attractive method to obtain energy from the surrounding under different meteorological conditions (Liu et al., 2018b). The solar cell can also be associated with a PENG to harvest mechanical energy and solar energy. Yoon et al. discussed a hybrid power generator (Figure 5D) that included a PENG and an organic solar cell (Yoon et al., 2015). Wu et al. developed a fan-shaped hybrid energy harvester (Figure 5E) that can work together or individually, to collect wind energy, chemical energy, and solar energy. This form of hybrid energy harvester consists of an electrochemical cell, a TENG and a solar cell by attaching a solar cell to the top of the device and placing the Cu and Al electrodes in the acrylic tube of the TENG (Wu et al., 2014). In 2016, Wang et al. introduced and applied this idea to the construction of smart cities (Figure 5F), where they designed a hybridized nanogenerator that included both a TENG and a solar cell. Compared with the traditional wind turbines and solar cells, this hybridized nanogenerator occupies a smaller area and is less expensive, so it can be used on a large scale in cities (Wang et al., 2016a).

Additional Types of Hybridized Nanogenerators

Additional types of energy can also be harvested by nanogenerators, such as chemical energy and thermal energy. Electrochemical cells can transform chemical energy into electrical energy while pyroelectric effects are commonly used to collect heat energy from changes in temperature with time. Since chemical energy, mechanical energy, and thermal energy do not always exist together in the environment, there is a need to develop energy units that can simultaneously collect the two energies separately by utilizing combined devices. Yang et al. reported an electrochemical cell operated cooperatively with a TENG to scavenge chemical and mechanical energy effectively. Figure 6A is an example of the hybridized nanogenerator structure's principle scheme. One of the electrodes is a Cu/NaCl solution/Al structure where copper and aluminum films are used as energy collecting materials and electrode materials. A TENG was formed by the separation between the aluminum electrode and PDMS. The PDMS membrane can be used not only as the friction material of a TENG but also as a protective layer for the electrochemical cells. This device was used to illuminate up to 30 green LEDs (Yang et al., 2013).

Lee et al. presented a soft hybridized generator to collect mechanical energy and thermal energy sources. A diagram of the vertically stacked hybrid device is shown in Figure 6B that could scavenge thermal energy and mechanical energy from human movement and temperature. The TENG component was formed using ZnO nanowires for harvesting the energy associated with human body movement. The thermoelectric nanogenerator operates on the basis of thermoelectric materials that consisted by BiTe-Se and BiSb-Te powers (Lee et al., 2013). Wang et al. developed a composite nanogenerator based on one-structure to scavenge thermal and mechanical energy sources by a combination of tribo-piezo-pyroelectric effects. Figure 6C shows a diagram of the hybridized nanogenerator and its assembly. The hybridized nanogenerator contains a PDMS composite film, PVDF nanowires, and a poled PVDF film along with indium tin oxide transparent electrodes covering both surfaces. The composite nanogenerator can illuminate two light bulbs (Wang et al., 2016b). As a result of the limit in working time of batteries, Liu et al. showed a TENG combined with a Li-ion battery that shared same electrodes. A schematic of the hybrid power device is shown in Figure 6D. The solid Li-ion battery includes TiO_2 nanotubes acting as an anode, whereas the

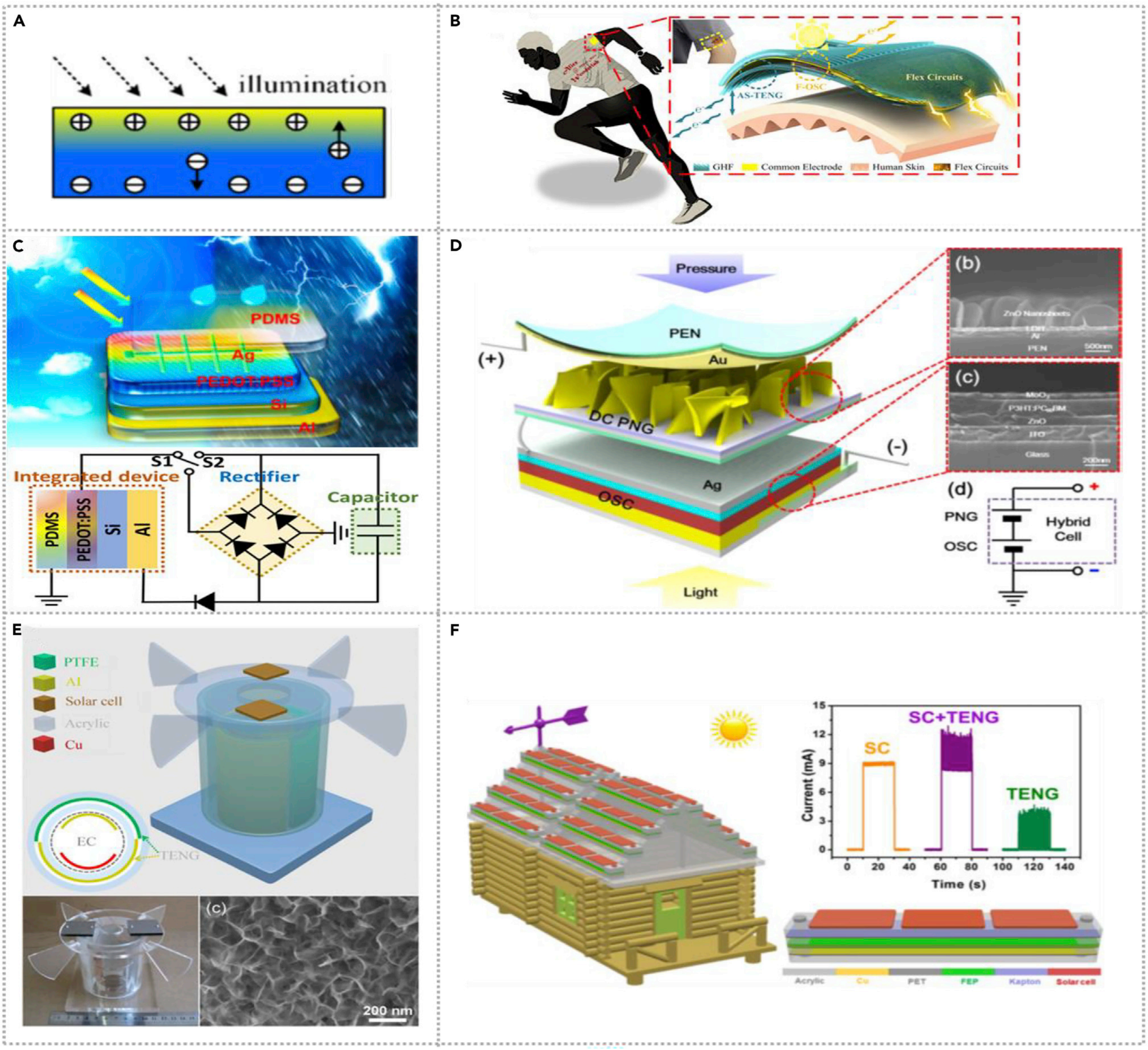

Figure 5. Fundamentals of Solar Cells and Several Structures of Hybridized Nanogenerators Based on Solar Cells

(A) Schematic of photovoltaic effect. Reproduced with permission, from Zhang et al., 2018b, Copyright 2018, Elsevier Ltd.

(B) Flexible and self-cleaning hybrid energy scavenging system. Reproduced with permission, from Ren et al. (2020), Copyright 2019, Elsevier Ltd.

(C) Demonstration of integrated hybrid power system as an energy harvester and its circuit diagram. Reproduced with permission, from Liu et al. (2018b), Copyright 2018, American Chemical Society.

(D) 3D diagram of a hybridized solar cell and piezoelectric nanogenerator. Reproduced with permission, from Yoon et al. (2015), Copyright 2015, Elsevier Ltd.

(E) Schematic and image of fabricated hybrid energy harvester to harvest wind, solar, and chemical energies. Adopted with permission, from Wu et al. (2014), Copyright 2014, Tsinghua University Press and Springer-Verlag Berlin Heidelberg 2014.

(F) Schematic of a hybridized nanogenerators used on roof of model house. Adopted with permission, from Wang et al. (2016a), Copyright 2016, American Chemical Society.

cathode is based on $LiMn_2O_4$ (LMO) nanoparticles and the solid electrolyte is based on a polyethylene oxide-$Li_{(1+x)}Ti_{(2-x)}Al_x(PO_4)_3$ (PEO–LATP) material. The PEO–LATP–LMO and the TiO_2 nanotubes can produce electricity from its periodic contact separation, which operates as a TENG. The TENG component of the devices can produce a ~33.5 μA output current, while the output voltage can reach 188 V. The solid Li-ion battery component can store electric energy up to 15μAh (Liu et al., 2017).

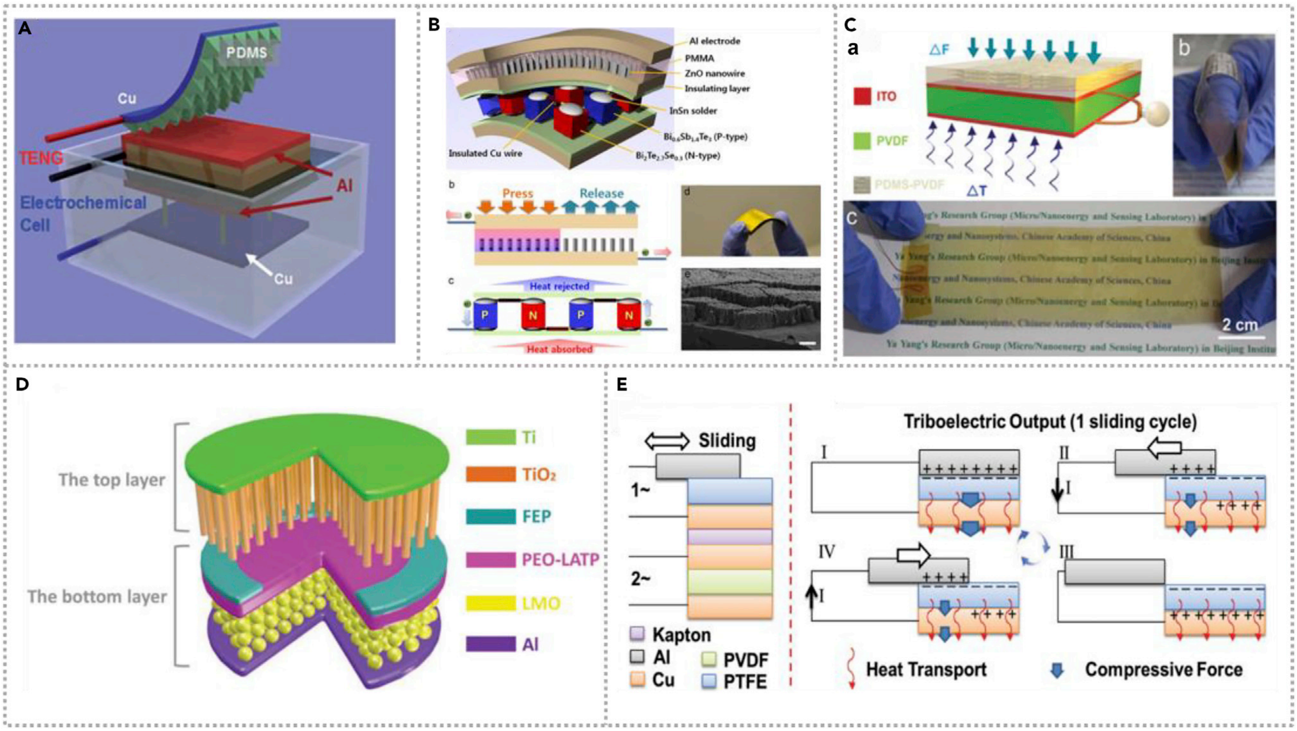

Figure 6. Other Types of Structures for Hybridized Nanogenerators

(A) Schematic of hybrid energy cell to harvest mechanical and chemical energies. Adopted with permission, from Yang et al. (2013), Copyright 2013, The Royal Society of Chemistry.

(B) Schematic of vertically stacked hybrid nanogenerator to harvest mechanical and thermal energies. Adopted with permission, from Lee et al. (2013), Copyright 2013, Elsevier Ltd.

(C) A hybridized nanogenerator's image and schematic to scavenge thermal and mechanical energies. Reproduced with permission, from Wang et al. (2016b), Copyright 2016, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

(D) Schematic of convoluted power device. Reproduced with permission, from Liu et al. (2017), Copyright 2017, WILEY-VCH.

(E) Structure of a hybrid cell and working mechanism of TENG. Reproduced with permission, from Zi et al. (2015), Copyright 2015, WILEY-VCH.

Zi et al. reported hybridized pathogenesis to harvest mechanical energy associated with sliding friction. The hybridized nanogenerator combines a pyroelectric-piezoelectric hybrid generator with triboelectric nanogenerator. The device structure and its working mechanism are depicted in Figure 6E. The TENG size was 62.5 cm^2 and produced a power density of 0.15 W/m^2 at a 4.41 Hz sliding frequency. Meanwhile, the pyroelectric-piezoelectric hybrid cell can scavenge thermal energy from mechanical energy induced from a normal force and friction-induced heat (Zi et al., 2015).

APPLICATION OF HYBRIDIZED NANOGENERATORS

Wearable electronics are at a risk of a loss of power owing to the limited working time of batteries and they need to be recharged or replaced. The invention of a variety of hybridized nanogenerators, which can simultaneously harvest mechanical energy, solar energy, and other forms of energy, provides new ideas to solve the need for a continuous energy source for self-powered electronic devices. The different parts of the energy harvesting unit may work simultaneously or individually, or they may be used in parallel or series to dramatically increase current or voltage, respectively. In recent years, hybridized nanogenerators have acted as wearable devices, self-powered sensors (Jiang et al., 2019) and have been used to power electric devices.

The hybridized triboelectric-electromagnetic nanogenerator and hybridized triboelectric-piezoelectric nanogenerator can be employed in a variety of scenarios, such as wearable devices and self-powered sensors. To scavenge blue energy, Wen et al. presented a hybridized TENG-EMG nanogenerator. The device can serve as a source of energy to illuminate several LEDs without any storage or power regulating devices;

Figure 7. Hybridized Nanogenerators' Industrial Applications Based on TENG-EMG and TENG-PENG

(A) Schematic of an integrated energy harvester board floating in the sea, which consists of solar cell panels, wind-driven generators, and array of hybridized nanogenerators. Reproduced with permission, from Wen et al. (2016), Copyright 2016, American Chemical Society.

(B) A hybridized electromagnetic-triboelectric nanogenerator integrated in a commercial shoe for harvesting biomechanical energy. Adopted with permission, from Zhang et al. (2015), Copyright 2015, American Chemical Society.

(C) A self-powered electronic watch. Adopted with permission, from Quan et al. (2015), Copyright 2015, American Chemical Society.

(D) A self-powered sensor to monitor traffic. Adopted with permission, from Askari et al. (2017), Copyright 2016, Elsevier Ltd.

(E) A large number of hybridized generators for harvesting large amounts of blue energy. Adopted with permission, from Feng et al. (2018), Copyright 2020, WILEY-VCH.

(F) Demonstration of novel elastic impact-based non-resonant hybridized generator for many practical applications. Adopted with permission, from Rahman et al. (2020), Copyright 2018, Elsevier Ltd.

(G) Several general-purpose sockets and plugs that can be integrated with the hybridizing nanogenerators. Adopted with permission, from Shi et al. (2016), Copyright 2015, WILEY-VCH.

(H) A remote emergency call system to detect real-time falling down. Adopted with permission, from Guo et al. (2018), Copyright 2018, Elsevier Ltd.

a diagram of the device is shown in Figure 7A. In addition, they have developed an energy-harvesting panel floating in the sea, which can include several generators to harvest wind energy, solar energy, and mechanical energy (Wen et al., 2016). Zhang et al. used a hybridized TENG-EMG nanogenerator inside shoes to scavenge biomechanical energy sources, as illustrated in Figure 7B. The device was installed on the shoes' heels to illuminate a circle of LEDs. A Li-ion battery can be effectively charged by the device, and it can power a pedometer sensor that can count people's steps, energy, and distance results (Zhang et al., 2015). Quan et al. illustrated a composite nanogenerator that was able to scavenge biomechanical energy from wrist movement to power a watch, as shown in Figure 7C. The watch can operate for 456 s after charging the 100-μF capacitor in 39 s. When the device charges a Li-ion battery for approximately 32 min, the watch can operate for 218 min (Quan et al., 2015). Askari et al. reported a hybridized TENG-EMG transducer including four freestanding TENG and four EMG to monitor road traffic, as demonstrated in Figure 7D. When a car passes speed bumpers, the sensor can harvest energy from the speed bumpers' mechanical vibration and convert them to an electrical signal to monitor traffic. Compared with a single EMG or TENG, the hybridized electromagnetic-triboelectric nanogenerator can produce a high charging voltage and a short charging period (Askari et al., 2017). To scavenge ocean wave energy, Feng et al. presented a honeycomb-like nanogenerator that contains an electromagnetic nanogenerator and a triboelectric nanogenerator. The hybridized nanogenerator can power 108 green LEDs, as shown in Figure 7E (Feng et al., 2018). Rahman et al. presented a hybridized generator that contains two contact-mode TENG and a nonlinear EMG. They examined the output performance of different forms of motion, such as walking, running, and handshaking, as given in Figure 7F. The hybridized generator can be installed in a backpack to harvest the vibrational energy generated by jogging as a portable device. The hybridized generator can also recharge a commercial smart band and a commercial smartphone (Rahman et al., 2020). Shi et al. presented a hybridized piezoelectric-triboelectric nanogenerator. To enable the nanogenerator to charge portable electronics, they have projected a number of universal plugs and sockets, such as a commercial thermometer, LED light and a temperature transducer, which is shown in Figure 7G (Shi et al., 2016). Guo et al. presented a hybridized piezoelectric-enhanced triboelectric nanogenerator based on an all-fiber construction that can be used as smart clothing (Figure 7H). As an important part of a self-powered microsystem, the device can easily assemble sensor devices and ultimately integrate seamlessly with the wearer's clothing. The device can monitor the motion of the arm to send different signals by computer and smart phone and send an SOS distress message to a mobile phone (Guo et al., 2018).

Hybridized nanogenerators based on the solar cell and other types of nanogenerators can harvest the energy from sunlight, chemical energy, and so on. Li et al. reported a wearable solar-thermal-pyroelectric nanogenerator that can achieve high power output by using polarized polyvinylidene fluoride and modified reduced graphene oxide. Its output performance can be up to 21.3 mW/m^2. They adapted the hybridized nanogenerator into a wearable outdoor bracelet (Figure 8A) that can scavenge mechanical energy by the movement of wrist and the solar energy. Between the "hand down" and the "hand up," there is a temperature difference of 5°C; therefore, the thermal effect can be used to generate electricity from a nanogenerator (Li et al., 2020). Wang et al. reported a hybridized nanogenerator that contains one electromagnetic nanogenerator, one triboelectric nanogenerator (TENG), and one thermoelectric generator (ThEG). The device can be assembled in a bicycle, which is shown in Figure 8B. The TENG, EMG, and ThEG can illuminate a globe light, respectively. When a person rides the bicycle, the electricity generated by the hybridized nanogenerator can charge a mobile phone. In addition, it also can power a high light beam, which can be used to ride a bicycle at night (Wang et al., 2016c). Qian et al. demonstrated a self-driven disaster monitoring transducer network on the basis of a hybridized TENG-EMG nanogenerator and a solar energy cell that can scavenge energy from wind and sunlight. They demonstrated three self-driven transducer systems that consist of a vibration sensor to monitor earthquakes (Figure 8C_1), a wireless transceiver to reserve alarm information and a temperature sensor to detect forest fires (Figure 8C_2). The self-powered wireless natural disaster monitoring network's flow chart is shown in Figure 8C_3. The study provides people with a new way to monitor natural disasters (Qian and Jing, 2018).

CONCLUSION AND PERSPECTIVES

Recycling ambient forms of energy from the surrounding environment is an attractive method to satisfy the world's sustainable development and long-term energy needs and to reduce our reliance on batteries by providing self-powered operation to electronic items, sensors, and Internet-of-Things devices. In recent years, materials and devices have been exploited to convert a number of forms of energies into electricity. The collection of mechanical energy can be achieved using a triboelectric nanogenerator, piezoelectric nanogenerator, and electromagnetic generator. In addition, pyroelectric nanogenerators and thermoelectric nanogenerators both can scavenge heat energy, whereas electrochemical energy and solar energy can be obtained from electrochemical cells and solar cells, respectively.

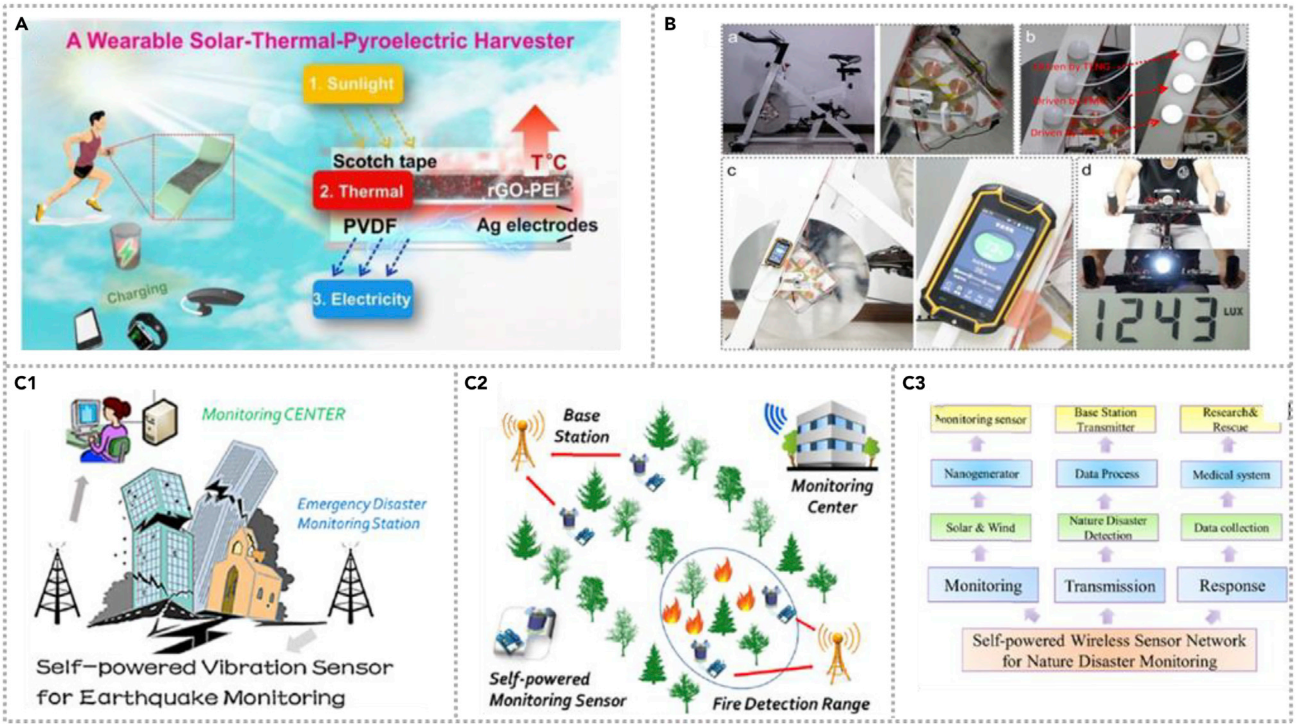

Figure 8. Hybridized Nanogenerators for Industrial Applications Based on the Solar Cell and Other Types of Nanogenerators

(A) Solar triggered pyroelectric nanogenerator system as a wearable power source for outdoor sports applications. Adopted with permission, from Li et al. (2020). Copyright 2020, Elsevier Ltd.

(B) Photograph of the hybridized nanogenerator installed on a commercial bicycle. Adopted with permission, from Wang et al. (2016c). Copyright 2016, Elsevier Ltd.

(C_1) A practical application of the WH-EHs to realize a self-powered sensor network to monitor forest fires. Adopted with permission, from Qian and Jing (2018). Copyright 2018, Elsevier Ltd.

(C_2) Schematic of the WH-EHs as a self-powered sensor network to monitor earthquake. Adopted with permission, from Qian and Jing (2018). Copyright 2018, Elsevier Ltd.

(C_3) Schematic of the self-powered wireless natural disaster monitoring network's operation flow chart. Adopted with permission, from Qian and Jing (2018). Copyright 2018, Elsevier Ltd.

Hybridized nanogenerators are attractive as they have two main benefits. First, the integrated structure can be used to collect different forms of energy anytime and anywhere. Thus, devices and sensors can always be continuously powered by the range of available energy in the environment. Second, the different parts of the device unit can be in parallel or series to increase the output current or voltage, respectively. Therefore, a hybridized energy unit can be designed to collect energy in two or more ways.

In the next few years, we should focus on the following aspects to further develop hybridized nanogenerators: First, the output performance should be promoted to drive more types of electronics; this can be achieved by materials development or improved device design. There is also a need to understand in greater detail the impact of the hybrid approach on the collective efficiencies of the system to develop successful hybridized generators. Then, the structure and materials should be more stable to accommodate energy harvesting in a variety of environments. In addition, the application of the hybridized nanogenerators can focus on wearable devices and textile-based devices. With the progress of these technologies and the continuous efforts of researchers, the hybridized nanogenerator will continually make breakthroughs and wide applications.

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AUTHOR CONTRIBUTIONS

T.Z. and Y.Y. wrote the manuscript and prepared the figures. T.Y., M.Z., C.R.B., and Y.Y. discussed and revised the manuscript.

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