Hybrid photovoltaic-triboelectric nanogenerators for simultaneously harvesting solar and mechanical energies

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Abstract

Owing to its potential to maximize the power output, hybrid energy harvesting technology has attracted more research interest. Boosting merits such as renewable energy sources and high output, hybrid photovoltaic-triboeletric nanogenerator (HPTNG) is considered as one of the promising power sources for next-generation smart electronics. To date, there is still a lack of a comprehensive review of the latest development and challenges of HPTNGs. Herein, we systematically summarize the recent advances of the hybrid photovoltaic-triboelectric energy-harvesting system. In particular, the structural flexibility and simplification of the hybridized device is described, followed by the detailed discussion from perspectives of the input mechanical energy sources, the output interaction between triboelectric nanogenerators and solar cells, as well as the functions and applications of the HPTNGs. Finally, the main challenges and perspective for the future development of HPTNGs are discussed.

Keywords: hybrid energy harvester, solar energy, mechanical energy, triboelectric effect, photovoltaic effect

1. Introduction

The intensification of energy crisis and the increasing awareness of environmental protection is spurring replacement of traditional fossil fuels with sustainable and renewable energy sources. In recent year, natural and green energy sources such as solar, wind and water have attracted much research interest in the pursuit of renewable energy (Fig. 1) [1-6]. At the same time, with the rapid progress of the Internet of Things, smart and portable electronic products are becoming essential in people’s daily life. However, most of the conventional power sources such as batteries and supercapacitors have rigid structures and no self-charging ability. Hence, there is an urgent need to develop sustainable energy harvesting technologies that can convert ambient energy into valuable electricity, as the green power supplies for next-generation electronics.

In this respect, various sustainable energy harvesting technologies based on photovoltaic [7-9], piezoelectric [10-12], triboelectric [13-15], electromagnetic [16-18], thermoelectric [19-21] and pyroelectric [22-24] effects have been developed over the past few decades, for light, mechanical, and heat energies harvesting. To further realize the maximum of the electric power and the use of multiple renewable ambient energies, it is ideal to design a hybrid energy harvester by integrating two or more generators in a single device [25-30]. However, electromagnetic generators have disadvantages such as the rigid structure and large space occupied [16]; piezoelectric and pyroelectric nanogenerators are limited by the necessity of high voltage poling [11,22] and thermoelectric nanogenerators require a sustainable temperature difference between two electrodes [21]. By contrast, energy harvesters based on triboelectric and photovoltaic effects show more flexible structure design and less/easier pre-treatment requirements [7,15] Moreover, considering the complementary output performance of triboelectric nanogenerators (high voltage but low current) and solar cells (high current but low voltage), a hybrid energy harvester based on photovoltaic and triboelectric effects is highly promising and has attracted considerable attention for smart electronics.

To date, several reviews described hybrid nanogenerators [31-38], but mainly focused on the development of different kinds of hybrid energy harvesting technologies, while hybrid photovoltaic-triboelectric devices have only been described briefly. For example, the first reported review concerning the hybrid energy cells presented only one example about the hybrid photovoltaic-triboelectric system for solar and mechanical energies harvesting [31]. Although Ryu et al. have reported the recent advances in hybrid energy harvesters for sustainable energy harvesting [34], the integration of mechanical and photovoltaic energy harvesters is considered as one of the hybrid energy harvesting systems, and there is insufficient information on more specific photovoltaic-triboelectric energy harvesters. Recently, Pang et al. have summarized the progress of hybrid TENG-based energy harvesting systems, but the main focus is the concept, design, and applications and there is only a brief introduction on the hybrid TENGs and solar cells [38]. Therefore, a more comprehensive review focusing on the hybrid photovoltaic-triboelectric energy harvesting system will be useful to the scientific community in order to stimulate the corresponding technological development.

In this review, recent progress of hybrid photovoltaic-triboelectric nanogenerators (HPTNGs) is described. This review begins with the working principles of the photovoltaic and triboelectric effects. After presenting the hybridized structure design of HPTNGs with emphasis on the device flexibility and structural simplification, the mechanical energy sources of TENGs in the hybrid cells are classified and the effect of TENGs on the performance of solar cells are highlighted in detail. Following that, the functions and applications of HPTNGs are described as summarized in Fig. 1. Finally, the challenges and perspective for the future development of HPTNGs is discussed.

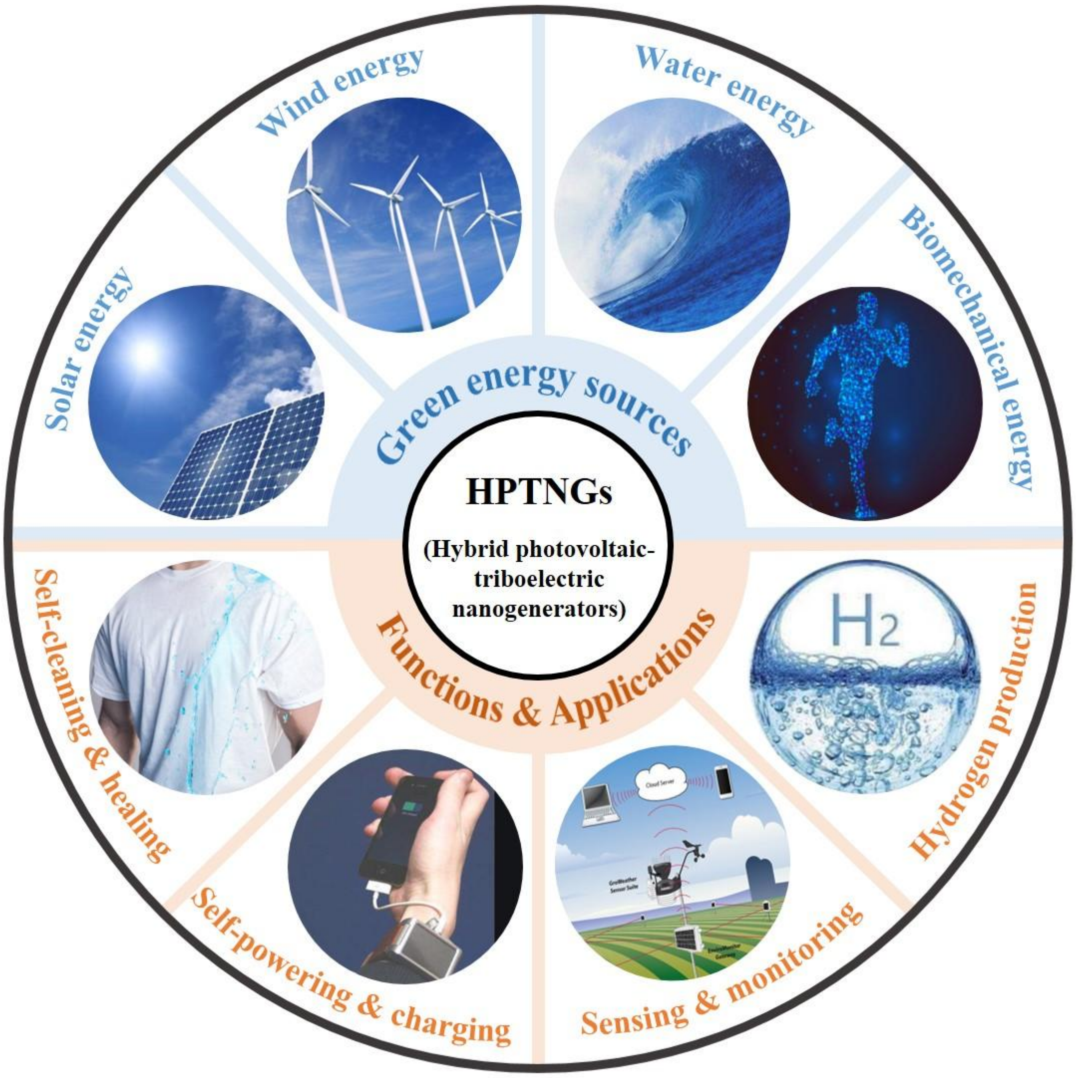

Fig. 1 Development of hybrid photovoltaic-triboelectric nanogenerators (HPTNGs): Green energy sources including solar, wind, hydro biomechanical ones and various functions and applications such as self-cleaning/healing, self-powering/charging, sensing/monitoring, and hydrogen production.

2. Photovoltaic and Triboelectric Effects

2.1 Photovoltaic Effect

As one of the most promising renewable energy harvesting technologies, solar cells can convert solar energy into usable electricity via photovoltaic effect [39]. When sunlight impinges a solar cell, the semiconductor will absorb light energy and then electron-hole pairs and electrical currents are generated as shown in Fig. 2a [40-42]. Among different output evaluation parameters of solar cells, the power conversion efficiency (PCE) is the most common and important one defined as the ratio of the output energy to input solar energy as shown by the following equation:

$$PCE(\%) = \frac{P_{\max}}{P_{in}} = \frac{V_{OC} \times J_{SC} \times FF}{P_{in}} \times 100 \quad (1)$$

where P_{in}, V_{OC}, J_S ,and FF are the input solar energy, open-circuit voltage, short-circuit current, and fill factor, respectively. Since both the temperature of the solar cell and the spectrum and intensity of sunlight affect the PCE, the measurement conditions must be standardized in order to compare different solar cells. In most studies, the assessment is carried out under AM 1.5 conditions at room temperature [43-48].

The maximum voltage and current of solar cells are V_{OC} and J_{SC}, respectively and there is zero power at these points because V_{OC} occurs only at zero current, and vice versa. In conjunction with V_{OC} and J_{SC}, FF is the maximum power of a solar cell. As shown in Fig. 2b, FF can be regarded as not only an area of the largest rectangle that fits the I-V curve, but also a measure of the "squareness" of the solar cell. The corresponding equation is:

$$FF = \frac{P_{\max}}{V_{OC} \times J_{SC}} = \frac{V_{\max} \times J_{\max}}{V_{OC} \times J_{SC}} \quad (2)$$

There are many factors such as materials selection, device structure, and fabrication methods affecting these parameters of solar cells. Hence, many corresponding approaches have been developed for enhancing the output performance of the solar cells in recent years [49-53]. Generally, solar cells can be categorized into several types as shown in Fig. 2c, including silicon-based solar cells (Si-SCs) [54-56], dye-sensitized solar cells (DSSCs) [57,58], organic solar cells (OSCs) [59,60], quantum-dot solar cells (QDSCs) [61], as well as perovskite solar cells (PSCs) [62,63]. Up to date, all of them except PSCs have been reported to be suitable light energy harvesters in HPTNGs.

2.2 Triboelectric Effects

Based on contact electrification and electrostatic induction, triboelectric nanogenerators (TENGs) were invented by Wang et al. in 2012 [64]. This energy harvesting technology offers a novel approach to convert wasted and disordered mechanical energy into useful electricity. Taking the contact-separation working mode as an example. When the device is released from an external force, two triboelectric materials separate from each other, leading to the opposite static charges generated on the separated surfaces (Fig. 2d), owing to the electrostatic induction. Consequently, a potential difference between two attached electrodes is induced, leading to free charges flowing between the electrodes to maintain electrostatic balance and generating a current signal. When the triboelectric pair is completely separated, a new equilibrium is reached between the opposite charges on the electrodes. Once the force is applied again, the electrons flow back quickly and an opposite current signal is generated [65-67]. In this regard, the generated charges should be theoretically equal during contact and separation as described in Fig. 2e and the triboelectric potential (V) and current (I) are expressed as:

$$V = -\frac{1}{C}Q + \frac{\sigma d}{\varepsilon_0} \quad (3)$$

$$I = C\frac{\partial V}{\partial t} + V\frac{\partial C}{\partial t} \quad (4)$$

where *C, Q,* σ, *d,* and ε_0 are the system capacitance, transferred charges, surface charge density, gap distance, and vacuum permittivity, respectively. It is noting that there is no charge transfer (*Q=0*) at open-circuit (OC) condition. Therefore, the second term of the voltage equation is the V_{OC} for contact-mode TENGs. In terms of the current equation, the first and second terms represent the potential change between two electrodes from triboelectric charges and the capacitance variation with the changed distance among electrodes due to mechanical deformation, respectively.

In order to enhance the triboelectric output, various physical and chemical approaches have been proposed to modify the work function, electron affinity, surface roughness, and chemical structure [68-71]. According to the electrode configurations and arrangement of the triboelectric layers, TENGs are normally divided into four main types, namely the vertical contact-separation mode [72,73], lateral sliding mode [74], single-electrode mode [75,76], and freestanding triboelectric-layer mode [77] as shown in Fig. 2f. All these modes have been individually or simultaneously exploited by HPTNGs for light and mechanical energies co-harvesting.

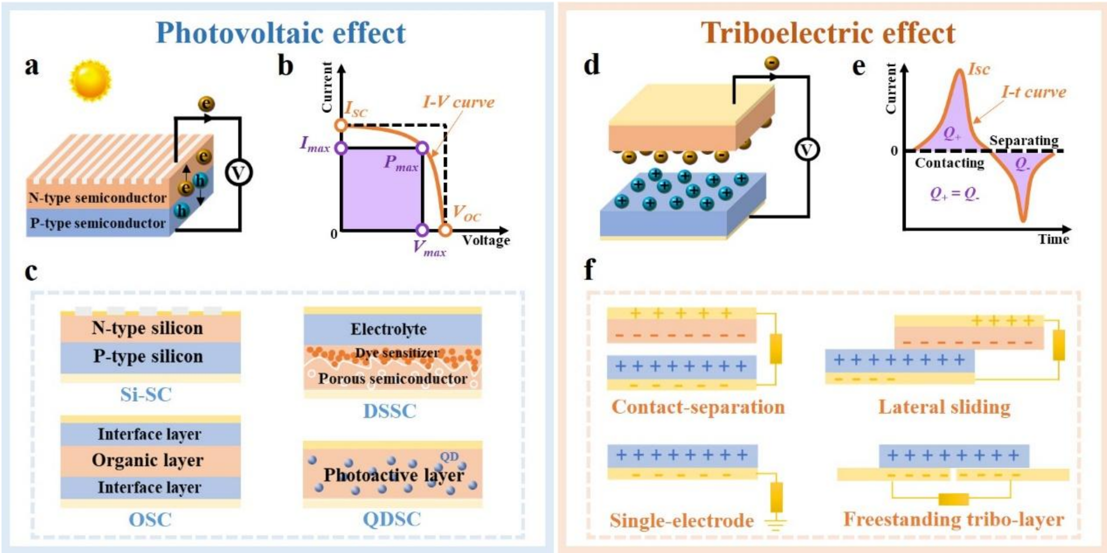

Fig. 2 Photovoltaic and triboelectric effects: (a) Working principle, (b) I-V curve, and (c) Different types of solar cells: (d) Working principle, (e) I-t curve, and (f) working modes of TENGs.

3. Hybridized Design

Considering that the physical structure of a common energy harvesting device affects the output, fabrication complexity and cost, as well as applications, it is necessary to systematically study and analyze HPTNGs from the perspectives of structural flexibility and simplification.

3.1 Structure Flexibility

In light of the structural flexibility, the reported HPTNGs have either the rigid or flexible structure. Among different rigid structure shapes, the most common one is the cuboid-like rigid structure, which can be found in many previous reports [78-82]. Herein, therefore, special shapes such as cylindrical, spherical and disk shapes, are described in this review.

In 2014, Wu et al. developed a cylindrical hybrid energy cell consisting of a TENG, a solar cell, and an electrochemical cell [83]. As shown in Fig. 3a, two Si-SCs are placed on top of the hybrid cell to ensure adequate solar light adsorption and harvesting. The TENG containing an Al film and a PTFE film is attached to the inner side of the cylindrical tube and these two films contact with and separate from each other by wind-induced rotation of the blade-like acrylic plates in the fan. Similar structure design has been proposed by Qian and Jing [84]. Inspired by a lantern swaying in the wind, a lantern-like HPTNG was introduced by Cao et al. [85]. As shown in Fig. 3b, the self-powered hybrid nanogenerator is composed of TENG, DSSC, Li-based battery and LEDs. The working mechanism of TENG is based on the freestranding triboelectric-layer mode in which the FEP film on the rolling rod surface and ITO strips constitute the triboelectric pair. Moreover, an all-in-one hybrid power source proposed by Xu et al. [86] is composed of four spherical TENG units around and two commercial solar cells at the center as shown in Fig. 3c. The TENG unit consists of a multilayer structure sealed in a PP shell fabricated by stacking copper disks and acrylic spacers and the amount of FEP pellets filled among the disk is adjusted by the electrode area to optimize the output. At the same time, Qiu et al. have proposed a sliding TENG-based control disk interface comprising PTFE films, copper electrodes, commercial solar cells, and electronic circuits (Fig. 3d) [87] and this design enables capturing of different kinds of mechanical energies for use in various occasions.

Compared to the rigid structure, the flexible design of HPTNGs will be more suitable for wearable applications [88-94], which can be briefly classified into three types based on the solar cells (including OSC, Si-SCs and DSSC). For example, Fang et al. have incorporated TENG and OSC into a thin film to fabricate an all solution-processed flexible hybrid nanogenerator for capturing solar and mechanical energy [88]. As shown in Fig. 3e, the top transparent single-electrode TENG contains an FEP film and a PI/AgNWs electrode and the OSC structure involves PH1000, P3HT:ICBA, PEI, PEDOT:PSS and PI/AgNWs from top to bottom. This is the first reported flexible HPTNG for concurrently solar and mechanical energies harvesting. Following that, Song et al. reported two flexible hybrid devices based on TENGs and solar cells [92,93]. Fig. 3f shows a top transparent TENG with ITO and ETFE films as the triboelectric pair, a Si-SC, as well as a Li-ion battery. While Fig. 3g shows a self-charging power bracelet with a single-electrode TENG consisting of silicone rubber as the triboelectric layer, a fibrous DSSC (ALD-TiO_2/TiO_2 NPs/Pt wire/electrolyte/tube), and a supercapacitor, in which solar and mechanical energies harvested by the devices can be stored for further use.

On the other hand, several flexible hybrid power textiles integrating fibrous TENGs and solar cells into clothing materials have been proposed by Wang et al. [89-91]. Take the one shown in Fig. 3h as an example, the fabric TENGs are composed of Cu-coated PTFE strips and Cu electrodes and the photovoltaic component consists of PBT, Cu, Mn, ZnO/Dye, CuI, and Cu wires from inside to outside. The single layer of fabric can be easily woven into clothes, curtains, and tents for wearable applications.

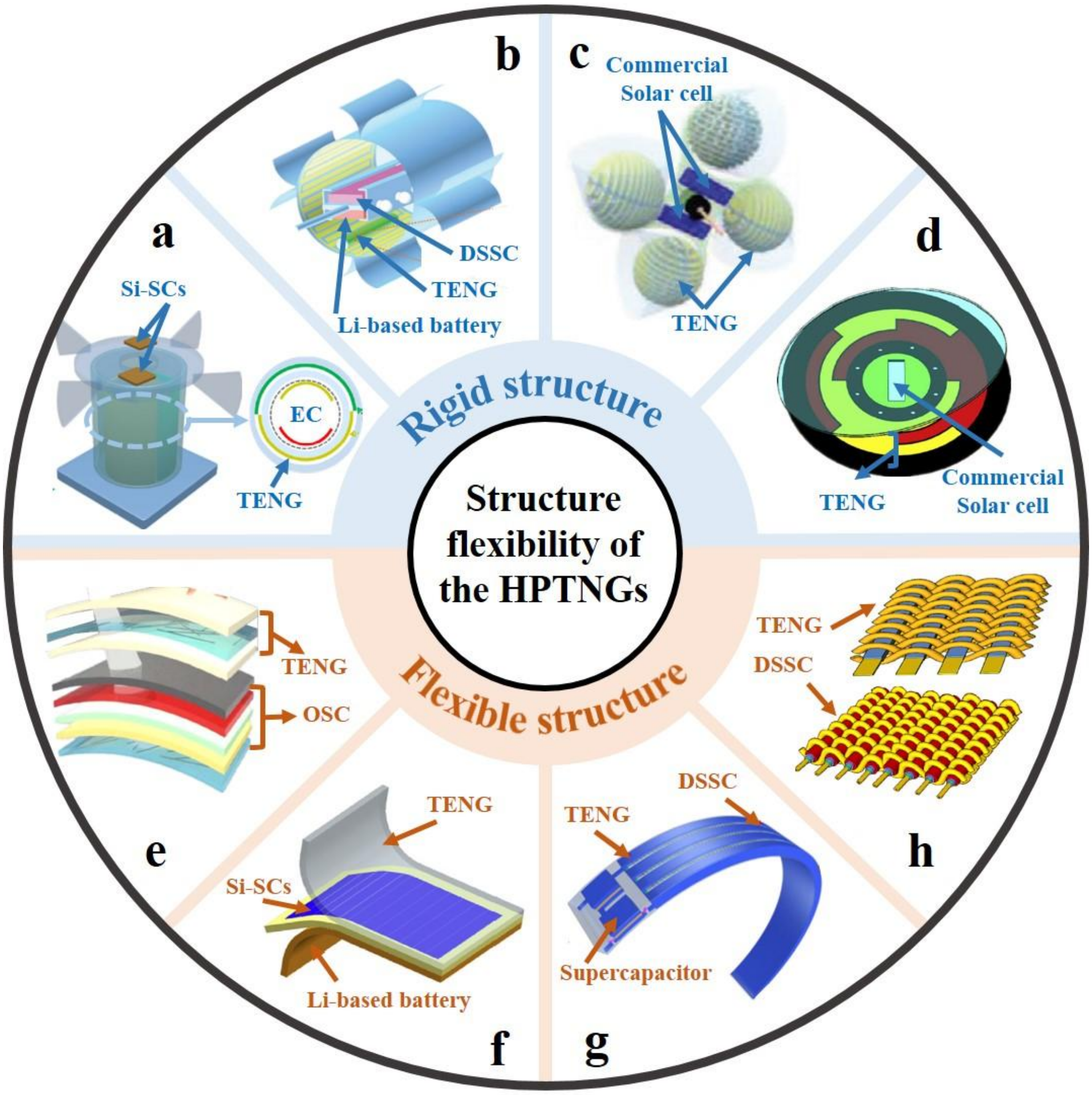

Fig. 3 Structural flexibility of HPTNGs: (a) Schematic of the hybrid energy cell. Reproduced with permission from Springer (2014) [83]. (b) Schematic of the self-powered lantern. Reproduced with permission from Willey-VCH (2018) [85]. (c) Schematic of the hybrid power source. Reproduced with permission from Willey-VCH (2020) [86]. (d) Schematic of self-powered control disk. Reproduced with permission from Elsevier (2020) [87]. (e) Schematic of the flexible hybrid cell. Reproduced with permission from Elsevier (2015) [88]. (f) Schematic of the flexible hybrid energy harvesting device. Reproduced with permission from Elsevier (2019) [93]. (g) Schematic of the flexible hybrid power bracelet. Reproduced with permission from Elsevier (2019) [92] (h) Schematic of the hybrid power textile. Reproduced with permission from Springer Nature (2016) [90].

3.2 Structure Simplification

In most reported studies concerning photovoltaic and triboelectric effects, the design of TENGs is usually independent of the design of solar cells [83,92,95-97], because there are typically no shared components between TENGs and solar cells, leading to more complex device structure, manufacturing and application restrictions. Therefore, it is necessary to simplify the structure of HPTNGs, of which the simplified structure in the reported works can be categorized into two types: the one-mutual-electrode structure and all-in-one structure.

In the one-mutual-electrode structure, the TENGs and solar cells share a common electrode. Yang et al. have firstly proposed a hybrid energy cell integrating a contact-separation TENG and a Si micropyramid solar cell (Fig. 4a) [98]. The top TENG consists of a transparent PDMS nanowire array and an ITO film, whereas the bottom solar cell contains the ITO film, Ag grid, SiN film, n+ emitter layer, p type Si layer, p+ back surface field layer, and Al film. The middle mutual electrode (ITO film) is not only the triboelectric layer with PDMS in the TENG, but also the transparent electrode for the Si-SC. Inspired by the fabrication process of textiles, Wen et al. have presented a self-charging hybrid power textile system including fibrous DSSCs, TENGs and supercapacitors [89]. The TENG is composed of cover layers of DSSC and supercapacitor as shown in Fig. 4b, where the tribo-positive Cu film shared with DSSC continuously contact with and separate from the tribo-negative PDMS film shared by the supercapactior. Furthermore, Ren et al. have proposed a flexible common-electrode hybrid energy harvester based on a single-electrode TENG and an OSC [94]. Fig. 4c shows that the TENG consisting of mircro/nanostructured (MNS)-PDMS and ITO/PEN films can contact human skin directly to generate electricity and the ITO film is also regarded as the anode of the OSC composed of

MNS-PDMS/PEN/ITO/MoO_3/P3H T:$PC_{61}BM$/Al.

To further simplify the hybridized structure, several all-in-one structured HPTNGs have been developed in recent years. Liu et al. have firstly developed an all-in-one structured hybrid device by integrating a TENG and a heterojunction Si-SC [99]. As shown in Fig. 4d, the TENG which contains a triboelectric layer (imprint PDMS) and an electrode (Ag/PEDOT:PSS) is used to harvest raindrop energy. The solar cell includes all components of the hybrid device (PDMS/Ag-PEDOT:PSS/Si/Al) in which the PDMS film is the protective layer to avoid contamination and corrosion of the solar cell in the ambient. Based on the similar design concept, Liu et al. have also proposed a wrinkled nanostructured PDMS film to protect the bottom Si-SC (Fig. 4e) [100]. With the assistance of this anti-reflective layer, a better energy harvesting efficiency was obtained (Detailed mechanism will be discussed in Section 5). Moreover, the wrinkled nano-PDMS film also improves the triboelectric output in combination with the bottom Ag/ITO film in the single-electrode TENG in the all-in-one structured HPTNG. Recently, the authors in the same research group have replaced the PDMS layer with the superhydrophobic SiO_2 film as shown in Fig. 4f [101]. Thus, the all-in-one structured hybrid device containing a TENG and a Si-based SC is able to more efficiently co-harvest solar and mechanical energies.

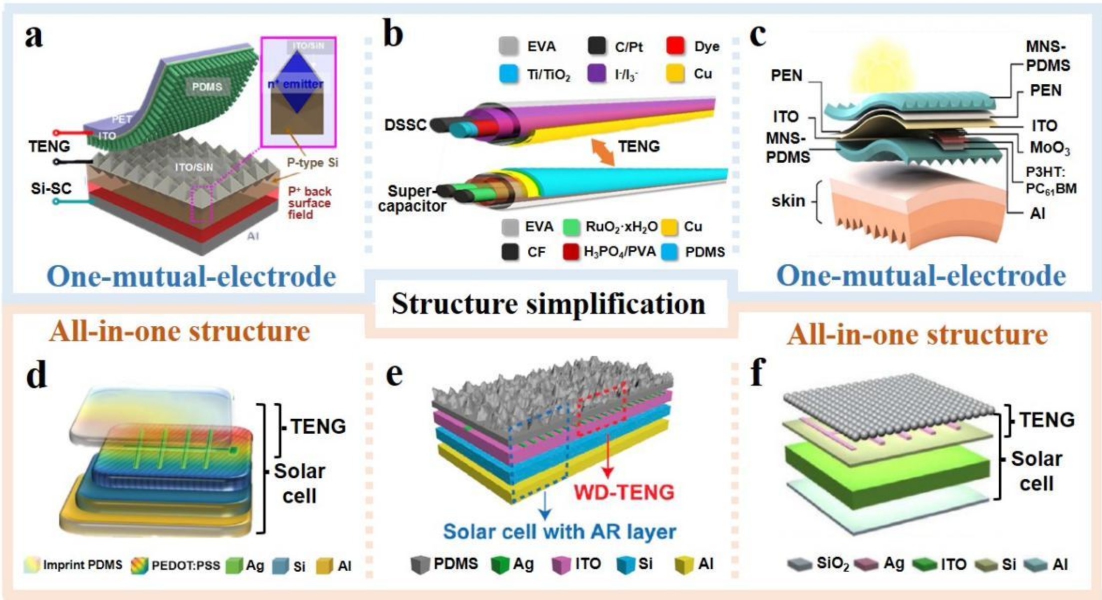

Fig. 4 Structure simplification of HPTNGs: (a) Schematic of hybrid energy cells. Reproduced with permission from American Chemical Society (2013) [98]. (b) Schematic of hybrid fabric structures. Reproduced with permission from American Association for the Advancement of Science (2016) [89]. (c) Schematic of the flexible hybrid energy harvesting system. Reproduced with permission from Elsevier (2020) [94]. (d) Schematic of the integrated device. Reproduced with permission from American Chemical Society (2018) [99]. (e) Schematic of the hybrid energy harvester. Reproduced with permission from Elsevier (2019) [100]. (f) Schematic of the hybrid energy harvester. Reproduced with permission from IOP Publishing (2021) [101].

4. Mechanical Energy Sources

In terms of light energy harvesting, the energy comes from either natural sunlight or artificial indoor lights. Since the light sources are not in direct contact with the energy harvesters, there are no significant effects other than materials selection. However, different mechanical energy sources can affect device fabrication, structure design, and application; thus, it is necessary to categorize HPTNGs according to the mechanical energy sources such as water energy, wind energy, and biomechanical energy.

4.1 Water Energy

There are usually three water mechanical energy sources used in HPTNGs including raindrop, water wave and water flow. Among them, Raindrop is the most common one since it compensates the performance reduction of the solar cells in rainy days. As shown in Fig. 5a, integrating rain-TENGs with solar cells makes it possible for the hybrid devices to effectively work in both sunny and rainy days [81]. The first hybrid photovoltaic-triboelectric cell for solar and raindrop energy harvesting was developed by Zheng et al. [102]. Considering the fact that a transparent protective layer is usually covered on the surface of the solar cell, this group has replaced this layer by a transparent TENG (PTFE/ITO/PET). The working principle of the single-electrode TENG for raindrop energy harvesting can be found in Fig. 5b. It is known that electrostatic charges will be generated when water drops fall or flow through an insulating tube and the water drops and materials in contact are charged oppositely [103,104]. When water drops approach the PTFE film, the potential difference drives electrons flowing from the ground to the electrode. Thus, an instant positive current will be produced until the potential difference disappears. When the positively charged water drops leave, electrons on the electrode will quick flow back to ground to establish an opposite current before the potential difference decreases to zero. With periodical contact and separation, electric output is produced continuously. Following this mechanism, many other HPTNGs that can capture solar and raindrop energies have also been reported in recent years [80-82,95,99-101].

Apart from raindrop energy, water wave energy and flow energy have also been utilized by HPTNGs [105-107]. For example, Zhang et al. have proposed a hybrid energy ball to harvest solar and ocean energy [105], which consists of a TENG-based self-charging power system and a PET shell (Fig. 5c). When the energy ball floats in the ocean, it can work in both sliding-freestanding and contact-separation modes depending on the test environments. Similarly, Liu et al. have proposed an all-weather IoT platform containing a triboelectric-electromagnetic hybridized generator and a solar cell for water wave and solar energies harvesting [106]. Different with the above report, Wei et al. have reported a hybridized mechanical and solar energy harvesting system for self-powered hydrogen generation as shown in Fig. 5d [107]. The structure comprises a rotatory disk-shape TENG as the external power source to capture mechanical energy from flowing water based on the triboelectric effect.

4.2 Wind Energy

Similar to water energy, wind provides another source of renewable and green energy that is often wasted or ignored in our daily lives. In 2014, Guo et al. firstly combined an airflow-induced TENG with a DSSC to capture wind and light energy [79]. As shown in Fig. 5e, there is a flexible PTFE film between the two Cu electrodes attached to the Si/glass substrate. The charge distributions and potential distribution are analyzed by finite element simulation. During air flow, the PTFE film is negatively charged due to rubbing against two electrodes. As the PTFE film approaches the bottom electrode, electrons will flow to the top electrode through the external circuit to balance the negative charges on PTFE. Conversely, electrons on the top electrode are transferred to the bottom electrode when the PTFE film is close to the top electrode. Wang et al. [108] have proposed a transparent flag-like TENG composed of a tribo-negative PTFE film and a tribo-positive electrode (Al or ITO) as shown in Fig. 5f in combination with a solar cell to form a hybrid nanogenerator-based self-powered sensing network for wind and solar energies harvesting.

At the same time, Qian et al. have presented a hybridized solar-wind energy harvester for natural disaster sensing and monitoring [84]. The external rotational motion drives the rotator in the harvester leading to easy hybridization of the TENG with eighteen EMGs. The sliding-electrification mechanism of the TENG is illustrated schematically in Fig. 5g. When the rotator rotates clockwise or counterclockwise, the PTFE layer contacts the Al layer and charges are transferred at the interface to produce an equal amount of positive and negative charges on the two layers. During rotation, electrons flow back and forth between the two electrodes to establish electric field equilibrium and an alternating current. Based on the same rotation mechanism, Cao et al. [85] have also developed a self-powered lantern-like HPTNG for wind and solar energies harvesting. To realize self-powered functions in a smart city, Wang et al. [96] have further presented a hybridized nanogenerator placed on the roof of a simulated house to harvest solar and wind energies from the city environments.

4.3 Biomechanical Energy

Considering that the human body is not only an abundant kinetic energy source but also the application terminal of wearable electronics, it is desirable to develop wearable nanogenerators function on human motion energy harvesting. In recent years, HPTNGs replying on human motion and solar energies harvesting such as wearable cells, composite fibers and smart textiles, have attracted increasing attention.

Towards the applications of wearable power sources, a flexible hybrid nanogenerator with a TENG and an OSC covered by cotton fabric is displayed in Fig. 5h [88]. During daily activities, the TENG contacts with and separates from the fabric and the OSC absorbs the sunlight to generate electricity based on the triboelectric and photovoltaic effects, respectively. Similar reports by attaching/wearing flexible HPTNGs on the clothes/bodies for human motions and light energy harvesting can also be found in other reports [92,94,109]. For instance, Jung et al. [109] have proposed a 3D Cu ball-based TENG and non-fullerene organic photovoltaic cell system that can harvest energy from human activities and indoor lighting.

Different from the above studies, Wen et al. [89] fabricated a hybridized power fabric system to capture energy from body motion and outdoor sun. As shown in Fig. 5i, the energy harvested by the fibrous TENG and DSSC is stored in fibrous supercapacitors and the device can be woven into clothes. Furthermore, Pu et al. [91] have integrated the fiber-based DSSC and TENG fabrics into wearable fabrics directly to fabricate a wearable power textile for harvesting solar and human motion energies. Taking the TENG fabrics as an example as illustrated in Fig. 5j, two pairs of sliding TENGs, fabrics of the sleeve and underneath the arm are used to harvesting arms swing energy during people walking and running. The latter has two interdigitated metal electrodes, while the former has a series of parallel grating segments and the parylene and Ni on the fabric surface serve as the triboelectric layers to generate electricity.

4.4 Hybrid Mechanical Energy

Endowing HPTNGs with hybrid mechanical energies harvesting ability can not only more effectively utilize the wasted energies but also maximally enhance the output performance of the hybrid systems. In the photovoltaic-triboelectric hybrid panel developed by Zheng et al. in 2015, a transparent dual mode TENG that can simultaneously harvest raindrop and wind energies is put on the solar cell [110]. Inspired by the same idea, Roh et al. [111] have also developed a unified harvesting module including a top rain-TENG, a middle solar cell, and a bottom wind-TENG as shown in Fig. 5k. Aiming at the same goal, Xu et al. [86] have proposed an all-in-one power source that integrates spherical TENGs with solar cells (Fig. 3c), making it possible for simultaneous harvesting of wind, rain, and solar energies.

Apart from raindrops, mechanical energies arising from vibration, displacement, and human motions can also be combined with wind energy [90,112,113]. For example, Cho et al. [113] have proposed a TENG and an air-stable QDSC to synthesize a hybrid energy harvester. When using sound (80-0 dB) and wind (35 cm diameter fan) as the mechanical energy sources, respectively, the output voltage and current generated by sound are higher than that by wind (Fig. 5l). Furthermore, Chen et al. [90] have proposed a micro-cable power textile that consists of a fabric TENG and photovoltaic unit for ambient sunlight power gathering (Fig. 3h). As shown in Fig. 5m, the smart unit harvests not only wind energy to produce power from a moving car, but also human hand-shaking motion to charge a 2 mF capacitor to 2 V in 60 s.

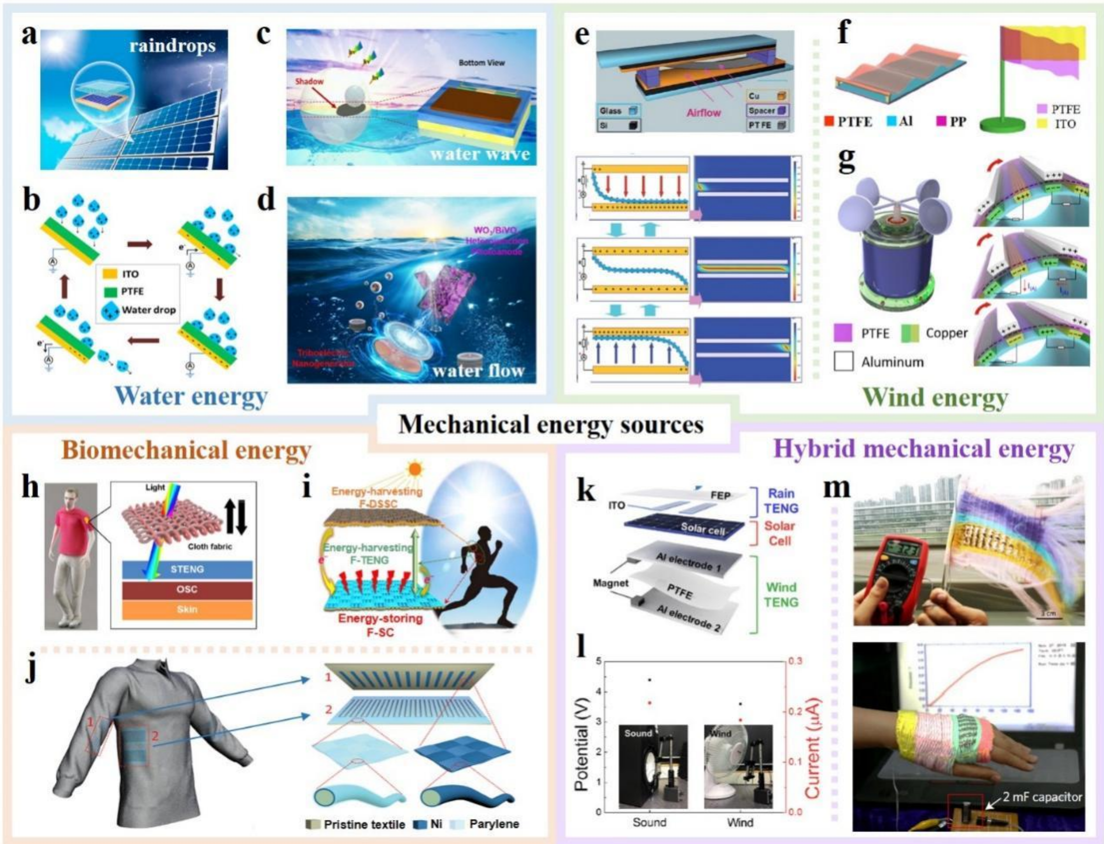

Fig. 5 Mechanical energy sources of HPTNGs: (a) Schematic of the hybrid cell for solar and raind energy harvesting. Reproduced with permission from American Chemical Society (2020) [81]. (b) Working principle of the TENG for rain energy harvesting. Reproduced with permission from Elsevier (2014) [102]. (c) Schematic of the hybrid energy ball for solar and flowing water energy harvesting. Reproduced with permission from Springer Nature (2021) [105]. (d) Schematic of the hybrid mechanical and solar energy-driven self-powered hydrogen production system. Reproduced with permission from Springer (2020) [107]. (e) Schematic of airflow-induced TENG and working mechanism. Reproduced with permission from Royal Society of Chemistry (2014) [79]. (f) Schematic of wind-driven TENGs. Reproduced with permission from Elsevier (2017) [108]. (g) Schematic of the wind-driven hybrid nanogenerator and mechanism. Reproduced with permission from Elsevier (2018) [84]. (h) Schematic of the cell integrated into fabrics. Reproduced with permission from Elsevier (2015) [88]. (i) Schematic of self-powered fabrics for solar and human motion energy harvesting. Reproduced with permission from American Association for the Advancement of Science (2016) [89]. (j) Schematic of the power textile and TENG fabric pairs. Reproduced with permission from Willey-VCH (2016) [91]. (k) Schematic of the harvesting module for capturing solar, rain, and wind energies. Reproduced with permission from Elsevier (2020) [111]. (l) Photographs and output of the hybrid nanogenerator for sound and wind energy harvesting. Reproduced with permission from Royal Society of Chemistry (2018) [113]. (m) Photographs of micro-cable textiles for wind and human motion energy harvesting. Reproduced with permission from Springer Nature (2016) [90].

5. Effects of TENG on Solar Cell Performance

In hybrid energy-harvesting systems, it is important to investigate the potential impact of the interactions between single components on the performance of the system. Considering the different working mechanisms and device designs of TENGs and solar cells, the effects of TENG on the performance of solar cells in HPTNGs are usually more obvious and important than those of the solar cells. Among reported HPTNGs, the effects of TENGs on the solar cell output can be divided into three categories as shown in the following.

5.1 No effects

"No effects" means that the existence of TENG does not impact the performance of the solar cell in HPTHGs. As shown in Fig. 6a, Shao et al. [97] have proposed a multifunctional hybrid power unit for blue energy harvesting, in which commercial Si-SCs are placed on the four TENGs. Light absorption is not affected and neither is the conversion efficiency of the solar cell. Similar structures with TENGs on top of or beside solar cells have also been reported in other works to avoid potential negative interactions between photovoltaic and triboelectric effects [83,84,86,89,90,92,96,108].

However, the effects between TENGs and solar cells have not been reported even though the former is placed on the latter [88,114,115], because in some cases, the top TENG is transparent. For instance, Ma et al. [93] have conducted the external quantum efficiency (EQE) measurement of the solar cell covered by the ETFE/ITO film to study the impact of TENG on the solar cell. The curve in Fig. 6b shows a spectral response range of 300-850 nm demonstrating that the bottom solar cell can operate under visible light illumination. On the other hand, the inset in Fig. 6c presents a hybridized power panel containing a transparent top dual-mode TENG and a bottom solar cell developed by Zheng et al. [110] .To evaluate the potential effect of the dual-mode TENG on the solar cell, the J-V curves of the hybrid cell and solar cell integrated with 3 mm-thick glass are compared under 100 mW/cm^2 light irradiation. J_{SC} of the hybrid cell is only a little higher than that of the solar cell, indicating the top TENG does not significantly affect the conversion efficiency. However, a more direct comparison is needed to investigate the performance interactions between TENGs and solar cells. Liu et al. [99] have observed that the PCE differences of the solar cell with or without the top transparent rain-PDMS of 10 parallel devices are in the range of ~±3% (Fig. 6d) thus indicating negligible influence of the PDMS (transmittance of ~95%) on the solar cells.

5.2 Negative effect

On the other hand, negative effects have been commonly reported even if the top TENG has high transparency. For example, a hybrid cell has been developed by Yang et al. and a commercial solar cell is put under a self-healing TENG [82]. Although the TENG has a high transparency of 96-100%, the conversion efficiency of the hybrid cell decreases slightly to 0.184% compared to the original 0.189% of the bare solar cell under the same illumination conditions. For those with lower transparency, the negative impact of TENGs on the solar cells is more obvious. Roh et al. [111] have observed that compared to the bare solar cell, the electrical output of the solar cell with a top rain-TENG (ITO/FEP) decreases the voltage and current by 0.4 V and 2 uA, respectively. Meanwhile, the conversion efficiency of the solar cell revealed by Jeon et al. decreases from 6.1% to 5% after incorporation of a top TENG (PDMS/ITO/PEN) [95]. Similar reduction has also been disclosed by others as shown in Fig. 6e,f, in which the PCE of the solar cell drops from 16% (bare solar cell) to 14% (hybrid cell) due to light absorption by the TENGs [98,102]. Moreover, Dudem et al. [112] have studied TENG as the cover layer on DSSC and observed negative impact such as J_{SC} dropping from 16.98-17.85 mA/cm^2 to 12.75-13.31 mA/cm^2. Nevertheless, introduction of HNMA-PDMS and ZnO NWs layers enhance the output slightly as shown in Fig. 6g because of larger transmission over a wide wavelength range.

5.3 Positive effect

Interestingly, there are some researches discovering the positive effect of TENG on solar cell's performance with similar enhancement mechanism. For example, Ren et al. [94] have used a grooved micro/nanostructured haze thin film (GHF, as the light-trapping layer for the solar cell and triboelectric layer for the TENG) on the light entrance surface of solar cells. As shown in Fig. 6h, light scattering and anti-reflection of GHF improves light absorption and further enhances J_{SC} and PCE from 8.65 mA/cm^2 and 2.89% (bare solar cell) to 9.82 mA/cm^2 and 3.29%, respectively. According to Yoo et al.'s study [80], a 0.01% improvement in the solar-weighted transmittance for the covered TENG is able to increase the FF and PCE of the solar cell by 0.5% and 0.17%, respectively. To enhance light absorption, Liu et al. [100] have fabricated nanostructured wrinkled PDMS film as the protective, covering, and triboelectric layer as shown in Fig. 6i. Due to the anti-reflective property, the nw-PDMS coated solar cell absorbs better than the bare solar cell with J_{SC} and PCE of the former reaching 40.7 mA/cm^2 and 13.57%, respectively, compared to the original values of 36.73 mA/cm^2 and 12.55%. Coating anti-reflective nano-SiO_2 layers on the solar cells also increase PCE from 15.17% to 15.71% (Fig. 6j) [101]. Another improvement strategy has been reported by Wang et al.[81] who introduce carbon dots to the PVA/PEI film to increase the transmittance of the covering and triboelectric layer, as shown in Fig. 6k. Consequently, the PCE of the solar cell increases from 13.6% to 14.6% after adding carbon dots. However, the output of the hybrid cell is not compared with that of the bare solar cell without the top layers and so it is hard to unambiguously identify the role of the carbon dots.

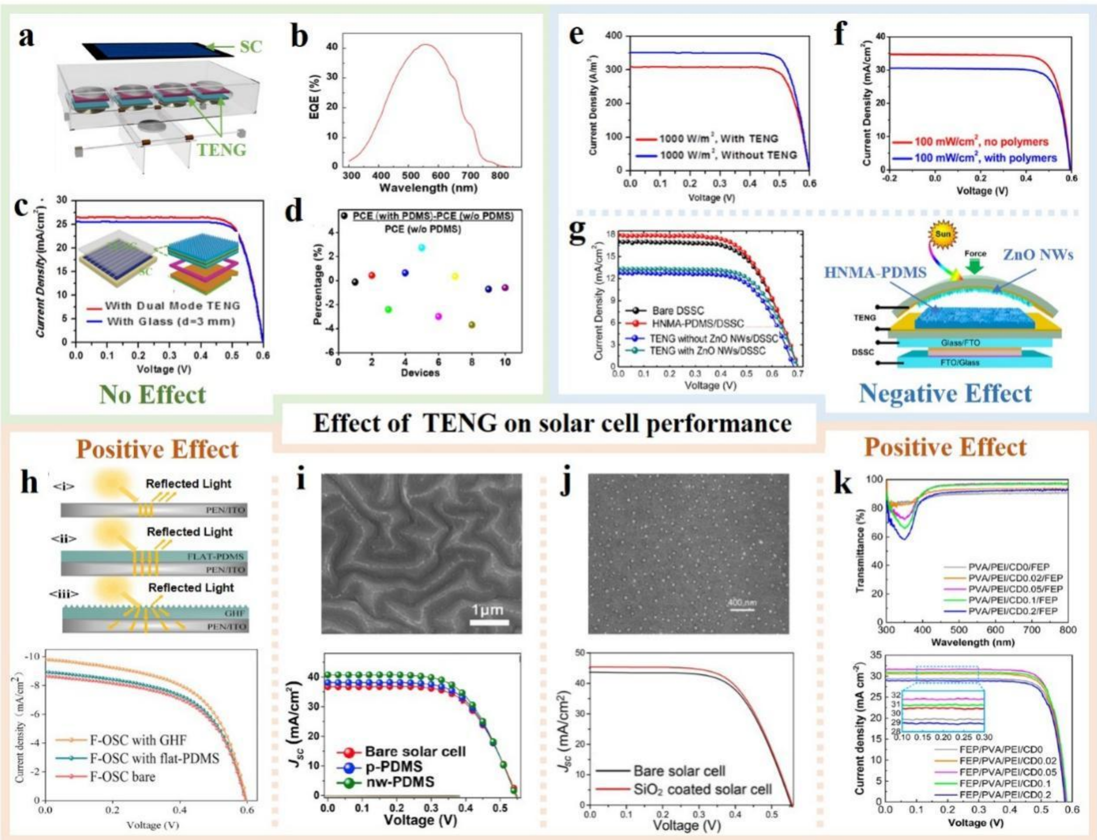

Fig. 6 Impact of TENGs on the performance of solar cell in HPTNGs: (a) Design of a hybrid power unit with the solar cell on top of the TENG. Reproduced with permission from Elsevier (2017) [97]. Copyright 2017, Elsevier. (b) EQE curve of the ETFE-covered Si-SC. Reproduced with permission from Elsevier (2019) [93]. (c) J-V curves of Si-SCs covered with TENG and glass. Reproduced with permission from Willey-VCH (2015) [110]. (d) PCE changes of the solar cell

integrated with TENG compared to that without TENG. Reproduced with permission from American Chemical Society (2018) [99]. (e) J-V curves of Si-SCs with and without polymers. Reproduced with permission from American Chemical Society (2013) [98]. (f) J-V curves of Si-SCs with and without the top TENG. Reproduced with permission from Elsevier (2014) [102]. (g) J-V curves of DSSC for different states and schematic of the hybrid cells. Reproduced with permission from American Chemical Society (2016) [112]. (h) Schematic showing the reflection mechanism and J-V curves of F-OSCs. Reproduced with permission from Elsevier (2020) [94]. (i) SEM image of the nw-PDMS film and J-V curves of various solar cells. Reproduced with permission from Elsevier (2019) [100]. (j) SEM image of the SiO_2 film and J-V curves of the solar cells. Reproduced with permission from IOP Publishing (2021) [101]. (k) Transmittance of FEP-covered PVA/PEI/CDs films and J-V curves of various solar cells. Reproduced with permission from American Chemical Society (2020) [81].

6. Functions and Applications

6.1 Self-Cleaning and Self-Healing

Accumulation of dust particles on the solar panel surface blocks light penetration consequently reducing the power generation and life span of solar cells in HPTNG systems, and therefore, endowing the HPTNGs with self-cleaning capability is very useful. Jeon et al. [95] have prepared a water-TENG with a superhydrophobic surface on the solar cells with the self-cleaning ability. As shown in Fig. 7a, the microbowl PDMS layer prepared by soft lithography exhibits an average contact angle of more than 150º thereby enabling droplets to remove airborne dust particles. The PCE of the self-cleaning hybrid cell which is 84.27% compared to the initial performance is much higher than that covered by the flat PDMS (15.45%). Following this mechanism, plasma etching has been employed as another technology to endow a TENG with the self-cleaning property [80]. Moreover, another self-cleaning hybrid composed of a commercial hydrophobic FEP film as the protective and triboelectric layer on top of the solar cell [111]. Since the surface contaminants can be easily removed with water, the transmittance of the cleaned TENG can be maintained (Fig. 7b) with V_{OC} and J_{SC}, decreasing only slightly from 3.8 V and 25 μA to 3.6 V and 20 μA, respectively. Similarly, Ren et al. have prepared a grooved haze thin film (GHF) as the triboelectric and protective layer on the OSC [94]. As shown in Fig. 7c, the hydrophobic GHF shows good properties after cleaning surface dusts. The solar cell with GHF recovers 80% of the initial efficiency after ten contamination and cleaning cycles compared to 52% of the flat PDMS. Recently, Liu et al. have used sol-gel method and fluorination treatment to synthesize a superhydrophobic SiO_2 film with self-cleaning function to cover the solar cell [101].

In addition to the self-cleaning property, self-healing of the top TENG is equally important, as it can protect the solar panel under mechanical stress and damage. However, it is hard to achieve self-cleaning and self-healing simultaneously, because a self-healing film usually has a hydrophilic surface, whereas a self-cleaning film requires a hydrophobic surface. Recently, a hybrid system with a self-cleaning and self-healing TENG has been developed by Yang et al. [82]. Self-cleaning is accomplished by incorporating fluorinated nanosilica into the HS-PDMS matrix. The self-healing mechanism is illustrated in Fig. 7d, where the dynamic imine bonds are formed by the Schiff base reaction to act as both the polymer cross-linking and self-healing points for the PDMS-NH_2 network. Compared to the original cell, the self-healing TENG being scratched by a blade shows almost the same charging behavior for five cycles, indicating excellent stability and repeatability of the hybrid energy-harvesting system.

6.2 Electronics Powering and Charging

Powering and charging of electronic devices is the most important function and the final aim for all kinds of energy harvesters. Through suitable power management circuit, the electricity generated by HPTNGs can power electronic gadgets and charge energy storage devices. Zheng et al. [110] have reported a power panel consisting of a top dual mode TENG and a solar cell which can simultaneously harvest sunlight, raindrops, and wind energies. As shown in Fig. 7e, when water drops (20 mL/s) drip on the dual-mode TENG, 10 and 20 commercial green LEDs are lit up by the water TENG and water-contact TENG, respectively. In combination with the solar cell, the hybrid power panel can power 50 LEDs. During charging of a 3.3 μF capacitor, the voltage increases to 0.6 V initially (upon 100 mW/cm^2 light illumination) and increases further to 19 V in 39 s with the help of the rectified dual-mode TENG. To realize the sustainable energy supply in a smart city, Wang et al. have designed a hybrid power supply based on photovoltaic and triboelectric effects to capture wind and solar energies [96]. The hybridized device shows better output current (~12 mA) and charging voltage (~2.1 V/10 min), compared to that of individual Si-SC (~9 mA, ~1.7 V/10 min) and TENG (~9 mA/Si-SC, ~2.0 V/10 min). As shown in Fig. 7f, the temperature-humidity sensor can be driven after the four integrated hybridized nanogenerators under room-light illumination at a wind speed of 15 m/s for several seconds. To power wearable and portable electronics, a micro-cable power fabric that can harvest solar and human motion energies has been reported by Chen et al. [90]. It is found that the hybrid output (~80 V/2 μA) under light and vibration condition is the sum of fabric DSSC (~4 V/0.2 μA) and fabric TENG (~75 V/0.05 μA). With mechanical excitation under natural daylight, the hybrid power textile is able to charge a 2 mF capacitor to 2 V in 60 s. Moreover, this smart wearable textile can also charge a cell phone and power electronic watch as shown in Fig. 7g. Similar charging and powering capabilities have been achieved from other photovoltaic-triboelectric cells [92,98]. For example, Song et al. have fabricated an elastic and sustainable self-charging power source to capture solar and human motion energies, where the hybrid current of ~9.3 μA consist of ~8.3 μA from DSSC and ~1 μA from TENG [92]. Moreover, an electronic watch can be driven for 85 s after charging the supercapacitor to ~1.8 V for only 75 s. Recently, Jung et al. [109] have developed a hybrid system consisting of a TENG and an organic photovoltaic cell (OPV) to power indoor electronics (Fig. 7h). The hybrid output (~10 V/2 μA) comes from the individual output of OPV (~1.5 V/5 μA) and TENG (~8.5 V/1 μA). Compared to the individual TENG-based (~0.6 V) and OPV-based (~0.9 V) self-charging devices, this system can more effectively and rapidly charge the capacitor (~1.25 V/40 s/10 μF) and Li-ion battery using only indoor light and human motion.

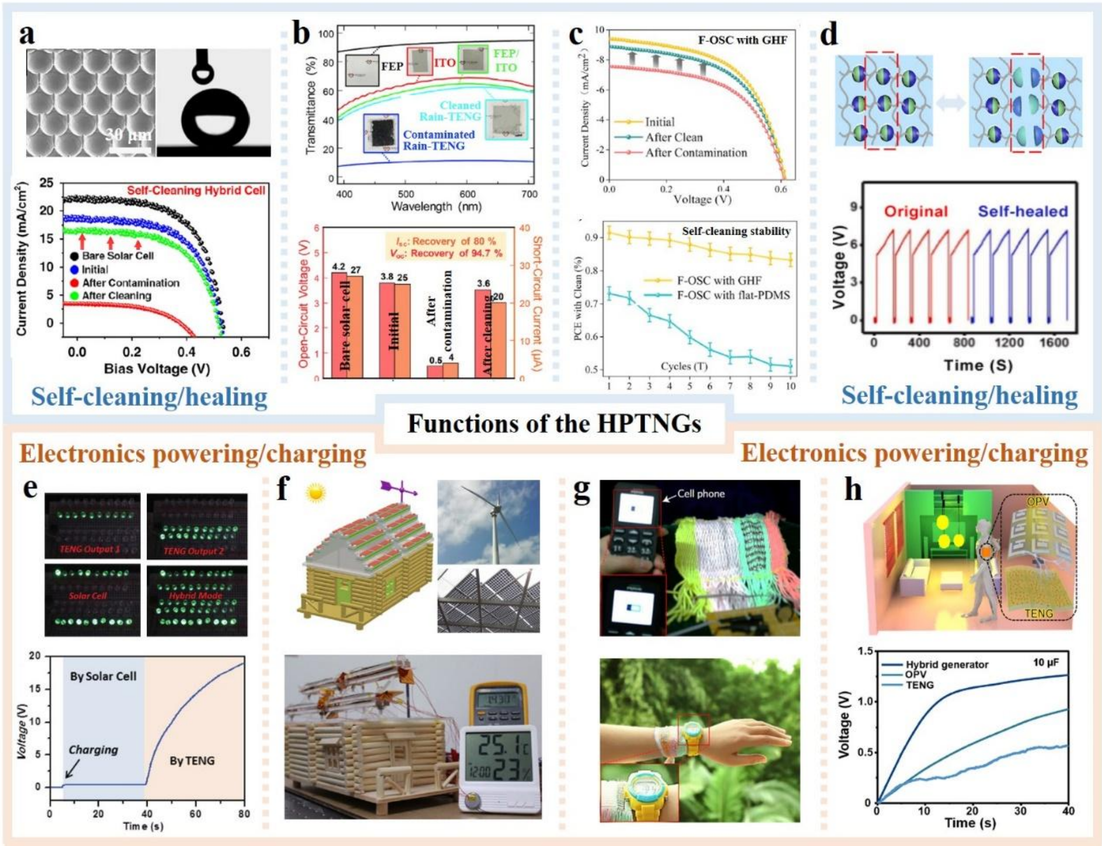

Fig. 7 Functions of HPTNGs: (a) Physical properties of microbowl PDMS and I-V curve of the self-cleaning hybrid cell. Reproduced with permission from Elsevier (2015) [95]. (b) Transmittance of various films and output of solar cells. Reproduced with permission from Elsevier (2020) [111]. (c) J-V curves of F-OSC with GHF and PCE changes of F-OSCs after cleaning for 10 cycles. Reproduced with permission from Elsevier (2020) [94]. (d) Self-healing process of dynamic imine bonds and charging behavior of hybrid cells for 5 cycles. Reproduced with permission from Elsevier (2021) [82]. (e) Commercial LEDs driven by a single or hybrid power panel and charging behavior of the hybrid power panel. Reproduced with permission from Willey-VCH (2015) [110]. (f) Schematic of hybrid cells simulating wind and solar energy harvesting and powering a humidity-temperature sensor. Reproduced with permission from American Chemical Society (2016) [96]. (g) Hybrid power textile powering commercial electronics. Reproduced with permission from Springer Nature (2016) [90]. (h) Schematic of the indoor hybrid energy harvesting system and charging behavior. Reproduced with permission from Elsevier (2020) [109].

6.3 Sensing and Monitoring

The practical applications of hybrid energy harvesters are usually related to the Internet of Things, such as temperature sensing and weather monitoring [83,108]. For instance, Roh et al. [111] have proposed a unified harvesting module containing two

TENGs for wind and raindrops energy harvesting and one solar cell for light energy harvesting. As shown in Fig. 8a, the hybrid module is a weather sensor as it can detect weather conditions such as rain, wind, and sunlight boding well for environmental monitoring in a smart environment such as a farm. At the same time, Xu et al. [86] have prepared a hybrid all-in-one power source with spherical TENGs and solar cells. As shown in Fig. 8b, the self-powered soil moisture sensor for intelligent farm irrigation is powered by the hybrid cell with a 1.5 mF storage capacitor. If the soil is too dry, that is, moisture level below the threshold, the information will be sent to a computer to issue a red alarm so that watering will be triggered. If the moisture level is above the threshold, the color will be changed to green to cease watering. This sensor can conceivably prevent forest fire and pipeline monitoring can be implemented based on the same mechanism. Morevoer, Qian et al. have developed a sustainable power unit including a TENG, eight EMGs, and a solar cell for self-powered natural disaster monitoring [84]. As shown in Fig. 8c, the self-powered thermally sensitive monitoring system is designed for a certain fire detection range and the collected temperature information is forwarded to the nearest base station for continuous monitoring and decision of rescue operation. Based on similar theories, an earthquake monitoring system can also be designed with a self-powered vibration sensor for disaster prediction or safety analysis in rescue.

6.4 Water Splitting and Hydrogen Production

Production of hydrogen by water splitting is usually based on electrolytic catalysis which normally requires external power to drive the reactions. Yang et al.

have firstly developed a hybrid cell by integrating TENGs, thermoelectric cells, and solar cells which harvest mechanical, thermal, and solar energies [78]. As shown in Fig. 8d, there are two methods for water splitting. The first one uses the power generated by the hybrid cell to drive water splitting directly to generate H_2 without any external power source. It is found that the produced H_2 volume increases with increasing the splitting time showing a linear relationship, leading to the decrease of water surface level in the collection tube. The second method is to store the produced electricity in a Li-ion battery first and then use it in water splitting. The H_2 production volume bears an exponential relationship with the water splitting time as hydrogen production slows with time. Recently, Zhang et al. have proposed a hybrid energy-harvesting ball systems based on triboelectric and photovoltaic effects for water splitting [105]. By using balls in series as shown in Fig. 8e, the generated electricity is enough to realize water splitting during the day or night.

However, the relative rigid and complex structure increase the cost and complexity in actual applications. Chen et al. have prepared micro-cable structured hybrid textile to drive electrochemical reactions [90], and similar linear relationship between the H_2 volume and splitting time is observed. It can conceivably split water in a lake by harvesting solar and wind energies. Li et al. have further proposed a system with a flexible TENG to boost the water splitting efficiency of the photoelectrochemical (PEC) cell with the assistance of charged Li-ion batteries [116]. As shown by the schematic diagram of the TENG-PEC cell and the image of water splitting in Fig. 8f, obvious H_2 bubbles are emitted when the battery is charged to 1.5

V and the instantaneous current reaches more than 9 mA. The improved water splitting performance is mainly caused by the better electron-hole separation efficiency.

According to the same mechanism, Wei et al. have recently proposed a hybridized mechanical and solar driven self-powered hydrogen production system [107], where a rotatory disk-shape TENG and a $VO_3/BiVO_4$ heterojunction photoanode supply the power and produce H_2, respectively. In particular, this work has focused on the comparison of hydrogen generation under dark and illumination conditions. H_2 evolution occurs only upon sunlight irradiation when the rotation speed of the TENG is 60 rpm. As shown in Fig. 8g, similar peak photo currents and dark currents can be obtained when the rotation speed exceeds 130 rpm. If the speed is further increased to 160 rpm, the H_2 production rate reaches 5.45 μL/min (dark condition) and 7.27 μL/min (illumination), suggesting promising potential in PEC hydrogen generation.

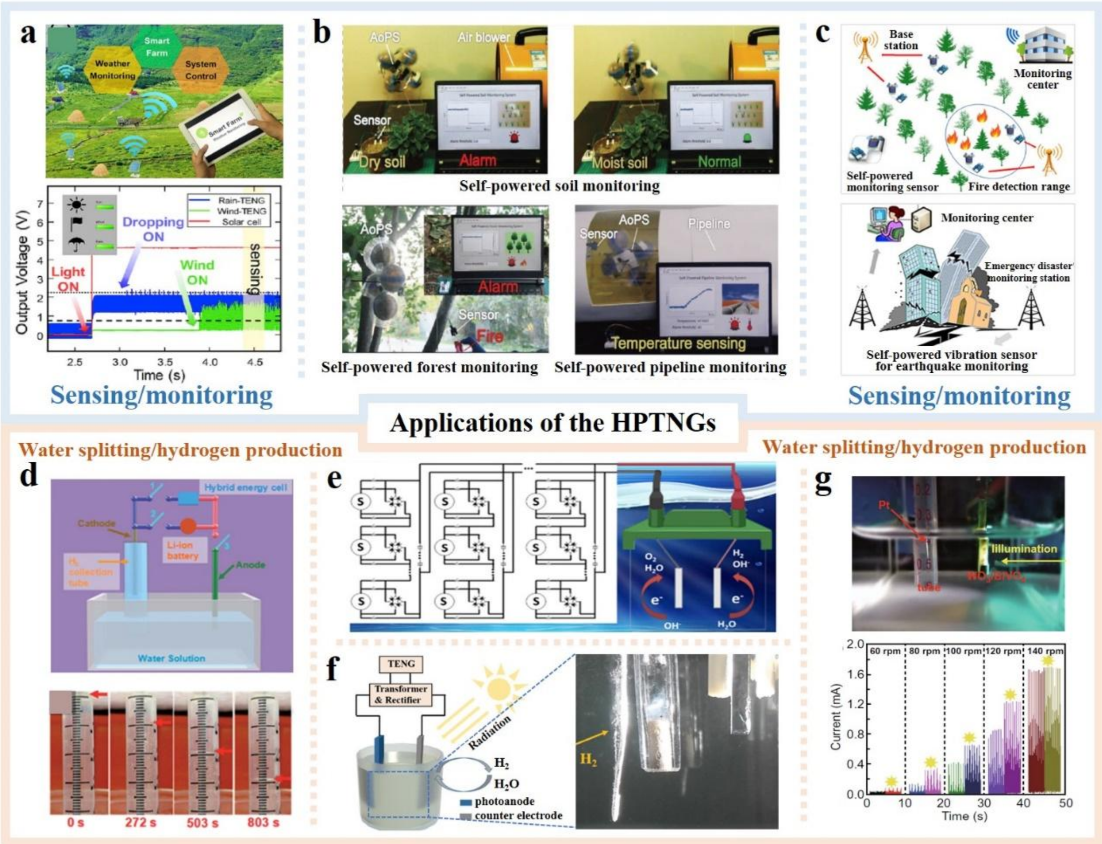

Fig. 8 Applications of HPTNGs: (a) Hybrid module as a self-powered weather sensor in a smart farm. Reproduced with permission from Elsevier (2020) [111]. (b) Hybrid power sources for self-powered soil, forest and pipeline monitoring. Reproduced with permission from Willey-VCH (2020) [86]. (c) Hybrid nanogenerators for self-powered forest fire and earthquake monitoring. Reproduced with permission from Elsevier (2018) [84]. (d) Self-powered water splitting system and H_2 collection. Reproduced with permission from Royal Society of Chemistry (2013) [78]. (e) Circuit management of self-powered hybrid systems for seawater splitting. Reproduced with permission from Springer Nature (2021) [105]. (f) Schematic hybrid cell and H_2 generation process. Reproduced with permission from Willey-VCH (2017) [116]. (g) H_2 collection under illumination and output current with and without illumination. Reproduced with permission from Springer (2020) [107].

7. Summary and Prospective

Similar to other hybrid energy harvesting technologies, development of HPTNGs faces difficulties and much work is required towards commercialization. Fig. 9 summarizes the main challenges and perspective of HPTNGs concerning device and structural design, energy input and output, functions, as well as applications.

7.1 Device and Structure

With regard to device fabrication and structural design, all-in-one flexible hybrid power sources are ideal for wearable electronics [32,86,117-119]. Unlike rigid hybrid cells that tend to be bulky and heavy, flexible and integrated hybrid devices have many advantages such as light weight, flexible working environments, and low cost. However, there are still many challenges and difficulties from the viewpoint of materials selection, synthesis, fabrication, and integration.

The flexible hybrid system requires both flexible TENGs and solar cells. Although flexible TENGs can be produced relatively easily due to the merits of broad materials selection, flexible solar cells are difficult to manufacture. For example, device fabrication on a flexible substrate is more difficult than that on a rigid substrate, while the performance of the former is usually lower than that of the latter [120-122]. Furthermore, most flexible solar cells have not been introduced to wearable applications, as the absorption layers and electrons are often sensitive to mechanical stress. On the other hand, most all-in-one structured HPTNGs reported so far are rigid, whereas flexible ones either share only one mutual electrode among TENGs and solar cells or are independent of each other. Therefore, the most important and urgent task confronting the development of flexible all-in-one HPTNGs is to fabricate flexible solar cells with high output and mechanical resistance, and then further integrate with flexible TENGs.

7.2 Input and Output

The energy for photovoltaic cells comes from natural sunlight or artificial light, but the mechanical energy sources for TENGs are much more extensive. The common mechanical energy sources for HPTNGs are wind, water, and human motion. Although these energy sources are clean and sustainable, more mechanical energy sources need to be developed to meet different needs for practical applications. For instance, sound energy is a green energy source but there have been few studies as a mechanical energy source for HPTNGs [113]. Considering that people spend a lot of time indoor, more efficient indoor light harvesting technology is needed but to the best of our knowledge, there has been only one report on photovoltaic-triboelectric hybrid cells that capture indoor light energy [109]. In this case, HPTNG with a top transparent film that can flutter like a flag, can be fabricated. The user can put the HPTNG on the TV, a position that is not only near to the sound source but also able to catch the indoor light. When the user watches TV, the voice comes from the TV could cause the fluctuant air pressure nearby and further the film vibration of the HPTNG. Thus, the developed HPTNG can simultaneously harvest sound energy and indoor light energy.

Normally, the influence of solar cells on the output of TENGs is minimal because it mainly depends on the internal characteristics of TENGs and the external pressing media. However, the effect of TENGs on the performance of solar cells may not be negligible if TENGs are placed on the solar cells to protect the solar cells from corrosion and contamination and to complete the continuous “contact and separation” cycles. This often requires the top TENG to have high light transparency. Although anti-reflective TENG layers have been developed to enhance the conversion efficiency of the solar cells underneath, the performance needs further improvement.

Therefore, HPTNGs should be designed by optimizing the interactions between the TENGs and solar cells.

7.3 Functions and Applications

In addition of harvesting clean energy, another important reason for combining solar cells and TENGs is the complementary output, because TENGs have a high voltage but low current while solar cells have a high current but low voltage. However, the different power characteristics (AC output for TENGs but DC output for solar cells) and large internal impedance differences (Megohm level for TENGs but Ohm level for solar cells) require suitable power management circuits in the hybrid photovoltaic-triboelectric system. So far, most hybrid TENG-based cells store the energy in capacitors and batteries first and then the energy is used to charge electronic devices [123-127], and HPTNGs are no exception. Furthermore, there are very few researches specifically studying the power management circuit of PTHNGs, making the development of this field urgent and challenge.

Besides, most reported HPTNGs are used in self-powered weather sensing, environmental monitoring, and hydrogen producing but many personal and biomedical applications such as pulse and breath monitoring have not been studied yet. It can be expected that HPTNGs will have an excellent prospect in human health monitoring. For instance, if a person is sensitive to sunlight, he/she can wear the hybrid device to monitor the heart rate as the sunlight intensity changes during the day. If the sunlight is too strong, the heart rate tends to increase and immediate attention can be paid if abnormal signals are detected. Therefore, while it is important to design

HPTNGs for traditional powering and charging applications, monitor of human health will be another important application in the future.

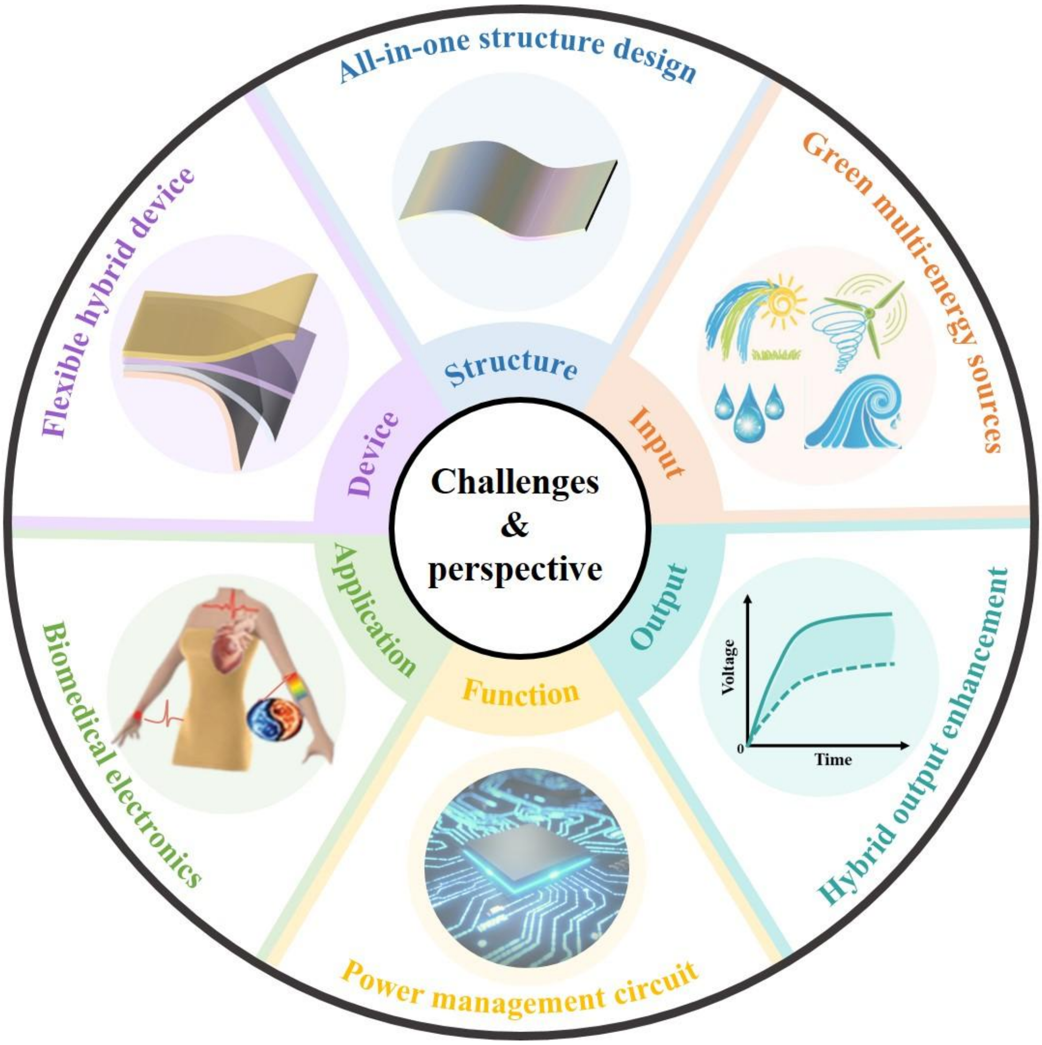

Fig. 9 Challenge and prospective of HPTNGs: Device and structural design, input and output, functions, and applications.

Table 1. Summary and Comparison of reported HPTNGs.

Hybrid device		Structure Flexibility	Mechanical Energy Source	Hybrid output/*charging* performance	Functions & Applications	Ref
Tribo-	Photo-					
CS[a)]	Si-SC	NO	Mechanical	2.5V (0.6V/SC+1.9V/TENG)	Powering, Charging	[98]
CS	Si-SC	NO	Mechanical	/	Water splitting	[78]
CS	DSSC	NO	Wind	~6.5μA (3.5μA/SC+3μA/TENG)	Powering, Charging	[79]
SE[b)]	Si-SC	NO	Raindrop	~22V (1V/SC+21V/TENG) *(33μF):0.6V/SC to 3.5V/530s/TENG)*	Powering, Charging	[102]
SE	Si-SC	NO	Wind	~66V (6V/SC/EC+52V/TENG) *(10μF): ~5V/100s (3.5V/SC/EC, 3V/TENG)*	Powering, Charging	[83]
SE/CS	Si-SC	NO	Raindrop/Wind	*(3.3μF): 19V/80s (0.6V/SC+18.4V/TENG)*	Powering, Charging	[110]
SE	Si-SC	NO	Raindrop	~3.2V (0.6V/SC+2.6V/TENG)	Powering, Charging, Self-cleaning	[95]
SE	OSC	YES	Biomechanical	~2V (0.45V/SC+1.55V/TENG) *(10μF): ~0.45V/17s*	Charging	[88]
CS	DSSC	NO	Wind/Mechanical	20V (~0.7V/SC, 18V/TENG)	Self-cleaning	[112]
CS	Si-SC	NO	Wind	~12mA (9mA/SC, 4.5mA/TENG) *(LB): 2.1 V/600s (1.7V/SC, 2.0V/TENG)*	Powering, Charging	[96]
FT[c)]	DSSC	YES	Biomechanical	~24μA (12uA/SC, 14μA/TENG) *(LB): 10min charging/98min discharging*	Powering, Charging	[91]
CS	DSSC	YES	Biomechanical	~80V/0.25μA (4V/0.2μA/SC+75V/ 0.05μA/TENG *(2mF): 2V/60s*	Powering, Charging, Water splitting	[90]
CS	DSSC	YES	Biomechanical	*(Self-charging): 3.6V/6.5h (1.8V/SC+1.8V/5.4h/TENG)*	Charging	[89]
CS	PVC[d)]	NO	Mechanical	*(10μF): ~5.1V/120s (4.2V/CS+PTNG, 3.6V/PyENG+PTNG)*	Charging	[114]
CS	Si-SC	NO	Water wave	*(33μF): 3V/60s (1.8V/SC+0.45V/EMG+0.8V/TENG)*	Powering, Charging	[97]
SE	Com.[e)]	NO	Wind	~11V (6V/SC, 6V/TENG) *(10 mAh Li-B) 2.7 V/540s*	Powering, Charging, Sensing	[108]
CS	PEC[f)]	NO	Mechanical	/	Water splitting	[116]
SE	Si-SC	NO	Raindrop	*(Capacitor): 0.9V/165s (0.6V/SC+0.3V/TENG)*	Charging	[99]
FT	DSSC	NO	Wind	150μA (60μA/SC+90μA/TENG) *(LB): 0.88h charging/4.12h discharging*	Powering, Charging	[85]
CS	PVC	NO	Mechanical	*(0.33 μF): ~1.1V/10s (0.2V/PVC, 0.6V/PyENG, 0.9V/PTENG)*	Charging	[115]
CS	QDSC	NO	Wind/Sound	*(200μF): ~11V/190s (3V/SC+8V/TENG)*	Sensing, Charging	[113]
FT	Com.	NO	Wind	*(330uF): 1.5V/3.5s* *(470uF): 2.2V/25s*	Powering, Charging, Monitoring	[84]
CS	Si-SC	YES	Mechanical	*(LB): 3.65 V/6.5s/SC to 3.86 V/1.6h/TENG*	Charging	[93]
SE	DSSC	YES	Biomechanical	~9.3mA (8.3mA/SC+1mA/TENG) *(self-charging) 1.8V/75s*	Powering, Charging	[92]
FT	Com.	NO	Raindrop	~6V (1V/SC+5V/TENG)	Self-cleaning, Charging	[80]
SE	Si-SC	NO	Raindrop	*(3.3μF): 0.8V/5.8s/SC to 3.1V/160s/TENG*	Charging	[100]
SE	Si-SC	NO	Raindrop	*(1μF): 0.345V/SC to 0.6V/110s/TENG*	Powering, Charging	[81]
FT	Com.	NO	Raindrop/Wind	*(470μF): ~3.6V/250s (1V/SC+2.6V/TENG)*	Powering, Charging, Monitoring	[86]
CS	PVC	NO	Biomechanical	~10V/6μA (1.5V/5μA/SC+8.5V/1μA/TENG) *(10μF): 1.25V/40s (0.9V/SC, 0.5V/TENG)*	Charging	[109]
SE	Com.	NO	Biomechanical	/	Sensing	[87]
FT	Si-SC	NO	Raindrop/Wind	~33V/25μA (5V/24μA/SC, 6-20V/0-11uA/TENG)	Sensing, Self-cleaning, Powering	[111]
SE	OSC	YES	Biomechanical	*~1.25V (0.4V/SC, 0.75V/TENG)* *(10μF): 0.72V/400s (0.4V/SC+0.32V/TENG)*	Self-cleaning, Charging	[94]
FT	PEC	NO	Water flow	/	Water splitting	[107]
FT	Com.	NO	Water wave	/	Water splitting	[106]
SE	Si-SC	NO	Raindrop	*(1μF): 0.85V/4.4s/SC to 3.5V/160.6s/TENG*	Self-cleaning, Charging	[101]
FT	Com.	NO	Raindrop	*(2.7μF): 5.2V/2s/SC to 7.2V/~180s /TENG*	Self-cleaning/healing, Charging	[82]

Note: [a]Contact-separation mode, [b]Single-electrode mode, [c]Freestanding triboelectric-layer mode; [d]Photovoltaic cell, [e]Commercial solar cell, [f]Photoelectrochemical cell. Since some research works didn't provide detailed information about the solar cells used, these marked cells (PVC, Com. and PEC) may be one of those five types (Si-SC, DSSC, OSC, QDSC and PSC).

In this review, recent progress of hybrid photovoltaic-triboelectric energy harvesting systems are described, from the working principles and hybridized structure design to mechanical energy input and output interaction among TENGs and solar cells, and further to the functions and applications of HPTNGs, as summarized in Table 1. In spite of the rapid development, better understanding and continuous improvement of this hybrid system are needed to address the following areas. First, flexible solar cells with outstanding mechanical resistance and integration with flexible TENGs must be developed to produce all-in-one HPTNGs for wearable applications. Second, more ambient mechanical energy sources such as sound energy are desirable to widen the application of HPTNGs. The interactions between TENGs and solar cells and how to maximize the hybrid output are also important factors to be considered. Last but not least, similar to other TENG-based systems, the important goal for HPTNGs is to be able to power and charge commercial electronics directly without external storage systems. The potential of HPTNGs in the biomedical field such as health monitoring is also quite large but much work is needed to bring the technology to fruition.

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