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# Recent advances in triboelectric nanogenerator based self-charging power systems

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ABSTRACT

Over the last few decades, tremendous efforts have been focused on developing high performance energy storage systems such as batteries and supercapacitors for the applications in portable devices. However, limited lifetime of these storage systems is still a crucial challenge, meaning inconvenient recharging or replacement is inevitable. Since 2012, a novel technology of triboelectric nanogenerator (TENG) has been proposed for converting tiny mechanical energy into electricity, and various breakthroughs have been achieved for self-powered systems. Integrating TENG with energy storage devices could be a promising way to provide sustainable power supply for long-term operations. In this review article, we present the recent advances in the TENG-based self-charging power systems (SCPSs), which will have significant applications in internet of things, portable electronics, and wearable electronics. Hybrid SCPSs combining other energy conversion technologies are also included. The key approaches for improving the total efficiency of the SCPSs are systematically summarized. Finally, some of the important challenges and future directions to be pursued are also highlighted.

## 1. Introduction

With the rapid development of internet of things (IoTs) [1,2] and portable electronics [3,4], the demand for renewable, sustainable and environmental-friendly power supply is becoming increasingly significant. On the one hand, IoTs needs widely distributed sensors to various applications, and the number of such units can be huge in the order of billions to trillions; on the other hand, the electronic products trend to small size, intelligence, and multifunctional, and the power consumption is also getting higher [5–7]. In this case, higher requirements are needed for the power supply devices. The most conventional technology is using electrochemical energy storage devices, such as supercapacitors (SCs) and batteries, which all have limited lifetime. Frequent recharging or replacement will lead to great inconvenience and high maintenance cost under certain conditions. To address this challenge, an effective strategy is to improve the energy density of supercapacitors or batteries, and extensive research efforts have been dedicated to this goal [8,9]. In addition, integrating energy-harvesting and energy storage devices into self-charging power systems (SCPSs) could be an alternative approach, so that the environmental energy can be simultaneously scavenged and stored for sustainable power supply [10,11].

There are a few important forms of energy that could be harvested from our living environment, including thermal, solar, biochemical and mechanical. Among them, mechanical energy would be the most widely distributed energy form, and is nearly independent to the weather and working environment. Triboelectric nanogenerator (TENG) has been proven as a powerful technology for converting low-frequency mechanical energy into electricity, with unique advantages of high efficiency, high power density, light weight, low cost, diverse material selectivity, simple design and environmental friendliness [12,13]. All these merits make it a promising technology to be applied for compensating the energy consumption of the supercapacitors/batteries through integration with them, as schematically illustrated in Fig. 1. Thus, the operational time of the energy storage devices can be elongated, or even a self-sufficient power system could be formed for powering electronics.

Recently, significant efforts have been made in the TENG for harvesting various kinds of mechanical energy [14–16]. Realized through the integration of supercapacitors/batteries and energy-harvesting

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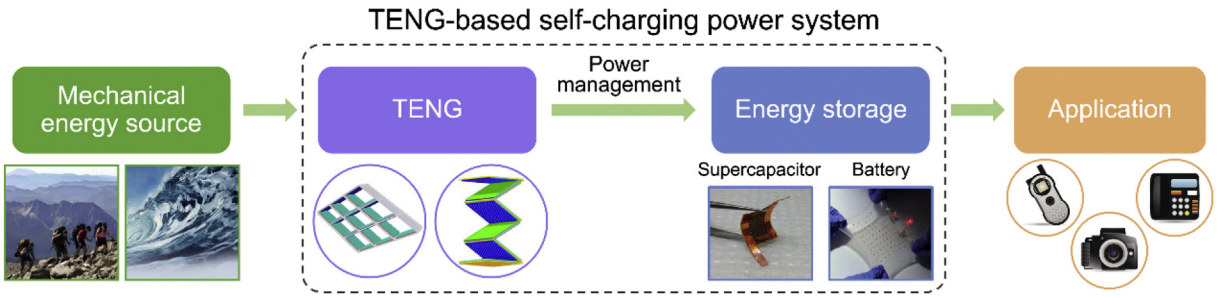


**Fig. 1.** Illustration of TENG-based SCPSs. "TENG:" Reproduced with permission [21,22]. Copyright 2013, American Chemical Society. "Supercapacitor:" Reproduced with permission [23]. Copyright 2013, Nature Publishing Group. "Battery:" Reproduced with permission [24]. Copyright 2013, Nature Publishing Group.

devices based on various mechanisms (pyroelectric, thermoelectric, photovoltaic, piezoelectric, and triboelectric), the self-charging capability has also been widely reported [17–20]. Herein, this review focuses on the recent progress of SCPSs by integrating TENG with energy storage devices (mainly supercapacitors and batteries). The power management circuits for improving the energy-storage efficiency of the SCPSs are also reviewed. Besides, we will further discuss the direct-current TENGs and self-discharge suppressing strategy for simplifying and optimizing the SCPSs. At last, some perspectives and challenges for the future development of TENG-based SCPSs are discussed.

## 2. Triboelectric nanogenerator

Triboelectrification is usually considered as a negative effect and need to be prevented in our daily lives. In 2012, the TENG was first invented for converting mechanical energy into electricity (Fig. 2a) [12], based on the coupled effects of triboelectrification and electrostatic induction, which is a revolutionary breakthrough in the technology of energy conversion and utilization. The detailed working mechanism of the TENG is illustrated in Fig. 2b [25]. When the surfaces of two dissimilar materials are brought into physical contact, triboelectric charges

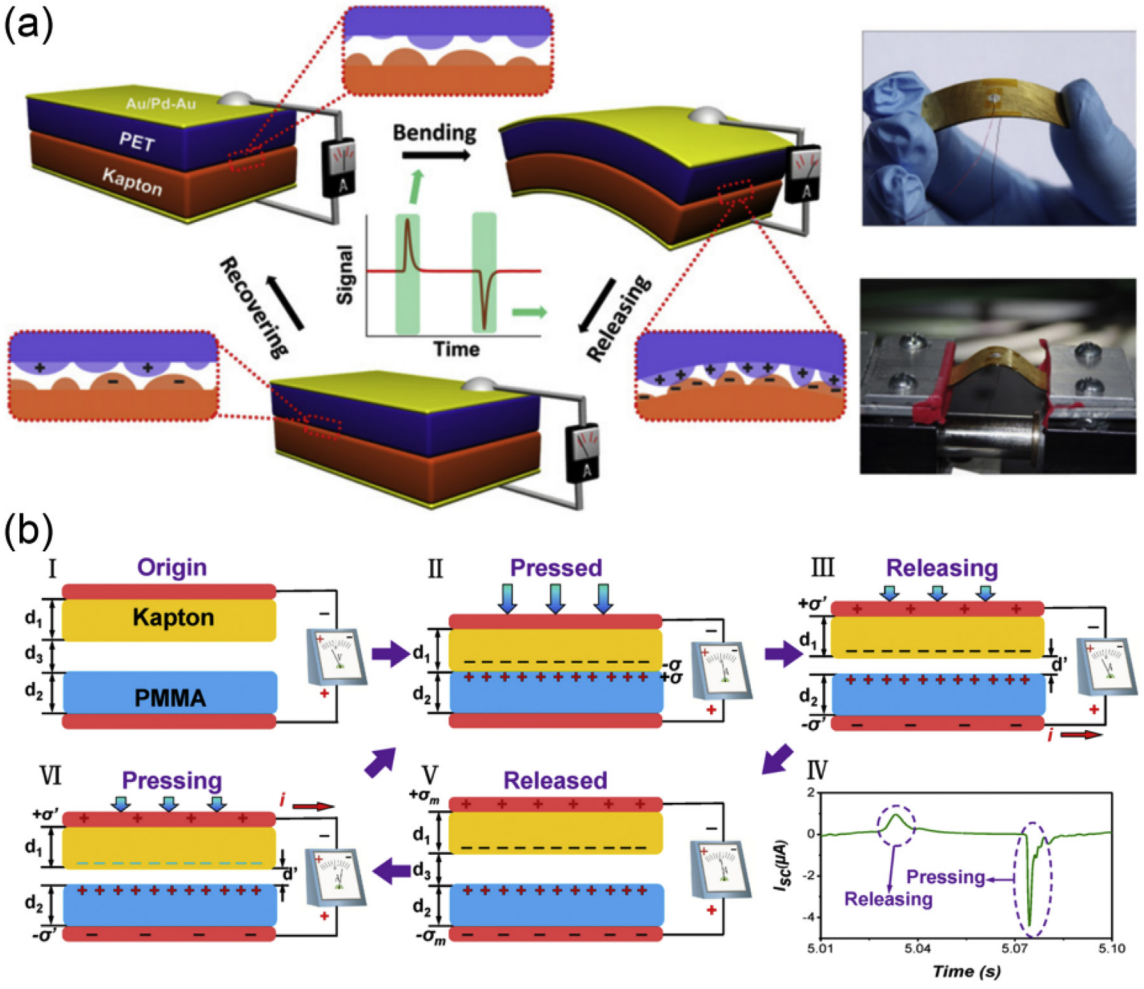


**Fig. 2.** Invention and working mechanism of the TENG. (a) The construction and photographs of the first TENG. Reproduced with permission [12]. Copyright 2012, Elsevier. (b) working mechanism of the TENG. Reproduced with permission [25]. Copyright 2012, American Chemical Society.

will be created on the two contacted surfaces. Then a potential difference can be generated when the two surfaces are separated by mechanical motion, which will drive electrons to flow back and forth between the two electrodes attached on the backside of the two materials.

Most recently, Wang has presented that the fundamental theory of the TENG can trace back to Maxwell's equations by including the contribution made by the surface polarization charges [16]. The output current of the TENG is directly related to the Maxwell's displacement current, which can be defined as [26].

$$\boldsymbol{J}_{\mathrm{D}} = \frac{\partial \boldsymbol{D}}{\partial t} = \varepsilon \frac{\partial \boldsymbol{E}}{\partial t} + \frac{\partial \boldsymbol{P}_{\mathrm{S}}}{\partial t}$$

where $\boldsymbol{J}_{\mathrm{D}}$ is the displacement current, $\boldsymbol{D}$ is the electric displacement field, $\boldsymbol{E}$ is the electric field, $\boldsymbol{P}_{\mathrm{S}}$ is the polarization density arising from the surface polarization, and $\varepsilon$ is the material's permittivity. In the Maxwell's displacement current, the first term is the current induced by the varying electric field. It leads to the discovery of electromagnetic wave that later being taken as the approach for developing radar, radio, TV, telegram, and most recently wireless communication technology. While the second term presents the current caused by the polarization field of surface electrostatic charges and is the theoretical origin of nanogenerators. This term gives birth of our nanogenerators and could possibly drive the development of new energy technology and self-powered sensors for the new era - the era of IoTs, big data, and artificial intelligence.

Ever since the first report of the TENG in 2012 by Wang et al., the areal output power density of the TENG reaches 500 W/m$^2$ [27], and an instantaneous conversion efficiency of ~70% has been demonstrated [28]. Despite the varieties of TENGs in electrode configuration and direction of polarization change, generally they could be divided into four basic working modes, as shown in Fig. 3 [14]. The vertical contact-separation mode utilizes the polarization in vertical direction. The lateral sliding mode utilizes the polarization in lateral direction due to the relative sliding between two contact surfaces. The single-electrode mode is designed for harvesting energy from a freely moving object without attaching a conduction line. The freestanding triboelectric-layer mode is introduced for power generation using electrostatic induction between a pair of electrode. Additionally, the theoretical models of these fundamental modes have also been extensively studied [29].

Based on the four above-mentioned working modes, the TENG can be utilized to harvest different kinds of mechanical energy from the ambient environment, such as vibration [30,31], human motion [32,33], wind [34,35], rain drop [36], water flow [37], and so on. Besides the small mechanical energy, the TENG can even harvest large-scale blue energy by connecting multiple units into a network [38,39]. Moreover, the TENG can be applied in the field of self-powered active sensing since it can directly transform mechanical stimuli to electrical signals without additional transducers. Relevant works include pressure sensors, tactile sensors, motion sensors, photoelectric sensors, and chemical sensors [40–50]. However, TENG cannot be directly used for driving most electronic devices due to its irregular alternating-current (AC) output characteristic. An energy storage unit, such as supercapacitor and battery, is required to store the energy harvested by TENGs and to provide a regulated and manageable output. TENG-based self-charging power systems developed by hybridizing TENG and different energy storage technologies will be individually discussed in the sections below.

## 3. TENG-based SCPSs

Our surrounding environment has an abundance of wasted mechanical energy in various forms. Therefore, combining TENGs and energy-storage devices (supercapacitors or batteries) into self-charging power systems could be an effective strategy to collect wasted mechanical energy for sustainable power supply. In this section, we will briefly introduce the latest developments in TENG-based SCPSs.

### 3.1. Integration with supercapacitors for SCPSs

Supercapacitor is a promising energy storage technology, which can provide high power density, long cycle life over a wide range of working temperatures [51]. Especially, the solid-state SC with superior flexibility, portability, and safety, affords a very promising option for portable and wearable electronics [52]. In consideration of the short operation time of the SC, integrating it with the TENG could build up a sustainable self-powered system by scavenging mechanical energy in our daily lives. In this section, we will highlight the recent advances in the SCPSs containing supercapacitors with various configurations.

#### 3.1.1. Fiber/textile-based SCPSs

Flexible, wearable TENGs and supercapacitors play two major roles in energy harvesting and storage for self-powered wearable electronics. Given weaving the TENG or supercapacitor into a textile, it is ideal to have these devices in the form of fiber. In 2015, Wang et al. first reported a fiber-based SCPS, which consists of a fiber-based TENG and fiber-based SCs [53]. Vapor-phase hydrothermal method was employed to synthesize the $RuO_2{\cdot}xH_2O$@carbon fibers as two symmetric electrodes of the fiber-based SC. Meanwhile, the TENG was designed via PDMS coated on carbon wire electrodes. A rectifier was used to convert the AC output of the TENG to direct-current (DC) output. Thereafter, Pu et al. developed a solid-state yarn SC with reduced graphene oxide as active materials, as shown in Fig. 4a [54]. The fabricated yarn supercapacitor exhibited high

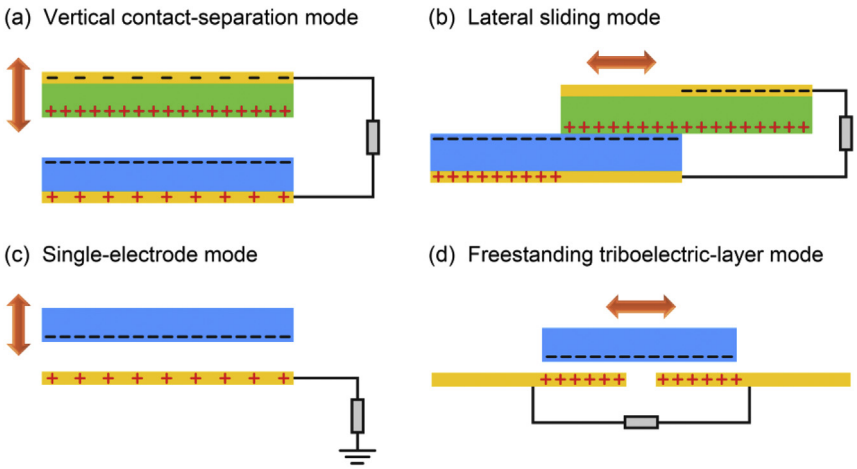


**Fig. 3.** The four fundamental modes of the TENG. (a) The vertical contact-separation mode. (b) The lateral sliding mode. (c) The single-electrode mode. (d) The freestanding triboelectric-layer mode.

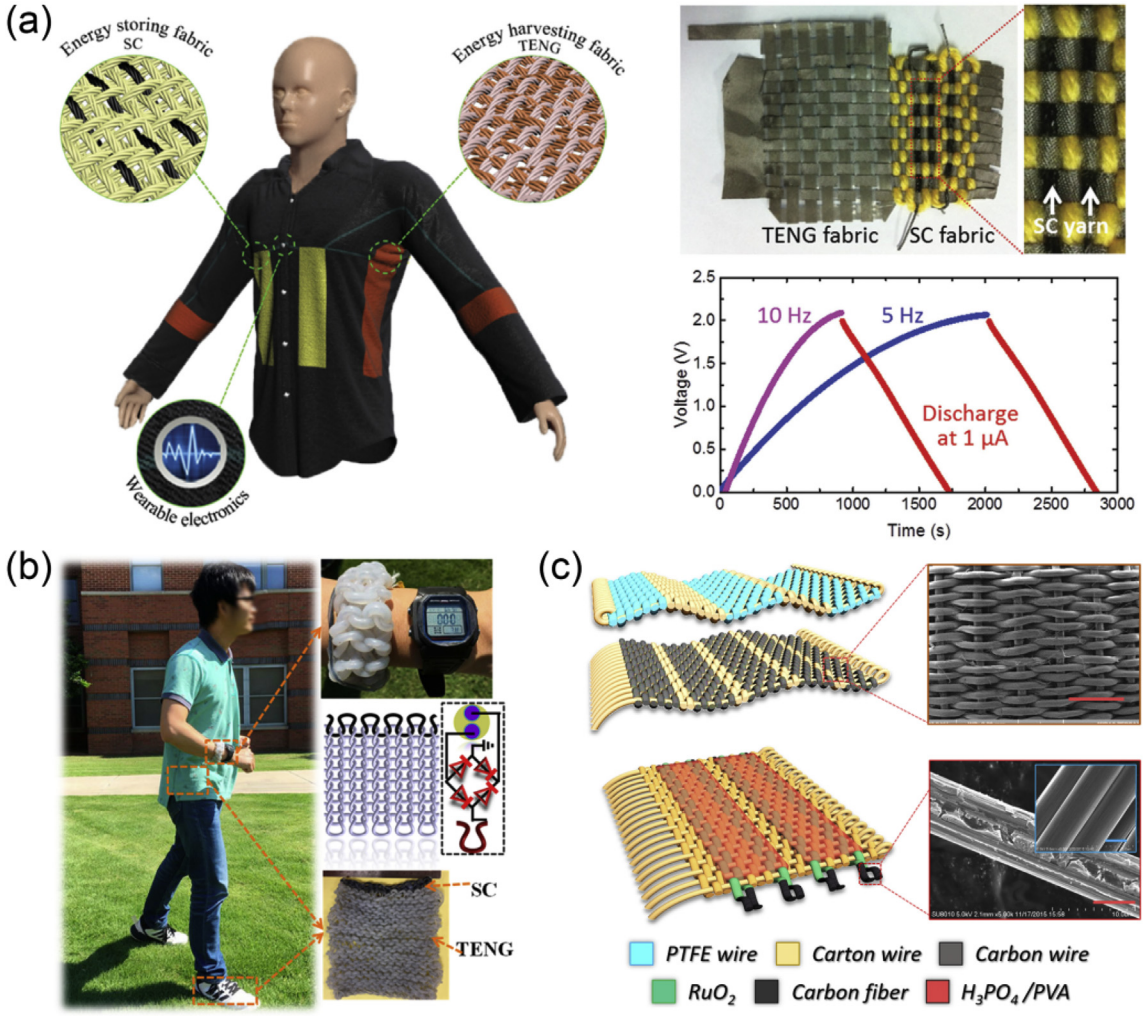


**Fig. 4.** Fiber/textile-based SCPSs with supercapacitors. (a) Schematic diagram, photograph and charge/discharge curves of an all-textile SCPS that integrates a textile TENG and fiber SCs. Reproduced with permission [54]. Copyright 2016, John Wiley and Sons. (b) Scheme, photograph and equivalent circuit of an all-yarn-based SCPS composed of fiber TENG and SC. Reproduced with permission [56]. Copyright 2017, American Chemical Society. (c) Structural design of the self-charging power textile that integrates a fabric TENG and woven SC. Reproduced with permission [58]. Copyright 2018, Elsevier.

capacitance (13 mF/cm), stable cycling stability (96% for 10 000 cycles), lightweight and excellent flexibility. By weaving the yarn SCs together with a TENG textile into a single cloth, a self-charging power textile has been demonstrated. The three-series SC can be charged by the TENG to 2.1 V in 913 s at 10 Hz, and then discharged at 1 μA for 808 s. Zhang et al. also developed a textile-based tailorable TENG, which can be applied for harvesting water energy [55]. By integrating with textile-based SCs, they realized an all textile-based SCPS.

Dong et al. presented a stretchable and washable all-yarn-based SCPS that is able to simultaneously harvest and store human motion energy for powering wearable electronics (Fig. 4b) [56]. The whole system was obtained by knitting a TENG fabric and solid-state yarn SCs together. Song et al. also developed a fabric-based SCPS by integrating a sing-electrode TENG with a flexible SC [57]. The SCPS can be directly woven among the cloth and utilized to convert the human mechanical energy into electrochemical energy. Utilizing traditional weaving craft, Chen et al. proposed a SCPS consisting of a fabric TENG and a woven SC, as shown in Fig. 4c [58]. This SCPS possesses the capability of harvesting daily activities form human beings, such as walking and running, and meanwhile storing the generated energy. Under the frequency of 1.5 Hz, it could be charged to about 1.5 V in 2400 s, and then used to power an electric watch. Zhao et al. fabricated a high performance supercapacitor based on metal-organic framework (MOF)-derived nanowire hybrid arrays on carbon nanotube (CNT) fibers [59]. By combining with a flexible TENG, a SCPS was developed for harvesting and storing energy simultaneously.

### 3.1.2. *Thin film-based SCPSs*

One of the greatest challenges for the development of flexible electronics is the requirement of thin, lightweight, and flexible energy harvesting and storage devices. Luo et al. reported a thin film-based SCPS by integrating a TENG and micro-supercapacitors into a single device [60]. The high integration of these two components was realized through the double-faced laser engraving of the polyimide (PI) thin film. Two sides of the laser-induced graphene electrodes were used separately for fabricating the TENG and micro-supercapacitors. The SCPS could be charged directly by mechanical motions and then used to power small electronics. Later, this team further presented a transparent and flexible thin-film based SCPS, as shown in Fig. 5a [61]. A grid-like indium tin oxide (ITO) film was utilized as electrode for the TENG. The solid-state SCs array based on interdigitated electrodes of 3D Au@$MnO_2$ were fabricated on the backside of the TENG. The whole device shows a high optical transmittance of 67.1% and is capable of harvesting mechanical energy form different kinds of finger motions, and storing the generated energy to drive mobile electronics. Under fast finger sliding, the SCPS could be charged to 2.5 V within 2094 s and discharged at 1 μA for 1060 s. In

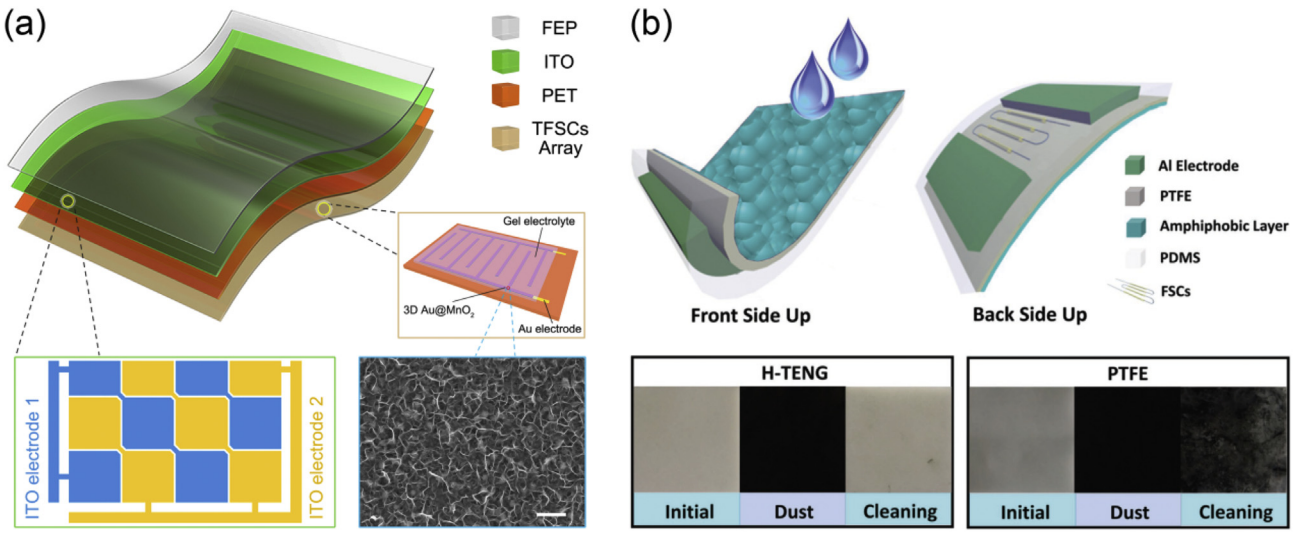


**Fig. 5.** Thin film-based SCPSs with supercapacitors. (a) Schematic illustration and SEM image of the transparent and flexible self-charging power film. Reproduced with permission [61]. Copyright 2016, American Chemical Society. (b) Schematic diagram and self-cleaning property of the SCPS consists of a hydraulic TENG and several embedded fiber SCs. Reproduced with permission [62]. Copyright 2018, John Wiley and Sons.

addition, it can be utilized as an intelligent sliding unlock system to identify personal characteristics. Zhang et al. fabricated a self-cleaning SCPS by embedding four fiber SCs in a hydraulic TENG, as shown in Fig. 5b [62]. An amphiphobic PTFE film was used as the triboelectric surface of the TENG, enabling the whole system self-cleaning. α-$Fe_2O_3$/reduced graphene oxide was utilized as the active material of the SC. A self-cleaning power raincoat based on the SCPS was demonstrated to be able to harvest and store energy from water drops, and continuously power a light-emitting diode (LED). Wang et al. developed an all-plastic-material based SCPS that using polypyrrole (PPy) as triboelectric electrode of the TENG and active material of the SC [63].

Paper itself has many advantages compared to plastic and glass substrates because of its lightweight, low cost, high flexibility, and environmental friendliness, making it a great candidate as the substrate to fabricate energy harvesting and storage devices for thin film electronics. Guo et al. reported an ultralight cut-paper-based SCPS that utilizes paper as the substrate for both the TENG and solid-state SC [64]. The SCPS has been demonstrated to be easily placed in a wallet and used as sustainable power source for driving a temperature sensor and an electric watch. Song et al. also fabricated a solid-state CNT/paper-based SC, achieving high areal capacitance of 18.3 mF/$cm^2$. With a rectifying circuit, the paper-based SC was then integrated with two wrinkled PDMS-based TENGs to form a sandwich-shaped SCPS [65]. Sun et al. proposed an ultralight SCPS, which consists of electrospun paper TENG as energy harvester and electrospun paper SC as energy storage [66]. The energy from human movement can be scavenged and stored by the SCPS, and then used to drive a calculator and an electronic watch.

### 3.1.3. *Package structure-based SCPSs*

The above SCPSs integrated TENGs and SCs into one device. However, the rectifying circuit is typically separate. Yi et al. developed a stretchable and waterproof SCPS for harvesting energy from diverse deformation [67]. As shown in Fig. 6a, the TENG, SCs, and rectifier were all sealed in a silicone rubber to form a package. Carbon black coated on the silicones were used as the electrodes for the stretchable TENG, and polypyrrole/carbon black film served as the active material of the SC. The energies of pressing, stretching, twisting, and bending can all be harvested and stored in the SC. Guo et al. also reported a shape-adaptive self-charging power package, as shown in Fig. 6b [68]. The stretchable SC with specific capacitance of ~1 mF/$cm^2$ was designed utilizing the kirigami architecture. By using silicone rubber and silver nanowire (Ag NW) as the triboelectric material and electrode, a shape-adaptive TENG was fabricated. Finally, these two parts were connected with a rectifier and then assembled by a silicone rubber sealing process. This power package was capable of harvesting hand flapping energy and sustainably powering an electric watch.

Wang et al. developed a bioinspired TENG with patterned interconnected cellular structures, utilizing silicone rubber as the encapsulation/triboelectric layer and physiological saline as the electrode [69]. The TENG could effectively harvest biomechanical energy, with a maximum instantaneous power density of ~11.6 W/$m^2$. By combining with a rectifier and a micro-supercapacitor sharing the same solution, the whole SCPS can be achieved, as shown in Fig. 6c. Jiang et al. developed a package structure-based SCPS that integrates a single electrode mode TENG with a MXene-based micro-supercapacitor into a monolithic device, as shown in Fig. 6d [70]. A rectifier was inserted into the package to convert the AC output of the TENG to DC output. The whole device can be worn on the forearm and charged by human motion for powering small electronic devices. Recently, Zhou et al. fabricated a stretchable TENG and SC based on folded carbon paper, as energy-harvesting and energy-storing device respectively [71]. A self-charging power package was then assembled by encapsulating these two components through a rectifier into silicone rubber. Li et al. fabricated a fully packaged keyboard-shaped TENG for harvesting the biomechanical energy from typing [72]. Then the TENG was further integrated with a PPy-based SC as a SCPS. Zhao et al. designed a SCPS by integrating an antibacterial $SiO_2$/Ag-doped polyamide (PA) membrane and two SCs in one device [73]. The PA membrane can vibrate between two electrodes of two SCs as a TENG for harvesting the wind energy.

## 3.2. *Integration with batteries for SCPSs*

Battery is superior to supercapacitor in energy density, which is the vital parameter for practical applications. Various kinds of batteries have become ubiquitous in their applications, including smartphones, tablets, and even battery-powered vehicles [74,75]. This section will focus on the SCPSs by integrating batteries with TENGs.

In 2013, Wang et al. first developed a flexible SCPS by integrating a TENG and a Lithium-ion battery (LIB) [76]. As shown in Fig. 7a, the integration of was realized through developing a flexible LIB on the top of an arch-shaped TENG structure. When mechanical motion is applied onto the SCPS, the TENG part can efficiently generate electricity, and the rectified energy can be stored in the LIB part. A new working mode, the "sustainable mode", was proposed. The SCPS in this mode can offer a

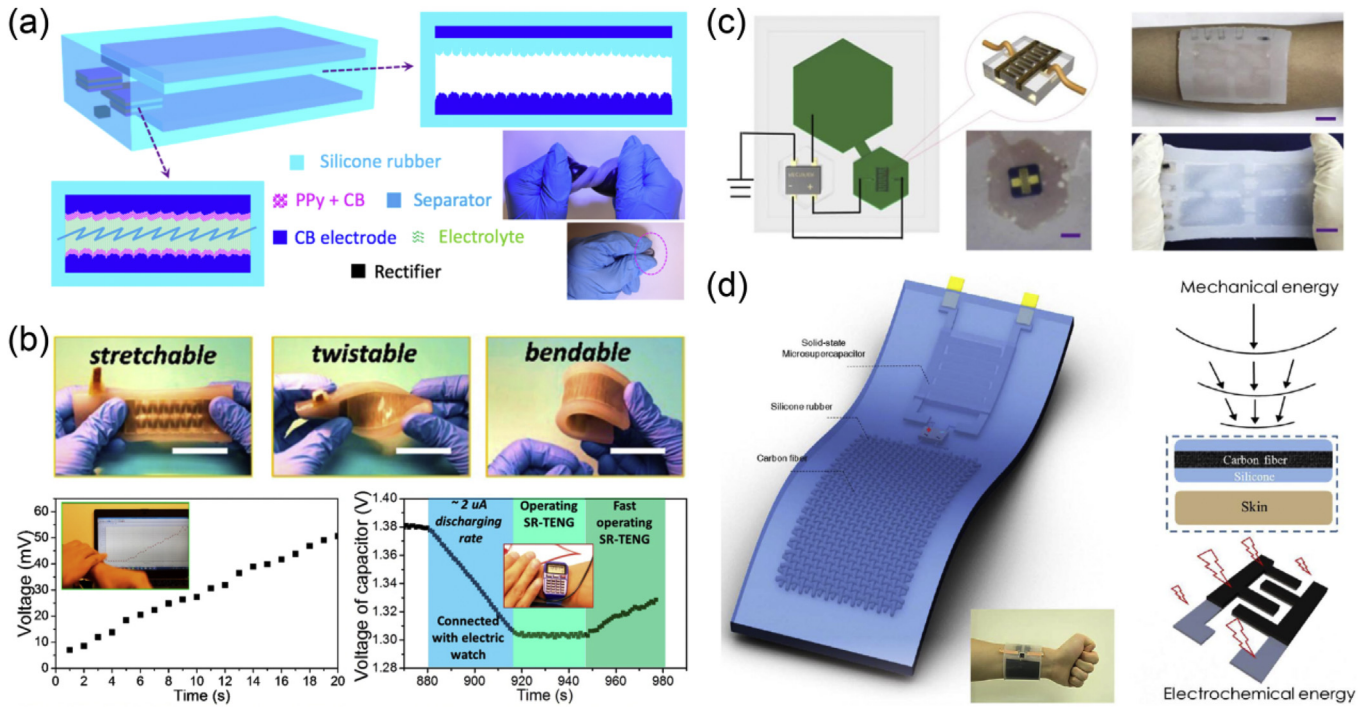


**Fig. 6.** Package structure-based SCPSs with supercapacitors. (a) Schematic diagram and photographs of a stretchable and water-proof self-charging power system. Reproduced with permission [67]. Copyright 2016, American Chemical Society. (b) Photographs and charge/discharge curves of the all-in one shape-adaptive self-charging power package. Reproduced with permission [68]. Copyright 2016, American Chemical Society. (c) Schematic illustration and photographs of the self-charging power package with a bioinspired stretchable TENG and a micro-supercapacitor sharing the same solution. Reproduced with permission [69]. Copyright 2017, Elsevier. (d) Schematic diagram and mechanism of self-charging power package with a TENG and a MXene-based micro-supercapacitor. Reproduced with permission [70]. Copyright 2018, Elsevier.

constant current of 2 μA at the voltage of 1.55 V for over 40 h (compared to 3.5 h for the LIB alone), and continuously power a UV sensor. Pu et al. reported a wearable SCPS by integrating a textile TENG as energy harvester and a flexible LIB belt as energy storage, as shown in Fig. 7b [77]. Soft polyester fabric was selected as the substrate, and consecutively coated with conductive Ni film (Ni-cloth) and insulating parylene film (parylene-cloth). The TENG was woven with Ni-cloth and parylene-cloth as longitude and latitude lines. Ni-coated textile was used as the current collector, and $LiFPO_4/Li_4Ti_5O_{12}$ was used as the cathode/anode of the LIB. Electric energy converted form human motions by the textile TENG was demonstrated to be capable of charging the LIB belt, which then was used to power a heartbeat meter with remote communication with a smart phone. Liu et al. developed a convoluted power device by hybridizing internally a solid LIB and a TENG, where the two different parts share common electrodes [78]. Under constant pressures, it is a solid LIB that can be used to store electric energy. Under periodical pressures, the device works as a TENG to convert mechanical energy into electricity and store in the solid LIB.

Except for human motions, the SCPSs can also harvest other kinds of mechanical energy. Gao et al. designed a SCPS that can simultaneously scavenge and store wind energy into chemical energy [79]. A flexible solid LIB was implanted into the middle dielectric film of an elasto-aerodynamics-driven TENG, so that the solid LIB and the TENG are hybridized as a single unit. Under the wind speed of 24.6 m/s, the solid LIB can be charged from 1.5 V to 3.6 V, where the corresponding storage capacity was about 0.035 μAh. Additionally, several other SCPSs for harvesting wind energy with similar structure were also reported [80, 81].

Besides, the selection of appropriate battery systems or electrode materials is of great importance for TENG-based SCPSs. High energy density, high cycling stability, safety, and easiness to integrate in SCPSs are of the prior concerns. Zhang et al. investigated the influences of the pulsed output of TENG on LIB polarization and dynamic behaviors [82]. It has been demonstrated that LIBs based on the phase transition reaction have higher energy efficiencies and enhanced coulombic efficiencies for being charged by TENGs. Furthermore, the pulse current has a positive effect on improving the cycling stability and decreasing the charge-transfer resistance. Several other studies have tried different battery systems, such as 3D Cu@Si@Cu-based LIB [83], $Li_3V_2(PO_4)_3$ or $LiFePO_4$-based LIB [84–87], Li-S battery [88], and solid-state sodium-ion battery [89]. However, the above-mentioned battery systems using in the SCPSs have the disadvantages of expensive, heavy and big size. Therefore, developing the next generation of batteries using Mg, Ca, or Al with lower cost, less weight and volume could also be a future development direction for the TENG-based SCPSs [90–92].

### 3.3. Hybrid SCPSs combining TENG with other energy harvesters

The energy produced by TENG itself is relatively small. In order to enhance the energy-harvesting capability, TENG and other energy-harvesting technologies can be combined together to form a hybrid energy-harvesting device, so that various types of environmental energy could be simultaneously scavenged. Therefore, hybrid SCPSs with hybrid energy harvesters may be an effective approach to meet the demands of larger electronics and thus widen their practical applications.

Wen et al. developed an all-fiber-based hybrid SCPS, as shown in Fig. 8a [93]. Outdoor sunshine and random body motion energies can be converted into electricity by using the dye-sensitized solar cells (DSSCs) and TENGs, and then further stored as chemical energy in SCs. Since each component of the SCPS is all-fiber-shaped structure, the hybridized system can be woven into individual fabrics to fabricate smart clothes for wearable electronics. Pu et al. also developed a hybrid energy harvesting system by integrating a grating-structured TENG fabric with fiber-shaped DSSCs [94]. As shown in Fig. 8b, these two parts were integrated together into a textile for simultaneously harvesting solar light and human motions. And the generated energy was then stored in a battery as power

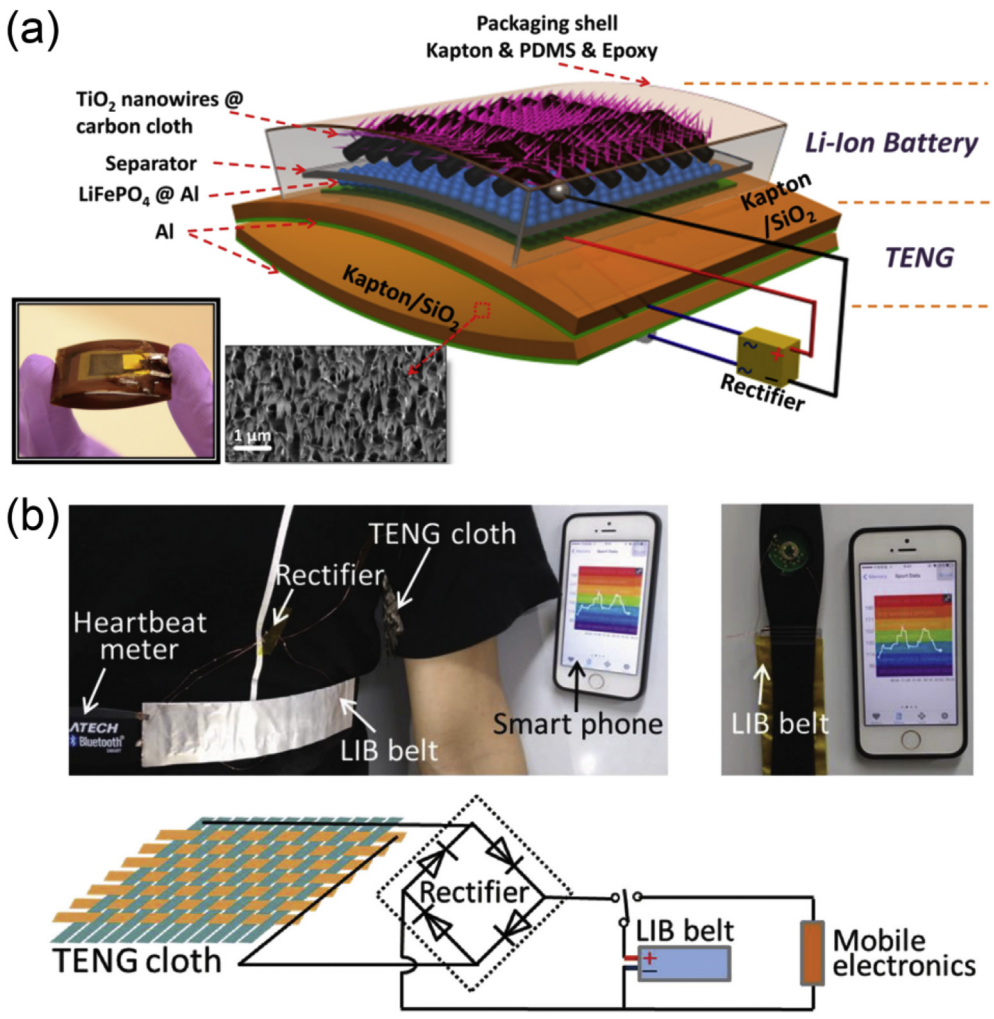


**Fig. 7.** SCPSs with batteries. (a) Schematic diagram and photograph of the flexible self-charging power unit integrates a TENG and a LIB. Reproduced with permission [76]. Copyright 2013, American Chemical Society. (b) Photographs and equivalent circuit of a SCPS that consists of a textile TENG and a flexible LIB belt. Reproduced with permission [77]. Copyright 2015, John Wiley and Sons.

supply to operate wearable electronics.

Qin at al. developed a smart hybrid SCPS by integrating a hybrid nanogenerator with an electrochromic SCs array [95]. As shown in Fig. 8c, the hybrid nanogenerator was composed of a piezoelectric nanogenerator and a TENG sharing the same silver electrode, with output voltage and current of 150 V and 20 μA. Hydrothermal reaction was employed to achieve Ag nanowires/NiO as the active materials of the electrochromic SC, which possess high capacitance of 3.47 mF/cm$^2$. During the self-charging process, the charging states can be estimated according to the color change with naked eyes. What's more, TENG has been integrated with electromagnetic generators for wide-frequency mechanical energies harvesting [96,97]. TENG has also been reported to integrate with thermoelectric generators, or pyroelectric nanogenerators, so that mechanical energy and thermal energy can be simultaneously harvested [98–101].

## 4. Optimization strategies for energy transfer and storage

To be applied for practical applications, the performance of the TENG-based SCPSs needs to be improved. Energy transfer efficiency from TENG to energy storage unit is the pivotal parameter of the SCPSs. Besides, self-discharge of energy storage devices also has a significant influence on the charging efficiency of the SCPSs. In the following part, we will systematically summarize the optimization strategies for energy transfer and storage based on different components. For each of component, design strategies and their impact on improving the performance of SCPSs will be discussed.

### 4.1. Power management

TENG usually has the output characteristics of high voltage, low current/charge transfer, and large internal impedance. These characteristics lead to low energy transfer efficiency in either powering electronics or charging a supercapacitor/battery, which usually have relatively low impedance [29,102,103]. To store the energy harvested by the TENG, above-mentioned SCPSs are traditionally realized by a direct connection between TENG and energy storage unit through a rectifier. However, this may lead to low energy-storage efficiency due to the huge impedance mismatch between these two components. Therefore, to address this problem, proper power management circuits are required to maximize the efficiency for practical applications.

Zhu et al. first introduced transformer into the radial-arrayed rotary TENG for tremendously reducing the output voltage and boosting the output current, which substantially reduces the impedance of the TENG [104]. Through a power management circuit (consisted of a transformer, a rectifier, a voltage regulator and capacitors), the TENG-based power--supplying system can provide a continuous direct-current power for driving commercial electronics, such as LEDs, alarms, digital clocks, and cellphones. However, the transformer only has a satisfied performance with matched high-frequency, otherwise a huge power loss would occur

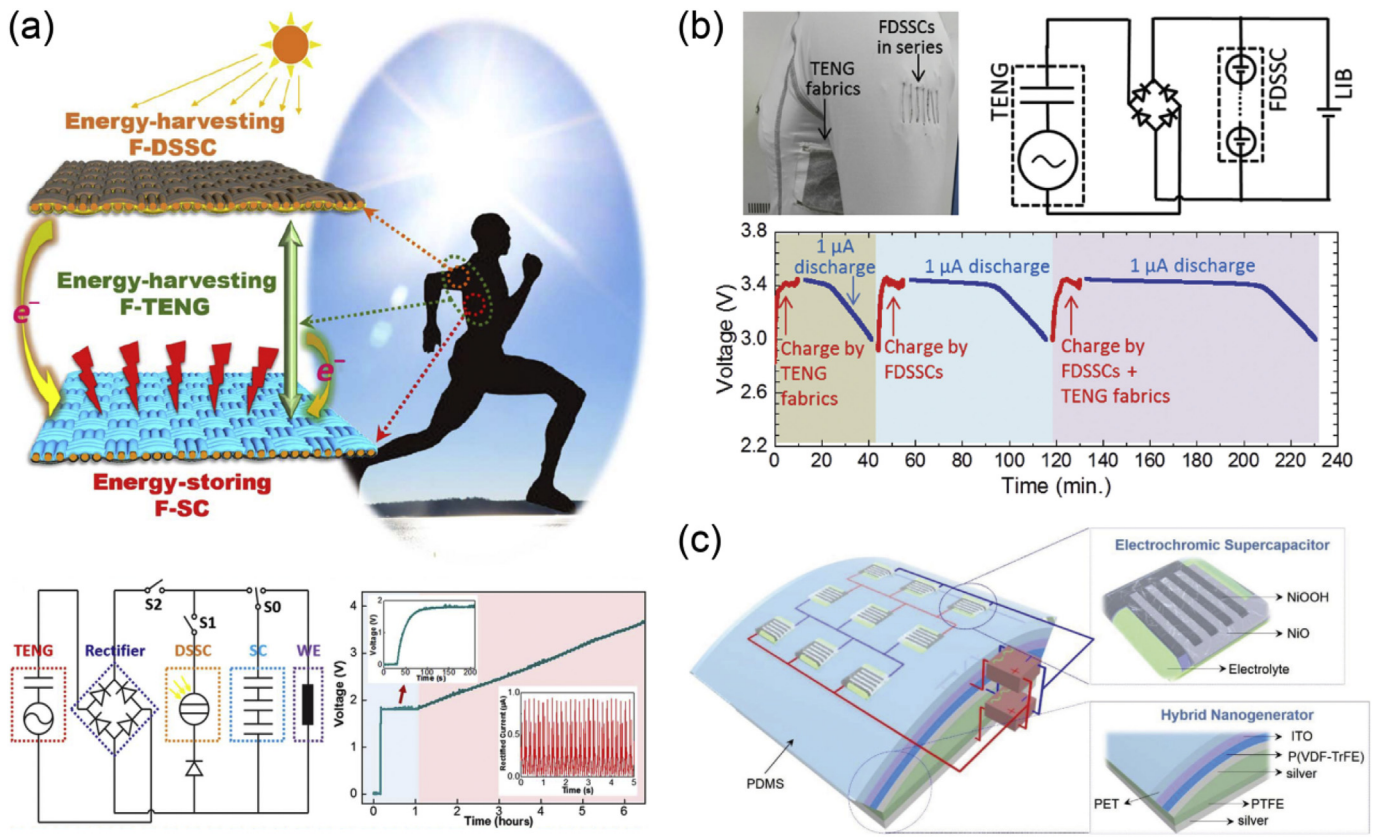


**Fig. 8.** Hybrid SCPSs integrating TENG with other energy harvesters. (a) Schematic diagram, equivalent circuit and charging curve of an all-fiber-based hybrid SCPS, which is made of a fiber-shaped TENG, a fiber-shaped DSSC and a fiber-shaped SC. Reproduced with permission [93]. Copyright 2016, American Association for the Advancement of Science. (b) Photograph, equivalent circuit and charge/discharge curve of a hybrid SCPS consists of a TENG fabric, fiber-shaped DSSCs and a LIB. Reproduced with permission [94]. Copyright 2016, John Wiley and Sons. (c) Schematic illustration of the flexible self-charging electrochromic power package that integrates a hybrid piezo/triboelectric nanogenerator and electrochromic micro-supercapacitors. Reproduced with permission [95]. Copyright 2018, John Wiley and Sons.

[105]. Therefore, Niu et al. designed a two-stage power management circuit for the SCPS, which is universally applicable to all types of TENGs with pulsed outputs [106]. As shown in Fig. 9a, this universal circuit consists of a logically-controlled switching system and coupled inductors. With such a power management system, the SCPS can achieve 60% AC-to-DC efficiency and provide a continuous DC electricity of 1.044 mW (7.34 W/m$^3$) for continuously driving various conventional electronics, such as such as pedometers, thermometers, scientific calculators, wearable watches, and radio-frequency wireless transmitters.

Xi et al. also proposed a universal power management strategy for TENG by maximizing energy transfer, DC buck conversion, and self-management mechanism [107]. This management circuit is shown in Fig. 9b. At a low frequency of 1 Hz with the power management module, the matched impedance of the TENG can be reduced from 35 to 1 MΩ at 80% efficiency, and the stored energy in charging a 1 mF capacitor can be improved by 128 times. In addition, with universality and high efficiency for different modes TENG, similar power management strategy consisting of inductors was also reported [108].

Different from the above inductor-based management circuits, Tang et al. focused on inductor-free circuit for power management of the TENG [109]. As shown in Fig. 9c, the circuit is based on an array of self-connection-switching capacitors. The capacitors are first serial-connected in the charging operation and then connected in parallel for power output. It can lower the output voltage and improve the output current/charges with minimized energy loss. Besides, similar management circuit based on capacitors from serial to parallel connection was also reported [110].

Zi et al. focused on the switch-based circuit for power management of the TENG [111]. With the aid of the V-Q plot of the TENG, they designed a rational charging cycle by using a motion-triggered switch to modulate the charge flow in the SCPS, as shown in Fig. 9d. Compared with the direct charging cycle, the designed cycle can enhance the charging rate and improve the energy-storage efficiency (up to 50%). Though using a switch is effective for managing and improving the output performances of the TENG, its elaborate design will make the system more complicated and expensive. Cheng and Yang et al. developed a self-powered air discharge switch for the TENG [112,113]. As shown in Fig. 9e, the switch's on/off state is controlled by the voltage of the TENG itself. When the load resistance is lower than 2 MΩ, the output energy is increased by 31 times in comparison with the TENG without a switch [112]. Ghaffarinejad et al. further introduced a new management circuit based on Bennet's charge doubler, which is inductor-less with no need for switches or external control [114]. Future efforts are still needed to improve the efficiency of the management circuit and also reduce its size. To be applied in flexible and wearable electronics, every component of the power management circuit should preferably have good flexibility in the future. Zhang et al. reported the flexible and transparent high-voltage diodes that feature high rectification ratio and high breakdown voltage, demonstrating well compatibility and integration possibility with TENG [115].

### 4.2. *Direct-current TENGs for SCPSs*

Because of the AC output characteristic of the TENG, the generated energy by the TENG cannot be stored in energy storage devices unless a rectifying circuit is used. Besides, the rectifier is a dissipative unit, and its

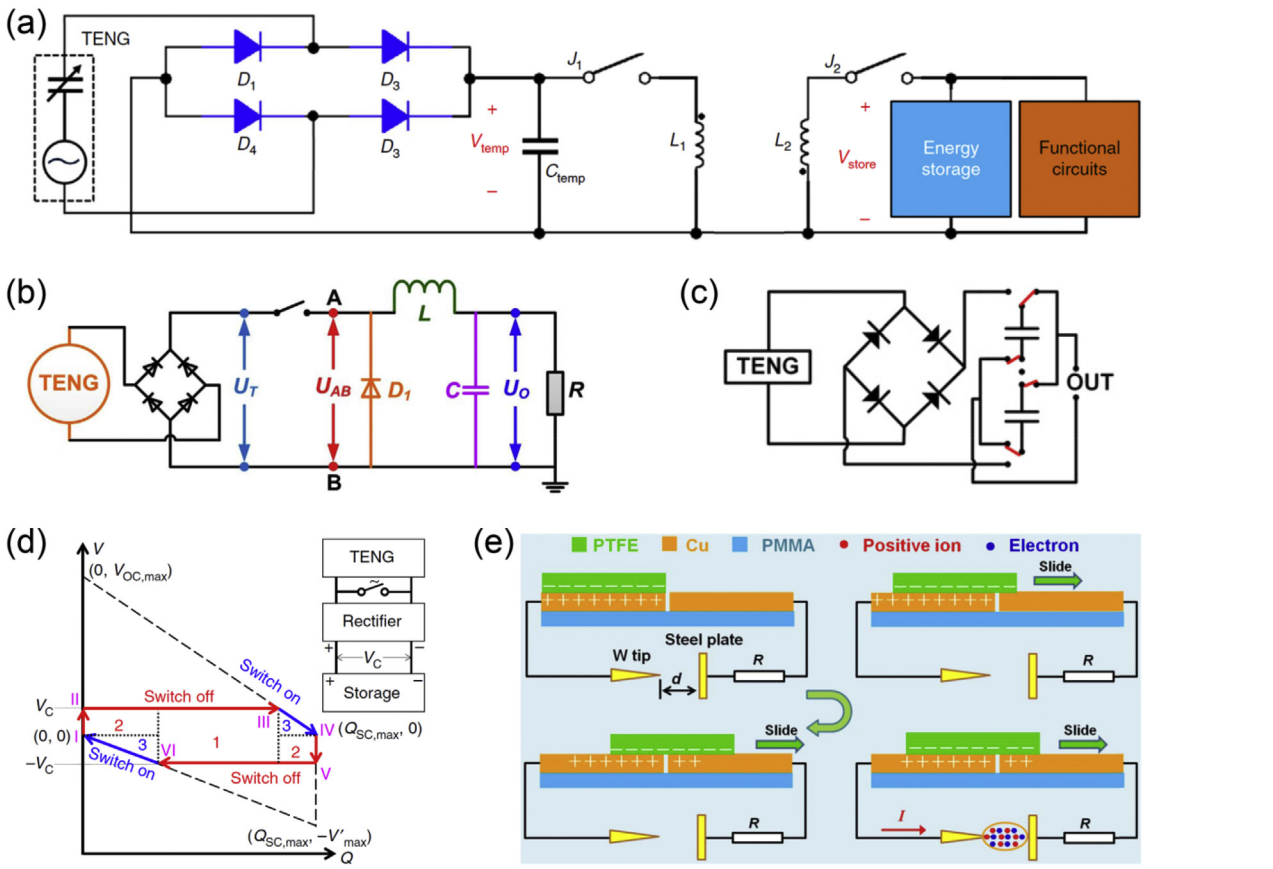


**Fig. 9.** Power management circuits for TENG-based SCPSs. (a) A universal management circuit based on logically-controlled switches and coupled inductors. Reproduced with permission [106]. Copyright 2015, Nature Publishing Group. (b) AC-DC buck conversion of a universal management circuit. Reproduced with permission [107]. Copyright 2017, Elsevier. (c) A management circuit for TENG with self-connection-switching capacitors. Reproduced with permission [109]. Copyright 2014, IOP Publishing. (d) A rationally designed charging cycle for maximizing energy-storage efficiency by adding a motion-triggered switch. Reproduced with permission [111]. Copyright 2016, Nature Publishing Group. (e) A strategy with self-powered air discharging switch for improving the output performances of TENG. Reproduced with permission [112]. Copyright 2018, Elsevier.

power consumption is appreciable if the output of TENG is small. Designing DC-TENG would be a solution to store the scavenged mechanical energy without using a rectifier, which could also greatly improve the convenience of the self-charging power system.

In 2014, Yang reported a wheel-belt structured DC-TENG, as shown in Fig. 10a [116]. The working mechanism of this DC-TENG is based on the continuously accumulated triboelectric charges on the two wheels, which will induce a corona discharge to drive the flow of electrons through external load. This DC-TENG has been demonstrated to directly drive 1020 LEDs and charge a capacitor without using a rectifier. Zhang et al. also developed a DC-TENG that consists of two disks and two pairs of flexible electric brushes, as shown in Fig. 10b [117]. During the rotation, flexible electric brushes automatically switched between two electrodes, so the current can be reversed in the second half cycle and a direct current is generated. Under a rotation speed of 750 rpm, the TENG can deliver a maximum power density of 25 $mW/m^2$. The structure of these DC-TENGs is relatively complicated, which is not suitable for versatile application scenes ranging from large-scale TENG arrays to flexible electronics. By utilizing the air breakdown induced ionized air channel, Luo et al. designed a novel DC-TENG for harvesting contact-separation mechanical energy with simple structure [118]. The working mechanism of this DC-TENG is shown in Fig. 10c. The DC-TENG has a maximum peak output power of ~1.83 mW, and the produced electric energy could be stored without using a rectifier. Owning to its simplicity in structure, this mechanism was further applied to fabricate a flexible DC-TENG, suggesting its potential application in directly building flexible SCPS for flexible electronics.

### 4.3. Suppressing self-discharge of energy storage devices

Self-discharge has been an inevitable issue that causes loss of stored energy for energy storage devices, especially supercapacitor [119–121]. When using small power energy harvester, such as TENG, to charge the storage devices, it often takes a relatively long time to finish the charging process. In this situation, self-discharge would severely limit the applications of energy storage devices for collecting wasted small energy from the ambient environment. Therefore, suppressing self-discharge of the energy storage devices is of great importance to the TENG-based SCPSs.

Xia et al. recently introduced a liquid crystal 4-n-pentyl-4′-cyanobiphenyl (5CB) in the electrolyte to reduce the self-discharge of supercapacitor, as shown in Fig. 11 [122]. When the supercapacitor was charged, the electric field induced alignment of 5CB molecules can cause enhanced fluid viscosity via the electrorheological effect, which impeding the diffusion of ions and redox species. Compared with the blank SC, the leakage current of the 5CB SC could be drastically reduced by 82%. It has been demonstrated the 5CB SC with low self-discharge rate can effectively improve the charging efficiency from TENG, and extend the period of continuous power supply for driving small electronics.

## 5. Summary and perspective

In this review, the recent advances of TENG-based self-charging power systems are systematically summarized. In particular, hybrid SCPSs that could simultaneously harvest multiple environmental

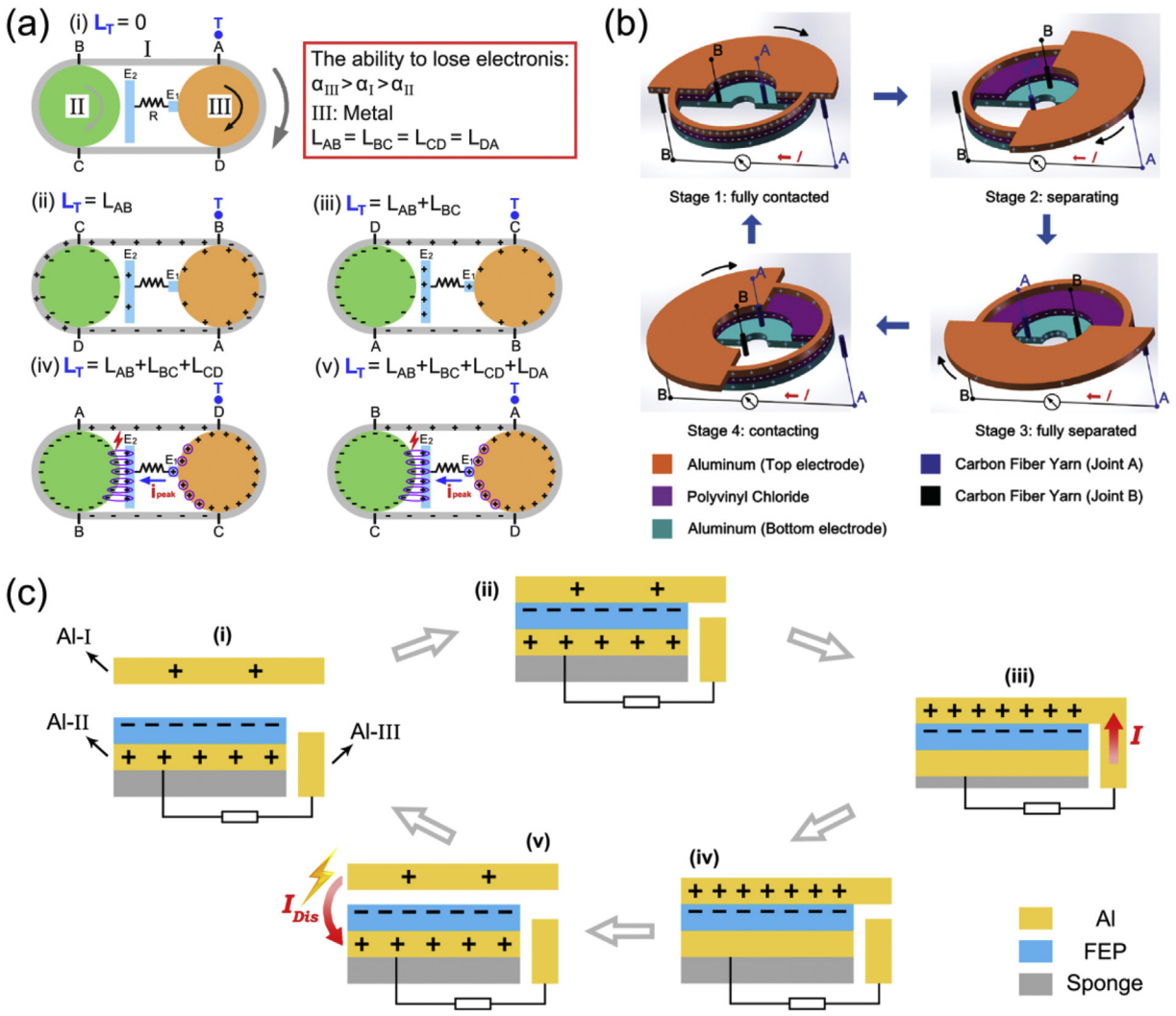


**Fig. 10.** Working mechanisms of DC-TENGs for SCPSs. (a) Working mechanism of the wheel-belt structured DC-TENG. Reproduced with permission [116]. Copyright 2014, John Wiley and Sons. (b) Working mechanism of the rotating disk based DC-TENG. Reproduced with permission [117]. Copyright 2014, John Wiley and Sons. (c) Working mechanism of the DC-TENG achieved through the ionized air channel caused by air breakdown. Reproduced with permission [118]. Copyright 2018, John Wiley and Sons.

energies have been attracting increasing attention. Several optimization strategies for improving the performance of the SCPSs are also discussed. These research studies promote the field of mechanical energy harvesting and storage for building up self-powered systems, in which multifunctional electronic devices can be sustainably powered up by the TENG-based SCPSs through collecting environmental mechanical energies. Through the continuous research on the TENG as well as other related technologies, we believe that the TENG-based SCPSs will have a drastic impact and could be applied for practical applications in the near future.

Even though significant progress has been made to date, future works are still required for integrating TENG with energy storage units. Future researches on the following aspects should be carried out.

(1) The performances of TENG and energy storage units in the SCPSs are both typically low. Most of the reported research works about TENG-based SCPSs focus on the conceptual demonstration. To pave the way for practical application, more future works in materials' optimization are urgently needed to improve the performances of each integrating units, including output power, energy density, stability, and so on.
(2) The enhancement of the system efficiency is the most essential issue. In general, the low energy transfer efficiency from the harvesting to storage units is due to the impedance mismatch between TENGs and energy storage devices. On the one hand, various kinds of power management circuits have been demonstrated to lower the impedance of the TENG. The development of more effective management circuits is significant. On the other hand, the importance of choosing the appropriate supercapacitor/battery systems (including electrode materials, electrolytes, separators, current collectors, and so on) should not be underestimated. The impedances and capacities of energy storage devices need to match the pulsed output of TENG.
(3) Further studies in innovative structural designs are also needed to expand the application range in mechanical energy harvesting. It would be preferable if multiple kinds of mechanical energy or even other sources of environmental energy such as thermal and solar energy could be harvested simultaneously. Meanwhile, optimization of system integration in the SCPSs will make them more feasible for scale-up fabrication and to meet the demands of practical applications.
(4) Considering the relative low output power of the TENGs, self-discharge, especially of supercapacitors, must be largely suppressed, which could dramatically reduce the performance of the TENG-based SCPSs. Research efforts should be dedicated to

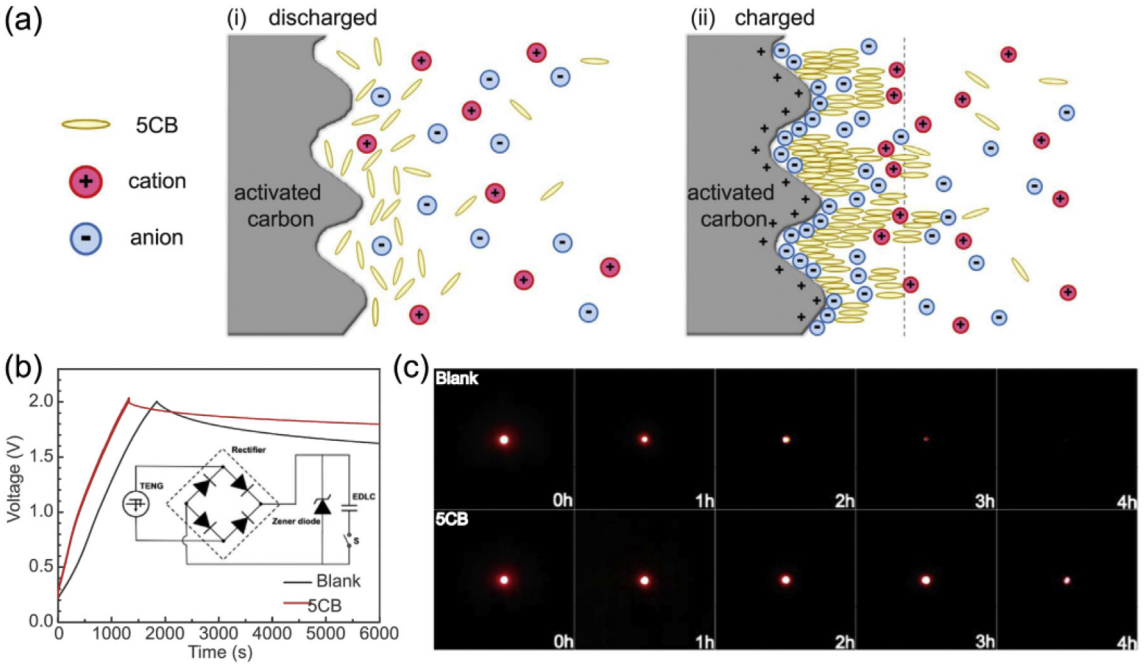


**Fig. 11.** Suppressing self-discharge of SCs via electrorheological effect of liquid crystals. (a) The electrode-electrolyte interface of a supercapacitor with 5CB added in the electrolyte. (b) Charge/self-discharge curves of the SCs with and without 5CB in the electrolyte. (c) LED lights powered by blank and 5CB SCs, before lighting the LEDs, EDLCs were first charged to 2 V and subjected to self-discharge of 0, 1, 2, 3 and 4 h. Reproduced with permission [122]. Copyright 2018, Elsevier.

solving the leakage problem of energy storage devices in the future.

(5) As for Li ion batteries, one must study the efficiency for energy storage under pulsed TENG input instead of the conventional DC input. A systematic study on the ion diffusion and transport under the pulsed driving force across the isolating membrane is important for storing TENG generated power [86].

(6) Based on Maxwell's displacement current, using TENG for wireless energy delivery is an interesting research field [123]. The development of TENG-based SCPSs with wireless charging capability is attractive and important for medical security, wearable electronics, and distributed sensing [124].

(7) Developing TENG-based SCPSs with more superior flexibility is also a meaningful and promising research direction for next-generation portable, wearable smart electronics.

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