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Review

From Triboelectric Nanogenerator to Uninterrupted Power Supply System: The Key Role of Electrochemical Batteries and Supercapacitors

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Abstract: Currently, significant advances have been made in the field of high-performance energy storage technologies, such as Li-ion batteries and supercapacitors. However, the limited lifespans, as well as the frequent charging or replacement requirements, pose a set of challenges for their application in the Internet of things (IoTs), because the full power of the IoTs can only be realized by the sustainable operation of physical objects, especially embedded sensors, for the purpose of connecting and exchanging data with other devices and systems continually in real-time. A viable option for achieving the sustainability of the IoTs may be the combination of renewable energy harvesting technologies such as triboelectric nanogenerators (TENGs) with electrochemical energy storage technologies, where TENGs can harvest mechanical energies from ambient environments and transform them into electricity for charging electrochemical batteries and supercapacitors (SCs) conveniently, thus developing a new type of TENG-based uninterrupted power supply (TENG-UPS). In this review, we begin from a brief description of the operating mode of TENG and the integration strategy of TENG-UPS. The latest advances in the TENG-UPS are then thoroughly discussed from the perspective of structural design and system integration. Cutting edge developments of the as-designed self-powered sensing systems are then concisely illustrated to disclose the application potential in the IoTs. The main obstacles and future prospects for developing TENG-UPS-based intelligent systems are also highlighted in terms of design and manufacture at the conclusion. We expect this review will appropriately shine a light on the understanding of the key role of electrochemical energy storage devices in the development of TENG-based energy harvesting technology as well as the self-powered intelligent systems.

Keywords: uninterrupted power supply; triboelectric nanogenerator; batteries; supercapacitors; energy harvesting

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1. Introduction

Today, the magic of the Internet of things (IoTs) is moving beyond visibility and directional reporting to promote a more sustainable future for the world by connecting people, processes, and objects seamlessly [1–4]. The IoTs transforms collected data into descriptive insights and directional workflows, thus changing the world we live in, from optimizing sensor resources in the manufacturing industry, crop growth, and water resources survey in the agricultural industry, to the intelligent physiological monitoring in the medical and health care industry [5–9].

On the other hand, most IoT intelligent devices are not directly connected to the power network themselves and mainly rely on batteries to obtain power for continuous operation [10,11]. However, in the current trend of miniaturization, even if smart devices have a very low energy consumption level, the limited capacity built-in battery is not enough to support long-term operation [12–14]. Therefore, sufficient power for intelligent devices is the key to achieving long-term operation and fulfilling the full power of the IoTs [15,16]. This problem may be solved either by increasing the capacity of electrochemical power sources or by combining them with renewable energy harvesting devices, considering there will be no drastic change in energy consumption of the equipment [17–19]. Taking into account the significant annoyance and high maintenance costs for portable electronic gadgets that may be caused by frequent replacement or recharging, integrating various renewable energy collection devices with storage devices through circuit management systems to create a self-charging uninterrupted power source may be more reasonable in realizing the sustainable operation of the IoTs [20–22].

Triboelectric nanogenerator (TENG) was invented in 2012 and is undergoing fast progress in tandem with the notion of switching to cleaner forms of energy, such as thermal, mechanical, biochemical, and solar, as well as any other form of environmental energies [23–25]. Based on the coupled effects of contact electrification and electrostatic induction, TENG represents a significant technological advance in converting various mechanical energies present in the ambient environment into electrical energy [26]. Because of its benefits for environmental friendliness, low cost, sound efficiency, and a wide range of material alternatives, it has been extensively employed in several varieties of self-powered electronic gadgets, such as wireless sensors [27–29], implanted medical equipment [30–34], chemical sensors [35,36], electrochemical processes [35,37,38], household appliances [6,7], security detection systems [39,40], human-machine interfaces (HMIs) [41–43], and artificial intelligence (AI) [3,44].

Up to now, the performance of TENG has been enhanced in various ways, including by the alteration of materials, the construction of micro and nanostructures, and the creation of novel device architectures [45,46]. However, the mechanical energy that comes from the environment and the body itself is generally unstable and irregular. As a result, TENG always outputs pulse current with corresponding random amplitude and frequency. Coupled with the ultra-high voltage and the intrinsic high impedance, it is rather difficult for TENG to be utilized as a direct power source [39,47–49].

Fortunately, with the help of the power management circuit, electrochemical energy storage devices, such as Li-ion batteries and supercapacitors, are capable of storing the output of TENG and supplying electronic equipment with steady and consistent direct current (DC) power [50–52]. The merging of TENG with energy storage technology (SC or battery) leads to the invention of TENG-based uninterrupted power supply (TENG-UPS), which effectively compensates for their energy consumption and extends the working duration of electronic equipment.

Here, this review concentrates on how TENG and energy storage units have integrated to advance TENG-UPS recently, as schematically shown in Figure 1. We first quickly go through the TENG and TENG-UPS operating theories. The most recent advancement in uninterrupted power supply based on the combination of electrochemical batteries and supercapacitors with TENG is then succinctly explained. At the end of this review, the challenges and opportunities that TENG-based TENG-UPS will face in the future are also outlined and discussed.

Figure 1. TENG-based uninterrupted power supply (TENG-UPS).

2. TENG and Uninterrupted Power Supply Systems

2.1. Working Principle of TENG

The connection of the triboelectric effect and the electrostatic induction effect may be used to explain how the TENG produces electric energy. When the device is affected by an external force, two insulating polymers are in close contact. Due to their different positions in the friction sequence, the surfaces they contact will generate static charges of equal size and opposite polarity. Electrons will then begin to migrate back and forth between the two electrodes attached to the backs of the two materials as soon as the two surfaces are mechanically separated [53,54]. TENG's performance has consistently increased since it was created in 2012. There are currently four operating modes for this device: vertical contact separation type, sliding type, single electrode type, and independent type. Vertical contact separation type and sliding type are the most fundamental; the latter two are expansions of the former two forms [55,56].

The primary use of a TENG is to generate electricity for small electronic devices or to collect energy from the environment and use it to generate power for larger electronic devices [57,58]. The TENG sensor can eventually gather a lot of energy from the environment, such as vibration energy produced by people walking, mechanical vibration energy, water energy, and so on. This energy can be captured using the four operating modes of the TENG mentioned above or by combining them. TENG also has promising future application opportunities in the area of self-powered active sensing [59,60].

2.2. Working Principle of TENG-UPS

Directly driving the majority of electrical equipment is challenging because of TENG's erratic alternating current (AC) output characteristics. To offer a controllable and adjustable continuous output for electronic equipment, the alternating current produced by TENG is transformed into a direct current after being coupled with the rectifier bridge and stored in the electrochemical energy storage unit (such as supercapacitors and batteries) [61–63]. The battery or supercapacitor will be able to store more energy as the TENG-UPS is regularly squeezed by an external force. The TENG-UPS may be concurrently charged and drained when linked to an external load. TENG-UPS is a steady direct current (DC) power source because it can transform erratic and unreliable AC output into consistent DC output.

3. TENG-UPS

The efficient collection of lost mechanical energy to create sustainable power supply may be accomplished by integrating TENG and energy storage equipment (supercapacitor or battery) into the uninterrupted power supply system. This section will primarily introduce the most recent developments in TENG-based TENG-UPS.

3.1. Integration with Supercapacitors for the Construction of TENG-UPSs

After more than 20 years of intensive development, supercapacitors are now a possible energy storage technology [51,64,65]. In terms of mobility, safety, operational temperature range, power density, and lifecycle, supercapacitors outperform batteries. They offer a lot of promise as a choice for portable electrical devices because of these benefits. SCs and TENG can be used to create a TENG-UPS that is sustainable and harvests mechanical energy from daily activities [66,67]. The main topic of discussion in this part will be the development of SC and TENG-integrated TENG-UPS.

3.1.1. Flexible/Wearable TENG-UPSs via Integration of TENG with SC

With the development of personal electronic products, the pursuit of wear resistance becomes more and more important. Smart electronic textiles cannot use traditional energy storage technology because they are not wearable and have low power. On the other hand, because of its softness, extensibility, and even washability, TENG in fibers, yarns, woven, or knitted textiles is often reported [68,69]. Therefore, it is essential to develop a wearable TENG-UPS that is functional to open the door for wearable electronic items. By combining a TENG with SC of heterostructure air-placed paper, Yang et al., developed a paper-based UPS that was permeable and resistant to wear (Figure 2). For P-TENG and P-SCS, coated CNT-WPU is employed as a current collector and paper-based electrode, respectively (Figure 2a). The P-TENG triboelectric couple uses a highly porous and mechanically solid air-laid paper with a felt surface and thread surface that not only exhibits exceptional flexibility and cloth-like permeability (333 mm s^{-1}), but also good wet stability (85% voltage retention after four soaking cycles) (Figure 2b). Additionally, P-SCS constructed from a gel electrolyte and paper-based electrode may efficiently store triboelectricity [70]. Liu et al., developed a TENG-UPS fabric in 2019 that consists of an energy storage yarn-type asymmetric SC and a complete yarn-based energy harvesting TENG. Both an electrode in TENG and a one-dimensional current collector in Y-ASC were created from a common polyester yarn that had a conformal Ni/Cu coating (Figure 2d). The positive and negative electrodes of the yarn SC are coated with Ni-Co bimetallic hydroxide (NiCoBOH), and the negative electrode has a hydrothermally self-assembled RGO/CNT coating. High area and power densities, outstanding cycle performance, and adaptability are all characteristics of solid-state Y-ASC (Figure 2d–g). TENG yarns may be woven into regular textiles with the necessary fashion design to harness a high yield of energy from daily human activity (60 V open circuit voltage and 3 A short circuit current). The electronic watch may be powered by the built-in uninterrupted power supply cloth without extra battery charge [71].

To simultaneously harvest mechanical energy and store energy, Yang et al., used an exterior one-dimensional TENG and an SC to create a flexible coaxial fiber. As shown in Figure 2h, carbon fiber bundles are utilized in such coaxial fibers as active and electrode materials for the SC and as electrode materials for the TENG. In addition to serving as the triboelectric substance of TENG, silicone rubber also functions as a diaphragm between the SC and TENG. The energy storage device (specific capacitance is 31.25 mF g^{-1}) exhibits good capacitance performance and stability. Fabric that serves as the power source for wearable electronic devices may easily be woven using coaxial fiber as the foundation. By repeatedly pressing the external TENG, the internal SC can be charged, and then the electronic devices can be driven (Figure 2j–m) [72]. A very stretchy and machine-washable complete yarn uninterrupted power supply textile (UPST) was demonstrated by Kai et al. It can simultaneously gather biomechanical energy and store it by fusing a TENG and SC into a fabric (Figure 2n). The yarn is created by covering three-layer twisted stainless steel/polyester fiber yarn with silicone rubber. Carbon nanofibers (CNF) and poly (3,4-ethyldioxythiophene)-poly(styrene sulfonate) (PEDOT: PSS) are dip coated on bundles of carbon fiber (CF) to create the all-solid symmetric yarn SC, which is created constantly. Knitted TENG fabric has a maximum instantaneous peak power density of 85 mW m^{-2}, which is sufficient to power at least 124 light-emitting diodes (LED) (Figure 2p–q). It demonstrates that the suggested design is a viable, long-term power source for worn electronic devices [73].

Chen and colleagues used the conventional weaving method to alternately braid wires to create an integrated self-powering/self-charging power textile. It has been demonstrated that the TENG-UPS can generate energy from routine everyday activities (such as walking and running) and provide power for wearable electronic devices (Figure 3a–c) [74]. An inflexible, unpleasant, and hostile rectifier bridge is required by the majority of textile TENG utilized for energy collecting to convert AC to DC to power electronic devices. This severely restricts both its potential for use and for further study. Thus, using DC fabric TENG and symmetric fiber SCs, Chen et al., developed an uninterrupted power supply textile. DC-TENG has a plain weave structure and is constructed of PA non-conductive fibers that are separated by PA non-conductive fibers used as warp yarns and PA conductive fibers used as weft yarns. A total of 416 serially linked LEDs may be lit up with ease via F-TENG. Additionally, a calculator and water pressure gauge powered by a solid-state yarn SC made of carbon fiber and poly (3,4-ethyldioxythiophene): sodium polystyrene sulfonate (PEDOT: PSS) was developed (Figure 3d–f) [75]. To continuously harvest and store biological movement energy, Mao et al., reported a whole yarn type uninterruptible power supply system connecting TENG and SC. As shown in Figure 3g–k, PTFE fibers were wound around carbon fibers at PDMS/MnO_2 NW elastic fiber to create yarn fiber TENG. Fiber-TENG can easily light up 200 LEDs linked in a series, generate a maximum output voltage of around 380 V, and use diverse biological motion energy sources. TENG also weaves the asymmetrical all-solid-state yarn SC. Its high bulk energy density and outstanding cycle stability make it a highly effective energy storage device [76].

For energy storage and harvesting, Han et al., developed a multipurpose coaxial energy fiber. The energy fiber is made up of an SC, a pressure sensor with coaxial geometry, and an all-fiber form TENG (Figure 4a). The outside sheath is made of fiber TENG operating in single electrode mode, while the core is made of fibrous SC, which stores energy using a green activation method. A self-powering pressure sensor comprises the inner layer (covered with Ag) and the outside friction layer. Each energy source's electrical performance is extensively investigated. The fiber SC has excellent cycle stability (96.6% retention), a decent charge/discharge rate capability, and a length-specific capacitance density of 13.42 mF cm^{-1}. At its peak, a fiber TENG may produce 2.5 W of power. It can power electric watches and temperature sensors (Figure 4b–f) [77].

Generally, there is a gap between the optical fiber TENG and SC, which will prevent them from interacting with each other. However, this will lead to larger and more inconvenient optical fiber equipment in operation, and thus reduce the mechanical stability. In view of this, Zhao et al., have developed a self-mixing smart fiber with asymmetric coaxial structure, which can simultaneously capture and store the mechanical energy obtained. (Figure 4g–j). Due to the strong mechanical and chemical resistivity of P(VDF-TrFE-CTFE) polymer on the surface of hybrid smart fiber devices, self-charging smart fibers show high mechanical durability under repeated stress, and the use of commercial detergents also has high washing resistance. The progress in the field of smart fiber electronics provides a huge opportunity to build a new device platform based on fiber/textiles and enables people to freely overcome the limitations that previously hindered the development of self-powered wearable electronic products. The development of self-charging technology provides a great opportunity to establish a new equipment platform based on fiber/textile electronics [78].

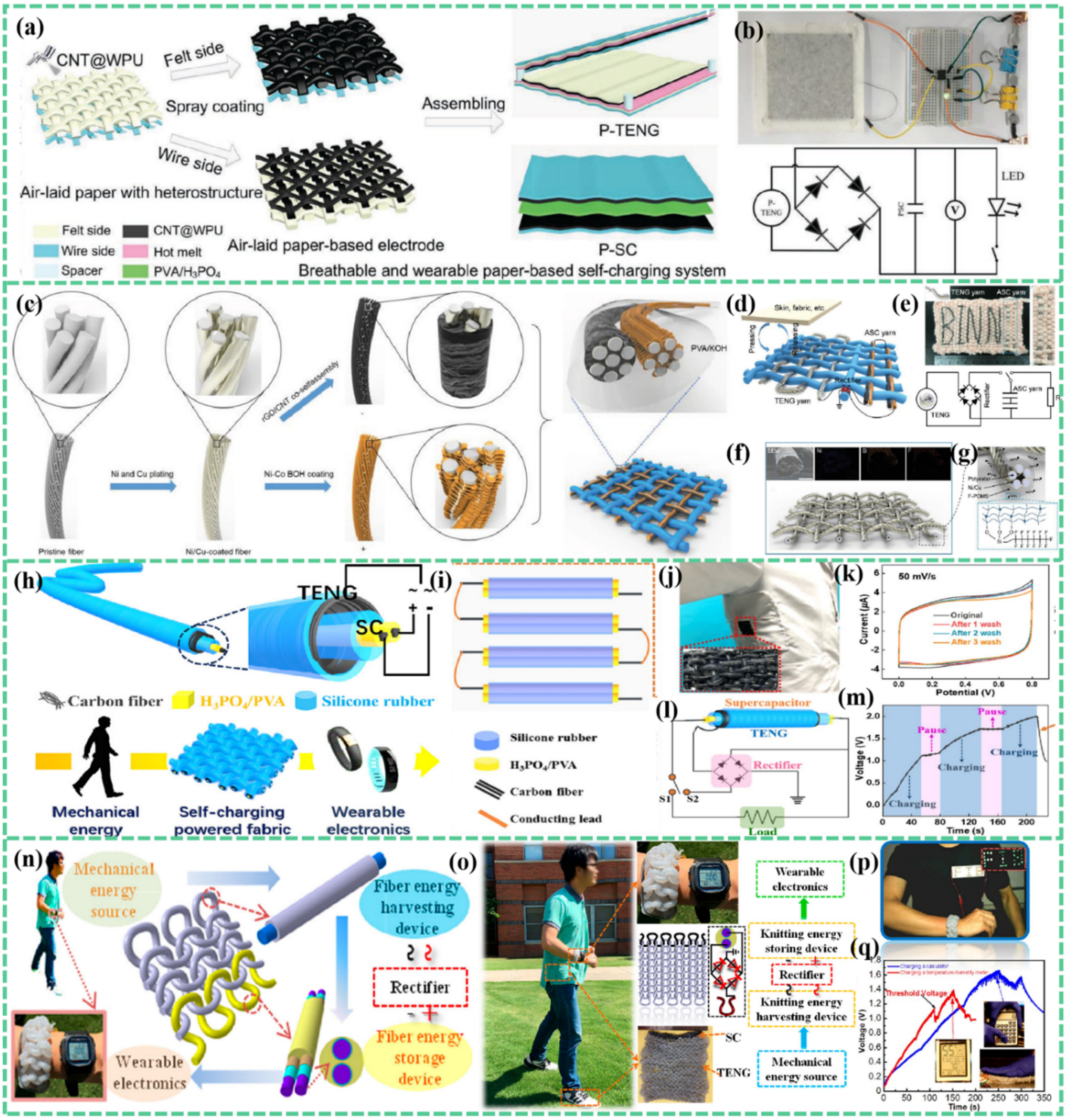

Figure 2. Wearable TENG-UPS textile integrated with TENG and SC. (**a**–**b**) A breathable and wearable TENG-UPS is developed by integrating P-TENG and P-SC. (**a**) Structure of a breathable and wearable TENG-UPS. (**b**) Digital image and circuit diagram of TENG-UPS. Reproduced with permission [70]. Copyright 2019, Wiley-VCH. (**c**–**g**) TENG-UPS composed of energy collection TENG and energy storage yarn type asymmetric SC. (**c**) Schematic illustration of the fabrication procedure of Y-ASC. (**d**) Schematic illustration of the TENG-UPS. (**e**) Photograph of a TENG-UPS textile. (**f**) Schematic illustration of a TENG textile woven by Ni-coated conductive yarns with a shell coating of F-PDMS. (**g**) A scheme of the surface fluorine-containing groups on the chemically modified F-PDMS. Reproduced with permission [71]. Copyright 2019, Wiley-VCH. (**h**–**m**) A flexible coaxial TENG-UPS fiber with a fiber-shaped TENG outside and a fiber-shaped SC inside. (**h**) Fabrication process of the coaxial TENG and SC fiber. (**i**) Schematic illustration of the series connection of the integrated SCs. (**j**) Photograph of the fabricated textile into cloth. (**k**) GCD curve of SC before and after three times of washing. (**l**) Circuit diagram of the SCPs. (**m**) Charging and operating curve of SC. Reproduced with permission [72]. Copyright 2018, American Chemical Society. (**n**–**q**) A highly stretchable and washable all-yarn-based TENG-UPS knitting power textile composed of fiber TENG and fiber SC. (**n**–**o**) System configuration of self-charging knitted strong textiles. (**p**) LED warning sign on a shirt. (**q**) Charging curves. Reproduced with permission [73]. Copyright 2017, American Chemical Society.

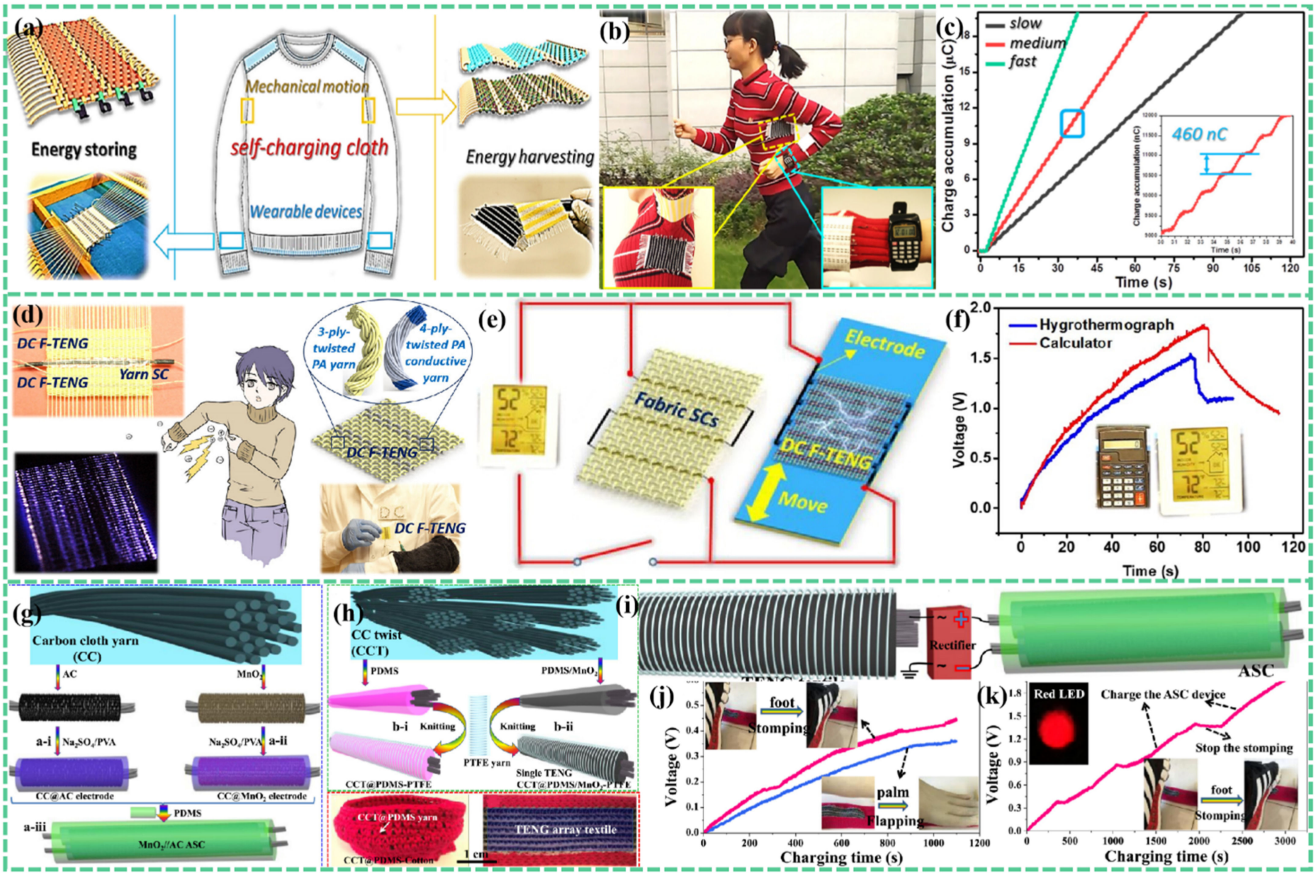

Figure 3. TENG-UPST fabricated with fiber-based TENGs and fiber-based SCs. (**a**–**c**) A one-piece TENG-UPST integrating a fabric TENG and woven SC for simultaneously harvesting and storing body motion energy to sustainably drive wearable electronics. (**a**) Schematic illustration of the FS-FTENG and the W-SC. (**b**) Showcase in running. (**c**) V-t curve of SCPT at 1.5 Hz operating frequency. Reproduced with permission [74]. Copyright 2018, Elsevier Ltd. (**d**–**f**) TENG-UPS fabric integrated with direct current TENG and fiber SCs. (**d**) Fabrication process and schematic illustration of the DC F-TENG. (**e**) Circuit diagram of the self-charging textile. (**f**) Charging curves of fabric SCs by DC F-TENG. Reproduced with permission [75]. Copyright 2018, American Chemical Society. (**g**–**k**) All-in-one TENG-UPST developed by integrating fiber TENG with all-solid-state fiber-based asymmetric SC. (**g**) Schematic diagram of manufacturing process of yarn type asymmetric SC. (**h**) Schematic of the round-tripping knitting process for TENGs. (**i**) Schematic diagram of the TENG-SC device. (**j**) ASC charging curve of TENG array fabric under different movements. (**k**) Charging voltage of TENG array as a function of charging time by the foot stomping motion. Reproduced with permission [76]. Copyright 2021, Elsevier Ltd.

The fact that many TENG-UPSs based on SCs are constructed from a mass of fibers or threads puts TENG and SC at risk for deformation damage. Therefore, putting diverse conductive and active elements on a common fabric substrate is the most straightforward method to build uninterrupted power supply fabric. Cong et al., demonstrated using elastic coplanar uninterruptible power supply cloth in 2020 (Figure 4k–n). When the transverse and longitudinal tensile strains are 600% and 200% respectively, the fabric electrode still has good conductivity. Depending on the fabric, the maximum surface capacitance is 50.6 mF cm^{-1}. Stretchable TENG made of fabric can provide an open circuit voltage of 49 V and a peak power density of 94.5 mW m^{-2}. Small electrical gadgets can also be powered sporadically using it without the need for extra charging [79]. Therefore, the basic fabric structure provides UPST, which is an efficient and adaptable design carrier and implementation platform.

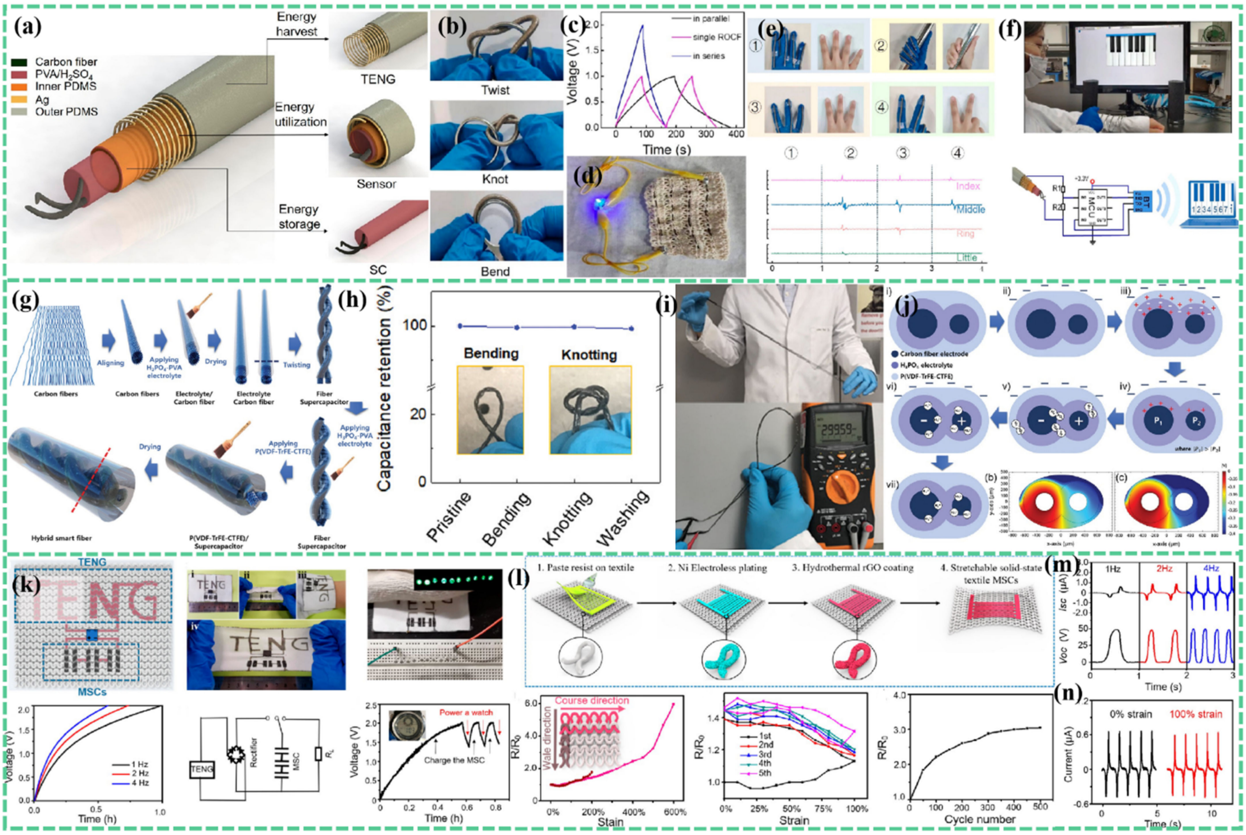

Figure 4. All-in-one uninterrupted power supply fibers and uninterrupted power supply textiles developed from fabric substrate (**a**–**f**) Multifunctional coaxial energy-autonomy fiber composed of an all fiber-shaped TENG, SC, and pressure sensor. (**a**) Structure diagram of TENG, sensor, and SC. (**b**) Photographs of different mechanical deformations. (**c**) GCD curves for two SCs in parallel and in series. (**d**) Photo of a blue LED powered by energy storage fabric. (**e**) Real-time voltage sensing signals under different gestures. (**f**) Photograph and circuit diagram of the energy fiber as the tactile interface of the electronic piano. Reproduced with permission [77]. Copyright 2021, American Chemical Society. (**g**–**j**) A hybrid intelligent self-charging fiber with asymmetry coaxial structure by a spontaneous energy generation and storage. (**g**) Schematic diagram of step-by-step manufacturing process of hybrid intelligent optical fiber. (**h**) Capacitance retention of hybrid smart fibers. (**i**) Scalability of hybrid smart fiber. (**j**) Schematics of self-charging mechanism of the hybrid smart fiber. Reproduced with permission [78]. Copyright 2020, Wiley-VCH. (**k**–**n**) Stretchable coplanar uninterrupted power supply textile with resist-dyeing TENG and MSCs. (**k**) Stretchable coplanar UPST. (**l**) Manufacturing process. (**m**) I_{sc} and V_{oc} at various motion frequencies. (**n**) I_{sc} of the stretchable TENG at tensile strains of 0% and 100%. Reproduced with permission [79]. Copyright 2020, American Chemical Society.

3.1.2. Film-Based TENG-UPS

The production of flexible electronic products requires high standards of lightness, thinness, and flexibility. Paper is a common material for TENG-UPS unit construction due to its light weight, low cost, environmental protection, and ease of manufacture. Inspired by paper electronic devices, thin film structures are gradually being used to develop wearable and flexible electronic products. By combining paper TENG (P-TENG) with paper SC, Shi et al., manufactured portable and long-lasting TENG-UPS. As the electrode and positive triboelectric layer of P-TENG, cellulose paper/PPy composite was utilized; nitrocellulose membrane (NCM) served as the negative triboelectric layer (Figure 5a). The power density displayed by P-TENG was 0.83 W m^{-1}, and the high output load voltage was 60 V. The P-SC composed of cellulose paper/Ppy and gel electrolyte also performed well. TENG-UPS generated by combination of P-TENG and P-SC can supply power for various electrical equipment (Figure 5b–f) [80].

Sun et al., showed an electrostatic spinning paper-based supercapacitor (EP-SC) as an energy storage unit, and a friction electric nanogenerator (EP-TENG) as an energy trap (Figure 5g–h). In the arcuate EP-TENG, conductive carbon paper serves as the electrode, non-conductive pan paper serves as the triboelectric layer, and both conductive carbon paper and non-conductive pan paper are employed as the EP-SC's capacitive material. Electronic watches and calculators can be powered by using fully flexible electrospinning paper [81]. Additionally, accelerating the transition to transparent, flexible, and portable electronic devices is the development trend of portable wearable personal electronic devices and intelligent security systems. Luo et al., constructed a transparent and flexible self-charging power film (SCPF), which can be used as an information input matrix or a self-energy supply system coupled with an energy storage device (Figure 5i–l). TENG's electrode was composed of 3DAu-MnO film. Energy storage was completed by all-solid-state interdigital TFSC array. The whole apparatus can harvest mechanical energy from the quick movement of the finger and has a high transmittance of 67.1%. More importantly, the device can identify personal characteristics by capturing electronic data related to bioelectricity, applied pressure, sliding speed, etc., during sliding movement [82]. Additionally, a self-charging SC power cell was recently presented by Kumar Shrestha et al., (Figure 5m,n). In addition to an ionic liquid electrolyte and an electrode made of cobalt nanoporous carbon, laser-induced graphene, and copper (Co NPC/LIG/Cu), the device employs poly (vinylidene fluoride co hexafluoropropylene) P(VDF-HFP) as a polymer separator. The TENG's positive and negative triboelectric layers are made of nylon 6*6 nanofiber and Co NPC/LIG/P(VDF-HFP) film, respectively. With 2.5 mW power output, TENG can effectively charge SPC to 210 mV in 9 s. To control T-Rex's "leap" and "duck" motions in the gaming interface, dynamic and static signals from SPC devices are employed, and various SPC charge levels are utilized as smart switches to turn on intelligent appliances [83].

Qin et al., demonstrated an intelligent uninterruptible power pack that combines a hybrid TENG with an electrochromic micro uninterruptible power array to change the color to display the charging state (Figure 6a). AgNW/NiO is used as the electrode material of electrochromic SC, with high capacitance (3.47 mF cm^{-2}) and reliable cycle performance (80.7% of 10,000 cycles). To meet the self-charging standard, the hybrid TENG can provide a high output voltage of 150 V and a high output current of 20 A. Under the periodic mechanical deformation caused by human hand impact, the integrated electrochromic uninterruptible power supply array can self charge to 3V and light the LED (Figure 6b–f). During self-charging, the charging level can be determined by comparing the color with the naked eye [84]. Song et al., established an integrated sandwich-shaped TENG-UPS unit that can effectively convert mechanical energy into electrochemical energy and collect and store energy by combining a wrinkled PDMS-based TENG and a CNT/paper-based solid-state SC [85]. Furthermore, three TENG-UPS linked in series are utilized as the power supply, which may drive commercial calculators to function continually and act as electrochromic devices for smart windows in the coloring and bleaching processes.

Elastic and sponge structures are also common in energy storage and energy harvesting systems, in addition to thin film structures. For example, Li et al., demonstrated a copper doped PDMS sponge as a flexible supercapacitor and a flexible and robust TENG electrode (Figure 6g,h). The SC shows good energy storage capacity, excellent mechanical and long-term stability. It retains its functionality when folded 180 degrees and squeezed to 50% of its original thickness. The LED may be lit in around 50 min by charging the three series-connected SCS to 2.4 V using S-TENG at 3 Hz (Figure 6i–k). The development of wearable personal electronic devices and integrated devices may benefit from the use of this porous metal sponge [86]. Ma et al., established a paper-based TENG-UPS to capture the mechanical energy produced by hand movement and store it in an MSC (Figure 6l–o). The TENG-UPS is significantly simplified by the integration of the TENG with independent structure and the MSCs on the flat surface on a single sheet of paper, reducing the need for extra wire bonding, circuit bonding pads, and packaging operations. Power can be supplied to the wireless location sensor [87].

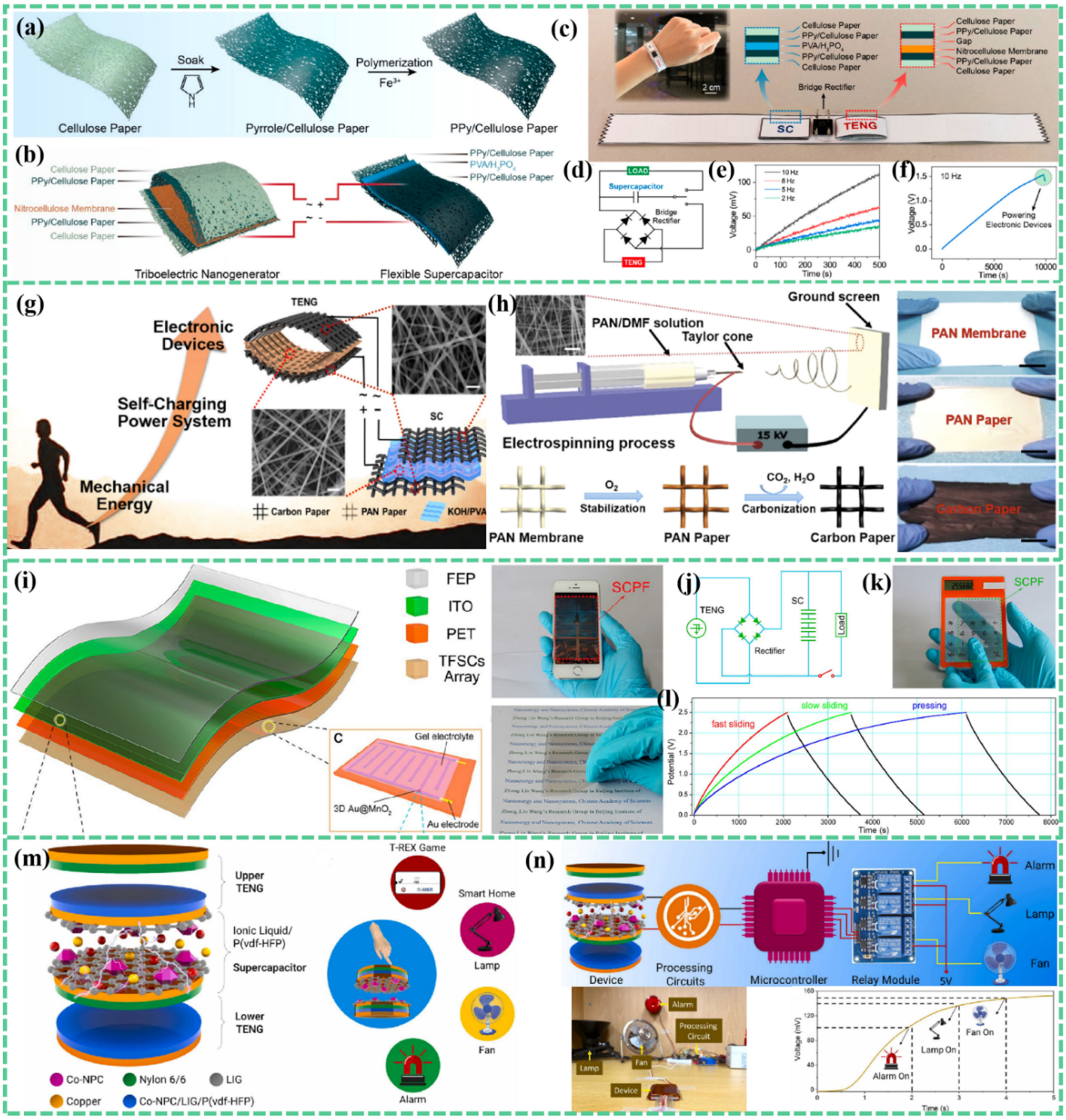

Figure 5. TENG-UPS with film structure. (**a**–**f**) A paper-based TENG-UPS consisting of a paper-based TENG and a paper-based SC. (**a**) Schematic diagram of manufacturing process of PPy coated cellulose paper. (**b**) Structure diagram of TENG-UPS. (**c**) Paper-based TENG-UPS wristband integrating the P-TENG and P-SC. (**d**) Equivalent circuit diagram. (**e**) Charging curves of the P-SC charged by the P-TENG at different frequencies. (**f**) Voltage–time curve of the P-SC that is charged by the P-TENG and then used to power an LCD. Reproduced with permission [80]. Copyright 2019, American Chemical Society. (**g**–**h**) An ultralight and flexible TENG-UPS via all electrospinning paper based on TENGs as energy harvester and all electrospinning paper-based SCs as storage device. (**g**) Schematic diagram of TENG-UPS. (**h**) Schematic illustration of the fabrication process. Reproduced with permission [81]. Copyright 2017, Elsevier Ltd. (**i**–**l**) A transparent and flexible UPSF that functions either as a TENG integrated with an energy storage unit or as a self-powered information input matrix. (**i**) Schematic illustration of the transparent and flexible TENG-UPS. (**j**) Circuit diagram of the transparent and flexible TENG-UPS. (**k**) Photograph of a calculator driven by the TENG-UPS. (**l**) Charging curves. Reproduced with permission [82]. Copyright 2016, American Chemical Society. (**m**,**n**) A TENG-UPS, which can store energy generated by TENG without rectifier or external circuit through "triboelectrochemical mechanism". (**m**) Schematic diagram of TENG-UPS layer by layer structure. (**n**) System architecture for demonstrating the T-Rex game on the smartphone. Reproduced with permission [83]. Copyright 2022, Elsevier Ltd.

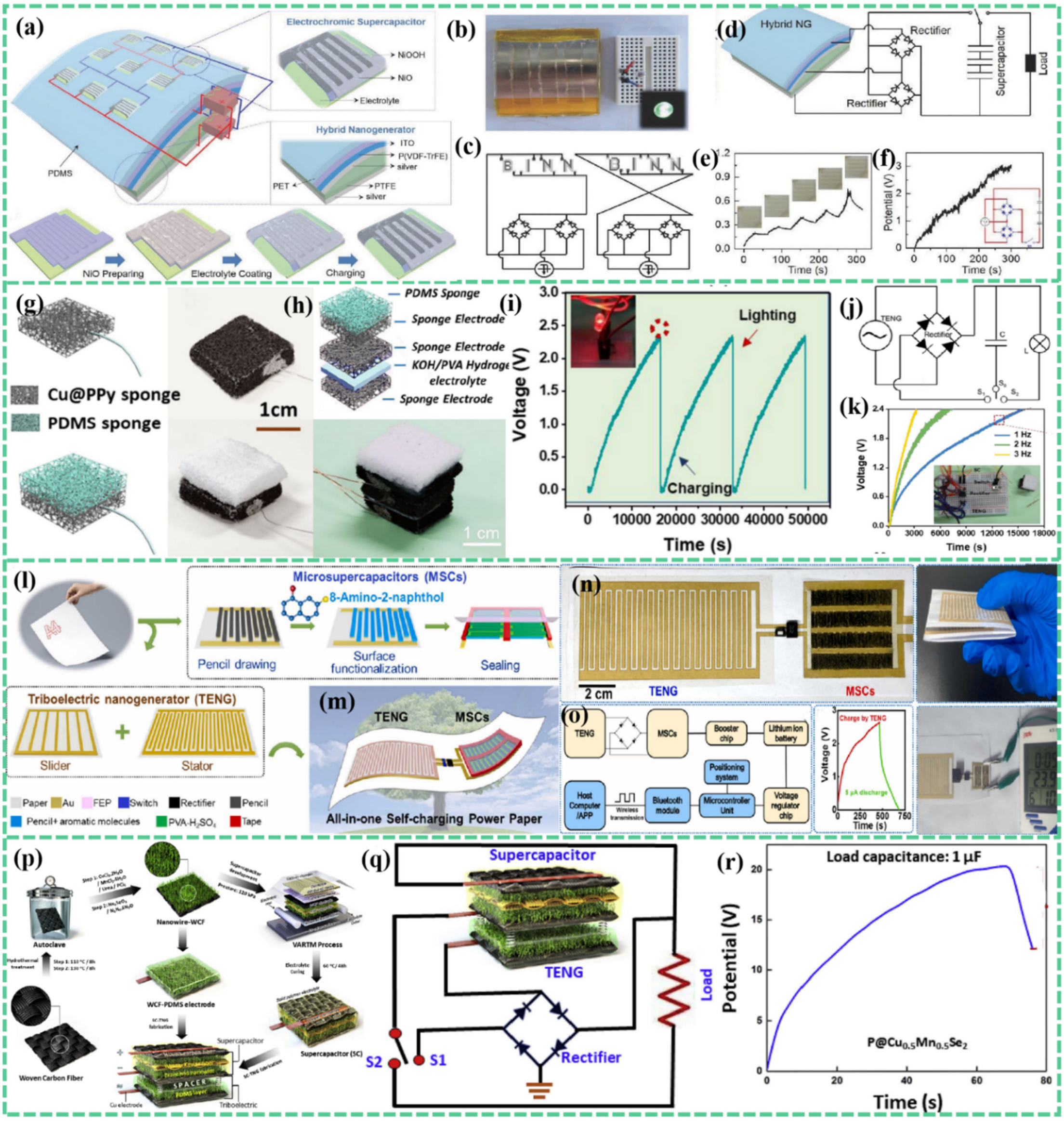

Figure 6. TENG-UPS with film and sponge structure. (**a**–**f**) Hybrid piezo/triboelectric-driven self-charging electrochromic supercapacitor power package. (**a**) Schematic illustration of the self-charging power package. (**b**) The self-charging power pack serves as the power supply for the LED lights. (**c**) Equivalent circuit of forward and reverse connection. (**d**) The equivalent circuit of the smart self-charging power package. (**e**) Real time self-charging process of electrochromic μ-SC under continuous palm impact. (**f**) Charge in series under continuous palm impact. Reproduced with permission [84]. Copyright 2018, Wiley-VCH. (**g**–**k**) Elastic Cu@PPy sponge-based TENG and SC. (**g**) Diagram and photograph of sponge TENG. (**h**) Schematic diagram of hybrid energy harvesting and storage. (**i**) V-t curve of sponge SC in charging mode. (**j**) Circuit diagram of the energy supply mode. (**k**) Charging curve of SC at different TENG frequencies. Reproduced with permission [86]. Copyright 2019, Elsevier Ltd. (**l**–**o**) A paper-based UPS device for generating and storing power. (**l**) Fabrication of TENG and in-plane MSCs. (**m**) Illustrations of the concept. (**n**) The unfolded power paper and the folded one. (**o**) Equivalent circuit and voltage profile of the three MSCs in series charged by the TENG and discharge curve of MSCs. Reproduced with permission [87]. Copyright 2022, Elsevier Ltd. (**p**–**r**) Multifunctional TENG and SC based on woven carbon fiber. (**p**) Fabrication of TENG-SC device. (**q**) Electric circuit diagram of the TENG-SC device. (**r**) The potential generated and stored at the SC by the TENG. Reproduced with permission [88]. Copyright 2020, Elsevier Ltd.

Using woven carbon fiber as the basis, Biplab K. Deka et al., developed a multipurpose TENG-UPS (Figure 6p–r). By developing P-doped Cu-Mn selenide nanowires on the surface, the WCF electrode is improved. The positive electrode of TENG is made of the polydimethylsiloxane-coated nanowire WCF, while the negative electrode is made of the SC's polyester-based outer surface. The equipment can adapt to various external climatic conditions and has good mechanical performance. The TENG-UPS can be used for various electronic devices, including autonomous cars and unmanned aircraft [88].

3.1.3. Packaged TENG-UPSs

The above TENG-UPS combines TENG and SC into one equipment; however, their waterproof performance is limited. In view of this, it is a good choice to encapsulate them in polymers. An integrated form adaptable uninterrupted power supply pack was shown by Guo et al. in 2016 (Figure 7a). A proportionate stretch of up to 215% may be achieved with the kirigami paper-based supercapacitor (KP-SC), which also has a 5000 charge/discharge cycle reliability rating and outstanding mechanical durability (2000 stretch/release cycles). Silicone rubber and Ag nanowires are the ingredients of TENG. It has a tensile state of 100%, an output charge of 160 nC, and an open circuit voltage of 250 V (Figure 7b,c). This power unit has the ability to continually power the electronic meter while also collecting hand energy. TENG-UPS may also be cleaned because the parts are silicone rubber-sealed [89].

In 2020, Li et al., designed a self-cleaning and self-charging device with biomimetic integration based on laser-induced graphene (LIG) technology that can harvest energy from swaying plant leaves and rains. Power generation (MTENG) and energy storage (SC) are the two parts of this apparatus (Figure 7d–f). This self-charging device, which is based on laser-induced graphene technology, has exceptional flexibility, a powerful self-cleaning effect, steady electrical output, and high integration. The equipment has waterproof and self-cleaning qualities thanks to the lotus leaf bionic structure that was created on its surface using the template approach, which enables the equipment to retain steady output in a humid environment [90].

Song et al., successfully combined scalable double-sided micro supercapacitors (D-MSC), flexible independent TENG, and power management modules to create an effective self-charging smart bracelet (Figure 7g–j). The carbon nanotube polydimethylsiloxane (CNT-PDMS) conductive elastomer-based D-MSC was optimized to exhibit steady electrochemical performance and mechanical toughness. The power management module (PMM) used for F-TENG production has a peak voltage of 305 V. Based on FPCB technology, they can effectively collect human motion energy. In daily human activities, mechanical energy is captured by an effective power management module and simultaneously stored in the supercapacitor, allowing the pedometer and humidity thermometer to continue working [91].

In a wearable, flexible monolithic device, Jiang et al., developed a very compact TENG-UPS that combines an MSC based on Mxene with a TENG (Figure 8a–d). The device can use and store random energy from human actions in standby mode, and when active, it can power electrical devices [92]. Zhou et al., built FC-TENG and FC-SC on the basis of folded carbon (FC) paper, which are, respectively, used as energy collectors and storage devices. This kind of high Young's modulus carbon paper has geometric design and super tensile property. It can make the power unit work normally even in severe deformation, such as bending, twisting, or rolling. The packaged equipment also performs well in terms of waterproofing. The self-charging unit may successfully charge electrical gadgets by extracting mechanical energy via hand tapping, foot stomping, and arm contact [93]. Yang et al., developed a completely flexible TENG-UPS that integrates MSC with TENG using oxidized single-walled carbon nanotubes and polymer electrodes [94]. In 10,000 tensile test cycles, the completely stretchy MSC with oxidized single-walled carbon nanotube/polyvinyl alcohol electrode demonstrated a double-layer capacitance of 20 mF cm^{-2} at 0.1 mA cm^{-2}, as well as increased mechanical flexibility and stretchability. Silver nanoparticles embedded with oxidized single-walled carbon nanotubes were used to create a stretchable current collector based on polydimethylsiloxane. Furthermore, the TENG can charge the MSC of the completely extendable TENG-UPS unit from 0 to 2.2 V in 1200 s and power the commercial digital clock for roughly 10 s (Figure 8e–i). Using an integrated TENG-UPS and a touch sensor, Chun et al., suggested a clear and adaptable multi-functional electronic system (Figure 8j–l). For the electrodes of TENG, touch sensors, and SC, they utilized single-layer graphene (SLG) sheets. A separator made of a PVA-LiCl impregnated electrospinning polyacrylonitrile (PAN) pad was inserted between two symmetric SLG electrodes on a polyethylene naphthalate (PEN) substrate to create the first transparent, capacitive, and flexible electronic devices. The device constitutes the top panel of multi-functional electronic equipment and plays a role as a sensitive and fast response touch sensor and a supercapacitor based on electrochemical double-layer capacitor (EDLC) [95].

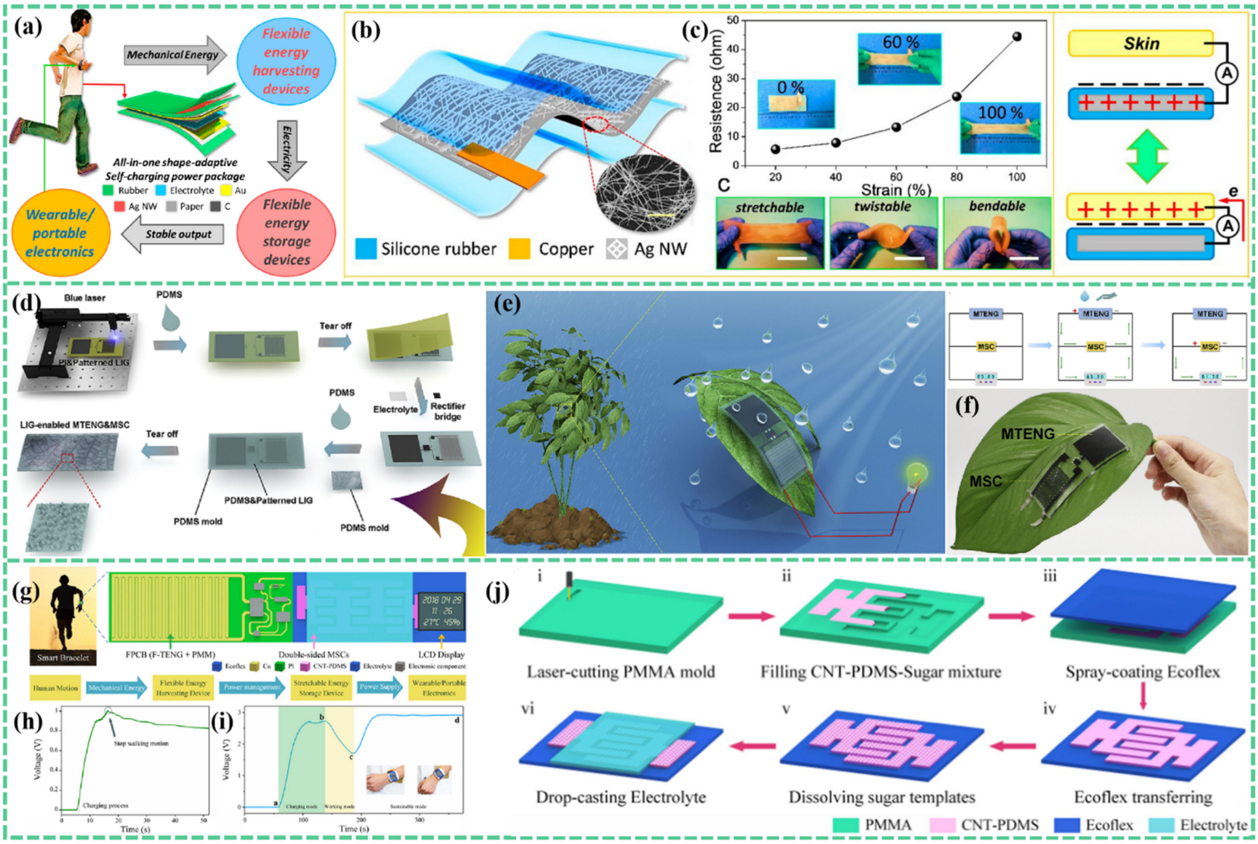

Figure 7. (**a**–**c**) All-in-one shape-adaptive TENG-UPS package for wearable electronics. (**a**) The working mechanism of the integrated adaptive self-charging module. (**b**) Structural scheme of the silicone rubber based flexible TENG. (**c**) Dependence of resistance of the Ag NW based electrode under various strain and the TENG under various mechanical deformations, stretching, twisting, and bending. Reproduced with permission [89]. Copyright 2016, American Chemical Society. (**d**–**f**) An integrated self-cleaning and self-charging device with bionic surface. (**d**) Schematic illustration of the fabrication process of device. (**b**) Digital photograph of lotus leaf. (**e**,**f**) Photo of the device attached to the leaf. Reproduced with permission [90]. Copyright 2020, Elsevier Ltd. (**g**–**j**) An uninterrupted power supply smart bracelet integrating an independent TENG, a power management module, and a D-MSC in the Ecoflex substrate. (**g**) Schematic diagram of efficient self-charging smart bracelet for portable electronic devices. (**h**) V-t curve during walking motion and self-discharge. (**i**) V-t curve in different modes. (**j**) Manufacturing process of tensile MSC. Reproduced with permission [91]. Copyright 2019, Elsevier Ltd.

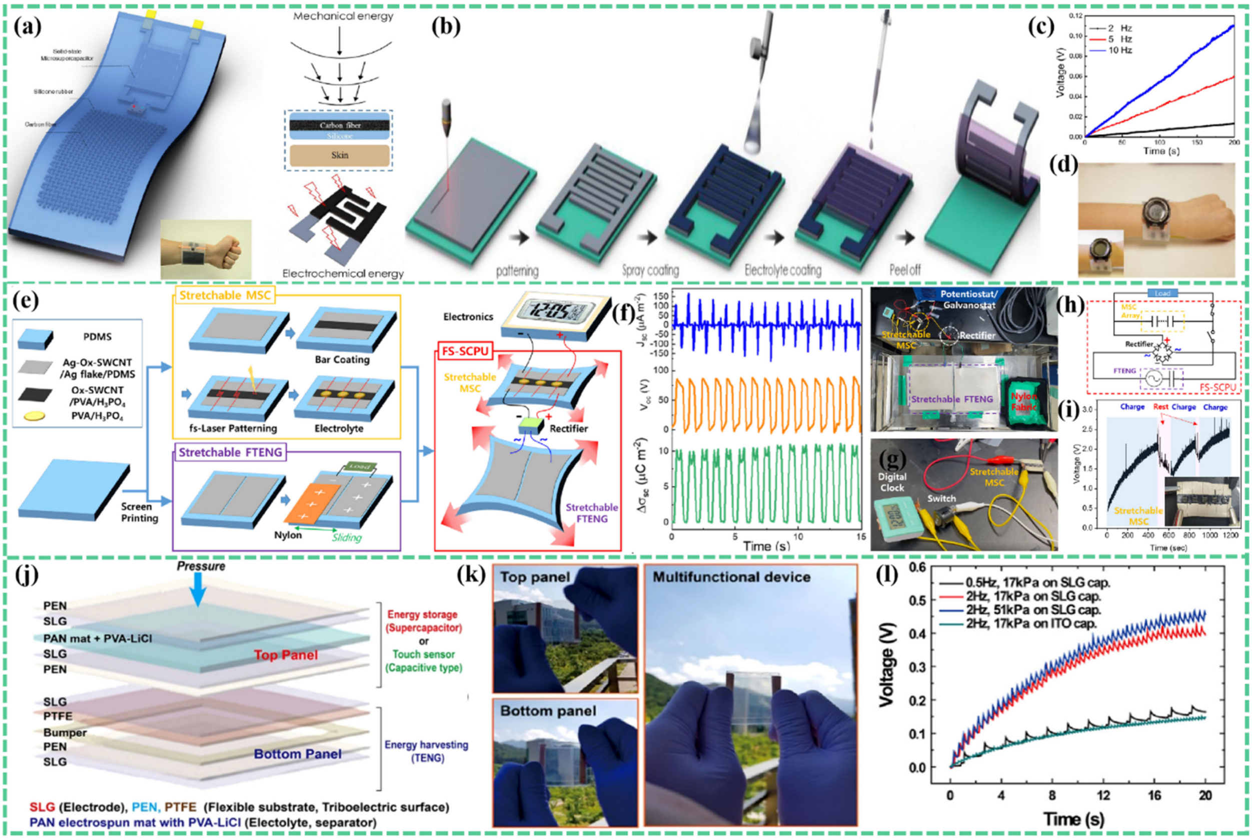

Figure 8. (**a**–**d**) An electrochemical MSC based on Mxene is integrated with a TENG as a wearable TENG-UPS. (**a**) Schematic diagram of the whole device. (**b**) Schematic illustrating fabrication protocols of $Ti_3C_2T_x$ MSC. (**c**) Charging curve of the MSC charged by TENGs at various frequencies. (**d**) Digital photos showing MSC to drive a digital watch. Reproduced with permission [92]. Copyright 2018, Elsevier Ltd. (**e**–**i**) A fully stretchable UPS device with MSC and TENG based on oxidized single wall carbon nanotube/polymer electrode. (**e**) Schematic of the fabrication process for the FS-UPS with stretchable MSC and FTENG. (**f**) Short-circuit current density (J_{sc}), open-circuit voltage (V_{oc}), and transferred charge densities ($\Delta\sigma_{sc}$) generated by stretchable FTENG. (**j**) Photographs of FS-UPS and commercial digital clock powered by FS-UPS. (**h**) Circuit diagram of FS-SCPU. (**i**) Charging curve of the MSC component of FS-UPS. Reproduced with permission [94]. Copyright 2021, Elsevier Ltd. (**j**–**l**) A single layer graphene-based transparent, multi-functional TENG-UPS, and touch sensing system. (**j**) Schematic illustration of multifunctional electronic devices. (**k**) Photos showing transparency of multi-function devices. (**l**) Curve of the charging voltage versus the time of our all-in-one TENG-UPS. Reproduced with permission [95]. Copyright 2019, American Chemical Society.

3.2. TENG-UPSs via Integration of TENG with Batteries

Batteries are a common component in many portable electronic devices, including Bluetooth headsets, smart wristbands, mobile phones, tablets, and laptop computers, thanks to their high-rate discharge capability and extended lifecycle. The integration of batteries and TENG will highlight TENG-UPS in this part.

Wang's research team originally developed the TENG-UPS combined with TENG and LIB, which can concurrently harvest and store ambient mechanical energy (Figure 9a–c). External triggers will cause mechanical movement to generate alternating current, and LIB can be used to store rectified electric energy. In this sustainable mode, TENG-UPS is capable of supplying a constant and long-lasting 2 A direct current that may be utilized to power the UV sensor continually [96]. To store the energy produced by the TENG, Li et al., designed a flexible LIB that resembled a sheet and was constructed of a quasi-solid gel electrolyte (Figure 9d–f). The flexibility of gel electrolyte enables it to withstand various deformations, including bending, twisting, and even being compressed into balls without losing its function. The mechanical strength, flexibility, and puncture resistance of the flexible battery are very good. The flexible LIB stores the rectification energy from TENG, enabling the watch to operate continuously. [97]. Tian et al., reported a $FeSe_2$ carbon nanotube ($FeSe_2$-CNT) hybrid microsphere as the anode material of LIB. $FeSe_2$-CNT hybrid LIB is capable of withstanding high-voltage TENG pulses and can be directly charged by TENG to steadily gather energy [98]. Li et al., developed and built a high-performance flexible lithium-ion battery utilizing LiMn0.6$Fe_{0.4}PO_4$/C(LMFP/C) as the positive electrode material [99]. The battery is very adaptable and recyclable. After 300 bends, there is no discernible performance reduction in the battery. To build a wearable self-charging power pack, a flexible TENG is linked with a flexible battery. TENG can harvest mechanical energy and transfer it to electrical energy, which can then be used to charge the battery and power the flexible electrochromic film. $LiMn_{0.6}Fe_{0.4}PO_4$ is used as the cathode material of flexible lithium-ion batteries and the electrochemical component of self-charging power packs (Figure 9g–m). More intriguingly, Hong et al., designed an energy collection and storage system made up of a wireless power transmission coil, TENG, SC, and LIB (Figure 9n–p). In the combined system, the coil is LIB and SC wireless, while TENG accelerates the charging process. The flexible and elastic structure of the system allows integration with the human skin [100].

TENG-UPS may also gather mechanical energy from sources other than human motion. For instance, Luo et al., developed a TENG based on a $0.94(Bi_{0.5}Na_{0.5})TiO_3$-$0.06Ba(_{0.25}Ti_{0.75})O_3$/polyvinylidene fluoride (BNT-BZT/PVDF) composite film that was utilized to capture wind energy and employs an all-solid-state lithium-ion battery (ASS-LIB) as an energy storage device (Figure 10a). TENG can provide output voltage and current of 400 V and 45 A respectively. In addition, the ASS-LIB can be quickly charged to 3.8 V in 58 min utilizing wind-driven TENG (Figure 10b,c). It can operate 12 white LEDs in parallel or pH meters constantly [101]. Wang et al., developed a combination of TENG and flexible ZIB integrated in a specifically designed flexible 3D spacer fabric, which can concurrently harvest mechanical energy from human motion and store electrical energy through batteries (Figure 10d). Through the use of external mechanical energy, fabric TENG may produce V_{oc} of around 10-15 V and I_{sc} of 3-4 A. Additionally, the flexible ZIB attained its highest specific capacity of 265 mAh g^{-1} (Figure 10e,f) [102]. Lu et al., developed a self-powered device that can effectively store pulse current and has excellent cycle stability using flexible quasi solid sodium battery and TENG (Figure 10g–i). The combination of complex and flexible battery and TENG shows its potential as a powerful and flexible self-power supply system and proves its ability as a feasible energy storage component [103].

Various other battery technologies are also under development, including lithium sulfur battery, sodium ion battery, zinc ion battery, etc. However, the above TENG-UPS solutions have the disadvantages of high price, high cost, and large volume. The future development of TENG-UPS based on TENG may also be towards the next generation of batteries using magnesium, calcium, or aluminum, which are cheaper, heavier, and smaller. According to the above research, multi-functional fabric structure can be used as a reliable and adaptable design carrier and implementation platform for self-charging power textiles.

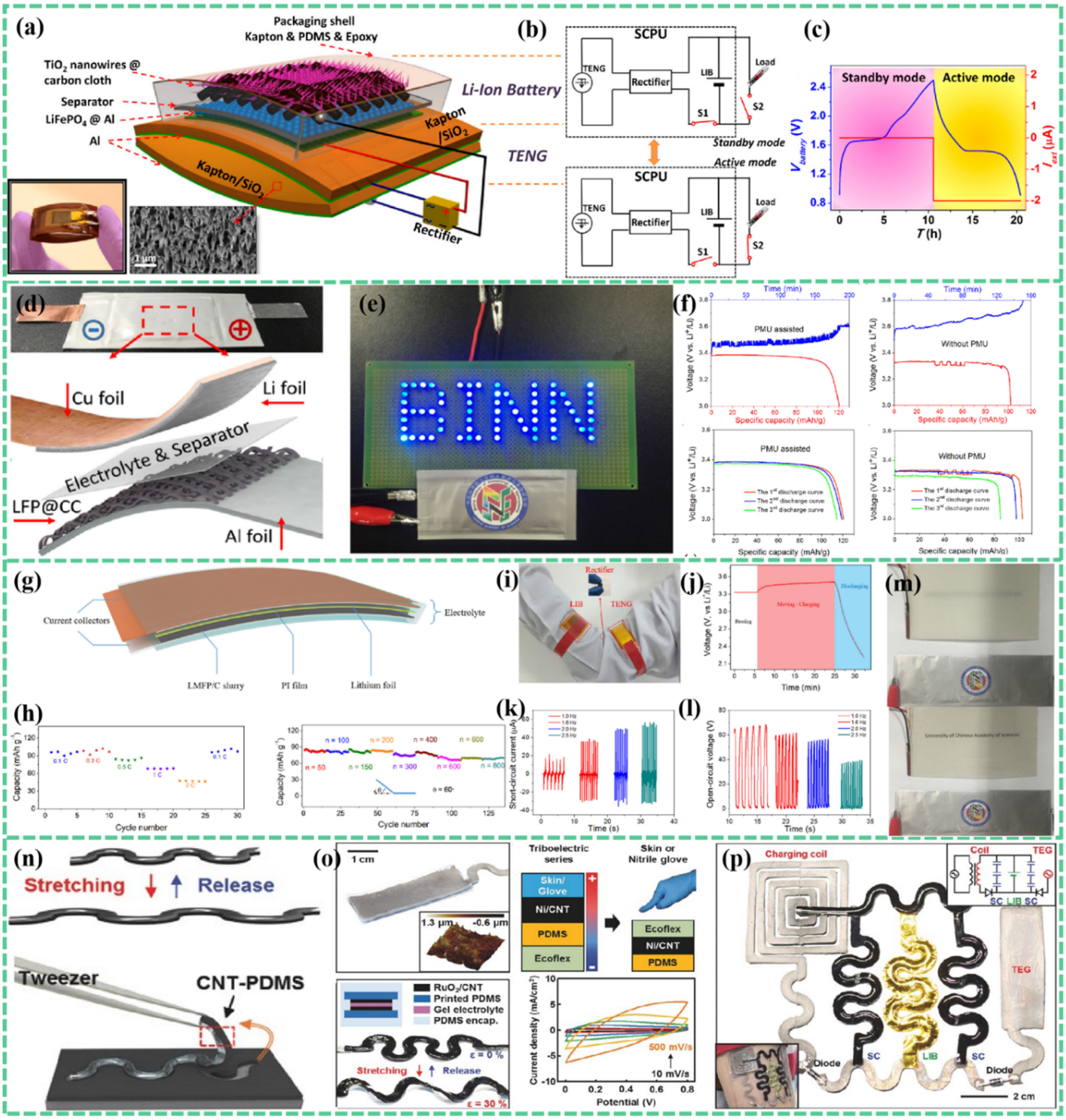

Figure 9. (**a**–**c**) A mechanical energy collector based on TENG and an uninterrupted power supply unit based on LIB. (**a**) Schematic diagram showing the detailed structure of the TENG-UPS. (**b**) TENG-UPS circuit diagram of TENG component and LIB component integration. (**c**) Voltage distribution diagram. Reproduced with permission [96]. Copyright 2013, American Chemical Society. (**d**–**f**) A quasi-solid gel electrolyte flexible LIB for storing pulse energy generated by a TENG. (**d**) Photograph and structural schematic of the cell. (**e**) Demonstration of an LED screen showing the letters of BINN. (**f**) Electrochemical performance of the quasi-solid flexible cell. Reproduced with permission [97]. Copyright 2018, Elsevier Ltd. (**g**–**m**) A flexible wearable TENG-UPS pack integrated with TENG and flexible LIB. (**g**) Schematic of the flexible LIB battery. (**h**) Electrochemical performance of the quasi-solid flexible cell. (**i**) Photo of wearable UPS. (**j**) Charge and discharge curves of the flexible LIB. (**k**) Short-circuit current of the flexible TENG at different impact frequencies. (**l**) Open-circuit voltage of the flexible TENG at different impact frequencies. (**m**) Photographs of the flexible cell powering a flexible electrochromic membrane. Reproduced with permission [99]. Copyright 2018, Elsevier Ltd. (**n**–**p**) A novel stretchable electrode based on a lateral comb-like CNT network for high-performance stretchable TENG-UPS. (**n**) Peeling-off of the stretchable CNT-PDMS nanocomposite pattern. (**o**) Image of a stretchable SC in its stretched and released state. (**p**) Integration of a wireless power transmission coil, TENG, SC, and LIB into a wearable UPS. Reproduced with permission [100]. Copyright 2017, Wiley-VCH.

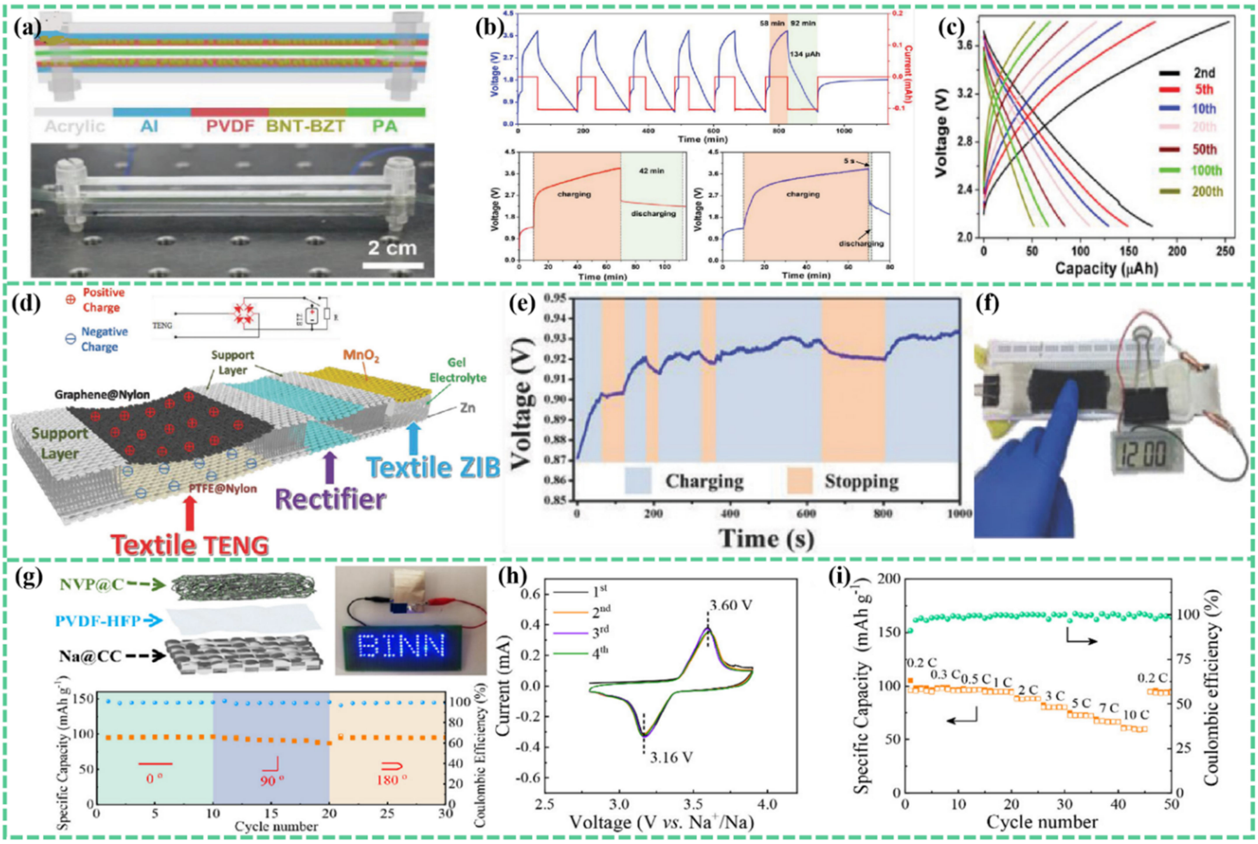

Figure 10. (**a**–**c**) A TENG-UPS that uses TENG to collect wind energy and effectively store the converted electric energy in a matching ASS-LIB. (**a**) A schematic diagram of the TENG. (**b**) Applications of the TENG-UPS in self-powered electronics. (**c**) Electrochemical performance of ASSLIB. Reproduced with permission [101]. Copyright 2022, Wiley-VCH. (**d**–**f**) A TENG-UPS device was integrating a TENG and a ZIB on a flexible 3D spacer fabric. (**d**) Manufacturing protocol and schematic diagram of energy harvesting and storage device. (**e**) The voltage evolution characteristics of the flexible ZIB under the normal charging and stopping modes. (**f**) Electronic watch driven by flexible ZIB charged by TENG through manual pressing. Reproduced with permission [102]. Copyright 2018, Wiley-VCH. (**g**–**i**) A flexible quasi-solid state sodium battery for storing pulsed electricity generated by a TENG. (**g**) Schematic illustration of the NVP-C | PVDF-HFP | Na-CC sodium battery. (**h**) CV curves at 1 mV s^{-1}. (**i**) Rate capability at different current densities. Reproduced with permission [103]. Copyright 2020, American Chemical Society.

3.3. Hybrid TENG-UPS

The output power of a single TENG may be limited, which is insufficient to meet consumption of electronic devices in the long run. Combining two or more generators may be a reasonable design, which can effectively collect energy from the environment [104–106]. Wen et al., proposed a hybrid TENG-UPS textile in 2016, which can simultaneously collect energy from random body movements and external sunlight. This system then stores the energy in an electrochemical energy storage unit. The charging efficiency of UPST has been significantly increased by using fiber-shaped dye-sensitized solar cells (for solar energy) and fiber-shaped TENG (for random body motion energy). Both of the harvested energies can be easily converted into electrical energy and then further stored as chemical energy in fiber-shaped SCs [107]. Ma et al., constructed a TENG-UPS panel by combining lithium-ion batteries, solar cells, and TENG to immediately store the gathered energy and minimize excessive energy loss (Figure 11a). The utilization of current collectors, substrates, and packing materials is considerably reduced in integrated devices. TENG can charge the 2.1 mA h lithium-ion battery from 3 V to 3.6 V, while the solar cell can charge the battery to 3.86 V (Figure 10b–g). Compared with the case where only solar cells are used, the performance of the hybrid equipment has been significantly improved [108]. Similar to this, Xiong et al., developed a TENG fabric with grating structure and integrated fiber optic dye-sensitized solar cells into their textile-based energy harvesting system (Figure 11h–l). As complimentary power sources, FDSSCs and TENG textiles are included in a piece of clothing. These power sources are employed to gather energy from sunlight and human motion, which is then further stored as chemical energy in LIB [109]. Song et al., developed a flexible dye-sensitized solar cell and skillfully built TENG into it (Figure 11m–o). Both the AC energy from the TENG and the DC energy from the solar cell may be simultaneously stored using a supercapacitor. It may efficiently be incorporated into a flexible wristband to power a range of portable electronic devices, including temperature sensors, LED lights, and electronic timepieces [110].

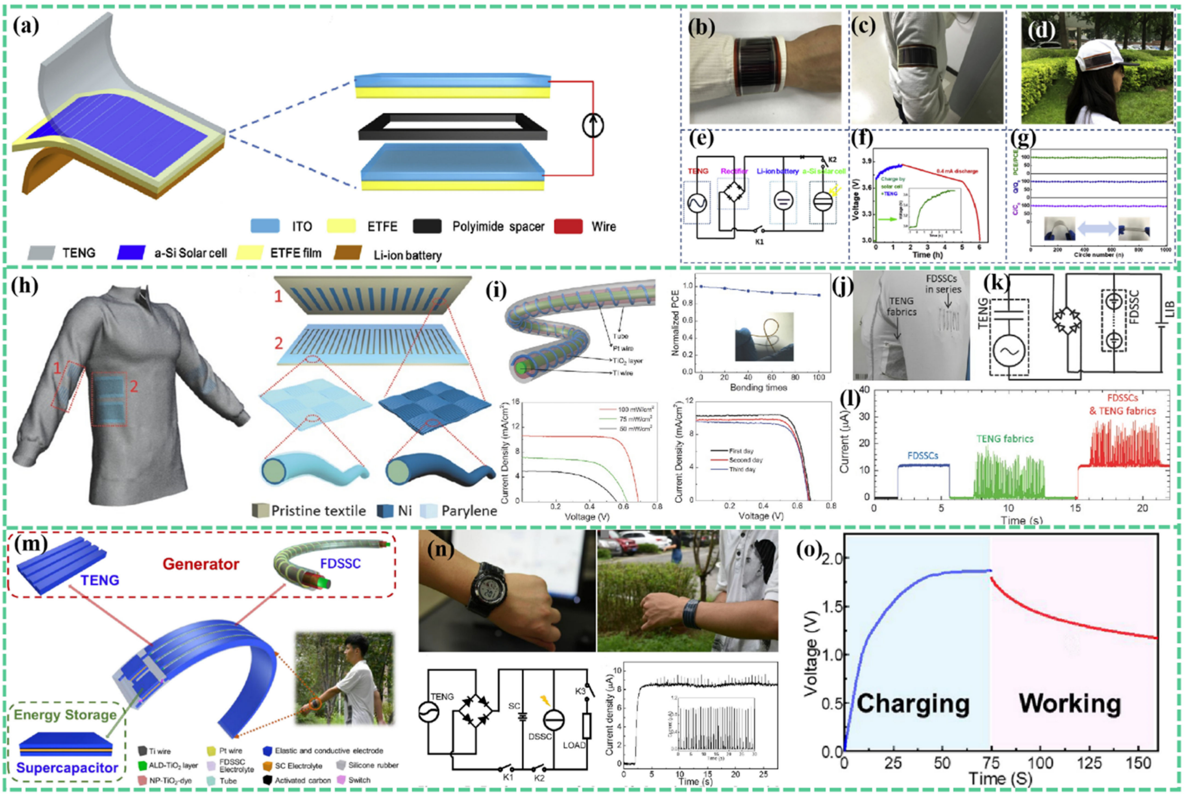

Figure 11. Wearable TENG-UPS device with hybrid energy collection method. (**a**–**g**) A flexible TENG-UPS panel for harvesting and storing solar and mechanical energy. (**a**) Structure diagram of the hybridized flexible energy harvesting device. (**b**–**d**) Photograph of the wearable energy harvesting device attached to the textiles of wrist. (**e**) Equivalent circuit of hybrid harvesting system. (**f**) Voltage distribution and corresponding discharge curve of the hybrid system. (**g**) The PCE value of the solar cell, the Q_{sc} value of TENG, and the capacity of the LIB to bend 1000 times between 0° and 120°. Reproduced with permission [108]. Copyright 2019, Elsevier Ltd. (**h**–**l**) A wearable power textile integrating a fabric TENG and a fibrous dye-sensitized solar cell. (**h**) The scheme of the configuration of the TENG fabrics. (**i**) Fiber-shaped dye-sensitized solar cell. (**j**) A photo of a power-textile with a pair of TENG fabrics. (**k**) Equivalent circuit of TENG-UPS. (**l**) The short-circuit current of FDSSCs, TENG fabrics, and the hybrid energy-harvesting device. Reproduced with permission [109]. Copyright 2016, Wiley-VCH. (**m**–**o**) A highly elastic uninterruptible power supply that collects both solar energy and mechanical energy. (**m**) Schematic of the UPS bracelet. (**n**) Performance of the self-charging bracelet with SCs, FDSSCs, and TENGs. (**o**) The voltage profile of the SCs charged by the harvesting devices, and corresponding working curve for powering an electronic watch. Reproduced with permission [110]. Copyright 2019, Elsevier Ltd.

To achieve high output performance, Zhang et al., developed a hybrid energy collecting bracelet that works in tandem with dual electromagnetic EMG and TENG (Figure 12a,b). Two magnetic coils for EMG, two copper tapes attached to the TENG module's shell construction, a magneton with electret polytetrafluoroethylene (PTFE) material as the triboelectric layer within the shell, and a power management circuit make up the energy harvesting bracelet. It has a connecting space for RuO_2 and is an SC. Most electronic gadgets, including as calculators, relative humidity and temperature sensors, can be powered for a few minutes by the SC with a light wrist shake [111]. Along with solar energy and TENG, the approach of combining biochemical and biomechanical energy has also been steadily investigated. For instance, Yin et al., proposed a wearable bioenergy microgrid (Figure 12c–h). Through TENG and BFC modules, the system sequentially absorbs biomechanical and biochemical energy, then modifies the energy through supercapacitors to provide high power. As a result, the strengths of the two bioenergy harvesters balance out the weaknesses of BFC due to delayed sweating and TENG owing to lack of activity [112].

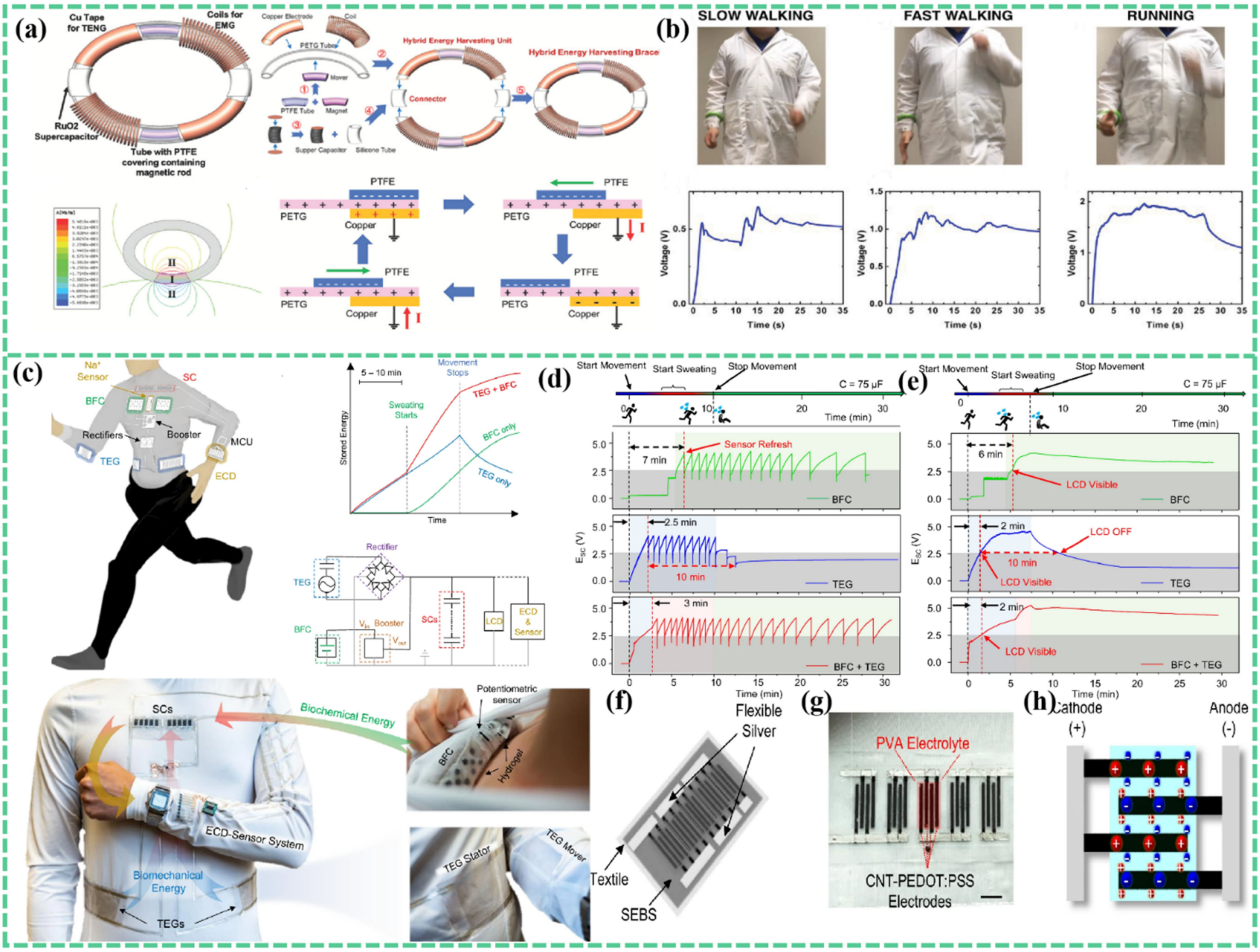

Figure 12. (**a**,**b**) A hybrid energy harvesting bracelet combines dual electromagnetic and TENG to harvest wrist movement. (**a**) The fabrication process and working mechanism of the hybrid energy harvesting bracelet. (**b**) Photograph and voltage of SCs measured under slow walking, fast walking, and running actuations. Reproduced with permission [111]. Copyright 2019, Wiley-VCH. (**c**–**h**) Harvesting of biochemical and biomechanical energy by sweat-based BFC and TENG. (**c**) Design and concept of the multi-modular energy microgrid system. (**d**–**e**) V-t curves under different operating modes. (**f**) Schematic image of the textile-based SC energy storage module. (**g**) The photo image of the printed SC module. (**h**) Charge storage mechanism of hybrid SC cells. Reproduced with permission [112]. Copyright 2018, Wiley-VCH.

4. Summary and Perspective

In a word, this paper comprehensively summarizes the latest development of uninterruptible power supply systems, which integrate energy collection device TENG and energy storage device battery/SC. This strategy brings hope for the development of the next generation of portable electronic products independent of energy. Different flexible and even wearable TENG-UPSs have been developed to convert and store mechanical energy from the environment, which can be used as a sustainable power supply for portable and wearable electronic devices. This paper reviews and discusses the recent development of TENG-UPS composed of TENG and supercapacitor/battery. We definitely believe that TENG-UPS based on TENG will have great potential to shine in our life in the near future, which is due to the continuous development and improvement of TENG-UPS.

Although remarkable progress has been made through the TENG-UPS strategy of integrating TENG and electrochemical energy storage devices, there are still some problems. For example, one of the main obstacles when integrating TENG with the energy storage module is the low efficiency of energy transmission from TENG to the energy storage module. Long term sustainability is another key measure of power availability. Here, we provide workable alternatives and more investigation to get over these challenges.

(1) The performance of TENG and energy storage units in TENG-UPS is typically quite poor in practical applications for a variety of reasons, making them unable to power electronic equipment for an extended period of time. The total energy conversion efficiency is also significantly decreased by the self-discharge behavior of TENG-UPS and the high threshold voltage of LIBS. Currently, concept demonstration continues to be the main focus of research on TENG-based TENG-UPS. More research is urgently required to enhance the output performance of TENG and their integration with energy storage devices in the future, including increasing output power, energy density, and stability through structural design and material optimization. The external packaging of TENG-UPS shall be made of excellent hydrophobic materials to protect it from the adverse conditions of the external environment.

(2) Low energy transmission efficiency between TENG and an energy storage apparatus is caused by impedance mismatch, which is the primary factor impacting the system's efficiency. The power management circuit has a high efficiency and is applicable to all TENG modes, significantly lowering the impedance of TENG. The energy conversion efficiency has improved significantly over the past few years, although it is still rather low. Thus, developing more efficient management circuits is quite important. Additionally, choosing an energy storage system is crucial, and additional work has to be performed to align its impedance and capacity with the TENG's pulse output. The need to create more efficient management circuits is still very important and urgent.

(3) Promising research is being conducted in the area of flexible wearable portable electronic items for the coming generation. Another crucial aspect of TENG-UPS is their wearable design. Flexible substrates should be employed, yet some stiff components, including energy storage systems and power management systems, still need to be made smaller. Additionally, it has to be developed in the direction of multi-function, such as simultaneously gathering several types of mechanical energy or other environmental energy (such as solar and thermal energy) [113,114]. The hybrid device may draw energy from the environment in many modes either separately or simultaneously, allowing the electronic device to be powered by any external energy source that is accessible.

(4) In addition, the wearability and comfort of TENG-UPS are also crucial. Considering that they are wearable, different components should be tightly connected into a system and should be able to take on a variety of shapes to adapt to human activities without stimulating people. In general, an external load is needed to accelerate the power generation of TENG, which might be uncomfortable for a person. Therefore, greater focus should be placed on wear resistance and comfort in order to fulfill good working performance.

(5) Another area of study that has received a lot of attention is wireless energy transmission. The future of medical, sensing, and other IoT technologies depends greatly on the development of TENG-UPS with wireless sensing capabilities.
(6) Cost efficiency is another crucial factor. The majority of reported self-charging power systems are now proof-of-concept prototypes made in laboratories using expensive raw materials and intricate manufacturing techniques, which are far from real-world implementations. As a result, the price of raw materials and the method used to prepare them must be taken into account while designing and creating TENG-UPS. This is the main issue and the only means by which the self-charging power system may be used commercially.

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