Review on Self-Sustainable Power Generation Technologies for Future Typical Wearable Applications

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ABSTRACT

Wearable technology can effectively meet the needs of practical applications, and has broad market prospects in military, fire protection, medicine and health, sports, and more. Self-powered energy systems with miniaturized, lightweight, highly flexible, stretchable, bendable, and wearable properties can meet the needs of the new generation of wearable electronic devices, thus receiving extensive attention. First, the latest progress and existing problems of flexible solar cells, flexible triboelectric nanogenerators, flexible piezoelectric nanogenerators, flexible thermoelectric generators, as well as energy harvesting devices for sweat power generation are reviewed. Second, the development and challenges of flexible Li-ion batteries and flexible supercapacitors for energy storage devices are summarized, and the progress of energy management strategies is discussed. Third, the main applications of self-powered systems in wearable electronic devices, such as Individual Soldier Equipment, Protective Clothing Devices and Smart Wearable Electronic Devices, are introduced. Finally, future development of self-powered energy systems for wearable electronic devices is discussed.

1. INTRODUCTION

With the rapid development of wearable technology and intelligent electronic technology, the market demand for individual soldier equipment [1-2], and intelligent special clothing [3-4], especially the rapid growth of smart wearable electronic devices [5-7], comfort and safety are their common basic requirements. The implantation of air cooling, liquid cooling, micro-environment monitoring, multi-function display and other equipment has made the power supply system more and more important. However, the traditional power supply has prominent problems, such as large volume and weight, strong rigid structure and repeated charging, which is not conducive to portability. Portable, flexible and wearable self-powered systems

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*Corresponding Author: yuminli@xpc.edu.cn have become a hotspot, which includes energy harvesting, energy storage, energy management and energy application. From the perspective of wear ability, it should have the characteristics of small volume, lightweight, and strong flexibility. From the angle of the technical requirements, it should have the characteristic of high efficiency, high conversion efficiency, high security, and long life, as shown in Figure 1.

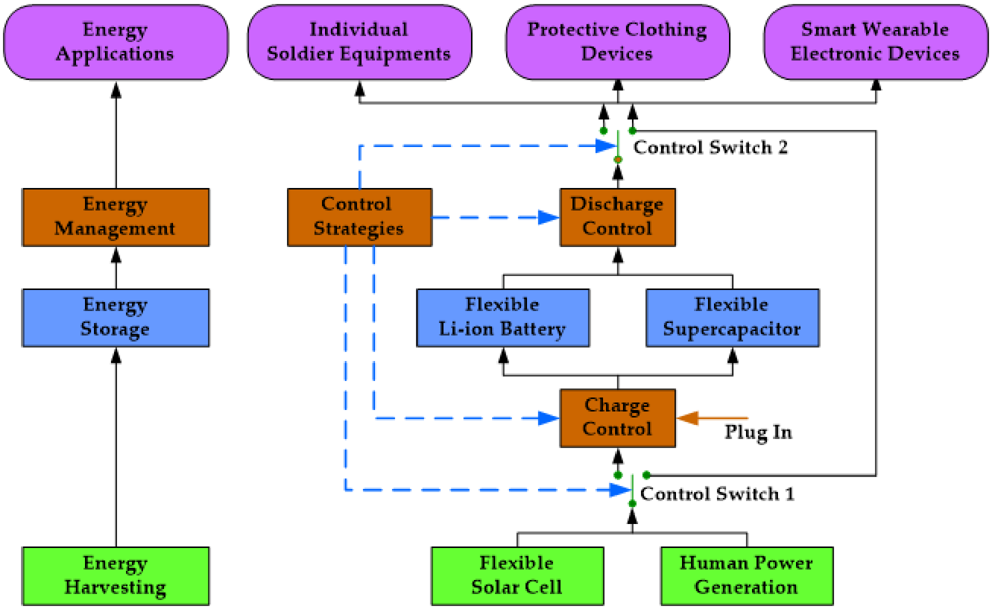

Figure 1. Schematic diagram of self-sustainable system for wearable applications

Energy harvesting mainly includes the collection of solar energy [8-9] and human energy [10-11]. Solar energy is not only an inexhaustible sustainable clean energy, but also a solar cell technology that becoming more and more mature, and energy conversion efficiency is also constantly improving. Human body is a huge source of energy, which exists in the form of mechanical (heartbeat, chewing, walking, running and other body movements), heat (body temperature), chemical (sweat) and other forms. It mainly releases in the form of movement and heat, and the energy harvesting technology and methods are also increasing. The full combination and utilization of the two energy sources provide a possibility to realize a wearable self-sustainable system.

The energy storage system mainly adopts a flexible lithium-ion battery [12-14] and flexible supercapacitor [15-17] hybrid energy storage system. Among them, Li-ion batteries have the characteristics of high energy ratio and low power density ratio, while supercapacitors are the opposite. The combination of these two power sources thus has attracted extensive attention. This new parallel hybrid power system will combine the advantages of Li-ion batteries and supercapacitors to avoid their defects. The result is a new power source with high energy and high-power density.

Energy management [18] mainly refers to the control technology of charging between energy harvesting and energy storage and discharging between energy storage and energy application to optimize the efficiency of both. When charging, there are two sources of energy:

one is the external power supply, and the other is provided by the energy harvesting part. The former is used when conditions permit, and the latter is used when it is in the field or without external power. These two energy sources complement each other to provide a sustainable energy system.

The applications of energy mainly include individual soldier equipment, protective clothing devices and smart wearable electronic devices.

Since the previous review articles mainly focus on one part or two parts, the content is not comprehensive. This prompted us to consider from a global perspective and review the progress and problems of the whole system of the energy harvesting, energy storage, energy management and energy application system. Finally, some major challenges and further research directions of the whole system are discussed.

2. ENERGY HARVESTING

Energy harvesting is important for the whole system, mainly in the form of flexible solar cells and human energy conversion. In sunny places, energy comes mainly from solar cells, but also the human body. When it is cloudy or at night, energy comes from the body. Due to the limitations of sunlight intensity, discontinuity and instability, as well as the limitation of energy produced by human movement and sweat, the disadvantages of a single application are prominent. However, the perfect combination of the two is a promising strategy for a sustainable energy system, as shown in Figure 2.

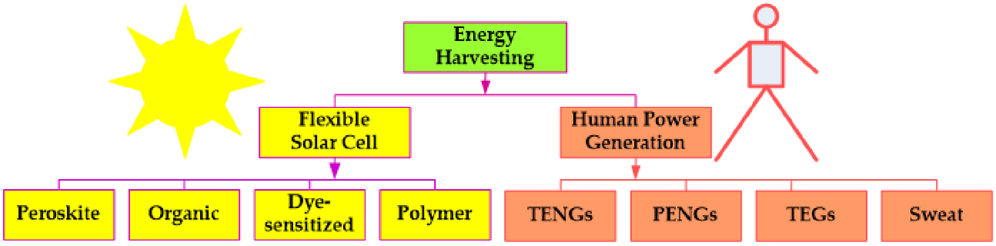

Figure 2. Energy harvesting system

2.1. Flexible Solar Cell

Solar energy is the most abundant, cleanest and most promising renewable energy sources in the world. With the rapid development of wearable technology, flexible solar cells have attracted more and more attention. The most critical technical indicator of flexible solar cells is conversion efficiency, and folding should also be considered for wearable applications. The conversion efficiency of flexible solar cells varies with different materials. The photoelectric conversion efficiency is expressed as follows [19]:

$$PCE = \frac{J_{SC} V_{OC} FF}{P} \tag{1}$$

where J_{SC}, V_{OC}, FF and P are short circuit current, open circuit voltage, fill factor, light power density, respectively.

Table 1. Overview of photovoltaic parameters and bending performance of representative flexible perovskite solar cells

Materials	PCE **(%)**	J_{SC} **(mA/cm²)**	FF **(%)**	V_{OC} **(V)**	**Folding condition/ bending radius (mm)**	**Remaining** PCE **of initial value (%)**	**Year**	**Ref.**
perovskite	10.12	18.21	74.14	1.01	300/4-10	90	2020	[20]
	13.33	20.51	67	0.97	500/<10	>90	2021	[21]
	9.73	16.48	61.8	0.956	1000/10	89	2021	[22]
	20.14	22.76	77.62	1.14	1000/5	86.8	2022	[23]
	19.80	22.95	75	1.14	3000/2.5	94.5	2022	[24]

Table 2. Overview of photovoltaic parameters and bending performance of representative flexible organic solar cells

Materials	PCE **(%)**	J_{SC} **(mA/cm²)**	FF **(%)**	V_{OC} **(V)**	**Folding condition/ bending radius (mm)**	**Remaining** PCE **of initial value (%)**	**Year**	**Ref.**
organic	15.2	25.8	70.2	0.84	1000/2	>90	2020	[25]
	13	26.1	69	0.72	1000/0.5	97	2020	[26]
	12.71	22.61	69.1	0.814	-	-	2021	[27]
	6.85	13.7±1.22	62±1	0.76±0.01	-	-	2021	[28]
	14.37	24.77	74.35	0.780	1000/0.5	96	2022	[29]

Table 3. Overview of photovoltaic parameters and bending performance of representative flexible dye-sensitized solar cells

Materials	PCE **(%)**	J_{SC} **(mA/cm²)**	FF **(%)**	V_{OC} **(V)**	**Folding condition/ bending radius (mm)**	**Remaining** PCE **of initial value (%)**	**Year**	**Ref.**
dye-sensitized	6.16	12.28	76.09	0.66	500/5-1	>92	2020	[30]
	6.08	14.54	66	0.62	-	-	2020	[31]
	5.69	10.248	75.3	0.737	5500/-bending angles 0°–360°	84.7	2021	[32]
	5.38	10.37	76.15	0.68	500/2	>90	2021	[33]
	3.74	6.72	67	0.83	-	-	2022	[34]

Current research mainly focuses on flexible perovskite solar cells, organic solar cells, dye-sensitized solar cells and polymer solar cells, the specific characteristic parameters are as shown in Table 1 to Table 4. Li et al. adopted a simple vacuum-assisted low temperature where they achieve a flexible perovskite solar cell device with the PCE of 20.14% on PET/ITO substrate. Meanwhile, V_{OC} can reach as high as 1.14 V [22].

Although the conversion efficiency of solar cells continues to improve, there is still a big gap in wearable practical applications. In the future, new flexible solar cell materials should be sought, or the structure design and manufacturing process of existing materials should be continuously improved to improve the light conversion efficiency, so as to achieve the purpose of practical application. At the same time, the combination of flexible solar cells and fabrics should also be focused to improve the comfort and safety of wearing.

Table 4. Overview of photovoltaic parameters and bending performance of representative flexible polymer solar cells

Materials	**PCE (%)**	**J_{SC} (mA/cm^2)**	**FF (%)**	**V_{OC} (V)**	**Folding condition/ bending radius (mm)**	**Remaining PCE of initial value (%)**	**Year**	**Ref.**
polymer	2.46	9.9 ± 0.7	39.6±2.6	0.61	350/7.4	92	2020	[35]
	15.28	25.14	73.6	0.826	-	-	2021	[36]
	12.59	17.07	77.2	0.96	-	-	2021	[37]
	8.94	15.64	64	0.89	500/5	62	2021	[38]
	13.51	24.45	64.79	0.85	500/5	80	2021	[39]

2.2. Human Power Generation

Human body releases energy in various forms all the time. More and more researchers are paying attention to how to efficiently collect this energy and effectively convert it into electricity. In recent years, many researchers have focused on the energy generated by exercise, heat and sweat. With the continuous advances of triboelectric nanogenerators (TENGs) [40], piezoelectric nanogenerators (PENGs) [41], thermoelectric generators [42] and sweat power generation technologies [43], the efficiency of energy harvesting continues to improve and shows great potential in practical applications.

2.1.1. Flexible triboelectric nanogenerator and piezoelectric nanogenerator

The triboelectric nanogenerators are based on the coupling effect of contact electrification and electrostatic induction. Piezoelectric nanogenerators are based on the piezoelectric effect, which can collect random energy generated by human movement in daily life and continue to convert mechanical energy into electricity. The power supply device is widely used in wearable devices, biological medicine, health monitoring, military and other fields. This is an important direction for low-cost, sustainable and green new energy research.

Output power is the main performance index of flexible triboelectric nanogenerators and piezoelectric nanogenerators. To obtain good output characteristics, two kinds of friction materials with opposite polarity should be selected to increase the surface charge density and charge transfer efficiency. Table 5 shows the characteristics of the flexible triboelectric nanogenerator of different materials. Wang et al. developed a stretchable and shape-adaptable LS-TENG based on potassium iodide and KI-Gly liquid electrolyte as a working electrode for harvesting human energy. The LS-TENG has good output performance (V_{OC} of 300 V, J_{SC} of 17.5 mA m^{-2}), maintaining stable output performance without degradation under 250% tension stretching and 10,000 repeated contact separation movements [44]. High piezoelectric coefficient materials should be selected or developed for piezoelectric nanogenerators to obtain high power output. Table 6 shows the characteristics of piezoelectric nanogenerators of different materials. HTPENG prepared by electrostatic spinning PLLA and electrostatic spraying PVDF has a unique "microspheres@nanofibers" structure, greatly improving the electrical output performance of HTPENG. It is excellent in thin thickness devices, V_{OC}=35.693V, J_{SC}=8.066uA, and power density= 525.12mW /m^2 [52]. Since the main working mode of the flexible triboelectric nanogenerator and piezoelectric nanogenerator is directly attached to the skin surface or indirectly attached to clothing, the material should also have excellent flexibility, biocompatibility and comfort. Another main factor affecting the performance of flexible triboelectric nanogenerators and piezoelectric nanogenerators is structural design. From the energy acquisition unit to the energy processing unit, the matching structure design is essential to obtain a more stable output.

Table 5. Characteristics of flexible triboelectric nanogenerator of different materials

Materials (Name)	**Power Density (mW m^{-2}/MΩ)**	**Open circuit Voltage (V)**	**Short circuit Current (uA)**	**Number of lighting up LED**	**Year**	**Ref.**
LS-TENG	2000/-	300	17500	>150	2020	[44]
PFL@WFCF-TENG	631.5/-	135	7.5	360	2021	[45]
Silicone Rubber-based	1.3/10	>200	20	60	2022	[46]
CNFs/MXene	1.2/10	24.9	1.61	10	2022	[47]
GO-CC-TENG	31360/400	91.4	0.75	20	2022	[48]

Table 6. Characteristics of flexible piezoelectric nanogenerators of different materials

Materials (Name)	**Power Density (mW m^{-2}/MΩ)**	**Open circuit Voltage (V)**	**Short circuit Current (uA)**	**Number of lighting up LED**	**Year**	**Ref.**
BCPENG	3.59mW cm^{-2}/-	43.5	0.638	5	2020	[49]
Ag NWs/Sm-PMN-PT	7.48μW cm^{-2}/70	83.5	1.2	-	2021	[50]
3D-BCZT@Ag	29.02μW/10	38.6	5.85	-	2021	[51]
HTPENG	525.12 mW m^{-2}/-	35.693	8.066	1	2021	[52]
A-PNG	26.7μW cm^{-2}/10	18	-	5	2021	[53]

2.1.2. Thermoelectric generators

Thermoelectric generator (TEGs) is a device that converts heat directly into electrical energy using the thermoelectric effect (Seebeck effect). Flexible thermoelectric generators can be used to convert human body heat into electricity, which is a promising low-power wearable electronics power source. However, the performance and efficiency of flexible TEGs devices reported so far lag behind rigid TEGs devices.

Table 7. Characteristics of flexible thermoelectric generators of different materials

Materials (Name)	DC-ThEG	PEDOT/ Ag_2Se/CuAgSe	$Ag_{1\ 8}Se$	$Bi_{0\ 3}Sb_{1\ 7}Te_3$	STEG
S (μVK^{-1})	-	78.2	-	147	186
K ($Wm^{-1}K^{-1}$)	-		-	1.6	1.1
Σ	-	470 S cm^{-1}	816 S cm^{-1}	1470 S cm^{-1}	6.9×10^4 S m^{-1}
Power Density/ Maximum Power	3.44 μW m^{-2}	1.55 μW/44K	46.8 W m^{-2}/50K	33.9 mW/75°C	2.7 mW cm^{-2}/50K
Open Circuit Voltage/ Maximum Voltage	151 mV/50°C	50 mV/44K	28 mV/50 K	2.2V/75°C	181.7mV/50K
Internal Resistance (Ω)	-	-	415	35	4
Location	arm	arm	wrist	wrist	hand/wrist/elbow
Year	2020	2021	2021	2021	2022
Ref.	[54]	[55]	[56]	[57]	[58]

The main reasons affecting the conversion efficiency and output power of flexible thermoelectric generators include thermoelectric materials, structure design and processing technology. Excellent thermoelectric materials should have a high S, low κ and high σ. The higher S, the higher the thermal voltage. The lower κ, the larger the temperature gradient. The higher σ, the smaller the Joule heating effect. Table 7 shows the characteristics of flexible thermoelectric generators of different materials. Shi et al. proposed a new STEG structural design with 50 pairs of bulk thermoelectric legs, connected by flexible electrodes inspired by

Kirigami. The device was fabricated by sacrificial layer assisted welding. When ΔT=50 K, the power density can be increased to 2.7 mW/cm^2, and the open circuit voltage can reach 181.7mV [58]. The structure of flexible thermoelectric generators must be better integrated with the complex dynamic thermal surface of the human body to effectively capture the temperature gradient between the skin and the environment to improve the power density. According to optimizing the key parameters such as device shape and size and improving the integration technologies such as substrates and electrodes, the energy loss can be reduced, and the output performance of flexible thermoelectric generator can be improved to meet the power-related requirements of more wearable technology applications.

2.1.3. Energy from human sweat

Generating electricity from biological fluids (such as blood, tears, saliva, urine and sweat, etc.), especially human sweat is one of the ideal solutions to solve the energy source of wearable and portable electronic devices. Now, there are two main ways to use sweat to generate electricity. One is a biological battery that uses enzymes or microorganisms as catalysts, using REDOX active metabolites in sweat (such as lactic acid, glucose or alcohol) to convert chemical energy in human sweat into electrical energy through enzymatic electrochemical reactions [59]. The other is a collection device that absorbs water from the evaporation of sweat and converts it into energy. Zhang et al. designed an energy harvesting device [60] that can convert absorbed sweat into electricity through a wearable energy harvesting device and power light-emitting diodes.

Building a human sweat power generation system with stable energy output and good circulation ability mainly depends on the generation, extraction, storage and transformation of sweat. The amount of sweat generated by the human body is influenced by many factors, such as gender, age, exercise status, physiological status and ambient temperature. However, sweating in hot weather and strenuous exercise is a natural process. When the human body is in this state, sweat should be utilized to generate electricity. In addition, sweat is rich in components (water, sodium chloride, a small amount of urea, lactic acid, fatty acids, etc.). Currently, only a small part of sweat components is used in reported researchers, mainly concentrated in glucose and lactic acid. There is a need to further expand and discover the application of other components in the power generation process. In addition, the sweating areas of the human body are widely distributed, covering all parts of the skin of the body, especially the forehead, neck, torso, waist, back of the hands, and forearms. The adaptability of sweat power generation devices to the human body needs to be further studied.

3. ENERGY STORAGE

The storage system after energy harvesting is a key part of the whole system, which mainly includes flexible Li-ion batteries and flexible supercapacitors. Flexible Li-ion batteries are mainly used to provide the energy required by the load for a long time, while flexible supercapacitors are mainly used to meet the energy requirements of the load in a short period of time for high-power pulse current discharge. The hybrid energy storage technology of flexible Li-ion batteries and flexible supercapacitors makes full use of different energy storage methods with different characteristics, combines energy and power energy storage, and gives full play to the advantages of their respective energy storage technologies.

3.1. Flexible Lithium-ion Battery

Li-ion batteries are extensively used in electric vehicles, mobile communications, electric energy storage, aerospace and military industry and other fields because of their advantages of high energy density, big average output voltage, small self-discharge, long cycle life and good safety performance. It is one of the most attractive energy storage systems and plays an indispensable role. However, traditional Li-ion batteries are rigid, which greatly limits their wide application in flexible electronics technology. Flexible Li-ion batteries are one of the most promising energy storage devices in wearable electronics, electronic skin, rolling shutter displays and implantable medical devices because of their advantages of being flexible, stretchable, foldable and light weight. Its two important parameters are energy density (E_l) and power density (P_l) are. They can be calculated according to Eqs. (2), (3) [61]:

$$E_l = \int_0^t \frac{IV}{m} dt \tag{2}$$

$$P_l = \frac{1}{t} \int_0^t \frac{IV}{m} dt \tag{3}$$

where I, V, m, and t are the current, electric potential, mass of the active materials, and discharging time, respectively.

In practical application, flexible Li-ion batteries should have the following characteristics: (1) High enough storage capacity under the premise of lightweight and miniaturization; (2) In various deformation states such as deformation, bending, and stretching, the performance is stable enough; (3) Environmental protection and high safety. The key to realizing fully flexible Li-ion batteries is to find, design and develop new materials and structures. Flexible Li-ion batteries are mainly composed of anode, cathode and electrolyte. Each part of the material should have high electrical conductivity, high flexibility, high thermal stability, high chemical stability and no pollution. Flexible electrode materials mainly include carbon-based, MXene, polymer and textile materials. Among these flexible electrolyte materials, the liquid electrolyte is easy to leak during mechanical deformation, so that composite solid polymer electrolyte and gel polymer electrolyte are commonly used. Table 8 shows the characteristics of flexible Li-ion batteries with different materials. A one-pot formation method of cryptomelane manganese oxide nanowires based freestanding anode for lithium-ion storage was reported. The porous electrode structure via such a one-pot synthesis makes it capable of multidimensional lithium-ion accessibility and volume change suppression. As a result, the mechanically flexible anode exhibited charge capacities of 1312 mAh g^{-1} after every 10 cycles at the current densities of 0.1 A g^{-1} [66]. The common FLIBs structures mainly include thin-film type, fiber type, wavy, island connection, paper folding and bamboo slip structures. In addition to materials and structures, the development of high-performance flexible Li-ion batteries requires changes in manufacturing processes, such as electrode fabrication, electrolyte injection and battery packaging.

Table 8. Characteristics of flexible Li-ion batteries with different materials

Materials	**Performance ($mAh\ g^{-1}/A\ g^{-1}$)**	**Remaining capacity of initial value ($mAh\ g^{-1}$)/ cycles/current density ($A\ g^{-1}$)**	**Year**	**Ref.**
fNiO/GP	998/0.1	359/600/1	2020	[62]
Co@ZnO/CNFs^{-2}	1003.2/0.1	1104.9/150/0.1	2021	[63]
Si@C NFs	1162.8/0.1	762.0/100/0.1	2021	[64]
bInSb@C	733.8/0.2C	411.5/200/3C	2022	[65]
α-MnO_2/graphene	1312/0.1	525/400/1.0	2022	[66]

3.2. Flexible Supercapacitor

The prominent advantages of a flexible supercapacitor are high power density, fast charge and discharge speed, long cycle life, good safety and stability, and can transport large currents, without memory effect, and low pollution. Especially, it can be flexibly integrated with textiles, which is ideal. The green energy storage device has received extensive attention from researchers and has broad prospects in flexible electronics. The energy density (Es) and power density (Ps) are two important parameters for evaluating supercapacitor. Their expressions respectively are as follows [67]:

$$E_s = \frac{1}{2}\frac{CV^2}{UC_i} \tag{4}$$

$$P_s = \frac{1}{4}\frac{V^2}{UC_iR} \tag{5}$$

where V, R, C and UC_i are the potential window, equivalent series resistance, total capacitance, and the mass or the volume, respectively.

The energy storage performance of flexible supercapacitor mainly depends on fabrication materials and structure design. Flexible supercapacitors generally consist of electrodes, electrolytes and separators. The electrode materials should choose active material with good electrical conductivity, high stability, large specific capacitance and good mechanical properties. Electrolyte material should have the characteristics of good ionic conductivity, strong stability, and high operating. Table 9 shows the characteristics of flexible supercapacitors of different materials. $CuCo_2S_4$ with yolk shell structure was grown on NiO nanosheets by hydrothermal method and vulcanization. The obtained specific capacitance of NiO@$CuCo_2S_4$ reached 1658 Fg^{-1}, showing the best electrochemical performance. Besides, the asymmetric supercapacitor composed of NiO@$CuCo_2S_4$ positive electrode obtains an extremely high energy density of 73 $Whkg^{-1}$ at a power density of 802 W kg^{-1} and has excellent cycle stability [72]. Developing and designing a new flexible supercapacitor structure that meets the practical needs of portability and wear ability without affecting performance is crucial for achieving seamless integration and perfect integration between the device and the human body.

Table 9. Characteristics of flexible supercapacitor with different materials

Materials	**Capacity (Fg^{-1})**	**Energy Density ($Whkg^{-1}$)**	**Power Density ($W\ kg^{-1}$)**	**Capacitance retention (%) /Cycles**	**Year**	**Ref.**
AC/AA (CaCl2)/AC	158	19.54	493.29	99.93/5000	2020	[68]
ZnO QD/NPC/CNF	644.4	33.8	800	83.1/5000	2021	[69]
Ti3C2 with MoS2 and Cu2O	1459	60.5	103	90/3000	2021	[70]
CNF(CLACF)	225	4.20	1220	97.3/10000	2022	[71]
NiO@CuCo2S4	1658	73	802	91/5000	2022	[72]

4. ENERGY MANAGEMENT

Energy management plays an important role in any energy system. The energy management of the system provides flexibility and reliability for the full utilization of the energy of the whole system. For wearable devices, it is becoming increasingly important to apply sound energy management strategies to achieve a sustainable energy system, which can not only improve the efficiency of the system, but also save energy.

Flexible lithium-ion battery and supercapacitor hybrid energy storage system gives full play to the great advantages of lithium battery energy density and supercapacitor power density and makes up for its shortcomings. Consequently, a new type of source with high energy and high-power density is formed to meet the application of the wearable self-powered system.

4.1. Work Pattern

When the whole system works properly, flexible solar cells, friction nanogenerators, piezoelectric nanogenerators and thermoelectric generators can directly power electrical devices or equipment. When energy is surplus, it can power flexible Li-ion batteries and supercapacitors. When the environment changes, such as when there is no sun and the flexible solar cells cannot provide power, other generators can continue to keep the system running. When the power is insufficient, the flexible Li-ion batteries and energy stored in a supercapacitor can be used. At this point, when the low-power device is working, the flexible lithium-ion battery can directly power. The supercapacitor can be used to power when the load or large power equipment is suddenly increased, and a spare charging port is reserved. In case of special circumstances or external power supply, a flexible Li-ion battery and supercapacitor can be charged in time.

4.2. Control Strategies

To fully and efficiently utilize the generated energy, a charge and discharge control strategy is particularly important. Energy management strategies should not only adapt to different working conditions, but also ensure more reasonable power distribution between different power sources and prolong the life of energy storage devices. There are energy management strategies based on rules, optimization and learning, as shown in Figure 3. These strategies have been maturely applied in the energy management systems of electric vehicles and photovoltaic power generation [73], as well as in the energy management of wearable self-sustainable systems.

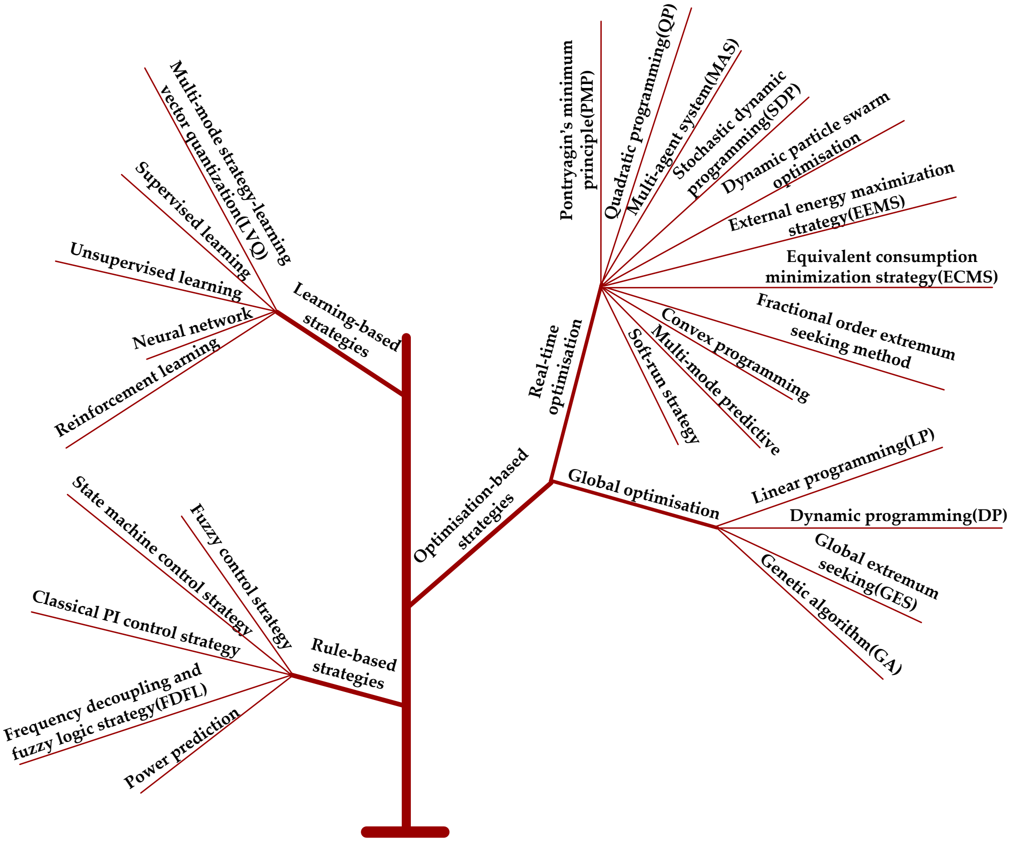

Figure 3. Classifications of the energy management strategies [74]

5. ENERGY APPLICATIONS

With the gradual increase of people's requirements for the comfort of special clothing and the safety of wearable electronic products, and the increasing number of integrated individual soldier combat system (such as the military personal combat system integrates more and more advanced instruments and equipment, medical and fire protection microenvironment monitoring and comfort of regulating equipment, wearable sport and health monitoring devices), the types and functions of various special equipment increase, and energy demand is also increasing, as shown in Figure 4.

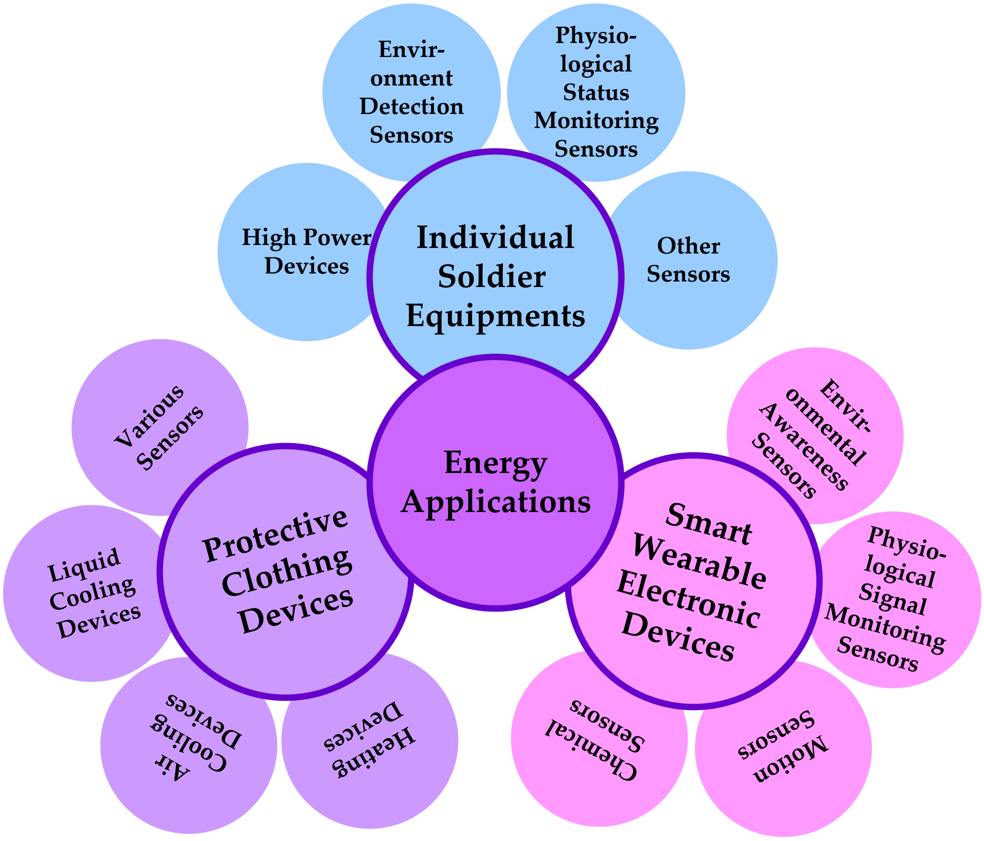

Figure 4. Energy applications

5.1. Individual Soldier Equipment

Individual soldier combat system plays a critical role in current information and future battlefield of higher technology. With the continuous progress of technology, the types and quantities of individual equipment are also increasing [75]. Electronic equipment mainly has two types. One is high-power, mainly including a radio station, a navigation positioning system, communication equipment, data terminal equipment, and so on. The other is small power, mainly including a variety of sensors, such as ambient environment detection sensors (temperature and humidity, air pressure, light intensity, radiation, etc.), soldiers' physiological status monitoring sensors (heart rate, respiration, blood pressure, temperature, etc.) [76], and other sensors (optics, infrared, thermal, etc.). Such equipment can effectively enhance individual combat capabilities and increase the need of greater power.

The electronic equipment of individual soldiers over-relies on a large number of batteries to support the power supply system, which greatly limits the flexibility of individual soldiers. It can no longer meet the needs of soldiers to cope with complex battlefield environments and complete diversified tasks. It is imperative to develop a new type of individual soldier power supply system with lightweight, small volume, large power output and long endurance. The self-sustainable system proposed cannot only provide energy for low-power equipment as a powerful supplement to the energy of individual combat systems, but also has an efficient energy control management system to provide continuous, safe and reliable electrical energy. It can effectively reduce the personal burden and greatly improve the operational efficiency.

5.2. Protective Clothing Devices

Protective clothing is the first barrier to ensuring the safety of workers. Many hazardous industries have developed protective clothing suitable for their own operations and environmental characteristics. According to different application fields, protective clothing can be divided into medical and health care, fire protection, aerospace, biochemistry, etc. With the development of intelligent clothing and intelligent wearable technology, the demand for intelligent protective clothing is becoming higher.

To improve the comfort, safety and intelligence of protective clothing, more and more electronic devices have been widely used in protective clothing, such as various sensors (temperature and humidity, gas, pressure, heat, smoke, radiation, etc.) [77] and liquid cooling, air cooling or heating devices [78]. These devices need a lot of electricity to properly run. Compared with carrying a large number of batteries as a power source, the power supply method proposed in this paper cannot only improve the safety, but also greatly improve the operation efficiency.

5.3. Smart Wearable Electronic Devices

With the rapid development of artificial intelligence, the flexible electronics and wearable technology is rising rapidly, and the wearable device industry has great development potential. The core device of wearable devices is a sensor that can sense the information of the human body in real-time, collect information about the external environment, and process the information for people's reference. The wearable sensor mainly includes environmental awareness sensors (temperature, humidity, light, wind speed, etc.), physiological signal monitoring sensors (heart rate, electroencephalogram, muscles, etc.), motion sensors (position, pressure, gesture, etc.) and chemical sensors (such as glucose, PH and lactic acid, etc.), to real-time probe of various human main signs and biomarkers. It is mainly used in medical health [79], sports [80], professional sports, and other fields [81].

The power supply unit is a key factor to ensure the continuous, real-time and reliable monitoring of sensors. The development of low-power sensors can realize energy saving, but more importantly, it is how to realize self-power of equipment. Self-powered systems that combine solar cells with human power generation technology are an ideal solution. The convergence of multiple technologies and strong demand will surely drive wearable technology to a broader market.

6. FUTURE DEVELOPMENT AND PERSPECTIVE

The huge demands for wearable electronic devices urgently require energy self-supply systems to ensure long-term, reliable and stable operation. The demand for green energy is also increasing as the energy shortages and environmental pollution increases. Combined with flexible Li-ion batteries and supercapacitors, the flexible solar cells and the body energy are used as an energy harvesting and storage device to build a self-powered energy system. It cannot only provide a good solution to the problem of energy and the environment, but it also enables the whole system to operate continuously without the need for an external power supply. This is seen as promising research for future wearable technology. This paper comments on the research progress and existing problems of wearable self-sustainable systems in recent years from four aspects: energy harvesting, energy storage, energy management and energy application. Although a lot of research has been made, further efforts are needed to achieve practical applications of fully flexible and wearable self-sustainable power sources.

(1) For energy harvesting systems, whether it is solar cells or human body power generation, it is necessary to constantly seek new technologies, new materials and design new structures to improve the energy conversion efficiency of devices.
(2) For energy storage systems, current research mainly focuses on flexible Li-ion batteries and supercapacitors. Storage efficiency is key and needs to be continuously improved and optimized in materials, structures and technologies. Further research should also explore more energy storage methods for application in wearable systems.
(3) For the energy management system, there is not much research on wearable technology. Suitable and advanced control strategies can greatly improve the entire efficiency and practicability of the system.
(4) For energy application systems, the development and design of low-power sensors applied in different fields can greatly save energy consumption.

With the continuous development, innovation and integration of energy harvesting, storage, management and application technologies, self-sustainable wearable electronic devices will play an increasingly important role in various application fields.

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