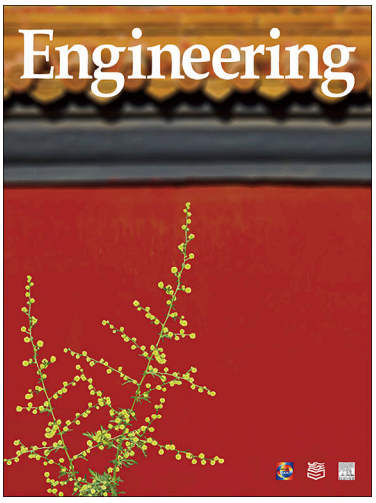
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Views & Comments

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Views & Comments

Advanced Ambient-Energy-Harvesting Technologies for the Autonomous Internet of Things

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1. Introduction

As a core component of the digital economy, Internet of Things (IoT) technology is having a profound impact on society, from productivity to lifestyle. As important components in IoT systems, sensors play major roles in detecting environmental parameters, including light, sound, humidity, and temperature, as well as biological signals, such as blood pressure and heart rate. The number of IoT nodes is predicted to reach the trillion-device level by 2030 [1]. Against this background, the traditional battery-based energy-supply mode is encountering challenges such as insufficient endurance, high maintenance costs, and high environmental impact, both in terms of waste and as a drain upon limited resources for producing batteries. Harvesting energy from ambient sources is expected to overcome this issue for autonomous IoT nodes, promoting an energy transition from the traditional mode to a sustainable energy-supply mode. In recent years, various novel ambient-energy-harvesting technologies have been developed, and remarkable accomplishments have been made. In this opinion article, we aim to analyze the status, challenges, and opportunities of established and emerging energy-harvesting technologies. We first provide an overview of current advanced ambient-energy-harvesting technologies and corresponding principles. Next, we summarize the application scenarios of these energy-harvesting technologies and outline the main challenges and prospects.

2. Advanced ambient-energy-harvesting technologies

Ambient energy sources are energy sources that are already present in the built environment; thus, the IoT based on ambient energy sources would not require dedicated sources to be specifically installed. Examples of ambient energy sources include solar energy, mechanical energy, thermal energy, electromagnetic waves, bioenergy, and so forth. Ambient-energy-harvesting technologies convert these sources into electrical energy, enabling a sustainable energy supply for electronics with low-power consumption. As shown in Fig. 1, such ambient-energy-harvesting technologies comprise photovoltaic cells (light), piezoelectric and triboelectric generators (mechanical energy), thermoelectric generators (heat), ambient radiofrequency energy harvesters (ARFEHs) (electromagnetic waves), biofuel cells (BFCs) (bioenergy), and multi-source integrated systems [2,3]. The key characteristics of these advanced energy-harvesting technologies are summarized in Table 1 [2,4–10].

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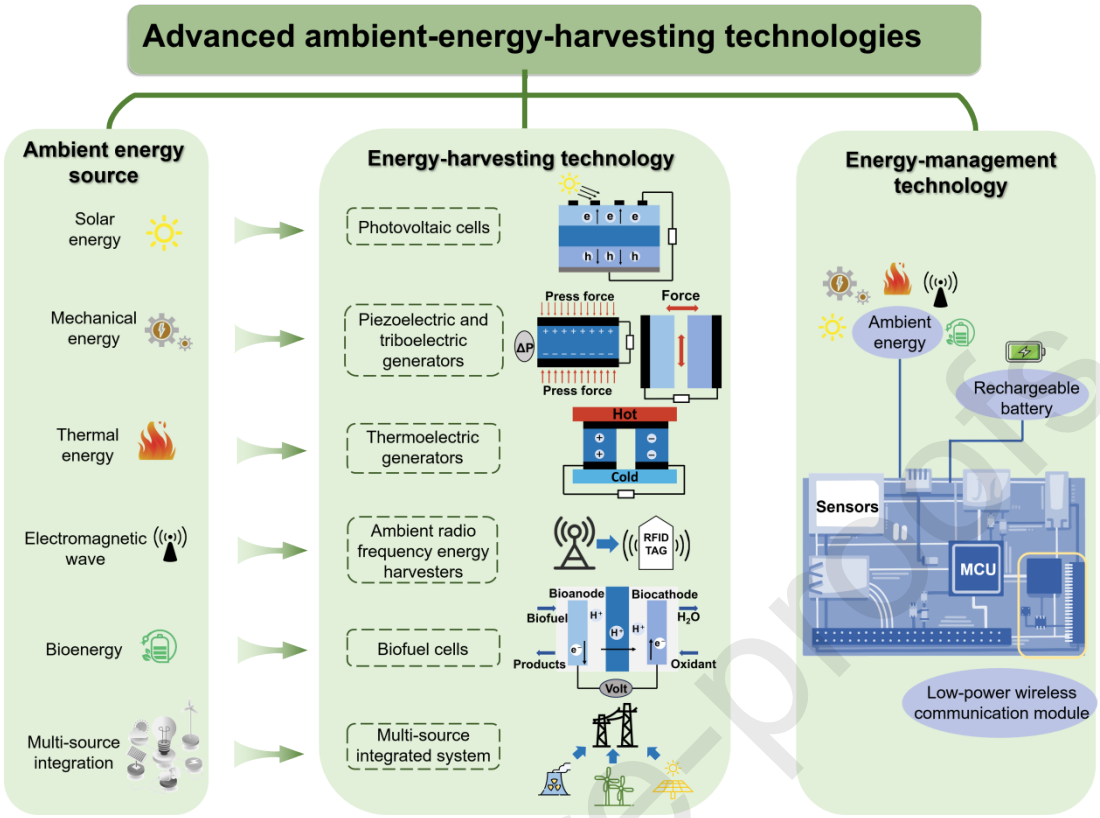


Fig. 1. Illustration of various advanced ambient-energy-harvesting technologies. Δ *P*: pressure change; RFID: radiofrequency identification; MCU: microcontroller unit.

Table 1

Advanced energy-harvesting technologies and their characteristics.

Technology	Energy source	Basic principle	Power density ($W \cdot cm^{-2}$ or $W \cdot cm^{-3}$)[a]	Pros	Cons	Refs.
Photovoltaic cells	Light	Photovoltaic effect	0.003–0.2	High conversion efficiency, high deployability, mature technology	Rely on light conditions	[2,4]
Piezoelectric/ triboelectric generators	Mechanical	Piezoelectric/ triboelectric effect	1×10^{-7}–0.1 (piezoelectric)/ 1×10^{-7}–0.05 (triboelectric)	Good flexibility, suitable for wearable devices	Medium energy density, actuation required, insufficient long-term stability	[5,6]
Thermoelectric generators	Heat	Seebeck effect	1×10^{-8}–7×10^{-5}	No moving parts, maintenance-free	Rely on temperature difference, high cost	[7]

Radiofrequency technology	Electromagnetic wave	Electromagnetic induction	1×10^{-8}–3×10^{-7}	High deployability, non-contact energy harvesting	Rely on signal strength and distance, low power density	[8]
Biofuel cells	Bioenergy	Biomolecule catalytic redox	1×10^{-7}–1×10^{-4}	Sustainable power supply	Rely on environment, limited lifespan	[9]
Multi-source integration	Multi-source	—	0.001–0.5	High reliability	High cost	[10]

[a] Power density units are $W \cdot cm^{-2}$ for photovoltaic cells, triboelectric generators, thermoelectric generators, and radiofrequency technology, and $W \cdot cm^{-3}$ for piezoelectric generators and biofuel cells.

2.1. Photovoltaic cells

The core principle of light-energy-harvesting technology is the photovoltaic effect—that is, the conversion of photon energy from natural sunlight or an artificial light source into electrical energy through photovoltaic cells. This technology is applicable to outdoor devices, such as smart street lamps and environmental monitoring sensors, as well as indoor low-power wireless IoT nodes that communicate using a range of protocols, such as radiofrequency identification (RFID) tags, Bluetooth low energy, passive Wi-Fi, Zigbee, and LoRa. Among the variety of ambient energy sources available, lighting outdoors and indoors benefits from a comparatively high energy density, making photovoltaics an appealing energy harvester for the IoT. To date, besides the silicon-based cells that currently dominate large-scale outdoor power generation and hydrogenated amorphous silicon devices for indoor photovoltaics (IPVs), a variety of next-generation photovoltaic materials and devices have been successfully explored, including compound thin-film cells, perovskite cells, and organic cells [4]. IPVs in particular have attracted increasing attention with the rapid development of the IoT. Perovskite-based IPV cells have now achieved the highest reported power-conversion efficiency of all IPV technologies, at 43.54% under white light-emitting diode (WLED) indoor light (1000 lux, 3000 K, 301.9 $\mu W \cdot cm^{-2}$) irradiation [11]. This substantially exceeds the <10% power-conversion efficiency values found for typical commercial amorphous silicon IPVs [12]. To further address the toxicity issue of lead-based perovskites, it is essential to develop efficient, stable, and environmentally friendly IPV materials. Chen et al. [1] successfully developed high-efficiency planar heterojunction antimony trisulfide (Sb_2S_3) IPVs, achieving an efficiency of 17.75% under 1000 lux WLED irradiation. The Sb_2S_3 mini-module was further employed for a self-powered IoT for the first time to realize real-time monitoring and collection of environmental data. Thus far, the efficiency of antimony selenosulfide ($Sb_2(S_xSe_{1-x})_3$) solar cells has been boosted up to 20.34% under 1000 lux indoor illumination [13].

2.2. Piezoelectric and triboelectric generators

Mechanical energy-harvesting technologies typically involve the conversion of the low-frequency mechanical energy widely available in the environment into electrical energy, with common mechanisms including the piezoelectric effect and triboelectric effect. The piezoelectric effect refers to the physical phenomenon in which materials (e.g., piezoelectric ceramics) generate electric charges under the action of mechanical stress. Flexible piezoelectric nanogenerators (PENGs) developed based on this effect not only respond sensitively to external mechanical stimuli and output electrical signals but also convert mechanical energy in the environment (e.g., vibration, friction, and air flow energy) into electrical energy, exhibiting unique advantages in fields such as electronic skin, smart wearable devices, and self-powered microelectronics [14]. For example, Xia et al. [15] designed core–shell heterogeneous composite fiber PENG devices by introducing barium titanate-coated silver (BT@Ag) particles into the composite fiber shell layer. Benefitting from the flexibility, light weight, and high deformation sensitivity endowed by piezoelectric spinning technology, this PENG device effectively captured low-frequency mechanical energy such as noise, vibration, and wind. A fully self-powered soil moisture detection system was successfully constructed by integrating this PENG device with energy-management circuits, low-power communication modules, and narrowband IoT devices. Here, the collected energy was stored in a capacitor of approximately 3300 μF through a rectifier circuit for powering the detection system. During a sensing cycle, the voltage of the supercapacitor was charged to 5 V by the PENG flag, providing sufficient power for completing a wireless sensing operation.

The triboelectric effect refers to the physical phenomenon in which contact and friction between different materials lead to charge accumulation and transfer. Triboelectric nanogenerators (TENGs) developed based on this effect can not only efficiently convert mechanical energy into electrical energy but also synchronously output electrical signals characterizing mechanical motion, demonstrating unique advantages in fields such as the IoT, sensor networks, and robotics. Compared with traditional thermoelectric and piezoelectric materials, TENGs show significant technical advantages, including a wide range of material options (e.g., polymers, metals, and ceramics) and strong adaptability to energy harvesting. In particular, they excel at utilizing common low-frequency mechanical energy, such as from human movement, equipment vibration, or air flow disturbance. This capability breaks through the traditional technology's reliance on high-frequency mechanical excitation. In an innovative application within biomedicine, researchers designed a capsule-shaped self-powered cardiac pacemaker based on the coupling principle of triboelectric and electrostatic induction, pioneering a brand-new model of biomechanical energy self-capture for medical devices [16]. This achievement lays a key technical foundation for the clinical transformation of battery-free implantable medical devices.

2.3. Thermoelectric generators

Thermoelectric energy-harvesting technology is based on the Seebeck effect, in which thermoelectric conversion is achieved through the temperature gradient at both ends of the material, converting the naturally occurring temperature differences in the environment (e.g., the temperature differences between the human body and the air, or between equipment and the environment) into electrical energy. The core mechanism is based on the fact that the temperature difference generates an electrical potential difference, and the heat flux density determines the output power produced. This characteristic makes this technology particularly suitable for efficient utilization in an environment with a temperature difference of ≤20 °C. Recent studies have shown that the exploration of efficient thermoelectric materials (e.g., nanostructured materials) and the optimization of thermal-management designs have significantly increased energy-harvesting efficiency, especially in the utilization of waste heat from industrial equipment and vehicle exhaust. Liu et al. [17] from Shanghai Jiao Tong University developed a thermoelectric chip based on micro-electromechanical systems (MEMS), which is capable of generating electricity based on a very small temperature difference of 0.001 K. This breakthrough holds great significance for efficient temperature sensing and power generation through radiant cooling, opening up new avenues for sustainable energy. Jiang et al. [18] achieved the integration of photothermal management–electrical energy conversion through the design of nanocomposite fabrics with a double-layer structure that enable a significant cooling effect of 2–3 °C below the ambient temperature. When such fabrics are integrated with flexible thermoelectric devices, the cooling performance of the nano-fabrics effectively reduces the operating temperature of the thermoelectric device and improves the thermoelectric conversion efficiency. The innovative application of thermoelectric technology in the field of human energy recovery offers a feasible solution for the long-term operation of low-power IoT devices in scenarios without external power sources.

2.4. Ambient radiofrequency energy harvesters

Radiofrequency (RF) signals widely distributed in the ambient environment (e.g., wireless communication and broadcast transmission) can be converted into direct-current power by ARFEHs, which typically comprise a broadband antenna and a rectifying device as the essential elements. Compared with other traditional ambient energy sources such as solar and wind power, RF energy has significant advantages: all-weather availability unaffected by day, night, or climate; easy accessibility naturally compatible with wireless communication networks; and low-power integration capabilities that can be adapted to small electronics. In response to the performance bottleneck of traditional RF rectifiers in low-power environments, Sharma et al. [8] from the National University of Singapore achieved an important breakthrough based on material innovation in the development of the rotary rectifier antenna: This device can operate stably within a wide power range of –62 to –20 dBm (covering typical ambient RF signals), overcoming the reliance of traditional rectifiers on high input power. The research group successfully employed the spin rectifier to continuously power commercial temperature sensors, where the device exhibited outstanding weak-signal energy-capture capabilities. Ambient RF energy is expected to be another core green-energy supply solution for the large-scale deployment of passive IoT electronics. Yang et al. [19] proposed a non-von Neumann architecture intelligent fiber system, which directly utilizes the ambient electromagnetic field to drive micro-inductive coils inside the fibers to generate induced currents, while simultaneously sensing human movement or physiological signals in real time through impedance changes. The presence of the human body in non-von Neumann architecture wearable devices (including body occlusion during normal wearing) is the core foundation of the devices' energy collection and stable performance. It has been found that the electromagnetic energy collected under human body coupling is significantly higher than that under air coupling within the range of 0–15 MHz. This finding confirms the advanced nature and promising prospects of the non-von Neumann architecture. The integrated design of energy harvesting, information perception, and wireless transmission enables a single fiber to serve as both an energy-harvesting unit and a sensor node and communication

antenna, providing unique advantages including battery-free operation, high integration, and self-sustaining operation in the field of wearable devices. That said, unlike other energy-harvesting methods, the design of RF energy-harvesting devices must consider the communication regulatory restrictions in different regions, including available frequencies and maximum output power, which affect the amount of energy that can be collected.

2.5. Biofuel cells

Bioenergy-harvesting technology captures the energy generated by biochemical reactions or life activities. Microbial fuel cells (MFCs), as typical biological batteries, utilize the metabolic processes of electroactive microorganisms to convert the chemical energy of organic substances (e.g., glucose and lactic acid) into electrical energy. The essence of its working principle is that, when microorganisms decompose a substrate, electrons transfer to the extracellular space through the respiratory chain, resulting in an electric potential difference between the electrodes. After miniaturization and flexible design, such devices can directly meet the power-supply requirements of low-power devices such as smartwatches and pacemakers. Chen et al. [20] developed a wearable BFC based on metal gel electrode materials, using ascorbic acid (AA) in human sweat as the fuel. An oxidation reaction was catalyzed by electroactive enzymes (e.g., AA oxidase), and oxygen in the air was used as an oxidant to complete the electron transfer, forming a stable potential on the surface of the flexible electrode. The anode and cathode materials used in this device enable it to achieve a maximum output power density of 35 $\mu W \cdot cm^{-2}$ at a low AA concentration of 0.5 $mmol \cdot L^{-1}$ and possess a long-term stability of 30 days. This device can monitor the AA concentration in sweat in real time without an external power supply, and the electrical energy it generates not only drives the sensor module but also transmits data to the terminal equipment via radio channels.

2.6. Multi-source integrated systems

Because ambient energies are inherently discontinuous and unstable, a single-source energy-harvesting system is restricted by the specific ambient conditions, such as a too-low wind speed or insufficient light illumination. By integrating various energy-harvesting technologies (e.g., triboelectric, electromagnetic induction, and photovoltaic), a multi-source integrated system allows for the complementary harvesting of different energy sources. Moreover, through modular design and intelligent regulation, a multi-source integrated system can offer greater ambient adaptability, significantly improving the reliability and energy-utilization rate of the energy-harvesting system. For instance, Peng et al. [10] proposed a triboelectric–electromagnetic hybrid wind-energy-harvesting and sensing device (TEH-WSD) comprising a triboelectric–electromagnetic hybrid generator (TEHG) and a multi-channel triboelectric nanogenerator (MC-TENG) for wind direction and speed sensing. When the light is weak, wind energy is collected to supplement the power supply; when the wind speed is insufficient, ambient vibration energy is utilized to maintain operation. This significantly reduces the system's reliance on a single energy source, ensuring a continuous and stable energy supply in complex environments and increasing the reliability of energy supply by 30%–50%. The TEH-WSD can collect wind energy through TEHG to power small electronic equipment such as temperature and humidity sensors. Moreover, the integrated MC-TENG can directly convert the mechanical signals of wind speed and direction into electrical signals, enabling the real-time monitoring of ambient parameters without additional energy supply.

3. Application scenarios for the autonomous IoT

By leveraging ambient-energy-harvesting technologies and integrating wireless-transmission modules, a self-powered IoT system can synchronize data to terminal electronics, supporting remote monitoring and intelligent decision-making. This provides a self-powered solution with no external power supply for unattended scenarios such as smart agriculture monitoring and field sensor networks. At present, ambient-energy-harvesting technologies have a wide range of application scenarios in modern life, production, and science and technology, with typical contexts including smart homes, smart factories, smart agriculture, smart power, medical health, and wearable devices, as shown in Fig. 2 [21]. For example, photovoltaic cells enable more powerful and aesthetic wireless sensors in smart buildings and smart homes. Han et al. [22] proposed an all-weather, self-sustaining flexible node based on perovskite solar cell (PSC) modules. This IoT node is applicable to all irradiance and enables comprehensive three-dimensional data collection in an indoor–outdoor–aerial environment. With its powerful wireless-transmission capability and intelligent perception function, the flexible PSC module and self-sustaining flexible node (FPSM-SSN) system can not only intelligently perceive temperature changes and realize the automatic control of smart homes but also show great application potential and broad development prospects in fields such as smart cities, automation, and human–computer interaction.

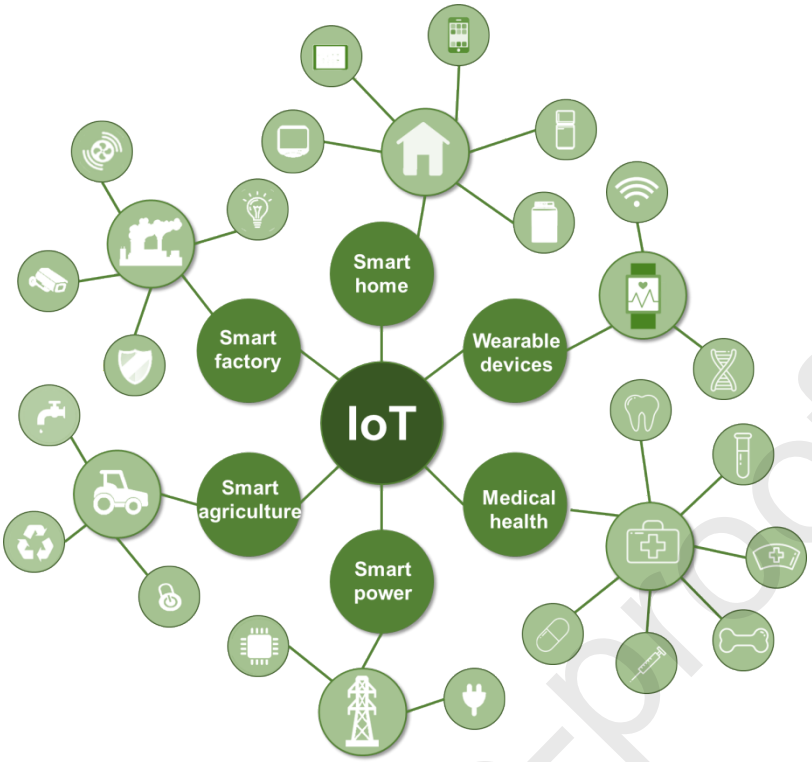


Fig. 2. Application scenarios for different advanced ambient-energy-harvesting technologies for the autonomous IoT.

In recent years, wearable monitoring devices have become a hot topic for scientific research, especially in the field of medical health detection, where light-weight and intelligent wearable devices play an irreplaceable role. Wearable health-monitoring electronics integrate various sensors to monitor users' physiological data in real time, helping users better understand and manage their own health conditions. Ding et al. [23] developed a fingertip-wearable microgrid system driven by sweat that integrates autonomous energy management and efficient metabolic monitoring. Specifically, the sweat from fingertips, as a natural biochemical fuel, is collected by microfluidic paper channels through osmosis and guided into BFCs. In the BFCs, metabolic products such as the lactic acid in sweat undergo redox reactions under the action of enzymes, thereby generating electrical energy. The electrical energy is then used to charge a scalable AgCl–Zn battery, providing stable energy support for the entire system. The *in-situ* energy-supply mode breaks through the traditional biosensor's reliance on batteries and continuously supplies energy utilizing the body's own metabolic products. This fingertip-wearable microgrid system is expected to provide a simple and feasible solution for future wearable electronic devices and health management.

4. Conclusions and outlook

To date, there are nearly 17 billion IoT nodes worldwide, the majority of which rely on cables or batteries for power. This approach not only incurs high maintenance costs but also increases the risk of data loss during power outages. Various emerging ambient-energy-harvesting technologies provide feasible solutions for building self-powered IoT systems. By harnessing energy from the surrounding environment, IoT devices can operate autonomously without the need for frequent battery replacements or external power sources. This not only increases the efficiency and lifespan of IoT devices but also reduces their environmental impact by promoting energy sustainability. As the IoT ecosystem continues to expand, the development and integration of energy-harvesting technologies will be essential in creating a more efficient, interconnected, and environmentally friendly network of smart devices.

However, despite the significant progress made in ambient-energy-harvesting technologies, as cutting-edge emerging technologies, they still present a series of challenges, such as power density and efficiency limitations, environmental adaptability and reliability, energy management and system integration, cost and commercialization bottlenecks, and device miniaturization and wearability. The wide deployment of self-powered IoT nodes is still constrained by the lack of a stable

and continuous energy supply, as well as limited power density. Fig. 3 summarizes the challenges presented by various ambient-energy-harvesting technologies and the next steps that must be focused on.

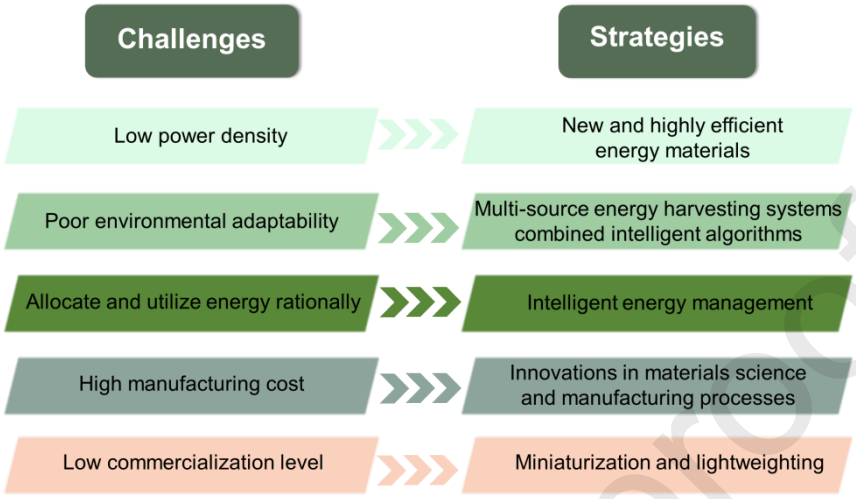


Fig. 3. Challenges presented by ambient-energy-harvesting technologies and potential strategies.

(1) **Increasing power density.** At present, the low power density of ambient energy sources (e.g., low-intensity vibration, scattered light) results in limited energy harvesting and further restricts application scenarios. How to further increase the power density remains the focus of ambient-energy-harvesting technologies. Against this background, exploring new efficient and low-cost energy-harvesting materials (e.g., emerging perovskite-inspired absorbers for IPVs) and fully taking advantage of advanced nanotechnologies (e.g., two-dimensional materials, special nanostructures) are expected to further increase the energy density of various technologies.

(2) **Improving environmental adaptability.** Due to the limitations of environmental conditions (e.g., light intensity, temperature difference, and vibration frequency), ambient energy shows significant intermittency and volatility, leading to difficulty in achieving real-time matching between energy supply and load demand. This may further cause performance fluctuations in equipment or even power outages. The limitations of single-source energy harvesting have prompted multi-source energy-harvesting systems to become the research emphasis in the future. The use of intelligent algorithms such as reinforcement learning and fuzzy control can contribute to the dynamic optimization and autonomous management of the system, thereby improving the stability of the system in complex environments. By integrating with edge computing and fifth-generation (5G) technology, ambient-energy-harvesting technologies could provide reliable and sustainable energy support for a wider range of IoT applications.

(3) **Optimizing energy management.** For seamless IPV integration in IoT electronics, series-connected cell modules and appropriate power-management hardware are crucial to maximize energy extraction. The energy-management system (EMS) is the core module that ensures the efficient storage, distribution, and utilization of the weak ambient energy collected. Due to the intermittent, low power density and fluctuating characteristics of ambient energy, the EMS must dynamically coordinate energy collection, storage, conversion, and load requirements. Each module works collaboratively to achieve a closed loop of energy collection–conversion–storage–distribution, thereby maximizing the energy efficiency and reliability of the system. The energy-management algorithm and system integration design of multi-source energy-harvesting systems are rather complex, as it is necessary to coordinate the dynamic characteristics of different energy sources and consider the application scenarios and requirements at the load end. How to efficiently collect, store, and allocate multi-source energy remains a key challenge. Intelligent energy management might be an important research direction in the next step. This requires the design of advanced algorithms for the unified management and distribution of energy, such as the adoption of adaptive control, predictive control, and other methods. An adaptive control algorithm is suggested to automatically regulate the energy-allocation strategy according to the current operating status of the system and the energy collection and storage conditions, in order to adapt to constantly changing ambient conditions.

(4) **Reducing costs to realize commercialization.** At present, the manufacturing costs of certain high-efficient energy-harvesting devices are relatively high (e.g., due to advanced nanomaterials and semiconductor materials). Moreover, energy-conversion micro-devices and high-precision energy-management chips rely on imports or special processes and have high unit prices, making it difficult to achieve large-scale commercialization. In terms of materials utilization, costs could be reduced by exploring inexpensive electrode materials (e.g., carbon and copper) to replace precious metal electrodes, recycling waste materials from energy-harvesting devices (e.g., piezoelectric and thermoelectric modules), and carrying out the independent research and development of RF chips (e.g., GaN- or SiC-based RF chips). In terms of device manufacturing, establishing a modular production chain and adopting precision processing technology and automated assembly processes are critical to achieve commercialization.

(5) **Miniaturization of energy-harvesting devices.** For wearable devices and implantable medical devices, energy-harvesting modules must be highly miniaturized while maintaining high energy densities. These advanced technologies still suffer from a low commercialization level and have limitations in terms of size, weight, and flexibility, making it difficult to meet users' demands for device portability. To address these issues, the core components of these devices must be lightweight and functionally integrated materials. Advanced micro–nano processing and packaging technologies would also help to promote device miniaturization.

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References

[1] Chen X, Shu X, Zhou J, Wan L, Xiao P, Fu Y, et al. Additive engineering for Sb_2S_3 indoor photovoltaics with efficiency exceeding 17%. Light Sci Appl 2024;13(1):281.

[2] Pecunia V, Occhipinti LG, Hoye RLZ. Emerging indoor photovoltaic technologies for sustainable Internet of Things. Adv Energy Mater 2021;11(29):2100698.

[3] Liu R, Wang ZL, Fukuda K, Someya T. Flexible self-charging power sources. Nat Rev Mater 2022;7(11):870–86.

[4] Green MA, Dunlop ED, Yoshita M, Kopidakis N, Bothe K, Siefer G, et al. Solar cell efficiency tables (version 65). Prog Photovolt Res Appl 2025;33(1):3–15.

[5] Bairagi S, Shahid-ul-Islam, Shahadat M, Mulvihill DM, Ali W. Mechanical energy harvesting and self-powered electronic applications of textile-based piezoelectric nanogenerators: a systematic review. Nano Energy 2023;111:108414.

[6] Du T, Chen Z, Dong F, Cai H, Zou Y, Zhang Y, et al. Advances in green triboelectric nanogenerators. Adv Funct Mater 2024;34(24):2313794.

[7] Yan Q, Kanatzidis MG. High-performance thermoelectrics and challenges for practical devices. Nat Mater 2022;21(5):503–13.

[8] Sharma R, Ngo T, Raimondo E, Giordano A, Igarashi J, Jinnai B, et al. Nanoscale spin rectifiers for harvesting ambient radiofrequency energy. Nat Electron 2024;7(8):653–61.

[9] Wang X, Han F, Xiao Z, Zhou X, Liu X, Chen Y, et al. 3-D printable living hydrogels as portable bio-energy devices. Adv Mater 2025;37(18):2419249.

[10] Peng W, Ni Q, Zhu R, Fu X, Zhu X, Zhang C, et al. Triboelectric-electromagnetic hybrid wind energy harvesting and multifunctional sensing device for self-powered smart agricultural monitoring. Nano Energy 2024;131(Pt B):110272.

[11] Ma Q, Ma M, Liu L, Yang P, He W, Zhang X, et al. Wide-band-gap perovskite solar minimodules exceeding 43% efficiency under indoor light illumination. Device 2023;1(6):100174.

[12] Grandhi GK, Koutsourakis G, Blakesley JC, De Rossi F, Brunetti F, Öz S, et al. Promises and challenges of indoor photovoltaics. Nat Rev Clean Technol 2025;1(2):132–47.

[13] Gao H, Li J, Peng X, Huang Y, Zhao Q, Wang H, et al. Band gap adjustable antimony selenosulfide indoor photovoltaics with 20% efficiency. Sol RRL 2024;8(18):2400389.

[14] Tang W, Sun Q, Wang ZL. Self-powered sensing in wearable electronics—a paradigm shift technology. Chem Rev 2023;123(21):12105–34.

[15] Xia J, Lu H, Chen G, Lin D, Yang W, Liu C, et al. High performance piezoelectric nanogenerator by fiber microstructure engineering toward self-powered wireless sensing system. Nano Energy 2024;128(Pt B):109901.

[16] Zheng Q, Wei Y, Li D, Zeng Z, Li Z. Choosing energy sources for battery-free pacemakers. Device 2025;3(6):100746.

[17] Liu Z, Zhang S, Wu Z, Mu E, Wei H, Liu Y, et al. High-performance integrated chip-level thermoelectric device for power generation and microflow detection. Nano Energy 2023;114:108611.

[18] Jiang W, Liu JZ, Wang Z, Wang H, Liu X, Wang L, et al. Scalable self-cooling textile enabled by hierarchical nanofiber structures with thermoelectric properties. Device 2025;3(1):100564.

[19] Yang W, Lin S, Gong W, Lin R, Jiang C, Yang X, et al. Single body-coupled fiber enables chipless textile electronics. Science 2024;384(6691):74–81.

[20] Chen Y, Wan X, Li G, Ye J, Gao J, Wen D. Metal hydrogel-based integrated wearable biofuel cell for self-powered epidermal sweat biomarker monitoring. Adv Funct Mater 2024;34(42):2404329.

[21] Chen X, Hu H, Zhou J, Li Y, Wan L, Cheng Z, et al. Indoor photovoltaic materials and devices for self-powered Internet of Things applications. Mater Today Energy 2024;44:101621.

[22] Han W, Nie R, Yin B, Zhang J, Qiu S, Wei J, et al. All irradiance-applicable, perovskite solar cells-powered flexible self-sustaining sensor nodes for wireless Internet-of-Things. Adv Funct Mater 2025;35(32):2425697.

[23] Ding S, Saha T, Yin L, Liu R, Khan MI, Chang AY, et al. A fingertip-wearable microgrid system for autonomous energy management and metabolic monitoring. Nat Electron 2024;7(9):788–99.

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