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# Harnessing Energy for Wearables: A Review of Radio Frequency Energy Harvesting Technologies

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**Abstract:** Wireless energy harvesting enables the conversion of ambient energy into electrical power for small wireless electronic devices. This technology offers numerous advantages, including availability, ease of implementation, wireless functionality, and cost-effectiveness. Radio frequency energy harvesting (RFEH) is a specific type of wireless energy harvesting that enables wireless power transfer by utilizing RF signals. RFEH holds immense potential for extending the lifespan of wireless sensors and wearable electronics that require low-power operation. However, despite significant advancements in RFEH technology for self-sustainable wearable devices, numerous challenges persist. This literature review focuses on three key areas: materials, antenna design, and power management, to delve into the research challenges of RFEH comprehensively. By providing an up-to-date review of research findings on RFEH, this review aims to shed light on the critical challenges, potential opportunities, and existing limitations. Moreover, it emphasizes the importance of further research and development in RFEH to advance its state-of-the-art and offer a vision for future trends in this technology.

**Keywords:** radio frequency energy harvesting; wearable device; power efficiency; antenna; power management

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## 1. Introduction

Energy harvesting (EH) is the process through which energy is derived from external sources, captured, and stored for small, wireless autonomous devices, such as those used in wearable electronics and wireless sensor networks. The sources of EH include wind energy, thermal energy (mechanical load), salinity gradients (temperature gradients), kinetic or ambient energy (vibrations), and solar energy (light). Among them, the RFEH system has been developed to wirelessly power and enable device operation, harnessing the RF signals from the environment. This technique circumvents the need for rigid and dense batteries and has been authenticated through design, simulation, optimisation, and experimental results. However, the development of effective and efficient RF electronics for off-body and on-body communications in applications still poses significant challenges [1–3].

Radio frequency (RF) refers to the oscillation rate of an alternating electric current or voltage, as well as the electric, magnetic, or electromagnetic field associated with it. The electromagnetic radiation spectrum encompasses a range of frequencies, spanning from 3 kHz up to 300 GHz. These frequencies are utilised for wireless communications or radar signals. RF waves are generated when an alternating current passes through a conductive material [4]. They prove advantageous for wireless energy harvesting, enabling the wireless powering and operation of devices even in scenarios with limited RF energy available. The characteristics of RF include the following: its ability to penetrate walls, its lack of requirement for a direct transmission route, low power consumption (less than

1mW of power), a good operating range (3 to 30 m), and support for data rates up to 1 to 2 Mbps. The applications of RF technology encompass telemetry, wireless meter reading, remote control, vehicle monitoring, wireless data terminals, access control systems, robot remote control, biological signal acquisition, wireless home security systems, and more [5,6]. Currently, RF transmission from hundreds of thousands of radio transmitters is prevalent worldwide, including mobile base stations, cellular phones, and television broadcasting terminals [7]. In fact, RF is helpful in wireless energy harvesting because it is used to directly power up battery-less systems and for battery activation purposes. Also, it can be used for remote battery recharging, waking up sensors in sleep mode, and to power up wireless sensor networks (WSNs).

Energy harvesting has gained significant attention in recent years as a promising field for capturing and converting ambient energy into usable electrical power. This approach offers distinct advantages, especially in applications where conventional battery-based power sources are not feasible or have limitations in terms of lifespan and power density. By harnessing energy from sources like light, heat, vibration, and radio frequency (RF) signals, energy harvesting technologies provide a sustainable and self-sufficient solution for powering various devices and systems. This growing interest in energy harvesting stems from its potential to address challenges in renewable energy, wireless sensor networks, Internet of Things (IoT), and wearable electronics.

Zhang et al. [8] conducted research on the design of radio frequency (RF) energy harvesting for battery-less self-sustaining applications. To enhance power transmission, an antenna and rectifying circuit were designed, utilising a T-shape LC matching network in between. The designed antenna array facilitates the harvesting of RF power in multiple frequency bands, and the received RF power is improved and utilised for powering electronic devices. The study demonstrates the potential of RF energy harvesting for powering low-power devices and highlights the importance of optimising the antenna design and matching circuit for maximum power transfer efficiency. This research is relevant for the development of sustainable and energy-efficient wireless communication systems for the Internet of Things (IoT) and other applications.

Adami et al. [1] emphasized the importance of the material used in the fabrication of antenna designs, as it directly impacts the amount of RF energy that can be harvested and wirelessly transferred to power electronic devices. Fabric antennas, which are made of textile materials, are gaining popularity due to their flexibility and comfort in wearable technology applications [9–11]. On the other hand, rectenna arrays are used to convert electromagnetic energy into direct current (DC) electricity. These arrays consist of multiple dipole elements and are useful in harvesting RF energy from various sources, such as ambient radiation, Wi-Fi signals, and cellular networks. The size and arrangement of rectenna elements affect the overall efficiency of energy conversion, making it an important consideration in the design of energy-harvesting systems. Figure 1 further explains the components of the RF power harvesting system.

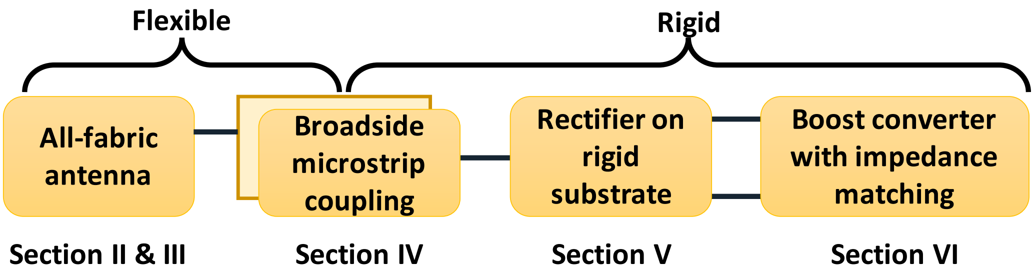

**Figure 1.** Block diagram of the radio frequency (RF) power harvesting system [1].

Integrating wearable electronics with RF wireless power transfer is not an easy task and currently faces several challenges for obvious reasons. These challenges include accounting for the stability, efficiency, and radiation pattern of the antenna on the moving body [9]. According to [10], the main challenge in the RF-powered dual-hop relay system is achieving high energy harvesting is compounded by the inherent nature of RF propagation, which is associated with very high transmission path losses. Additionally, the interconnections between the rigid and flexible subsystems are taken into consideration, along with the power management of the circuits, to maximise the power output of the device [11]. Broadside and omnidirectional antennas have been employed to fabricate textile rectennas operating in the UHF to millimeter-wave (mmWave) frequency range [12–15]. However, the rectennas described above have only been studied and characterised as steady-state continuous power sources. In the past, rectennas coupled with energy storage devices have been the subject of system-level experiments. For example, rectennas were connected to a power management integrated circuit (PMIC) boost converter in a commercial setting [16–19]. In [17], a sensor node was charged for 8 min by an incident RF power density of 12.6 W/cm$^2$ before being powered by a 7 mF commercial supercapacitor. In [12], a 1.3 mF electrolytic capacitor was charged, while a textile-based rectifier was described. In [20], a rectenna integrated with an electrolytic capacitor and a buck converter with a range of up to 2 m was presented as a sensor node for railway monitoring. For sub-W/cm$^2$ power densities, a 3D-printed enclosure incorporating RFEH and a solar cell was employed to charge an electrolytic capacitor through a boost converter IC.

Currently, electromagnetic waves are utilised to power implantable biomedical devices, enable wireless charging, support WSN (Wireless Sensor Network) nodes, and power other devices. Radio frequency recording is especially important in biomedical devices, especially when implanted in the body, to extend the life of the batteries in their structure. RF has become an important energy source due to the abundance of 300 MHz to 3000 MHz RF waves in various wireless applications such as broadcast, mobile, satellite and Wi-Fi communications [21]. This abundant energy can be harvested and stored in batteries for IoT applications.

In summary, the integration of wearable electronics and RF wireless power transfer poses significant challenges due to various reasons [21]. Firstly, the interconnections between rigid and flexible subsystems must be carefully designed to ensure reliable and contactless electrical connections. Secondly, the stability and efficiency of the antenna on a moving body must be considered to ensure continuous power transfer. Lastly, effective power management strategies must be employed to maximise the power output of the device while minimising power losses. Despite these challenges, the potential benefits of RF wireless power transfer for wearable electronics, such as self-sustainability, convenience, and safety, make it a promising technology for future applications. This article reviews the state-of-the-art for RFEH in the three main areas of materials, antenna design and power management to provide an overview of the technology and its future trend.

## 2. Materials

In [15], a review is conducted on textile applications in antenna design, with an emphasis on developments in e-textiles, including surface resistivity. The use of textiles in antenna design aids in collecting health-related data and communicating data with devices. This application of textiles in electrical engineering, known as smart clothing or e-clothing, dates back to 1993.

The efficiency of the antenna in transmitting wirelessly available energy is determined by the RF power harvested. Additionally, the resistivity of a material is important as it enables the use of suitable materials in the appropriate places in electrical and electronic components. Textile-based antennas demonstrate potential in wearable devices for communicating various information with other electronics or computers. Integrating wearables directly into clothing (smart or e-clothing) is more convenient than attaching them to the body [22,23]. For example, surface resistivity and non-conducting textiles: surface resistivity is used to evaluate insulative materials where high resistance characteristics are desirable [24]. Non-conductive materials, also known as insulators, either prevent or block the flow of electrons. This aspect affects the wireless energy transfer to devices, as it bridges the connectivity to the flow of electrons.

Therefore, there is a demand for using materials with the lowest loss and thicker structures [25]. Thicker materials with high resistivity help reduce the electric fields on the body, thus lowering the antenna performance itself for the same input power. Variation in distance also aids in minimising harm to the user's body. The use of multi-band antennas is also beneficial in assessing the performance of textile devices. Hence, it is necessary to choose or select suitable materials, as shown in Table 1 The choice of material in fabricating the antenna design is of utmost importance. It determines the amount of RF energy that can be harvested and transferred wirelessly to power system devices, as depicted in Figure 1. Thus, it enhances the efficiency and widens the frequency range of the RF energy harvesting system. The focus on fabric materials in this selection is to cater to a wide range of device applications and improve the efficiency of the RF devices. The selection of cotton fabrics and polyester materials is due to their extensive use in the industry, as detailed in Table 1.

**Table 1.** Surface resistivity of some commercial e-textiles and permittivity of commonly used fabrics [15].

| **E-Textile** | **Surface Resistivity ($\Omega^2$)** |
|---|---|
| Silver jersey knit fabric | 2 |
| Silverell fabric | 5 |
| Nickel copper ripstop fabric | 0.03 |
| Pure copper polyester taffeta fabric | 0.05 |
| Ripstop silver fabric | 0.25 |
| Commonly Used Fabrics Permittivity | |
| Fabrics | Permittivity ($\times 10^{-2}$) |
| Wash cotton | 151 |
| Curtain cotton | 147 |
| Polyester | 144 |
| Polycot | 156 |
| Jeans cotton | 167 |
| Floor spread | 146 |

The selected materials discussed above focus solely on fabric materials for a wide range of applications. The topmost materials are polyester and cotton fabrics, widely used in the garment industry. Additionally, there is UV-curable polyurethane acrylate-based standard interface material and a waterproof interface material from Smart Fabric Inks Limited. In this work, the two-line method, as shown in Table 2 above, is used to characterise various flexible materials and textiles. It provides an estimation of the material characteristics over a relatively wide frequency range. It was observed that the loss tangent for these materials is estimated to have better or similar accuracy than that obtained with FR4.

Furthermore, in [26], a research review is conducted on materials, structure, and innovative features in communication and sensing. It is noted that flexible materials in a low-profile structure are required when used on different parts of the human body for wearable antenna design. The low-profile antenna structure can also be mounted on buildings and cars. These antennas often have high input impedance and maintain small height and width, mostly in the form of microstrip patch antennas [27]. An antenna system comprises a source, destination, and relay, where the source generates and transmits the signal, the destination receives and processes the signal, and the relay acts as an intermediary for enhanced communication [28].

**Table 2.** RF harvester system.

| Dedicated RF Harvester Systems | Ambient RF Harvester Systems |
|---|---|
| They have dedicated RF sources | They have ambient RF sources. These are sources that are not solely dedicated to providing RF energy transfer. |
| A cost of constructing RF sources to specifically provide the RF energy to be used is incurred. As such, the RF energy is not free. | The RF energy is essentially free. It uses already constructed RF sources. |
| Suitable for devices with QoS (Quality of Service) constraints, and they are fully controllable. | Not controllable. |
| Provide higher power densities, and it is a predictable energy supplier. | It is not a predictable energy supplier. |

Moreover, it is estimated that approximately 28 billion smart devices will be connected worldwide using legacy technologies in 2021. This connection will be highly advantageous for applications in consumer electronics, building security, and automation. Once accomplished, RF energy will provide improved value for wireless energy harvesting globally.

Additionally, surface resistivity is utilised to evaluate insulative materials, where high resistance characteristics are desirable, as indicated in Table 2. Overall, wireless energy harvesting plays a vital role in ensuring the harvest and storage of RF energy to power electronic devices remotely while also promoting self-sustainability and environmental friendliness by harnessing RF energy from the surrounding environment, as shown in Figure 2. With the advancements in broadcasting technologies, the availability of ambient RF power density has exponentially increased. Sources of RF power density include wireless fidelity (Wi-Fi) signals [13–15,29,30], AM/FM radio [31,32], mobile base stations [1,33–37], television (TV), and digital television (DTV) [16–18,38], as illustrated in Figure 2. Top of Form.

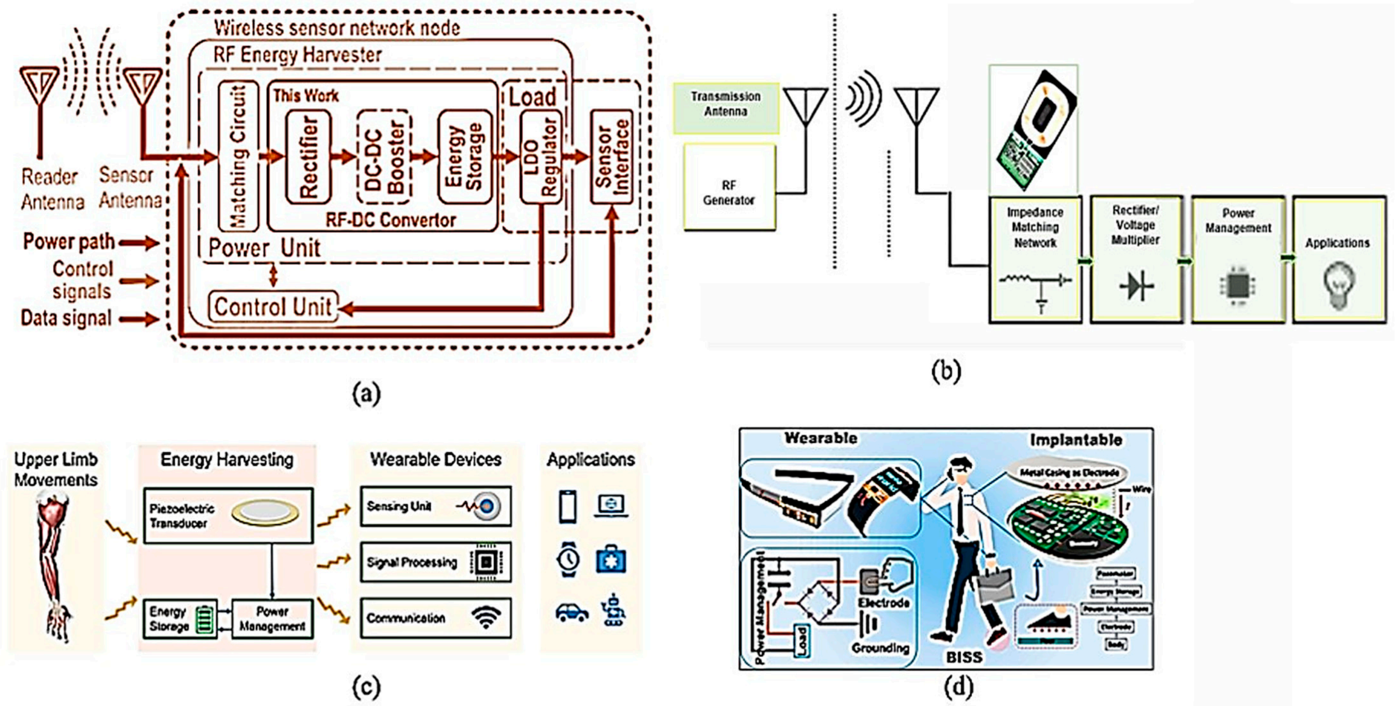

**Figure 2.** (**a**) Radiofrequency (RF) energy harvester block diagram [39]. (**b**) An overview of RF energy harvesting [40]. (**c**) Piezoelectric energy harvesting for applications involving wearable, self-powered upper limbs [41]. (**d**) Devices that harvest energy include the reintroduction of device power [42].

A self-powered triboelectric tactile sensor with metallised nubs, which enables the sensor to generate its own power, is shown in Figure 3. The flexible printed circuit plays a crucial role in the system. This flexible printed circuit features a grating slider that enhances its flexibility, as well as a microfluidic-based sweat sensor diagram that is seamlessly integrated with the flexible circuitry, as illustrated. These components work together to enable the ultra-thin epidermal piezoelectric sensor to accurately monitor arterial pulses in real time while ensuring comfort and flexibility for the wearer [43].

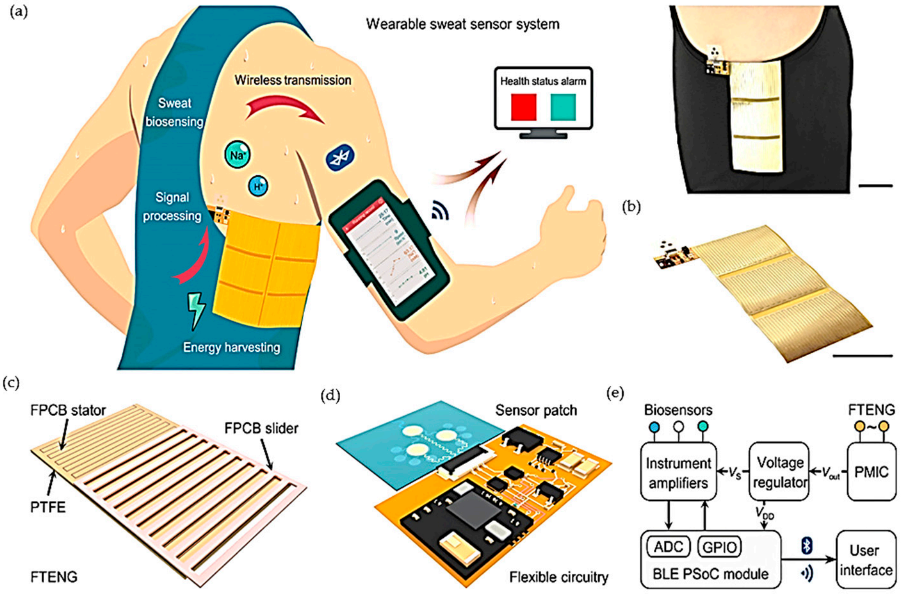

**Figure 3.** Ultra-thin epidermal piezoelectric sensor for self-powered, real-time arterial pulse monitoring [43]. (**a**) Triboelectric tactile sensor with metallised nubs that is self-powered. (**b**) 4 cm optical image of a flexible printed circuit (**c**–**e**) Flexible printed circuit with grating slider, microfluidic based sweat sensor diagram integrated with flexible circuitry, and clock diagram of overall system.

Figure 4a illustrates commonly used configurations for RF energy harvesting setups. The depicted setup demonstrates the viability of powering multiple wearable devices through RF energy harvesting, thereby enabling self-sustainability and eliminating the need for external power sources in various applications, including healthcare monitoring, sports, and IoT devices [44]. In Figure 4b, the illustration demonstrates the contact of both signal and ground electrodes of the transmitter and receiver with the skin, facilitating energy harvesting from this contact area [45,46].

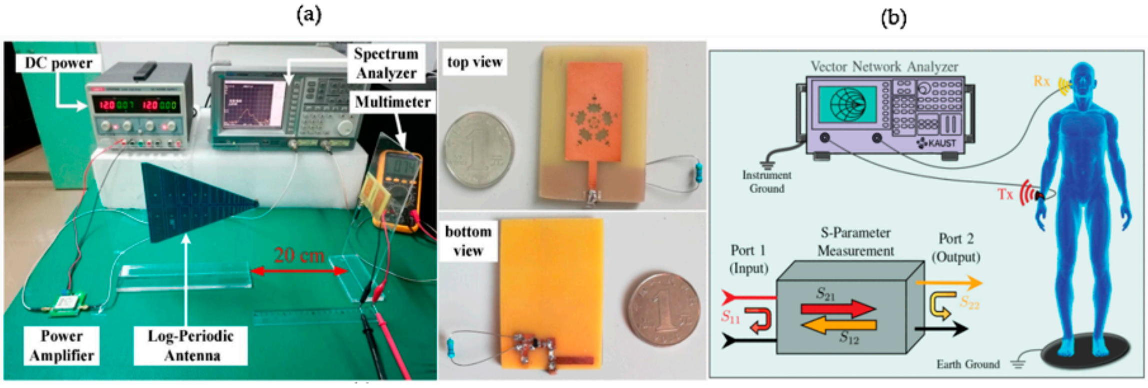

**Figure 4.** (**a**) Complete measurement setup for RF energy harvesters [44]. (**b**) Multiple wearable devices can be powered by body-coupled energy harvesting [46].

RFEH technology has many advantages over other energy, sources such as thermal, solar and vibration. The popularity of radio frequency energy makes it suitable for providing stable power for many biomedical devices. RFEH is a low-energy technology (other than solar) that can be used to power IMDs. Unlike solar and solar thermal methods, RFEH is not affected by light, physical motion, or heat. The working distance of the cutting machine depends on the operating frequency. It defines the DC output power performance of the RFEH system. The performance of the RFEH system can be clearly explained by monitoring it with an open load, as the load voltage and current are dependent on the load impedance. In some applications, such as measuring equipment, voltage is more important than current. In contrast, in others, such as LEDs, current is most important. The sensitivity of an RPEC system is defined as the minimum power required for operation. Sensitivity trade-offs are affected by the input impedance of the Complementary Metal Oxide Technology (CMOS), and efficiency is negatively affected by the leakage current of the high-performance node.

### *Flexible and (Rigid)*

Flexible materials are characterised by their ability to bend or compress easily without cracking under normal conditions. One example of such material is graphene, which is the thinnest and strongest existing material. In its carbon form, graphene can conduct electricity and heat more effectively. Flexible materials are often used in packaging applications, such as pouches, liners, and seals. On the other hand, non-flexible (rigid) materials are those that cannot be easily bent without breaking. These materials maintain their shape and can support their own weight when rested upon parallel edges.

In [47], the focus was on safety and reliability monitoring systems for railway transportation. To ensure the device's proper functioning, sensors and electronic components requiring an electric power supply are necessary. Energy harvesting techniques from primary sources are employed to achieve widespread distribution of electrical energy. The study explored different concepts of energy harvesters for both on-board and wayside applications, discussing their advantages and disadvantages and identifying the most promising solutions.

Ref. [31] conducted research on flexible electrically resistive-type strain sensors, with a particular emphasis on polymer fibrous mats for monitoring human movement. The demonstrated results showed that flexible strain sensors have a wide range of applications in smart wearable devices. Table 3 presents flexible conductive materials along with their thickness and conductivity.

**Table 3.** The flexible conductive materials with their thickness and conductivity [26].

| Conductive Material | Thickness t (mm) | Conductivity σ (Sm) |
|---|---|---|
| EgaIn liquid fillet | 0.08 | $2.5 \times 10^5$ |
| Polyleurethene–nanoparticle composite sheet | 0.0065 | $1.1 \times 10^6$ |
| Zoflex + copper | 0.175 | $1.93 \times 10^5$ |
| Silver flakes+ Fluorine rubber | N. A | $8.5 \times 10^4$ |
| AgNWPDMS | 0.5 | $8.1 \times 10^5$ |
| Copper-coated taffeta | 0.15 | $3.4 \times 10^6$ |
| PANICCO | 0.075 | $7.3 \times 10^3$ |
| Meshed fabric | 0.057 | $2 \times 10^5$ |

Furthermore, ref. [14] investigated scalable free-standing polypyrene films for wristband-type flexible thermoelectric power generators aimed at energy harvesting. The study revealed the granular morphology of the films and suggested that reducing the thickness of the device while increasing the concentration of p-toluene sulphuric acid (PTSA) could be beneficial. The films also demonstrated good potential for harvesting heat from hot-curved surfaces. Additionally, [34] focused on the small and flexible structure of the antenna, highlighting its excellent impedance matching, good efficiency, broad bandwidth, and high gain, which make it suitable for simultaneous data transmission and reception in 5G body-centric applications.

Furthermore, ref. [35] conducted an investigation and developed a programmed sensor using an Arduino board. The sensory data collected by the sensor were uploaded to cloud storage for access by connected devices in a smart home. The results demonstrated that online monitoring and analysis of sensory data stored remotely in the cloud were successful.

## 3. Antenna Design

An antenna is a device that can transmit and receive electromagnetic signals and convert them into electrical signals. These signals can be transmitted or received in several directions depending on the antenna capacity, allowing communication between distant locations. Antennas are classified into three main categories: directional antennas, characterised by a narrow beam; semi-directional antennas that operate at a certain angle; and omnidirectional antennas that radiate signals in all directions. For example, microwave antennas can transmit signals from one space to another and coordinate transmission lines in free space between two or more targets. Below are the basic parameters of the antenna:

Polarisation: This refers to the formation of electric field fluctuations in a plane [48] and the region where wave radiation occurs [49].

Radiation pattern: Describes the radiation of field intensity in different angular directions on a plotted graph [50]. The antenna radiation pattern can also be explained as a function of spatial coordinates [48].

Bandwidth: In [51], the bandwidth is defined as the percentage deviation of the narrow band frequency of the antenna in relation to its lower and upper limits or its ratio to the centre frequency. Ref. [49] also states that it is a measure of antenna performance relative to a certain characteristic.

Impedance matching: The impedance matching can be defined by the maximum power transfer theory, as stated in Equation (1):

$$Z_e = Z_x \tag{1}$$

here, $Z_e$ and $Z_x$ represent the source impedance and the impedance load. Equation (1) ensures maximum power transfer between impedance load and impedance source while maintaining constancy.

Return loss: This refers to the ability of an antenna to release power from its source [52]. Mathematically, return loss is defined as:

$$P_{RL} = 10 \times \log 10 \frac{P_{in}}{P_r} \tag{2}$$

where $P_{in}$ and $P_r$ represent incident power and reflected power. $P_{RL}$ represents return loss.

Directivity: This represents an antenna's ability to focus its radiation at a targeted point [53]. Alternatively, it is the ratio of the average radiation intensity of the antenna to the radiation intensity in all directions at the focus.

Power gain: Power gain, also known as radiation efficiency, is the isotropic ratio of the antenna output power to the power of the reference antenna in the focused area. The receiver power can be expressed as given by Equation (3):

$$P_R = \frac{P_T G_T G_R \lambda^2}{\left(4\pi R\right)^2} \tag{3}$$

where $P_R$ represents the antenna received power, $G_R$ represents the receiving antenna gain, $P_T$ represents the transmitted power, $G_T$ represents the transmitting antenna gain, $R$ represents separation distance between transmitting and receiving antenna, and $\lambda^2$ is the wavelength of the transmitting wave [54]. The path loss due to free space is given by Equation (4)

$$P_L = \frac{\left(4\pi f R\right)^2}{G_T G_R c^2} \tag{4}$$

Furthermore, ref. [55] conducted a study on antenna systems for RF energy harvesting using radio frequencies. RF signals are transmitted from various sources such as base stations, Wi-Fi routers, cell towers, TV, and radio broadcast stations. The goal of RF energy harvesting is to power low-power devices without the use of batteries. The article focused on the different frequency ranges that can be used, the parameters for system model design, and the circuitry required to convert the low voltage output to a high voltage output for efficient RF power harvesting in various applications. This concept is consistent with the law of conservation of energy, which states that "Energy can neither be created nor destroyed, it can only be converted or transformed from one form to another". RF energy is currently transmitted from a variety of sources, including telephones, televisions, and radio stations [55].

In [56,57], research was conducted to address the need for continuous power support in wireless sensor networks without using batteries. The antenna device designed in this study is suitable for rectenna applications at the universal mobile telecommunication system (UMTS) frequency range from 1.92 to 2.17 GHz. This device captures the power of impinging RF signals, rectifies it, and stores it using rectenna grades. The antenna consists of planar dipoles with a specific layout printed on a dielectric substrate with double negative (DNG) electromagnetic properties. This hybrid structure allows for a larger amount of RF power to be gathered compared to ordinary dielectrics, making it suitable for RF power harvesting, known as the rectenna.

Furthermore, [19] worked on screen-printed patch antennas and rectennas for RF power transfer and harvesting on textiles. The two-line method on a planarised polycotton substrate was used. The results showed that the substrate performed better than a third of standard FR4. The paper recommends improvements in resistance to chemicals and increased electrical and mechanical robustness performance of the textile device.

Similarly, ref. [58] studied a high-gain rectenna at 2.45 GHz using a two-layer low-cost FR4 substrate with air-gap technology. The design includes an antenna and open stub rectifying circuits with a feedline. This technique aims to increase the antenna gain. The rectenna design achieved an output voltage of 0.46 V with an input power of 0 dBm and a maximum input power of up to 6 V. The device offers advantages such as low cost, easy integration, high gain, low profile, and simplicity in design, making it applicable in various wireless communication and RF energy harvesting applications.

Moreover, ref. [59] examined the application of patch antennas in various fields, including civil engineering, military, mobile and GSM communication sectors, and the healthcare sector, for communication purposes. After investigation, a gain of 8.27 dB and a VSWR of 1.18 were obtained, which is commendable and close to the calculated resonance frequency. The research indicates that the resonant frequency and dielectric constant are dependent on the patch antenna.

Additionally, ref. [16] conducted experimental work on antenna design, mainly modifying the ground plane of the antenna known as defected ground structure (DGS). The parameters used and optimised in the study included reflection coefficient, bandwidth, DGS, USWR, and gain.

Similarly, ref. [60] investigated coating design for helical and loop antennas at varying refractive indices and angles. The study used a copper substrate, and the incidence angle on the reflectance spectrum was investigated. The results showed that reflectance increases at shorter wavelengths, shifting towards the wavelength. It was also observed that a shift in incidence angle affects the wavelength's function. This study aligns with previous research, indicating that adjustments made to certain parameters can positively or negatively affect the variation of angle positions, thereby impacting antenna efficiency.

Furthermore, ref. [33] studied the use of high-impedance surfaces (HIS) to design a compact and low-profile multi-in multi-out (MIMO) antenna for wearable applications. The MIMO antenna achieved good port-to-port isolation without increasing its geometric size. The antenna design employed a pair of degenerated characteristic modes of a circular loop antenna, and four elements of high-impedance surface were chosen to match the antenna profile, resulting in improved antenna gain. Simulation results aligned with the measurement results, demonstrating the antenna's robust performance against the human phantom and a low specific absorption rate.

Likewise, ref. [61] conducted two investigations: one on the aperture field for different solid geometries and another on a typical radiator of a printed microstrip patch antenna dipole. The analyses showed that a higher compact shape of the Radiating Circular Aperture (RCA) was obtained, leading to improved lightweight feed for large reflector gains. This finding enhances the compatibility of the device in terms of antenna performance.

In [37], research was focused on the vision of next-generation 5G wireless communications, including improved data rate, latency, quality of service (QoS), capacity, radio access network (RAN) design, air interfaces, smart antennas, cloud, and heterogeneous RAN. Simulation experiments were conducted to explore possible future research works, demonstrating the functionality of the antenna device.

In summary, antenna design plays a crucial role in checking the specific absorption rate of RF energy harvesters. Planar multilayer fabric patch antennas with a ground plane are particularly suitable for fabric wearable antennas, offering improved efficiency compared to designs without a ground plane.

### *3.1. RF Energy Harvesting for Antenna Design and Characteristics*

Receiver antennas play an important role in RF energy harvesting (RFEH) systems. It serves to capture the RF signal received from the extended source and has a significant effect on the conversion efficiency. Antenna resonance optimisation can be achieved in single or multiple frequency bands. High-gain receive antennas are needed to meet the high-power input requirements of software packages such as remote charging of mobile phone batteries, wake-up sensors, and powering wireless sensor networks [62]. The antennas must provide sufficient power for these applications, even with limited ambient signals. Desirable characteristics in RFEH antenna design include power amplification, wide bandwidth, miniaturisation with maintained efficiency, and circular polarisation to minimise mismatch losses. When designing antennas for biomedical applications, such as wearable and implantable antennas, factors such as flexibility, durability, light weightiness, and safety are crucial considerations. Therefore, this section discusses the design, characterisation, and configuration of implants and wearable antennas used in the RFEH system. A wireless battery-free sweat sensor system designed to detect sweat composition in real time is shown in Figure 5 [63]. A multi-functional sweat sensor, as illustrated in the schematic diagram, is worn as a monitoring film and connected to an electrochemical analyser. The collected data are then transmitted wirelessly to a smartphone via Bluetooth for analysis and monitoring [63–65].

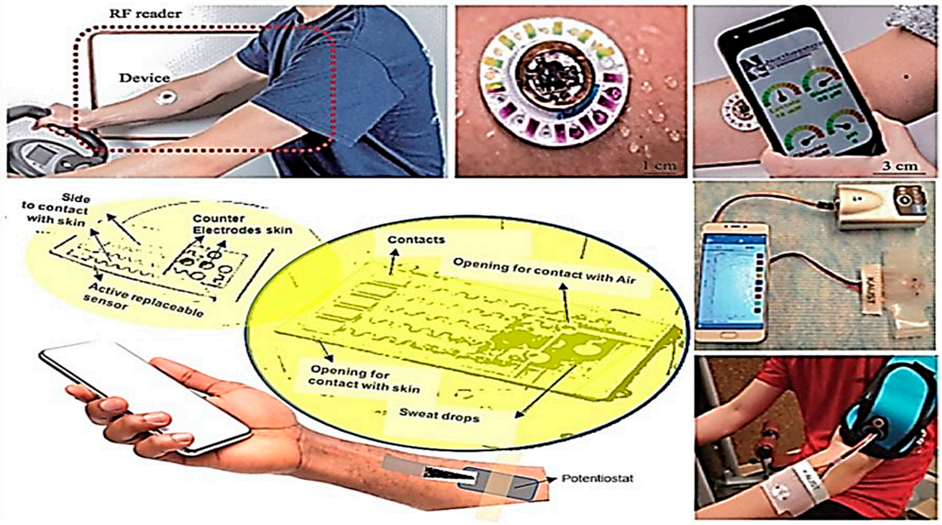

**Figure 5.** Wireless battery-free sweat sensor system for RF energy harvest with a smartphone Bluetooth wirelessly transmitter for analysis and monitoring [64,65].

### 3.2. RF Wearable Energy Harvesting Antenna Design

Antenna integration in wearable medical equipment necessitates conformal and nonobtrusive designs. Mechanical deformations of wearable antennas can significantly impact bandwidth and centre frequency, particularly when operating in limited areas where even minor changes can detune the optimised frequency. The ground plane plays a crucial role in isolating the wearable antenna from anatomical and physiological loads, as well as absorptive losses. Wearable antennas are constructed using various dielectric and conductive materials chosen for their ability to withstand mechanical deformations such as twisting, bending, and wrapping while also providing protection from electromagnetic radiation. Fabric and non-fabric materials have been utilised to fabricate wearable antennas, but the proper characterisation of fabric materials is essential prior to use [66]. Textile materials, including felt cloth, polyester cotton, and cordura, are commonly used in wearable antennas for RF energy harvesting due to their widespread availability [67–69]. These textile antennas can adopt different topologies, such as monopole and patch antennas, and operate in single or dual bands. Non-fabric flexible thermoplastic materials with secure dielectric properties are also employed in many RFEH wearable antennas. For instance, [70] proposed a double dipole antenna printed on Kapton, and [71] suggested a monopole antenna printed on a polyethylene terephthalate (PET) film. Ref. [72] described a dual-band patch antenna built on a polydimethylsiloxane (PDMS) substrate.

Furthermore, wearable antennas for RFEH need to be flexible enough to accommodate stretchable skin deformations or human motions [73]. Stretchable antennas experience a decrease in resonant frequency when stretched [74], thus limiting their use for strain sensing and integrating them with commercially available chips presents challenges as well. Moreover, the lossy nature of human tissues significantly reduces the radiation efficiency of flexible antennas [75–77]. Therefore, for communication and radio broadcasting, an extended antenna with high characteristics and insensitivity to resonance frequencies is required [8,78–82]. Because of their unique electromagnetic properties and high electrical efficiency, tensile and plain steels are suitable for the manufacture of radiating elements. In the published work [83], a laser stretchable wideband dipole antenna was proposed using resistive laser-induced graphene (LIG) patterns selectively coated with metal and mounted on an elastomeric substrate.

During radiation performance measurements of the bendable antenna, both mechanical and electromagnetic properties were considered using a customised stretcher. The stretchable multiband dipole antenna maintained its performance under various deformation modes, including stretching, twisting, and bending.

### 3.3. RF Energy Harvesting with Implantable Antenna Design

Whether for RF energy harvesting (RFEH) or data transmission in IMDs (implantable medical devices), implantable antennas are an essential component in electromagnetic energy transformation [62]. Designing implantable antennas presents additional challenges compared to wearable antennas due to their placement inside the body. The primary limiting factor affecting the performance of implantable antennas is dielectric loading from fluids and body tissues. To maximise the chances of successful integration, miniaturisation techniques play a crucial role in configuring implanted antennas by reducing their size to the minimum possible. Researchers have proposed various types of miniaturised implantable antennas for RFEH, each tailored to a specific scenario. To improve power transmission, a circular dual-band implantable antenna with a radiating slotted overlay supplemented by an external metal reflector positioned behind the human hand has been developed [84]. The radiating metallic patch had a size of 10.8 mm, matching the material and the superstrate to ensure contact with the surrounding tissue. For enhanced efficiency of the wireless power link, a portable planar inverted F-antenna (PIFA) with a matching layer on the arm was developed specifically for RFEH [85].

### 3.4. RF Wearable Inkjet-Printed Energy Harvester

Additive manufacturing has grown in industrial importance due to its environmental friendliness and economy in manufacturing processes such as 3D printing and inkjet printing. These emerging technologies aim to significantly reduce the number of re-necessary machining steps, including the elimination of etching mechanisms, thereby increasing manufacturing efficiency. In environments where disposable or disposable items need to be hygienically maintained, such as hospitals, wearable sensor devices are often the preferred choice. Additive manufacturing makes it possible to build many circuit components into a device, leading to a reduction in the overall cost of the device. Recent advances in manufacturing and performance have made inkjet technology suitable for sensor and RF applications. Consequently, ref. [86] proposed a design enabling near-field RF energy harvesting (RFEH) for wearable sensors through an additive manufacturing process. The study builds circuit prototypes by combining conductive traces made using conductive inkjet printing and masking technology solutions with integrated circuit components.

Additionally, S-parameters were used to estimate the input power for RF to DC conversion circuits. The circuit achieved a peak output power of 0.146 W for the H-field harvester and 0.0432 W for the E-field harvester. To verify the functionality of two-way radio-powered harvesters, they underwent a battery of tests using a microcontroller communication module and LEDs, both in bottle and body bending conditions. The results of these analyses confirm the flexibility of inkjet energy harvesting devices, making them suitable for use in wearable biosensors. In addition, the work presented in [87] used 3D printing and inkjet technology to develop a flexible and wearable energy-autonomous body-based sensor network fully operational for RFEH using a hand-held two-way radio in the 464.5 MHz UHF band. Both the backscatter RFID tags capable of sensing and the wearer's hands are equipped with an energy harvester, with one harvesting the energy of the 464.5 MHz signal to power the tags and the other converting the same signal into direct current. Compared to conventional ambient energy harvesters, this alternative device shows higher efficiency. The system utilised energy harvesting designs, utilising the rectifier's DC and second resonance frequencies to support two additional functions. Traditional 3D printing methods often require significant time and material to fabricate desired structures. Therefore, ref. [88] proposed a fabrication method to develop an origami RF harvester system employing the same principles of origami folding as those used in low-frequency applications. This ingenious method eliminates the need for support materials and significantly reduces fabrication time.

### 3.5. RF Textile-Based Wearable Energy Harvester

The integration of miniature electronics and conductive materials into wearable devices holds the potential to establish the paradigm of wearable technology [89]. Fabric rectennas can be employed in battery-free, body-centric wireless communication systems.

Numerous antennas for wireless communication have been reported to be fabricated using textile materials [83,90]. Some studies have combined a textile antenna with a rectifier circuit built on a printed circuit board (PCB) to create a wearable device for power harvesting [67]. Rectennas can operate at a single frequency or two different frequencies. In the 4.65 GHz textile rectenna described in [91], jeans cotton was utilised as the substrate, while copper tape was employed for the radiating element. An input power of 5 dBm was applied to generate a DC output voltage of 400 mV from the textile rectenna, achieving a maximum power conversion efficiency (PCE) of 55%. By combining a sub-1 GHz broad-beam rectenna with an off-body antenna operating at 2.4 GHz, ref. [92] developed a textile rectenna that operates simultaneously at both frequencies. This rectenna demonstrated a PCE of 63.9% and a DC output of 650 mV at a power density of less than 0.8 $Wcm^2$. Subsequently, a comprehensive textile rectenna system was presented in [93]. This rectenna utilises RF power harvesting to establish an innovative power management platform. The rectenna is designed to operate with wireless networks that utilise the 900 MHz, 1800 MHz, and 2.4 GHz frequency bands. Nonlinear methods are employed to test the RF properties of the textile rectenna, while electromagnetic simulations are utilised to numerically characterise the textile equipment and antenna layout. The system does not require a battery and can operate on a weak RF signal (15 dBm) due to its inherent autonomy.

### 3.6. RF Flexible and Stretchable Energy Harvester

Mechanical deformations such as stretching or bending have a significant detuning effect on the frequencies of wearable rectennas, resulting in reduced performance. While the miniaturised thin-film rectifying circuit design and matching network can provide robust mechanical properties, the size of the antenna within the rectenna is limited to a specific range for the target radio frequencies of ambient wireless energies. Additionally, the conversion efficiency of existing rectennas operating at a single frequency is greatly diminished for low-power RF energies under dim lighting conditions (less than 1 mW) [62,84,85]. This reduction is partly attributed to the characteristics of the limiting diode and increased losses in the transmitter and impedance-matching circuits. To address the need for integrating received RF energy across a wider bandwidth during deformations, it is crucial to design and demonstrate a high-performance stretchable wideband antenna based on previous experience. In this context, ref. [94] presented a design for a stretchable wideband rectenna that exhibits resilience to mechanical deformations, operates efficiently, and integrates external RF power across the entire frequency spectrum. The proposed design combines magnetic resonance techniques with laser-based fabrication to create a highly effective stretchable wideband rectenna with compatible mechanical properties. This integration of the rectenna with various laser-induced graphene (LIG) sensors enables the development of expandable all-LIG devices for remote sensors and wearables.

Furthermore, a comprehensive rectenna system based on textiles was presented in [93]. This rectenna utilises RF power harvesting to establish an innovative power management platform and is designed to operate with wireless networks that utilise the 900 MHz, 1800 MHz, and 2.4 GHz frequency bands. Nonlinear methods are employed to test the RF properties of the textile rectenna, while electromagnetic simulations are used to numerically characterise the textile raw material and antenna layout. The system does not require a battery and can operate on a weak RF signal (15 dBm) due to its inherent autonomy.

To mitigate the inefficiency of a flexible RFEH system, the utilisation of multipath and antenna diversity to achieve quasi-omnidirectional RF reception enhances the system's ability to successfully receive energy in its natural environment. In order to leverage the advantages of plastic wrapping form and ambient RFEH operation in indoor settings, the study by [95] proposes a 3D flexible antenna diversification approach that can be incorporated into rectangular packaging. By employing a Rogers 4003 substrate in the design of the angle and polarisation diversity antenna, the issue of poor substrate performance is addressed while maintaining small antenna size, high isolation, and high radiation efficiency. Rectenna measurements were conducted in various realistic scenarios. Scenario S1 involved the use of a standard antenna patch to measure ambient power in all directions and locations. Scenario S2 employed a regular antenna patch and rectifying circuit A to calculate absorbed power in all directions and at all points (Rectenna 1A). In Scenario S3, a packing box connected to Rectifier B was utilised, incorporating four patch antennas oriented in opposite and perpendicular orientations (Rectenna 1B). Scenario S4 involved physically separating the rectifier from the antenna (Rectenna 2), while in Scenario S5, the rectifier was physically integrated into the antenna (Rectenna 3). The efficiency of both the flexible rectenna diversity configuration and regular patch diversity was evaluated in these scenarios.

## 4. Power Management

Power management is a feature of computing devices that allows users to control the amount of electrical power consumed by the underlying device, minimising usage. Examples of devices that incorporate power management include copiers, computers, CPUs, GPUs, and computer peripherals such as monitors and printers, which turn off the power or switch to a low-power state when inactive.

In [7], a hybrid energy harvester is presented to enhance the network lifetime of Internet of Things (IoT) devices. This device model utilises both RF energy harvesting and thermal energy harvesting to increase the lifespan of the devices. To further enhance the device's performance, a supercapacitor is employed to store the harvested energy at a sufficient level to power the devices. The study observes that the network lifetime of the hybrid energy harvesting network is significantly extended compared to a network without any energy harvesting. Further exploration of other sources of energy harvesting can be incorporated to study this device. The core energy subsystem module comprises the energy harvester, energy storage, and energy manager.

Furthermore, ref. [68] introduces a radio frequency-based powering device that aims to convert RF energy into usable energy. The harnessed energy can directly power untethered devices or supplement batteries and other storage components. Additionally, the paper suggests that power management devices for energy harvesting can be simplified, as depicted in Figure 6 [96].

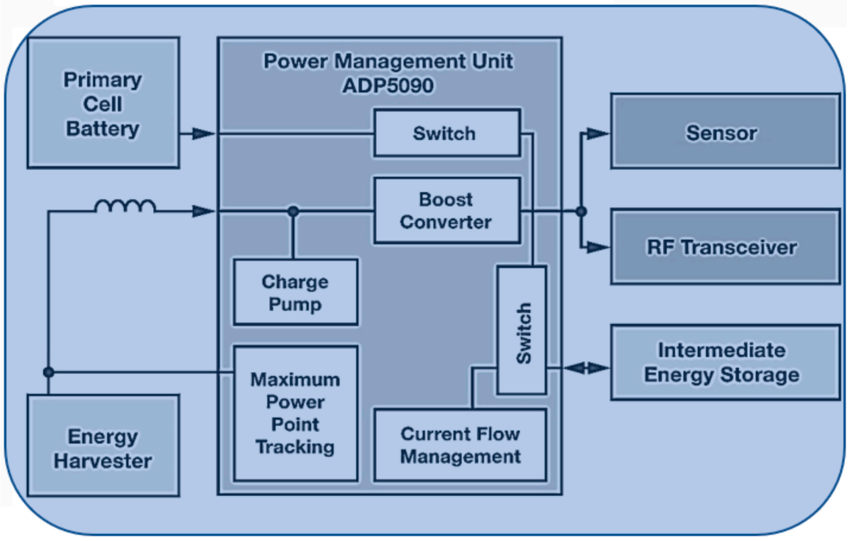

**Figure 6.** Power management device for energy harvesting applications [96].

Figure 5 above depicts the power management diagram for an energy harvesting device and its applications. The setup includes start-up circuitry with a charge pump that enables a start-up voltage of 380 mV on the input. The internal circuitry is powered by the output voltage, which serves as the node that powers the load of the energy harvesting system.

In [97], the development of simple and effective devices that can be used as energy-efficient autonomous sensors that outperform existing state-of-the-art solutions is being explored. For the acceptable voltage levels for the load, the device uses a microstrip line discrete component board with a bulk device and is optimised for two different power sources for RF energy harvesting. The phase rectifier consists of two different Schottky diodes in two different topologies using a diode and a two-phase Dixon charge pump. Offering better performance than commercial products and reaching a maximum range of up to 22 m with its high RF power, D-Wise collects energy, making it suitable for IoT applications.

In addition, ref. [98] reviews the development of energy harvesting for low-power embedded structural health monitoring (SHM) sensing systems. The research focuses on transitioning the concept of energy harvesting for embedded SHM sensing systems from laboratory research to field-deployed engineering prototypes. The paper also discusses current energy harvesting applications and system integration, concluding with defining future research directions and concepts of energy harvesting technology methods.

Condition monitoring has the potential to reduce machine breakdown losses, enhance productivity and operational safety, and deliver significant benefits to various industries [99]. Energy harvesting technologies have garnered attention from engineers due to their ability to convert microwatt or milliwatt level power from the environment, enabling the implementation of maintenance-free machine condition monitoring systems with wireless sensor networks. Additionally, ref. [96] introduces an interesting energy system setup, as illustrated in Figure 7. It illustrates the energy harvesting system for wireless environmental sensors. The sensor is utilised to detect various gases such as $CO_2$, humidity, and temperature. The harvester plays a crucial role in energy harvesting, with solar energy being the most common type. The harvester generates electricity, which is then converted into useful voltage or current to power the system or charge intermediate energy storage devices like batteries and supercapacitors.

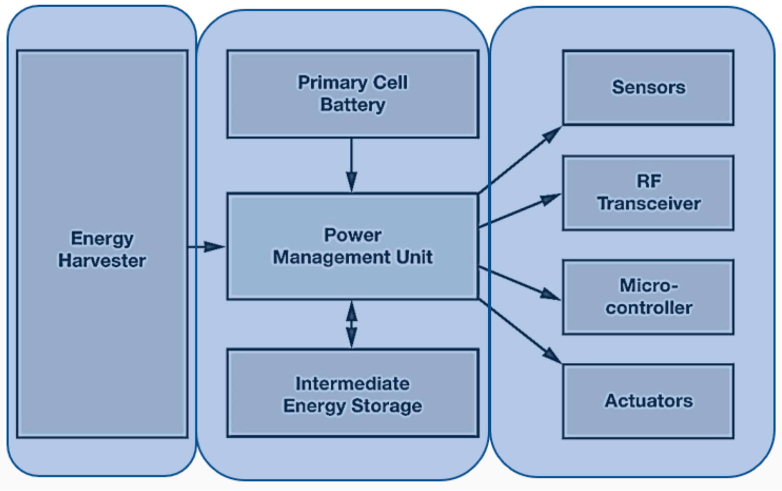

**Figure 7.** Energy harvesting system setup [96].

In [100], a critical review of energy harvesting technologies in roadway applications was conducted. The focus was on harvesting principles, prototype development, economic considerations for each harvesting technology, and implementation efforts. Roadway harvesting is categorised into three groups based on the energy harvesting source: solar radiation, mechanical energy from vehicles, and pavement heat. This technology generates green renewable energy that can be utilised in roadside applications to power LED lights, sensors, and microprocessors for various data collection purposes. In conclusion, these harvesting technologies have reached a sufficient level of development to generate self-sustainable roadside electrical power.

Furthermore, ref. [66] conducted a feasibility review of wind turbine technology for highway energy harvesting. The aim was to utilise natural wind energy in the most effective manner to achieve maximum electric output. Therefore, the government can consider implementing a suitable type of wind turbine configuration on highways at a low cost, taking advantage of the moving vehicles on both sides of the road. In renewable energy sources, solar energy and wind energy can be combined and used to generate electricity. The combination of solar panels and wind turbines will be beneficial in cases of non-functioning or when supported by other sources, ensuring continuous power supply without being affected by day and night or any emergency breakdown. Other sources of energy and the energy requirements for different applications are detailed in Figure 8 [96]. It depicts a 10 $cm^2$ harvester that generates energy from various types of harvesting. The left side shows the energy generated, while the right side displays the energy consumption for different tasks. The logarithmic power scale is positioned at the center. A comparison of the RF energy harvesting based on the parameters studied is shown in Table 4.

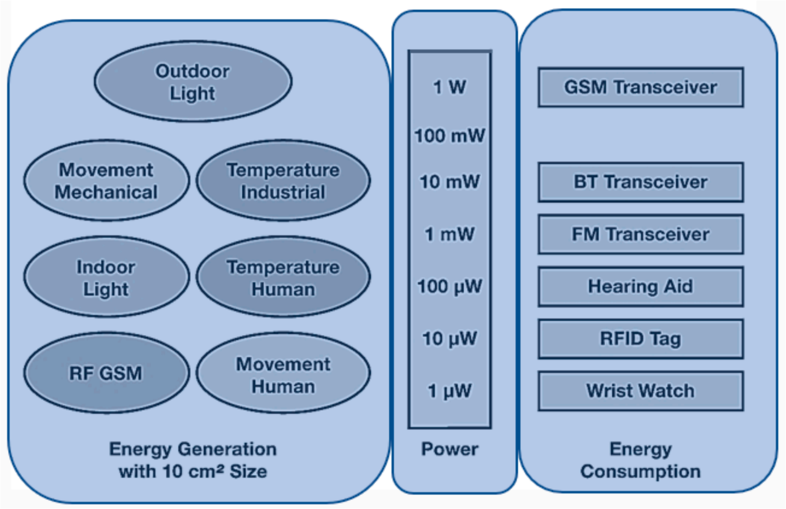

**Figure 8.** Different sources of energy and the required energy requirements of different applications [96].

**Table 4.** Comparison of the RF energy harvesting [101].

| Parameter | 2019 TMTT | 2018 TMTT | 2016 TMTT | 2018 AWPL | 2013 IMWS | 2013 IMS |
|---|---|---|---|---|---|---|
| Frequency (GHz) | 2.45 | 2.45 | 0.85, 1.85 | 2.45, 5.5 | 1.8, 2.45 | 0.9, 1.8, 2.45 |
| Rectifier Architecture | RBR | Half-wave | Greinacher | Greinacher | Half-wave | Dickson |
| Number of Stages | 4 | 1 | 2 | 2 | 1 | 4 |
| Peak PCE (dBm) | 37% at 13 | 56.0% at −10 | 44.2% at −10 | 36.0% at 5 | 75.1% at 12 | 43% at 16 |
| Load Resistance at Peak PCE (kΩ) | 20 | 3 | 9.53 | 12 | 0.917 | 0.012 |
| Output Voltage at −10 dBm (V) | 1.70 | 0.41 | 0.65 | 0.49 | 0.50 | 0.24 |
| Voltage Improvement (%) | 315 | 0 | 58 | 20 | 22 | 42 |

### 4.1. Impedance Matching Network

Power loss can be reduced or completely eliminated through the utilisation of an impedance matching network, which ensures efficient transfer of energy from the generator to the load. Maximum power transfer is achieved when the impedance of the output antenna matches that of the load. If there is an impedance mismatch, the incident wave will be reflected by the load. In the RFEH system, the rectifier acts as the load, while the receiver antenna captures radio frequency (RF) energy. To minimise unnecessary loss caused by the re-radiation of higher-order harmonics produced by the bridge rectifier, the impedance matching network also functions as a low-pass filter [102]. Achieving impedance matching between the source and the load is crucial for the optimal performance of the RFEH, irrespective of the input power, frequency, or load resistance. The architecture of a WLAN energy harvest system is shown in Figure 9.

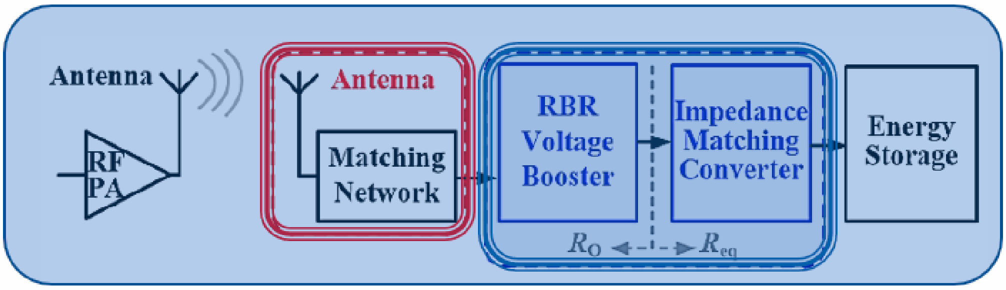

**Figure 9.** Architecture of the WLAN energy harvesting system [101].

Furthermore, ref. [103] conducted a comprehensive review of the efficiency of RF energy harvesting systems. They noted that RF energy serves as an alternative means of acquiring energy for wireless devices directly from RF sources in the environment. The study also presented various components such as energy storage devices, voltage multipliers, rectifiers, transmission mediums, impedance matching circuits, antennas, and more. The primary focus was placed on analysing the input and output power ratios at each block. The researchers thoroughly characterised the system parameters and identified the RF configuration that achieved the highest efficiency, resulting in maximum output power.

### 4.2. Rectifier Circuit Design and Topologies

The rectifier plays a crucial role in converting the RF voltage collected by the receiving antenna into a DC voltage suitable for various electronic circuits. The main design limitation of the rectifier lies in the challenge of generating DC voltage from a relatively weak input power [104]. There are two primary categories of rectification circuits: diode-based rectifiers and metal-oxide-semiconductor field-effect transistor (MOSFET) rectifiers. Diode-based rectifiers are more popular in practical applications due to their smaller forward voltage drop compared to MOSFET circuits. Optimal diodes with low forward voltage are preferred for their increased power conversion efficiency (PCE). In rectenna applications, Schottky barrier diodes are commonly employed [105].

The half-wave rectifier, consisting of a single diode (D1), represents the most basic rectifier topology. However, its use is often inadequate for most applications. On the other hand, the full-wave rectifier, showcased in Figure 10, is the preferred choice due to its superior performance. In comparison, the bridge rectifier offers higher power efficiencies, lower output ripples, and lower reverse breakdown voltages compared to its counterparts [106]. The conversion efficiency of RF energy to DC current is given by Equation (5). where, $P_{RF}$ is the input RF power and $P_{DC}$ is the output DC power.

$$\eta_{RF} = \frac{P_{DC}}{P_{RF}} \tag{5}$$

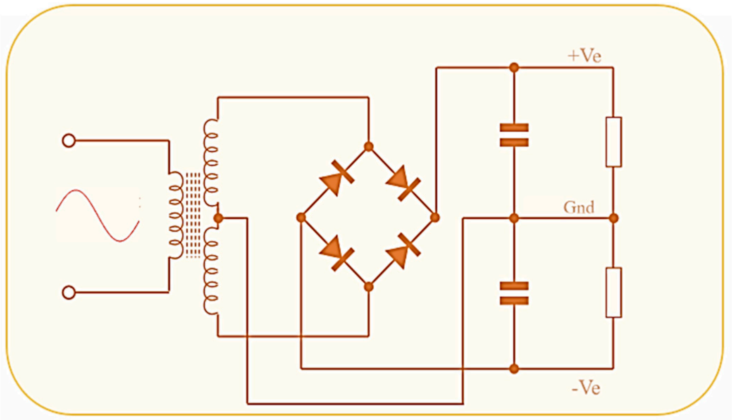

**Figure 10.** Circuit layout of a full-wave rectifier [106].

The power management circuit plays a crucial role in matching the output load of the RF device to an optimal impedance, thereby maximising the rectification efficiency of the device. The storage capacitor is also utilised to assess the converter efficiency and boost the output voltage, contributing to the overall efficiency improvement of the RF energy harvester.

### *4.3. Challenges and Future Work*

Wearable sensors face limitations in size, highlighting the challenges in RF wearable energy harvesting, such as efficiency improvement, limited RF power density, integration into wearable devices, miniaturization, and materials/fabrication techniques. Future work includes exploring multi-band energy harvesting, integrating energy storage and power management systems, developing hybrid energy harvesting systems, and designing adaptable solutions for different environmental conditions. Implementing RF harvesters in wearable medical devices poses challenges related to connectivity, power conversion, radiation efficiency, and mechanical deformations. Advancements are needed in lightweight and flexible rectenna designs for efficient RF energy harvesting. Additionally, considerations for power density, energy storage, and network-based design are crucial in wearable energy harvesting. The challenges and future directions in RF wearable energy harvesting have been summarized and presented in Table 5 for comprehensive understanding and guidance in this field. It guides researchers in identifying areas of improvement and motivates them to contribute towards advancing the field. It also provides readers with insights into the potential future directions and areas that require attention, fostering collaboration and knowledge exchange.

**Table 5.** Challenges and future directions in RF wearable energy harvesting.

| Challenges | Future Directions |
|---|---|
| Efficiency Improvement | • Multi-band energy harvesting approach by exploring methods to harvest energy from multiple RF bands simultaneously.<br>• Enhancing the energy conversion efficiency of RF energy harvesting. |
| Limited RF Power Density | • Power management systems by developing advanced power management systems to optimise energy harvesting and utilization.<br>• Addressing the limited availability and variability of RF power in the environment. |
| Integration and Design | • Energy storage integration by integrating energy storage solutions for efficient energy utilization and extended device operation.<br>• Designing compact and comfortable RF energy harvesters for seamless integration into wearable devices. |

**Table 5.** *Cont.*

| Challenges | Future Directions |
|---|---|
| Miniaturization | • Hybrid energy harvesting systems combining RF energy harvesting with other complementary energy sources for enhanced overall energy harvesting efficiency.<br>• Overcoming size constraints while maintaining performance and comfort. |
| Materials and Fabrication Techniques | • Environmental adaptability by developing adaptable energy harvesting systems to accommodate varying environmental conditions.<br>• Exploring new materials and fabrication methods for efficient and scalable RF energy harvesting devices. |

Table 6 provides a concise summary of important research studies in the field of RF energy harvesting. It highlights the research focus and key findings of each study. This table serves as a valuable reference for researchers and practitioners, offering an overview of significant advancements and contributions in RF energy harvesting research.

**Table 6.** Research on RF energy harvesting.

| Study | Research Focus | Key Findings |
|---|---|---|
| [107] | Lifetime enhancement of wireless sensor networks (WSNs) through energy harvesting and efficient RF to DC conversion | - RF energy is abundant but has low power density, making RF energy harvesting an attractive solution for WSNs.<br>- Designing RF energy harvesting systems involves challenges such as achieving maximum power conversion efficiency (PCE) at low input power and optimising rectifier circuit and antenna topologies.<br>- Recent antenna designs are featured, considering their structure, attributes, and materials. |
| [54] | Review work on rectifier circuits and matching networks | - Developed a framework for designing ambient RF energy harvesting systems.<br>- Identified challenges in conversion efficiency, bandwidth, and form factor.<br>- Emphasised the importance of achieving high conversion efficiency under varying load and input power conditions. |
| [32] | Investigation on enhancing energy efficiency in 5th generation IoT | - Investigated an integrated model with combined control unit components.<br>- Delaying the select and sleep mechanism (SSM) resulted in reduced power consumption.<br>- Compared with the Traditional Zooming Scheme to demonstrate improved energy efficiency. |
| [108] | The development of a sophisticated control system that proficiently governs the power generation and consumption dynamics within the microgrid. | - Focused on maximising efficiency in the electricity distribution of a microgrid.<br>- Employed an off-grid hybrid renewable energy system with a power management controller.<br>- Validated the application through a case study of an isolated mosque in Morocco. |
| [76] | Investigation of magnetic and electric energy harvesting technologies in power grids | - Reviewed energy harvesting methods for electric and magnetic fields in power grids.<br>- Aimed to address power supply issues through energy harvesting techniques.<br>- Highlighted the potential for low-power sensing of simple parameters within a wider serviceable range. |

**Table 6.** *Cont.*

| Study | Research Focus | Key Findings |
|---|---|---|
| [67] | Enhancing the performance of energy harvesting sensor networks for environmental monitoring applications | - Utilising clustering and transmission power adjustment improves power distribution and network performance.<br>- It resulted in a 20% improvement in packet delivery ratio, a 10% increase in network lifetime, and reduced delay by minimising hop count. |
| [70] | RF energy harvesting for wireless communications (RF-EHWC) | - Harvesting RF energy from the environment makes wireless sensor networks self-sustaining.<br>- The study explores hardware design, RF energy distribution, implementation, and applications in smart healthcare services for animals, 5G-assisted RF-EHWC, and wirelessly charging wearable devices. |
| [109] | Energy harvesting technology roles in 5G networks by providing sustainable power sources. | - Energy harvesting plays a crucial role in extending device and network battery life by harnessing energy from environmental sources and ambient radio frequency signals.<br>- The study covers energy conversion methods, models, propagation, and requirements in 5G networks. |
| [110] | Wide input range, voltage compensated RF-to-DC power converter. | - The design efficiently converts RF signals to DC voltages by applying optimum compensation voltage produced by subthreshold auxiliary transistors.<br>- The compensated rectifiers achieve higher efficiency over a wider input power range. The design demonstrated a measured power conversion efficiency (PCE) above 20% while driving a resistive load. |
| [11] | Optimisation of RF energy transfer through modelling | - RF energy transfer is subject to path loss, resulting in low RF power available on the rectenna and low RF-to-DC conversion efficiency.<br>- Optimisation is crucial for both the subsystem and rectenna to balance efficiency and boost converter performance. |
| [111] | Circuit conversion design for ambient energy harvesting at ultra-high frequency (UHF) | - The study investigates power conversion efficiency and output voltage theoretically for ambient energy harvesting at UHF.<br>- Specific circuit design considerations are explored. |
| [112] | Wearable and Implantable medical devices (IMDs) and their power supply challenges | - Identified system elements for enabling optimised device operation.<br>- Characteristics required for efficient RFEH implementation.<br>- Identification of gaps in RFEH implementation<br>- Exploration of future research opportunities in the field. |
| [113] | Flexible and wearable hybrid RF and solar energy harvesting system for powering wearable electronic devices | - Compared to a single solar cell, the hybrid system provides an additional 35.6–769.5% output power when RF source power varies from 4 to 10 dBm.<br>- The proposed flexible and wearable RF-solar energy harvester has the potential for practical use in powering various devices |

**Table 6.** *Cont.*

| Study | Research Focus | Key Findings |
|---|---|---|
| [114] | Harvesting radio frequency energy (RFEH) for self-powered micro-systems | - Improved sensitivity and input power range of the converter.<br>- Better performance compared to previously reported results.<br>- Enables self-powered micro-systems with efficient energy harvesting. |
| [115] | Wearable RF energy-localised harvester for powering a Bluetooth sensor module | - Shows potential for powering small electronic devices in wearable applications.<br>- Harvested power density of 2.75 $\mu$W/cm$^2$ and supports battery-free Bluetooth temperature and humidity sensor. |
| [116] | Challenges with on-device batteries in ultra-low power wearable devices and the emergence of wireless power transmission technologies | - Batteries in wearable devices pose constraints in usability and functionality, including periodic charging and e-waste generation.<br>- Wireless power transmission technologies offer a potential solution for unobtrusive and seamless charging of wearable devices.<br>- Existing solutions, such as RF signals, lasers, and electromagnetic fields, face challenges related to infrastructure requirements and power transmission magnitude.<br>- Further research is needed to develop wireless power transmission technologies that overcome these challenges for wearable devices. |
| [115] | Development of a wearable RF energy-localised harvester for powering a Bluetooth sensor module | - The harvester was made of flexible materials for a compact and low-profile design.<br>- The harvested power supports a battery-free Bluetooth humidity sensor and temperature with a power density of 2.75 $\mu$W/cm$^2$.<br>- The system demonstration of RF energy harvesting showcases the potential to power small electronic devices for wearable applications. |
| [117] | Feasible study of wearable energy neutral operation (ENO) while maintaining robustness in wireless textile body area network (TBAN) | - Reliability and energy issues are challenges faced by TBAN.<br>- Numerical results show stable power levels and improved packet error rate and battery power with the proposed optimisation algorithms.<br>- DQN-based optimisation performs better than Q-Learning, achieving a 14% improvement in PER and 56% improvement in battery pow |

## 5. Conclusions

This article focuses on energy harvesting technologies aimed at overcoming battery limitations in wearable devices, particularly in sports and biomedical applications. It provides a comprehensive review of current innovations, emphasizing essential characteristics such as flexibility, stretchability, lightness, and intended use. The article explores various energy sources applicable to wearables and discusses flexible and textile-based energy harvesting technologies, including solar, thermoelectric, piezoelectric, and triboelectric fabrics. Hybrid solutions that combine multiple energy harvesting techniques are also examined to enhance overall energy extraction efficiency. Performance and applicability are compared for each transduction mechanism, highlighting the advantages of the examined solutions. Triboelectric energy harvesting stands out as the most promising option due to its simple fabrication process, large-scale implementation, and significant output power values. The article concludes by discussing the challenges and future directions on RF energy harvesting technologies to further enhance output power. The findings contribute to the development of energy-autonomous wearable devices and provide insights for future advancements in wearable energy harvesting systems.

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