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A comprehensive review of ambient RF energy harvesting in wireless systems

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Abstract

Radio Frequency Energy Harvesting (RFEH) has emerged as a promising solution to power the next generation of low-power devices in the Internet of Things (IoT), smart cities, healthcare, and industrial monitoring. By converting ambient or dedicated RF signals into usable electrical energy, RFEH enables battery-free, maintenance-free, and sustainable device operation. This review explores the fundamentals and system architecture of RFEH, including rectenna design, impedance matching, energy management, and hybrid harvesting strategies. Advancements in multi-band antennas, metamaterials, and rectifier topologies are analyzed alongside emerging concepts like ambient backscatter communication, AI-driven energy optimization, and wireless information and power transfer (WIPT). Furthermore, we discuss applications across biomedical systems, structural health monitoring, and wearable electronics, while addressing challenges such as low energy density, miniaturization, interference, and standardization. Finally, the review highlights future research directions, emphasizing the role of 5G/6G networks, edge intelligence, and hybrid systems in shaping resilient, self-sustaining wireless ecosystems.

Keywords: Radio Frequency Energy Harvesting (RFEH); Rectenna; Wireless Power Transfer (WPT); Ambient Backscatter Communication; Hybrid Energy Harvesting; AI Integration; Edge Intelligence; Wireless Sensor Networks (WSNS); 5G/6G Networks; Internet of Things (IOT); Internet of Energy (IOE)

1. Introduction

The world is becoming increasingly connected, with billions of devices forming the backbone of the Internet of Things (IoT), smart cities, healthcare monitoring, and industrial automation [1]–[3]. These devices, from tiny medical implants to wireless sensor networks in buildings and bridges, all need a reliable source of energy to function. For decades, batteries have been the primary solution, but their limited lifetimes, high replacement costs, and environmental impact make them unsustainable for large-scale deployments [2]–[5]. In many cases, such as embedded sensors or biomedical implants, replacing batteries is not only inconvenient but sometimes impossible [3], [5]. This challenge has sparked significant interest in Radio Frequency Energy Harvesting (RFEH), a technology that converts ambient radio waves emitted by Wi-Fi routers, mobile towers, and broadcasting systems into usable electricity [1], [4].

At its core, an RFEH system consists of an antenna to capture radio waves, a rectifier to convert them into direct current, and an energy management unit to store and regulate the harvested power [2], [5]. Together, these components form a rectenna. Two main approaches exist: Ambient RF-EH, which passively captures signals already present in the environment, and Wireless Power Transfer (WPT), where transmitters are purposefully deployed to deliver energy [3], [5]. Ambient harvesting is convenient but suffers from low power density, while WPT can provide higher energy levels at the cost of additional infrastructure [4], [5]. To address these issues, researchers are developing compact antennas (fractal, spiral, conformal), wideband impedance matching circuits, and highly efficient rectifiers with multipliers and

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boosters [2], [3]. More advanced systems also incorporate multiple antennas with adaptive algorithms, while AI-driven optimization enables devices to adjust intelligently to changing RF conditions [2], [3], [5].

Beyond powering devices, RFEH is transforming wireless communication. Techniques such as ambient backscatter communication allow devices to reuse existing RF signals to transmit data without generating their own, thereby reducing energy consumption [6]. Similarly, Simultaneous Wireless Information and Power Transfer (SWIPT) frameworks combine communication and energy delivery for greater efficiency [6], [20]. To improve reliability, hybrid systems are being developed that integrate RF with solar, thermal, or vibration energy, ensuring devices remain operational even when one source is unavailable [11], [12]. The role of artificial intelligence and edge computing is also expanding enabling predictive energy management, efficient power allocation, and protection against interference and security threats [13], [14]. Real world prototypes already demonstrate feasibility, such as RF-powered concrete sensors for structural health monitoring and wearable devices powered by Wi-Fi signals [7]–[10], [17], [18]. While solar remains the dominant renewable energy for outdoor use, RF harvesting is especially valuable indoors, at night, or near strong RF emitters [19]. With the rollout of 5G and future 6G networks, the availability of RF energy is expected to increase dramatically, making RFEH not just a research interest but also a practical enabler of the Internet of Energy (IoE) [1], [3], [19], [20]. Recent work has thus shifted toward addressing the practical challenges that hinder large-scale deployment [1]–[5]. The central issue lies in the inherently low and variable energy density of RF signals, which makes efficient antenna design, impedance matching, and rectifier performance critical for reliable operation [2], [3], [9]. Studies indicate that optimizing these components can significantly extend the lifetime of wireless sensor networks and enable battery-free operation in healthcare and smart city applications [5], [8], [10].

In addition, RF harvesting is increasingly being integrated with communication technologies. Ambient backscatter communication enables ultra-low-power connectivity by recycling existing RF signals, reducing dependence on dedicated transmitters [6], [7], [13]. Similarly, multi-antenna method improves spatial coverage and energy transfer efficiency, making RF harvesting more practical for distributed IoT deployments [9], [14]. To overcome intermittency, hybrid systems combining RF with solar, thermal, or vibration sources are being explored, ensuring higher reliability under real-world conditions [3], [7], [15]. Emerging approaches also leverage AI-driven energy management, where machine learning algorithms predict energy availability and optimize consumption across sensing, processing, and communication tasks [2], [9], [16]. Comparative studies suggest that although solar often provides higher power densities, RF energy harvesting is uniquely suited for indoor and infrastructure-dense environments, especially when supported by dedicated RF transmitters [19], [20]. Taken together, these complementary characteristics establish RF-EH not merely as an isolated research field but as a foundational enabler of hybrid, AI-assisted energy ecosystems poised to power next-generation IoT and wireless communication systems.

2. Fundamentals and System Architecture of Rf Energy Harvesting (RFEH)

Radio Frequency Energy Harvesting (RFEH) is becoming a key contender in the search for sustainable ways to power small, connected devices especially in the Internet of Things (IoT) world [1]–[5]. The idea is straight forward but powerful: the air around us is full of invisible radio waves from mobile networks, Wi-Fi routers, broadcast towers, and countless other communication systems [1]. Instead of letting this energy go unused, RFEH systems capture it, convert it into electricity, and use it to run devices like wireless sensor nodes (WSNs) often without the need for batteries [3][5].

An RFEH-based wireless system typically works through four main stages [2][4], as shown in Fig.1

- Rectenna Feeding Technique (RFT) – capturing and directing radio waves into the system as efficiently as possible;
- Rectenna Module – a combination of an antenna, RF/DC converter, impedance matching network, and DC/DC converter that turns those waves into usable power [2][5];
- Wireless Sensor Energy Budget Optimization (MEB-WS) – designing devices to consume very little energy so they can run on limited harvested power; and
- Energy Management – storing, distributing, and regulating that power so the device works reliably over time [1][4].

There are two main approaches: Ambient RF Energy Harvesting (A-RF-EH), which uses signals already present in the environment, and Wireless Power Transfer (WPT), where energy is sent directly from a transmitter to a device [3][5]. Ambient harvesting is more passive and convenient but limited by low power levels, while WPT can deliver more energy but requires dedicated transmitters. Both face challenges such as energy loss over distance, conversion inefficiencies, and unpredictable availability [1][4].

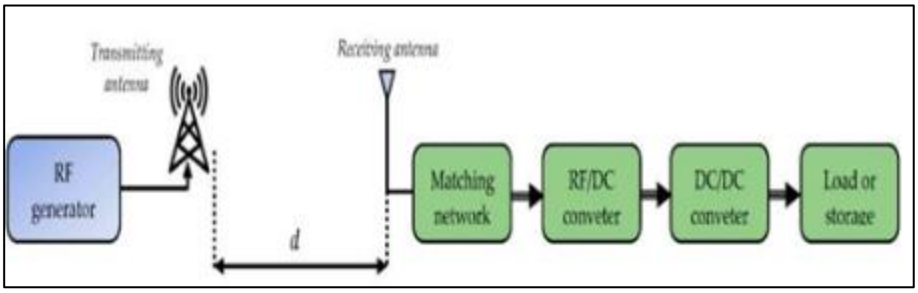

Figure 1 Far-field WPT and RF/DC conversion blocks of an RF-EH system [1].

Researchers are pushing the boundaries in several areas: improving rectenna designs, developing multi-band and metamaterial-assisted harvesters, and using AI-based energy management so that devices can adapt in real time [2][4][5]. Hybrid systems that combine RF harvesting with solar, thermal, or vibration energy are also being explored to improve reliability. These advances open the door for long-lasting, maintenance-free devices in smart cities, industrial systems, healthcare implants, and even space applications [1][3][5].

Still, the technology must overcome issues like low energy density, miniaturizing antennas without losing performance, electromagnetic interference, and the cost of scaling production [4][5]. But with the arrival of 5G, 6G, and other advanced networks increasing the number and variety of RF signals in the air, the potential is only growing [1][3]. If efficiency keeps improving, RFEH could move from being a basic research topic to a standard way of powering billions of devices that are quietly and sustainably using energy that's already all around us [2][5].

3. Antenna And Rectenna Design Optimization

The efficiency of an RFEH system depends heavily on how well its antennas and rectennas are designed [2][3]. The antenna acts as the system's "first contact" with ambient RF signals, and the rectenna combining the antenna with the rectifier turns those captured signals into usable DC power. Poor design here can undermine the performance of even the most advanced energy management strategies [2]. For medical applications, biocompatible antenna materials are essential for safe operation in the human body [3]. These advancements are particularly important in ultra-low-power applications, where every microwatt counts. Some systems are now going beyond fixed designs and adapting to changing conditions [3]. Multi-antenna setups with phase-control algorithms such as brute force (BF), sequential testing (ST), and codebook-based (CB) methods allow the system to "tune" itself for maximum energy capture. While BF is energy and time-intensive, and CB requires high-resolution components, ST has emerged as the most practical approach, offering strong performance without excessive complexity [2][3].

To make these components more effective, researchers have experimented with a wide range of antenna geometries such as slotted designs, meandered lines, fractals, spirals, and conformal shapes, each offering trade-offs in size, efficiency, and directionality as represented in Fig.2 [3]. The choice of impedance matching method, whether lumped or distributed, can also make a significant difference in how efficiently energy flows from the antenna to the rectifier [2][3].The rectifier stage itself has been refined with low-loss AC–DC converters, voltage multipliers, and boosters, ensuring that even small amounts of captured energy are wasted minimally [2].

Just like at the system level, antenna and rectenna designs still face the same core challenges such as low ambient power density, size constraints, interference, and regulatory limits [2]. But as AI-driven control, hybrid harvesting, and dense wireless networks become more common, these components are evolving into highly adaptable, efficient, and scalable solutions [3]. In the end, they form the beating heart of next-generation RFEH systems, where every captured signal translates into sustainable power for the connected world [2][3].

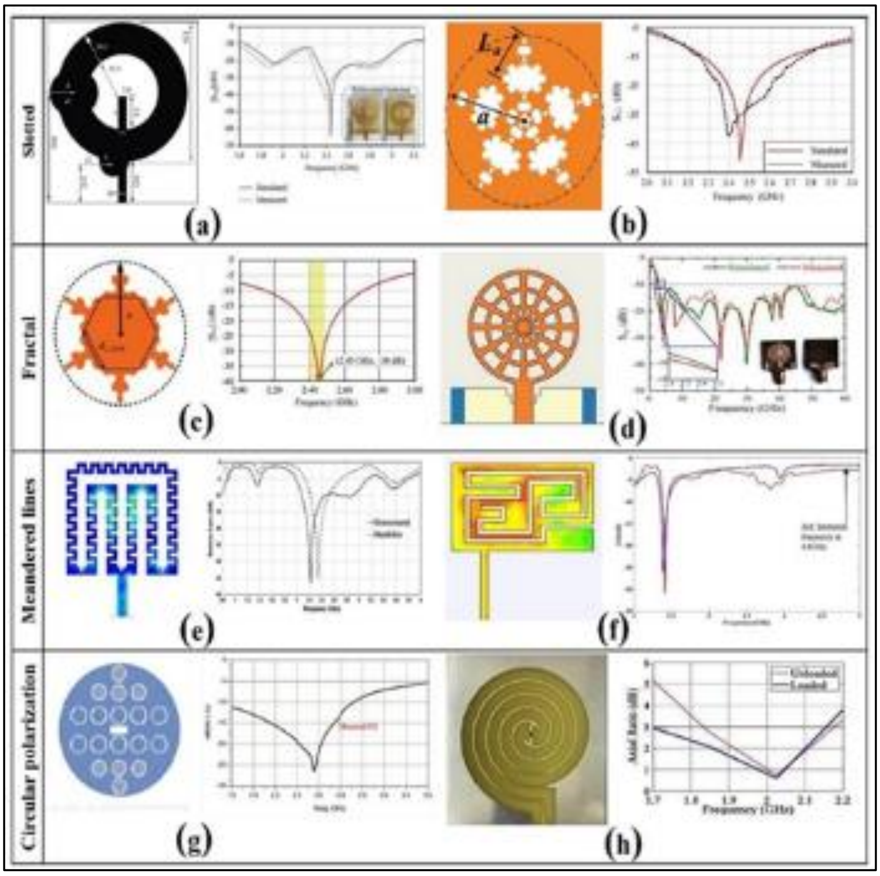

Figure 2 (a) and (b) slotted wideband antennas, (c) and (d) fractal wide and multiband antennas, (e) and (f) meandered lines wide and multiband antennas, (g) and (h) circular polarized ultra-wideband antennas [3].

4. Wireless Transmission and Passive Communication

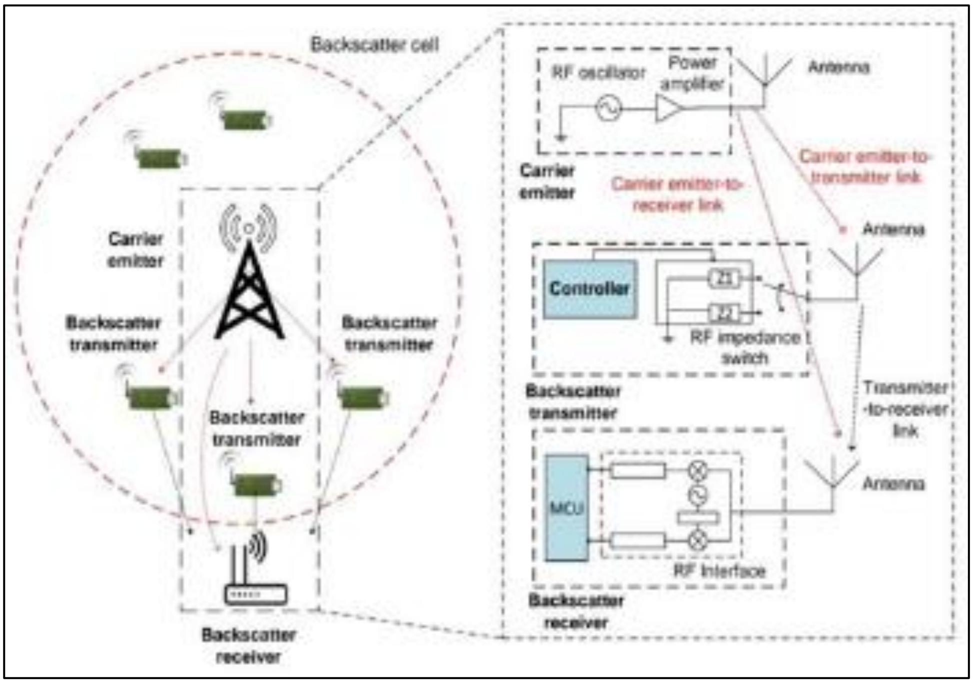

Figure 3 A general bistatic backscatter communications architecture [6].

Building on the earlier discussion of RF energy harvesting, wireless transmission techniques have evolved to not only capture energy but also enable communication without additional power expenditure [6]. One such approach is ambient backscatter communication, where smart devices make use of existing RF signals from sources like TV, Wi-Fi, or cellular networks to exchange data without generating their own signals [6]. This is particularly valuable for low-power applications such as wireless sensor networks and IoT devices, where energy efficiency is critical. The technology often uses bistatic backscatter systems with separate transmitter and receiver units and is closely tied to methods like RFID, passive communication systems, and wireless energy harvesting which delves into system architecture, modulation and coding schemes, and how ambient backscatter synergizes with energy harvesting to meet both communication and power needs in resource-constrained networks as shown in Fig.3 [6].

In parallel, sustainable Wireless Energy Transfer (WET) through RF energy offers a practical solution for powering IoT devices without reliance on batteries, which are costly and impractical for large-scale deployments [6]. By designing eco-friendly transmitters and low-complexity circuits, WET minimizes both the carbon footprint and RF pollution while ensuring secure power delivery without energy leakage [6]. This approach makes it possible to wirelessly power low-energy devices reliably and over the long term, making it an essential enabler for future IoT systems where sustainability and scalability are as important as performance.

5. Hybrid Energy Harvesting and AI Integration

Building on the earlier advances in RF-based energy harvesting, researchers are now looking beyond single-source solutions and moving towards hybrid energy systems that can keep devices running more reliably in the real world [2]. The idea is simple but powerful capture ambient RF energy from everyday sources like mobile towers, Wi-Fi routers, or TV broadcast stations, and then combine it with other renewable inputs such as solar, thermal, or vibration energy [2]. This way, even when one source drops, another can fill the gap. At the heart of this approach there are improved rectenna designs, compact systems that merge antennas with rectifiers to efficiently convert RF waves into usable electricity [2]. These are now being paired with smart impedance matching circuits and advanced materials like metamaterials to draw energy from multiple frequencies at once [2]. But there are still challenges: RF power levels can be very low, energy availability isn't always predictable, antennas need to be small yet efficient, and interference or regulatory limits can hold things back [2]. This is where AI and machine learning come in. By predicting energy patterns, adjusting system parameters in real time, and scheduling power usage intelligently, AI can help these hybrid harvesters work at their best under constantly changing conditions [2]. The result is a pathway to battery-free, maintenance-free devices that could thrive in applications from smart city infrastructure to industrial IoT, medical implants, and even satellites [2]. With 5G rolling out and 6G on the horizon, these AI-driven hybrid systems could form the backbone of a truly sustainable and interconnected world powering billions of devices without ever needing to replace a battery [2].

6. Applications and Protocols

Figure 4 RFEH Applications [2].

As RF energy harvesting technology matures, its applications are moving from lab concepts to practical deployments across healthcare, industrial automation, smart cities, and wearable tech [2][3][7][10] as shown in fig 4. For low-power systems like portable electronics, wireless sensor nodes (WSNs), and implantable medical devices (IMDs), RF energy offers a sustainable alternative to batteries especially as modern electronics become increasingly energy-efficient through nano/microfabrication advances [3][8].

A typical RFEH system consists of three main components: a receiving antenna, an impedance matching circuit, and an AC–DC rectifier [7]. Together, these capture and convert ambient RF signals from the environment into usable DC power [8][9]. Researchers are experimenting with a variety of antenna geometries like slotted, fractal, spiral, meandered lines, and even conformal designs to balance compactness with efficiency [3][8]. Both lumped-element and distributed-element matching circuits are being tested to optimize performance for specific applications [9]. On the power conversion side, RF–DC rectifiers and voltage boosters are being fine-tuned to deliver the micro- to milliwatts needed by low-power biomedical sensors, wearable electronics, and IoT nodes [7][10].

Beyond RF alone, hybrid systems are demonstrating impressive capabilities [8]. Prototypes have harvested UHF digital TV signals from over 6 km away, while dual-band harvesters (915 MHz and 2.45 GHz) and Wi-Fi harvesters capture power from multiple frequencies simultaneously [7][10]. Wearable organic electrochromic devices powered by on-body harvesters highlight the growing potential for smart textiles and medical monitoring [9]. These solutions not only cut out the need for battery replacements but also support continuous, maintenance-free operation in remote or hard-to-reach environments [7]. Efficient operation in the field also depends on choosing the right communication protocols [8]. Studies comparing Bluetooth v5.0, NB-IoT, Sigfox, and 5G show that Bluetooth v5.0 and NB-IoT are generally more energy-efficient, while Sigfox and 5G can be more power-hungry depending on network conditions [7][9]. Factors such as sensor type, device spacing, data packet size, and routing strategy all affect how much harvested energy is available for actual data transmission [10].

Recent work is also tackling the adaptability problem in RF systems, which often use static setups that underperform when signals fluctuate [7][9]. Dynamic multi-antenna approaches using methods like (BF), (ST), and (CB) phase adjustments help improve signal capture [3][9]. Of these, ST offers the best real-world trade-off between performance and complexity, especially in multi-antenna, multi-transmitter environments [10].Taken together, these developments point to a future where RF and hybrid energy harvesters, combined with optimized protocols, can deliver reliable, secure, and eco-friendly power for billions of connected devices enabling a truly battery-free Internet of Things as shown in fig.5 [3][8][10].

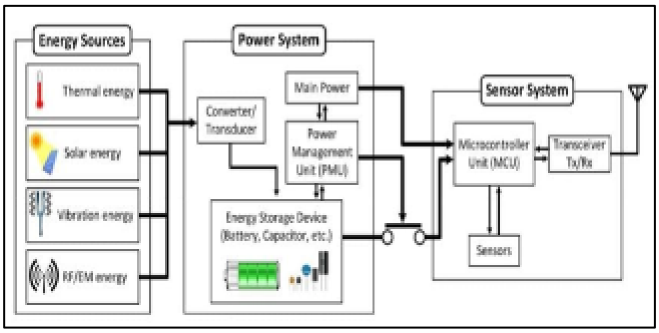

Figure 5 Energy-Harvesting-enabled wireless sensor platform systems [9].

7. Hybrid Energy Harvesting Systems

Hybrid energy harvesting has emerged as a promising solution to the limitations of single-source energy systems, enabling continuous power generation by integrating multiple transduction mechanisms such as piezoelectric, triboelectric, electromagnetic, solar, and RF energy [11] [12]. This approach not only boosts overall power output but also improves space utilization and ensures reliable operation under varying environmental conditions [11]. Recent reviews highlight diverse hybrid configuration like piezoelectric + electromagnetic or piezoelectric + triboelectric systems and their applications in smart transportation, infrastructure monitoring, healthcare, aerospace, marine systems, and industrial environments [11]. Building on these concepts, recent advancements have moved towards compact, application-specific hybrid solutions, such as a chip that combines RF energy harvesting with solar power as shown in Fig.6 [12].

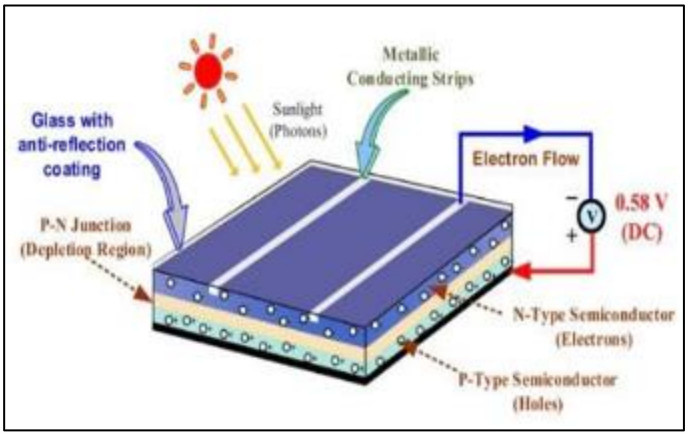

Figure 6 Photovoltaic cell composed of two semiconductor layers: an N-type layer with an abundance of electrons and a P-type layer with an abundance of holes [12].

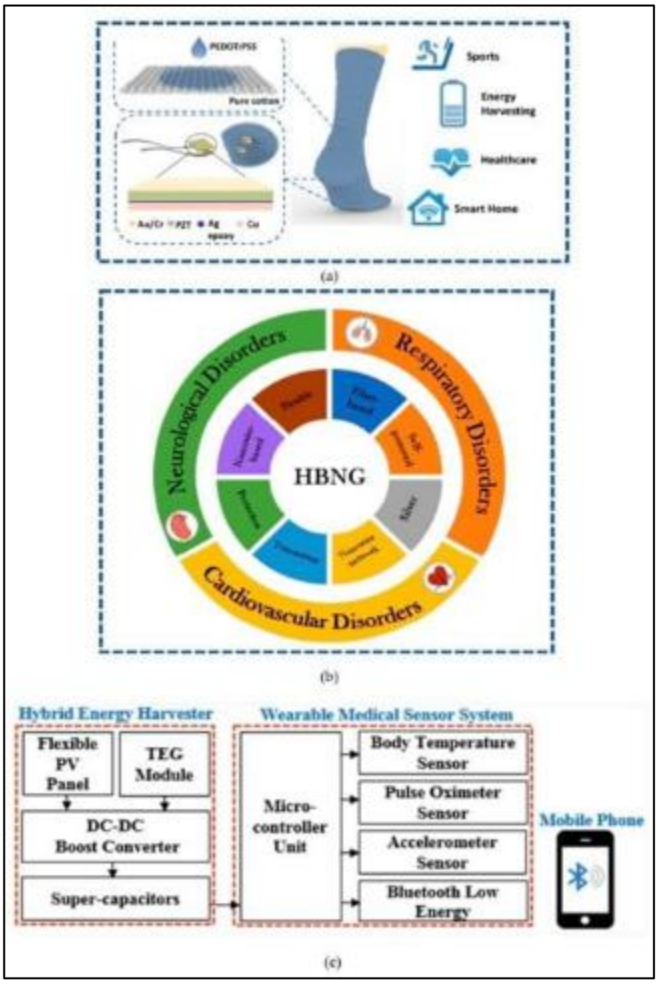

Figure 7 (a) Schematic diagram of hybrid PE-TE self-functional socks created by Zhu et al; (b) graphical overview of the different physiological problems that may be monitored using hybrid nanogenerators; (c) schematic diagram of the self-powered hybrid system for healthcare applications by Mohsen et al [11].

This design integrates a high-efficiency RF rectifier, solar harvester with charge pump, DC combiner, overvoltage protection, and low-dropout regulation to deliver a stable 3.3 V output, making it suitable for IoT devices such as wearables, and biomedical systems [12]. By merging different energy sources, these systems demonstrate how hybridization can extend device lifetimes, improve performance, and pave the way for greener, self-sustaining electronics as shown in Fig.7 [11][12].

8. AI And Edge Intelligence in RF-EH

The integration of edge AI into the IoE is transforming the way energy networks operate by bringing computation and decision-making closer to end devices [13]. This shift reduces latency, enables real-time analytics, lowers power consumption, and improves privacy compared to cloud-dependent systems as shown in Fig.8(a)[13]. Techniques such as on-device computation, edge server collaboration, private inference, and edge-based AI training have shown strong potential for enhancing IoE performance. Practical applications span smart grids, renewable energy management, and intelligent demand-response systems as shown in Fig.8(b) [13].

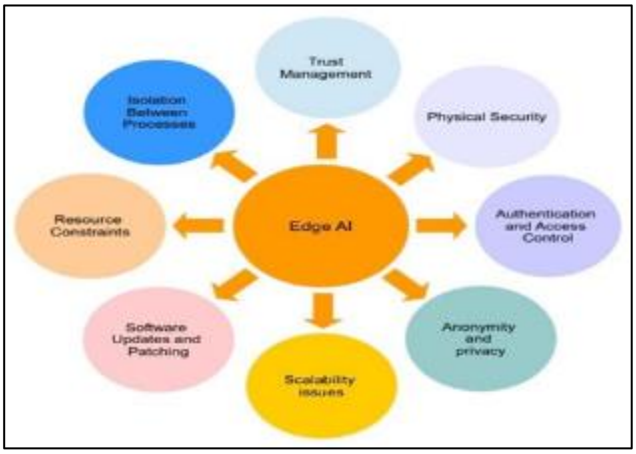

Figure 8 (a) A summary of the main security and privacy issues in edge AI systems [13].

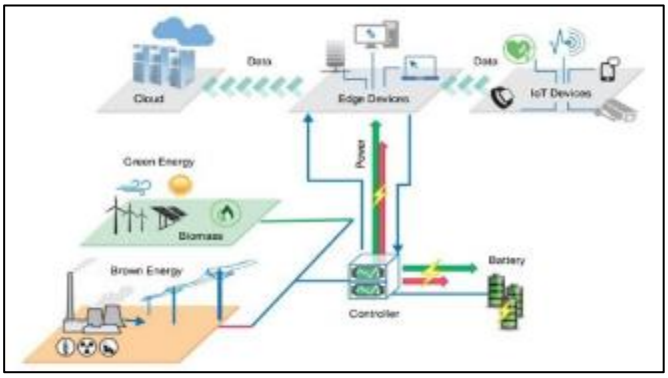

Figure 8 (b) Flowchart of the framework proposed to integrate Edge AI into a microgrid [13].

Despite challenges in security, processing capabilities, interoperability, and standardization, emerging technologies like 5G, federated edge AI, deep reinforcement learning, blockchain, and generative AI promise to further strengthen the capabilities of edge-powered IoE [13]. Complementing this trend, AI is also playing a critical role in enhancing the security of energy harvesting systems [14]. By leveraging machine learning and federated learning, AI can improve intrusion detection, encryption, authentication, and threat intelligence in both uplink and downlink communications. This is crucial for countering threats like spoofing, jamming, and data manipulation, which can impact renewable and RF-based EH sources. Hybrid energy harvesting approaches that combine multiple sources can improve reliability but also introduce added complexity an area where AI excels in optimization and security management [14]. Together, edge AI in IoE and AI-driven security in EH present a powerful synergy, enabling energy systems that are not only intelligent and efficient but also resilient and secure in the face of evolving challenges as shown in Fig.9 [13][14].

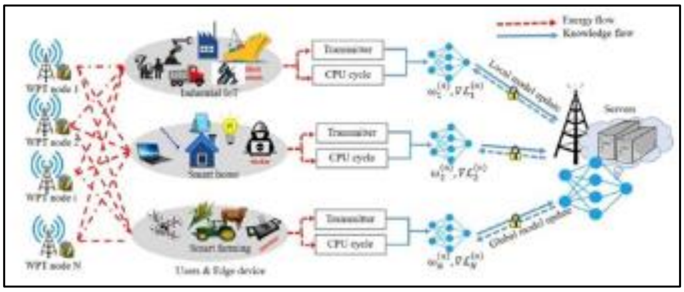

Figure 9 Scenario of application of AI in the security of EH [14].

9. Safety regulation and standardization

Radio Frequency Energy Harvesting Networks (RF-EHNs) have gained significant attention as a sustainable method to replenish energy for wireless devices. By harvesting ambient RF signals from surrounding environments, RF-EHNs enable prolonged operation of devices while meeting quality of service (QoS) requirements [15].

Research contributions in this area span system architectures, RF harvesting circuit design, and specialized communication protocols that optimize efficiency. Additionally, multiple network models including single-hop, relay-assisted, multi-antenna, and cognitive radio networks have been investigated for their potential to enhance scalability and reliability. Nevertheless, key challenges such as efficient resource allocation, circuit miniaturization, and large-scale deployment remain open areas for exploration [15].

In parallel, Edge Artificial Intelligence (Edge AI) has emerged as a transformative paradigm to address real-time data processing challenges in IoT-driven ecosystems. By embedding intelligence at the network edge, closer to the data source, Edge AI reduces latency, enhances privacy, and lowers dependency on centralized cloud infrastructures [16]. Its taxonomy covers cloud, fog, and edge computing layers, integrating machine learning and deep learning to enable fast, adaptive decision-making. Despite its rapid progress, Edge AI continues to face constraints related to limited resources, security vulnerabilities, and scalability [16]. The complementary strengths of these two domains create opportunities for next-generation IoT systems that are both energy-autonomous and intelligent. While RF-EHNs ensure sustainable energy supply, Edge AI empowers devices with adaptive intelligence for secure, scalable, and efficient operation. Together, they establish the foundation for future wireless networks capable of supporting diverse applications in smart environments.

10. Real-World Deployments, Prototypes, and Future Directions.

In the era of smart communication, RF-EH has become a practical route to powering autonomous sensor nodes from ambient or dedicated RF fields. Achieving meaningful RF-to-DC power transfer hinges on well-engineered antennas, impedance-matching networks (IMN), and rectifiers, with rectenna topologies (single-band, multiband, compact) already enabling low-power IoT and body-area applications yet wideband matching and high PCE in miniaturized footprints remain open challenges [17].Translating these building blocks into the field, structural health monitoring (SHM) has emerged as a compelling testbed: RF-powered sensor nodes embedded in concrete demonstrate long-lived, battery-free operation. Active RF-SNs sustain ZigBee links at low incident powers, while passive RF-SNs leverage square-chirp backscatter to combat concrete attenuation; experiments report successful links from depths >13 cm, validating durable, autonomous SHM deployments as shown in Fig.10 [18].

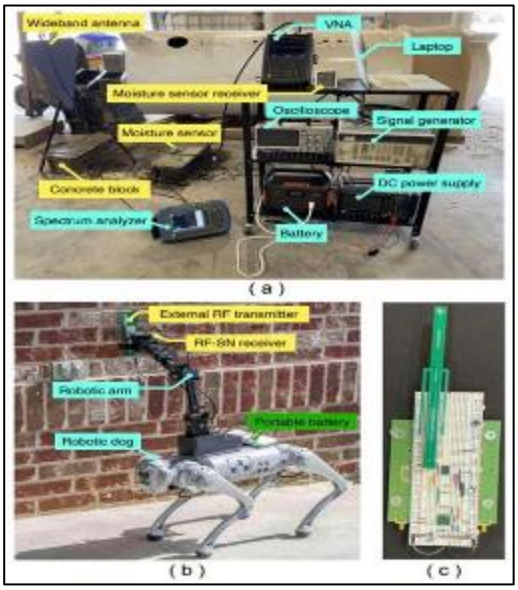

Figure 10 Experimental platform of SHM system, (a)Experiment setup (b)Application scenario of RF-SN with a robotic dog, (c)Prototype of the passive RF-SN [18].

Beyond single-source designs, hybrid harvesting clarifies where RF fits relative to light. Comparative studies in urban settings show solar irradiance dominates RF by orders of magnitude, even under shade or moonlight; RF becomes attractive mainly in constrained-light windows (cloudy nights, new-moon phases) or near strong RF emitters (Wi-Fi APs, cell towers). Consequently, photovoltaic (PV) remains primary, with rectennas as complementary harvesters for dark conditions or close-proximity RF tempered by rectenna cost considerations [19]. Critically, RF's role now extends from power to joint power-and-data via Wireless Information and Power Transmission (WIPT). Frameworks such as SWIPT, WPCN, and WPBC unify energy delivery and communication, but their efficiency hinges on harvester modelling: linear, diode-nonlinear, and saturation-nonlinear models reshape optimal waveforms, modulation, beamforming, and resource allocation. Notably, diode-induced nonlinearities can improve the achievable rate energy region, guiding PHY/MAC co-design for next-gen links [20]. Fig.11 illustrates different architecture of WIPT [20].

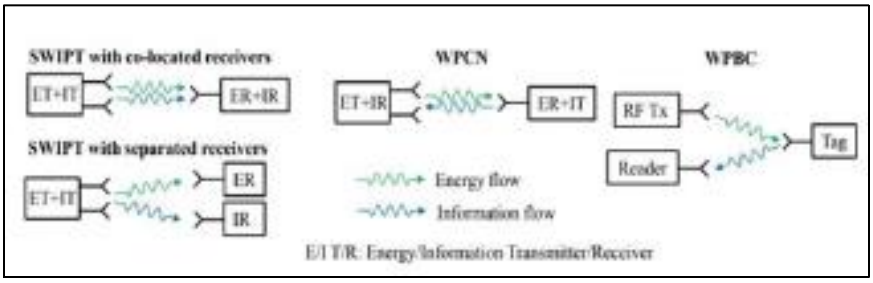

Figure 11 Different WIPT architectures [20].

11. Conclusion

Radio Frequency Energy Harvesting stands at the intersection of sustainability and connectivity, offering a pathway to power billions of devices without relying on conventional batteries. By leveraging advancements in rectenna design, impedance matching, hybrid energy harvesting, and AI-driven optimization, researchers are steadily addressing the challenges of low energy density, miniaturization, and efficiency. Real-world deployments in healthcare, structural monitoring, and smart infrastructure already demonstrate the practical potential of RFEH systems.

Yet, significant opportunities remain. The integration of wireless power and information transfer, AI at the network edge, and standardized protocols can transform RFEH from a niche technology into a mainstream enabler of the Internet of Energy. The arrival of 5G and 6G networks will only amplify the availability of RF signals, making large-scale, battery-free IoT deployments feasible. Looking ahead, the synergy of RF harvesting with other renewable sources, combined with intelligent energy management, holds the promise of a sustainable, secure, and self-powered digital ecosystem.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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