Iraqi Journal of Industrial Research, Vol. 13, No. 1 (2026)

Open Access

Iraqi Journal of Industrial Research (IJOIR)

Journal homepage: http://ijoir.gov.iq

Current Status and Future Prospects in Sustainable Wireless Energy Transfer: A Comprehensive Review

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Article information

Article history:

Received: February, 12, 2026

Accepted: May, 10, 2026

Available online: June, 14, 2026

Keywords:

Wireless power transfer,

Energy harvesting,

Wireless sensor networks,

Internet-of-things,

Radio frequency

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DOI:

https://doi.org/10.53523/ijoirVol13I1ID646

Abstract

Wireless power transfer (WPT) and energy harvesting (EH) is a fundamental technology for supplying energy wireless powered devices which operate continuously without battery assistance. This survey summarizes RF-based WPT and ambient energy harvesting (EH) methods in the field of IoT sensor network. This paper reviews recent advances in hardware, including small antennas, low-power rectifiers, and metamaterial-analogous concepts that improve the reception and conversion of power. Near-field methods, including inductive and capacitive coupling will be compared to far-field RF and microwave techniques, where the former are limited to short distances whereas radiative techniques may allow for long-distance metrics at the expense of higher attenuation losses. Moreover, the paper sheds light on network-level approaches like Simultaneous Wireless Information and Power Transfer (SWIPT) and efficient scheduling. Despite these advancements, ambient RF power densities are quite low, and system integrations are still complex, which limits the maximum power that can be realized using this technology. This work reviews the trends in the background, their associated challenges, and the roadmap to achieve real self-powered IoT systems.

1. Introduction

Distribution of wireless sensor networks (WSNs) and Internet-of-Things (IoT) deployments represent valuable opportunities to improve existing application domains such as smart cities [1]. Real time distributed data collection for applications such as healthcare monitoring environmental sensing, etc. As the number of wireless devices increases, the demand for high throughput and reliability connection becomes critical. Separation of energy utilization provides a similar distribution of energy consumption and can also reduce network congestion through dynamic variations of the network topology as mobile sinks or mobile sensor nodes [2, 3]. Nevertheless, low-power sensors tend to use small batteries that have a very limited capacity and therefore lead to a short network lifetime and a high frequency of required maintenance in the field [4]. It translates to either far more efficient power consumption or new energy generators for expected operational extension.

The recent emergence of this new strategy known as energy harvesting (EH) has attracted much interest due to the fact that it addresses the energy bottleneck in wireless sensor networks (WSNs). EH systems are systems which capture energy from the environment (e.g. solar, wind, mechanical vibration or radio-frequency (RF) energy) then transduce the energy into electrical energy [5, 6]. With these renewable input sensor nodes can greatly extend their lifetime and decrease the dependence on the main battery [7]. Essentially, harvesting can turn a WSN into a robust, self-sustaining system with minimal maintenance. To enhance energy conversion efficiency, researchers are gradually advancing the harvester designs (e.g., flexible single-halide perovskite solar cells optimized for the indoor use case of IoT devices) [8].

However, ambient sources are inherently random. The amount of harvestable energy can differ dramatically with time and environment [9, 10]. This creates a challenge for system design as nodes have to cope with uncertain energy resources. This concept necessitates the use of strong Energy management and scheduling algorithms to achieve a smooth compromise between very low sensing and transmission and the incoming energy profile. In spite of these limitations, however, EH-augmented WSNs have matured to the point where they can drive a large variety of sustainable applications, such as environmental sensors, industrial automation and wearable health monitors, that would be otherwise infeasible [6, 7].

Other method of perpetually running is wireless power transfer (WPT) along with ambient EH. In the wireless powered sensor networks (WPSNs), sensor nodes are powered using RF or magnetic wave radiation from dedicated transmitters [7]. I would suggest that WPT allows for node operability in the absence of the physical connectors (e.g., wired charging or replaceable batteries) that would be necessary with most other technologies. Indeed, WPT can “remove the necessity for replacing the traditional battery” in a sensor network [11]. Contemporary WPSN architectures, for instance, free sensors to be affixed to walls or even move [12]. This can cut maintenance by several orders of magnitude: sensors can be continuously charged from microwave or other inductive beams rather than by manual battery swaps.

Research work on incorporating WPT into network design has been an ongoing area of investigation; Engineers investigate various schemes that partition the spectrum between data and energy, such as simultaneous wireless information and power transfer (SWIPT). In reality however, WPT deployment is subject to challenges: transmission loss increases with distance, and energy and data streams share the same channel, allowing for interference between the two [13]. Nonetheless, this is a very convincing proof-of-concept at a fundamental level. Several surveys note that by using wireless chargers and intelligent scheduling, sensor networks can be kept alive indefinitely [11, 14]. For example, one architecture uses power beacons distributed in the environment so that sensor devices “can overcome the battery bottleneck with an extended battery life and to overcome the battery replacement” problem [15].

The combination of EH and WPT is beginning to underpin next-generation “smart” systems where energy sustainability and security are equally important. For instance, solar-powered roadside units (RSUs) in vehicular networks have been studied with embedded hybrid intrusion-detection systems. Qutaiba Ali et al. proposed an on-board intrusion-detection framework for a solar-powered RSU, explicitly designing the IDS to work within the tight energy constraints of the node [16]. This highlights how energy-efficient hardware and resilient networking must co-design to support secure, always-on service. Likewise, in smart grids – which rely on both distributed renewable generation and extensive sensor communication – researchers are applying machine learning to detect false-data-injection attacks as part of a comprehensive strategy for robust operation [17].

Emerging applications reinforce this trend. Consider connected and autonomous vehicles, which are forecast to rely more and more heavily on fog and edge computing infrastructures to process sensor data, for instance. It is now apparent that having roadside and in-vehicle sensors continually powered in an environmentally friendly manner (e.g. by solar charging stations or embedded PV panels) is a key aspect of sustainable transportation networks. Wireless charging and ambient EH are enticing in all these scenarios because they minimize greenhouse footprint and maintenance cost, while enabling the ultra-high uptime demands of modern IoT services.

To summarize, there are two streams of parallel strategies fueling the vision of never-ending IoT networks. The first is ultra-low power: strictly limiting the power consumption for sensing, processing and communication through optimized protocols and hardware. The other is to enable dependable recharging: to allow nodes to harvest energy from the environment or from dedicated WPT sources. In principle, for a network employing distributed power beacons, no battery swaps are necessary [15]. Moreover, even more autonomy in sensor operation can be achieved by integrating hybrid approaches that provide solar, thermal, vibrational, and WPT inputs to fill supply gaps accordingly. These approaches work towards infinite lifetime of sensor node through energy waste reduction and harvest whenever feasible. We review the state of the art in these domains. It presents an overview of energy-harvesting technologies and WPT techniques for WSNs, discusses the architectures of the power-management and conversion units, and analyzes the difficulties of large-scale network design with variable renewables. Our contributions are:

1. Performs a systematic analysis of WPT-EH architectures by exploring tradeoffs between coupling mechanisms, deployment environment and circuit complexity.
2. Covers wave propagation, miniaturization of antennas, and energy reliability under obstruction or multipath environments as functions of the chosen frequency.
3. Provides a systematic comparison of convergence behavior, computational complexity, and scalability of optimization techniques in WPT/EH systems.
4. Provides a taxonomy that connects hardware integration strategies to WPT-EH application requirements in specific domains.
5. Sheds light on the engineering challenge of a closely coordinated design of power electronics and harvesting interfaces to ensure sustainability in energy-truncating field-deployed applications.
6. Demonstrated various real-world WPT-EH applications in IoT, industrial and UAV systems to further reduce the reliance on batteries.

As shown in Figure (1) the details of the survey are depicted. The second section outlines the Review methodology. Section 3 outlines various past surveys. Section 4 focuses on far-field and near-field approaches that explicitly trade off efficiency and range. Section 5 evaluates performance metrics. Section 6 focuses on hardware developments for rectifiers, antennas and metamaterials for enhanced conversion efficiency. Section 7 reviews optimization strategies. Instead of sustainable energy transfer operations, see for suitable practical realizations of WPT–EH purposes in Section 8. Section 9 outlines some of the new directions that we find particularly exciting, such as intelligent control and hybrid architectures. Lastly, Section 10, gives Conclusions.

2. Review Methodology

This review focuses on the advances over the past recent years on EH and WPT for IoT-enabled WSNs from 2019 to 2025 making this review timely and pertinent as it presents the state-of-the-art developments in this area. The recent contributions include emerging technologies such as SWIPT, intelligent optimization and 6G-driven applications. On the other hand, our pre-2019 references are curated to only include key theoretical foundations, early protocol designs, and baseline system models in WSNs and energy harvesting. These fundamental works set the historical stage and provide the fundamental principles of modern innovations linking classical methodology with contemporary research direction.

This section outlines the method for conducting the systematic review, following Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [18] to facilitate transparency and reproducibility. Searches on the individual electronic databases were exhaustive, with the search expressions being iteratively refined to achieve the maximum specificity and sensitivity. For all references, the data was extracted by searching through academic databases (IEEE; Science Direct; Elsevier; Wiley; IET; and MDPI) by connecting titles with keywords such as “wireless power transfer”, “energy harvesting”, “RF“, “IoT”,”WPT” and “sensor networks” during the time span of 2019–2025. After filtering out duplicate and non-related results, over 18,000 studies were screened based on title and abstract, mainly searching studies related to the mechanisms of WPT or energy harvesting in IoT backgrounds. We retained 87 papers of high relevance for closer examination. Contributions in hardware design (e.g., antennas, rectifiers, metamaterials), system architecture (e.g., SWIPT, wireless power networks), and optimization methods for the papers were inspected. This systematic method of searching ensured that both theoretical and technological developments were included in the synthesis, ensuring a reliable platform for synthesising the current understanding of these questions in the field. The PRISMA model for this study is shown in Figure (2).

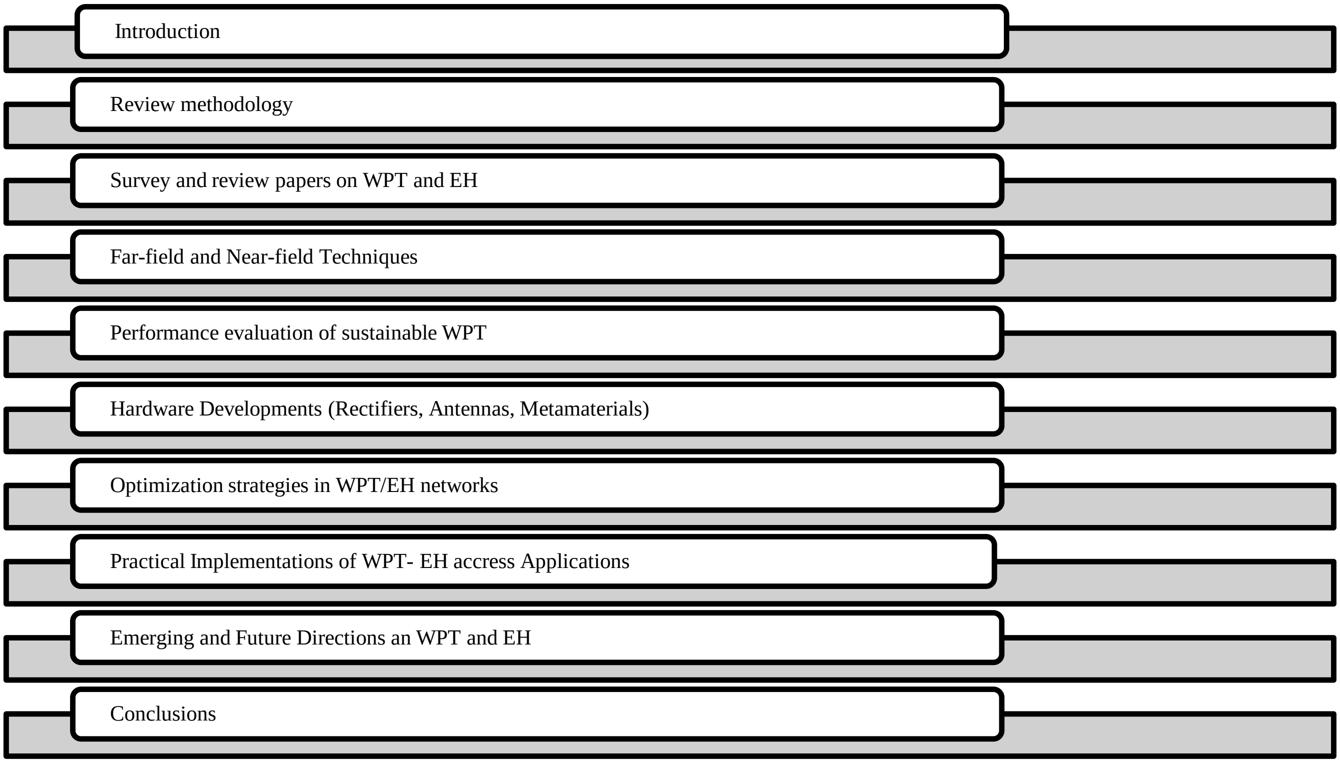

Figure (1): Outlines of the survey.

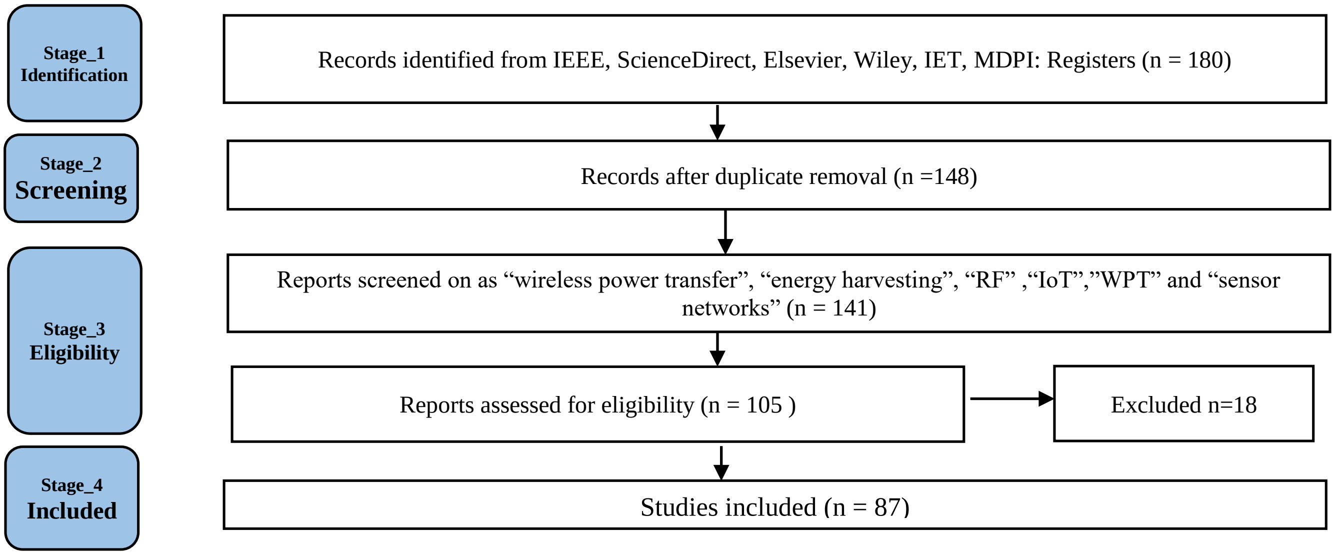

Figure (2): PRISMA flow diagram detailing the selection process for articles on “RF”, “IoT”, “WPT”.

3. Survey and Review Papers on WPT and EH

Such surveys may differ broadly or narrowly as to their theme. Others present high-level summaries across several aspects of WPT/EH, as in the case of [19], which presents a high-level summary of integrating wireless power and EH into future communication networks, and [20], which summarizes recent advances across the field. On the other hand, most are domain- or component-specific. Papers [21–24] explore the hardware in detail, covering design methodologies, but they focus only on hardware sub-systems (antennas or rectifiers). Some focus on specific application areas: Consider [25] and [26] for example which provide an in-depth survey of the challenges in two specific application domains, biomedical implants and underwater sensor networks respectively, both of which exhibit constraints that are orthogonal to those found in more general surveys (e.g., body safety, water propagation). Broad surveys often categorize content by taxonomy of technologies or use-case whereas narrower ones may enumerate design categories or compare technical metrics within their niche. Some themes overlap (e.g., several reviews discuss rectenna technology ([23, 27])) while others take different approaches (e.g., antenna design vs. system integration).

These works share some common limitations. One of the few common issues is the absence of standard quantitative benchmarks: functions in most surveys are qualitative comparisons of techniques without standardized metrics or cross-cutting performance evaluations, hindering objective benchmarking of approaches against one another. This is compounded by the fact that taxonomies risk becoming stale/siloed, which is another limitation. Old paradigms (e.g. component-based reviews of WPT and EH) have treated WPT and EH separately, while new paradigms (e.g. metasurface based WPT [28]) blur such lines, necessitating a more integrative approach to classification. Moreover, most dedicated surveys do not consider system-level integration, which is a term somehow covered by broader papers such as [29], however, this gap is still remarked in the literature.

On the other end of the spectrum, a few of them do provide us strong contributions by integrating knowledge and providing gaps/challenges, however the latter are few. The extensive hardware reviews (such as [22] and [24]) provide not only an inventory of what has been done, but also a description of the most significant key design trade-offs and directions in which improvement is possible (for instance, [24] makes specific suggestions for broadband rectifiers and for multi-band sub-rectifier combinations as promising approaches for the application of this technology in conditions with variable efficiency [30, 31]). Domain-specific surveys [25] highlight important challenges (e.g., size, safety, and reliability for implants) and “milestones” in that direction, creating helpful roadmaps for researchers. Similarly, newer surveys such as [27] propose integrative frameworks by introducing recent solutions (metasurfaces) regarding the limitations of conventional rectenna systems through spatial energy focusing [31]. In general, the most impressive surveys both summarize prior art and critically highlight gaps (e.g., [32] and [19] each identify directions in research that must be addressed for efficient and network-integrated WPT) to provide guidance for future work in this rapidly-evolving area. Table (1) shows the recent survey on WPT AND EH, Table (2) shows the Summary of Technologies, Research Type, and Experimental Validation in WPT/EH Literature.

Table (1): Recent survey on WPT and EH**.**

Ref.	Primary Focus Area	Scope	Temporal Coverage	Application Domains Discussed
[20]	Integration (general WPT/EH developments)	Broad (field-wide)	Last ~5 years (recent advances)	Multiple domains (IoT, smart devices, etc.)
[22]	Hardware (RF rectifier circuits)	Narrow (circuit component)	Full historical (to 2021)	General – component applicable to all WPT/EH
[24]	Hardware (rectifier design & challenges)	Narrow (design issues)	Current (last ~5 years)	IoT sensors, RF-powered devices (smart cities)
[26]	Applications (underwater WPT/EH methods)	Narrow (marine domain)	~Last 10 years (all known work)	Underwater sensor networks, marine robotics
[27]	Hardware (RF rectennas overview)	Narrow (specific device)	Contemporary snapshot (circa 2021)	Low-power sensors, ambient RF devices (IoT)
[28]	Hardware (metasurfaces in WPT/EH)	Narrow (specific approach)	Recent (~2015–2022)	Future wireless networks (e.g. RIS-aided IoT)
[29]	Integration (wireless networks + WPT/EH)	Broad (field-spanning)	Technology trends (future vision)	Wireless networks (6G, IoT, communication)
[32]	Hardware & Techniques (mmWave, MIMO, NF WPT)	Broad (multi-topic)	Tech trends (current & emerging)	Multiple: IoT sensors, comm. devices, etc.
[33]	Hardware (antenna designs for ambient RF EH)	Narrow (specific topic)	Full historical overview (to date)	Ambient IoT devices, RFID, low-power sensors
[34]	Applications (IoT power solutions)	Narrow (IoT domain)	Recent ~5–10 years	Internet of Things (sensor nodes, RFID tags)

[35]	Hardware (metamaterials-assisted WPT)	Narrow (specific approach)	Full historical (to 2022)	Various (mid-/far-field WPT: charging, sensors)
[36]	Applications (powering wireless sensor networks)	Narrow (WSN domain)	Recent (~2010s to 2020)	Wireless Sensor Networks (environmental, etc.)
[37]	Hardware (rectenna arrays advancements)	Narrow (subtopic focus)	Trends (recent progress to 2025)	Far-field WPT (e.g., IoT networks, UAV power)

Table (2): Summary of Technologies, Research Type, and Experimental Validation in WPT/EH Literature.

Ref	Main Focus	Research Type	Experimental Validation?	Notes
[20]	Wireless energy harvesting & transfer review	Survey / Literature Review	No	Comprehensive overview of RF/energy harvesting trends
[22]	Rectifier circuits for RF EH/WPT	Survey	Some Measurement Examples	Focus on circuit conditions and performance
[24]	Rectifier design challenges	Survey + Analysis	Illustrative Examples	Discusses bandwidth, input power range issues
[26]	Underwater energy harvesting & WPT	Systematic Review	Limited (literature)	No direct experiments; focus on marine systems
[23]	Antenna design for rectennas	Review	Yes (cited works)	Combines literature and measurement results
[27]	Rectenna performance	Conference summary	Limited	Broad overview with example designs
[28]	Metasurface-aided WPT/EH	Review	No	Focus on metasurface architectures
[29]	Future networks + WPT/EH	Perspective / Survey	No	Technology scan for next-gen wireless
[32]	WPT trends (mmWave, THz, MIMO)	Review	No	Broad survey in IEEE Microwave Magazine
[33]	IoT + RF EH/WPT	Review	No	Survey of techniques for IoT systems
[34]	Autonomous wireless devices & RFIDs	Review	Some Case Studies	Focus on device ecosystem
[35]	Metamaterials/metasurface for WPT/EH	Review	Some Experimental	Applications in arrays/metasurfaces
[36]	Powering wireless sensor nodes	Survey + Examples	Yes (reported designs)	Automotive electronics context
[37]	Rectenna arrays for RF EH/WPT	Review	Some Prototypes	Focus on arrays and performance trends

4. Near-Field and Far-Field Techniques

There are strengths and limitations to both near-field WPT systems as well as to far-field WPT systems, and they are therefore used in applications that serve very different purposes. Near-field WPT techniques, like inductive and resonant coupling, provide high efficiency power transfer for small distances, usually exceeding 50% for coil links [25]. This gives them an advantage to be used for medical implants, wearable electronics, an d devices that need to function in the order of a few centimeters from the power source. The primary benefit of near-field WPT is its intrinsic safety as the energy is well confined in the vicinity of the receiver so that the surrounding tissue exposure is estimated to be controllable. For instance, implanted systems [38] can ensure that the SAR remains within safe limits during operation. Although, distance further than a meter will rapidly decrease the efficiency of the system as the magnetic and electric fields will decay rapidly, therefore restricting the near-field WPT to short-range.

In contrast, far-field WPT transmits power at a distance by propagating electromagnetic waves like microwaves or radio frequency (RF) beams. As previously discussed in our article on distance charging, it allows for wireless and mass charging of distributed IoT nodes or sensors, although its poor overall efficiency stems from much of the energy transmitted dispersing before reaching a receiver. Real-world implementations, such as rectenna-based far-field WPT [39], can reach only a few percent efficiency at several meters. Moreover, transmit power at far field is limited by the safety regulation for the exposure of human beings to EM fields, which intends to keep the power density against μW–mW/cm² [38]. However, these constraints can be overcome by the use of sophisticated focusing techniques like phased arrays, beamforming and metasurfaces [28], [40] to focus the energy onto a target without exceeding the safety limits and thereby enhance the incident power density. These systems generate narrow and very high intensity beams, which allow high range and efficiency, however, a careful control of alignment or dynamic tracking is needed, otherwise, localized over-heating may occur.

Hybrid systems utilize the near-field and far-field WPT benefits and balance system efficiency, range and safety among multiple combined energy sources. These designs are composed of ambient EH (e.g., solar, thermal or background RF) and focused WPT for energy boosting upon demand [41, 42]. To give a representative example, achieve continuous background RF signal harvesting and periodic high-power RF beam receiving by using dual-mode antenna [41]. An alternate approach integrates solar EH and microwave WPT [42], so that while under most conditions the IoT platform operates through harvested solar energy, during low light conditions it can switch to power available from low-power microwave harvesting. These hybrid models exemplify the trade-off amongst range, power and safety: near-field achieves maximum efficiency but at limited range; far-field affords range, but sacrifice efficiency; and hybrid configurations try to have credits for both parameters, yet at safe threshold of exposure limits [43].

Near-field and far-field systems are both steadily evolving as trends in the research. Regarding new technologies on both transmission and receiver sides for far-field WPT, next-generation transmission techniques, based on: e.g., multiple-input multiple-output (MIMO) beamforming [40] and intelligent reflecting surfaces, can be integrated with novel receiver types, where novel wideband and multiband rectifiers can be adopted in high-gain antennas and metasurfaces to capture more harvested power. Near-field developments are solution-oriented, aiming for getting used to them being as effortless as possible for the user; to illustrate, body-coupled WPT [44] allows power transfusion through the human body itself, which means that wearable can be used without cumbersome connectors. This in turn manifests into application domains: near-field for biomedical, wearable, and EV charging applications dominate because safety and energy are key concerns whilst far-field for remote [22] IoT and RFID networks as it can harness a few microwatts to drive ultra-low-power nodes [21].

Standardized performance metrics are another common challenge across the literature. Coupling or coil efficiency is usually reported for the near-field works, coupled with SAR analysis for safety 25, whereas RF-to-DC conversion rates, antenna gain is what is reported for far-field works 22. Network-level WPT studies 48 either look at total energy harvested or communication impact rather than physical efficiency. Measurement conditions differ—reporting “50% efficiency” at the rectifier [45] vs. “5 mW at 5 m” received power [39]—so direct comparison is hard. In addition, safety analysis is uneven; biomedical and high-power applications discuss thermal and regulatory compliance, but few far-field IoT-related studies have devised a means of verifying safety or have even assumed safety [16]. This inconsistency also points to the lack of unified evaluation metrics that cover both efficiency and exposure aspects.

Wireless communication channels are frequently modeled using statistics to account for multipath propagation and environmental variableness. Rayleigh and Rician distributions are often used to model small-scale fading with the presence or absence of line-of-sight components respectively, while Nakagami-m generalizes fading severity [13]. We model the large-scale fading as log-normal shadowing, which accounts for the attenuation of the signal caused by obstacles [8, 11, 12, 29, 46].

5. Performance Evaluation of Sustainable WPT

The performance of sustainable WPT and EH for IoT and Wireless Sensor Networks (WSNs) can be measured using several important parameters: efficiency, harvested energy, network lifetime, coverage, and cost-performance ratio. Efficiency (η) defines the ratio of received power to transmitted power, harvested energy (Eh) is the usable energy collected per unit time, network lifetime (Tlife) is the expected operational duration before manual intervention is required, coverage (R) represents the maximum transmission range, and cost-performance (Cp) compares normalized lifetime energy cost across different deployment strategies. These parameters are closely linked, and improvement in one often leads to direct enhancement in the others. For near-field inductive power transfer (IPT), efficiency can be modelled by [11, 14, 47]:

$$\eta\mathrm{IPT} = (k^2\,\mathrm{QT}\,\mathrm{QR}) / (1 + k^2\,\mathrm{QT}\,\mathrm{QR}) \qquad (1)$$

Here, k is the coupling coefficient, and QT and QR are the quality factors of the transmitter and receiver coils. The coupling coefficient is inversely proportional to the cube of the distance ($k \propto 1/d^3$). This shows that IPT efficiency decreases cubically as the separation distance increases. In practice, IPT maintains efficiencies above 80–90% only for ranges of a few centimeters or less [46].

Magnetic resonance wireless power transfer (MR-WPT) extends the useful range of IPT by exploiting resonant coupling. Its efficiency is given as [14, 15]:

$$\eta\mathrm{MR} = (k^2\,\mathrm{QT}\,\mathrm{QR}) / [(1 + k^2\,\mathrm{QT}\,\mathrm{QR}) + (\Delta f / f0)^2] \qquad (2)$$

Where Δf is the detuning from resonance and f0 is the resonant frequency. Resonant systems are highly sensitive to frequency mismatches, but they can still achieve efficiencies above 70% at distances up to one meter when properly tuned.

For microwave wireless power transfer (MWPT), the Friis transmission model applies. The received power is [48, 49]:

$$\mathrm{Pr} = \mathrm{Pt}\,\mathrm{Gt}\,\mathrm{Gr}\,(\lambda / 4\pi R)^2 \qquad (3)$$

Where Pt is transmitted power, Gt and Gr are antenna gains, λ is wavelength, and R is distance. The usable power is then obtained after rectification [22, 23]:

$$\mathrm{Pusable} = \eta\mathrm{rect}\,\mathrm{Pr} \qquad (4)$$

Here, ηrect is the rectifier efficiency, typically ranging from 40% to 70%. This highlights how propagation losses and rectifier performance combine to limit end-to-end efficiency.

Laser power transfer (LPT) uses optical beams to deliver energy over larger distances. The received power at the photovoltaic (PV) receiver is [50, 51]:

$$\mathrm{Pr} = \mathrm{Pt}\,\eta\mathrm{opt}\,\eta\mathrm{PV}\,e\char`^(-\alpha R) \qquad (5)$$

Where ηopt is optical focusing efficiency, ηPV is photovoltaic conversion efficiency, and α is the attenuation coefficient of the medium. While highly directional, LPT is constrained by line-of-sight requirements, atmospheric scattering, and safety considerations related to high-intensity beams.

Hybrid energy harvesting (HEH) systems integrate multiple sources such as solar, RF, vibration, and thermal energy. The total harvested energy in a time window Δt is [8, 9]:

$$\mathrm{Etot}(t) = \Sigma\,\eta i\,\mathrm{Pi}(t)\,\Delta t \qquad (6)$$

Where Pi(t) is the available power from source i and ηi is its conversion efficiency. Because many renewable sources are stochastic in nature, probabilistic models such as Markov chains are used to capture state transitions (for example, Sunny/Cloudy for solar conditions). The expected network lifetime is given by [5, 8, 52]:

$$\mathbf{Tlife = (Einit + E[Etot]) / Pcons} \qquad (7)$$

Where Einit is the initial stored energy, E[Etot] is the expected harvested energy over the lifetime, and Pcons is the average energy consumption of the node [49].

The outcomes of these models can be illustrated with performance comparisons. Table (3) shows the efficiency trends of different WPT technologies across various distances. Near-field IPT is the most efficient at very short ranges but becomes ineffective beyond a few centimeters. MR-WPT sustains useful efficiency up to meters, while MWPT and LPT are better suited for long-distance applications, albeit at lower efficiency [53].

Table (3): WPT efficiency vs. distance [11–14, 32, 46].

Technology	Range	Peak Efficiency	Efficiency at 1m	Efficiency at 5m	Efficiency at 10m
IPT	0–10 cm	90%	10%	≈0	≈0
MR-WPT	0–2 m	85%	70%	40%	<10%
MWPT	1–100 m	60%	55%	30%	10%
LPT	1–1 km	50%	45%	25%	15%

Hybrid harvesting shows clear benefits compared to single-source approaches. Table (4) demonstrates the contributions of solar, thermal, RF, and vibration sources in a hybrid configuration. Solar energy dominates the harvested budget, but thermal and vibration harvesters provide additional stability under variable light conditions, and RF ensures baseline operation in dense urban areas [54].

Table (4): Contribution of different energy harvesting sources in HEH systems [4, 8, 9, 47, 48].

Source	Avg. Power Density	Conversion Efficiency	Contribution in HEH (%)
Solar	15–100 mW/cm²	15–25%	45%
Thermal	20–50 mW/cm²	8–12%	20%
RF	1–100 µW/cm²	30–70%	15%
Vibration	10–200 µW/cm²	20–35%	20%

The hybrid model demonstrates that nodes can operate autonomously up to 95% of the time, compared to only 65% when powered by solar energy alone. This improvement highlights the necessity of hybrid configurations in environments where single sources are unreliable [54]. Cost-performance is another critical aspect for large-scale deployments. The normalized cost-performance metric is given as [51]:

$$\mathbf{Cp = (Cinstall + Cmaint + Cenergy) / Elifetime} \qquad (8)$$

Where Cinstall is the installation cost, Cmaint is the maintenance cost, Cenergy is the energy cost, and Elifetime is the total lifetime energy delivered. Table (5) compares the results for battery-only systems, grid-powered beacons, and sustainable green power beacons (gPBs) that integrate renewable energy harvesting [43].

The results clearly indicate that although battery-only systems are cheap initially, they are unsustainable for large-scale IoT due to frequent replacement and maintenance costs. Grid-powered beacons improve lifetime energy cost, but sustainable green power beacons outperform both by offering the lowest cost per kWh while aligning with environmental goals.

Table (5): Cost-performance evaluation for a 1000-node IoT deployment [5, 6, 20, 36, 49].

Method	Lifetime (years)	Cost ($/node)	Energy/Node (kWh)	Cp ($/kWh)
Battery-only	2	45	12	3.75
Grid-powered PB	5	60	50	1.20
Green PB (solar+RF)	5	75	100	0.75

From these evaluations, several insights emerge. IPT is efficient only for very short ranges, while MR-WPT provides a balance of range and efficiency suitable for practical mid-range applications. MWPT and LPT, though less efficient, are indispensable for long-range or specialized scenarios. HEH is essential for improving reliability and extending network lifetime, while cost-performance analysis demonstrates the long-term viability of sustainable WPT approaches.

Looking forward, optimization methods such as reinforcement learning can dynamically adapt charging schedules and resource allocation to enhance real-world performance. Energy-aware routing that incorporates harvested energy into decision-making can extend lifetime further. Multi-objective optimization frameworks balancing efficiency, safety, and cost are also required, particularly for large-scale deployments.

The mathematical modeling and evaluation results confirm that sustainable WPT integrated with HEH provides the best balance of efficiency, resilience, and cost-effectiveness for next-generation IoT and WSN infrastructures.

6. Hardware Developments (Rectifiers, Antennas, Metamaterials)

In terms of hardware developments specifically for WPT/EH presented recently, however, there is still a need for more multi-band operation, wider bandwidths, and high efficiency even at low power levels. Some two band rectifiers (examples include [43, 55, 56]) achieve >70–80% conversion efficiency throughout many different frequencies [57], using methods of harmonic tuning or novel architectures (e.g. class-F, Doherty). We see a strong presence of metamaterial and metasurface-based designs: papers [58-59][22] combine rectifiers into absorber arrays and obtain high efficiency (≈50–65%) but use them to absorb power from arbitrary polarizations and incident angles [35, 20]. The problem is particularly acute in ambient RF settings, where signals arrive from various angles that can be neither predicted nor controlled, and thus this wide-angle, polarization-insensitive approach directly solves that design challenge. A significant direction is thus the microminiaturization and environmental-friendly nature (specifically a screen-printed rectifier [60] on cork, and an e-textile antenna [61] for wearable), emphasizing integration and embedding capabilities of WPT/EH into IoT devices and clothing.

Higher frequencies are pushing the new frontiers of WPT: rectification at 3 GHz has been reported; in paper [62], an mmWave triband rectifier is demonstrated at 24/28/38 GHz with efficiencies ~40–44% [63] suggesting the potential (and complexity) of WPT at 5G bands. Similarly paper [64] employs improved Schottky diodes [65] and achieved >50% at 24 GHz. In addition, there is a chain of mmWave rectifiers—important as well (but they usually require > 10–15 dBm input so they lose efficiency at the low power end). The addition of element matching networks [62] and 64 × 16 multi-antenna system [63] and beam-switching rectenna array [66] to achieve extend the range by realizing better RF-to-Dc power directionality; Even more creative ways of diodes in conjunction with metasurfaces for design simplification and out phasing to realize wider bandwidth for higher DC output [26].

However, there are still significant challenges in producing high efficiency under very low ambient RF power and with concurrent multi-source harvesting. While there becomes some works over hybrid energy (e.g. RF + solar in [42]), stability under varying loads (inverse-Doherty in [67]), the effective multi-source integration is still at the initial level. In general, the hardware contributions we have surveyed — from GaN-optimised rectifiers [39] to body-coupled antennas [68] — indicate a trend towards more integrated, more versatile WPT/EH systems and sets the stage for effective ambient EH by self-powered sensors and wearable. Table (6) shows recent research papers categorized by efficiency, frequency band, and hardware type. Table (7) shows the convergence, complexity, and scalability columns to the optimization comparison.

Table (6): Recent research papers by efficiency, frequency band, and hardware type.

Efficiency Classification	**Efficiency Category**	**Number of Papers**
	High (≥80%)	6
	Moderate (50–79%)	13
	Low (<50%)	1
	Not Reported / N/A	25
Frequency Band Classification	**Frequency Band**	**Number of Papers**
	2.4 GHz ISM	16
	5.8 GHz ISM	11
	Dual-Band (2.4 & 5.8 GHz)	9
	mmWave (24–38 GHz)	4
	Sub-GHz / MHz / Powerline	4
	Broadband / Multi-band	5
	N/A or Multi-source	3
Hardware Type Classification	**Hardware Type**	**Number of Papers**
	Antenna / Array	7
	Rectifier	14
	Rectenna (Integrated)	9
	Metasurface Absorber	3
	Hybrid System	3
	Coil / Inductive / Wires	3
	Review	2

Table (7): Convergence, complexity, and scalability columns to the optimization comparison in WPT/EH Literature.

Ref.	Optimization Model Type	Performance Metrics	Application Scenario	Simulation Tools/Platforms	Convergence	Computational Complexity
[40]	Power minimization	RIS-assisted MIMO WPT	MATLAB (CVX)	Converges iteratively	Very High	Low–Moderate
[43]	Outage; diversity gain	WPT-assisted NOMA IoT	MATLAB	Immediate (analytical)	Low	High
[44]	Secrecy vs. energy	Secure SWIPT	MATLAB	Converges iteratively	High	Moderate
[57]	Harvested DC power	General WPT link (nonlinear EH)	MATLAB	Guaranteed (convex)	Low	High
[65]	Total harvested energy	UAV multi-user WPT	MATLAB (CVX)	Converges iteratively	High	Low–Moderate (trajectory complexity)
[69]	Non-convex time allocation (convex splitting/search)	Total harvested energy	UAV-enabled WPT (single UAV, multi-user)	MATLAB	Converges to local optimum	Medium–High (iterative search)
[70]	Network lifetime; throughput	Solar-powered WSN (agriculture)	MATLAB/Python	Converges slowly (training-dependent)	High (training overhead)	High (distributed learning possible)
[71]	Sum harvested energy	IRS-assisted WET	MATLAB	Probabilistic convergence	High (population-based)	Moderate

[72]	Output DC power	MIMO WPT (multi-antenna RX)	MATLAB + circuit sim	Fast (partial closed-form)	Medium	Moderate
[73]	Sum rate vs. harvested energy	Full-duplex WIPT	MATLAB	Converges iteratively	Medium–High	Moderate
[76]	Min harvested energy	Multi-UAV WPT	MATLAB	Converges locally	Very High	Low
[77]	Energy focusing efficiency	Multi-user multipath WPT	MATLAB	Direct (no iteration)	Low	High
[78]	RF-DC efficiency	RF WPT waveform design	MATLAB + ADS	Converges locally	High	Moderate
[79]	Output DC power	MIMO WPT	MATLAB	Converges analytically/locally	Medium–High	Moderate
[80]	Min harvested energy	UAV WPT (2-user)	MATLAB	Guaranteed (structured solution)	Medium	Low
[81]	Latency vs. energy	Low-latency SWIPT relay	MATLAB	Local convergence	High	Moderate
[82]	Rate, sensing, energy	IoT with ISAC + SWIPT	MATLAB	Converges (Pareto solutions)	Very High	Moderate
[84]	Power fairness vs. sum energy	Multi-user WPT (IoT)	MATLAB	Fast convergence	Low–Medium	High
[85]	Min harvested energy (fairness)	Multi-user MISO WPT	MATLAB (CVX)	Converges to local optimum	High (convex subproblems)	Moderate

7. Optimization Techniques in WPT/EH Networks

A number of formal optimization frameworks have been used to analyze WPT and EH networks, indicating a transition from idealized models to more practical, and non-linear aspects. In fact, a common thread among most works is the inclusion of nonlinear EH models (for example, diode-based or logistic models) into the design [67, 57], which renders the optimization problems non-convex (in general). Most works use successive convex approximation (SCA) or other types of convex reformulation to deal with these instead. Specific examples include iterative approximation of non-convex objective by convex subproblems for UAV trajectory and power optimization [21] [57] problems. These approaches exploit certain established characteristics (e.g., the convexity in the reciprocal power (e.g., see [57])) to quickly provide near-optimal solutions.

Metaheuristic and learning-based approaches also come into play. A Q-learning controller for power and data routing in a sensor network is presented in [70] that sacrifices short-term and instant-on-optimality in favor of long-term network longevity. In the same vein, [71] also provides a global search for a decent phase configuration of IRS at the expense of avoiding the use of gradient information by applying Particle Swarm Optimization to the IRS assisted system. They are useful for non-convex and black-box objectives but sensitive to parameter ranges and lack global optima guarantee. By contrast, a more structured problems (beam forming [72, 73], resource allocation [74, 75]) often allows for semi-analytical solutions or provable optimal algorithms by leveraging structure of the problem (e.g. water-filling-like power allocation or closed-form beam vectors [38, 70]).

In the multi-user case, one of the central desires is the balance between the fairness and global efficiency. Some schemes maximize the minimum harvested energy thereby providing fair service across the operational duration whereas others focus on maximizing sum energy or system throughput. In particular, it has been show that under non-linear EH, time-division approaches attain a higher throughput than simultaneous transmission, serving as an evidence of scheduling being a constructive dual in the "convex–concave" EH context [41 , 67], for example, future trends already merging WPT with communication (WIPT, NOMA) and even sensing (ISAC) [76], will only be feasible through a multi-objective optimization enabling a trade-off among information, power and sensing performance. While these studies provide very complicated algorithms and show promising large performance improvements, the validation is usually only in simulation.

Realistic models (e.g., multi-stage rectifiers in [73]) and stability analyses [77] have been employed, yet real-world deployment issues, e.g., about hardware constraints, channel unknowns and scalability, are still tackled but represent a new horizon. But there is no range of physical prototyping in this theory-desiring explorative search. And future work should demonstrate that these optimizations can obtain the same performance in actual dynamic, interference-prone environments on a resource-limited hardware. But more sophisticated adaptive approaches (e.g. model-free RL [70]) are likely to be adopted and are expected to develop to the stage of WPT/EH networks that approaches practical implementation by addressing the integrated network utility maximization the joint the energy, data transport and other QoS experience level.

The comparative advantage of each approach often depends on context: convex optimization offers optimality and reliability given tractable models, heuristics and learning offer flexibility and easy integration of complex factors, and each must be tailored to the network's needs (throughput vs. fairness, etc.). In summary, the surveyed works demonstrate significant progress in algorithmic control of WPT/EH networks, but also underline the necessity of bridging the remaining gap to real-world implementation and cross-layer integration. Table (8) shows the Comparison of Optimization Techniques in WPT/EH Networks.

Table (8): Comparison of Optimization Techniques in WPT/EH Networks.

Ref.	Optimization Model Type	Performance Metrics	Application Scenario	Simulation Tools/Platforms
[40]	Alternating optimization (beamforming and RIS phase via SCA/SDR)	Transmit power minimization (meet EH targets)	RIS-assisted MIMO WPT (multiple devices with required energy)	MATLAB (CVX for subproblems)
[43]	Analytical comparison (closed-form outage and diversity analysis)	Outage probability; diversity gain trade-off	IoT uplink: WPT-assisted NOMA vs. Backscatter NOMA (cooperative devices)	MATLAB (analysis + simulation)
[44]	Convex-concave optimization (secure SWIPT, iterative)	Secrecy rate vs. harvested energy trade-off	Cognitive WET system (secure comm to secondary user while powering primary or eavesdropper)	MATLAB (simulation)
[57]	Convexity analysis of non-linear EH model (proved convex under variable transform)	Harvested DC power maximization (convex property)	General WPT link (nonlinear rectifier behavior)	MATLAB (analytical & numerical)
[65]	Non-convex trajectory optimization (solved via successive convex approximation – SCA)	Total harvested energy (multi-user sum)	UAV transmitter powering multiple ground nodes (multiuser WPT)	MATLAB (CVX for subproblems)
[69]	Non-convex time allocation (solved via convex splitting or search)	Total harvested energy (sum across devices)	UAV-enabled WPT (single UAV, multi-user ground network)	MATLAB (simulation)
[70]	Reinforcement learning (Q-learning heuristic)	Network lifetime; data throughput	Solar-powered WSN in agriculture (cooperative charging & routing)	Custom simulation (MATLAB/Pytho)
[71]	Metaheuristic – Particle Swarm Optimization (PSO)	Sum harvested energy (global maximum search)	IRS-assisted WET (one BS, multiple EH devices via RIS)	MATLAB (PSO algorithm)
[72]	Mixed approach – closed-form beam solution (RF combining) + iterative optimization (DC combining)	Output DC power; gain of RF vs. DC combining	MIMO WPT to a multi-antenna receiver (single-user, multiple rectennas)	MATLAB + circuit simulation
[73]	Iterative resource allocation (beamforming for DL/UL)	Sum info rate vs. harvested energy	Full-duplex WIPT (BS simultaneously sends power and receives data)	MATLAB (simulation)
[76]	Non-convex joint optimization (trajectories + power via iterative convex approx.)	Min harvested energy (fairness)	Multi-UAV WPT network (multiple drones powering devices)	MATLAB (custom iteration)
[77]	Signal design (time-reversal beamforming, no iterative opt.)	Harvested energy; power focusing efficiency	Multi-user WPT in rich multipath (time-reversal focusing)	MATLAB (waveform simulation)
[78]	Non-linear waveform optimization (non-convex, iterative)	RF-to-DC efficiency; harvested power	RF WPT system (multisine transmit waveform design)	MATLAB + circuit simulator (ADS)
[79]	Non-convex transmit optimization (analytical derivations for optima)	Output DC power (TX efficiency gain)	MIMO WPT (transmit covariance design for single/multi-user)	MATLAB (theoretical + simulation)

[80]	Optimal control solution (1D trajectory design with closed-form segments)	Min harvested energy (2-user fairness)	UAV-aided WPT (single UAV shuttling between two devices)	MATLAB (simulation)
[81]	Non-convex joint optimization (power and scheduling)	End-to-end latency vs. harvested energy	Low-latency relay network with SWIPT (fast information relay powered by WPT)	MATLAB (simulation)
[82]	Multi-objective optimization (joint ISAC waveform design)	Communication rate, sensing accuracy, EH power	IoT network with ISAC and SWIPT (simultaneous sensing & power)	MATLAB (simulation)
[84]	Heuristic resource allocation (greedy & bisection algorithms)	Sum harvested power vs. minimum device power (fairness)	Multi-user multi-band WPT (MISO transmitter, IoT devices)	MATLAB (custom simulation)
[85]	Alternating SCA (time-sharing + beamforming)	Min harvested energy (fairness across users)	Multi-user MISO WPT (BS with multiple antennas, non-linear EH)	MATLAB (convex solvers)

8. Practical Implementations of WPT with EH Across IOT, Industrial, and UAV Applications

WPT-EH systems depicted in Table (9) from IoT, industrial and UAV domains. Due to remote operation demands, SMK through IoT sensors adopts a hybrid power source by integrating far-field microwave WPT and ambient PV, thermal, and vibration harvesting with a large battery [83]. Using dedicated 915MHz transmissions [84], Powercast uses RF based WPT to power environmental sensors without batteries over distances of tens of meters. The Wiliot ultra-thin tags [85], powered entirely by ambient RF, can thus passively generate the BLE communication required for asset tracking phase, and also during the acquisition phase as long as a BLE transmission power is present in the proximity of the tag. Reach's.

RF mesh system emits coordinated beams to UAVs and equipment for industrial and aerial usage, achieving greater than 50W of sustained reception at 6m from a 256W transmission array [86]. Powermat focuses on parked drones and uses a ruggedized inductive charger achieving 300W air-gap delivery at 150mm [87]. Stalker UAS owned by Lockheed Martin have been able to stay aloft for greater than 48 h by exploiting on-board PV receivers to convert laser light directly into electricity [88]. This comparison shows different methods of expanding the operating time of the device using WPT and EH by maximizing the performance in various power levels, environmental ambient conditions, and deployment scenarios.

Table (9): Practical Implementations of WPT with EH.

Ref	RF Focus	Rectifier	Antenna	Metasurface/ Metamaterial	IoT	Practical Implementations	Core Focus
Ullah et al. [21]	Yes	No	Yes	No	Yes	No	Antenna technologies for ambient RF EH and WPT
Halimi et al. [22]	Yes	Yes	No	No	Partial	No	Rectifier design challenges (broadband, extended input range)
Wagih et al. [24]	Yes	No	Yes	No	Yes	No	Rectenna antenna design for RF EH and WPT
Shinohara[27]	Yes	Yes	Yes	Partial	No	No	Trends in wireless power transfer (mmWave/THz rectennas, MIMO-WPT, near-field)
Alcaraz López & Suto[33]	Yes	No	Yes	No	Yes	No	RF EH and WPT for powering IoT devices
Niotaki et al. [34]	Yes	Yes	Yes	No	Partial	No	RF EH and WPT for energy-autonomous devices and RFIDs
Zhou et al. [35]	Yes	No	No	Yes	Partial	No	Metamaterials and metasurfaces for WPT and EH
La Rosa et al. [36]	Yes	No	No	No	Yes	No	Techniques for powering wireless sensors via EH and WPT
Shome et al. [37]	Yes	Yes	Yes	No	Partial	No	Rectenna array advancements for RF EH and WPT
This survey	Yes	Yes	Yes	Yes	Yes	Yes	Comprehensive review of the integration of WPT and EH for IoT.

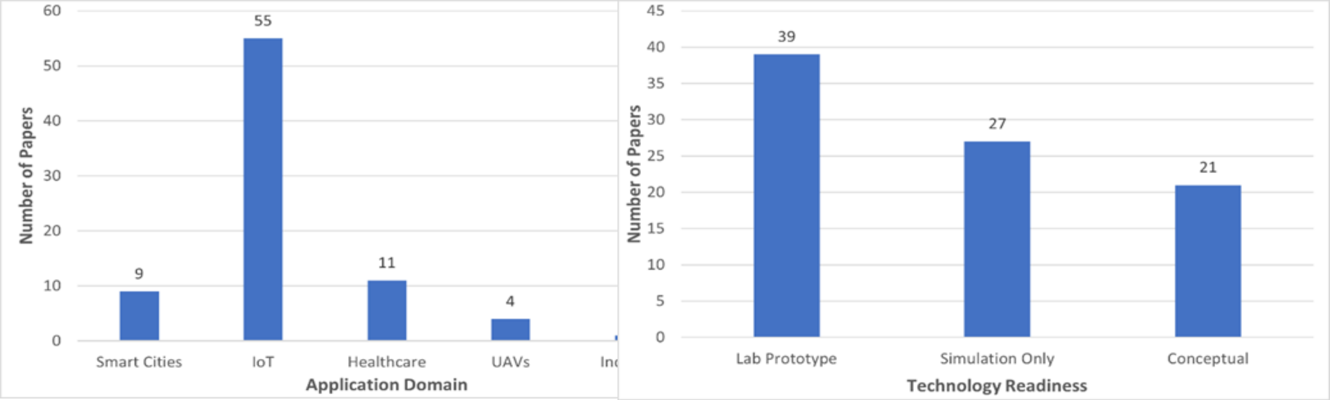

Figure (3): Recent research papers by Technology readiness, and application domain.

In particular, the network-level techniques including scheduling, resource allocation, and SWIPT are also the key enablers for the EH wireless network performance. In contrast to conventional systems, EH-enabled networks need scheduling strategies that take stochastic energy arrivals, and energy causality constraints into account [5], [8]. Static resource allocation schemes are also outperformed by adaptive ones, which dynamically allocate power and time resources according to channel conditions and energy availability at the transmitter [10, 41]. In addition, SWIPT-based approaches allow joint EH and information transfer, and thus give rise to a limit on the rate–energy tradeoff that needs to be optimized by utilizing respective time-switching or power-splitting architectures [12, 13, 15]. One of the important messages is the high interdependence between these techniques, and the need for joint optimization of all to guarantee energy efficiency, reliability and scalability to the operation of an IoT network.

9. Emerging and Future Directions in WPT and EH

Battery-free electronic systems emerge as WPT and EH converge due to advancements in hardware, control, integration and material. Several futuristically oriented research themes are emerging across these works. Significantly, WPT will begin to be integrated with the communication and sensing: simultaneous information/power transfer and ISAC frameworks should realize battery less networks with joint communication and power delivery to the devices [81]. Another trend is the penetration into mmWave and THz WPT, where high frequencies allow to powering dense bunch of nano-IoT devices, but THz rectifiers are still not efficient enough [32, 64]. AI and advanced algorithms are also used in various applications spanning from machine-learning-optimized antenna designs [82] to intelligent power control (e.g., PSO optimization in reconfigurable metasurface systems [71]). In the same breath, metamaterials and metasurfaces are transforming hardware with enhancements in the harvesting of energy, and the removal of the circuit limitations of conventional technology (e.g., it results in metasurface rectennas that do not require matching networks). UAVs facilitate mobile WPT that illustrates alternative methods of power delivery to remote sensors [89], while novel energy-harvesting materials for wearable (carbon-nanotube fibers, e-textiles) stretch the domain of WPT to bio-integrated devices [90, 61].

Several areas show paradigm-shifting potential. As shown in references [40, 81], the systems that integrating the sensing, communicating and powering are more and more focusing on treating the power as a service along with the data, namely joint sensing-communication-power systems [81] and RIS-assisted WPT architectures [89]. Third, utilizing high-frequency spectrum for WPT and compact energy recycling represents a paradigm shift for the network design [3332 These methods combined with sustainable ambient energy incorporation [91, 92] could pave the way to the ideal of everlasting zero-energy devices. Figure (3) classifies recent research papers by their application domains, and technology readiness respectively.

Gaps remain in experimental validation and deployment. A majority of proposals are confined to simulations [65, 69] or isolated lab prototypes [63, 42], lacking real-world field trials. High-frequency WPT suffers efficiency and component limitations (e.g., diode losses at THz [62]), and safety/regulatory constraints on high-power far-field transmission are unresolved. Integration maturity is low: sophisticated concepts, such as full-duplex WIPT [73] or network-wide energetic dispatch, have yet to be put in practice. Closing the chasms between these challenges and reliability will require future work that goes beyond materials matching to system-level prototyping, crossdisciplinary standards and prolonged viability assessment in field settings. This means that, without these steps, these novel WPT/EH technologies would not ever evolve to a point where they could be a practical deployment for the Internet-of-Things, smart cities, industrial automation, or UAV-enabled sensor networks [93]. AI-based predictive speed adaptation can optimize vehicle trajectories and charging schedules, improving efficiency, reliability, and deployment of future WPT systems [94].

10. Conclusions

The integration of RF-based WPT and EH offers a feasible solution for extending the lifetime of IoT devices and minimizing battery changes. Furthermore, enhancements in low-power RF harvesting systems such as antenna miniaturization, and impedance matching have considerably improved their efficiency. That said, the output power available is still limited as ambient RF energy levels are low and rectifier efficiency falls off at low input signals. To tackle these challenges, we will need integrated progress in material developments, circuit designs, and then adaptive control schemes that can adapt to changing conditions. Dynamic beamforming and smart SWIPT receivers can be exploited to enhance energy efficiency and thus they should be considered as avenues for future work.

Such high-level topics map directly too many of the goals of this survey, as they apply to WPT-EH architectures, trade-offs between coupled methods, deployment conditions, and circuit complexity, as well as hardware design to application requirements. The results also indicate difficulties in power electronics implementation with harvesting interfaces for reliable operation in systems that are deployed in the operating environment. The applications reviewed in IoT and industrial and UAV application domains show potential to reduce battery dependency. Advances along these lines are likely to facilitate the evolution of more sustainable and energy autonomous wireless sensor webs. Comparison of the related surveys with this work is presented in Table (10).

Table (10): Comparative Evaluation of the Related Surveys with This Work.

Name/Project	Domain	WPT Type	EH Source	Application	Key Metrics
SMK Battery-Free IoT Sensor System	IoT	Far-field RF/microwave	Indoor PV, thermoelectric, piezoelectric	Battery-free remote controls, environmental sensors	Range ~5 m; hybrid ambient + dedicated WPT
Powercast Battery-Less Sensor Network	IoT / Industrial	Far-field RF (915 MHz)	RF energy harvesting	Temperature, humidity, occupancy sensors	Range ~60–80 ft; µW-level power received
Wiliot Battery-Free IoT Pixel	IoT	None (ambient only)	Ambient RF (Wi-Fi, cellular)	Supply-chain and asset tracking	Passive BLE sensor tag; 0.2 mm thick
Reach Wireless Power Mesh Network	Industrial / UAV	Far-field RF mesh (915 MHz)	None (intentional RF beam)	Drone powering, industrial automation	6 m range; 256 W TX, 50 W RX
Powermat Inductive Drone Charger	Industrial / UAV	Near-field inductive	None	Drone charging on landing pads	≤150 mm gap; 300 W output
Lockheed Martin/LaserMotive Stalker UAS	UAV	Far-field laser	Laser to PV	Persistent UAV surveillance	48+ hr flight; >2400% battery-alone duration

Conflict of Interest: The authors declare that there are no conflicts of interest associated with this research project. We have no financial or personal relationships that could potentially bias our work or influence the interpretation of the results.

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