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Energy harvesting techniques for wireless sensor networks: A systematic literature review

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ABSTRACT

Energy harvesting has emerged as a promising avenue for addressing the constraints imposed by battery lifespan in wireless sensor networks (WSNs), paving the way for more sustainable and autonomous operations. This paper presents a comprehensive and systematic literature review (SLR) that critically examines the latest advancements and methodologies in energy harvesting for wireless sensor networks (WSNs). The review encompasses the entire system architecture, including energy storage and power management systems. The review is based on bibliometric analysis and a detailed examination of an extensive collection of 196 peer-reviewed studies published between 2014 and 2023. The text provides a comprehensive assessment of diverse technologies, techniques, and mechanisms for extracting energy from environmental sources, including thermal, light, mechanical, radio frequency, chemical, and biological, to power a wireless sensor node device. Furthermore, the concepts of transducers, energy sources, and energy types are elucidated and defined, thus establishing a lucid framework for classifying and analyzing these techniques and technologies. Additionally, key trends, challenges, and future research directions are identified, emphasizing areas that require further exploration to advance the field, particularly in battery-less systems employing capacitors and supercapacitors.

1. Introduction

Wireless Sensor Networks (WSNs) have emerged as a transformative technology with diverse applications ranging from environmental monitoring to industrial automation [1]. The sustained operation of WSNs, however, hinges on the efficacy of their power sources. In response to the growing need for prolonged autonomy and environmentally conscious practices, energy harvesting technologies have risen to prominence [2]. From solar and thermal to mechanic and electromagnetic, this work scrutinizes the methodologies, innovations, and challenges associated with extracting energy from diverse sources [3].

Energy harvesting for WSN has been actively explored since at least 2003 [4] joining the techniques to save energy to extend the WSN node's lifespan, referred to as ***mote***. Its significance has grown in the last years expanding energy sources and the ability to extract it from the environment. This technology offers the potential to extend battery life, tending in the last works to manage battery-less systems, thereby eliminating the need for expensive and potentially unsafe components [5]. This approach has the additional benefit of reducing costs and safety concerns while also aligning with environmentally friendly practices by reducing battery disposal and its associated environmental impact [6].

Given the constant progress in WSNs and the increasing importance of sustainable energy solutions, this SLR is justified by the need to consolidate the current state of knowledge and guide the development of more efficient energy harvesting systems. Although numerous studies have investigated energy harvesting techniques for wireless sensor networks, there is a lack of comprehensive reviews that systematically

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Acronym list

AI	Artificial Intelligence
C-SC	Capacitors – Supercapacitors
DSSC	Dye Sensitized Solar Cells
EDLC	Electric Double-Layer Capacitors
EH-WSNs	Energy Harvesting in Wireless Sensor Networks
EESD	Electrochemical Energy Storage Devices
EMF	Electromagnetic Field
E-TriG	Electret-based Triboelectric Generator
FEP	Fluorinated Ethylene Propylene
HESS	Hybrid Energy Storage System
HVAC	Heating, Ventilation, and Air Conditioning
IC	Integrate Circuit
IMN	impedance matching network
I_{SC}	Short Circuit Current
ISM	Industrial Scientific and Medical band
MH	Metal Hydride
MPPT	Maximum Power Point Tracking
OPV	Organic photovoltaics
PCE	Power Conversion Efficiency
PMC	Power Manager Circuit
PMS	Power Management System
PCM	Phase Change Material
PMIC	Power Management Integrated Circuits
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PTFE	Polytetrafluoroethylene
PV	Photovoltaic system
PZT	Piezoelectric
RQ	Research Question
SC	Supercapacitor
SECE	Synchronized Electric Charge Extraction
SLA	Sealed Lead Acid
SLR	Systematic Literature Review
STC	Standard Measurements Conditions for universal use according to IEN61215
SoC	State of Charge of the battery
TEG	Thermoelectric Generator
TENG	Triboelectric Nanogenerator
T-PENG	Textile-based Piezoelectric Nanogenerators
V_{OC}	Open Circuit Voltage
WSN	Wireless Sensor Network

synthesize these findings to provide a clear organizational and comprehensive framework in the vast field of energy harvesting techniques and technologies for WSNs. In this sense, this study is motivated by the necessity to identify, classify, and characterize the diverse array of approaches within the expansive field of EH-WSN, which encompasses multiple research areas. It aims to establish more comprehensive classification schemes around their different components.

This paper **aims** to offer a comprehensive examination of EH-WSN, exploring techniques, trends, and challenges. Consequently, this work offers a distinctive contribution in the form of a more comprehensive and accurate classification system than previously documented by SLRs. In contrast to existing reviews, this scheme makes a clear distinction between *energy sources*, *energy types*, and harvesting elements, referred to as *transducers*. This enhanced classification addresses the shortcomings in classification accuracy, thereby providing greater clarity and precision in understanding the components and processes involved in energy harvesting systems. This enables the examination of a diverse range of energy harvesting technologies, encompassing thermal, optical, mechanical, radio frequency, chemical, and bioenergy sources. Furthermore, this review conducts a comprehensive trend analysis, identifying key advancements and future research directions in the field of EH-WSNs. This approach ensures that researchers and practitioners can better navigate the complexities of energy harvesting technologies and their applications in WSNs. By conducting a comprehensive analysis of these varied sources, the review offers a unified perspective on the present state of the art and emerging trends in energy harvesting for WSNs.

The rest of the paper is structured as follows. In Section 2, a review of *Previous work* related to the subject to establish a foundation is presented. Section 3 outlines the *Materials and methods* used to conduct the SLR. In Section 4, the *Results and analysis* are presented, beginning with a *bibliographic analysis* aimed at addressing the research questions. In light of the aforementioned analysis, Section 5 presents a *Discussion*, while Section 6 offers a concise *Analysis and implications*, including a subsection dedicated to discussing the *Theoretical contribution* of this paper. The final section comprises *Conclusions*.

2. Related works

A non-systematic review exposed several previous studies on energy harvesting for WSN devices. The compilation can be grouped into three categories for better organization and clarity, *specific environmental power source*, *specific application scenario*, and *overview encompassing the broad spectrum of the HE-WSN universe*.

Consider specific environmental power source groups to join the most referenced energy sources. Table 1 shows the papers organized by energy sources.

In the second group, several works have provided comprehensive reviews within specific fields of application. For instance, Sohail et al., 2024 [27] and Wang et al., 2020 [28] have focused on medical devices, while Ali et al., 2023 [29] have delved into wearable technologies. Additionally, Hidalgo-Leon et al., 2022 [30] have examined intelligent buildings, and pipeline monitoring has been scrutinized by Ashraf Virk et al., 2022 [31].

In the last group of interest, some works that seek to address EH-WSN from a broader perspective, are more closely aligned with the objective of this study. An extensive analysis of EH-WSN has been conducted in papers like Shaikh and Zeadally 2016 [2], Adu-Manu et al., 2018 [32], Calautit et al., 2021 [33], Sanislav et al., 2021 [34], Singh et al., 2021 [3] and Williams et al., 2021 [35], including the Power Manager Circuit (PMC) and storage system. The authors categorize the literature based on energy source, power density, and energy transduction type. However, a systematic method for consolidating the foundational works of their research is not proposed. Furthermore, an analysis of the reviewed studies reveals a lack of identification of trends in energy source utilization or energy harvesting methods.

Table 1
Review articles categorized by type of energy.

Energy Source	Papers
Photovoltaic	Hao et al., 2022 [7]; L. Liu & Choi, 2021 [8]; H. Sharma et al., 2018 [9].
Thermoelectric Generator	Siddique et al., 2017 [10]; Jaziri et al., 2020 [11]; Kandi et al., 2023 [12]; S. M. Yang et al., 2022 [13]; Jabri et al., 2023 [14].
Mechanic	Siddique et al., 2015 [15]; S. Wang et al., 2015 [16]; Wei & Jing, 2017 [17]; S. Sharma et al., 2022 [18]; X. Ma & Zhou, 2022 [19]; Lai et al., 2022 [20]; X. Zheng et al., 2023 [21]; Jiang et al., 2023 [22]; Hossain et al., 2023 [23]; L. Liu, He, Han et al., 2023 [24].
Radio Frequency	P. Sharma & Singh, 2023 [25]; D. Chen et al., 2023 [26].

Shaikh and Zeadally 2016 [2], Adu-Manu et al., 2018 [32], Ang et al., 2022 [36] and Singh et al., 2021 [3] proposes comprehensive classification schemes for EH-WSN but there is no clear distinction between the energy source (sun, wind, etc.), energy type (mechanic, electromagnetic, etc.), and transduction technique (piezoelectricity, solar cell, etc.). A noteworthy classification is that established by Alajingi and R, 2023 [37] where clustering into three broad categories: replenished (renewable) energy, reserved (depleting) energy, and capture energy sources. However, this classification has the same problem previously described.

It is interesting to note that, because of the variable nature of energy in EH-WSN, the *prediction models* are pointed by various authors [2,32] as the direction of future research.

In summary, a clearer classification can be established to differentiate between the various components comprising EH-WSN systems. Additionally, it is crucial to identify global trends, analyze the potential near future, and address challenges faced by each method individually.

3. Materials and methods

The study is divided into two phases. The first phase involves a non-exhaustive bibliometric analysis to determine tendencies. The second phase is a Systematic Literature Review (SLR) of the last ten years to provide a deeper analysis of methods, techniques, technologies, and their limitations in powering WSN nodes.

A SLR focuses on a particular inquiry, employs clear and transparent methods for conducting a comprehensive literature search, and critically assesses individual studies. The aim is to conclude the existing knowledge and gaps in understanding related to a specific question or topic [38]. This employs the PRISMA 2020 [39] as a guideline, evaluating prior studies on methods for collecting, storing, and managing energy for WSN devices.

3.1. Research questions

The Research Questions (RQ) that this paper attempts to answer have been formulated based on the CIMO scheme (Context, Intervention, Mechanisms, Outcomes) [40]. According to the research objective, the primary research question (RQ) is proposed as follows: *In the context of harvesting energy (Context), what methods or technologies are implemented (Intervention) for capturing converting, and storing environmental energy (Mechanism) to achieve a sustained and continuous power supply to WSN nodes (Outcome)*, which is decomposed into the following RQ:

- **RQ1**: What methods or technologies are implemented for *harvesting energy* from the environment to power *WSN nodes*?
- **RQ2:** What are the conditions and contexts in which *energy harvesting methods and technologies* have been utilized to power nodes within *wireless sensor networks*?
- **RQ3:** What are the documented outcomes or results of implementing *energy harvesting* methods and technologies to ensure an indefinite power supply to WSN nodes?

3.2. Identify keywords

PICO (Population, Intervention, Comparison, Outcome) is an acronym commonly used in evidence-based medicine and healthcare research to help structure clinical research questions. PICO is widely extended to other research fields as social [41] and computer sciences [42]. An adaptation of the PICO framework in software engineering, as suggested by Kitchenham and Charters [43], is presented for identifying keywords and formulating search strings from research questions as follows:

- **Population/Problem:** WSN nodes that require an indefinite power supply.
- **Intervention:** Methods or technologies are implemented for harvesting energy from the environment.
- **Comparison:** In this study, we analyze and compare various approaches outlined in the literature for harvesting energy from the environment.
- **Outcomes:** Metrics on the prevalence of methods or technologies for harvesting energy in literature. The selected metrics are detailed in the related section.

The identified keywords are *energy harvesting* and *wireless sensor networks*; each becomes a set of keywords for search. In each set, the primary keyword is paired with its synonyms as follows:

- **Set 1:** *energy harvesting*; *energy scavenging; energy harvester*; *harvester*; *harvesting***.**
- **Set 2:** *wireless sensor network*; *wsn*; *sensor node*; *iot device.*

The statement for all databases was ("*energy harvesting*" OR "*energy harvester*" OR "*energy scavenging*" OR "*harvester*" OR "*harvesting*") AND ("*wireless sensor network*" OR "*wsn*" OR "*sensor node*" OR "*iot device*").

3.3. Bibliometric analysis

Conducting a comprehensive literature analysis in the dominion of EH-WSNs is essential for gaining an exhaustive understanding of the current state of research, identifying key trends, and exploring potential avenues for future investigations. This analysis is conducted by examining scientific production retrieved from Scopus, a leading academic database known for its comprehensive coverage of scientific literature.

Scopus is enriched with peer-reviewed publications from journals and conferences from academic research databases such as IEEE Xplore, ACM Digital Library, ScienceDirect, and Springer. It's important to note that no databases are exhaustive; therefore, we regard it as a representative sample, enabling the inference of trends and providing insights into the validity and ongoing relevance of the topic for further investigation.

The objective of this study is to gain deeper insights into the complexities of energy harvesting methodologies for WSNs by leveraging the advanced search capabilities and analytical tools of Scopus, in conjunction with the visualization capabilities of VOSviewer.

3.4. Search strategy

To select the papers for the review a two-step screening was performed, preliminarily and exhaustively. In the preliminary stage the title, the abstract, and the keyword were observed to identify the possible relevance of the article. Subsequently, a comprehensive examination of the selected papers was conducted to identify the final articles to be included in the review.

3.4.1. Eligibility criteria

To prevent bias, the criteria used for including or excluding articles based on their abstracts, primary bibliographic data in the initial selections, and conclusions are outlined as follows.

Inclusion criteria: the following rules were used to include the paper in the review.

- All the keywords or synonyms appear in the title *and/or* the abstract.
- The study was performed by the end of the year 2023. The date range considered for this study spans from 2014 to 2023, encompassing the entire 2023.
- The articles are written in the English language.
- Only articles from journals.
- The paper should implicitly focus on potential applications of the harvested energy to power WSN nodes. Ideally, the research should

articulate a test or experiment within this specific application context.

Exclusion criteria: the following rules were applied to exclude the paper from the review process.

- Two or more papers from the same study. In this case, the most recent or complete are selected.
- Centered in prolonging the network lifetime using saving energy techniques, for example, clustering techniques, routing, resource allocations, scheduling, etc.
- Papers about power transfer.
- Review papers.
- Full text is not accessible.

3.4.2. *Information sources*

To address the research question posed, a systematic search was conducted for articles in the indexed electronic databases ScienceDirect, IEEE Xplore, and Web of Science, as detailed in Table 2.

3.4.3. *Data collection process*

Starting from the search statements, the initial search retrieved **1280** publications from three electronic databases, limited to the interval *from 2014 to 2023* (the last ten years). Specifically, Web of Science yields **184** publications, IEEE Xplore yields **547**, and ScienceDirect yields **549**. Applying a filter to include only research papers published in journals reduces the total to **645**, with **102** from Web of Science, **143** from IEEE Xplore, and **400** from ScienceDirect. Using Zotero as a bibliographic manager, **30** duplicate references were detected.

Fig. 1 was created using the template provided by PRISMA as a flowchart [39] that summarizes the process of selecting the literature to review, starting from the last filtering made automatically by the databases.

In the first screening, the title and abstract were reviewed. Papers that potentially met the eligibility criteria for this research were selected. After this process, **272** records remain. In the second and final screening, which consisted of reading and analyzing the documents, **76** were eliminated considering that they did not include all the elements for this investigation. Finally, **196** articles were eligible for review, summarized in Table 3, represented by articles *from 47 to 243* in the literature referenced in this paper.

4. Results and analysis

In this section, we delve into the identified bibliography. Initially, we employ a bibliometric approach utilizing Scopus tools and VOSviewer for an overview. Subsequently, we conducted an in-depth SLR analysis to answer the RQs.

Table 2
Sources of information and associated search statements.

Indexed database	Search statement
ScienceDirect	Title, abstract, keywords: ("energy harvesting" OR "energy harvester" OR "energy scavenging" OR "harvester" OR "harvesting") AND ("wireless sensor network" OR "wsn" OR "sensor node" OR "iot device")
IEEE Explore	(("Document Title":energy harvesting) OR ("Document Title": energy harvester)) AND (("Document Title":wireless sensor network) OR ("Document Title":wsn) OR ("Document Title": sensor node) OR ("Document Title":iot device)) AND (("Abstract": energy harvesting) OR ("Abstract":energy harvester)) AND (("Abstract":wireless sensor network) OR ("Abstract":wsn) OR ("Abstract":sensor node) OR ("Abstract":iot device))
Web of Science	(TI=("energy harvesting" OR "energy harvester" OR "harvester" OR "harvesting" OR "energy scavenging") AND TI=("wireless sensor network" OR "wsn" OR "sensor node" OR "iot device")) AND (AB=("energy harvesting" OR "energy harvester" OR "harvester" OR "harvesting" OR "energy scavenging") AND AB=("wireless sensor network" OR "wsn" OR "sensor node" OR "iot device"))

4.1. *Bibliometrics*

The first step is performing a basic bibliometric analysis using Scopus tools, focusing on two dimensions: the temporal evolution of publications and the types of documents. The objective is to highlight the relevance and significance of the research topic. The search statement for Scopus is shown below:

- ***TITLE-ABS-KEY ("energy harvesting" OR "energy harvester" OR "harvester" OR "harvesting" OR "energy scavenging") AND TITLE-ABS-KEY ("wireless sensor network" OR "wsn" OR "sensor node" OR "iot device")***.

The search yielded ***7586*** documents, offering a broad overview of the EH-WSN landscape without additional filters or time intervals. Fig. 2, generated using Scopus tools, on the left, illustrates the number of publications per year, indicating a notable increase in interest in recent years. This surge reflects heightened scholarly engagement and attention to the topic, setting the stage for innovative research. Furthermore, the distribution of publications by document type reveals that 46.5 % are conference papers and 44.8 % are articles, highlighting the significance of academic conferences and comprehensive articles in scholarly discourse.

VOSviewer is a tool commonly used for visualizing and analyzing bibliometric networks [44–46], including co-authorship networks, co-citation networks, and keyword co-occurrence networks. VOSviewer employs clustering algorithms to group nodes with similar characteristics. Once clusters are identified, VOSviewer provides visualizations that highlight these clusters. Nodes within the same cluster are often assigned similar colors, making it easy to distinguish them. The size of the nodes or clusters may represent their significance within the network.

A thesaurus was created around the two main terms " wireless sensor network" and "harvesting system" to condense the network. Due to the scope of the search, terms such as "WSN", "IoT", and "sensor node" are considered to be in the same context and treated as synonyms. These synonyms were identified from the lists of keywords labeled by VOSviewer in the first analysis without a thesaurus and are depicted as follows:

- **wireless sensor network**: wsn, wireless sensor networks, wireless sensor network (wsn), wireless sensor network (wsns), sensor nodes, sensor networks, wireless node, wireless sensor node, energy harvesting wireless sensor nodes, energy-harvesting sensor nodes, energy harvesting sensors, internet of things, internet of thing (iot), internet of things (iot), iot, iots.
- **energy harvesting:** energy-harvesting, energy harvesting (eh), energy harvester, energy scavenging, harvesting energy, harvester, harvesters, harvesting, energy harvesting system.

Using references to 7586 documents collected in Scopus and exported as a CSV file, a network visualization map is constructed by ***co-occurrence analysis***, revealing results through visual clusters. A map based on ***bibliographic data*** was constructed with ***70 minimum occurrences*** of the ***30110 keywords*** found in the documents. As a result, 192 keywords meet the threshold and are represented in the network shown in Fig. 3.

As a result, the network has five clusters.

- Red cluster (65 items). Includes the two major nodes "wireless sensor network" and "energy harvesting". It also includes terms such as "wireless communication", "scheduling", "reinforcement learning", "stochastic systems", "cognitive radio", etc. This indicates that the

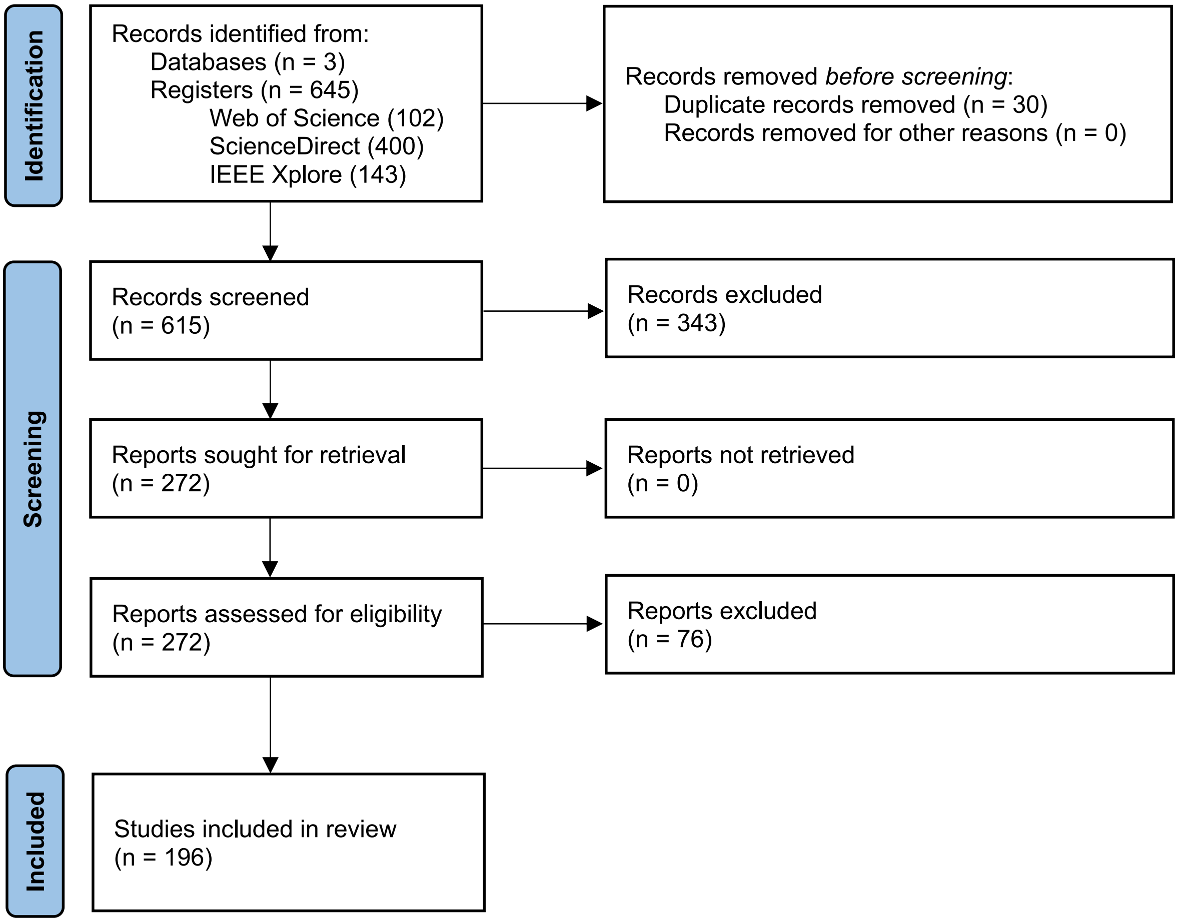


Fig. 1. PRISMA 2020 flow diagram for new systematic reviews which included searches of databases and registers.

cluster is related to the network's mechanism to work appropriately as an EH-WSN, especially for the "energy efficient" that is the third most relevant node. It is interesting to note that the second most relevant node is "energy transfer".

- Green cluster (47 items): The cluster appears to be more heterogeneous as it contains significant nodes such as "sensors", "environmental monitoring", "ZigBee" and "solar energy". This may be indicative of solar energy, via the utilization of a "photovoltaic cell", representing a form of energy more frequently referenced in the literature for monitoring applications, particularly those pertaining to the environment. Furthermore, the cluster includes "thermoelectric generators" and their synonyms.
- Blue cluster (40 items): The presence of keywords such as "piezoelectric", "triboelectric", "mechanical energy", "kinetic", "vibration", etc., and synonyms, suggests a thematic concentration on energy harvesting methods and technologies related to elements that extract energy from mechanical sources. This cluster exposes the application of the piezoelectric principle as the primary mechanism of transduction. "Piezoelectricity" is linked to "Sensors", suggesting that the authors have used or proposed to use it in monitoring applications.
- Yellow cluster (21 items): In this cluster, it is possible to appreciate a semantic proximity to the red cluster. We can find terms like "energy", "routing protocols", "prediction", "network lifetime" and synonyms and related terms. From this point of view, the terms in this cluster could be added to the red cluster.
- Purple cluster (19 items): This cluster focuses on RF harvesting methods. It is interesting to note the inclusion of the term "battery-less" in this cluster, implying that either battery-less systems are more extensively described, or the associated methods are more prominent. This suggests that RF harvesting is a promising technique for powering battery-less systems.

In summary, it can be observed that the main energy source is mechanical, mainly using piezoelectric and triboelectric effects such as transducer, solar, thermoelectric, and RF. This conclusion is consistent with the main subjects systematized in Table 1.

4.2. RQ1: Anatomy of the last ten years, methods or technologies for harvesting systems

In Section 2 Related works we explored how various authors classified EH-WSN by integrating transducers, sources, and energy types. To enhance the precision of the classification, these concepts have been distinctly separated and clearly stated:

- **Energy source:** entity that creates energy, for example, wind, sea waves, sun, antenna, electricity in a wire, etc.
- **Energy type:** Type of energy produced by a source, for example, light, heat, electromagnetic wave, mechanical vibration, etc.
- **Transducer type:** A device that, based on a physical principle, transforms ambient energy into useable electricity.

This approach represents a significant novelty in the field, offering a more accurate and detailed classification scheme than those found in previous studies. By introducing this novel classification method, the review addresses the shortcomings of existing reviews in terms of classification accuracy and trend analysis, thereby providing a more comprehensive and precise understanding of energy harvesting technologies for wireless sensor networks.

Table 3
Papers organized according to the type of energy, the transducer used, and the source of the energy.

Energy	Transduction	Source	Paper
Heat	TEG	Automotive engine	[47]
		Gas turbine	[48]
		Sun	[49–53]
		Gradient indoor/outdoor	[54]
		Phase change material (PCM)	[55–58]
		Heat pipe	[59–61]
		Industrial machines	[62,63]
		Laboratory conditions	[64–69]
		Thermal resonator	[70]
Light	PV	Sun	[49,52,71–88]
		Artificial (Indoor)	[89–103]
EMF	Coil	Power lines	[104–107]
RF	Rectenna	GSM 900 MHz	[108]
		1.8 GHz	[109,110]
		UMTS 2.1 GHz	[108,109]
		TD-LTE 2.3 GHz	[108]
		IMS 2.4 GHz band	[111–117]
		2.66 GHz	[109]
		2.1–2.7 GHz	[110]
		3.2 GHz	[118]
		IMS 5 GHz band	[115,119]
		5.4 GHz	[118]
		LTE850 and LTE 900 bands	[120,121]
		915–920 MHz	[122–125]
		Multiple bands	[108–110,115,117,118]
Mechanical movement	Magneto-mechano-electric	Laboratory conditions	[126,127]
	Triboelectric	Car wheels	[128]
		Human body	[129–132]
		Laboratory conditions	[133–144]
		Railway	[145–147]
		Waves	[148–153]
		Rain	[154,155]
		Wind	[85,156–163]
	Piezoelectric	Automotive engine	[47,164,165]
		Electromagnetic field	[166–170]
		Human body	[171–173]
		Industrial machinery	[174,175]
		Jet engine	[176]
		Laboratory conditions	[71,91,177–196]
		Pavement block	[197–200]
		Water flow	[201–203]
		Waves	[204]
		Railway	[196,205,206]
		Sound	[207]
		Wind turbine blades	[164]
		Wind	[159,207–217]
	Electromagnetic (magnet and coil)	Human body	[129,171,218]
		Laboratory conditions	[135,178,192,193,219–224]
		Agricultural machinery	[225]
		Industrial machinery	[226]
		Bridges	[227]
		Railway	[228–232]
		Sound	[233,234]
		Water flow	[235]
		Waves	[150,236,237]
		Wind turbine vibrations	[238]
		Wind	[49,72,85,156–159,208,215,239]
Chemistry	Electrodes	Corrosion	[240]
	Hydrovoltaic power generator	Electrolyte solution	[241]
Biology	Anodic and cathodic yarn	Bacterial respiration	[242,243]

Table 3 discloses the environmental sources associated with energy type and the techniques used to transform energy. This approach allows for a clear visualization of the relationships between the classification types defined before.

Some papers describe systems incorporating multiple power sources or transducer types. In that case, that paper appears in more than one row in Table 3. The tag "Laboratory conditions" indicates that the authors utilize a controlled laboratory system as an energy source without specifying the intended working environment for the proposed harvesting system.

Fig. 4 illustrates the distribution of papers based on energy sources, highlighting that mechanical energy is the most representative type, with more than half of the papers focusing on this energy source.

Fig. 5 summarizes the distribution of papers based on transducer type. Here, piezoelectric transducers emerge as the most referenced, followed by triboelectric and electromagnetic variants. Mechanical energy harvesting has garnered the most attention, with these systems predominantly leveraging vibrations from machinery, wind, and water flows. It is interesting to note that, as shown in Table 3, almost all systems that use wind as an energy source, usually use more than one transducer.

From the table and graphs presented above, it is evident that mechanical energy sources are prevalent among the selected papers and receive the most attention. Photovoltaic (PV) cells and thermoelectric generators (TEG) based on the Seebeck effect remain dominant transducers for harvesting energy from light and heat sources respectively. Additionally, rectennas have emerged as a foundation for battery-less systems. However, sources such as chemical and biological have notably less representation. All these works will be analyzed in greater detail in subsequent sections.

4.3. RQ2: Deployment and application scenarios

WSNs can be deployed across diverse scenarios using similar types of motes (sensor nodes). However, when WSN nodes incorporate harvesting systems, their viability is significantly influenced by the energy type available in the environment and the feasibility of harvesting. In this context, it is worth mentioning the different scenarios contemplated in the selected studios.

The following categories encompass papers where the authors explicitly state that their proposals are designed to function optimally within specific environments. A more thorough and critical examination of these papers reveals that many of these solutions can be utilized or adjusted for other contexts. In numerous instances, authors do not explicitly specify a particular working environment. In such cases, the category employed is "Not Referenced/Not Clear":

- **Agriculture:** Include the monitoring of environmental and soil variables in crop fields, as well as agriculture machinery. These solutions predominantly harness energy from sources such as the sun, wind, and flowing water, utilizing a wide range of transducers; this statement can be applied to both of the following two categories.
- **Smart home/building/city:** Encompasses applications ranging from monitoring indoor environments to city infrastructure, local weather, and air quality.
- **Water/Sea/Marine environments:** Refers to a system that collects energy from water bodies, primarily utilizing wave energy.

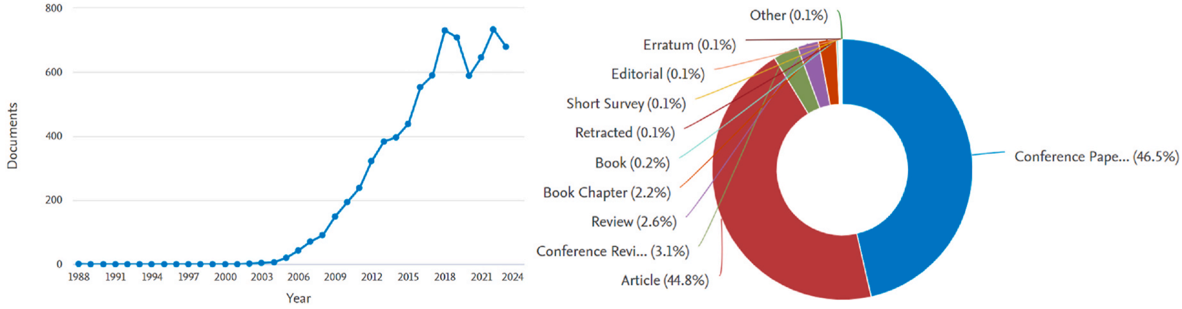


Fig. 2. Scopus statistics on studies authored by year (left) and by type of publication (right).

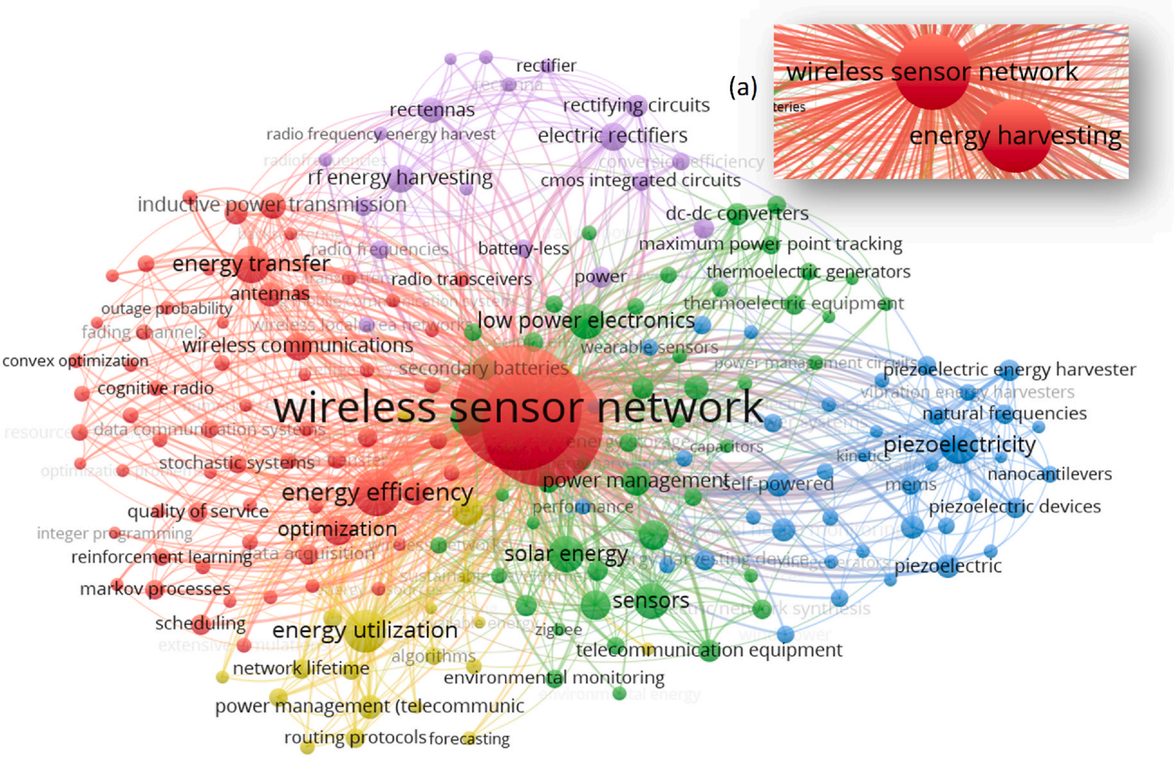


Fig. 3. VOSviewer analysis. a) larger nodes overlapped in the center.

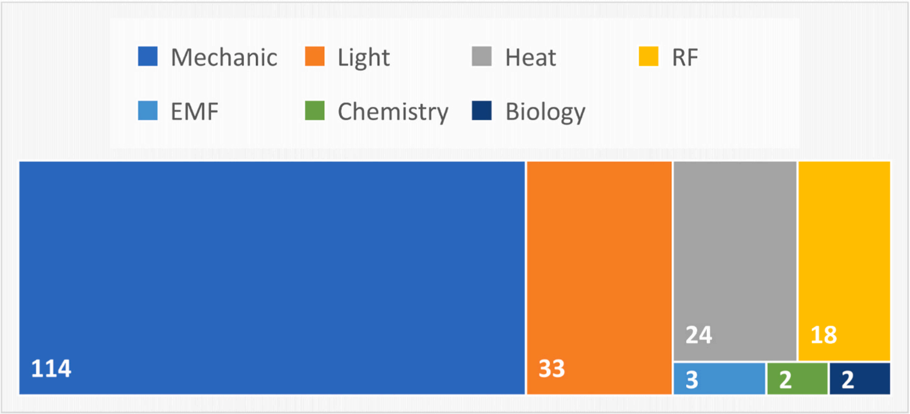


Fig. 4. Distribution of papers based on energy sources.

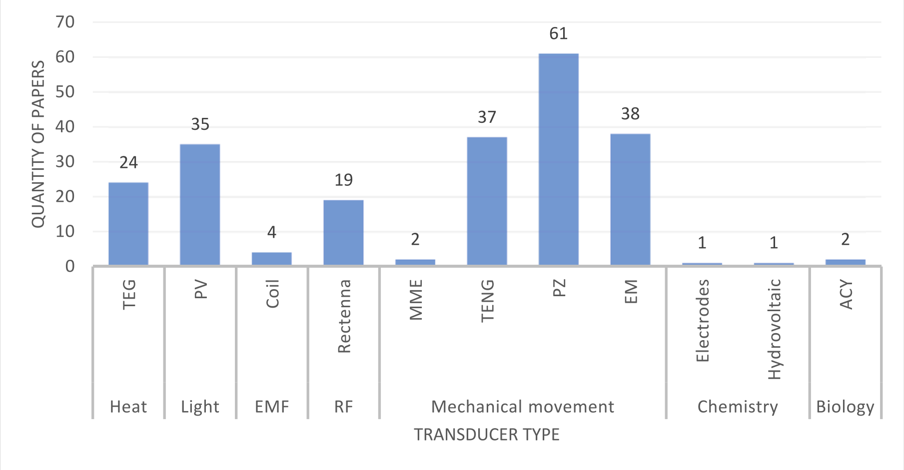


Fig. 5. Distribution of papers based on transducer type.

- **Transportation:** Apply to applications that harvest energy from modes of transportation, including trains, trucks, and cars. In this context, energy is primarily collected from vibrations generated by the movement of cargo vehicles.
- **Wearables/healthcare**: Encompasses wearable devices, implants, and other health monitoring devices, including pets.
- **Environmental outdoor:** This category can be viewed as a specific instance of "Not referred/Not clear," where authors imply that energy is harvested from outdoor environments, primarily sourced from the sun, wind, or water currents.
- **Industry:** While the industrial environment is known for its aggressive nature, it also represents a considerable amount of untapped energy resources that are often wasted in the operation of machinery, mainly heat, vibration, and electromagnetic fields.
- **Not referred/not clear:** This category encompasses papers that lack information about application scenarios or provide only broad and general suggestions for potential applications.

Fig. 6 shows the percentage of papers that are included in the different scenarios. Notably, a considerable proportion of the documents (48.8 %) lack a precise definition of the intended field of application for the proposed harvesting system. This limitation frequently arises as systems are predominantly tested in controlled laboratory conditions. Although this approach facilitates the design, construction, and validation of energy harvesting systems, it can present a challenge in identifying natural energy sources that closely replicate laboratory conditions and enable powered devices to perform as anticipated.

Presumably, items in the "Environmental outdoor category" could be associated with several other collected categories, but the authors do not explicitly provide details about the potential alignment.

5. Discussions, answering RQ3

In this section, we report observations derived from the analysis of selected papers.

5.1. Energy obtained from the harvester

The term "power density" is frequently utilized in review papers such as [3,32] as a metric to evaluate the potential of different energy sources for harvesting applications. It serves as a quantitative measure of the available energy per unit area or volume, thereby providing valuable insight into the feasibility and efficiency of energy harvesting systems.

Table 4 presents the power density organized by transducers. While power density serves as an effective descriptor for energy harvesting elements, only 15 % of the reviewed papers include this variable as part of their results. In successive subsections, it will be addressed each case in detail.

Although the amount of electrical energy obtained indeed depends on the efficiency of the transducer, as well as the area/volume of it

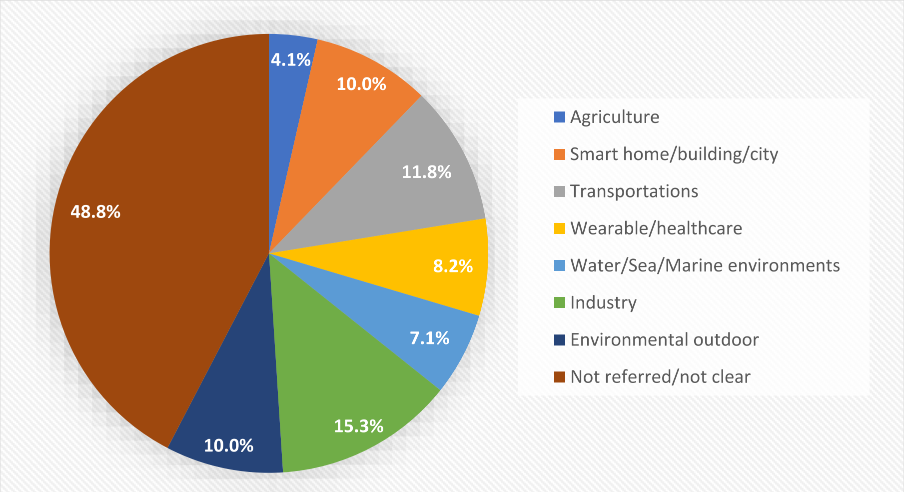


Fig. 6. Distribution of papers based on the application area.

Table 4

Maxima (peak) power density declared in papers, organized by transducers.

Transducer type	Papers	
TEG	Kim et al., 2018 [60] and	2.2 mW/cm^2
	Donmez Noyan et al., 2019 [64]	40 μW/cm^2
PV cell	Zhang et al., 2022 [101] and	90 μW/cm^2,
	Wu et al., 2022 [102]	4.51 μW/cm^2
EM	Maharjan et al., 2018 [106] and	14.67 μW/cm^3,
	Menéndez et al., 2019 [107]	25 μW/cm^3
Rectenna	Wagih and Beeby, 2022 [124]	From a 0.17 μW/cm^2
TENG	Huang et al., 2023 [129],	1568.4 W/m^3,
	Maharjan et al., 2018 [131],	5.14 mW/cm^3,
	Qian et al., 2017 [134],	13.86 W/m^2,
	Li et al., 2021 [138],	26 W/m^2,
	Xia and Xu, 2021 [137],	727.78 W/cm^2
	Xi et al., 2019 [149],	13.2 mW/m^2
	Hu et al., 2023 [155] and	97.2 mW/m^2,
	Zhang et al., 2021 [161]	4.8 W/m^2
PZ	Botteron et al., 2016 [91]	100 μW/cm^2
	Peddigari et al., 2023 [168],	0.85 mW/cm^3,
	Song et al., 2018 [169],	243 μW/cm^3,
	Peddigari et al., 2023 [219],	2660 μW/cm^{2}g,
	Rana et al., 2022 [194],	18.95 μW/cm^2,
	Yan et al., 2020 [188],	21 W/cm,
	Zhang et al., 2020 [186],	0.37 μW/mm^3,
	Cao et al., 2020 [202],	517 V/m^2,
	Izhar et al., 2023 [207],	2318 μW/cm^3
	Kan et al., 2021 [211],	5.493 mW/cm^3,
	Liu et al., 2019 [212],	0.36 mW/cm^3,
	Tang et al., 2023 [213] and	24.7 mW/mm^3,
	Jung et al., 2015 [217]	8.6 mW/cm^3
Electromagnetic	Paul et al., 2021 [219]	2660 μW/cm^{3}g^2
Hydrovoltaic	Yun et al., 2023 [241]	22.10, 19.14, and 22.12 W/m^3

exposed to the energy source to be transformed, power density is influenced by numerous environmental factors that cannot be constrained. For instance, in solar energy harvesting, power density is affected by the intensity of sunlight, the angle of incidence, and the efficiency of photovoltaic cells [7]. Similarly, in vibration energy harvesting, power density is determined by the amplitude and frequency of vibrations in the environment [17]. In light of the aforementioned considerations, the power density referenced in Table 4 pertains to the maximum attainable values under optimal conditions, represented as a peak. However, it is important to note that this does not align with the practical values that can be achieved and sustained in real-world scenarios.

Authors typically present their results in the order of power obtained in their experiments, often referring to the maximum power obtained and, in many cases, an average of it. In these cases, the descriptions of systems provide reference to a transducer as a device functioning in a certain environment.

While these descriptions may not be the most generalizing way of describing the transducer, they are likely more useful for transferring research experience to practical applications, which is the primary objective of most, if not all, of the consulted works. Consequently, we now find more diversity in values, even within the same energy source with the same type of transducer. For example, considering heat as a type of energy, typically utilizing TEGs, we can find values ranging from the highest, such as 272 mW obtained from a heat pipe at 70 °C, with a TEG-flexible area of 140 × 113 mm^2 [60], to the lowest, with 15.24 μW at $\Delta T = 20$ °C provided by solar energy [53].

The heat map shown in Table 5, the energy sources are depicted in the columns, while power ranges are represented along the rows using a natural logarithmic scale. Each number within the rows is a multiplier, indicating the quantity of solutions falling within a specific range of power values, as denoted in each cell. For instance, if a particular solution reports the collection of 2.2 mW of power using light as the energy source, then the corresponding cell located at the intersection of the 1 mW row (ranging from 1 to 10 mW) and the light column will be incremented by 1.

Since analyzing the detailed behavior and composition of transducers and energy harvesting techniques falls beyond the scope of this work, Table 5 focuses on visualizing the distribution and density of solutions based on their power across different energy sources. This provides valuable insights into the characteristics and performance of each energy source within the given context in a wide landscape. As observed in Table 4, not all authors declare the power density obtained from their solutions. Therefore, Table 5 only includes the solutions for which the power is declared by the authors. Note that the TENG, PZ, and EM entries are separated even though they harvest the same type of energy. This separation is due to significant differences in the amount of harvested energy among these energy-harvesting technologies.

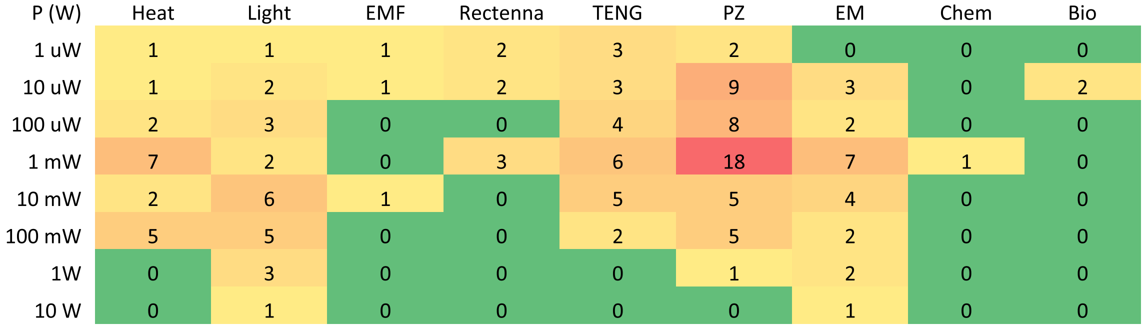
Globally, it is evident that most solutions acquire energy within the range of 1–10 mW, specifically in heat and mechanical energy.

In the case of light as an energy source, the range of harvested energy is typically more widely spread. This variability is primarily influenced by the size of the photovoltaic (PV) panel and the number of cells, which determine the amount of energy harvested. For papers that reference commercial panels with well-known energy density and efficiency, the PV can be dimensioned to meet the power requirements of the system in a specific environment. However, this is not the case for papers such as [101,102], which describe new processes and materials for PV cells, where the energy harvesting capabilities may vary significantly.

The lack of reference to the obtained power or power density in papers on rectennas is likely related to the inherent complexity of these technologies. The energy harvested by rectennas largely depends on the power radiated by the transmitting antennas from which the energy is obtained, as well as the distance at which they are located. These factors can vary significantly in different situations and environments, making it difficult to establish precise values of harvested power. Instead of

Table 5

Power generation heat map.



P (W)	Heat	Light	EMF	Rectenna	TENG	PZ	EM	Chem	Bio
1 uW	1	1	1	2	3	2	0	0	0
10 uW	1	2	1	2	3	9	3	0	2
100 uW	2	3	0	0	4	8	2	0	0
1 mW	7	2	0	3	6	18	7	1	0
10 mW	2	6	1	0	5	5	4	0	0
100 mW	5	5	0	0	2	5	2	0	0
1W	0	3	0	0	0	1	2	0	0
10 W	0	1	0	0	0	0	1	0	0

focusing on harvested power, researchers choose to concentrate on the efficiency of the transducers, i.e., the rectennas in this case. By evaluating efficiency, researchers can analyze how rectennas convert incoming electromagnetic energy into useable power, providing a more comprehensive measure of technology performance rather than simply the amount of power obtained. Consequently, the lack of reference to harvested power in papers on rectennas may reflect a preference for focusing on more fundamental and significant aspects of technology performance. In any case, the power harvested from RF sources is typically in the order of units or tens of microwatts.

Another factor that significantly impacts the amount of useable energy derived from the energy harvested by the transducer is the efficiency of the Power Management System (PMS). We have dedicated a section, Section 5.3, to discuss this aspect in detail.

A common method for presenting results is to include both the maximum and average power harvested, obtained over a specific value of resistance as a representation of the load. Like power density calculations, these maximum values often represent power peaks obtained under nearly ideal conditions. Also, it is common for the authors to provide the V_{OC} (Open Circuit Voltage) and I_{SC} (Short Circuit Current) in maximum peak values. It's important to note this, as these values may not be suitable for direct application in real-world scenarios.

5.2. Energy-Based harvesting mechanisms

In this section, the methods for generating electricity will be summarized based on the type of energy from the primary source, as outlined in the literature. In each of the subsequent sections, previously classified systems based on their specific types of energy used will be referred to, and briefly describe its energy obtaining mechanism. Due to the hybrid nature of many systems, which do not fit neatly into a single category, these hybrid systems will be briefly mentioned in the *"Hybrid system"* section. A more detailed analysis of the hybrid systems will be conducted in a final dedicated section. This will help identify trends, address challenges, and provide solutions.

5.2.1. Light and heat

Typically, the operation of machines, particularly industrial ones, dissipates unused energy, primarily in the forms of light, heat, mechanical vibrations, acoustic noise, and electromagnetic fields. In addition, Heating, Ventilation, and Air Conditioning (HVAC) systems in buildings, geothermal activity, solar thermal energy, and body heat, can be harnessed to power WSNs. In this sense, Markiewicz et al., 2020 [66] and Vostrikov et al., 2019 [67] demonstrate how a low-temperature gradient can be sufficient to power sensor nodes in a WSN.

Despite its potential, thermal energy harvesting faces challenges such as the low efficiency of TEGs, the need for significant temperature differences, and the complexity and cost of integrating these systems into existing infrastructure. Additionally, miniaturizing thermal harvesters to fit WSN nodes and ensuring their durability under varying conditions are critical concerns.

Thermoelectric generators (TEGs) using the Seebeck effect are the focus of the literature on the conversion of heat to electricity. Similarly, when light is used as the energy source, only studies using photovoltaic (PV) cells as transducers have been found. Both types of transducers are based on PN junction semiconductors, and their operating principles are well-known and thoroughly described in the literature [7,11].

The work in this field is focused on three main directions:

- Searching for energy sources and, if possible, amplifying them. A challenge for TEGs is to maintain the gradient between hot and cold sides.
- Seeking efficiency in the transducer may involve exploring new materials or different shapes and configurations.
- Looking for efficiency in the circuits that manage the collected electricity, aiming to avoid transfer losses and operate at the maximum power points.

Studies like Kim et al., 2023 [47], Deng et al., 2019 [49], Lee et al., 2018 [52], Xiao et al., 2023 [88] describe a hybrid system, so they will be treated in the corresponding section. The heat generated in solar panels results in transducer losses, which can be mitigated by using thermoelectric generators (TEGs) to create hybrid systems [244,245]. Notably, this idea has not been explored in the papers reviewed. It can be assumed that this potential hybridization either does not offer advantages in the environments and operating conditions of WSN nodes, or it is simply an unexplored area. In any case, it represents a niche opportunity, and we may see research in this area in the coming years.

In Wu et al., 2018 [48] a commercial device Bi_2Te_3–PbTe hybrid thermoelectric power module (56 × 56 mm^2) is embedded in a thermal isolation material penetrated by two heat pipes with a 200 °C at maximum. This scenario is only to simulate a gas turbine environment, where the main application is designed.

The heat transferred through residential or industrial pipelines, such as hot water or steam, serves as the energy source for Chen et al., 2016 [59], Kim et al., 2018 [60] and Lineykin et al., 2021 [61]. In these cases, the relevant factor is the method of coupling the TEG to the heat source, which has a cylindrical shape, unlike the flat surfaces of commercial devices.; Chen et al., 2016 [59], like Wu et al., 2018 [48], a heat pipe is inserted in the main pipe to conduct the heat fluid to two 1.1″ by 1.1″ Bi_2Te_3 TEG elements placed outside of the main pipe thermal insulator; Kim et al., 2018 [60] developed a flexible TEG designed to wrap around pipes of different diameters, a similar solution to the one proposed by Kim et al., 2020 [65]; Finally, Lineykin et al., 2021 [61] proposes using an aluminum profile to adapt the curved shape of the pipe to the flat shape of a commercial TEG type TES1-24102. In all cases, the heat is dissipated from the cold side of the TEG module by natural convection using heat sinks.

In the same line, Hou et al., 2017 [62] and Oliveira et al., 2023 [63] take advantage of the industrial waste heat. Sinse Hou et al., 2017 [62] developed a device powered by a commercial TEG TGM287-1.0-1.3, Oliveira et al., 2023 [63] studied the feasibility of extracting the operating heat of a motor from three CP85138 TEG modules from a mechanical coupling is evaluated in the feasibility study.

The sun, in addition to light, is an important source of heat that, although it can represent a problem for PV systems, can be used in solid thermoelectric systems [49–53]. Deng et al., 2019 [49], Lee et al., 2018 [53] describe a hybrid system, so they will be treated in the corresponding section. In this sense, Estrada-López et al., 2019 [50] Fang et al., 2023 [51] use a commercial CP60333 TEG module to collect heat from a sunlight concentrator based on a Fresnel lens. On the other hand, Shen et al., 2021 [53] manufactured their own planar TEG device in a novel shape to improve performance to collect the sun heat as well as to achieve miniaturization and low-cost manufacturing.

Normally there is a temperature difference between the interior and exterior of a building that is significantly accentuated by the use of HVAC depending on weather conditions [246]. This phenomenon is exploited by Lin et al., 2022 [54] who embeds a TEG in the space of a window profile with an inclination of 45° to better accommodate a 30 × 30 mm^2 commercial device 1261G-7L31-04CL.

Phase change materials (PCM exhibit the capacity to absorb and release considerable quantities of latent heat during phase transitions, such as those occurring between the solid and liquid states or between the liquid and gaseous phases. This property enables them to effectively stabilize temperature fluctuations [247]. This makes PCMs ideal for maintaining the temperature gradient required by TEGs, especially in environments with fluctuating temperatures. Peng et al., 2022 [55] proposes integrating gallium as PCM with TEG for WSN power supply in spacecraft; Elefsiniotis et al., 2015 [58] who test Erythritol and H120 in a high-temperature aircraft-specific application; Thi Kim Tuoi et al., 2022 [56] and Verma and Sharma, 2019 [121] a stable temperature is maintained from daily ambient temperature variations on one side of a TEG using PCM, Polyethylene glycol E600 in the first case, and water in the second case; and Fang et al., 2023 [51] a 3D-architected carbon-based photothermoelectric organic composite PCM energy harvester is designed and tested.

One step further in handling the temperature variations to maintain the thermal gradient between the TEG surfaces is a thermal resonator [248]. The goal is to develop a material with high *thermal effusivity*, combining rapid heat conduction and high thermal capacity, despite these properties usually being inversely related in most materials. In Cottrill et al., 2019 [70] the author of the concept and material himself presents a proof of concept using the energy fluctuations of the extreme climate of the Saudi desert.

Wang et al., 2023 [68] expose maybe the most interesting case in TEG elements, using a nuclear element as a heat source to design a radioisotope thermoelectric generator (RTG), basically a nuclear battery. The work explores different deployment scenarios such as confined space, unconfined space, and the deep-sea-polar region.

Regarding the studies that use light as a primary type of energy, it has been found that they are quite focused on exploiting the existing devices on the market [71,73,74,78–82,84,92,95,96,99,100,102,103]. Zheng et al., 2015 [71], Mihajlovic et al., 2016 [74], Sharma et al., 2018 [75], Loreti et al., 2019 [79], Salazar Cardona and Marulanda Tobon, 2021 [82] and Qi et al., 2021 [98] does not offer enough information about the panels they use. Only refer to the use of a 93.5-cm^2 PV panel of 420 mW as the maximum in Zheng et al., 2015 [71], 5W and 4.5 W PV panels in the Sharma et al., 2018 [75] and Salazar Cardona and Marulanda Tobon, 2021 [82] respectively, and Loreti et al., 2019 [79], declare a *small-size (micro) solar cell*. The rest are summarized in Table 6.

Table 6
Photovoltaic system described in the review papers.

Paper	Cell type	PV surface (mm)	Conditions
Commercials			
Visconti et al., 2016 [73]	Amorphous silicon - a-Si (AM-5907CAR)	75 × 55	Outdoor
Antony et al., 2020 [80]	Polycrystalline	–	Outdoor
Avlani et al., 2022 [84]	a-Si	50 × 60	Outdoor
López-Lapeña and Pallas-Areny, 2018 [76]	Monocrystalline (SLMD121H04)	43 × 14	Outdoor
Sadowski and Spachos, 2020 [81]	Monocrystalline	170 × 170	Outdoor
Anzola et al., 2019 [78]	Monocrystalline	–	Outdoor
Vracar et al., 2016 [92]	Monocrystalline (SLMD600H10)	35 × 22	Indoor
Haroun et al., 2022 [100],	polycrystalline	230 × 115	Indoor – 6600 lux LED
Politi et al., 2021 [99]	GaAs	140 × 140	Indoor
von der Ahe et al., 2018 [95]	Monocrystalline	22 × 6/cell 21 cm^2 total area	LED ligth
Yue et al., 2020 [96]	–	50 × 20	Indoor (200 lx)
Zhang et al., 2022 [102]	Organic Photovoltaics (InfinityPV)	110 × 230	Indoor (200–1000lux)
Manufactured by the authors			
Toh et al., 2014 [90]	Flexible a-Si	60 × 72	Indoor
Foti et al., 2014 [89]	Flexible a-Si	30 cm^2	Indoor
Botteron et al., 2016 [91]	a-Si	6 cells in 0.25 cm^2	Indoor
Paul et al., 2017 [93]	Monocrystalline	2.5 × 2.5 mm^2	Indoor

Presumably, because the photovoltaic cell model is well-known and accepted [249], and the management of power availability fluctuations is the main challenge in these systems, several of the selected papers are presented only up to the simulation stage [77,83,86,97,98]. In Kaur and Buttar, 2021 [83] the simulations show how the lifetime of the battery is incremented; Sharma et al., 2019 [77] explored duty cycles and network mechanisms; in Gupta et al., 2023 [86] the maximum power point tracking (MPPT) for solar panels is optimized using the Emperor Penguin Optimization algorithm; and Qi et al., 2021 [98] are focused on a hybrid energy storage system.

Although the PV systems market is largely dominated by silicon, it is not particularly efficient in indoor conditions. This is why the selected articles explore other types of cells. In academia and industry, there are high expectations for perovskite cells [250]. Olzhabay et al., 2021 [97] attempt to contribute by suggesting scenarios for WSNs with specific cells, grounded in simulation. On the other hand, Wu et al., 2022 [101] and Zhang et al., 2022 [102] explore organic photovoltaic (OPV) cells. While Zhang et al., 2022 [102] evaluates a commercial 110 × 230 mm^2 OPV from InfinityPV, Wu et al., 2022 [101] design and fabricate an OPV module using environmentally friendly solvents to improve photovoltaic performance.

A work that is quite out of the ordinary among those reviewed for this review, it is without a doubt. Speranza et al., 2023 [87]. A dye-sensitized solar cell (DSSC) integrated with a supercapacitor has been developed and tested. Despite garnering significant attention since its discovery, DSSCs have faced challenges related to large-area fabrication and long-term stability, impeding their development [251]. Speranza et al., 2023 [87] propose in the paper a solution to one of the problems, a common vacuum sealing method for integrating a supercapacitor with a DSSC.

A very interesting work is Ko et al., 2017 [94]. The system uses an energy storage element charged by a reconfigurable 128 × 96 pixels CMOS Active Pixel Sensor (APS), which operates in photoconductive mode for imaging and photovoltaic mode for harvesting, with mode switching based on frame rate or stored energy levels. The entire sensor node is implemented on a single die in 130-nm technology.

5.2.2. *Electromagnetic, from power lines to radio waves*

Another potential energy source is the electromagnetic fields generated in the power cables that supply the electric machines. These fields can be harnessed directly using coils [104,106,107] or converted into mechanical energy for further energy conversions [166–170]. This last group will be boarded into *the Mechanical* section.

Porcarelli et al., 2014 [104] presents a clamp to harvest energy and make power measurements in the same device. In Kang et al., 2017 [105] a Ø 12 cm and 25 cm long plastic tube covered with aluminum foil is placed between 765 kV power lines. A similar approach to collect the energy is followed by Maharjan et al., 2018 [106] who propose two C-shaped ferrites, each covered by a copper coil, which describes a split core that can be easily attached to a power wire of domestic electrical devices without cutting it. Here, the author successfully experiments with several domestic appliances as power consumers to feed node sensors designed for this application.

For its part, Menéndez et al., 2019 [107] uses two square electrodes as a harvesting element. Starting from the idea that the power obtained depends on the shape and position of electrodes and the electric field distribution, an MTTP is implemented using a servomotor to adjust the distance of the electrodes to the power line mechanically.

Rectenna is a device that has been used to transform radio frequency (RF) waves into useable electrical energy. As their name suggests, these devices consist of an antenna and a rectifier element. Like other instances, the output's strength correlates with the energy's intensity (in this case, the radio signal) reaching the transducer and the system's efficiency. Directly, this relates to the distance and alignment between the source and the receiver. The antenna's shape influences its sensitivity and gain at a specific frequency, while its impedance matching network (IMN) and rectifier block, typically composed of Schottky diodes, impact the system's efficiency.

This frequency selectivity makes many of the proposed systems multiband to take advantage of a greater diversity of RF sources [108–110,115,117,118].

Yang et al., 2018 [108] developed a small triple-band rectenna (GSM 900 MHz, UMTS 2.1 GHz, TD-LTE 2.3 GHz) conformed by a spoof LSP resonator consisting of an annular ring slot and a periodic array of T-shaped grooves. The rectifier is PCB printed and is composed of a Schottky diode, a DC-pass filter, and a resistive load. The application is proposed for human body self-monitoring and mobile healthcare in a Body Area Network (BAN), which presumably can bring serious challenges in its deployment due to the dimensions (the antenna has 70 × 60 mm^2, and the rectifier has over 110 × 45 mm^2) of the device as well as its sensitivity to changes in orientation.

Benkalfate et al., 2022 [109] propose a 40 × 30 mm^2 meander line antenna and IMN printed in the same PCB, that operates in GSM 1.8 GHz, UMTS 2.1 GHz, and LTE 2.66 GHz bands. Patil et al., 2023 [115] 2.4 GHz, 5 GHz two concentric open square loops for 2.4 and 5.2 GHz respectively. The interesting thing about this work is not so much the antenna but the way it is built, using a 3D printer.

An omnidirectional broadband rectenna array that operates in 1.7–1.8 GHz, 2.1–2.7 GHz Song et al., 2021 [110]. The array combines in a single 145 × 145 × 1.53 mm^3 PCB 12 Vivaldi slot rectenna elements (including the rectifier and the IMN each) around a circle shape to achieve an omnidirectional 3-D radiation pattern. According to the authors, the inner PCB circle can host the sensor node printed directly on a surface of 60 × 60 mm^2.

Ullah et al., 2023 [118] proposed a 10 × 10 mm^2 metamaterial unit cell able to operate in 3.2 GHz and 5.4 GHz. The cell describes an outer ring with a 45-degree-angled gap that contains two inverted T-shaped resonators. A 3x3 array structure was experimentally tested.

A stacked four-layer antenna integrated with a voltage doubler rectifier is proposed by Aboualalaa et al., 2023 [117]. The antenna operates in three frequency bands, 1.86–2.65 GHz, 2.84–3.64 GHz, and 5.34–6 GHz, but only the lower one is used for energy harvesting; the other two are for data communication. The device is formed by a driven element, a planar reflector, and a planar director which is composed of a periodic structure of a square patch with a hexagonal slot in its center. The rectifier is designed and optimized to operate at 2.45 GHz and built and tested separately.

The 2.4 GHz band is commonly used for short-range, low-power wireless communication systems, making it highly likely to encounter multiple devices operating in this frequency range in urban environments. This prevalence is likely why most rectenna research focuses on this frequency band [111–117]. Several of these solutions, in particular Dekimpe et al., 2019 [111], Koohestani et al., 2020 [112], Liu et al., 2023 [113]. They approach the issue broadly by suggesting an integrated device. In these studies, the antenna, the rectifier, and the IMN are all printed on the same PCB, and the sensor node's design and assembly are tailored to the energy conditions.

Dekimpe et al., 2019 [111] design, optimize, and implement a complete WSN node for a specific task combining the same type of BLE receive path antenna. Koohestani et al., 2020 [112] presents a 24.9 × 8.6 mm^2 rectangular section including a rectangular monopole patch and two truncated U-shaped slots. The rectifier is placed in a transversal way in the PBC substrate of the rectenna.

Liu et al., 2023 [113] antenna, rectifier, energy management circuits, and the mote are integrated on a single printed circuit board and a total size of 53 × 59.77 mm^2. The antenna is a 53 × 43.4 mm^2, side-fed microstrip structure enhanced by etching three rectangular slots. The same author presents another solution in Liu et al., 2023 [114] with a 118.12 × 51.335 mm^2 microstrip antenna formed of two radiating patches in an array connected to a 50 Ω microstrip line and two-stage voltage-doubling rectifier.

On the other hand, to try to alleviate the problem of the low amount of energy available Zhang et al., 2019 [116] proposes integrating a dedicated wireless power transfer (WPT) with the energy harvested by the rectenna.

Rajawat and Singhal, 2020 [120] and Verma and Sharma, 2022 [121] exploit the LTE bands at 850 and 900 MHz. Rajawat and Singhal, 2020 [120] simulate two variants of a microstrip patch antenna, with two and four slots respectively. Verma and Sharma, 2022 [121] design and test the performance of an energy flow control circuit working with an algorithm to control the energy flow. The harvester element is formed by an array of 10 commercial-off-the-shelf antennas. Each element array integrates the IMN and voltage multiplier.

An inverted F (PIFA) antenna for which the patch is 55 × 55 mm^2 is used by Xiao et al., 2016 [122]. The rectifier and IMN are implemented as a seven-stage Dickson charge pump that stores the harvested energy in a 120 μF capacitor bank.

On the other hand, at the 920 MHz band, Miller et al., 2020 [123] suggest a 12-element Yagi antenna and a single-stage fully cross-coupled RF-DC converter circuit up to 3.3 V. In the same frequency band, Wagih and Beeby, 2022 [124], introduce arrays consisting of six folded dipole antenna elements with the rectifier and the IMN printed in a circular shape with a diameter of 150 mm. The device is integrated and tested with a commercial DC-DC converter and BLE WSN node.

Tran and Chung, 2014 [125], developed a 3.3 × 7.5 cm^2 two-layer PCB that includes a PCB antenna and a commercial IC, the P1110 from Power-Cast, to manage RF harvesting. The system is optimized to operate within the 902–928 MHz frequency range.

5.2.3. *Mechanical*

Unlike classic thermomechanical or renewable energy wind or water systems for electrical generation that are based on generating circular movement based on flows, the systems used in EH-WSN take advantage of events that generate residual mechanical energy from the flows themselves, as well as movements and vibrations.

Nonlinear phenomena like mechanical resonance, nonlinear stiffness, and nonlinear damping can be exploited to increase the amplitude of vibrations and improve energy transduction [174]. Designing devices that capitalize on these nonlinear effects requires careful consideration of factors such as material selection, structural design, and excitation mechanisms [252]. Additionally, nonlinear dynamics design entails mitigating undesirable effects that can arise from nonlinear behavior, such as frequency detuning, amplitude saturation, and nonlinear damping-induced energy dissipation.

As shown in Fig. 4, this is the form of energy that has received the most attention in the last 5 years, with more than half of the papers selected. The main sources of energy, according with Table 3, are machines, the human body, as well as air and water flows.

5.2.3.1. Machinery. As previously described, from a mechanical perspective, vibrations and acoustic noise are typically undesirable byproducts of machine operation and are often wasted, both in an industrial environment and at the domestic level. Some solutions are quite simple, relying on a cantilever with a piezoelectric transducer tuned to the mechanical resonance frequency to effectively harvest the necessary energy from electric motors or other types of stable industrial vibration like Huet et al., 2022 [174], which also proposes a tuning mechanism by a cam, transformer banks like Wang et al., 2023 [175] with an AC fix frequency, train bogie like Dziadak et al., 2022 [205] and Wang et al., 2019 [206] and jet engines like Wang et al., 2020 [176]. Additionally, coupling effects and structural nonlinearity are used to broaden the response bandwidth, as demonstrated by Shim et al., 2022 [165]. Other mechanisms are more elaborate and will be briefly described below.

The research like [47,134,164,228,229,231,232] describe a hybrid system, consequently, they will be discussed in the corresponding section.

The passage of vehicles on railways [145,146,196], roads [197], and bridges [227] continually creates pressure and vibrations. In railways environment Shan et al., 2023 [196] present a piezo stack device that utilizes a longitudinal and torsional oscillation of plate springs to broaden frequency bandwidth; Zhao et al., 2017 [145] four springs maintain a gap between two triboelectric layers, aluminum, and Kapton that come into contact when applying the impact of vibrations in the upper layer; Gao et al., 2017 [146] exploits the confined moving magnet mechanism represented in Fig. 7 a).

To take advantage of the pressure exerted on the pavement by passing vehicles Hwang et al., 2019 [197] present a piezoelectric energy harvester designed to be embedded in the highway. Middle-size vehicles passing over at 90 km/h produce enough energy to operate a sensor node for at least 16 s. In McCullagh et al., 2014 [227] present a new improvement of a series of previous works to develop a parametric frequency-increased generator (PFIG) to harvest the vibrations generated by traffic on bridges [253–255]. The device includes a large inertial mass that moves back and forth, snapping between two latching magnets. These magnets are connected to springs attached to two electromagnetic transducers.

Back on trains, Liu et al., 2023 [230] developed a system to harvest vibrations from a train bogie's suspension system. A cylindrical permanent magnet is confined within a pipe, suspended between two permanent magnets at the ends. Additionally, a pair of springs prevents the central magnet from hitting the pipe's ends, ensuring efficient vibration energy harvesting. A pair of coils placed around the pipe react to a mobile magnet, generating electric energy.

A similar idea is presented by Wang et al., 2022 [225], which harnesses the wide vibrations of agricultural machinery. The mechanism consists of a stationary part fixed to the stripping header, with a coil mounted on a nylon tube, and a movable part with a magnet that moves up and down a nylon pillar inside the coil, driven by the undulating road and the force of a compression spring from the wheel.

An electromagnetic transducer that capitalizes the movement of a linear actuator in a machine is proposed by Sudhawiyangkul and Isarakorn, 2017 [226]. In this design, the sensor node is intended to monitor the actuator bearings. Therefore, it will be mounted on the carriage, and the coils, unlike other similar works, will be located on the moving part of the system.

A challenge scenario is faced by Castellano-Aldave et al., 2023 [238]. The device described utilizes the movement of inertial masses made of magnets in Hallbach arrays that interact with coils. It is capable of functioning for movements in any direction on a plane and harnesses the low-frequency oscillations of a wind turbine.

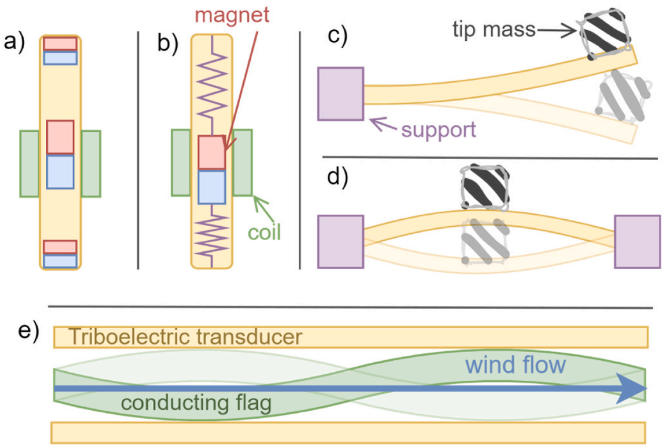


Fig. 7. Mechanical system representation: a) and b) depict a magnet acting as an inertial mass in a linear guide, suspended by a magnetic field (a) or springs (b). c) and d) show a beam, cantilevered (c) or fixed at multiple points (d). e) illustrates a flag waving within confined walls.

Mechanically, they not only take advantage of undesirable effects. Some machine movements can be used by inserting devices that do not affect their performance, as is the case of Qian et al., 2018 [128], Machado et al., 2022 [164] that capitalizes the rotatory movement, in the first case of a car wheel, and the second case of a wind turbine Blade's movement. Because these systems will be considered hybrids, an analysis will be done in the corresponding section.

Bi et al., 2021 [147] present an interesting work because it refers to its device as a battery. Similar to Xi et al., 2019 [149], the device consists of a series of discs separated by springs and stacked in layers, alternating between copper as an electrode and a polytetrafluoroethylene (PTFE) film on another layer of copper. This copper layer is attached to a mass that functions as an inertial element, this time collecting the vibrations of a train railway. The main innovation is that the copper electrode layer consists of two copper films covering a solid electrolyte (NaCl ionic gel) on both sides, which allows for more charge storage and transfer.

5.2.3.2. Waves and flows. Sea waves and flows of water and wind are natural energy sources traditionally exploited to obtain electrical power. While these systems usually use turbines to obtain variable magnetic fields from rotary motion, these low-power harvesting systems also take advantage of vortex-induced vibration, flutter, buffeting, and galloping produced by these flows. For its part, it is important to remember that waves generate movements in all directions. It is essential to consider this characteristic to efficiently capture wave energy.

It is interesting to note that, in this field, most systems that use wind as a type of energy include more than one type of transducer and/or present more than one energy transformation. This is the case of [49,85,156–159,208–210,215–217]. An inserting case is Izhar et al., 2023 [207] who take advantage of two energy sources, wind, and sound. Ahmad et al., in 2022 and 2023 [233,234], present two variants of hybrid vibroacoustic energy harvesting. All these papers will be treated as hybrid systems that will be aborded properly in a subsequent section.

Wu and Lee, 2014 [239] designed and implemented a windmill structure covered by a streamlined frame that selectively allows the wind to pass through the bottom half of the windmill. A permanent magnet is attached to the free of each blade, and a coil is attached to the low part of the frame, in the path of the magnet.

A fluttering movement of a flag forced by a wind flow is widely used in TENG harvesters [160–163]. A flapping wing comes into contact and separates the triboelectric materials in the generator, generating triboelectric charges on the surfaces. Zhang et al., 2021 [161] demonstrate how replacing a rigid flagpole with a flexible one significantly improves efficiency.

Another way to improve the efficiency is the electret-based triboelectric generator (E-TriG) [160,162,163]. These devices combine electrostatic and triboelectric effects for enhanced performance compared to traditional triboelectric generators. Wu et al., 2018 [160] use an aluminum film as a flexible flagpole to test several types of electret materials like PTFE, CYTOP, TOPAS, and COC, proving that in all cases, negative charging can improve performance. A single-layered silicon structure is presented by Lu et al., 2016 [133] where a mobile silicon element is attached to a fixed frame for four linear serpentine springs. The device features gap-closing interdigitated combs forming variable capacitance, with a thin electret layer covering its surface. On the other hand, Zhang et al., 2018 present two variants of the same device [162,163], with antecedent in Wang and Hansen, 2014 [256], which uses a mobile plate suspended by four flexible beans and a fixed plate covered by an electret material. The main difference is, that while in Ref. [163] the device has only one fixed surface, in Ref. [162] a sandwich structure is presented with dual electrets fixed surfaces.

Regarding the wind as an energy source, piezoelectric transducers share a similar design with triboelectric transducers for harnessing air currents. In these cases, the transducer is embedded in the “flag”, which must be deformed to generate energy. Therefore, piezoelectric transducers are typically more rigid, necessitating the addition of elements with shapes that interact effectively with the wind to enhance energy collection. Kan et al., 2021 [211] present a similar idea in Fig. 7 b), but a magnet is replaced by a cylinder shell suspended by four springs containing a piezoelectric element. A proof mass will be compelled to oscillate vertically. The introduction of a diamond-shaped baffle transforms the cylindrical shell from experiencing traditional single vortex-induced vibrations to engaging in complex coupling vibrations. A similar idea is presented by Usman et al., 2018 [214], where the wind flow moves alongside the aligned cylinders, where the upstream cylinder is fixed at one end and the downstream cylinder is positioned on top of an unimorph cantilever beam with an attached piezoelectric film. In Liu et al., 2019 [212] a fork-shaped bluff body improves the harvesting efficiency at low wind speeds by enhancing vorticity to achieve a higher airlift force. A bluff body and a galloping enhancement mechanism based on magnetic repelling force is developed by Tang et al., 2023 [213].

In the case of water flows, the vibrations resulting from pressure changes in pipelines are addressed by Khan and Ahmad, 2019 [235] and Cao et al., 2020 [202]. In both cases, an inserted plunger in the pipe collects the pressure changes as vertical vibrations. In the first case, the plunger transmits the movement to a force amplifier that activates a piezoelectric element. In the second case, the plunger strikes a spherical permanent magnet. Note that in neither case is the transducer submerged in water, unlike Sui et al., 2023 [203], which describes a hybrid system that will be described later.

Hu et al. present two interesting prototypes in 2022 [154] and 2023 [155]. Both devices take advantage of the periodic emptying of the rainwater tank of a rain gauge. This intermittent flow of water sets in motion two hybrid mechanisms described in the corresponding section to obtain power from a triboelectric element.

Waves generate low-frequency movement in all directions in a highly random manner. Starting from this point, a conductive floating case with a free triboelectric element inside can be shaken by the waves creating contact and separating both elements. This is the case of Wang et al., 2022 [152], Xia et al., 2023 [153], Zhao et al., 2020 [151] and Zheng et al., 2021 [237]. The last two papers describe hybrid solutions and will be further explored in the corresponding section.

Shi et al., 2017 [148] and Xia et al., 2023 [153] utilized spherical shapes. In the case of Shi et al., 2017 [148], a spherical frame coated in aluminum on both sides, it is located between two spheres covered with triboelectric material. Polydimethylsiloxane (PDMS), Kapton, and PTFE were tested as dielectrics, with PTFE demonstrating the best performance against water. Xia et al., 2023 [153] use wood balls as triboelectric materials into a single sphere.

On the other hand, Wang et al., 2022 [152] present a device with an internal regular tetrahedron covered by a PTFE surface and the inner surface consists of the aluminum electrode in a large regular tetrahedral. This configuration significantly increases the contact area due to the four flat surfaces of the tetrahedral shape.

Li et al., 2022 [236] incorporates three pairs of permanent magnets in the outer ring of a pendulum, forming the structure of the rotor. The stator comprises fixed coil structures on both sides, embedded in the frame for enhanced integration and integrated onto a printed circuit board (PCB) with optimized winding directions. In contrast Chen et al., 2020 [150] the generator is designed as a chaotic pendulum that combines electromagnetic and triboelectric transducers in a hybrid system, which will be further analyzed in the subsequent section.

A different idea is proposed by Xi et al., 2019 [149]. The presented device comprises a series of discs stacked in layers, alternating between copper electrodes and Fluorinated Ethylene Propylene (FEP) as the triboelectric element. The FEP layers enclose a mass that responds inertially to wave motion, compressing a spring that separates the top and bottom copper layers and alternately contacts them in cycles.

An interesting device is presented by Shi et al., 2021 [204], which is made up of two zigzag piezoelectric springs. Each *piezo-spring* is fixed at one end to an exterior frame and at the other end to an interior metal movable frame, which has an axis around which a metal sphere rotates. The inner frame is located between the two *piezo-spring*, resulting in the stretching of one spring and the compression of the other when the sphere moves.

5.2.3.3. *Human body.*

To capture the residual mechanical energy of the human body, it is assumed that only natural movements are used, such as locomotion or the use of a device or tool, but not an action directly focused on generating energy, such as turning a dynamo crank. Two pseudo-categories can be identified, *wearables* and *contextual* devices. Movements associated with walking and running activities concentrate most of the studies reviews in both categories [130–132,171,173].

Huang et al., 2023 [129] and Maharjan et al., 2018 [131] combine electromagnetic and triboelectric harvesting to exploit the same mechanical movement from the human body, squeezing and releasing in the first case and the movement of the computer's mouse on a pad in the second research. Since they are hybrid systems, they will be analyzed in the corresponding section.

The *wearables* are devices attached to clothing or directly on the body that continuously capture movement [257]. These devices take advantage the human motion [20], like flexions in the joints [173], as well as the swings when walking or running [131,171] and the pressure exerted by the footsteps [130,132].

Chamanian et al., 2019 [171] demonstrate the energy-neutral operation of a MicaZ mote uses two vibration-based harvesters, piezoelectric and electromagnetic attached to a runner's wrist showing, with the piezoelectric harvester achieving a 0.17 % duty-cycle through self-adjustment, and the electromagnetic harvester a 64 % increase in lifetime before sleep mode when no energy is available. A detailed description of the electromagnetic transducer is provided in previous work, by Chamanian et al., 2016 [258], following the model depicted in Fig. 7 a).

Liu et al., 2022 [130] developed a flexible textile-based triboelectric nanogenerator integrated into shoes, capable of harvesting mechanical energy from human walking. This device also generates an oscillating signal that accurately senses ambient relative humidity and temperature, achieving accuracy rates of over 94 % and 96 %, respectively, in addition to human walking frequency. It is possible to use these types of devices in various scenarios where human activity causes continuous deformation of the harvester. This is the aim of Sahu et al., 2022 [132], who developed a triboelectric harvester specifically focused on sports activities using waste textile materials. The research covers various cases of the studio, which include wearables and contextual devices that obtain energy from the punch on the boxing kit, the dibbling ball on the tennis table, or an athlete running.

A promising path towards WSN devices self-powered by human body movement is textile-based piezoelectric nanogenerators (T-PENG) [259], so it is recommended to follow their evolution.

The contextual devices are integrated into their environment, external to the human body's immediate vicinity like wearables, but positioned to interact with it. These devices can be installed in specific locations, such as floors, walls, or furniture, or can be part of tools or accessories, capturing the mechanical energy generated by human interaction. It is not only possible to extract energy from human interaction with these objects; such interaction can also be the event itself, and the presence, movement and direction can be determined [260]. This is demonstrated by the examples observed at the train tracks.

A wireless and battery-less switch represents a prime example of a contextual device, requiring the capability to harvest sufficient energy from the force of a human finger press to wirelessly transmit a command to an actuator. Cho et al., 2018 [181], address this challenge by experimenting with various shapes to optimize cantilevers for this specific application.

Research in this area is mostly focused on footfalls collected by floor tile energy harvesters, as they have the potential to generate energy for small devices beyond just WSN motes [261,262]. This is the case of Kim et al., 2018 [198], Luo et al., 2023 [199] and Song et al., 2019 [200]. All these works have in common the use of piezoelectric beans as harvester elements. In the case of Kim et al., 2018 [198] and Song et al., 2019 [200] the footfall force is transmitted directly to the flexible bean to deform it. Luo et al., 2023 [199] present an elaborate mechanism with double frequency-up conversion detailed in the *Hybrid system* section.

Other human activities, such as writing, can also generate movement. Kim et al., 2021 [172] place two piezoelectric elements into a pen: one cantilever to collect the swing motion during the writing and another to receive impacts when the pen's tip pushes against the paper. With this device, the authors successfully powered a ZigBee mote, concluding that it is possible to create a battery-less smart pen.

5.2.3.4. Laboratory conditions. As in other sections, many of the studies presented have only been validated in simulation or laboratory conditions, as categorized in Table 3. Unlike previous instances, this section specifically focuses on experiments conducted solely in simulations or laboratories without discussing their potential real-world application. Hybrid solutions as Shen et al., 2023 [143], Xing et al., 2022. [193], Lo and Shu, 2022 [191], Raja et al., 2023 [195], Xing et al., 2022 [193], Zhou et al., 2022 [192], Zou et al., 2021 [189] and Yu et al., 2015 [178] will be treated in the proper section.

The origami assembly presented by Hu et al., 2022 [139] allow overlaying layers subsequently in a structure flexible that guarantees the separation of the layers without external pressure.

Some research focuses on the search for new materials with triboelectric [137,138,140,141,144] or piezoelectric [186,188,194] properties that increase the efficiency of the transducers. In triboelectric material, these are the cases of Li et al., 2022 [138] who describe a transparent, stretchable and free-from-dehydration PVA-H3PO4 solid polymer electrolyte; Singh et al., 2023 [144] use a fish scale of Rohu fish; Tanguy et al., 2022 [141] develop natural lignocellulosic nanofibrils; Xia and Xu, 2021 [137] explore the triboelectric properties of a facial mask; and Nawaz et al., 2022 [140] extract Polystyrene (PS) from a wasted package to manufacture a TENG by adding copper and aluminum electrodes. For the piezoelectric part, Rana et al., 2022 [194] present a lead-free halide perovskite nanocomposite; similar to Yan et al., 2020 [188] who developed lead-free piezoelectric ceramic possesses both high piezoelectric charge constant and low impedance; and Zhang et al., 2020 [186] present manganese-doped sodium bismuth titanate-based lead-free ternary piezoelectric system.

In the case of piezoelectric elements, a common method to capture the vibrations that deform them involves using a flexible cantilever with an inertial element at the free end. Botteron et al., 2016 [91], Chen et al., 2014 [177], Gibus et al., 2020 [185] and Kim et al., 2020 [187] and Han et al., 2017 [179] reports methods to design cantilevers. On other hand Lampani, Gaudenzi, 2018 [180] successfully integrated the mote, transducer, and power management system (PMS) within a beam constructed from glass fiber fabric and epoxy resin. This innovative approach resulted in a structurally robust and fully energy-autonomous node. In the cantilever proposed by Li et al., 2019 [183], multiple branches, each ending with tip masses, are fixed to a tip mass of a main beam, all tuned to different frequencies to increase bandwidth.

The TENG device presented by Naval et al., 2023 [142] features a design with two pairs of mechanical contacts and two pairs of triboelectric electrodes, resulting in a dual AC/DC output. It is specifically engineered to harness vertical translational motion, addressing the limitations of traditional mechanical switching designs that rely on lateral sliding.

Besides the cantilever approach, buckling beam structures are presented. This is the case of Cao et al., 2022 [190] who proposed a method to create a mechanically-guided three-dimensional assembly structure to create a soft, piezoelectric energy harvester encapsulated in a buckling cross shape with a tip mass placed in the center. This feature avoids the collapse of the structure, enhances dynamical performance, and reacts to low-frequency and multi-directional vibrations. The device presented by Liu et al., 2019 [184] consists of two bi-stable buckled beams on common elastic supports, and with inertial masses incorporated at the center positions of each beam.

As seen above, a beam with an inertial mass that responds to vibrations has been widely used to embed a piezoelectric element in the deforming beam. However, the same principle can be applied to electromagnetic harvesters, where the mass tip is replaced by a permanent magnet that oscillates in the vicinity of a fixed coil as is the case of Rubes et al., 2021 [222] and Zhang et al., 2018 [224]. More complex structures to increase the nonlinearities are presented by Huang and Yang, 2021 [221], composed of four clamped-tunable flexible beams that deform because of vibrations and move a permanent magnet inside a coil. Paul et al., 2021 [219] tapered spring structure to increase nonlinearity. The two prototypes that it presents use an electromagnetic transducer element. The devices are composed of a trapezoidal structure fixed at the outer frame. In the center, two permanent magnets are attached to the structure and vibrate freely. Between the magnets a coil harvests electric energy from the fluctuating magnetic field.

Gao et al., 2020 [220] present a system very similar to Liu et al., 2023 [230], which features a suspended permanent magnet that acts as an inertial element enclosed in two aluminum caps filled with copper beads, facilitating smooth axial movement. Another similar idea is presented by Wu et al., 2023 [223]. This time the suspension is a metal serpentine hinge, very close to Shi et al., 2021 [204] and the magnet continues to be the inertial element. Another notable difference from Gao et al., 2020 [220], Liu et al., 2023 [230] or Xing et al., 2022. [193], the coils are arranged in layers and placed above and below the magnet's path and the magnets are three in alternate positions with the poles oriented to the coils.

5.2.4. *Chemical and biological*

The option of energy from spontaneous chemical reactions in nature, even of biological origin, to power WSN nodes has not been as explored as other sources. In this research, only four works have been identified in this regard.

Hire et al., 2022 [240] utilized reinforced concrete corrosion as a battery to power WSNs in a real-world immersed tunnel. In this system, the steel acts as the anode, releasing ions to the concrete solution, while titanium serves as the cathode.

A very interesting work is the one presented by Yun et al., 2023 [241] that promises to generate energy from water. Beyond taking advantage of the mechanical energy of water, in recent years is possible to find ways to extract energy from moisture [263], water vapor [264], or in this case, liquid water which are grouped under the umbrella of *hydrovoltaic devices*. Yun et al., 2023 [241] successfully manufactured a hydrovoltaic device in the laboratory using a metal/bacterial cellulose nanofiber bilayer membrane, employing a low-cost and simple manufacturing technique.

For its part, the use of living organisms such as bacteria to generate electricity can also be very revolutionary and complex to put into practice. In this sense Gao et al., 2020 [242] propose a yarn-based biobatteries, composed of an anodic yarn catalyzed with model exoelectrogens, organisms that are capable of generating electricity through the transfer of electrons to an external electrode, in this case, Shewanella oneidensis MR-1. The cathode is a yarn composed of a solid-state electron acceptor silver oxide covered with Nafion® as the proton exchange membrane. Veerubhotla et al., 2019 [243] disposable paper-based microbial fuel cell with which they successfully feed a BLE sensor module.

5.2.5. *Hybrid systems*

While some prior research papers have proposed a classification as "hybrid" for HE-WSN with multiple energy sources and/or transducers [3,32,34], the approach of this paper is to maintain a separate classification due to the specific scope defined in (RQ1). However, it should be noted that the unpredictable nature of power sources and the relatively low energy yield from certain transducers have led to the development of multiple solutions that evaluate various energy inputs and simultaneously employ diverse methods for energy collection [265].

We can find the **hybrid** in at least three categories:

- Multiple transduction methods with a single energy type.
- Multiple energy types with multiple transduction ways.
- Two or more energy transformations.

Multiple transduction methods with a single energy type address systems that capitalize on the same energetic event using more than one transducer to obtain energy. In this case, the source of energy could be more than one. In this review, only systems of this type have been documented using mechanical energy. Fig. 8 summarizes the concept where the transducers are exposed to the same energy type from the same source. On the left, the sources are a flow (water or air), and on the right, the source is vibration.

In Ahmad et al., 2023 [208] employ two different harvesters, piezoelectric and electromagnetic, to generate energy from wind flow, mimicking the behavior of a tree leaf.

On the other hand, Huang et al., 2023 [129] take advantage of the movement of a computer mouse on a pad. In this case, an array of coils embedded on the pad react to two magnets placed in the moving mouse. To capture more energy, the pad surface is covered by an array of interdigitated electrodes and PTFE as a dielectric layer forming a triboelectric nanogenerator. While satisfactory results are obtained in the laboratory, it is likely that in practice, the frequency and amplitude of the movements will not be sufficient to capture enough energy, at least in the applications proposed by the authors. Therefore, further investigation and optimization are needed to bridge the gap between laboratory findings and real-world applications.

In the form of a push button, Askari et al., 2018 [135] combine triboelectric and electromagnetic transducers. A two-end fixed flexible beam, with a permanent magnet on top and polyurethane element on bottom. Below, fixed to the base, a coil on which a Kapton-coated electrode is placed. When the beam is deformed the Kapton and polyurethane are fully in contact acting as a triboelectric element, and the magnet approximates the coil. The device is suggested to harvest in human walking, tie condition, and sensor. In applications related to human motion, the device is designed to capture the deformation of the foot curve during stepping, rather than the pressure against the ground, as is more common.

In Yu et al., 2015 [178] depicted a cantilever array architecture to deform piezoelectric elements. In addition, the tip mass is a permanent magnet that oscillates in the vicinity of a fixed planar square spiral coil printed in PCB.

Maharjan et al., 2018 [131] uses the swinging behavior of a human arm during walking to roll a magnetic ball inside a hollow bracelet recovered internally with PTFE. The outer surface of the bracelet is wrapped with interdigitated aluminum electrodes and copper coils. This structure forms a hybrid electromagnetic and triboelectric harvesting device.

On the other hand, Chen et al., 2020 [150] utilize waves to collect energy in a sea buoy with two transducers, triboelectric and electromagnetic. Similar to the principle described by Wang et al., 2022 [152], and Xia et al., 2023 [153], in Zheng et al., 2021 [237], the free element is a permanent magnet with a polyester fiber (PET) friction layer. Additionally, a coil is embedded between the triboelectric transducer's copper electrode and the acrylic chassis, creating a hybrid system that includes an electromagnetic harvester. Meanwhile, Chen et al., 2020 [150] use a chaotic pendulum mechanism consisting of a major and inner pendulum. The triboelectric transducer is installed in a major pendulum, conformed by a gold electrode as a mobile element and PTFE film as a fixed triboelectric element. The internal pendulum comprises three magnetic spheres equally placed along the rotating axis, and three coils are attached to the inner surface of the acrylic, positioned on the central swing sector, behind the gold electrode, composing the electromagnetic element. The primary pendulum adheres to a basic principle where it swings back and forth, synchronized with the oscillation of the water wave. Concurrently, the inner pendulum initiates its motion as the primary pendulum swings, resulting in a chaotic and unpredictable trajectory.

Hu et al., 2022 [154] present a unique system that utilizes the filling and emptying cycles of a rainwater tank. It consists of a cylindrical tank with copper rings serving as electrodes on the outside. A PTFE frame runs over the electrodes, creating a triboelectric device. The outer frame is connected to a floating element in the tank, so it rises as the tank fills. The tank is supported at the base by a bearing that allows it to swing. At the base, there is a PTFE-coated counterweight resting on a copper electrode, creating a second triboelectric transducer. This setup keeps the device upright but slightly tilted. When the tank is filled, the water inside acts as a counterweight, causing the device to pivot on its supporting axis. This movement separates the counterweight and allows an outer tube to slide. Once the tank is emptied, both the base and the outer frame return to their original position.

The second group is *Multiple energy types with multiple transduction ways*. In this scenario, the energy source could be the same for multiple energy types, as observed in the case of the sun, which serves as the source of both light and heat. Lee et al., 2018 [52] combine a traditional photovoltaic and thermoelectric generator to power the wireless sensor node in a floating device. Other papers are Deng et al., 2019 [49] introducing a platform that integrates a multisource energy harvesting module, encompassing wind, solar radiation, and thermal energy within a single device. Works like Wang et al. [85] and Qian and Jing 2018 [158] even exploit wind energy using two different transducers (which could fall into the previous category) along with a PV system.

Izhar et al., 2023 [207] present a case where wind and sound energy sources are combined in a piezoelectric plate. This plate is attached to a cambered wing on one side and covers a Helmholtz cavity on the other side.

Another device that takes advantage of two energy sources, waves, and wind, in the same transductor is described by Zhao et al., 2020

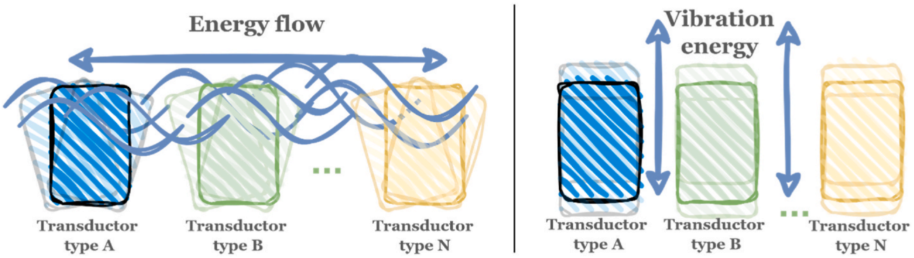


Fig. 8. Multiple transduction methods with a single energy type (mechanical): On the left, flow is used in all transducers, and on the right, a vibration source is utilized.

[151], which presents a shape conformed by a cone attached to a hemisphere referred to as tumbler-shaped by the authors. The electrode is made of copper, while the mobile part comprises a hollow polypropylene (PP) ball coated with polyvinylidene fluoride (PVDF), showcasing superior performance.

Ahmad et al., in 2022 and 2023 [233,234], present two variants of the same electromagnetic harvesting device that capitalize on two sources of energy: sound and vibrations. Both devices consist of a cantilever beam with a magnet as a tip mass and a micro planar and flexible coil, fabricated by lithographic techniques on both sides of a glass-reinforced epoxy laminate material (FR4) flexible sheet. The vibrations collected by the cantilever cause the movement of the magnet, while the acoustic pressure is harnessed by a Helmholtz cavity and collected as motion by the flexible coil, which acts as a diaphragm. The main difference between both papers is the shape of the magnet, where at [233] the magnet is a cube and at [234] it has a spherical shape. The referred papers do not specify the practical source of these vibrations, however, depict an industrial environment, where, effectively, high levels of sound and vibrations are common.

One particularly noteworthy paper is by Kim et al., 2023 [47]. The study is notable not only for its dual transducer system but also for the, in the author's words, "symbiotic relationship" between them. The solution is as simple as it is ingenious: one of the biggest challenges with using a TEG element for harvesting heat is maintaining the temperature gradient by keeping the other side cold. By adding a metal sheet to the cold side, the dissipation area increases. Furthermore, if this sheet vibrates, the dissipation effect is amplified. These vibrations can be captured by a piezoelectric element, which also generates electrical energy. Thus, an internal combustion engine can simultaneously provide both heat and vibration energy.

The final category involves *two or more energy transformations*. In this instance, the energy derived from the primary power source is converted into a different form of energy for amplification before its ultimate transformation into electricity. Fig. 9 summarizes the different approaches described in the reviewed papers.

J. Zhou et al., 2022 [192], Zheng et al., 2021 [215], Zhang et al., 2017 [216], and Jung et al., 2015 [217] use the circular motion obtained from a wind flow, and in Kamenar et al., 2016 [201] utilize river flow to continuously deform a piezoelectric element using a star-shaped piece that behaves like a set of cams as described in Fig. 9 a). In addition, J. Zhou et al., 2022 [192] and Zheng et al., 2021 [215] placed a magnet at the free end of the cantilever takes advantage of deformation to generate a variable magnetic field in a fixed coil. This approach allows the authors to leverage the same motion in two transducers (piezoelectric and electromagnetic) thereby enhancing the overall efficiency.

Rotary motion is converted into linear motion by Xing et al., 2022 [193]. based on the concept represented in Fig. 9 c). The rotating component inverts the position of a bearing moving on an axis every 180° that goes down by gravity, deforming two piezoelectric elements attached to the suspension's springs, as well as moving two magnets away from and toward the coils at the ends of the axis. This describes a broad movement that allows electricity to be generated at low frequencies. The same idea is explored by Raja et al., 2023 [195]. However, in this case, the rotation reverses the position to deform a cantilever that contains a piezoelectric element. In the main cantilever, a diverse set of 6 beams with masses tuned to different frequencies is attached to its tip mass, similar to Li et al., 2019 [183], to achieve greater bandwidth.

The same principle of reversing the rod to allow gravity to act on the bearings is employed by Machado et al., 2022 [164]. In this research, the device is connected to the wind turbine blade. The unique aspect here is that the system's design combines elements from both scenarios shown in Fig. 9 a) and c); the cantilevers are fixed within the chassis, and a set of cams on the bearing induce its deformation as the bearing moves along the axis. Because the bearing has a spring damper on both sides along the axis, the harvester responds to a higher frequency with low amplitude, a behavior expected in Fig. 9 a) representation; the authors test it by attaching the device to an internal combustion engine.

Fan et al., 2020 [156] also converts a wind flow into rotational energy which it uses directly in an electromagnetic transducer and, in a second stage, converts the rotary movement into linear to press a triboelectric transducer as shown Fig. 9 b).

Magnetic plucking technique [266], depicted in in Fig. 9 d), offers several advantages, such as increased energy harvesting efficiency, wideband operation, mechanical simplicity, reduced wear and tear, enhanced durability, low maintenance, scalability, and high reliability. This principle is used by Kuang et al., 2017 [173], Lo & Shu, 2022 [191] Hou et al., 2023 [209], and Kan et al., 2021 [210] where permanent magnets, with one placed in the movement collector element and the other in the piezoelectric cantilever; Qian et al., 2018 [128] and Qian et al., 2017 [134] where the intersecting of the magnets causes full contact between the electrode and the triboelectric element. Except Kan et al., 2021 [210], where the motion collector is a flexible beam with a cylinder that moves with the wind, in the rest of the proposals the magnet is attached to a rotating element [128,134,173,191,209].

The device developed by Kuang et al., 2017 [173] is worn on the leg and harvests energy from knee joint movements during walking. The device is composed of an inner cylinder that contains several beams with piezoelectric components and an outer ring containing equally spaced magnets that rotate during walking. For his part Lo & Shu, 2022 [191] a rotating disk is a laboratory construction and in Hou et al., 2023 [209] the rotary movement is obtained by a windmill.

On the other hand, Qian et al., 2017 [134] present a device with a seesaw shape that pivots at its center and is confined between two stops. Two parallel wheels that rotate together pass alternating two magnets located one in each one. These alternately attract the ends of the seesaw, causing the contact to continuously come into contact and separate the aluminum electrodes placed in the seesaw and the PDMS (Polydimethylsiloxane) that covers the stops. In Qian et al., 2018 [128], to measure the air pressure in a car wheel, the system uses a fixed permanent magnet attached to the brake caliper, while the harvester and

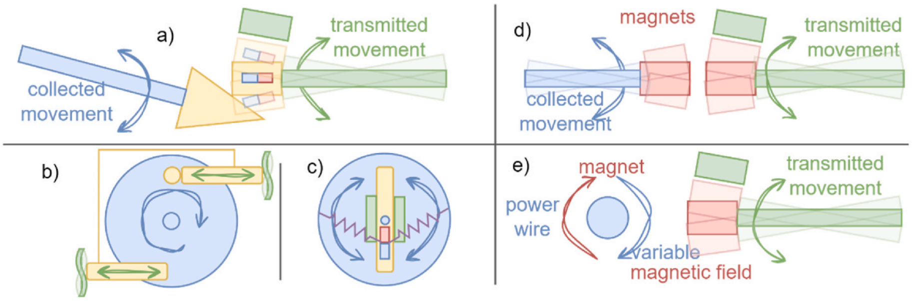


Fig. 9. Types of energy transfers. The blue shape represents the main source, the yellow is the mechanical transfer element, the red is the magnetic transfer, and the green is the transducer element. **a)** A cam hit the cantilever (plucking technique). **b)** and **c)** from rotatory to linear movement; **c)** magnet as inertial mass undergoes linear motion; **d)** magnetic plucking drags a second magnet, deforming the cantilever. **e)** The variable magnetic field from an AC power wire.

the entire mote rotate with the wheel. As the harvester passes by the magnet, an electrode, that also has a magnet attached, is attracted to it, and pressed against the triboelectric polymer, generating energy. Once past the magnet, gravity releases the electrode from the polymer, allowing the system to reset for the next rotation.

Zou et al., 2021 [189] describe a multiple-stable piezoelectric harvester. The device uses a flexible beam supported by one end like a cantilever. However, on the free side, it has a micro-bearing that slides along a curved track, deforming the beam. It is the track that receives the vibrations pushing against the bearing. At this point, it's possible to obtain multiple stable states and set the equilibrium point. This is categorized as a hybrid system according to the classification in this work because, in opposition to de internal systems previously described, there exists an energy transference between the collector of movement and the piezoelectric element to deform it.

In Cho et al., 2019 [166], Kwak et al., 2022 [167], Peddigari et al., 2023 [168], Song et al., 2018 [169] and Yeh et al., 2021 [170] the variable magnetic field induced in an AC power wire is capable of attracting and repelling a magnet located at the tip mass of a cantilever with a piezoelectric element as described in Fig. 9 e). In this setup, the magnetic field is transformed into mechanical movement, which in turn generates electrical energy through the piezoelectric element.

Gao et al., 2020 [228] propose an inertial pendulum to collect the vibration generated in the train suspension system as a rotatory movement transmitted by a gear ring to a classical electric generator.

In Luo et al., 2023 [229], Liu et al., 2022 [229], Zhang et al., 2023 [231], and, Zhuo et al., 2023 [232], the wide and the frequency of mechanical movement is amplified and involves several steps for a frequency-up conversion. In the first step, a twist-rod receives the force of footfall in Ref. [199] and the deformation of the railway due to the passage of a train in Refs. [229,232], and transmits it to a rotating disk, converting a linear movement into rotatory and increasing the frequency. In this first step, Zhuo et al., 2023 [232] add to the rod that collects the vibrations of the railway a structure of flexible hinges that makes the amplitude of the movement transmitted to the twisted bearing greater than that generated in the railway, adding one more amplification stage.

The subsequent stages have marked differences. In Luo et al., 2023 [229] the rotor includes several magnets that drag a piezoelectric cantilever as described in Fig. 9 d), culminating in the final transformation to electricity. In the case of Liu et al., 2022 [229], the force applied is sufficient to use, according to the authors, a *motion rectification module*, which is essentially a gearbox designed to increase the number of revolutions transmitted to a regular power generator. In Zhuo et al., 2023 [232] final step involves two types of transducers. The plucking unit consists of a series of piezoelectric elements (ranging from 2 to 6) that are struck by a series of plectrums positioned on the rotary axis. Additionally, the electromagnetic unit features a series of coils fixed in the frame, which respond to the varying magnetic field generated by permanent mobile magnets placed at the ends of a wheel. This wheel, which receives the rotary motion obtained in the first step, only turns in one direction.

The case of Zhang et al., 2023 [231] this first step is slightly different. Unlike other systems, it uses a double-sided rack instead of a twist-rod to transfer movement to two gears with an only-way bearing, ensuring one-way motion. When the rod moves down, only the left gear transfers rotation to its axis; when it moves up, the right gear does the same. Subsequently, a gearbox received the movement from both only-way axes, amplified, and moved a regular electric generator like in Refs. [228,229].

An interesting two-energy transformation example is presented by Xiao et al., 2023 [88], outlining a system that integrates solar energy harvesting, wireless charging, and wireless temperature sensing. Wireless charging performance is assessed between the transmitter and the sensor node. In this instance, solar energy serves as the energy source, yet the node is powered through wireless energy transfer. Other similar examples are Wen et al., 2020 [136] when the primary transducer is TENG.

Hu et al., 2023 [155] is a second option for harvesting energy from rain gauge emptying presented by Hu et al., 2022 [154]. In this case, the tank emptying mechanism uses the siphon effect, eliminating moving parts and creating a continuous water flow for an extended period. This flow drives an impeller that spins a drum covered with curved PTFE sheets. These moving sheets contact the copper sheets that make up the stator, closing the triboelectric device.

The last category has not been addressed in the review of publications cited above. It is argued that if there are energy transformations, even when the intermediate steps do not directly produce electricity useable by the mote, such solutions should be classified as hybrid systems.

5.2.6. *Partial conclusion*

The mechanisms presented for energy harvesting, mainly mechanical, are highly varied, ranging from simple to ingeniously complex and elaborate designs. This diversity makes the topic particularly challenging to address, due to the variety of approaches and solutions proposed.

Each energy harvesting mechanism is tailored to specific environments based on the availability of energy, both in terms of quantity and persistence over time, and always under the application's needs. Assuming that the solutions presented were chosen with practical criteria in mind for powering WSN sensor nodes, it is worth noting that many of these mechanisms have been tested in laboratory conditions or under controlled field conditions. Therefore, it would be highly beneficial to conduct studies on their behavior in real-world conditions over a significant period of operation.

The rectennas could provide a solution for battery-free systems, restricted to specific scenarios where the power source is nearby, the node has adaptive energy mechanisms, and the transmission period is lengthy.

The photovoltaic market is heavily dominated by silicon-based technologies, but these are not as efficient as one would expect in indoor environments, except for amorphous silicon (a-Si). This is evident in the selection of works exploring GaAs and organic photovoltaics (OPV) cells for such scenarios [267]. Despite certain limitations of these technologies [268], they are considered viable for niche applications where their performance advantages outweigh their specific disadvantages.

In vibration systems, the nonlinear dynamics design of the device is a key consideration for optimizing and maximizing energy conversion efficiency.

In mechanical systems, it is not uncommon to harvest energy from the event being monitored, and many times the system obtains sufficient energy available to collect additional environmental variables. For example, energy can be harvested from the detection of passing trains [145,146,196], cars [197] or pedestrians [198–200], as well as from switches that operate without wires or batteries [181]. The inclusion of an adaptive control mechanism based on Artificial Intelligence (AI) [260,269] can further optimize energy harvesting, allowing the system to dynamically adapt to varying energy availability and environmental conditions, and to extract useful information about the monitored event from the energy harvesting behavior.

Some of these solutions may not be very effective in the environments for which they are proposed. While they are necessary in remote locations without infrastructure or in domestic or industrial environments where adding power to a mote is complex, it can often be simpler, low cost, more effective, safer, and more efficient the using conventional power sources. For instance, in a car, it might be easier to run a cable from the battery to the engine to power a sensor, rather than relying on a more complex energy harvesting mechanism.

Several ways are presented to increase the efficiency of the devices, but it can be said that they all orbit between increasing the number and variety of transducers or amplifying the primary energy source through intermediate energy transformations before obtaining electrical energy. This results in a wide variety of hybrid systems, although structures can also be observed, especially mechanical ones, that combine multiple supports for the same type of transducer with the objective of the largest possible area of the energy spectrum like [142,183,184,190].

Emerging techniques and devices as organic photovoltaic panels [102], thermal resonators [70], hydrovoltaic [241] or the use of live microorganisms [242,243] need to be closely monitored as they advance and potentially enter the market, offering solutions to future challenges. Deployment of battery-free WSNs poses its own set of challenges.

5.3. Power management system (PMS)

In the context of HE-WSN, the power management system (PMS) ensures the capability to harness the limited power obtained from a highly variable energy source. WNS devices are designed to operate in a duty cycle that alternates between active work modes and low-power consumption modes [270]. This alternation is used by the PMS to accumulate and manage the energy harvested. According to Khan et al., 2015 [271] the PMS has to face two scenarios:

- **Energy consumption** represents all the energy needs of the mote and its subsystems. The adaptative power control is implemented, encompassing various aspects, including power network mathematics, voltage regulation strategies, management of energy storage elements through charging and discharging processes, and the utilization of duty cycle algorithms.
- **Energy provision** that encompasses an energy storage subsystem. Regularly this includes a capacitor as a primary energy buffer to face fluctuations both on the generation side and on the consumption side. This first stage will be the only one for energy-neutral elements. The second stage includes an element with a higher energy density such as a supercapacitor or a battery.

Fig. 10 a) represents the PMS position in the system. Unless the transducer can deliver at least the energy needed by the entire system during the active state, a typical cycle involves charging the storage system during the sleeping phase and using this stored energy during the active phase, as is shown in Fig. 10 b).

To achieve the sustainability of the system, the transducer must deliver enough power to keep the node in sleep mode, plus a surplus that will be stored. In these conditions, the node must sleep long enough so that at least the necessary energy for an active cycle is stored where it can do all its operations without interruption and go back to sleep. An adaptive charging circuit for harvesting systems is crucial because the load seen must be continuously adjusted for the PMS to match the Maximum Power Point (MPP) [272].

It is worthy of note that electrical models for circuit simulation, such as those presented by Ávila et al. [273], represent a significant area of interest. However, a non-comprehensive review of the literature in this field reveals a paucity of research output, suggesting that further investigation may be warranted.

A very good example is Porcarelli et al., 2014 [104]. The device harvests energy from the electromagnetic field generated by a power cable, like the method used in Refs. [106,107]. As the cable carries more current, the device collects more energy. It then calculates the interval during which the node must sleep to harvest sufficient energy, based on the current passing through the cable, to achieve self-sustained performance. In its specific application, which involves measuring the current passing through the cable, this irregularity in sampling is perfectly viable.

In this sense, works like Vracar et al., 2016 [92], Porcarelli et al., 2014 [104], Chew et al., 2019 [182], Lampani and Gaudenzi, 2018 [180], Lo and Shu, 2022 [191] and Li et al., 2022 [236] proposed their own PMS designed from discrete elements. In the case of Wu and Lee, 2014 [239] the PMS is as simple as a rectifier bridge that powers a thermostat and an RF oscillator. Toh et al., 2014 [90] designed a complete PMS including an MPPT from the LTC6906 oscillator, LMC7235 comparator, and op-amps. Kuang et al., 2017 [173] use a DC-DC step-down converter, LTC3388-3, controlled by a custom-designed MPPT circuit. A voltage supervisor, the LTC2935 (Linear Technology), was employed to control the capacitor's charge and discharge, ensuring the capacitor maintain sufficient charge for the node's operation.

The most common thing is that works that describe a PMS use a commercial IC. LTC3588-1 (Linear Technology) is the most used Integrated Circuit (IC) [145,177,178,184,194,195,199,206,217,222,225, 226,232]. Other IC used are LTC3105 [228], LTC3106 [79], LTC3108 [54,62,63,68], LTC3330 [73], ADP5090 [98] (Analog Devices), AEM10941 (E-Peas Semiconductors) [103], AEM30940 (E-Peas Semiconductors) [111], BQ25570 [79,95,100,243], LM2575 (Texas Instruments) [75], BQ25504 [69,74,91] (Texas Instruments), BQ25505 [71,84,105] (Texas Instruments) and MB39C811 (Fujitsu) [201]. It is to be noted that while the IC LTC3588 is intended by the manufacturer only for C-SC, the rest of the IC presented can also handle Li-Po and Li-ion batteries. It is necessary to highlight the IC, the P1110 from Power-Cast, specifically designed for RF harvesting in the 902–928 MHz band, used by Tran and Chung, 2014 [125].

An interesting proposal using a simple lithium battery charger IC, the LTC4071, to handle an SC is presented by Yue et al. [96]. The problem is that the IC calibrated for a lithium battery will stop delivering power below a certain threshold to prevent over-discharging the battery, creating dead zones, and wasting a significant portion of the capacitor's charge capacity. The inclusion of a boost circuit would be necessary to exploit this potential. This solution is adopted by Lin et al., 2022 [54] who combines the LTC4071 with the LTC3108.

Loretri et al., 2019 [79] offer a sophisticated solution to address this issue. Their approach involves a series connection of a harvester power management, the BQ25570, and a supercapacitor charger, the LTC3225. The flow of charges between the supercapacitor and the battery is overseen by a software-controlled using a LTC3106 as dual-path DC-DC converter. In this setup, the supercapacitor takes on the role of the primary power source, with the LTC3106 able to charge the backup battery whenever excess energy is available.

PMS is vital for the sustainability and efficiency of the harvesting systems in WSN. By effectively converting, storing, and managing

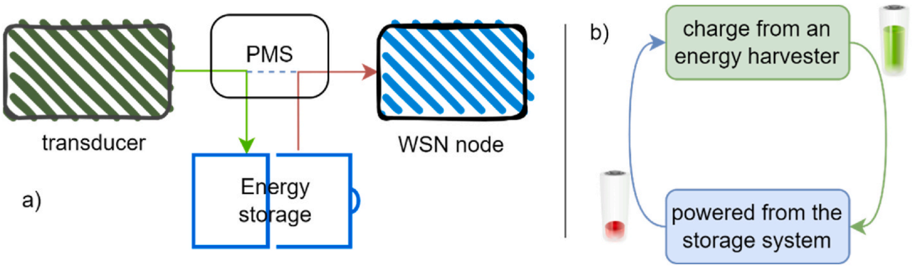


Fig. 10. Energy management for the mote. a) The simplified operation of the power management system (PMS). b) The work cycle of the storage system.

harvested energy, PMS ensures reliable sensor node operation even with fluctuating energy inputs. Key aspects include dynamic adaptation to the maximum power point of energy sources, minimizing energy loss, and energy-aware task scheduling.

5.4. Energy storage

Energy storage in HE-WSN is a critical aspect to ensure uninterrupted operation, especially during periods when the energy harvesting sources are unavailable due to the variable nature of these energy sources and, in many cases, the low levels of energy that can be collected.

The selected documents provide insights into various types of energy storage methods employed in the context of harvesting energy for Wireless Sensor Networks (WSN). These storage solutions aim to ensure uninterrupted operation and address variations in energy availability. The identified energy storage types encompass batteries, supercapacitors, and hybrid systems that integrate multiple storage technologies. Each storage approach comes with its own set of advantages and drawbacks, and their appropriateness depends on factors such as energy density, charging rates, discharging capabilities, and overall lifespan.

Fig. 11 illustrates the distribution of papers based on the energy storage element utilized. Note that not always we were unable to identify a distinct separation between capacitors and supercapacitors in the reviewed documents. As this distinction falls outside the scope of this document and considering the similar purposes and operations of these devices, we have combined them into the same category for analysis and introduced the acronyms C-SC (Capacitor and Supercapacitor) to refer to it.

As evident in Fig. 11, systems incorporating batteries constitute a relatively small portion of the reviewed papers, only 9 %. C-SC, compared to batteries, typically have a lower cost and a longer cycle life and are generally maintenance-free and eco-friendly. These factors could be crucial in explaining the growing interest in battery-free systems in WSN's ambit.

Not all the reviewed documents refer to a specific energy storage method. A significant portion of the documents, 33 %, solely focus on describing a transducer and present results from laboratory tests, particularly about the amount of energy they can deliver. This is more relevant in the paper related to piezoelectric elements, where almost half (23 out of 50 works) do not reference any specific energy storage device or method. Adding to the fact that, as we previously observed, piezoelectric transducers have garnered the most attention in the last 5 years, it suggests that we can anticipate an increase in the number of studies focusing on comprehensive harvesting systems for WSN in the coming years.

5.4.1. Batteries

Batteries can provide a stable and reliable power source for WSN nodes, ensuring continuous operation, especially when the power source is absent for long periods, like at night. Batteries have a high energy density and provide a predictable and consistent power output.

In scenarios where the energy harvested from the environment is inadequate to recharge a non-rechargeable battery, the sensor node maximizes the utilization of available harvested energy. The primary goal is to extract as much energy as possible from the harvesting system to power the node's operations. A non-rechargeable battery [71] supplements the energy needs when the harvested energy falls short of meeting the node's energy demands. The emphasis is on minimizing reliance on the battery and maximizing the use of harvested energy to extend the operational lifespan of the wireless sensor node. In this case, we can only refer to Dziadak et al., 2023 in the literature review [205].

Table 7 summarizes the types of batteries used in the systems presented in the papers selected for this review. There are more references to different kinds of lithium batteries and fewer mentions of NiMH and lead-acid batteries.

The type of battery used is not defined in Avlani et al., 2022 [84] and von der Ahe et al., 2018 [95] but, from the IC used for power management, the BQ25505 and BQ25570 respectively, it is inferred that the battery can be either Li-ion or Li-Po. Although Zheng et al., 2015 [71] uses a BQ25505 and declares the use of lithium rechargeable batteries, it

Table 7
Rechargeable batteries presented in the review papers and organized by technology and type.

Technology	Type	Paper
Lithium	Li-Po	Lin et al., 2022 [54], Kim et al., 2018 [60], Avlani et al., 2022 [84], Sadowski and Spachos, 2020 [81], Politi et al., 2021 [99], von der Ahe et al., 2018 [95] and Zhang et al., 2022 [102]
	Li-ion	Baranov et al., 2016 [72], Avlani et al., 2022 [84], von der Ahe et al., 2018 [95], Verma and Sharma, 2019 [57], Sharma et al., 2018 [75], Kaur and Buttar, 2021 [83], Salazar Cardona and Marulanda Tobon, 2021 [82], Xiao et al., 2023 [88], Olzhabay et al., 2021 [97], and Maharjan et al., 2018 [106]
	Coin 3V	Markiewicz et al., 2020 [66]
	No specified	Lee et al., 2018 [52], Visconti et al., 2016 [73], Gao et al., 2017 [146] and Zhao et al., 2017 [145]
No specified	AAA	Tran and Chung, 2014 [125] and Ahmad et al., 2023 [234],
NiMH		Anzola et al., 2019 [78] Wang et al., 2022 [225], López-Lapeña and Pallas-Areny, 2018 [76] and McCullagh et al., 2014 [227]
lead-acid		Antony et al., 2020 [80] and Khan and Ahmad, 2019 [235]

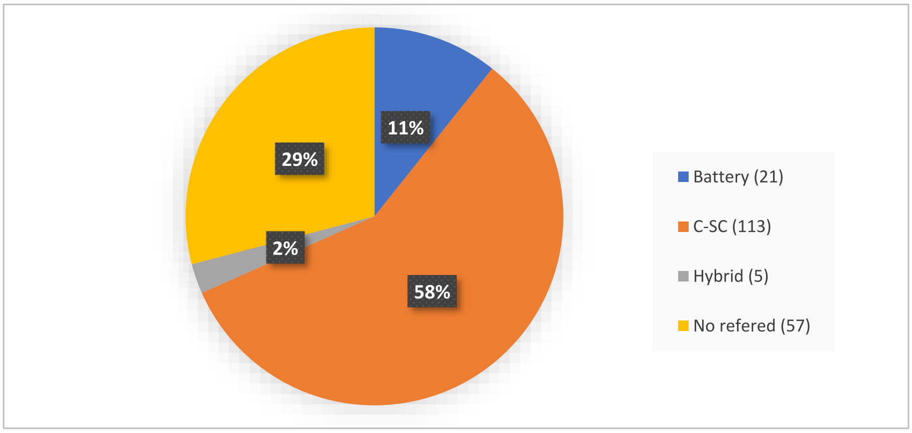


Fig. 11. Distribution of energy storage elements.

places them outside of the charging circuit.

Lee et al., 2018 [52] advocate for the use of lithium batteries as the optimal solution for their specified problem. However, they do not provide sufficient supporting evidence or detailed technical specifications. Instead, they simply mention a 5V battery pack. Given that standalone 5V lithium cells are not conventional, it is presumed that the authors may be referring to a comprehensive storage system, such as a commercial power bank, rather than an individual lithium cell. Visconti et al., 2016 [73], Gao et al., 2017 [146] and Zhao et al., 2017 [145] affirm the use of lithium batteries but do not offer any other specifications.

The systems powered by battery analyzed in the literature for this study predominantly rely on PV power, followed by EM (only 4 papers, [106,225,234,235]); It is notable the absence of other transducers in the systems under consideration. This observation could be attributed to several factors. We can speculate about the following facts:

- Solar cycles make the sun, as a power source, intermittently available, adding periods with low light availability and indoor environment, necessitating the use of high-energy-density storage for continuous system operations.
- Photovoltaic systems, when correctly exposed to light, can efficiently and sustainably harvest a considerable surplus of energy to power WSN nodes and charge connected batteries.
- Batteries maintain a relatively stable and predictable voltage during charging and discharging, which greatly simplifies PMS. Capacitors, on the other hand, exhibit a continuous voltage drop over time, necessitating the use of more complex devices to fully utilize the stored energy when the voltage has fallen below the mote's operating values.

The last notable case is Veerubhotla et al., 2019 [243], which, even though it does not describe any experiment with a battery, includes in the system specification table the possibility of using a Li-Po battery. Indeed, the author mentions the use of the PMC BQ25570, which, as described earlier, allows for the use of a supercapacitor (SC), as well as both Li-ion and Li-Po batteries.

5.4.2. Capacitors and supercapacitors (C-SC)

The distinction between a regular capacitor and a supercapacitor is determined by the design, construction, and intended use of the component [274]. EDLCs (Electric Double-Layer Capacitors) exhibit pseudocapacitance, a voltage-dependent phenomenon resulting in variable capacitance, which requires appropriate modeling. However, the voltage ranges within which supercapacitors operate allow them to be treated similarly to conventional capacitors with high capacitance values and a series of resistors and inductors [275]. Since the document primarily addresses their utilization, purpose, and operation, a combined discussion simplifies the presentation, maintaining focus on broader aspects.

The primary objective of energy storage is to store excess harvested energy when available and release it when needed to power the sensor nodes, but very often, the harvested energy is insufficient for the mote's energy needs. In such cases, the deep sleep part of the cycle is utilized to accumulate enough energy in a capacitor, enabling the mote to operate during the active part of the cycle at a minimum.

In this order of things, the value of C_S, representing the storage capacity can be selected based on the energy needed for the operational period, and it can be calculated by rearranging the capacitor discharging equation, as demonstrated below [182].

$$C_S = \frac{-t}{R_L \ln \frac{V_{CS,L}}{V_{CS,H}}}$$

Where C_S is the capacitance in the storage capacitor, R_L the load resistor, t the time V_{CS} the voltage in C_S, $V_{CS,L}$, $V_{CS,H}$ is V_{CS} in the low and the high levels.

Instead, the theoretical model of a SC can be treated as a transmission line with voltage-dependent distributed capacitance [276]. Equivalent circuit models utilize parameterized RC networks [277], so, in essence, the charge and discharge equations can differ slightly.

Observing the equation, managing energy from a capacitor can be more complex due to its voltage-dependent discharge characteristics, as mentioned previously.

Some works, like Chamanian et al., 2019 [171], described as an energy-neutral operation system. This refers to a system designed to balance its energy consumption and harvesting over time, when the energy harvested equals or barely exceeds the energy consumed. In this context, the classification boundaries become blurred, as the need to ensure the energy required for the normal operation of a mote and, relying on a capacitor, the storage capacity may be limited and not suitable for very long-term use; then, capacitor-only systems would tend to be energy-neutral operation systems.

This observation aligns with the widespread reliance on batteries in light-harvesting systems. Given that the sun serves as the primary and most efficient light source, the prolonged periods without sunlight render the continuous monitoring of the mote unfeasible. In addressing this challenge, Haroun et al. (2022) [100], Yue et al., 2020 [96] and Sultania et al. [103] suggest employing an SC coupled with a PV cell in indoor environments. While conventional PV cells may not be efficient enough in such conditions to recharge a battery, artificial light could potentially be available even at night, and the harvested energy can ensure the continuous operation of the system.

In these terms, the reviewed papers delineate a broad spectrum of capacitance values utilized in alignment with their respective objectives, contingent upon factors such as load, mote behavior, harvested energy, and source availability. The reported values vary significantly, ranging from as low as 0.47 μF to as high as 350F.

A notable example is provided by Lampani and Gaudenzi [180], which delves into the power aspect concerning the duration required to charge the capacitor and the time necessary for the device to execute a cycle operation. Specifically, a 12 mF supercapacitor takes 450 s to reach the threshold for enabling power to the microcontroller. In comparison, a 2200 μF capacitor requires 46 s, a 440 μF capacitor takes 10 s, and a 47 μF capacitor needs 1 s. Capacities of 47, 100, 220, and 440 μF allow for 1, 2, 4, and 7 transmissions, respectively, with the maximum voltage from the piezo being ±64V.

5.4.3. Storage hybrid systems

Hybrid systems usually refer to the simultaneous use of capacitors/SC and batteries. This combination aims to exploit the benefits of both technologies, providing a balanced and flexible solution to the variable nature of the energy harvested.

SC excels in delivering rapid bursts of energy and contributes to rapid charging and discharging cycles, ensuring quick response to changing energy needs, making them suitable for handling sudden spikes in power demand. Batteries, on the other hand, offer higher energy density for sustained, ensuring continuous operation during phases of low or no energy harvest.

Qi et al., 2021 [98] provide a theoretical foundation for battery-supercapacitor (SC) hybrid energy storage systems, followed by the presentation of their proposed solution for the performance of PV-based WSN mote. The authors divided it into two types of topologies, passive, which is the simplest combination of batteries and SCs, which essentially operates as a low-pass filter, and active where a PMS actively manages the charging of storage elements and the load demand.

Other paper, Loreti et al., 2019 [79] proposed a hybrid system when the battery is optional for economic and environmental reasons.

If is considered that every energy harvesting system utilizes a capacitor as an energy buffer to manage variations in source capacity and load demands, we can assert that a system employing a battery could be considered a hybrid system. In this sense, the difference between a hybrid system and a battery system, whether rechargeable or not, is apparently in the capacitor capacity. It is not within the scope of this paper to formulate or support such an approach, but we invite the reader to evaluate this idea so that it may be the subject of future classifications or taxonomies.

Another aspect to consider is the utilization of PMC, as demonstrated in Refs. [79,84,95,96,98,100,103,228,243]. This approach facilitates the interchangeability of storage elements, enabling the seamless replacement of Li-ion and Li-Po batteries, capacitors, and supercapacitors within PMS circuits without necessitating additional modifications.

6. Implications, trends, and outlooks

This section looks at the wider implications of our findings, highlighting the challenges and prospects that arise from the current state of research. It also explores the theoretical contributions of this work and outlines potential applications in both managerial and academic contexts. By addressing these aspects, we aim to provide a comprehensive understanding of the impact and future directions of energy harvesting in wireless sensor networks.

6.1. Challenges and perspectives

According to the reviewed literature, the main challenges include four fundamental aspects, the variability and intermittency of energy sources and the low amount of energy usually collected. In this regard, at least three major fields of action can be identified: optimizing energy conversion efficiency, enhancing energy storage capabilities, and developing robust and reliable energy management systems.

The aim of this type of research typically lies in its application for engineering purposes. Like any engineering effort, this involves tailoring the solution to specific application environments and ensuring the correct sizing for deployment. In this regard, to face the variable nature of energy sources, each deployment scenario and operating regime of the WSN must be evaluated individually. This consideration guides the correct sizing of energy collection and storage components, ensuring uninterrupted network operation even during periods of energy unavailability. Forecast models in combination with energy requirements have been pointed out as a direction for future research, both for the sizing of the systems to be deployed and for their adaptability in full operation.

The optimization of energy conversion efficiency and enhancement of storage capabilities pave the way for the development of new materials and manufacturing techniques. It is noteworthy to add the path opened in the research and development of techniques that include multiple energy transformations to increase the total efficiency of the system.

At this point, it should be noted that energy storage does not only refer to electricity but also encompasses other forms such as phase change materials (PCMs), where the latent heat absorbed or released during a phase transition is utilized for energy storage. This is a topic that, according to Scopus statistics, has gained increasing attention in recent years, so it should always be considered in future work.

Regarding energy management, at least two lines of research can be identified: from the point of view of the power management system (PMS), addressed in this work, and from the management of the mote's energy consumption. In an environment where the amount of energy collected can be very low, the main challenges in the PMC are its efficiency, its ability to react to the lowest possible levels of electricity generated by the transducers, and its ability to effectively manage energy storage.

On the other hand, the highest energy consumption in motes is mainly associated with radio interface activities. In these terms, the management of the mote's energy needs is relative to the radio duty cycle implemented by the mote itself. Then, power consumption ultimately is associated with the frequency of updating the data that the mote must send and the conditions and protocols of the network. This is visible in bibliometric analysis, where the *yellow cluster* is referred to as "routing protocols", "prediction", "network lifetime", etc. This is a line that has already had a longer journey with WSNs since it is an issue that has accompanied the topic since its beginning and has generated a multiplicity of network protocols and access to the medium. However, it is still possible to identify open issues, although these considerations are outside the topic of this research.

Fig. 12 attempts to graphically summarize challenges faced by EH-WSNs. In summary, this is a very complex subject that includes compatibility and interoperability among different components in sensor nodes, as well as addressing the scalability and sustainability of energy harvesting solutions. Looking ahead, advancements in materials science, nanotechnology, and electronic technologies offer promising opportunities to overcome these challenges and drive innovation in the development of more efficient and reliable energy harvesting systems. Furthermore, interdisciplinary collaboration and research efforts are crucial for exploring new approaches and applications, ultimately enabling the widespread deployment of energy harvesting technologies in diverse real-world scenarios.

6.2. Theoretical contribution

This systematic literature review (SLR) makes significant theoretical contributions to refine the classification, delineation, and elucidation of key concepts within the field of energy harvesting for wireless sensor networks (EH-WSNs). Firstly, a precise classification system is introduced that distinctly differentiates between various components of EH-WSNs. This system categorizes **transducers**, such as piezoelectric, triboelectric, and electromagnetic, alongside **energy types**, including mechanical, light, thermal, chemistry, and biological, and **sources of energy**, encompassing sun, wind, water flows, human motion, industrial machines, and a long etc. This novel approach addresses the shortcomings of existing reviews by offering a more accurate and detailed classification scheme. This separation of energy sources and harvesting elements, referred to as transducers, represents a significant advancement and is a unique contribution to the field of energy harvesting for

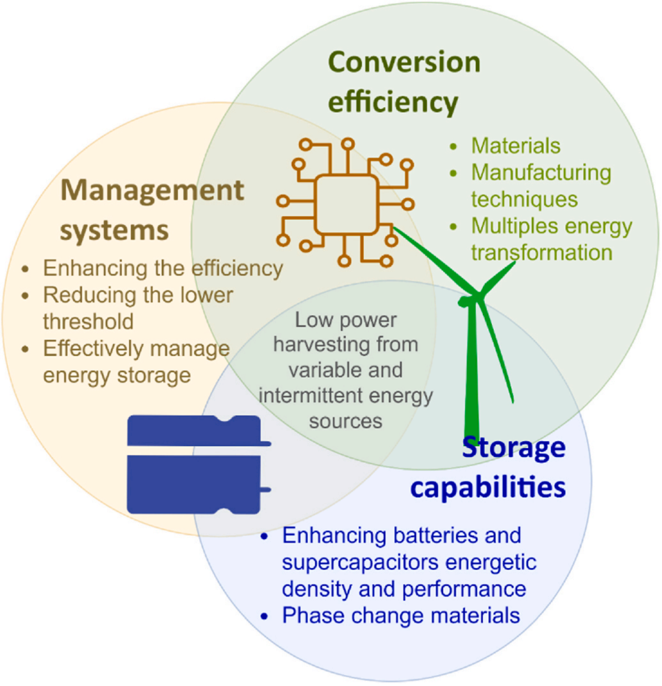


Fig. 12. Challenges faced by EH-WSNs.

wireless sensor networks.

Additionally, the fundamental concepts related to EH-WSNs are systematically delineated to enhance clarity and consistency in the literature. This includes defining the operational mechanisms of different transducers, the characteristics of various energy sources, and the specific types of energy harnessed by these systems. Such delineation helps avoid ambiguity and ensures a common understanding among researchers.

By addressing these innovative points, this SLR not only fills existing gaps in the literature but also advances the understanding and development of energy harvesting technologies for WSNs, ultimately contributing to the creation of more efficient, sustainable, and autonomous sensor networks.

6.3. Managerial and academic applications

The analysis and descriptions performed in this review offer practical guidance on the implementation and optimization of harvesting systems in the WSN field. The clear classification of transducers, sources, and energy types assists in better comprehension of the discourse around this field. By understanding the nuances of various energy harvesting technologies, managers can make informed decisions regarding the deployment of EH-WSNs in diverse environments, such as industrial settings, smart cities, and remote monitoring systems. This knowledge helps in reducing operational costs, improving system reliability, and achieving sustainable energy solutions.

Additionally, the review highlights the importance of adaptive charging circuits and power management strategies, which are crucial for maintaining the performance and longevity of WSNs. Managers can leverage these insights to develop robust energy management plans that ensure the continuous operation of sensor nodes, even in variable and unpredictable environmental conditions. This contributes to better resource allocation, minimized downtime, and enhanced overall system performance.

For the academic community, this review provides a comprehensive overview of the current state of research in EH-WSNs, identifying key trends, challenges, and future research directions. The precise classification and elucidation of concepts such as transducers, sources, and energy types offer a structured framework for further investigation. Researchers can build upon this foundation to explore new methodologies, develop innovative technologies, and address the limitations identified in the existing literature.

6.4. Future research agenda

The transition toward battery-free systems in WSNs signifies a substantial advancement in the creation of sustainable and maintenance-free IoT solutions. To fully realize the potential of these systems, future research must focus on several key areas. Firstly, advanced energy harvesting techniques require further exploration. This includes optimizing hybrid systems that combine solar, kinetic, and thermal energy sources, as well as integrating emerging technologies like bioenergy harvesting. Additionally, the development of adaptive algorithms that dynamically adjust harvesting parameters based on environmental changes and demand will be crucial for ensuring consistent power availability.

In terms of energy storage and management, research should prioritize the optimization of supercapacitors to enhance their energy density and reliability, particularly under long-term cyclic operation. Moreover, developing energy management protocols that can prioritize critical tasks and manage energy consumption more effectively will ensure continuous operation even in low-energy conditions. Communication protocols also need refinement, with a focus on ultra-low-power designs that minimize energy use during data transmission while maintaining network reliability. It is also important to develop protocols capable of handling intermittent operations due to energy fluctuations, which will help maintain data integrity in battery-free WSNs.

Furthermore, integrating battery-free WSNs with emerging technologies such as IoT, edge computing, and artificial intelligence offers exciting opportunities for enhancing real-time data processing and decision-making at the edge while conserving energy. Pilot projects and field trials in diverse environments should be conducted to assess the performance, reliability, and scalability of these systems, alongside comprehensive cost-benefit analyses to evaluate their economic and environmental impacts.

Lastly, addressing security and privacy concerns in battery-free systems is vital. Research should focus on developing energy-efficient security mechanisms that protect data integrity without significantly impacting energy consumption, as well as strategies to mitigate potential threats such as energy depletion attacks.

By addressing these challenges, the future of battery-free systems in WSNs is promising, with the potential to revolutionize sensor networks across various applications. This research agenda provides a pathway for advancing the field and contributing to more sustainable, efficient, and resilient technological ecosystems.

7. Conclusions

The pursuit of advanced energy harvesting methods and technologies for Wireless Sensor Networks (EH-WSN) remains a prominent focus within the scientific community, particularly in the development of battery-free systems leveraging capacitors and supercapacitors. This SLR, based on a meticulously selected collection of 196 studies published between 2014 and 2023, emphasizes the essential need to clearly define and distinguish concepts such as transducers, energy sources, and energy types. This clarity enhances the precision of research classification and analysis. Accordingly, this paper introduces a novel classification system for EH-WSNs, structured around these three distinct concepts.

In recent years, there has been a notable increase in research activity on mechanical energy harvesting systems, particularly piezoelectric systems, which represent the majority of studies on this subject. While the reported harvested energy varies widely—from microwatts to tens of watts—the most common values fall within the milliwatt range, which is often sufficient to power low-consumption motes that utilize energy-saving mechanisms based on duty cycles.

Rectennas offer a potential solution for battery-free systems in specific scenarios, such as when the power source is nearby, nodes have adaptive energy mechanisms and transmission periods are lengthy.

The photovoltaic market is dominated by silicon-based technologies, but these are less efficient in indoor environments, with the exception of amorphous silicon (a-Si). GaAs and organic photovoltaic (OPV) cells are being investigated for such scenarios, despite their limitations.

While some solutions may not be highly effective in their proposed environments, traditional power sources might sometimes be simpler, cheaper, and more efficient. Emerging technologies like organic photovoltaic panels, thermal resonators, and hydrovoltaic systems should be monitored for future applications. The deployment of battery-free WSNs presents unique challenges and opportunities. Many of these systems have been tested under laboratory or controlled conditions, indicating the need for studies on their real-world performance over extended periods.

The choice of an appropriate energy harvesting system largely depends on the energy demands of the sensor nodes and the environment's capacity to provide sufficient energy. Systems that achieve energy-neutral operation—where energy generation aligns perfectly with sensing events—can eliminate the need for long-term storage or gradually accumulate enough energy for data transmission. This highlights the importance of customizing energy harvesting solutions to meet specific application requirements and environmental conditions. For example, mechanical systems often harvest energy from monitored events, such as detecting passing trains, cars, and pedestrians, or electrical switches operating without wires or batteries. Adaptive AI control mechanisms can optimize energy harvesting by dynamically adapting to varying energy availability and extracting useful information about the monitored event.

The viability of battery-free systems is typically constrained by the availability of consistent and relatively high energy levels during events, coupled with the low energy consumption of the motes or the provision of sustainable energy storage for multiple inactive harvesting cycles. Nevertheless, it is reasonable to anticipate notable advancements in this field in the near future. Future progress in this field will depend on improvements in energy transducers, efficient energy consumption and management systems, predictive models, and the development of higher energy density storage devices beyond traditional batteries.

EH-WSN systems exhibit a vast diversity, ranging from simple to highly elaborate designs. This variety makes the topic challenging to address due to the numerous approaches and solutions proposed. Each mechanism is tailored to specific environments, considering the availability and persistence of energy to meet application needs.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT (free version) to improve readability and language. After using this tool/service, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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