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Energy harvesting in wireless sensor networks: A taxonomic survey

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Summary
Wireless sensor networks (WSNs) have aroused the conspectus attention of scholars due to their extensive deployment in the emerging fields of the Internet of Things (IoT's) and self-driven devices. But WSNs technologies having a major bottleneck has been associated with limited energy. Mostly research in WSNs has been focused on minimizing energy usage to extend the survival time of limited power source in a network. Energy harvesting can be addressing its energy-scarcity problem of WSNs, so it is giving popularity to Energy Harvesting in Wireless Sensor Networks (EH-WSNs). The paper presents a comprehensive taxonomic survey on recently energy harvesting techniques and algorithms that proposed by various authors and also examined the work done by the various researchers in the field of EH-WSNs. For the ready reference of the researchers, a concise summary and comparative analysis of various promising techniques for energy harvesting have also been included in the systematic survey. However, many equipment developed using the hybridization method in a singular package to get full advantages of available free energy, are explored in this review. The review on hybrid energy harvesting (HEH) systems can be considered as the originality of this article. However, the outdoor photovoltaics have been provided maximum power density about $\approx$100 mW/cm^3, and the piezoelectric harvesters have been given maximum voltage about 325 V but the current in very minute amount. The thermoelectric, rectenna and hybrid energy harvesters (EHs) have been given high efficiency more than 80%. Additionally, hybrid EHs have location/time-independent characteristics which harnessed power from more than one source that can be became more popular for upcoming leading technologies of self-driven or autonomous devices shifting from battery operated devices. Finally, the survey also identifies often challenges and various significant issues that still essential to be addressed to develop a cost effective, efficient, long-lasting, and almost maintenance-free energy harvesting systems for WSNs along with trail to their possible solutions for future perspectives.

KEYWORDS
energy harvesting systems, green technologies, hybrid energy harvesting, internet of things, systematic review, wireless sensor networks

1 | INTRODUCTION

With the rising of population and development in economy increases the power consumption intensely at worldwide in last few years, which leads to shorten of fossil fuels and rise in environment pollution.[1] These circumstances inspire extensive investigation on renewable energy harvesting and conversion techniques, such as triboelectric and piezoelectric (PZT) harvesters for mechanical energy, thermoelectric generator (TEG) for gradient heat energy, solar panels for sunrays, etc.[2,3] Nowadays, the continuous dependence on non-renewable energy sources and demand for energy has forced us to think about any alternative energy source or to convert the ambient energy available in our surroundings into the usable form. So, the focus of today's energy research is to facilitate neat and clean energy with sustainable development methodology that has led to introducing the concept of Energy Harvesting.[4] Energy harvesting is a process in which energy is obtained effectively and efficiently from external renewable energy sources like solar radiation, wind, geothermal, electromagnetic (EM) waves, hydro, etc. and is stored effectively for driving various application systems which may include wireless sensor networks (WSNs), wearable electronics, etc.[5] The concept of energy harvesting leads to reduce regular cost drastically, because once the infrastructure has been established, it can produce electricity with negligible cost from free available renewable sources in ambient environment.[6] The inherent constraints of renewable energy sources (wind or photovoltaic power systems) such as time or environment dependent characteristics, discontinuity which have been affected their integration into smart home design.[7] Because of increasing the necessity of power, energy harvesting has become common term that harnessed energy from unused waste ambient energy sources, which have to potential generating power of micro watt to milliwatt depending on environment conditions and system characteristics (aperture area, power conversion efficiency (PCE).[6] However among them, solar panels exploit the level of power from milliwatts to kilowatts or megawatts, beyond that, the rapid rise of PCE, which are up to 12.3% in organic solar cells (OSCs), 23.7% in perovskites,[8] 36–45% in inorganic or silicon solar cells. Typically, the limited current outcome of energy harvesting technologies is the major drawback, which further effects the power density and degrades the performance of the system. To resolve the persistent issues of increase in PCEs are going on as highly promising research highlights in the current technologies of various areas, in photovoltaic (perovskites, tandem, hybrid, organic and inorganic solar cells)[9,10] in thermoelectric (nano-TEG, pyroelectric), in piezoelectric (ferromagnetic, triboelectric nanogenerator (TENG), piezoelectric energy generator (PEG)) have been recently developed widely.

From last few years, WSNs with energy harvesting have fascinated prospectus attention of researchers due to their wide deployment and omnipresent nature in the emerging areas of Internet of Things (IoT's), Cyber-Physical System, home automation, and many other emergent areas, that leads to rapid rise in commercial use for near future.[11] The rising number of things (objects) have been linked to Internet as they have become inexpensive, compacted, and more advanced. These objects have been connected with Internet paving the technique toward the development of IoTs. Most IoT peripheral devices and IoT sensors are driven by low power batteries having shorten lifespans, which have been needed to be replaced after few years.[12] However, the operation of WSNs has been affected by lot of key issues and their own characteristics. The energy limitation has a major hurdle in WSNs so it is problematic to preserve its battery before it discharges.[13] Typically, a WSN is a group of static sensor nodes in the large count with low power capabilities which makes unreliable communication. To resolve this foremost issue, the design and deployment of high performance and efficient energy harvesting systems for WSNs topologies have been revealed.[14] This paradigm unlocks a new gateway for researchers that provide reliable and unlimited energy for WSNs.[15] Therefore, energy harvesting in WSNs (EH-WSNs) can be depicted as the best solution that used to produce power from ambient surroundings of a network and to deliver continuous power supply.[11]

The novelty of this work mainly discovers hybrid energy harvesting (HEH) systems in WSNs instead of a particular field, like other authors. The HEH systems have great potential in the foremost technology trends of upcoming era and remarkable future milestones for self-driven or autonomous devices. Harvesting hybrid energy from more than one sources in the neighboring environment is fascinating ever-increasing attention due to its abundant and time/location-independent characteristics. With rising demand of IoT's, it has been becoming more crucial for researchers and scientists to enhance the characteristics of WSNs like self-sustaining, self-configuring, and self adapting.[16] So, the HEH system is the best resolution for this bottleneck of unsaturated emerging technology. Also, the review widely classified energy harvesting techniques and discovers many powerful methods investigated by various researchers and get extensive discussion. The most important objective of this article is to get attention of researchers among the diverse range of energy harvesting systems for uprising field of WSNs.

1.1. | Design methodology

The research methodology has been followed for conducting this review because therefore, a lot of work has been done in EH-WSNs from the beginning of WSNs to till date. Moreover, researchers have published thousands of research paper in the respective area. Initially, the authors begins the collection phase of research papers for review process by searching the identified keywords, appropriate research area, and definitions (like "Power harvesting in WSNs", "Energy harvesting in WSNs", and "Energy efficiency in WSNs") from two databases (Web of Science and Scopus). The basis of research methodology, Web of Science (WoS), and Scopus databases has been taken into consideration to search for articles and shortlist from them with better citation to offer high rigorousness level of research. Therefore, total 326 research papers (excluding redundancy) were found at initial sample stage by searching Further, based on three criteria; (1) peer-reviewed journal, (2) read abstracts and conclusion that found close to the respective research area, and (3) Citations, phase of selections of papers has been made. The sarting sample of 326 research article has been evaluated by two reviewers to read abstract and conclusion parallelly and select only 189 papers that relevant to topic. After that three reviewers have been fully studied and rejected 52 papers and kept only 106 research papers that are appropriate and having virtuous citations. The review article examines the content of 137 research papers (included the reviewers recommendation and introductory part) presented on the topic of energy harvesting from 1998 to 2020 within different journals.

The overview of energy harvesting in WSNs has discussed in Section 1. The rest review paper has been prepared as follows. Section 2 expresses the purpose of energy harvesting in WSNs and importance of this review. Section 3 introduces energy harvesting techniques and sources with their power densities. Section 4 classifies the numerous energy harvesting systems for WSNs with research-oriented characteristics. Comparative study in tabular form among various EHs for WSNs is represented in Sections 5 and 6 signifies the open research challenges in WSNs. The conclusion remarks and future perspectives of the proposed taxonomic survey are discussed in Section 7.

2 | MOTIVATIONS FOR THE RESEARCH IN THE FIELD OF ENERGY HARVESTING FOR WSNs

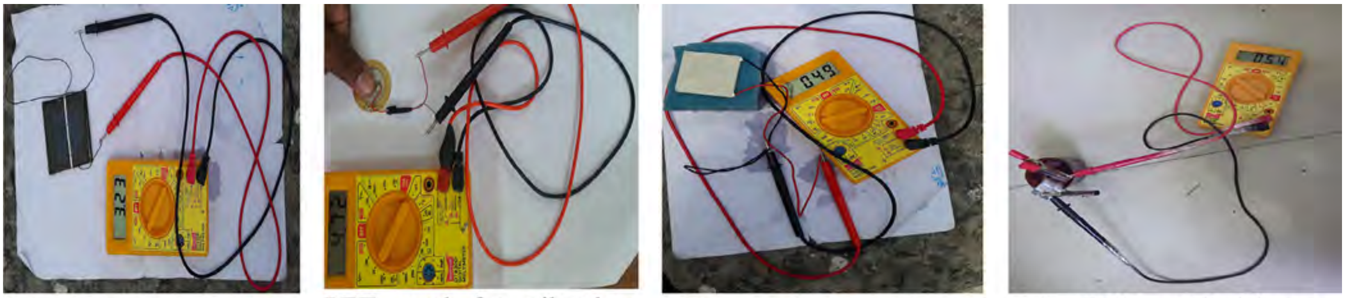
First, the concept of energy is directly collection of ambient energy available in the surroundings then energy conversion between a physical domain into electrical, that has rapidly increased a decade ago and is now become an innovative research and intensive application field and secondly, WSNs are an essential part of Internet of Things (IoTs) and also great importance from the viewpoint of applications.[17] The WSN is a salient technique that has been widely used for information collection including patient health monitoring, surveillance of battlefield, smart buildings, habitat monitoring, object tracking, military rescuing services, emergency circumstances, and monitoring of air quality.[18] Also, WSNs performed an important role for an actuating environment by alerting the accidental events occurs like change in pressure, temperature or humidity, leaks of harmful chemicals or gasses emission, humidity, vibration, fire, and many more other safety clues.[19]

But the major well-known problem in WSN is energy consumption because the major existing source of energy in sensor nodes is battery power. When a sensor node's energy has depleted, it will not fulfill its performance in the network. So, it requires an uninterrupted power supply continuously, whether sensor node in active mode means to communicate and process data or in sleep mode or in an inactive. These entire aspects encourage the usage of energy harvesting in WSNs. Due to emerging and unsaturated field of WSN have great importance, if it can be made long-lasting, autonomous, almost maintenance-free, cost-effective, efficient, and reliable energy harvesting systems.[14,16]

3 | CLASSIFICATION OF ENERGY HARVESTING SYSTEMS

There are many different ways that can be harvested energy comprises solar energy harvesting, thermal energy harvesting, Radio Frequency (RF) energy harvesting etcetera. The classification of the energy harvesting system is done conferring to the source from which power has to be harvested that is shown in Figure 1 and also Table 1 presents the performance of harvestable Ambient Energy Sources with power density. The energy harvesting system can be categorized based on the nature of energy harvested as[13]:

1. Mechanical energy harvesting system (from vibration, car engine compartment, compressors, mechanical stress, and strain).
2. EM energy harvesting system (from wireless communication, microwaves, infrared, cell phones, inductors, transformers, and coils).
3. Wind energy harvesting system (from wind, air).



Solar Cell used for light energy harvesting. PZT used for vibration energy harvesting. TEG used for thermal energy harvesting. Urine Cell used for biomass energy harvesting.

FIGURE 1 Manually testing of different energy harvesters by authors [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Performance of harvestable ambient energy sources with power density

S. No.	Harvested Method	Working Principle	Power Density	Characteristics	References
1.	Solar energy (outdoors)	Photovoltaic	15-100 mW/cm^3 – bright day 0.15-100 μW/cm^3 – cloudy day	Ambient, uncontrollable and predictable	20,21
2.	Solar energy (indoors)	Photovoltaic	6 μW/cm^3	Non-ambient, controllable	22,23
3.	Mechanical Energy/ Vibration/Motion	Microgenerator	800 μW/cm^3 (human activity – Hz) 4 μW/cm^3 (mechanism – kHz)	Non-ambient, controllable, unpredictable	24
		Piezoelectric	200 μW/cm^3 330 μW/cm^3 (Shoe insert)	Non-ambient, controllable, unpredictable	23,20
		EM	1–4 μW/cm^3 (Human motion) 0.21-0.8 mW/cm^3 (Industrial)	Non-ambient, controllable, unpredictable	25,26
		Electrostatic	184 μW/cm^3	Non-ambient, Controllable	23
5.		Seebeck or Peltier effect	40 μW - 10 mW/cm^3 (Industrial 5-20°C gradient) 30 μW/cm^3 (Human)	Ambient, uncontrollable, unpredictable	27,28
6.	Temperature Variations	Pyroelectric	10 μW/cm^3 Temperature rate 8.5°C	Non-ambient, uncontrollable, unpredictable	29
7.	Ambient RF	Rectenna	0.08nW - 0.1 μW/cm^3 (GSM 900/1800 MHz) 0.01 μW/cm^3 (Wi-Fi)	Ambient, uncontrollable, predictable	28
8.	EM Waves	Coils	125 μW/cm^3–2.65 Hz	Ambient, uncontrollable, predictable	30
9.	Hydro energy or Wind or Airflow	Turbine Triboelectric Generator	65.2 μW (5 m/seconds) 400 μW/cm^3 (TEG & TENG)	Ambient, uncontrollable, unpredictable	31
10.	Acoustic Noise	Diaphragms and PZT	0.003 μW/cm^3–75 dB 0.96 μW/cm^3–100 dB	Ambient, uncontrollable, unpredictable	32,33

4. Hydropower energy harvesting system (from flowing water, tides).
5. Geothermal energy harvesting system (from the internal heat of the earth).
6. Light energy harvesting system (captured from room light or sunlight through photosensor, photodiodes or solar panels).
7. Thermal energy harvesting system (from Sun radiations, waste energy from furnaces, heater, vehicle exhausts, and friction sources).
8. Human body energy harvesting system (from body parts movement, body temperature).
9. Biomass energy harvesting system (from biodegradable wastage, human urine, chemical, and biological sources).

4 | ENERGY HARVESTING SYSTEMS FOR WSNS

In wireless technology, WSNs has considered as the third phase of uprising that has been a prodigious effect on the human revolution.[34] The energy limitation has a major constraint in WSNs so it is problematic to preserve its battery before it discharges. Mostly research in WSNs focused on minimizing energy usage to extend the limited power source's survival time in the network. Therefore, EH-WSNs can be depicted as the method used to produce power from ambient surroundings of a network and to deliver continuous power supply for the overall network or a specific sensor node. Typically, sensor nodes to perform various tasks, comprise three basic sub-systems: (1) To acquire data, a sensing subsystem (2) To process local data, a processing subsystem and (3) To communicate data broadly, a wireless communication subsystem have been used. Also, a battery as a limited energy source provides power to each subsystem.

Basically, the classification of energy harvesting systems used in WSNs into two extensive classes based on energy sources; ambient sources and external sources. Ambient sources are present in the surrounding environment at almost free of cost and permanent. However, external sources are not permanently, they are deployed explicitly for the purpose of energy scavenging. These categories are further divided into many categories. Another way, the energy harvesting systems can be classified into two types, basis on the power that fed to the sensor nodes. (1) Energy harvesting without storage, where raw energy is transformed into electrical energy and directly fed to sensor nodes so, no need for battery storage. (2) Energy harvesting with storage that means transformed electrical energy has been first stored in batteries then provided to sensor nodes. Going through the existing literature, it found many authors suggested different energy harvesting techniques that are classified below in the Figure 2.

4.1 | Ambient sources

4.1.1 | Photovoltaic power generation from solar for energy harvesting in WSNs

Solar energy with its abundance in surroundings is a kind of inexhaustible, affordable, non-polluting, and absolutely clean energy source to eradicate the future energy issues in WSNs. The basic principle of photovoltaic generation has followed by solar energy harvesting systems that use photovoltaic materials to collect and absorb a large amount of photons optically. The harvested power is significantly dependent on the intensity of light. The assortment of solar energy as a power source becomes a realistic technical solution for WSNs. The solar energy having the only drawback that it is only obtainable office hours (for the indoor environment) or all through day time (for the outdoor environment). The other major hurdle in solar energy harvesting is weather conditions like cloudy, foggy but a battery needs ensure to operate sensors all around the clock. Generally, solar energy harvesting systems appropriate for outdoor applications. Here, a novel Transparent insulation materials (TIM) product designed using spacer fabric composites to harvest solar energy[35-37] presented efficient plug and play solar harvesting unit to evaluate Heliomote for Crossbow /Berkeley motes. The PV cells formed an array to harvest sunlight power for Wireless HART in,[38] micro-solar

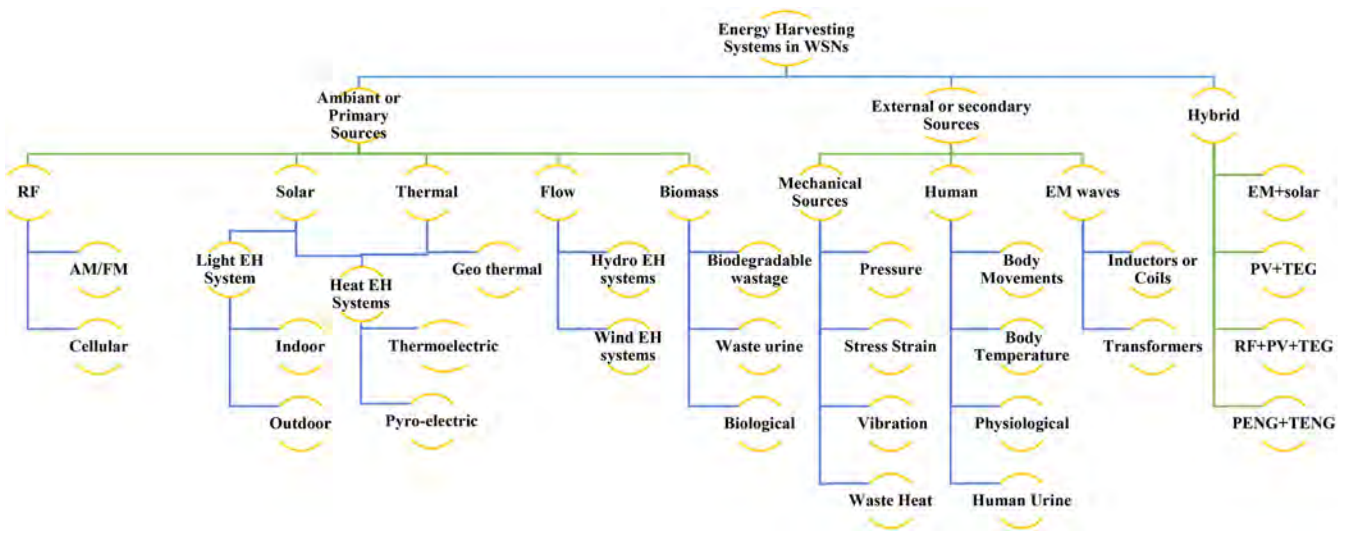


FIGURE 2 Categorization of energy harvesting in WSNs [Colour figure can be viewed at wileyonlinelibrary.com]

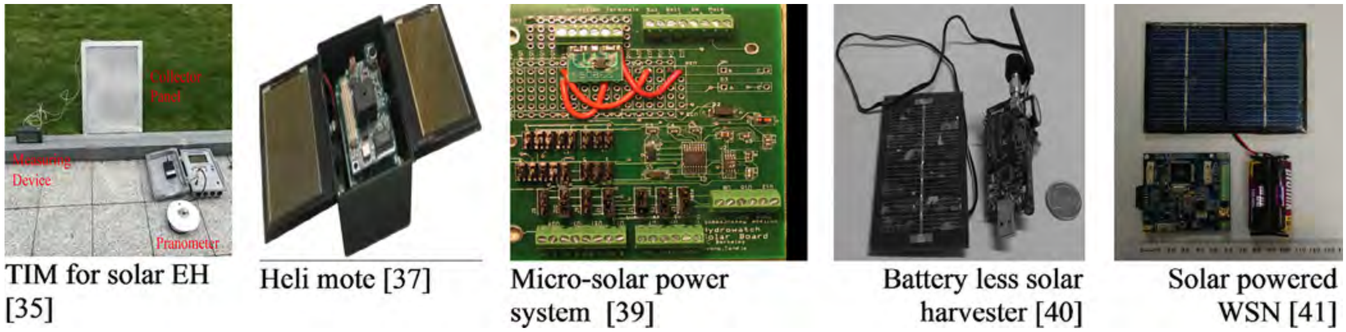


FIGURE 3 Solar EHs for WSNs [Colour figure can be viewed at wileyonlinelibrary.com]

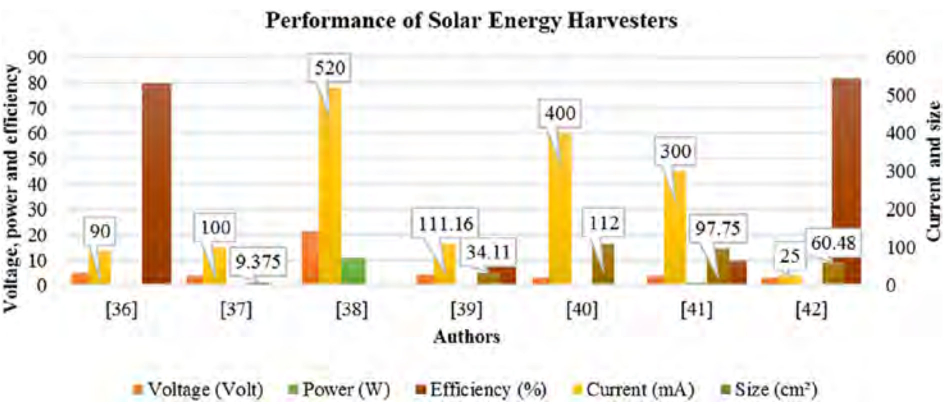


FIGURE 4 Performance of solar EHs [Colour figure can be viewed at wileyonlinelibrary.com]

power system,[39] battery-less solar EH,[40] long term solar-powered WSN,[41] and indoor light energy harvesting[42,43] are given in the following Figure 3. However, the future perspective in current photovoltaic technologies will be investigated as perovskites, organic, tandem, and hybrid solar cells for WSNs. The Figure 4 represents graphical view of performance for solar EH-WSNs.

4.1.2 | RF energy harvesting in WSNs

Basically, RF energy harvesting is a method of transforming ambient RF energy into useful electrical power. The RF energy harvesting unit contains an antenna to collect RF power and appropriate peripheral circuitry for electrical to DC change.[44] In context, the antenna also having too high gain and high radiation efficiency that make the best use of the output power captured from the ambient RF sources.[45] The Teflon substrate with 0.8 mm thickness used for rectenna fabrication and evaluated by various connecting with 50 Ω SMA port using signal generator E8257D and Keysight N5247A network analyzer which produced 3.97 V with peak efficiency of 65.8%.[46] A unique dielectric resonator antenna with slot to make hybrid (DRA + slot) broadband antenna with 120% impedance bandwidth and peak gain 9.9 dB[47,48] from TV broadcast with 6.6 dB gain developed for RF energy harvesting. A WSN powered through AM broadcast energy harvesting system that produced a power of 82 μW with an output voltage up to 14 V.[49] A RF energy powered temperature sensor (RFEH) has been proposed to sense high voltage appliances and a real alternative for passive surface acoustic wave (SAW).[50] While Reference 51 developed a dual-stage energy harvesting system that consists a seven-stage and ten-stage design suitable for low as well as higher power range and Reference 52 utilized the hybrid printed electronics technology to design a novel flexible RF energy harvesting system same as References 44, 53 to collect RF energy. An electrostatic vibration energy harvester (e-VEH) at macro-scale with Cockcroft–Walton rectenna has been experimentally tested to operate at 1 V at 1.53 $\mu W/cm^2$ and 0.5 V at 0.76 $\mu W/cm^2$. Reference 54 designed and implemented an RF energy harvesting prototype developed and implement by Reference 55 that can constantly operate TI eZ430 – RF2500 sensor with multiple modes at multiple city locations. Some commercial RF EH[56,57] are shown in Figure 5 and performance evaluation in Figure 6.

4.1.3 | Energy harvesting from flow in WSNs

Recently, the discovery of changing the flow of energy into electricity has been focused in today's research work.

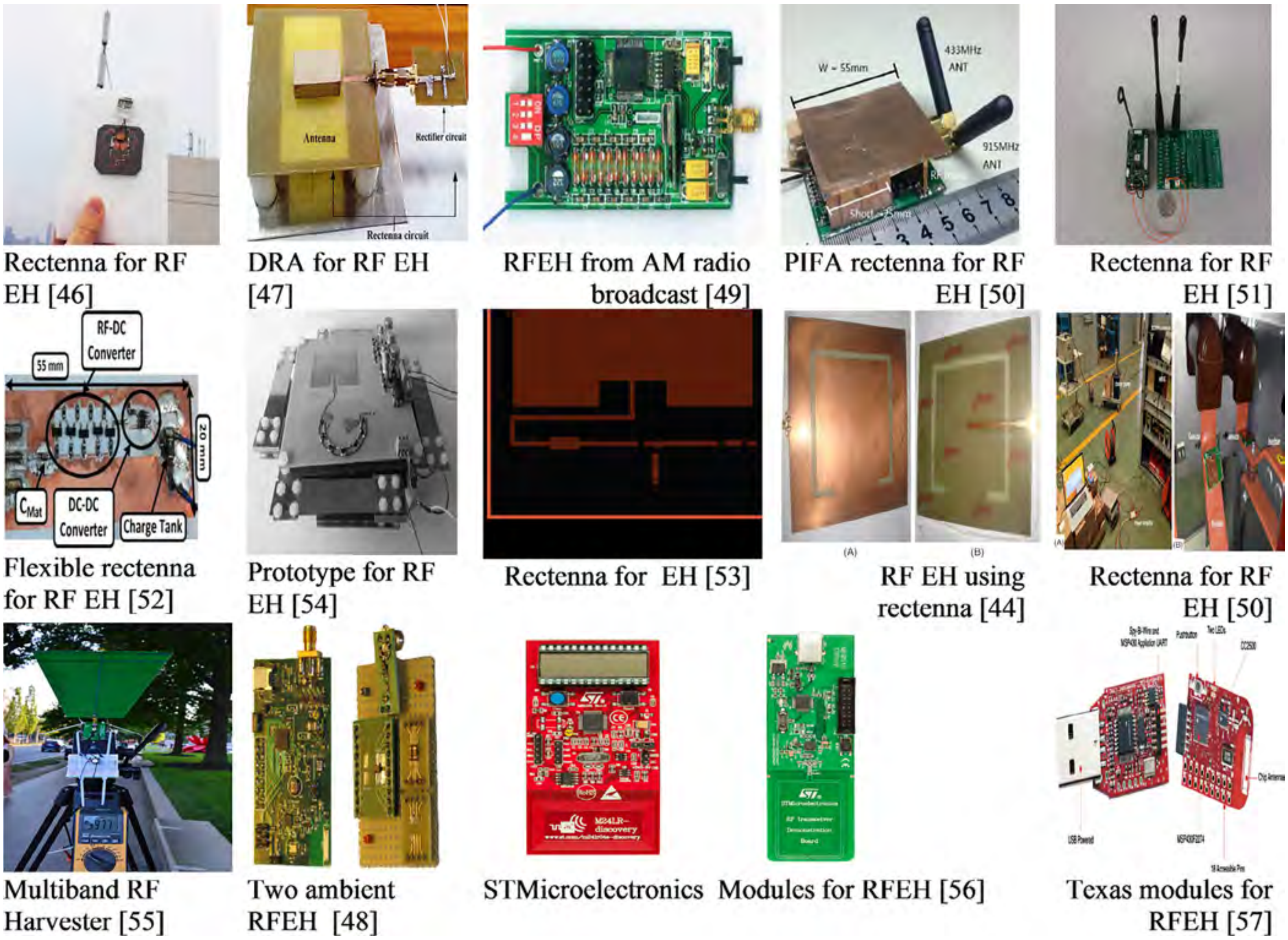
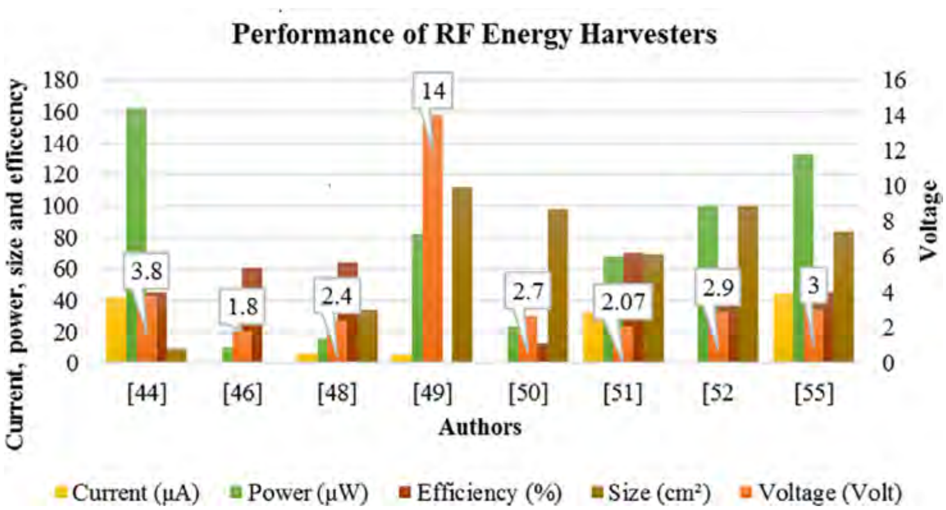


FIGURE 5 RF Energy harvesting systems [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 6 Evaluation of RF EHs [Colour figure can be viewed at wileyonlinelibrary.com]



In particular, flow energy having a good foundation of electricity supply having its exclusive physical appearance, such as environmentally preferable, clean, inexhaustible, and affordable.[58] The wireless sensor node deployment in the river having suitable power management embedded with miniaturized hydro-generator proposed by Reference 59 that collected the data through GSM transmission. Similarly, a duck-shaped fully enclosed triboelectric nanogenerator (TENG) presented by Reference 60 for effective energy

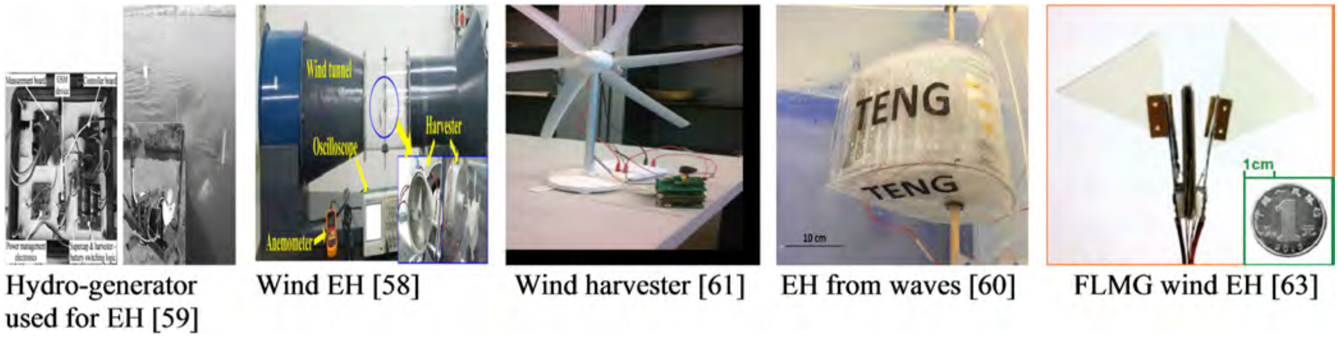


FIGURE 7 Energy harvesting from the flow [Colour figure can be viewed at wileyonlinelibrary.com]

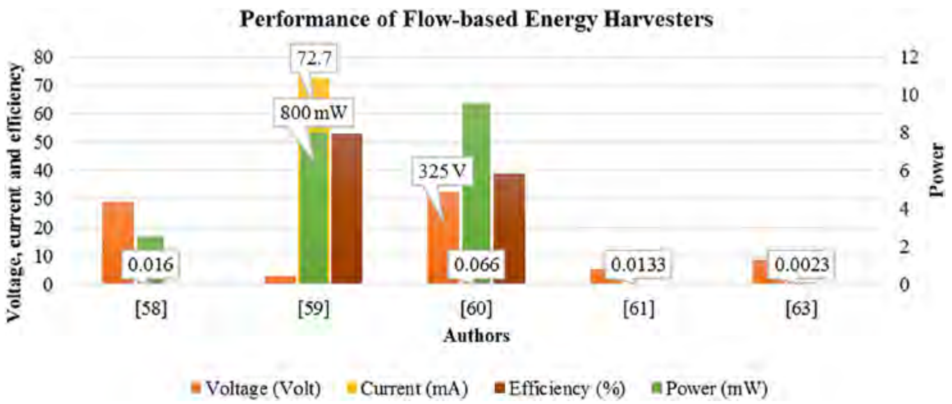


FIGURE 8 Analysis of Flow-based energy harvesting systems [Colour figure can be viewed at wileyonlinelibrary.com]

harvesting from low frequency and random waves of water. The rotational piezo-electric (PVDF) beam produces power using the impact-induced vibration from wind energy.[58] The problematic of wind EH addressed by References 61,62 to improve by predicting wind condition in the near future. Reference 63 demonstrated a novel flapping-leaf microgenerator (FLMG) that harvest wind flow energy and produced electric power from both triboelectric and piezoelectric parts from wind flow. The flow-based EH and their performance has been depicted in the following Figures 7 and 8, respectively.

4.1.4 | Biomass energy harvesting in WSNs

Biomass energy harvesting systems utilize certain categories of biomass that offers a very attractive route to meet partial energy needs.[5] The energy has been directly harvested from the cell membrane budding of Xenopus oocytes that extracted from feminine frogs and transferred through a proper electrical circuit to a capacitor connected to the cell.[64] Here, Reference 65 developed a piezoelectric ultrasonic flexible energy harvester (PUEH) array in an elastomer membrane that generates continuous current and voltage outputs more than 4 μA and 2 Vpp respectively. Similarly, bio-waste inexpensive porous eggshell membrane bio-nanogenerator (ESMBPNG) fabricated by Reference 66 as efficient piezoelectric that gives maximum output power of 238.17 μW. Reference 67 developed an efficient novel bio-waste hybrid EH for abundantly accessible usual self-arranged collagen leathery fish scale with a high power density of 28.5 μW/cm^2. Similarly, Reference 68 presented a biomechanical EH for the human natural motion and Reference 69 developed bioenergy harvester from living tree are shown in Figure 9. The bar graph depicted analysis of various parameters for bioenergy harvesters in Figure 10.

4.1.5 | Thermal energy harvesting in WSNs

Major large-scale production of electricity from heat, but also on a small scale it has been growing interest due to some salient feature having a long life, highly reliable and stationary parts. The major hindrance of low efficiency for its widespread adoption. The heat energy harvesting could be done using pyroelectric generators and TEG. The operation of TEG associates to four basic physical phenomena, namely, Peltier effect, Joule effect, Seebeck effect and the Thomson effect.[70] Here, a novel

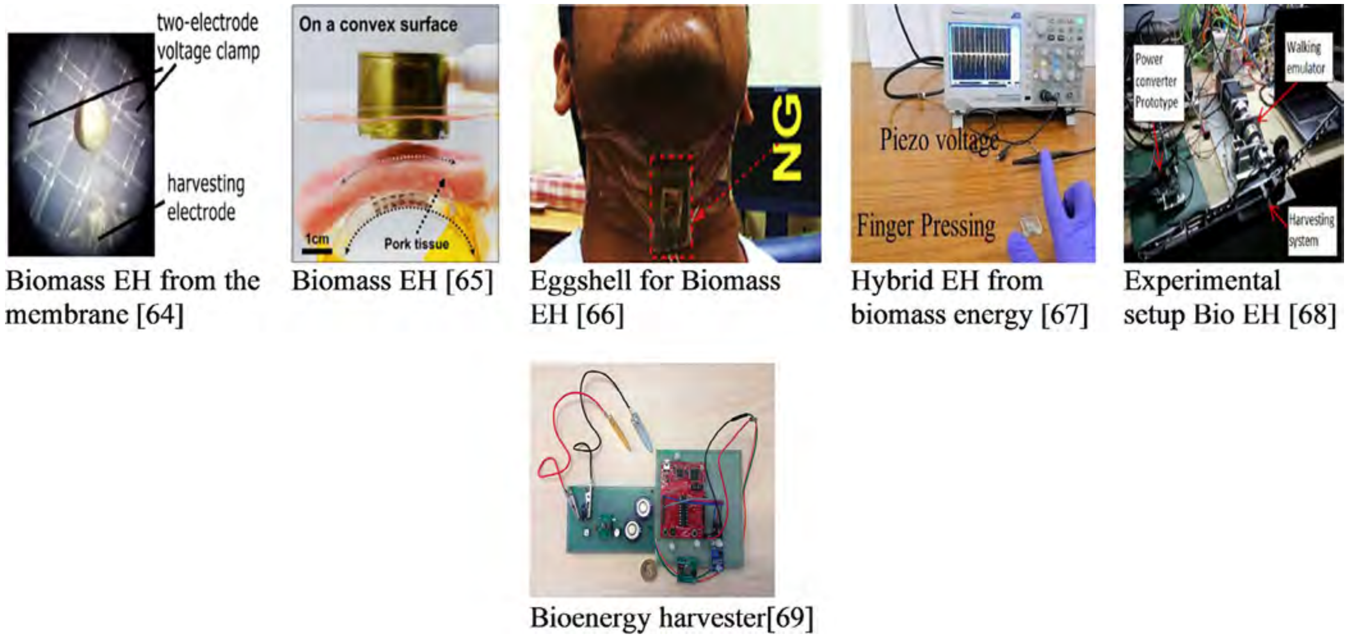


FIGURE 9 Bioenergy harvesters for WSNs [Colour figure can be viewed at wileyonlinelibrary.com]

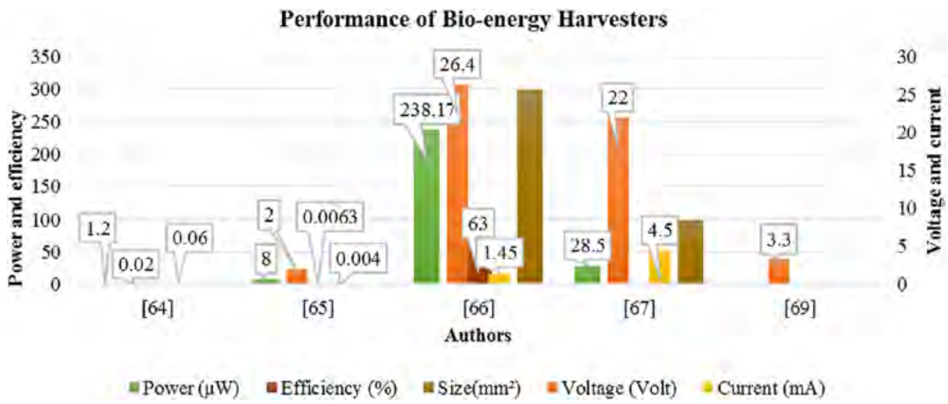


FIGURE 10 Performance analysis of Bioenergy harvesters [Colour figure can be viewed at wileyonlinelibrary.com]

reconfigurable thermoelectric array (RTA) energy harvesting system developed by Reference 71 using the CMOS process. In the same way, two prototypes have been developed for thermal energy harvesting utilizing a heat pipe for heat transfer from a source temperature near 250°C with output power 2.25 W and for higher-temperature primary loops extended the second design that can provide 3.0 W power with a hot-side temperature of 340°C.[72] Reference 73 designed three-slot nano-antennas and analyze at 30THz to collect infrared energy and Reference 74 explored pyroelectric materials to harvest infrared rays for thermal energy harvesting. Similarly, Reference 75 sandwiched CNT/PVDF/CNT to harvest a large amount of random heat from various chemical processes with an output voltage of 9.1 V and short-circuit current of 95 nA and free-standing TE foil developed by Reference 76 for flexible thermoelectric devices that high enough to drive the WSNs. In the same way, Reference 77 presents novel hydrogen based on pyroelectric EH to harvest the suspension kinetic energy for water splitting and self-powered sensor node harvest power of 84 μW from thermoelectric,[11] about 0.01–0.03 W from[7] and network of suspended nano TE.[78] Some thermal EHs with their evaluation parameters for WSNs are given in the below Figures 11 and 12.

4.2 | External energy sources

4.2.1 | Mechanical energy harvesting for WSNs

Kinetic energy harnessed from ambient vibrations has significant effort to produce electricity using one of the

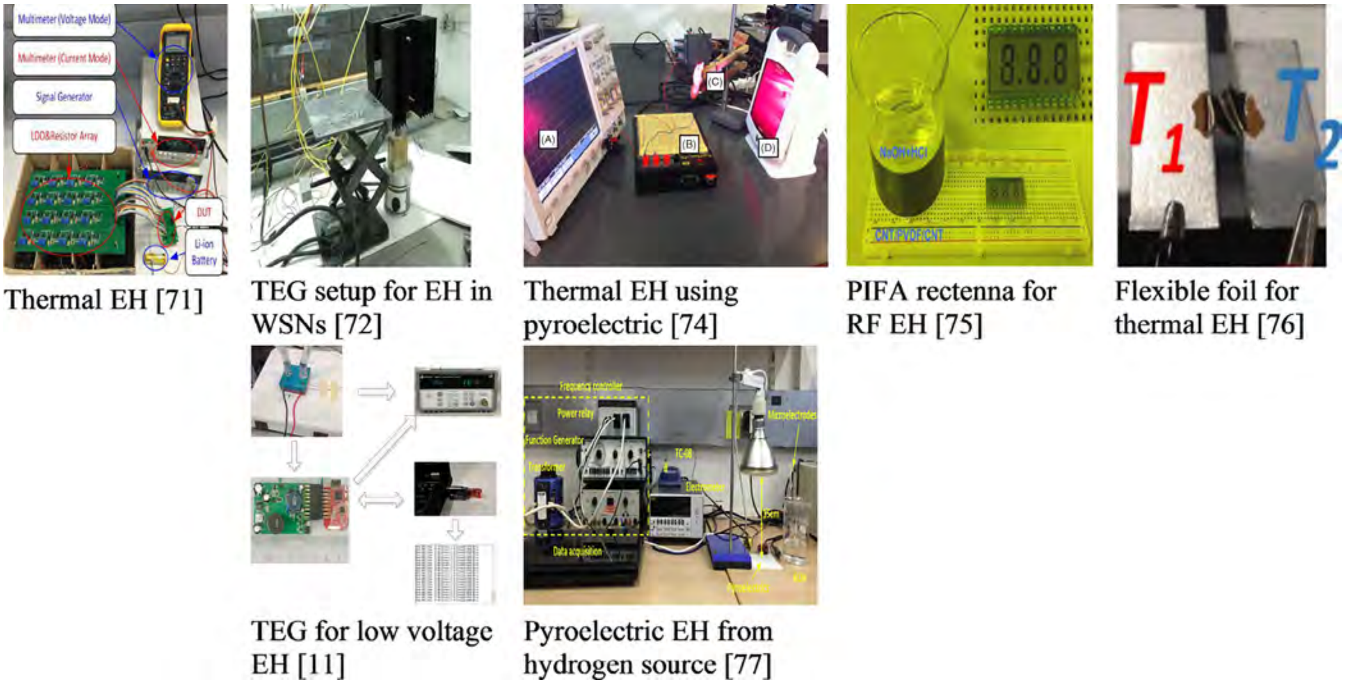


FIGURE 11 Energy harvesting for WSNs from thermal energy [Colour figure can be viewed at wileyonlinelibrary.com]

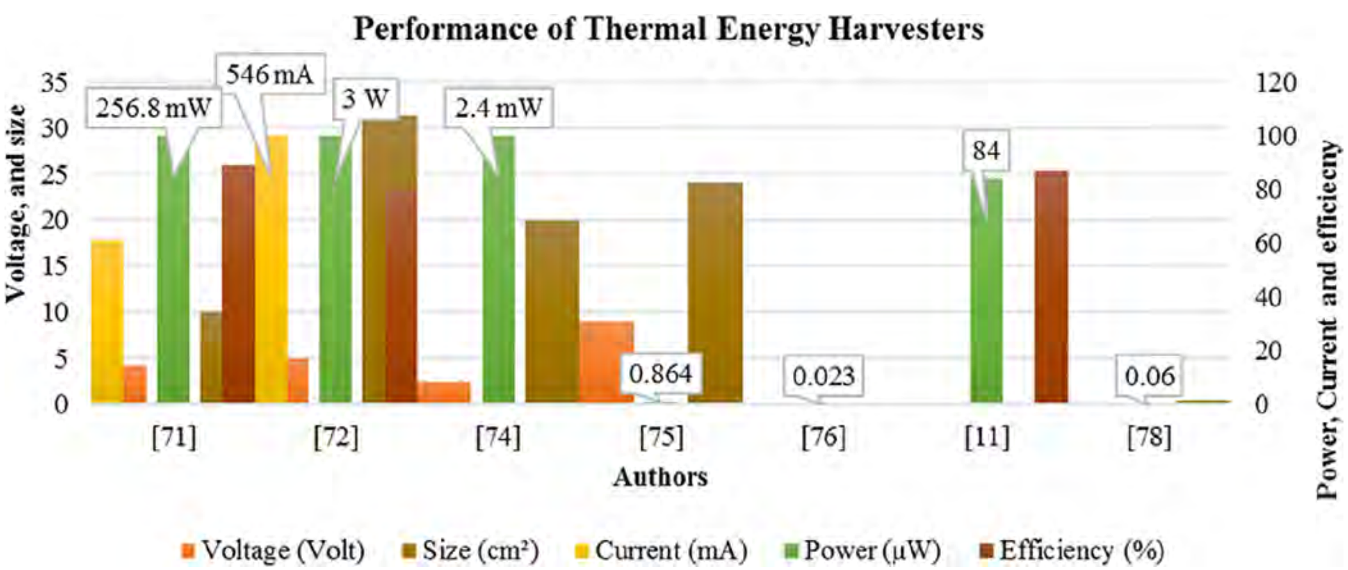


FIGURE 12 Various outcome parameters for thermal EHs [Colour figure can be viewed at wileyonlinelibrary.com]

following conversion principals, such as electrostatic, EM and piezoelectric that make recognition of a sustainable and renewable EHs.[79] Experiments of piezoelectric boxes harvest road energy in pavement,[4] impact-based piezoelectric road EH for smart highways,[80] a vibration-based bi-stable EM,[81] a Penta-stable energy harvest (PEH)[82] and a test station with cantilever structure,[83] parametrically forced pendulum EH[84] are mechanical EHs that utilized the piezoelectric technology. In the same way, a beam vibration produced using Hamilton's generalized principle on the basis of Euler Bernoulli beam theory,[85] vortex-induced vibration (VIV),[79] and PEH demonstrate a high efficiency to harvesting vibration energy for sensor nodes with an average power of 200 mW.[86] Similarly, autonomous triboelectric nano vibration accelerometer (TEVA)[87] and flexible PZT device[88,89] harvest power from biomechanical bending/unbending motions. However, Reference 90 developed a novel motor that can derive small electronic devices by harvesting the stator's vibration produced power and convert into electric power. Reference

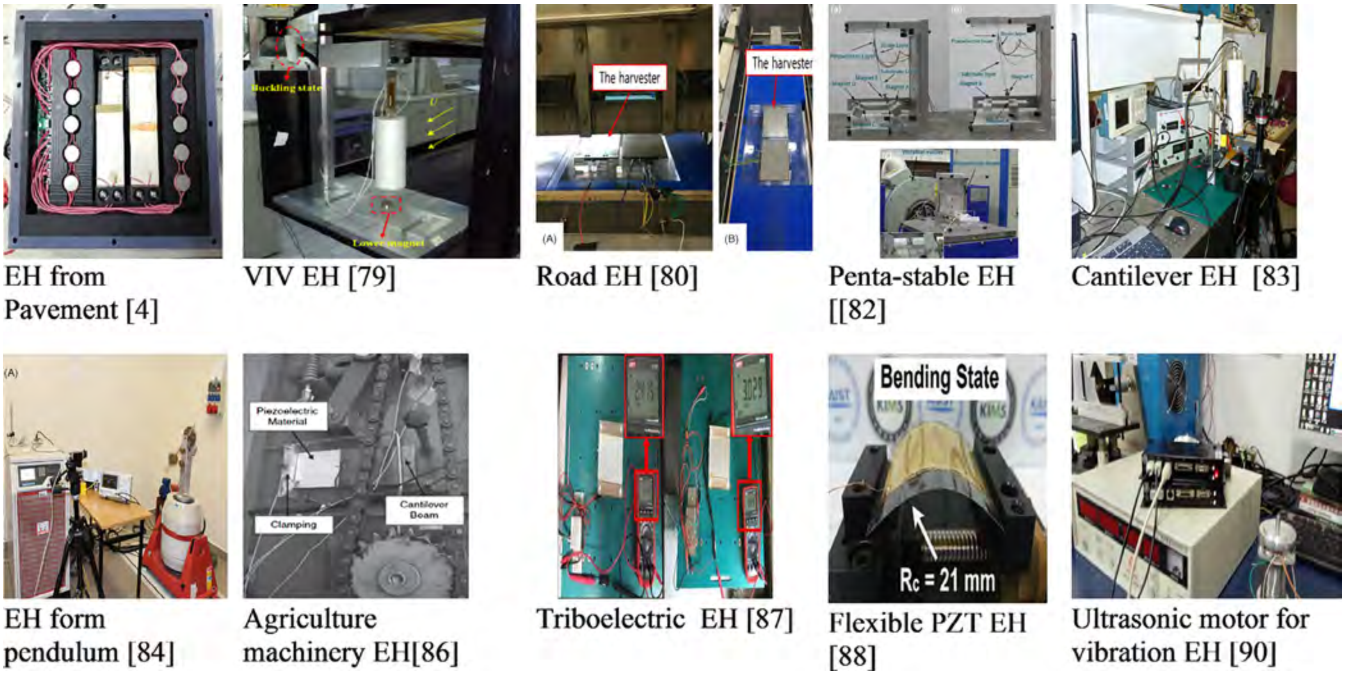
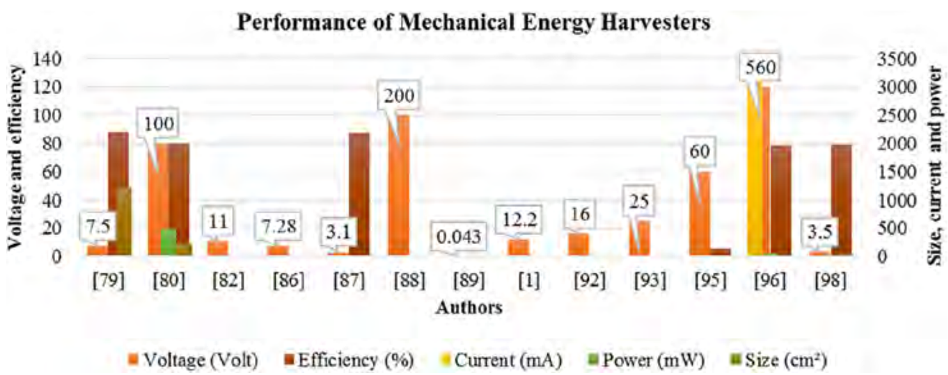


FIGURE 13 Various mechanical energy harvesting systems for WSNs [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 14 Performance parameters for mechanical energy harvesters [Colour figure can be viewed at wileyonlinelibrary.com]



91 presents a novel hydrogen source using semi-active damper with an electro-hydraulic approach based on pyroelectric EH to harness the suspension kinetic energy. A lead free ternary piezoelectric enhanced mechanical EH based on manganese-doped sodium bismuth titanate proposed by[1], which produces high electrical output as open circuit voltage (V_{OC}) of ≈12.2 V and power of 7.4 μW. Similarly Reference 92 developed a hybrid PZT microcubes based flexible PEG with metal–insulator–metal (MIM) structure, which gives high performance in terms of voltage V_{OC} of ≈16 V and power density of 50 μW/cm^3. Reference 93 prepared a piezoelectric composite generator (PCG) for mechanical energy harvesting based on bioinspired elastic 3-D three-dimensional electroceramic skeleton architecture with high performance in case of V_{OC} of ≈25 V, short-circuit current (I_{SC}) of 280 nA and power density of 2.6 μW/cm^{-2}. In the same way, Reference 94 developed highly enhanced 3D electro ceramic skeleton with sea porifera design for piezocomposite energy harvester (PCEH), which gives voltage, current density and power density of ≈23 V, ≈350 nA/cm^{-2} and ~ 2.0 μW/cm^{-2}, respectively that is ≈16 times greater than previous methods. An interlinked 3D piezoceramic skeleton for flexible PCEH optimized by Reference 95, which generates the voltage of ≈60 V, I_{SC} current of 350 nA, current density of 850 nA/cm^{-2} and power density of 11.5 μW/cm^{-2}, respectively that is ≈16 times greater than conventional methods. For WSNs energy harvesting from mechanical systems,[96] PVDF and PZT nano hybrid[97,98] are represented in the below Figure 13. The Figure 14 represented the outcome results of various mechanical EHs.

4.2.2 | Energy harvesting from human activities in WSNs

There is an idea to consider energy resource from the growing population which utilizes human activities as a rich source of energy. So, to harvest energy it is necessary to recognize the everyday human activities.[38] Auspiciously, a variety of ways for energy harvesting from humans, like through body heat, walking, broadly speaking, variations in finger position or locomotion, human respiration, heartbeat, the flow of blood, and many more other physical activities. But the major hindrance will be integrated them to miniaturize for easily human adoption and another is non-periodic, high acceleration and infrequent activities. Here, a wearable TEG[99] and wearable Pyroelectric nanogenerators (PyNG) scavenging energy from human respiration temperature fluctuations using PVDF thin film with a maximal power of 8.31 μW.[100] A wearable wireless sensing system powered by EH has been developed with system-level strategies and addressed various challenges in wireless sensing, power conditioning, energy harvesting, and their addition into a system[101] and a backpack for biomechanical EH has been proposed by Reference 102. In the same category, a self-powered smart patch on the basis of the triboelectric effect and electrostatic induction[103] and based on PZT ceramics ultra-flexible piezoelectric device for energy scavenging from heart motion.[104] A flexible amorphous silicon solar module as the power source integrating a lithium-ion battery for a wearable health monitoring device proposed by Reference 105 and a new wearable energy harvesting system that combined electrical energy source for EM and piezoelectric EH developed by Reference 106 and wearable TEG.[107] The energy harvesting from human activities has been shown in Figures 15 and 16.

4.2.3 | EM energy harvesting in WSNs

The EM induction based on Faraday's law has been followed by electromagnetic energy harvesters (EMEHs) and these devices have coil-magnet components. There, an EMEH developed by Reference 30 to harvest power about 125 μW from human body gesture. The proposed harvester has a power management AC–DC converter for battery-less reliable operation in WSNs. Similarly, Reference 108 followed the phenomenon of magnetic levitation (maglev) and implemented in the vibration harvester. The proposed idea for EH is on the basis of movable permanent cylinder magnet developed in a

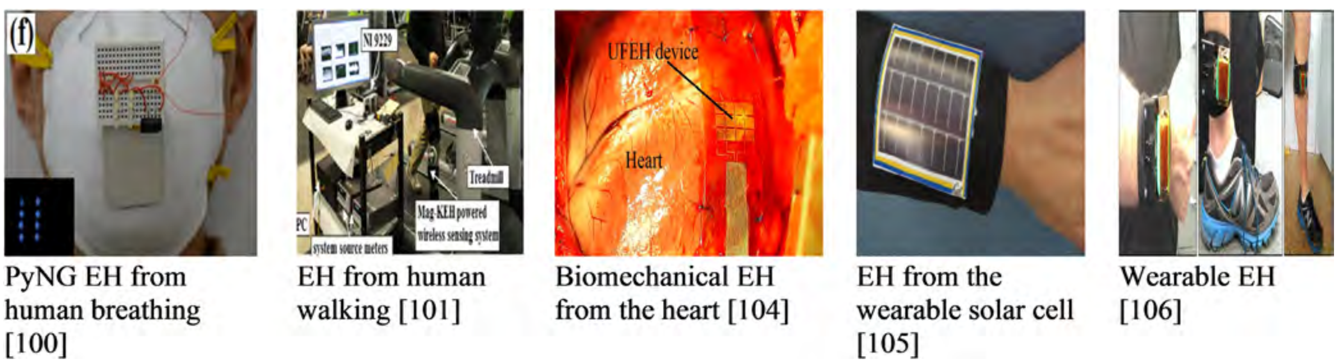


FIGURE 15 Human activities for EH-WSNs [Colour figure can be viewed at wileyonlinelibrary.com]

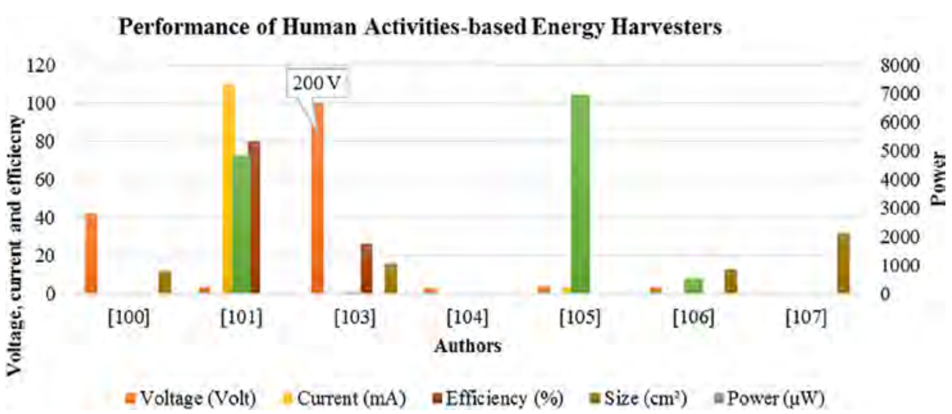


FIGURE 16 Evaluation of energy harvesting from human activities [Colour figure can be viewed at wileyonlinelibrary.com]

EM harvester for human body movements [30] Maglev for EH [108] EM EH using MEMS [109]

FIGURE 17 Electromagnetic EHs for WSNs [Colour figure can be viewed at wileyonlinelibrary.com]

coil.[108] The MEMS EMEH represented by Reference 109 for multi-frequency vibration energy harvesting employing two different topologies, single mass topology, and double mass topology. Figure 17 shows EM energy harvesting systems for WSNs.

4.3 | Hybrid energy harvesting in WSNs

The system capability to harness power from several energy sources simultaneously is known as hybrid energy harvesting (HEH) system. Energy harvesting modules based on piezoelectric, thermoelectric, and pyroelectric phenomena offer an attractive solution for energy consumption and leads to battery-less wireless sensor nodes that could be done sustainably operation without peripheral power sources.[110] Furthermore, harnessing multi-source energies from our surroundings is an active method for resolving power consumption challenges of wireless sensors and some small-scale individual electronic equipment. However, at the same time, these energies are not always available and depending on working or weather conditions, and several other parameters. In this review article, studies about HEH devices that consist of pyroelectric nanogenerator, triboelectric nanogenerator, solar cells, thermoelectric generator, and piezoelectric nanogenerator which utilized energy to light up self-powered sensors, electrochemical, and electronics needs. These investigations having critical significance for detecting, defense technology, environmental monitoring, medical science, and even individual electronics equipment.[111] A transparent flag designed by Reference 112 as hybrid TENG to harness wind and solar wind energy concurrently for smart self-powered sensing network and work as an empirical energy source. In the same way, Reference 113 reported a flexible hybrid device by combing piezoelectric nanogenerator (PENG) and TENG based on electrospun nanofiber mat to harness energy from soft surface or diversity touch energies like human skin. The maximum power with a peak of 0.11 $\mu W/cm^2$ from PENG and 84 $\mu W/cm^2$ from TENG can be produced by the harvesters. Similarly, a unique hybrid scheme combines three thermoelectric, vibration and magnetic energy harvesting system proposed by Reference 18 to derive low-voltage detecting applications inside power grids. The novel RF/PV hybrid EH[114,115] and a frequency selective surface (FSS)[116] hybrid rectenna model to harvest ambient sunlight and EM energy for autonomous wireless systems. A prototype consisted three various energy sources, a rectenna for RF energy, a piezoelectric PZT based cantilever capable to harness surroundings vibrations, and a solar cell in order to scavenge sunlight that capable to produce an extreme power of 241.3 mW.[117] Similarly, solar-piezoelectric HEH,[118] piezoelectric-EM[119-121] to collect solar energy, vibration and EM energy, concurrently. Reference 122 proposed novel hybridized power board that can harvest energy from wind, sunlight, and raindrop. An oval shape hybrid EH developed by Reference 123 which couples of EM and piezoelectric generators to achieve the average power output of 25.45 mW at 60 Hz. Further, for automated IoT sensors, EHs with hybrid light EM and EH has developed by References 124-127 . Various types of hybrid EH with their various performance parameters are given in the following Figure 18 and 19.

5 | RESEARCH FINDINGS/ COMPARATIVE ANALYSIS

This article recognizes some research gaps in previous review papers and covered the most popular approaches, factors, and performance measurement metrics that affect the energy harvesting technologies in WSNs. The review mainly included the hybrid energy harvesting systems that will become the necessity of autonomus devices in the upcoming era. The Table 2 depicts the comparative study among various EHs. The major representations of this survey can be shortened as follows:

6 | SIGNIFICANT ISSUES FOR OPEN RESEARCH

The WSN is a salient technique[18] and also an essential part of IoTs[17] that have been widely used for information

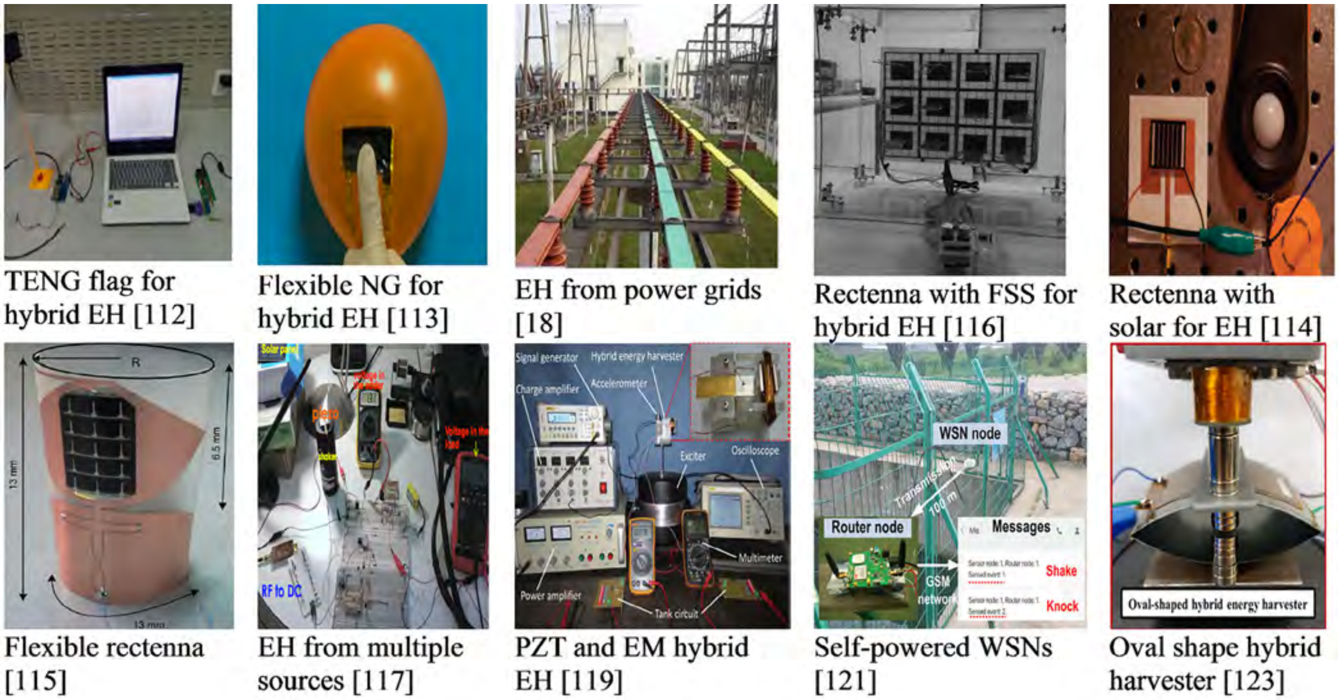


FIGURE 18 Hybrid energy harvesting models for WSNs [Colour figure can be viewed at wileyonlinelibrary.com]

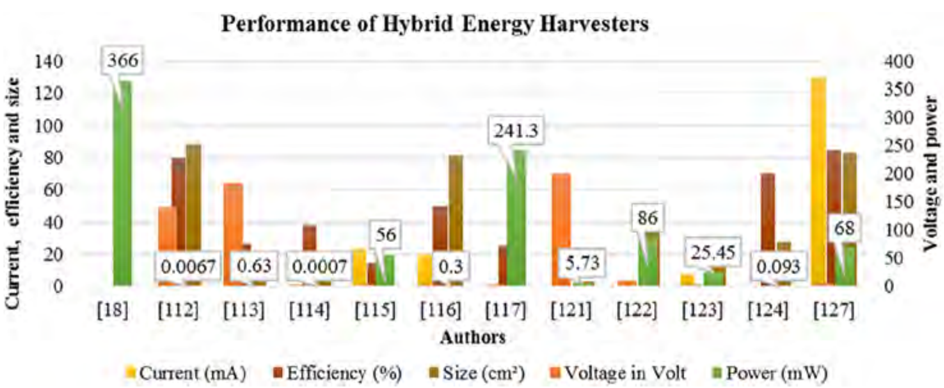


FIGURE 19 Performance of hybrid energy harnessing systems [Colour figure can be viewed at wileyonlinelibrary.com]

gathering with a wide range of applications including habitat monitoring, battlefield surveillance, intelligent buildings, object tracking, rescuing in military, emergency recovery, health monitoring, air quality monitoring.[19] WSNs have long been considered as the technology that has the potential of revolutionizing the World we live in.[128] However, there are a lot of key challenges that affects the performance of WSNs.[129]

- ***Develop an advanced hybrid system to eliminate energy consumption issues***: The energy efficiency is fundamental and frequently most important design challenge for a WSN. After the consumption of the energy, sensor will fail or scrapped and becomes useless. The constraint of power supply is a critical issue which obstructs the utilization of sensor network.[130-133]
- ***Software Approach***: From all design aspects, to the extent of our facts here primary need to develop a simulation environment (almost not exist) that can simulate all the performance parameters for EH-WSNs. Such a software approach will leads to rigorousness level of research in WSNs and becomes a valuable tool to design and analyze the performance of designed energy harvesting systems on large-scale deployment.
- ***Reliability and Quality of Services***: The important parameter Quality of Service (QoS) defined as level of service that provides to users by the WSNs. The better QoS is more difficult due to constantly change of network topology in WSNs. However, the problem occurs

TABLE 2 Comparative study of various EHs

S No.	Method	Size	Energy Availability	Technique	WSN Motes	Storage Type	Effici-ency	Software Approach
Photovoltaic EHs								
1.	ISEH[36]	-	5.0 V/450 mW	MPPT	ZigBee	Lithium Battery	80%	-
2.	Solar Panel[37]	3.75 cm × 2.5 cm	4.0 V/100 mA	MPPT	Berkeley/Crossbow motes, Mica2 motes	NiMH	-	-
3.	PV panel[38]	-	21.5 V/520 mA	-	WirelessHART	Li-PO	-	Multisim Circuit
4.	Hydro solar[39]	2.3″ × 2.3″	4.23 V/111.16 mA	MPP	Tmote Sky/TelosB mote	NiMH	13%	-
5.	Miniaturized PV[40]	112cm^2	50 mW	MPPT	Tmote Sky	Supercapacitor	80%	-
6.	Solar Panel[41]	115 cm × 85 cm	4 V/300 mA	MPPT	Mica2	NiMH	10%	-
7.	Solar EH[42]	3.75″ × 2.5″	3.24 V /25 mA	Power Manage-ment	Crossbow MicaZ	Ultracapacitor	82%	-
8.	Indoor Solar EH[43]	-	4.5 V/72.74 μW	MPPT	Humidity and Temperature Sensor	Supercapacitor		
RF Energy Harvesting Systems								
1.	Compact rectenna module[44]	14 cm × 14 cm	3.8 V/162 μW	Ring Slot Antenna	-	-	45.5%	CST and SPICE
2.	Fractal Loop[46]	45 mm × 45 mm	10 μW/cm^2 power	novel in-loop ground plane			61%	CST
3.	RF Rectenna[48]		2.4 V/15.8 μW	Dickson and Seiko S-882Z IC	Sensor	Capacitor	64% 45%	Experimental
4.	AM broadcast EH[49]	10 m	14 V/82 μW	Horizontal Antenna	Temperature Sensor	-	-	Experimental
5.	RFEH[50]	55 mm × 55 mm	2.7 V/23.4 μW	PIFA antenna	Temperature Sensor	Capacitor Bank	13.2%	Experimental
6.	Dual-stage RF-EH[51]	-	2.074 V /32.91 μA	LPD and HPD	Mica2 sensor mote	Capacitor	70%	ADS
7.	Flexible hybrid printed RF-EH[52]	10 cm × 10 cm	2.9 V	Catalyst based Copper Printing	stand-alone sensor platforms	Charge Tank	40%	ANSYS HFSS
8.	Multiband RF-EH[55]	-	3.0 V/44.4 μA	Tunable Circuit	TI ez430-RF2500	Battery Less	45%	ARCGIS
Flow based EHs								
1.	Rotational piezoelectric[58]	-	29 V/2566.4 μW	PVDF beam	WSN	-	-	FEM
2.	Miniaturized hydro-generator[59]	-	3.0 V/72.7 mA	Piezo-electric eel with plucking beam	GOLDFISH	UPS Battery	53%	GoSUMD, FEM, MATLAB
3.	Duck-Shaped TENG[60]	-	325 V/65.5 μA	Free-standing rolling mode	eZ430-RF2500T	Capacitor	39.01%	COMSOL
4.	Wind Harvester[61]	-	5.5 V/73 μW	ENO and ARRSES	Pow Wow platform	Supercapacitor	-	OMNeT++
5.	FLMG[63]	-	8.6 V/13.6 μW	Vortex shedding and wind-induced fluttering	Temperature Node	-	-	-

(Continues)

TABLE 2 (Continued)

S No.	Method	Size	Energy Availability	Technique	WSN Motes	Storage Type	Effici-ency	Software Approach
Bio-energy Harvesters								
1.	Bio cell[64]	20 µm	20 mV/1.2 nW	Potential of Xenopus oocytes	Bio-sensor	Capacitor	-	Pulse Fit
2.	PUEH array[65]	1.5 mm × 1.5 mm	2 V/4 µA	Multilayer Piezo	Bio-implantable micro-devices	Capacitor	0.0063%	FEA COMSOL
3.	BPNG[66]	2.0 cm × 1.5 cm	26.4 V/1.45 mA	Eggshell membrane (ESM)	Diagnostic sensor	Capacitor	63%	Experimental
4.	Bio-waste EH[67]	0.7 × 0.7 cm	22 V/28.5 µW	self-arranged collagen leathering	Bio-implants	Supercapacitor	-	Experimental
5.	Bio EH[69]	-	3.3 V	living-tree bioenergy	PBN	Supercapacitor	-	OMNeT++
Thermal EHs								
1.	TEG Array[71]	1.7 mm × 1.7 mm	4.2 V/256.8 mW	Reconfigurable array	WSN	Li-ion Battery	88.8%	Experimental
2.	TEG EH[72]	5.6 cm × 5.6 cm	5 V/0.547A/3.0 W	high intensity gamma radiation	CC2530 ZigBee	Li-ion Battery	80%	Experimental
3.	PZT based TEG[74]	20 cm²	2.5 V/2.4 mW	Spontane-ous electrical polarizat-ion	WSN	Capacitor	-	Experimental
4.	Flexible pyroelectric[75]	8 cm × 3 cm	9.1 V/95 nA	Chemical exothermic process	Temperature monitor	Supercapacitor	-	Experimental
5.	TE Foil[76]	4 mm × 4 mm	1.4 mV/0.08 mA	hybrid super lattices	Wearable circuit	-	-	Experimental
6.	TEG[11]	-	62 mV/84 µW	MPPT	WSN Monitoring	Supercapacitor	86.8%	Experimental
7.	Nano TEG[78]	0.5 cm²	23 mV/0.57 µA	SiN membranes	Temperature and airflow sensing	-	-	Experimental
Mechanical EHs								
1.	VIV[79]	35 cm × 35 cm	7.5 V/140 µW	Nonlinear magnetic forces	WSN	-	0.6%	Experimental
2.	Piezo EH[80]	15 cm × 15 cm	100 V/483 mW	Impact-based piezo-electric	WSN	-	-	MMLS3
3.	PEH[82]	155 mm × 7 mm	11 V	penta-stable piezo-electric beam	WSN	-	-	Experimental
4.	Agriculture Machines[86]	-	7.28 V/200 µW	Clock synchroniz-ation	WSN	-	-	Experimental
5.	TEVA[87]	-	3.1 V	Kapton nano structure	ZigBee	Lithium Battery	-	MATLAB
6.	Flexible EH[88]	2.5 × 3 cm	200 V/35 µA	AD-based PZT	MSP430F2274	Capacitor	-	Experimental
7.	ULR PZT[89]	19.25 mm²	43 mV/23.3 nW	MEMS	-	-		FEM and Experimental
8.	Lead free PEH[1]	120 mm × 12 mm × 0.9 mm	12.2 V/7.4 µW	Ternary piezo-electric	WSN and Biomedical	-	-	Experimental
9.	PEG[92]	1.8 cm × 0.6 cm	16 V	MIM structure with microcubes	-	-	-	FEA and Experimental

TABLE 2 (Continued)

S No.	Method	Size	Energy Availability	Technique	WSN Motes	Storage Type	Effici-ency	Software Approach
10.	PCG[93]	-	25 V/280 nA	Bioinspired 3D elastic electroceramic skeleton architecture	Self-powering	-	30%	Fourier spectral iterative perturbation method Software
11.	PCEH[94]	100 μm × 100 μm × 100 μm.	23 V/2.0 μW	Sea porifera 3D elastic electroceramic skeleton design	Wearable and Biomedical devices	-	-	VTK and FEM
12.	Flexible PCEH[95]	1 cm × 1 cm	60 V/350 nA	Bio fibril-Templated 3D Interlinked Piezo-ceramic skeleton	IoTs	-	5.62%	Experimental
13.	DEG[96]	15.7 cm^2	560 V/57 mW	Dielectric Elastomer	-	Lithium Battery	78.79%	Experimental
14.	PETs Array[98]	50 mm × 100 mm	3.5 V/254 μW	Synchron-ous electric charge extraction (SECE)	sensors	Capacitor	79%	Experimental
EHs for Human Activities								
1.	PyNG[100]	3.5 cm × 3.5 cm	42 V/2.5 μA	PVDF thin film	breathing sensor	Capacitor	-	Experimental
2.	Mag-WKEH[101]	3 mm × 3 mm	3.6 V/4.85 mW	PMM with MPPT and EAI	MCP9700 and HIH-5030 Sensors	Capacitor	80%	SPICE
3.	Smart patch[103]	4 cm × 4 cm	200 V/60 μW	Spontaneous friction	healthcare monitoring	Capacitor	26.6%	SPICE
4.	UFEH[104]	-	3.0 V	excellent piezo-electricity	biomedical implants	Lithium Battery	-	Experimental
5.	PV module[105]	-	4.1 V/3.4 mA 6.98 mW	LCO	health monitoring	Flexible lithium-ion Battery	-	Oriel Sol1A
6.	WE-Harvest[106]	38.5 mm × 34 mm × 37 mm	3.3 V/550 μW	Piezo-electric and EM energy	MCP9700	Capacitor	-	Experimental
7.	Wearable TEG[107]	4 cm × 8 cm	10mv/15nW	silk fabric-based	-	-	-	Experimental
EM Energy Harvesting systems								
1.	Wearable EM[30]	80 mm × 25 mm	4.6 V/130 μW	power-up activity	MicaZ mote	SMD capacitors	-	Experimental
2.	MEMS[109]	3.45 mm × 3.25 mm	0.43 μW	multi-frequency MEMS	WSN	-	-	FEM
Hybrid Energy Harvesting Systems								
1.	Three EH modalities[18]	-	366 mW	Holistic Topology	ZigBee node	Capacitors	-	Ansoft
2.	Hybrid NG[112]	110 mm × 80 mm	140 V/6.7 μW	Integrated Units	Smart Sensors	Li-ion battery	-	COMSOL
3.	TENG and PENG[113]	2.5 cm × 3 cm	183 V/630 μW	electrospun nanofiber mat	e-skins and healthcare monitoring	Capacitor	26.6%	COMSOL
4.	Hybrid RF/PV[114]	25 mm × 20 mm	3 V/643 nW	optimal rectifier topology	Autonomous applications	Capacitor	38%	ADS
6.	Solar+ EM[115]	13 mm × 6.5 mm	4.06 V/23.2 mA	Harmonic balance optimiza-tion	-	-	15%	HFSS
7.	Hybrid FSS[116]	90 mm × 90 mm	3.3 V/300 μW	FSS	IoT's	-	50%	CST MWS

(Continues)

TABLE 2 (Continued)

S No.	Method	Size	Energy Availability	Technique	WSN Motes	Storage Type	Effici-ency	Software Approach
8.	HEH[117]	-	4.17 V/241.3 mW	combined 3 different sources	WSN	Li-Ion batteries	25%	Oriel Sol2A
9.	Dual-stage piezoelectric[121]	2.1 × 1.4 cm	3.4 V/5.73 mW	threshold-triggered	Wireless alarming	Capacitor	-	Experimental
10.	Dual-mode TENG[122]	40 cm^2	11 V/86 mW	hybridized power panel	LEDs	Capacitors	-	Experimental
11.	Oval Shape EH[123]	56 mm × 28 mm	3.3 V/25.45 mW	effective hybridizat-ion of two distinct EH	IoT sensor module	Capacitors	-	Experimental
12.	Solar + EM[124]	114 mm × 24 mm	2.8 V/93 μW	Dual port self-oscillations	RF transceiver sensor	Capacitors	70%	ADS and Experimental
13.	Multisource EH[127]	83 cm^2	4.6 V/68 mW	MPPT	WSN	Li- polymer battery	85%	Experimental

in WSNs due to sustaining and re-installation the paths dynamically. The energy management protocols must provide certain level of QoS as required by the application.[134,135]

- ***Life Time or Robustness***: The sensor nodes should be worked for years, so the maximum network lifetime is an essential requirement for many applications. In order to achieve maximum lifetime requirements demanded, WSNs must be as vigorous as possible to permit individual connection or node failure.[130,133,136]
- ***Perfect Deployment of nodes***: The deployment described as implementing WSNs in real world geographical region. However, low data yield is another frequent issue of real-world employment of nodes that means enough amount of information or data is not delivered to the network as required. It is very challenging and inconvenient activity that depends on how sensor node will be deployed and the application's demographic location.[131,137]
- ***Efficient Energy Management with protocol and Miniaturization***: The essential objective of WSNs configuration is to make more efficient, less expensive, and light weight smaller systems. An assortment of extra difficulties can influence the design of WSNs.[130,131] Generally, WSNs are battery operated systems with restricted processing capability having less memory storage, limited energy as challenging problems.[132]

In order to fulfillment nodes power needs, the development of a hybrid system which harness ambient energy available from at least more than one sources or multiple source to eliminate power consumption issue which will have an important potential that can be made an excellent choice for deployment of WSN in a harsh conditions or remote places, instead of single energy sources as wind or solar, are impracticable due to above mentioned issues like unpredictability and uncertainty of produced power. To attain maximum life time, the WSNs should be established in such a way that individual node or connection failure can be tolerated and adapted. The designing of protocols in such a method that they should not become complex, but useful for decreasing power consumption.

7 | CONCLUSION AND FUTURE PERSPECTIVES

Going through the existing literature, it found many authors suggested different energy harvesting techniques that are classified in this review article. This survey identifies various energy harvesting systems that are used in WSNs to feed the power to nodes and also recognize conceivable fields of examination to expand EH-WSNs. Some research gaps have been found like, most of the researchers have designed a prototype in laboratory only without considering some physical environmental parameters (like lacking of light in night and cloudy days, wind or flow not steadily) that can create problems for real application. However, HEH approach can be made best technique that capable of surviving in the intended environment with considering all affective parameters discussed above. The further work can be extended up to develop a system which harness ambient energy available from at least more than one sources that will have important location/time-independent characteristics that can be made an excellent choice for deployment of WSN in a harsh conditions or remote places. Instead of single energy sources such as wind or solar, are impracticable due to above mentioned issues like unpredictability and uncertainty of produced power. Furthermore, the sensor developers, WSN authorities, researchers, and scientists might discover this review beneficial, as it shows a clean image of research in each individual domain mainly HEH systems in WSNs.

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