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A Review of Energy Harvesting Techniques for Self-Powered IoT Devices

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Abstract

The Internet of Things (IoT) manages a vast network of interconnected smart devices that collect, transmit, and analyze data from their environment using embedded components like processors, sensors, and communication equipment. These devices, which require efficient power sources, often rely on batteries that limit their operational lifespan and increase environmental impact. This paper provides a comprehensive review of energy harvesting techniques aimed at enhancing the longevity and sustainability of IoT devices. The methodology involves a comparative analysis of various energy harvesting sources such as solar, thermal, RF, and mechanical energy focusing on their efficiency, applicability, and integration within wireless sensor networks (WSNs). Key contributions include the identification of current limitations in energy harvesting technologies, such as low energy conversion efficiency and intermittency, and the proposal of solutions to optimize energy capture and storage. The results demonstrate that integrating multiple energy sources can significantly improve power availability and reduce dependence on conventional batteries. This review concludes by outlining the ongoing challenges and future research directions needed to develop efficient, reliable, and cost-effective energy harvesting systems for IoT applications.

Keywords: Energy Harvesting (EH), Wireless sensor networks (WSNs), "Internet of Things (IoT)".

الخلاصة

إن إنترنت الأشياء (IoT) تدير شبكة واسعة من الأجهزة الذكية المتصلة التي تجمع البيانات من بيئتها وتنقلها وتحللها باستخدام مكونات مدمجة مثل المعالجات والمستشعرات وأجهزة الاتصال. تعتمد هذه الأجهزة، التي تتطلب مصادر طاقة فعالة، غالبًا على البطاريات، مما يحد من عمرها التشغيلي ويزيد من التأثير البيئي. تقدم هذه الورقة مراجعة شاملة لتقنيات حصاد الطاقة بهدف تحسين طول عمر واستدامة أجهزة إنترنت الأشياء. تعتمد المنهجية على تحليل مقارن لمصادر حصاد الطاقة المختلفة مثل الطاقة الشمسية، الحرارية، الترددات الراديوية (RF)، والطاقة الميكانيكية، مع التركيز على كفاءتها، قابليتها للتطبيق، واندماجها ضمن شبكات الاستشعار اللاسلكية (WSNs). تشمل المساهمات الرئيسية تحديد القيود الحالية لتقنيات حصاد الطاقة، مثل انخفاض كفاءة تحويل الطاقة والتقطع، واقتراح حلول لتحسين عملية التقاط الطاقة وتخزينها. أظهرت النتائج أن دمج مصادر الطاقة المتعددة يمكن أن يحسن بشكل كبير من توفر الطاقة ويقلل من الاعتماد على البطاريات التقليدية. تختتم هذه المراجعة بتحديد التحديات المستمرة واتجاهات البحث المستقبلية اللازمة لتطوير أنظمة حصاد طاقة فعالة وموثوقة وذات تكلفة مناسبة لتطبيقات إنترنت الأشياء.

الكلمات المفتاحية : حصاد الطاقة , شبكات الاستشعار اللاسلكية , انترنت الاشياء

1. INTRODUCTION

Recent advancements in the reduction of devices with higher computational capability and ultra-low power communication technologies are encouraging the growing use of embedded electronics in our environment [1]. Every physical object , or thing, will become an information source capable of communicating with any other thing in the network as a result of this [1]. A new technology that has made it possible for worldwide machine networks to communicate is the Internet of Things (IoT), commonly referred to as the Internet of Everything [2]. From an industrial perspective, the IoT becomes significant when devices connected to the global machine network can communicate with one another for customer support, business intelligence applications, vendor inventory systems that meet their needs, and business analytics [2]. As a result of competitive pressure and unique technological solutions, industries are rapidly employing this technology [3-4]. The number of Internet connected devices will surpass the number of human beings on Earth [5]. Health care systems, smart buildings, environmental monitoring, and traffic management are among the primary uses of IoTs [2]. Wireless sensor networks present an important part of the IoT network with massive number of devices that employ energy harvesting. By incorporating remote real-time condition monitoring, WSN comes with a comprehensive list of reasonable installation and operation expenses, along with the advantages of high flexibility, low power consumption, and distributed intelligence [6]. A wireless sensor node in a WSN, as shown in Figure 1, is typically made up of four main components: a Central Processing Unit (CPU), a communication unit, a power unit, and a sensor unit [7].

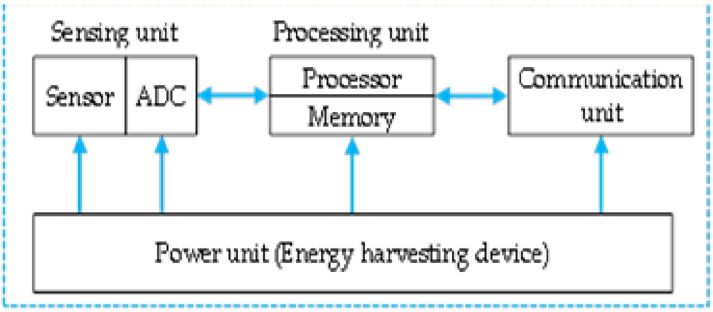

Fig.1 Wireless Sensor Node Structure [6].

Due to the short lifespan, low energy density, and low capacity of conventional batteries, the improvement of the power unit is an imperative challenge. Moreover, the notable increase in the power consumption of electronic gadgets has not translated into a major improvement in battery performance [6]. In reality, a lot of IoT applications require devices to have sustainable and self-sufficient power sources [1]. Fortunately, energy harvesting technologies allow the lost energy from machines or their surroundings like mechanical, magnetic, and electric fields, thermal, and electrical energy to be captured and used to power sensor nodes [7], This procedure entails converting external waste energy into electrical energy [8]. This method not only prevents battery pollution in the environment but also significantly extends the life of the sensor nodes and lowers monitoring system maintenance costs [6]. It is necessary to take into consideration the four general criteria that are indicated when designing any Internet of Things device that is based on energy harvesting. First finding out whether the environment is a good place for energy harvesters. Second, selecting the appropriate energy harvesting transducer. Third calculating how much energy the device will need to run, including how much power it will need to generate. Finally choosing a battery that can power the transducer in the event that electricity runs out. These are important factors that the product designers have to carefully consider [5].

The rapid proliferation of IoT devices has led to a critical need for sustainable power solutions. Traditional battery-powered systems are inadequate due to their limited lifespan and environmental impact. This research is motivated by the necessity to develop efficient energy harvesting techniques to ensure the longevity and sustainability of IoT devices. Current solutions, such as conventional batteries, offer limited energy capacity, necessitating frequent replacements, which are neither cost-effective nor environmentally sustainable. While various energy harvesting methods have been proposed, they often suffer from low energy conversion efficiency and intermittent energy availability. Among the existing energy harvesting methods, solar energy stands out due to its relatively high efficiency in outdoor environments. However, its reliance on consistent sunlight limits its effectiveness, particularly in indoor or shaded environments. This study aims to enhance the efficiency of IoT energy harvesting by exploring the integration of multiple energy sources, thus mitigating the limitations of reliance on a single source like solar energy. Our approach seeks to maximize energy capture and storage across varying environmental conditions. This review paper is structured as follows: Section 1 covers Energy harvesting and wireless sensor networks and Energy harvesting sources. Section 2 focuses on Categorization of energy harvesting methods. Section 3 focuses on Power Requirements for Condition Monitoring Based on WSN. Section 4 provides open research challenge of energy harvesting in IoT. Finally, there is a conclusion in Section 5.

1.1 Energy Harvesting and Wireless Sensor Networks (WSNs)

There are two primary components to the concept of energy: firstly, the direct gathering of ambient energy from the environment, followed by the conversion of physical to the electrical domain. This concept gained significant traction ten years ago and is currently a vibrant area of intense research and application. Secondly, WSNs are crucial components of the Internet of Things (IoTs) and are highly significant from an application standpoint [21]. Energy harvesting is the technique of converting ambient energy into electrical energy [2]. Energy harvesting systems can be divided into two categories: (1) those without the requirement for battery storage that immediately harvest ambient energy to power the sensor nodes, and (2) systems that first store the electrical energy that has been converted before supplying it to the sensor node [13]. In an actuating environment, WSNs played a crucial role by warning of undesired events such as changes in humidity, temperature, or pressure, leakage of hazardous chemicals or gases, vibration, fire, and many other safety indicators [22]. Research on WSNs focuses on battery-powered sensors for extended periods. However, emerging applications require sensors to operate for years or decades. Renewable energy harvesting is being studied as an alternative, but current systems are too large for WSNs [23]. Figure 2 illustrates an energy harvesting workflow based on light, temperature, motion, electromechanical field, and electromagnetic field [2].

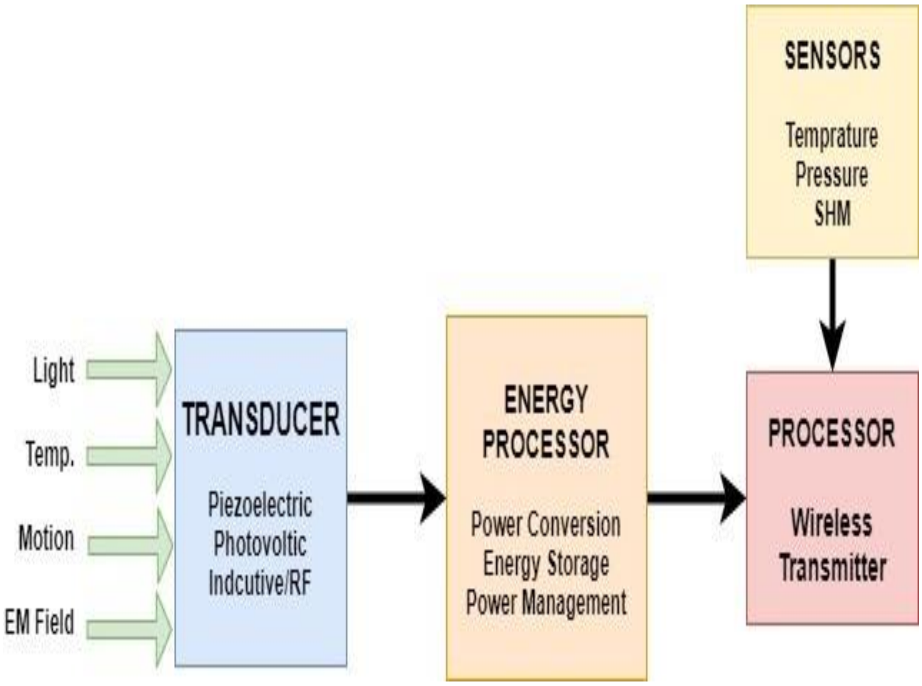

Fig.2 A workflow of energy harvesting [2].

However, the most well-known challenge in WSNs is energy consumption, as battery power is now the main energy source in sensor nodes. A sensor node will not function properly in the network after its energy is exhausted. Therefore, whether the sensor node is in active mode, which allows it to communicate and interpret data sleep mode, it needs a constant power supply [9-10]. Energy harvesting systems can effectively extend the lifetime of the networks for all kinds of WSN applications [9].

Over the last ten years, efficient energy harvesting from many sources, such as thermal, solar, wind, radiofrequency, sound, etc., has been achieved for low-power devices [11]. Figure 3 shows different kinds of systems for different energy harvesting methods, such as those from AC and DC sources [2].

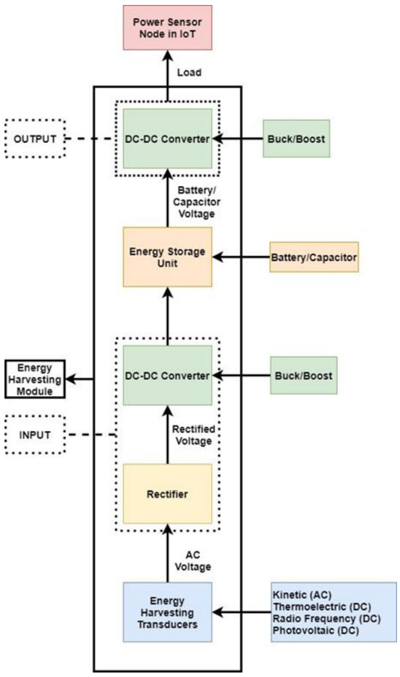

Fig.3 Mechanism for various energy harvesting techniques [2].

1.2 Energy Harvesting Sources

In order to collect enough energy from the surrounding environment for the device to use for sensing, acting, and communicating with the server, EH approaches employ a variety of energy sources. There are many situations in which energy harvesting technologies can significantly increase the energy, network longevity, and efficiency and reduce the cost and maintenance of the system. Examples of available energy sources in the environment that are frequently used for EH include solar, thermal, vibration, RF signals, and human body [1]. Figure 4 depicts different energy sources that utilizing to increases the longevity and effectiveness of IoT devices. Energy resources from the environment, such as the sun, wind, etc., or other energy sources, such as changes in temperature, motion, footfall, breathing, etc., are used to power the energy harvesting device [12].

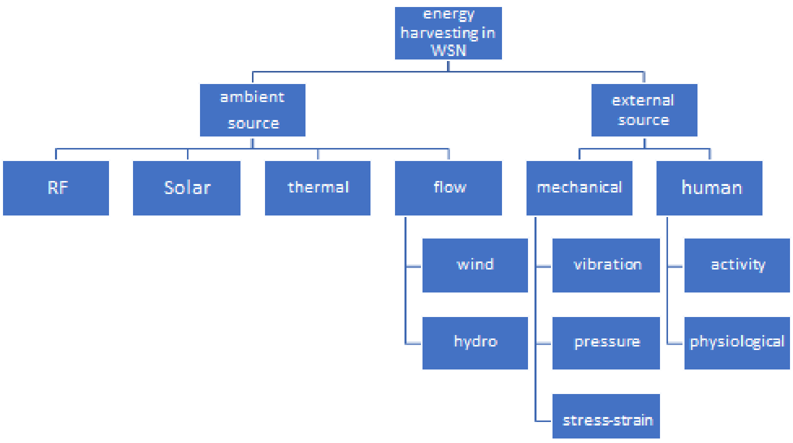

Fig.4 Shows the classification of WSN energy harvesting sources.

2. CATEGORIZATION OF ENERGY HARVESTING METHODS

2.1. Surrounding Sources

2.1.1. Radio Frequency Energy Harvesting

The global system for mobile communications (GSM), Bluetooth, Wi-Fi routers, TV broadcasters, and radar stations and other wireless communication networks are examples of ambient radio frequency RF sources that generate high electromagnetic fields from which electromagnetic energy is typically harvested [13-15]. Low-power IoT devices and consumer gadgets can be powered directly by the energy produced by RF energy harvesting systems [6]. Received radio waves are processed and converted into DC electricity for RF-based energy harvesting. There are several techniques to convert the RF signals into DC power, for example, single-stage or multistage, based on the intended application's needs (power, efficiency, or voltage) [9]. Antenna gain, source-to-destination distance, energy conversion efficiency, and source power are some of the variables that affect power harvesting. Between 50% and 75% is the usual range of RF to DC conversion efficiency across a 100 m input power range[16]. Just as WSNs have developed, so too has the Internet of Things (IoT) based on WSNs, with increased longevity and RF energy harvesting applications. For applications in the Internet of Things, Nguyen et al. [18] have developed a self-sustaining RF EH algorithm. The EH period is modified according on the traffic demand from IoT applications and the stochastic features of the incoming RF energy at sensor nodes. Figure 5 illustrates the typical structure of an RF energy harvesting circuit, which includes components such as the receiving antenna, impedance matching network, rectifier, and power management module.

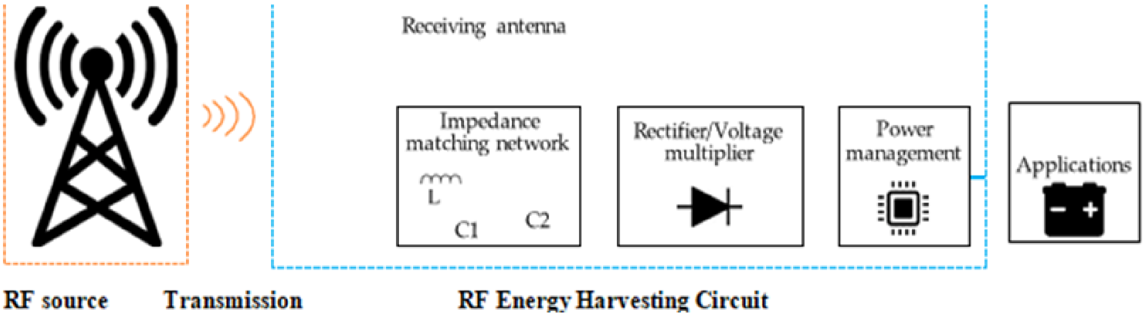

Fig.5 RF energy harvesting structure [6].

2.1.2. Solar Energy Harvesting

Light energy, such as that from artificial or solar light, is a ubiquitous and generally renewable energy source that can be captured and stored using photovoltaic technology to power sensor nodes [17]. In the last few years, a variety of photovoltaic materials have been employed to gradually improve devices performance [2]. Crystalline silicon, dye-sanitized solar cells (DSSC), organic photovoltaic (OPV), etc. are a few examples of these materials [18[19]. Photovoltaic (PV) is regarded as one of the most efficient EH methods for powering (IoT) devices because of its versatility in terms of output voltage and current as well as capacity [20,1]. In order to power autonomous IoT devices and enable on-device artificial intelligence, ambient PV cells are used [21]. PV energy harvesting is often better suitable for outdoor locations because of their exposure to sunshine [9]. At an average outdoor illumination level of 500 W/m2, poly-crystalline and amorphous silicon cells can attain efficiencies of 15% to 25%[22]. For indoor applications with 10 W/m2 of lighting, authors in [22] observed PV energy efficiencies ranging from 2% to 10%. Another single source solar energy harvesting device, Solar Biscuit [23], does not use a Maximum Power Point Tracking (MPPT) circuit but instead makes use of an integrated node and super capacitor. The solar cell is directly connected to this super capacitor. The super capacitor is input and output voltage regulators are absent from the Solar-Biscuit. The working principle of photovoltaic cells is shown in Figure 6, where sunlight is converted into electrical energy through the photovoltaic effect.

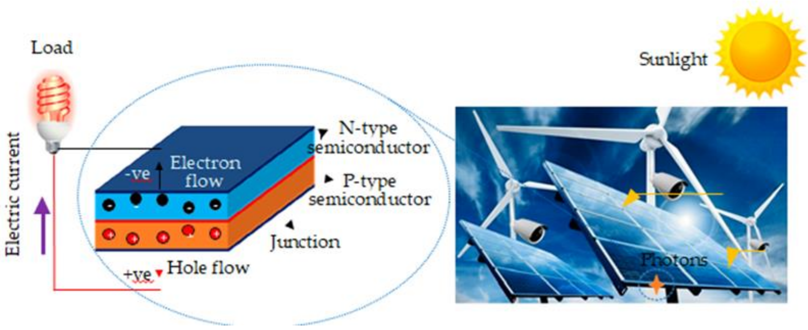

Fig.6 Working principle of photovoltaic cells [6]

2.1.3. Thermal Energy Harvesting

Thermal energy originating from environmental temperature fluctuations can be converted into electrical energy through many essential thermal conversion methods that rely on the Seebeck effect [24-27]. Variations in temperature, thermal power, and the main source of "heat" thermoelectric and pyroelectric energy harvesting techniques are used to extract energy from thermal sources [2]. A 5-8% harvesting efficiency can be attained with thermoelectric harvesting technology. Wireless sensors and battery-free IoT portable devices can use pyroelectric energy harvesting, which converts waste heat energy into electrical energy. Because it has the ability to transform temperature changes into electrical energy, it is a more appealing option for capturing waste heat energy [2]. However, one of the main limitations to thermal harvesting's widespread use is its low efficiency (5–6%) [9]. Recently, the creation of powerful modules and novel thermoelectric materials has led to an efficiency of above 10% [28-31]. As mentioned in [32], a thermoelectric generator is utilized to capture the inherent temperature differential between the earth and air in order to generate electrical energy. Analysis reveals that the best thermoelectric generator currently on the market has very low power conversion efficiency for the manner described above. The kind of soil and water content determine how much power is produced with this method [12].The use of thermoelectric conversion of human heat for power autonomy in human devices is investigated in this study [33]. Skin thermoelectric converters can produce more power per square centimeter than by solar cells, particularly in low light. Using specially made BiTe thermopiles and 100-W watch-sized thermoelectric wrist generators, the first sensor nodes driven by human heat were demonstrated in 2004–2005 [33]. Figure 7 depicts a prototype of a flexible circuit integrated onto the bracelet of the thermoelectric generator (TEG), displaying its application in human energy harvesting.

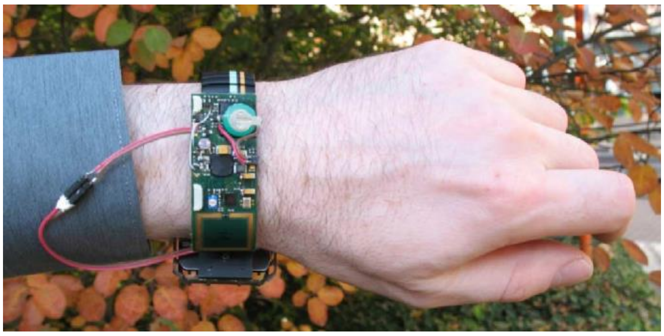

Fig.7 Prototype flex circuit integrated onto the bracelet of the TEG [33].

2.1.4. Harvesting Flow Energy

Typically, flow energy harvesting uses rotors and turbines that use the electromagnetic induction principle to transform rotational movement into electrical energy [9].

Harvesting wind energy: Despite being a readily available alternative power source with a daily output of 1200 mW, wind energy is typically bulkier than what is needed for wireless sensor networks (WSNs) [16]. In [34], Using a DC–DC boost converter with resistor simulation, an average electrical power of 7.86 mW is produced at an average wind speed of 3.62 m/s. The microturbine generated enough energy during low wind speeds to ensure that a TI eZ430-RF2500T sensor node operated correctly.

Harvesting energy from hydropower: Using the energy of falling or flowing water, hydropower, often known as waterpower, is produced. Currently, streams and rivers can accommodate several modest (350-1200W) commercial off-the-shelf units [9]. According to the observed data, a sensor node that transmits readings to the sink node every ten seconds may run on harvested energy for about two hours [35]. Underwater [36] suggested using a small hydro-generator in conjunction with a turbine; however, this conversion is difficult and may affect fluid flow. Within the case of surface-laid pipelines or pipeline in zone troublesome to reach, harvesting energy from solar and wind resources can be unpredictable and inefficient due to varying weather conditions. Vibration resulting from flow is typically the most prevalent and useful kind of vibration [41]. The electromechanical integrated tilt sensor developed by Wang et al. [42] is based on the liquid-solid interface Triboelectric Nanogenerator (TENG), as shown in Figure 8. and the sensor is made with Polytetrafluoroethylene (PTFE), a type of fluoropolymer known for its non-stick properties with copper electrodes sectioned on its surface, clean water flows inside, producing voltage signals that this self-powered tilt sensor measures to detect the ship's tilt degree in real time. The sensor's accuracy compares rather favorably to a commercial sensor.

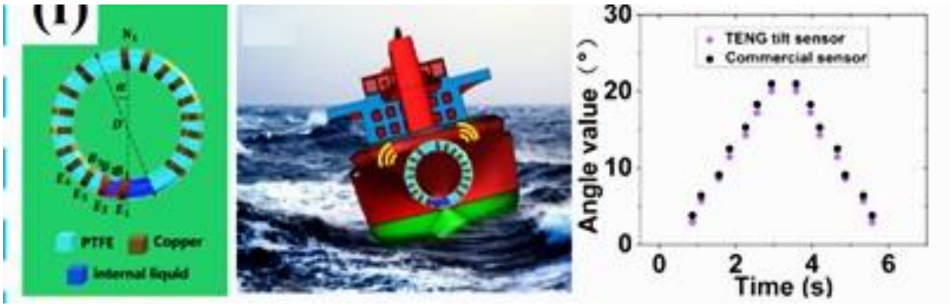

Fig. 8 A robust and self-powered tilt sensor for ship attitude sensing (Reprinted with permission from [37]. Copyright 2020 Elsevier).

2.2. External Resources

2.2.1 Harvesting Mechanical Energy

There are three primary methods for producing electricity from mechanical sources: piezoelectric, electrostatic, and electromagnetic [9]. In the environment, wasted mechanical energy is commonly seen in motions such as walking, driving, vibrating bridges, ocean waves, wind, and mechanical rotation [6]. It is a sustainable and ecologically friendly energy source that may be efficiently used to generate electricity for self-sufficient devices [6]. There are two categories of mechanical energy: potential energy and kinetic energy. Kinetic energy is associated with an object's mobility, whereas potential energy is associated with an object's position or the work it performs. Kinetic energy originates from motion, vibration, pressure, and human activity. For some Internet of Things devices to function constantly during their lifetime, they must be self-powered [2]. The Wang group created nanogenerators in 2006, which are devices that can turn tiny amounts of mechanical energy into electric current [38]. Piezoelectric materials immediately transform kinetic energy into useful energy in piezoelectric systems. Many researchers are using this material to create novel piezoelectric harvesters [39-41]. Shukla et al.'s research [47] shows that flow-induced surface vibration can produce a minor amount of energy that can be used to power small sensor networks using piezoelectric film. The limitations of this study included the use of a single pump frequency to examine the quantity of harvestable energy available and the lack of genuine natural frequency estimation of a pipeline network for different flow scenarios. According to Shukla et al., a typical sensor system made up of a microcontroller (MSP430FR5969) and an accelerometer (ADXL362) would use about 1.8V of electricity each. As shown in Figure 9, the fabricated energy harvesting module and the assembled rectifying electronics PCB demonstrate the process of charging a capacitor before subsequently powering the batteries in the sensor node.

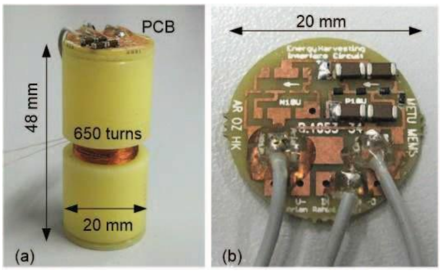

Fig.9 (a) The fabricated energy harvester, and (b) therectifying electronics PCB [42].

2.2.2. Human Energy Harvesting

The need for regular patient monitoring to enable medical personnel to take immediate and suitable action makes the healthcare industry one of the most significant uses of WSN [9]. Human monitoring is undoubtedly another significant use for energy harvesting technology, with potential for the creation of implantable or wearable self-powered or self-sustaining systems for movement tracking or therapy [43]. Wireless Body Area Networks (WBANs), which use sensor nodes that are installed on or inside the human body to continuously monitor physiological signs, have therefore gained a lot of attention lately [9]. All other sources are not as good as human-based energy harvesting, where nodes run on humans for long periods of time. Physiological factors that are intrinsic or activity-based can be used to extract energy from movement, finger position, body temperature, and blood flow [9]. Guo et al. [50] developed an Artificial Intelligence AI-enabled caregiving walking stick using a hybridized electromagnetic-triboelectric nanogenerator and a linear-to-rotary structure.Figure10 illustrates the collection and storage of conformal piezoelectric energy from heart, lung, and diaphragm motions [51].

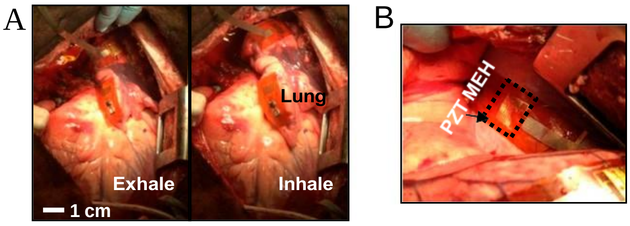

Fig. 10 (A) Image of a PZT MEH installed on a cow lung that has been cointegrated with a microbattery and rectifier. Voltage for these devices on the bovine as a function of time, (B) Picture of a PZT MEH on the diaphragm of a cow. For such a device on the bovine, voltage as a function of time [51].

As summarized in Table 1, various energy sources for IoT devices exhibit different characteristics, power densities, and efficiency levels, highlighting the strengths and limitations of each energy harvesting method.

Table 1. A Comparison of different energy sources [45, 46, 16, 12].

Energy source	Characteristics	Harvester	Power Density	Advantages	Disadvantages
Solar energy	Ambient, Uncontrollable, Predictable	PV Panel	15 - 100 mW/cm2	Consistent; Available during daytime; high output voltage	Not available in night; efficiency is low during cloudy days; Deployment Constraints
Wind energy	Ambient, Uncontrollable, Predictable	Anemometer	1200 mWh/day	Available in open areas	Not available in closed areas
Finger Motion	Active human power, fully controllable	Piezoelectric	2.1 mW	Available whenever needed	Energy is harvested only when finger is moved
Footfalls	Active human power, fully controllable	Piezoelectric	5 W	Available whenever needed	Highly variable output
Vibration (indoor Environments)	Ambient, Uncontrollable, Unpredictable	Electromagnetic Induction	0.2 mW/cm2	Without voltage source	Brittle materials
Thermal Energy	Ambient, Uncontrollable, Unpredictable	Thermocouple	≅50 mW/cm2	Long life, reliable with low maintenance	Low energy conversion efficiency
Motion	Non-Ambient, Controllable, Partly-predictable	iezoelectric	200 µW/cm2	Light weight	Highly variable output
Breathing	Passive human power, uncontrollable, unpredictable	Ratchet-flywheel	0.42W	Available all the time	
Radio frequency	Non-Ambient, Partly-controllable, Partly-predictable	Rectennas	1 µW/cm2	Sufficient in urban areas; very high energy density;	Few in suburbs; material in radioactive are extremely

				Allow mobility	dangerous; low power density

3. POWER REQUIREMENTS FOR CONDITION MONITORING BASED ON WSN

Electric energy in a WSN is mostly used to power the communication, processing, and sensing units, as Figure 1 illustrates. Furthermore, the applications that specify the real transmission rate and distance needed to accomplish an application's functions have a significant influence on the power consumption of WSNs [6].

3.1. Wireless Power Consumption of a WSN Based System

When creating an energy harvesting system should take into account two important factors prior to the design stage: the quantity and the pace of energy harvested over time [44-45]. It is challenging to consistently supply the device with enough power since energy harvesting from the environment is unpredictable, that is, the amount of power generated at any time instance is random [1]. Hence, it is possible to differentiate between different energy sources based on their predictability and controllability. Prediction is unnecessary with regulated energy sources because harvestable energy will always be available when needed. Energy from uncontrollable energy sources will be captured whenever it becomes available. If the energy source for non-controllable energy sources can be projected, it will also be easy to estimate when the energy source will be available again in order to gather energy [13]. Table 2 provides a summary of the various energy sources and their associated characteristics.

Table 2. Characteristics of various energy sources [9].

Energy source	Predictable	Controllable	Non-controllable
RF	√		√
Solar	√		
Thermal			
Flow			
Wind	√		
Hydro	√		
Mechanical			
Vibration		√	
Pressure		√	
Stress-strain		√	
Human			
Activity		√	
Physiological			√

The most difficult and demanding research component, aside from harvesting techniques, is to develop energy management strategies to effectively handle captured electricity in order to minimize loss. Having a power management component without sacrificing the harvesting concept is the best way to transform the captured energy. For the past ten years, researchers have been working very hard to develop the best solutions possible, like System on Chip (SOC) [46], Power management modules [47-48], power management strategies, and power integrated circuits (PMIC) [49-50]. The sensor unit, on the other hand, uses the least amount of power, usually in the microwatt or milliwatt range, as demonstrated by Table 3's sensor module specifications.

Table 3. Typical sensor characteristics and modules[6].

Sensor Type	Sensor	Resolution	Dara Rate (Hz)	Power Consumption (Measurement µW)	Power Consumption (Standby µW)
Accelerometer	ADXL345	10 bits	Max. 3200	100	0.25
Accelerometer	MPU-6050	16 bits	Max. 1000	1650	16.5
Accelerometer	LIS2DS12TR	16 bits	Max. 6400	270	1.26
Temperature	TMP006	0.03125 °C	1000	792	-
Temperature	D6T-44L-06	0.14 °C	-	25	-
Pressure	BMP280	0.18 Pa	1	9.042	0.33
Humidity	HDC1000	14 bits	1	2.46	1

Light	OPT3001	0.01 lux	1	4.5	-

Please see the datasheets for the different modules.

An important issue for IoT and energy-harvesting systems to deal with is the power management. The device's power generation and consumption balance determine the provocation. The device's consumption ratio determines whether the harvested power is greater or less than the generated power, as the harvesting source is erratic. Consequently, the continuous or discontinuous nature of the operational modes can be configured appropriately [5].

4. OPEN RESEARCH CHALLENGES

EH, in (IoT) faces several challenges that can impact its widespread adoption and effectiveness. These challenges range from technical to environmental and economic concerns. The key challenges in EH can be summarized as follows:

1. Efficiency of energy conversion: One of the main challenges is the efficiency of transforming surrounding energy sources (such as light, heat, or vibrations) into usable electrical energy. Many energy harvesting technologies have relatively low conversion efficiencies, which limits the amount of power available to IoT devices.
2. Intermittency and unpredictability of energy sources: Ambient energy sources are often intermittent and unpredictable. For instance, solar energy depends on time of day, weather conditions, and geographical location, making it challenging to ensure a consistent energy supply for IoT devices.
3. Energy storage and management: Efficiently storing and managing the harvested energy is crucial, especially since IoT devices must often operate continuously or on a predictable schedule. Energy storage solutions (like batteries or supercapacitors) need to be compact, efficient, and capable of charging and discharging cycles that match the device's requirements.
4. Size and integration challenges: Incorporating energy harvesting technologies into small or compact IoT devices can be challenging due to size, weight, and integration constraints. The energy harvesting apparatus must not significantly increase the device's size or complexity.
5. Cost: The initial cost of energy harvesting technologies can be high, especially when considering the economies of scale for deploying large numbers of IoT devices. This cost includes not only the energy harvesting components but also the necessary circuitry for energy management and storage.
6. Environmental impact: While energy harvesting aims to reduce dependency on batteries and their associated environmental issues, the materials and processes involved in producing energy harvesting devices also have environmental impacts that need to be considered and minimized.
7. Longevity and durability: Energy harvesting devices and the IoT devices they power must be durable and capable of operating under varying environmental conditions without significant degradation over time.
8. Regulatory and standards compliance: As with any technology deployed in public or critical infrastructures, energy harvesting solutions must comply with a range of regulatory standards and certifications, which can vary widely across different regions and applications.
9. Security Concerns: Ensuring the security of IoT devices powered by energy harvesting technologies is paramount, as these devices often collect and transmit sensitive data. Secure operation must be maintained despite the potentially limited power available for encryption and other security measures.

   Addressing these challenges requires ongoing research and development in materials science, electronics, and IoT system design. Advances in nanotechnology, low-power electronics, and energy storage solutions, alongside smarter energy management algorithms, are key to overcoming these hurdles and unlocking the full potential of energy harvesting in the IoT ecosystem.

5. CONCLUSION

A survey of the literature on several energy harvesting technologies for Internet of Things devices is presented in this research. One potential way to extend the life and improve the performance of IoT devices is to harvest energy from various sources, including the environment. Energy harvesting systems have a number of drawbacks, such as poor energy harvesting rates, scarce energy sources, inefficient systems, etc. In order to overcome these limitations, a lot of research has been done in the past, and new harvesting models have been developed. In this publication, we offer an overview and comparison of several energy harvesting methods, which could be helpful to academics researching energy harvesting. Energy harvesters are used extensively in a variety of application fields nowadays, such as industry, healthcare, agriculture, etc., and this is one of the crucial subjects that need additional study.

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