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Energy-Harvesting for IoT-based Wireless Nodes: A Progress Study

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Abstract: Energy-harvesting technology is a promising renewable energy source for many applications through deriving energy from ambient environments. In IoT-based devices, this plays a significant role in providing sustainable energy and overcomes the need for battery maintenance and replacement, leading to increased efficiency, reliability, and operation time. This paper focuses on energy- harvesting in the context of IoT-based wireless nodes, its current progress, and future expectations. The main components, energy dissipations, and powering sources of IoT-based nodes are, first, identified. Then, the various ambient energy-harvesting sources and general architecture of the IoT-based energy-harvesting node are presented and concisely discussed. Finally, a progress discussion on the current and future trends of energy-harvesting technology for IoT devices is provided from different aspects, while shedding light on the key challenges facing the growth of energy harvesting for IoT-based systems. Overall, the paper provides a contemporary study that helps researchers who are working in this area and aiming to participate in its developments.

Keywords: Energy-Harvesting, Energy-Efficiency, Internet of Things (IoT), Wireless Sensor Networks (WSN), Energy- Efficient IoT, Green IoT

1. Introduction

Internet of Things (IoT) technology is rapidly expanding in various sectors, playing a key role in a wide variety of innovative applications. This opens significant possibilities and promises numerous advantages in many domains, supporting both society and the working life [1], [2]. IoT applications cover a wide range of areas surrounding our daily life, such as smart grid, automation, smart mobility, smart building, health care systems, smart transportation, agriculture and breeding, environment monitoring, security and surveillance, and many others [3], [4]. However, IoT challenges appear in some key domains, including energy-related issues, as most IoT applications need continuous and stable energy sources in order to operate continuously and do the job perfectly for a longer period of time (months to years) [5]. Typically, the IoT-based nodes are equipped with elements having limited capabilities (e.g., battery, storage, processor) in order to make them smaller and minimize the operational cost [6], [7].

However, this leads to shortening nodes' lifetime if these resources are not utilized efficiently. Thus, the design and configuration of the IoT-based wireless nodes focus on minimizing unnecessary energy dissipations and maximizing the time in which the nodes remain working perfectly. For this, one given solution is enabling nodes to be in the active state for a very limited time ("on" state) when it is needed only and to turn into the sleeping state for the reset of time wherever there are no activities to be done. However, this may depend on the type of application and its requirements, which usually differ from one IoT system to another. Furthermore, As the number of IoT-connected devices is expected to

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increase in the near future, the mode of energizing these devices becomes a major challenge and requires efficient solutions, especially for systems that comprise a significant number of sensors and IoT-based devices [8]. For example, in smart parking systems, ultrasonic sensors are utilized for each parking space to detect whether there is a car or it is empty. The sensors are embedded in the ground pavement or mounted on the ceilings. Using cords for powering such sensors, installation and removal is a major construction issue that takes much time and cost. In another case, in the livestock field tracking system, a large number of battery-operated devices are usually used for monitoring animals. The battery replacement or maintenance process for all attached devices becomes more complicated and requires much time and effort. Energy-harvesting, which can be used to power IoT wireless nodes and other connected devices without a need for traditional batteries or power connection cords, is an effective solution that attracts attention and has shown its usefulness in various sectors recently [9]. Energy harvesting provides a sustainable and environment-friendly source of energy for nodes and helps in prolonging the longevity of the network lifespan in IoT-based systems.

This paper presents a progress study in which we discuss several aspects of energy-harvesting technology in IoT-based nodes, showing its importance, its main sources, and how it is rapidly improving. The rest of this paper is organized as follows. Section 2 introduces the components of IoT-based nodes and their powering sources. Section 3 provides brief discussions on the primary sources of energy-harvesting for IoT nodes. Section 4 presents the general architectural model for the energy-harvesting enable IoT node, while Section 55 provides a discussion on the current progress of the energy-harvesting technology, market growth, future trends and expectations, and key challenges. The paper is concluded in Section 6.

2. Components of IoT-based Node and Power Sources

In the IoT-based system, the major tasks of wireless sensor nodes are to collect data in a time-driven or event-driven model, perform aggregation/compression tasks, and send it to the central server. The typical architecture of the IoT-based node is depicted in Fig. **1**, which generally consists of four basic subsystems: sensing/identification unit, processing/computation unit, radio/ communication unit, and power supply unit [10].

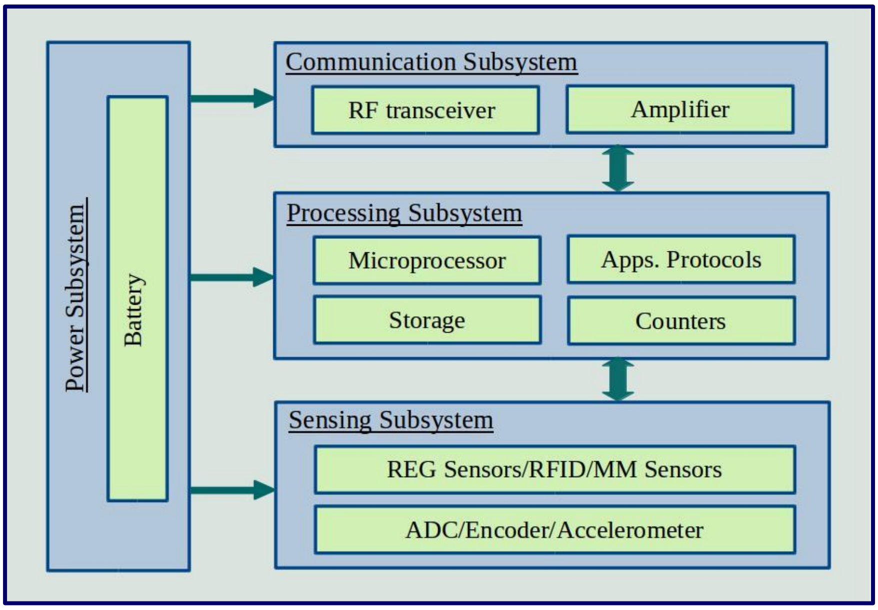

Fig. 1 - A general architecture of the IoT-based wireless node

The total energy expenditure of a node at a specific time is based on the operating state of the node, for which three different states are defined: active state, idle state and sleeping state [11]. In the active state, all the three units are running and the node consumes the maximum amount of energy. The highest amount of energy is consumed due to transmitting and receiving data packets at the radio subsystem [12], [13], while the sensing subsystem dissipates the lowest energy. The processing subsystem uses a higher amount of energy than that used by the sensing subsystem, but it is much less than that used by the communication subsystem [14]. The energy consumed during the active state depends on the transmission distance, application requirements, monitored event, and the type of activities carried out by each subsystem. In the idle mode (also called listening mode), the node just waits for possible communication from other nodes to receive incoming data packets. The energy dissipation in this state (which may equal 50%-100% of the receiving energy) is consumed by the CPU, communication radio, etc. [15], [16]. The node does not process any task during the sleeping mode, and the radio subsystem is usually turned off; thus, less energy is consumed [17]. However, there are a number of other energy dissipation sources that contribute to the actual energy consumption. These include packet collision, protocol overheads, packet losses, frame overhearing, computation overheads, physical channel errors, etc. [18], [19].

Generally, the power subsystem of the IoT-based node is the only unit responsible for supplying energy to all the other parts of the node, as seen in Fig. **1**. However, the power sources for this subsystem in the IoT-based nodes have been classified into three main categories, which are: (i) energy storage, (ii) power distribution, and (iii) power harvesting [20], as depicted in Fig. **2**.

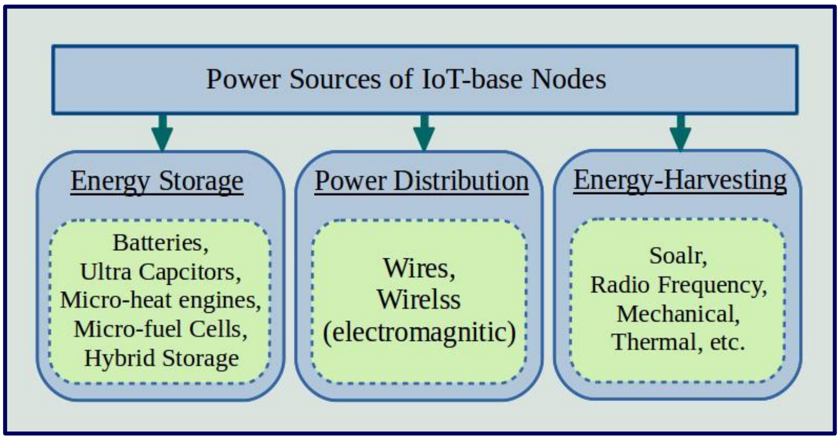

Fig. 2 - Power sources for IoT-based wireless nodes

However, as one of the node power sources, energy-harvesting has become one of the promising technologies of energy provision for powering small devices and wireless sensors in the IoT and cyber-physical environments [21], [22]. The past few years have shown that this technology has been broadly utilized in various IoT advancements and innovative applications worldwide [23]. The IoT devices and tiny objects can efficiently derive the energy from external signals in the surrounding sources and convert it, with different levels of efficiency, to electricity. Then, the obtained energy can be instantaneously utilized for the current operations or can be kept for the future supply [24]. This leads to bigger improvements in the system lifetime and overall network performance, including energy-saving, throughput, stability, and fault tolerance [25], [26].

3. Energy Harvesting Sources

Energy-harvesting techniques are being utilized in order to ensure a continuous energy source and achieve a perpetual node lifetime in the IoT-based systems by scavenging energy from external power sources. The external sources for energy-harvesting can be categorized into two primary groups: ambient sources and dedicated sources [27], [28]. Ambient energy sources are usually available in the surrounding environment. The energy can be obtained at a free cost but with significantly different levels of strength [29]. Dedicated energy sources refer to the power providers that are intentionally deployed for energy provision to wireless nodes that require an extra amount of energy [30]. Furthermore, the energy sources can be identified as controllable or noun-controllable. A controllable source ensures the availability of external energy to be harvested whenever needed, while a non-controllable source can provide harvestable energy whenever it is available [31]. Here, unlike the controllable source, a prediction model may be required for uncontrollable sources to assess the availability in the case of a predictable energy source and define the time of the next recharge cycle [32]. However, for any energy harvesting architecture, the nature of the energy source is the crucial parameter that defines the level and the rate at which the energy can be derived. The ambient energy-harvesting sources from which energy can be efficiently harvested are classified into four main categories [24], [27], [33], as listed below and illustrated in Fig. **3**.

- Solar-based energy sources.
- Radio frequency-based energy sources.
- Mechanical-based energy sources.
- Thermal-based energy sources.

Each of these categories has its own subcategories of energy harvesting sources from which electrical energy is obtained through various energy harvesting technologies. Below, we briefly elaborate on each of these categories, form which the appropriate technology can be chosen based on the nature of devices for which the energy is harvested, the purpose of the IoT system, as well as the location and environment.

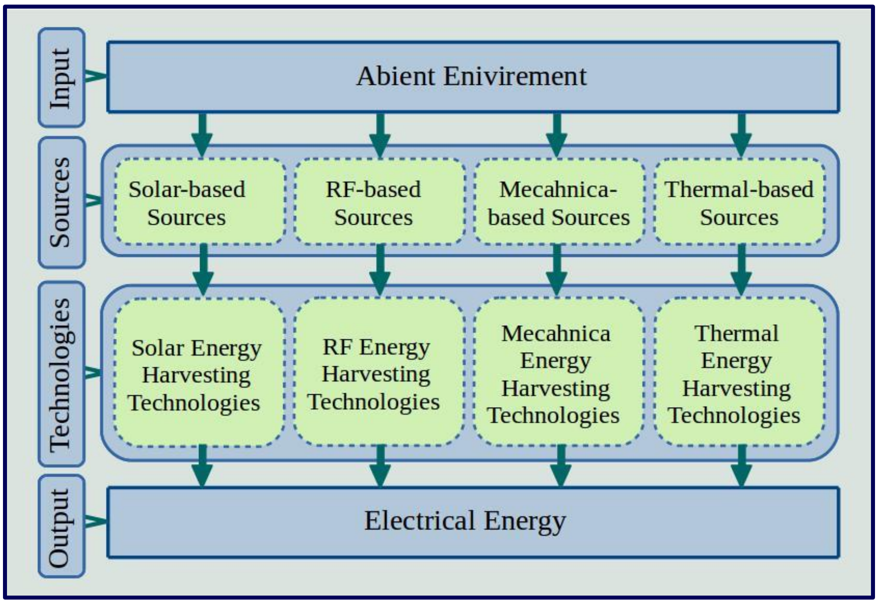

Fig. 3 - Ambient energy-harvesting sources for IoT-based wireless nodes

3.1 Solar-based Energy-Harvesting Sources

Solar power is a primary energy harvesting source utilized in WSNs and IoT-based systems. As an affordable and clean source of energy, it is regularly available. It is convenient for various implementations of energy-harvesting systems to overcome the problem of power consumption in the IoT limited-resources devices and wireless sensors [34]. These sources widely vary based on the technology used in the solar cell and the density of light applied to it (e.g., outdoor or indoors) [35], and hence, the conversion efficiency differs according to the level of illumination as reported in [36]. The tiny device contains a silicon micro-conductor electrical junction called a solar cell. This cell accumulates sunlight with adequate energy; then, the electrons start flowing through the I/O regulator into the attached load. The highest level of sunlight can be received during the daytime due to limitations during the night. Hence, the focus should be on obtaining the maximum possible efficiency of harvested energy during daylight hours [37].

3.2 Radio Frequency-based Energy-Harvesting Sources

Radio frequency-based energy-harvesting source, or RF-harvesting, is suitable to supply power for higher numbers of devices deployed in a large area [38]. It builds on the fact that the RF signals, having a frequency between [3kHz, 300GHz] range, can be used as a carrier for energy as an electromagnetic signal that can be converted to electricity for powering the resource-limited wireless networks [25], [27], [39]. There are two categories of RF harvesting nodes: out-of-band and in-band harvesters [40]. In the out-of-band RF harvesters, the frequency band of the received power signal can be different from that used for communication. This requires two separate antennas in the wireless node: one for deriving energy and the other for exchanging information, where the nodes can harvest energy and transmit/receive data simultaneously [41]. For the in-band RF harvesting nodes, the energy can be derived from the frequency band of the data transmission itself. In this case, the node can share the same antenna for information and energy-harvesting parts. Moreover, the energy and information can be obtained from the same RF input signal since this signal can carry energy and data as well [42].

3.3 Mechanical-based energy sources

Mechanical-based energy sources present in several ways in our environment. The changes in a physical object's motion or position can be exploited to obtain electrical energy that can be stored and then utilized for powering devices. Mechanical-based energy sources can be driven by different ways, such flowing fluid (like water and wind), rotational and linear motion, vibration, strain-deformation, sound, body movement, etc. [43]. For example, flow-based systems for energy harvesting usually use the concepts of electromagnetic induction to convert the movement of rotors and turbines into electrical power [44]. There exist many types of rotors in such techniques, including wind/air-flow-based and hydro-based (moving/falling water), which have been broadly adopted in several energy harvesting systems recently [45], [46]. Energy- harvesting from movement, pressure, vibration, and stress-strain can be achieved in several environments. For example, industrial machines, automotive, structures (bridges, railways), buildings, household appliances, etc. The power is harvested through a proper energy converter/generator (mechanical-to-electrical) using electrostatic, piezoelectric, or electromagnetic fundamentals [47].

3.1 Thermal-based Energy-Harvesting Sources

Thermal power can be harvested from many external sources such as heating radiators on a large-scale and human body temperature in small-scale scenarios. The energy can be derived by converting the thermal difference/gradients to electricity from the Seebeck effect with an attached load [24], [48]. Even though thermal energy harvesting has a low efficiency that limits its widespread adoption, smaller temperature differences can be achieved for wearable applications (for example, at 5K). In contrast, higher gradients are obtainable in other conditions such as indoor heaters. For example, the power densities that can be gained by microfabricated elements is recorded as follows: 0.60 uWmm2 for 1.12mm2, 0.37uWmm2 for 68mm2, and 0.14uWmm2 for 700mm2 devices [49], [50], [51].

However, choosing an appropriate energy-harvesting source is essential to achieve efficient and effective power harvesting and maximize the energy obtained. This depends on some factors such as the power level required by the wireless nodes according to the application, and the strength level of the source energy (e.g., sunlight, RF radiated signal, wind, vibration, etc.). Even though the converted energy at the harvesting node is generally a small amount (in order of microwatts/milliwatts); nevertheless, it is adequate to supply small devices and smart wireless objects.

4. General Architecture of Energy-Harvesting Node

The general architecture of the energy-harvesting node, as shown in Fig. **4**, consists of two major sets: (1) the information segment and (2) the energy-harvesting segment. The energy-harvesting part consists of three components: an energy harvester circuit, a regulator, a power control module, and a rechargeable battery/capacitor. The harvesting circuit accumulates the harvested energy and then passes it to the regulator circuit, converting it into electricity. This energy is then delivered to the power management module, which decides whether to use this energy can be used immediately for the current operation (harvest-use) or be stored in the battery for future use (harvest-store-use) [52]. Some of the energy-harvesting nodes do not have a battery; hence, harvested energy is directly used to power the sensor node subsystems [53]. For example, the passive RFID (Radio Frequency Identification) tag is a simple energy harvesting solution. It receives an inquiry signal from an RFID reader and directly uses this signal to power itself to respond to the reader with its identification data. In this case, the achieved energy must be more than the minimum energy required for the node operation. Otherwise, the node will fail to keep working and will be deactivated. In the complete IoT-based systems, which contain energy-harvesting nodes and non-harvesting nodes, the harvesting nodes, in most of the scenarios, are assigned to the power-hungry tasks, such as data aggregation and data transmission for more considerable distances. At the same time, the normal battery-operated sensors can do the other low-power operations and are assigned higher sleeping periods. Thus, extending the working time of non-harvesting nodes and keeping systems functioning well.

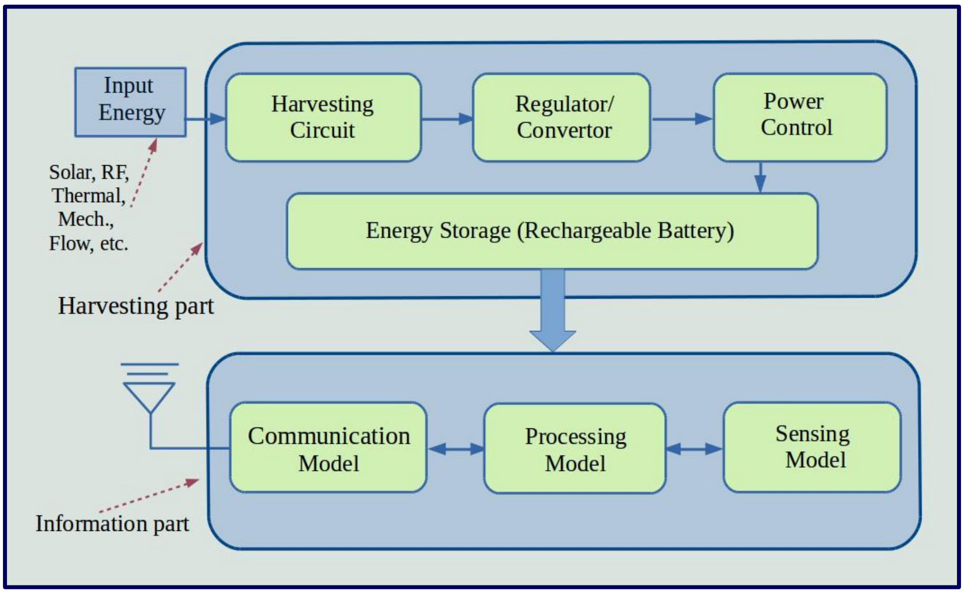

Fig. 4 - A general architecture of the energy-harvesting node

5. Progress and Future of Energy-harvesting for IoT

In the IoT-based systems, wireless nodes (sensors and actuators) are the main components responsible for data collecting and controlling other parts of the systems in connection with end-user devices and interfaces. Considering battery limitations and energy efficiency of such nodes have been identified as a must in the early design stage [54] in order to ensure sustainable and long-term operation. The world, the energy industry has started adopting renewable resources rapidly in various devices of IoT-based systems. However, this depends on the IoT application, the type of devices, their peak power demands, the type of harvester employed, its availability, and the harvested power density. All these together determine the available options for choosing the suitable energy harvesters [55], [56]. Fig. **5** shows the IoT-based devices with low power consumption, for which energy-harvesting is a highly practical solution. While Table 1 presents a comparison of the typical power densities for different sources of energy-harvesting technologies as presented in [56].

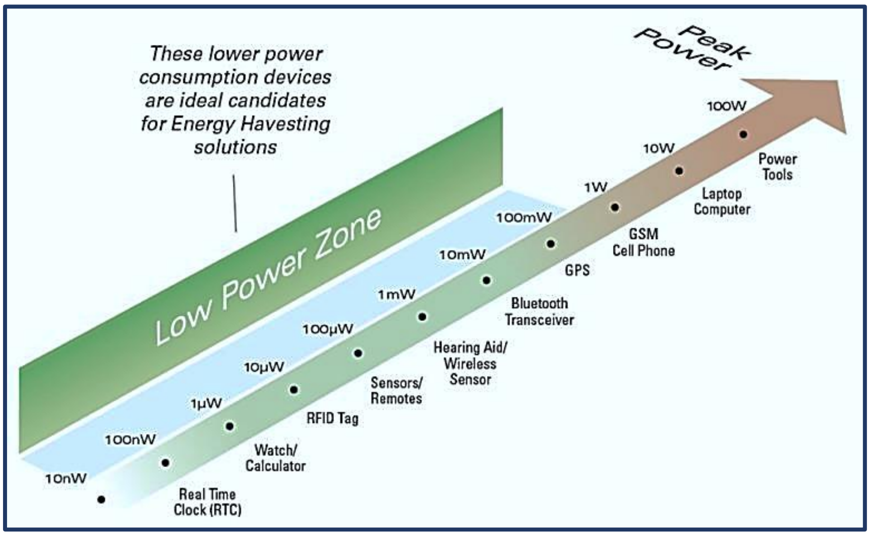

Fig. 5 - Peak Power Levels for Typical IoT Devices (Source: [55])

Table 1 - Levels of power density of different energy-harvesting sources

Energy Source	Power Density	Harvesting Methods
Solar (outdoors)	100 mW/cm3	Solar cells
Solar (indoors)	100 µW/cm3	Indoor solar cells
Vibration (machine option)	800 µW/cm3	Electromagnetic
Wind	177 µW/cm2	Generator
Thermal (industry)	10 mW/cm2	
Radio frequency	300 µW/cm2 to 2 mW/cm2	Patch/magnetic coil antenna

As the number of connected IoT-based sensors and devices increases, energy-harvesting has been considered the most potential solution to provide a free source of electricity and guarantee uninterrupted nodes' operation. In addition, it may decrease the cost of an IoT-based system while representing a clean and environment-friendly technology that can operate for extended periods without a need for maintenance and replacement of its components. [57].

Also, such rapid growth of IoT applications and other related technologies such as M2M, IIoT, smart cities, and additional development of advanced technologies are further expected to increase the IoT energy-harvesting market growth [58]. In its annual report, ConFlow Power Limited indicated that even though the number of players in the energy-harvesting for IoT-based devices and related application market is still low, the expectations of the market size showed that it is rapidly increases. For example, as given in [57] and shown in

Fig. **6**, the energy harvesting market size for the IoT-based devices in 2019 was estimated to reach $59 million, $52 million, and $25 million in Europe, North America, and Asia respectively; while in 2025 the estimation said that it will reach $96 million, $91 million, and $4 million for the same continents respectively.

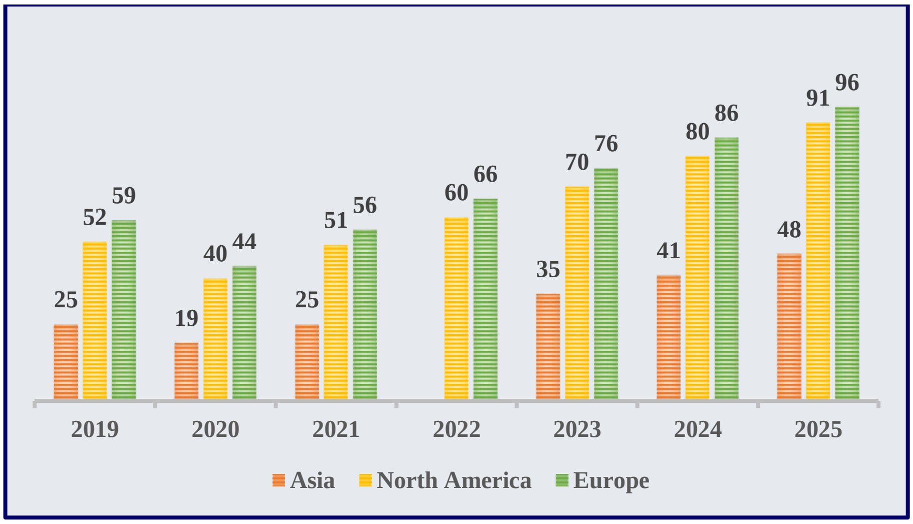

Fig. 6 - The market size of the energy harvesting for IoT-based devices in USD million

Recently, reducing the environmental impact of ICT components has been a generalized trend, which also applies to IoT-based systems in order to produce energy-efficient and sustainable smart systems. Thus, the growth in the integration of energy-harvesting technology into IoT-related products will reduce the use of traditional batteries, which has a direct impact on carbon emission reduction. Using energy harvesters with rechargeable batteries/ capacitors for the IoT-based wireless nodes is a promising solution, and can highly extend the nodes' lifetime. At the same time, it minimizes the cost as well as reduces the environmental footprints of batteries' waste pollution. Thus, increasing IoT-based devices that adopt energy-harvesting technology greatly contributes to making the environment green and reaching zero carbon emission by 2025 [59], [60].

Fig. **7** shows how the size of the unpolluted environmental area increases as the parentage of energy-harvesting implementation increases [61]. However, the footprints of the energy-harvester components themselves should be taken into account so that a special design of the energy harvester and the storage battery/capacitor must be carefully chosen so as to yield zero or minimized environmental footprints.

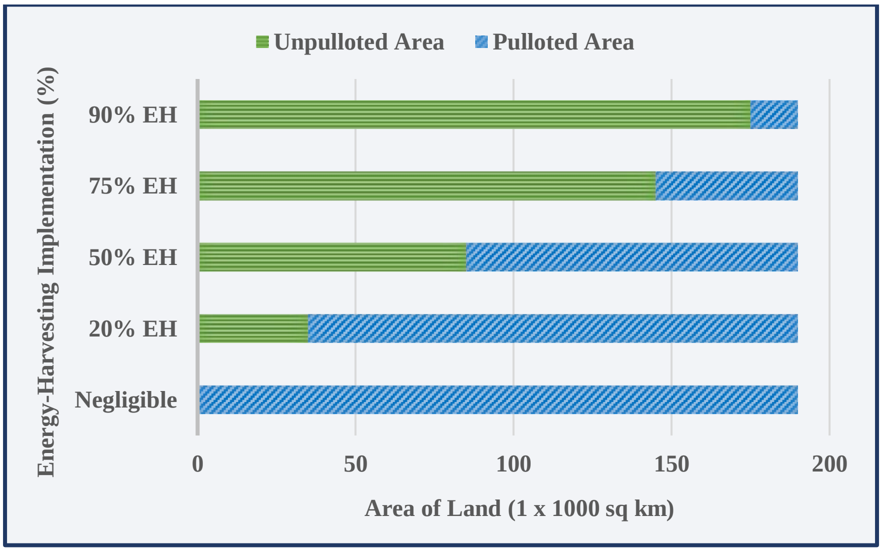

Fig. 7 - Positive impact of energy harvesting on the environment

Also, there are two main trends that make the energy-harvesting for IoT devices a perfect powering option in the near future. First is the wider adoption of IoT-based devices in various sectors and automation systems, while the second is the increased demand for using safe and clean power sources that require minimum maintenance, cost, and effort. In environments that are rich with IoT-enable devices such as industries, smart vehicles, and smart buildings, energy-harvesting can greatly help in reducing the cost of reinstallations and modifications of wiring and maintenance [62]. In such situations, the energy-harvesting techniques can be easily utilized, where a small amount of energy-driven from the ambient environment is enough to operate a sensor node. Thus, investments in energy-harvesting enabled IoT products will significantly reduce the cost and increase the adoption of sustainable energy equipment.

However, even though energy-harvesting technology shows a growing interest over the past few years, there are a number of challenges that should be considered and need more research studies and investigations. This includes the level of availability of energy sources in the environments adopting energy-harvesting technology, the level of the energy that can be harvested from the selected source, the type, size, and longevity of the harvested energy storage, and the techniques of combining energy from multiple energy harvesting sources, and the balancing between the harvested energy and the amount of energy consumed by IoT wireless nodes. [54], [63].

6. Conclusion

Energy-harvesting technology has been widely utilized in most IoT-based applications and smart systems, specifically, the applications in which the nodes are deployed once on a large scale and required to be working continuously for longer periods of time. In this paper, we provided a progress study on the energy-harvesting technology for IoT-based wireless nodes. We started with identifying the main parts of an IoT node, its energy dissipation behavior, and powering sources. We, then, discussed different ambient energy-harvesting sources of the IoT-based wireless node as well as its general harvesting architecture. We also provided a discussion on the current progress of this technology and its potential future trends and market growth, stating the major challenges that may face its adoption. However, energy-harvesting is a promising technology that enables IoT-based nodes to get reliable and sustainable energy sources and achieve long-lasting operations.

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