A Comprehensive Review on Techniques and Challenges of Energy Harvesting from Distributed Renewable Energy Sources for Wireless Sensor Networks

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***Abstract*—Wireless Sensor Networks (WSNs) have drawn a lot of interest from a variety of industries, such as industrial automation, healthcare, and environmental monitoring. Typically, these networks are made up of sensor nodes that run on batteries and depend on energy-efficient operation to extend their lifetime. Renewable and sustainable energies are suitable for wireless sensor networks. Energy harvesting from dispersed renewable sources, such as solar, wind, biomass, and vibration, has emerged as a possible approach to alleviate the limits associated with limited battery life. The state-of-the-art methods and difficulties associated with energy harvesting in wireless sensor networks (WSNs) from a variety of distributed renewable sources, such as solar, wind, vibration, and temperature gradients, are thoroughly reviewed in this study. The paper discusses the many techniques for extracting and converting energy from these sources, highlighting the benefits and drawbacks of each. This paper explores several energy harvesting techniques and challenges. The study also discusses the difficulties in integrating energy harvesting, including adaptive power management, energy forecast, intermittent energy supply, and integration issues. The assessment also highlights research gaps and potential future initiatives in the field of energy harvesting from renewable sources. Researchers, technologists, and policymakers working in the fields of renewable energy and wireless sensor networks would find this thorough assessment to be quite insightful. It illuminates how energy harvesting technologies may improve sensor network autonomy and sustainability, leading to breakthroughs in environmental monitoring and other vital applications. The development of sustainable, independent, and effective sensing systems is greatly aided by the investigation of methods and obstacles in energy harvesting for wireless sensor networks. In addition to addressing current issues, this research opens doors for innovation, fostering a more sustainable approach to data collection and monitoring, and having a positive effect on a number of industries.**

Keywords*—Energy Harvesting Techniques, Distributed Energy Sources, Wireless, Sensor, Networks

I. INTRODUCTION

The introduction of Wireless Sensor Networks (WSNs) has completely changed how we gather and use data in a variety of fields, including smart cities, healthcare, and industrial automation as well as environmental monitoring. These networks are usually made up of tiny, wirelessly-communicating sensor nodes that run on batteries. This allows real-time data gathering from hard-to-reach or distant areas. As Internet of Things (IoT) and wireless sensor networks (WSNs) grow in popularity, there is a growing demand for reliable protocols that can ensure high throughput and long lifespan. Device mobility, whether as mobile sinks or nodes, is a promising solution that can help with congestion mitigation and topology control, for example [1]. But one major drawback of WSNs is that these sensor nodes have limited energy storage, which limits how long they can operate for and often requires regular battery replacement or recharging. Coverage and quality detection are the two most important aspects of wireless sensor networks (WSNs) when it comes to factors like reduced power consumption and high service quality. Because of power limitations and the inability to replace batteries, network lifespan is a crucial component of network coverage in wireless sensor network (WSN) applications [2]. Energy harvesting methods, which entail absorbing and converting energy from dispersed renewable sources, such as solar radiation, wind, vibrations, and temperature gradients, have been the focus of research and engineering efforts to get over this constraint.

This study explains the various energy harvesting techniques. Numerous studies on the piezoelectric harvester have shown that the mechanical device's energy output can surpass the 1.4-volt threshold, making it appropriate for charging capacitors in electronic devices. The results of this investigation will be essential in easing society's energy crisis [3], Challenges of energy harvesting techniques include system administration, control, and optimization; economic challenges include high capital costs and unclear returns on investment [4], and effect of DERs in WSNs from such dispersed renewable sources. It also provides a thorough overview of the techniques and difficulties involved. The study highlights the possible applications and future prospects in this quickly developing sector, as well as addressing the crucial issues of adaptive power management and intermittent energy supply. For individuals who are interested in maximizing the potential of renewable energy sources to improve the independence and sustainability of wireless sensor networks, this study is an invaluable resource. The widespread use of wireless sensor networks (WSNs) has brought about revolutionary potential in several industries by enabling instantaneous data gathering, observation, and management in inhospitable or distant settings. Recently, wireless body area networks, or WBANs, have been used to monitor patient conditions both inside and outside of hospitals, athlete activity, military applications, and multimedia in an effort to improve people's quality of life so energy is important for WSNs here [5]. These networks use batteries as their main energy source since they are made up of small sensor nodes with constrained processing capabilities. Battery power is handy, but it has drawbacks since batteries have a limited capacity and must be often replaced or recharged. The investigation of other methods to increase the operating lifetime of WSNs has been spurred by this limitation.

Using energy harvesting techniques which include gathering and transforming energy from naturally occurring and dispersed renewable sources is one especially promising approach. These sources may take many different forms, including wind energy harvesting. Wind power prediction can enhance the technical and financial integration of wind energy into the current electrical grid and is required for the proficiency assessment of a potential wind site. In order to determine the best location for wind power generation, the study compares the analysis of wind power prediction between Kuala Lumpur and Melaka in Malaysia [6], The physical, optical, and electrical characteristics of single-halide Perovskite absorption materials based on cesium tin-germanium triiodide should be taken into account in order to provide the best photovoltaic application [7], mechanical vibrations, temperature gradients, and mechanical vibrations. With energy harvesting, sensor nodes may operate sustainably and autonomously, which lowers maintenance costs and improves network resilience. In the context of wireless sensor networks, this thorough analysis aims to provide a thorough examination of the methods used in energy harvesting from distributed renewable sources. It explores strategies for efficiently managing the captured energy and explores the complexities of energy conversion systems. The assessment also addresses the variety of difficulties that arise when putting energy harvesting systems into practice, such as the erratic and intermittent nature of renewable energy sources and the need for flexible power management techniques. The study also emphasizes the advantages and possible uses of incorporating energy harvesting into wireless sensor networks, highlighting the roles that these networks play in environmentally friendly and sustainable projects. The growing number of scientific and industrial applications for Wireless Sensor Networks (WSNs) has made it necessary for users to find other solutions for ensuring their continuous operation over extended periods of time. One such solution is the need to avoid relying exclusively on batteries, which have limited energy supply, storage capacity, and lifespan. Renewable energy could be a good solution for this WSNs. [8]. It also points up areas that need further investigation and creativity in the sector, promoting the search for fresh approaches and plans for getting over existing constraints. This thorough analysis offers insights and information that can motivate and direct developments in this dynamic and ever-evolving field, making it a useful tool for scholars, engineers, and policymakers interested in the nexus of energy harvesting, renewable energy sources, and wireless sensor networks.

This review adds a great deal to the topic of effective and sustainable sensor network design theoretically. First, it explains and delivers a wealth of knowledge on energy harvesting methods and renewable energy sources, which is one of its main contributions. For academics, engineers, and practitioners looking to use these sources for wireless sensor networks, the review is a useful resource. Subsequently, it delves into the crucial facets of energy management, highlighting tactics for maximizing energy use in sensor networks. The third aspect of the paper addresses the practical difficulties that arise from energy harvesting, such as the need for adaptive power control and intermittent energy supply [9]. This thorough analysis is a useful tool that expands our understanding of energy harvesting for wireless sensor networks. Its contributions include synthesizing existing information, offering useful perspectives, and outlining future directions for investigation.

II. Methodology

The goal of the review was to compile the body of knowledge regarding methods currently in use in wireless sensor networks (WSNs) for energy harvesting from dispersed renewable sources. The review's goal is to present a thorough and well-organized summary of the state of research and practice in this particular field by compiling data from multiple sources. An essential aspect of the study is the approach used to carry out an exhaustive evaluation of the methods and difficulties of energy harvesting from distributed renewable energy sources in wireless sensor networks. In order to ensure the review's comprehensiveness and dependability, this section describes the methodology used to locate, evaluate, and synthesize pertinent literature and data. The first and most important step was to do a thorough and methodical literature search across a wide range of academic databases, such as IEEE Xplore, ACM Digital Library, ScienceDirect, and Google Scholar. With careful consideration, a broad spectrum of keywords pertaining to energy harvesting, renewable energy sources, wireless sensor networks, and the accompanying difficulties and approaches were included in the search phrases. The gathered literature was then carefully examined for dependability, quality, and relevancy. This includes a first review of the entire texts, followed by a more thorough analysis based on the titles and abstracts. Books, reports, conference papers, peer-reviewed articles, and other works with significant scientific or engineering substance were the only ones that made the cut.

In order to guarantee a logical and cohesive flow, the review was methodically prepared. It is broken up into parts that deal with several facets of energy harvesting, such methods for harnessing solar, wind, vibration, and thermal gradient energy and various challenges of energy harvesting techniques. Each methodology is explained and contrasted with other methods in table sections based on how effective it is and how well suited it is for wireless sensor networks. The approach included a thorough analysis of energy management plans and energy storage options in addition to energy collecting methods. These factors were thoroughly examined in order to comprehend the best ways for captured energy to be distributed, stored, and used in wireless sensor networks.

A significant portion of the paper is devoted to discussing the difficulties associated with energy harvesting, including the erratic and intermittent nature of renewable energy sources and the need for adaptive power management [10]. The issues at hand are thoroughly examined, with an emphasis on viable remedies and optimal methodologies. The research included not just energy harvesting methods but also a thorough analysis of energy management strategies and energy storage options. To comprehend how captured energy may be efficiently disseminated, stored, and used inside wireless sensor networks, these factors were thoroughly examined. The assessment also gives careful consideration to the difficulties that come with energy harvesting, namely the requirement for adaptive power management and the intermittent and unpredictable nature of renewable energy sources [11]. Potential fixes and recommended practices are identified, and these issues are thoroughly examined. The authors used a critical and analytical approach to assess the advantages and disadvantages of different approaches and tactics throughout the review. In order to reach relevant findings and provide insights that may direct further study and advancement in the area, data was combined. The present comprehensive review employs a technique that is based on a methodical and exhaustive search of the literature, critical analysis, and a structured arrangement of the material. It guarantees that the review is a trustworthy and educational tool that provides a thorough grasp of the methods and difficulties involved in energy harvesting from distributed renewable sources in wireless sensor networks.

- Introductory part has been discussed in section II.
- Wireless sensor networks and effect of distributed energy resources (DERs) have explained in section III & IV.
- Various Energy harvesting techniques with their block diagram have been shown in section V thoroughly.
- In section VI, different kinds of distributed energy sources are described.
- Challenges of energy harvesting techniques are discussed in section VI.
- Discussion and conclusion have been explained in section VII and VIII.

III. Wireless Sensor Networks

Wireless Sensor Networks (WSNs) are networks made up of a lot of tiny, self-sufficient units called sensors or nodes that have sensors installed so they can observe and gather information from their surroundings [12]. A block diagram of wireless sensor network has been shown in Fig. 1.

These sensors may be of many different kinds, including motion detectors, humidity sensors, and temperature sensors, among others. These sensors then gather data, which is wirelessly sent to a base station or central node for further processing and analysis. In WSNs, sensor nodes are the basic building components. These nodes often run on batteries and have limited processing capability. They are in charge of observing their surroundings, gathering information, and corresponding with other nodes or a central base station. Nodes in a wireless sensor network (WSN) use wireless communication technologies like Bluetooth, Wi-Fi, Zigbee, or custom-designed protocols to connect with the base station and each other [13]. The needs of the network and the application determine which communication technology is best. It's possible that data gathered by different nodes is similar or redundant. WSNs often use data aggregation methods to conserve energy and limit the quantity of data transferred. It is possible to aggregate and condense data from many nodes before sending it to the base station. Since sensor nodes in wireless sensor networks (WSNs) are often battery-powered and may be placed in distant or harsh settings where battery replacement is difficult, energy efficiency is a key consideration. Nodes may sleep while not in use and wake up regularly to gather and send data in order to save energy.

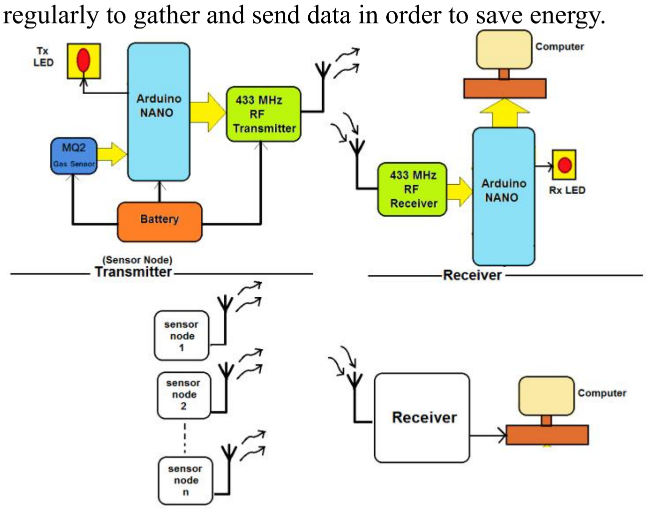

Fig. 1. Wireless sensor network

Energy management, scalability, routing algorithms, and fault tolerance are some of the difficulties that WSNs must overcome [14]. To increase the efficiency and dependability of WSNs, engineers and researchers are still working to solve these problems. To mitigate energy crisis researchers are trying to use distributed renewable energy sources in WSNs.

IV. Effect of DREs on WSNs

Wireless Sensor Networks (WSNs) may benefit greatly from Distributed Renewable Energy Sources (DRES), particularly in terms of increased operating capabilities, sustainability, and dependability [15]. The following are some of the main outcomes and advantages of DRES integration with WSNs. WSNs are often installed in hard-to-reach places where it might be difficult to provide a steady supply of electricity from the grid. By offering a localized and sustainable energy source, DRES like solar panels and wind turbines can lessen reliance on conventional power sources and increase the operational lifespan of networks. Sensor nodes may get a steady and sustainable power supply from renewable energy sources. This may make the WSNs more ecologically and economically friendly by lowering the need for expensive and logistically difficult battery changes.

DRES can guarantee that sensor nodes get power continuously, enabling WSNs to run around-the-clock [16]. This is essential for applications like surveillance or environmental monitoring that call for constant monitoring. It is simple to scale DRES to meet a WSN's energy needs. More renewable energy sources may be installed to fulfil the rising energy demand as the network expands or more sensors are added. WSNs with DRES lessen their total environmental effect and greenhouse gas emissions by using clean and renewable energy sources. This is in line with the increasing emphasis on sustainability and lowering technological systems' carbon footprints. DRES may save costs in the long run by lowering the need for maintenance and battery replacements, even if their initial setup costs might be quite costly. Additionally, DRES may be a more affordable option in places without grid connectivity [17]. Notwithstanding these benefits, it's important to remember that the efficiency of DRES in WSNs is dependent on a number of variables, such as the sensors' energy needs, the surrounding environment, and the renewable energy system's architecture. A dependable and effective integration of DRES into WSNs requires careful planning and system design.

V. Energy Harvesting Techniques

Using energy harvesting methods, many types of environmental energy are captured and transformed into useful electrical power. These methods are especially helpful in situations when changing batteries may be difficult or impracticable. Numerous methods exist for harvesting energy, including solar, wind, vibration, thermal gradient, hydropower, bioenergy, motion and kinetic, tribological, aeroelastic, and radio frequency energy harvesting [18]. These energy harvesting methods provide renewable power sources for a range of applications, such as remote sensors and environmental monitoring systems, IoT devices, and portable gadgets. The method of choosing is determined by a number of variables, including the energy source, the surrounding environment, the amount of power needed, and system design.

A. Solar Energy Harvesting

When photons of sunlight impact solar cells, they create a voltage that turns solar energy which is often produced from semiconductor materials like silicon into electricity. Block diagram of solar energy harvester can be seen in Fig. 2.

B. Wind Energy Harvester

Wind turbines generate power by harnessing the kinetic energy of moving air. Wind energy generation system has been shown in Fig. 3.

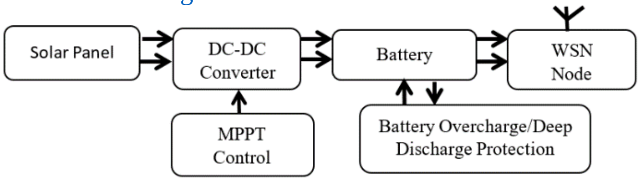

Fig. 2. Block diagram of solar energy harvester [19]

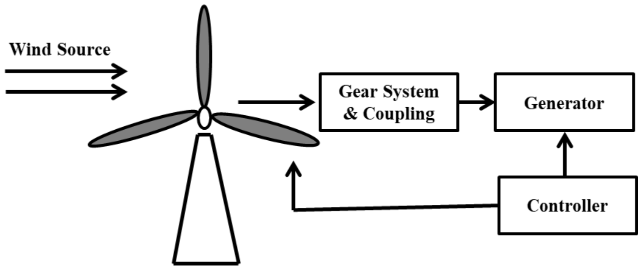

Fig. 3. Block diagram of wind energy harvester [20]

Wind turbines generate electricity by using the kinetic energy of flowing air to spin blades that are linked to a generator. Through the use of wind turbines, this breakthrough technology absorbs the kinetic energy of moving air and converts it into clean and reliable electricity. Wind power's potential is being realized in a variety of environments, ranging from onshore wind farms spanning broad fields to offshore installations located in enormous expanses of open sea.

C. Vibration Energy Harvester

When mechanical stress or vibrations are applied to piezoelectric materials, they produce electrical charges and transform kinetic energy into electrical energy. The relative motion of a coil and magnet is also used by electromagnetic induction devices to create an electrical current. Piezoelectric material vibrations and electromagnetics generator vibrations are the main mechanical vibration energy scavenging process shown in Fig. 4.

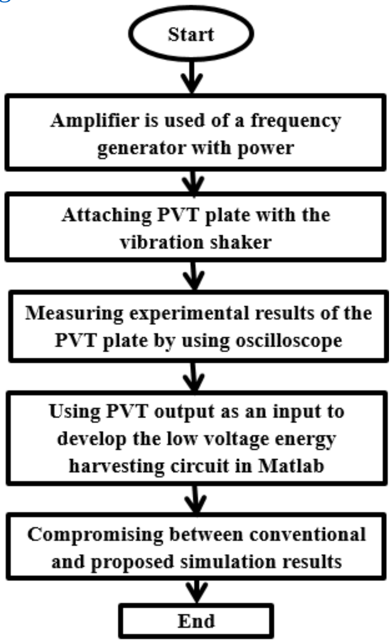

Fig. 4. Steps of mechanical vibration energy harvester [21]

D. Hydropower Harvester

Hydroelectric generators are devices that use the energy of flowing water typically in rivers or dams to produce electricity. These turbines use the kinetic energy of the tides to create power when they are submerged in tidal currents. Hydropower produces electricity by harnessing the energy of moving water, which is often found in dams or flowing rivers. Functional block diagram of micro hydro power plant interconnected with power system network has been shown in Fig. 5.

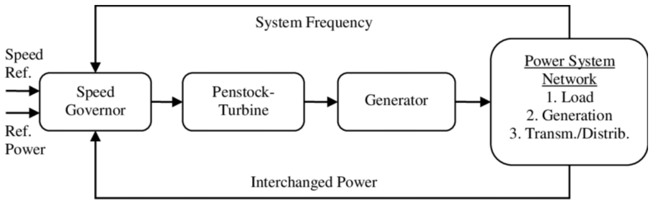

Fig. 5. Block diagram of hydropower harvester [22]

VI. Distributed Energy Sources

Small-scale, localized power generating and storage systems that are situated near to the point of electricity use are referred to as distributed energy sources, also known as decentralized or distributed energy resources (DERs) [23]. There are several advantages to energy stability, sustainability, and efficiency from these dispersed sources, which may function independently or be incorporated into the larger electrical grid. Reduced transmission and distribution losses, improved energy security, less environmental impact, and higher grid stability are just a few benefits of using distributed energy sources. To build energy systems that are more durable, effective, and sustainable, they are often employed in conjunction with centralized power generating. Distributed energy sources now constitute a significant portion of the global energy landscape due to technological and policy advancements in the field. Typical categories of dispersed energy sources consist of.

- Solar Photovoltaic (PV) Systems: These energy-generating devices use solar panels to convert sunlight into electricity. Typical examples of distributed solar energy include rooftop solar panels on homes and businesses.
- Wind Turbines: Wind energy is used to produce power from small wind turbines that are erected on private property or in wind farms. These turbines are often dispersed over different areas.
- Hydropower Systems: Often found in isolated or rural locations, small-scale hydropower systems, such as micro- or pico-hydro systems, capture energy from flowing water.
- Biomass Energy: Wood chips, agricultural leftovers, and organic waste are examples of organic materials that may be used as a distributed biomass energy source to produce heat, electricity, or biofuels.
- Geothermal Systems: These energy systems use distributed geothermal technology to harness the heat from the Earth to produce power and heat.
- Combined Heat and Power (CHP) Systems: Also referred to as cogeneration, CHP concurrently generates useable heat and electricity from a single energy source, usually biomass or natural gas. These systems are dispersed across commercial, residential, and industrial environments.
- Energy Storage Systems: Excess power may be stored for later use using batteries and other distributed energy sources. They aid in balancing the supply and demand for energy.
- Microgrids: Microgrids are small, self-sufficient electrical grids that may function both alone and in tandem with the larger grid. They often include load control, storage, and many dispersed energy sources.
- Geothermal Systems: These energy systems generate electricity and heat by using dispersed geothermal technologies to capture Earth's heat.
- Combined Heat and Power (CHP) Systems: Also known as cogeneration, CHP simultaneously produces electricity and usable heat from a single energy source, often natural gas or biomass. These systems are scattered across industrial, commercial, and residential settings.
- Energy Storage Systems: Batteries and other distributed energy sources may be used to store extra power for later use. They help to keep the energy supply and demand in balance.

VII. Challenges of Energy Harvesting Techniques

While energy collecting methods have many benefits, such as longer gadget lives and sustainability, there are some issues that must be resolved. It is sometimes necessary to use a multidisciplinary approach to address these issues, integrating knowledge of engineering, materials science, environmental science, and regulatory compliance. In order to overcome these obstacles and increase the applicability and prevalence of energy harvesting systems, research and innovation are still vital. Typical difficulties with energy collecting methods include the following.

- Intermittency: A lot of renewable energy sources, including wind and solar power, are sporadic, meaning they don't always exist. It may become difficult to offer a steady power supply as a result of this intermittency, which might cause changes in power production [24].
- Energy Storage: In order to buffer and store surplus energy produced by harvesting systems for usage during times of low energy supply, efficient energy storage is essential [25]. Appropriate energy storage system selection and upkeep may be difficult and costly.
- Energy Conversion Efficiency: Energy conversion devices (such as solar cells and piezoelectric materials) with low efficiency are often used to convert the gathered energy into electrical power. Increasing conversion efficiency is a major task in order to optimize energy use [26].
- Environmental Variability: The effectiveness of energy harvesting systems may be impacted by weather, temperature changes, and seasonal variations, making them unpredictable and difficult to maintain [27].
- Scalability: It might be difficult to scale up energy harvesting systems to match the power requirements of bigger networks or applications. It could need for a larger initial investment and more sophisticated infrastructure [28].
- System Integration: It's a difficult process that often calls for careful design and engineering to integrate energy harvesting systems into current devices or networks without impairing their performance or operation [29].
- Cost: The initial outlay for putting energy harvesting equipment into place, including parts like solar or wind turbines and energy storage options, may be substantial. A major obstacle is cost-effectiveness, particularly for small-scale applications [30].
- Adaptive Control: It is a technological problem to create control algorithms that can efficiently manage the energy that has been gathered, balance the supply and demand for energy, and adjust to changing circumstances [31]. For these algorithms to be reliable and efficient, they must be optimized.
- Durability: Systems for collecting energy may be subjected to severe external factors, which may cause wear and tear. It is essential to guarantee the robustness and enduring dependability of these systems, especially for installations situated in distant or inaccessible areas.

- Regulatory and Environmental Issues: Energy harvesting projects may have difficulties in adhering to environmental standards and taking into account ecological implications, such as the location of wind turbines or hydropower systems [32].
- Public Perception and Aesthetics: It may be difficult to gauge how the general public feels about energy harvesting devices, particularly in metropolitan areas. Certain systems may not appeal to everyone due to their look or noise level [33].
- Material Sourcing: Due to supply chain constraints, sourcing materials for energy harvesting systems, particularly for cutting-edge technologies like thermoelectric materials, may be difficult [34].

VIII. Discussion

The paper explores the main conclusions, ramifications, and more general insights from the study by providing a thorough analysis of the methods and difficulties of energy harvesting from distributed renewable energy sources in wireless sensor networks. In addition to providing a clearer comprehension of the study's importance and applicability, it helps to synthesize the information that has been obtained. The analysis shows that by offering a sustainable and independent power source, energy harvesting technologies have the ability to drastically alter wireless sensor networks. Systematic research has been done on methods for obtaining energy from renewable sources such as sun, wind, vibrations, and thermal gradients. We have outlined the advantages and disadvantages of each strategy as well as how well they operate in certain environments and with different network configurations. The present discourse emphasizes the significance of choosing the optimal energy harvesting technique in accordance with the particular attributes of the application. The review also shows that improving the use of captured energy requires appropriate energy management. Power optimization, adaptive power regulation, and effective energy allocation are some of the energy management techniques that have been thoroughly covered. This talk highlights how important effective energy management is to increasing wireless sensor networks' operational lifetime and lowering the frequency of battery replacement or recharge.

The difficulties posed by energy harvesting, such sporadic energy supply and the need for flexible power control, have been thoroughly discussed. The debate recognizes that these difficulties are inherent in the utilization of renewable energy sources and encourages the development of creative solutions, such as energy-aware routing protocols, adaptive duty cycling, and energy forecast models. The analysis also emphasizes how energy harvesting may be incorporated into wireless sensor networks to create more environmentally friendly and sustainable systems. Examples of applications in smart cities, industrial automation, and environmental monitoring have been shown, highlighting how these networks may be used to solve practical problems. This conversation highlights how energy harvesting in wireless sensor networks has the ability to revolutionize. In addition to recognizing the need of effective energy management and adaptive tactics, it emphasizes the need for a nuanced approach in the selection and use of energy harvesting systems.

In order to build a dependable and sustainable sensing infrastructure, Distributed Renewable Energy Sources (DRES) must be successfully integrated into Wireless Sensor Networks (WSNs) by overcoming technological, operational, and design obstacles. In order to power sensor nodes in WSNs, it is imperative to implement energy harvesting technologies that are efficient. To ensure that sensor nodes continue to operate, distributed renewable energy sources (DRES) like solar panels, wind turbines, or energy-scavenging devices can be strategically placed to replenish their energy reserves. Rechargeable batteries and super capacitors are examples of efficient energy storage systems that can be incorporated to ensure that excess energy produced by DRES during peak periods can be stored and used during times when energy availability is low. It is essential to choose and incorporate energy-efficient sensors that meet the application's sensing needs. Low-power sensors play a part in reducing the WSN's overall energy consumption. A comprehensive strategy that takes into account the unique needs of the sensor network application as well as the aspects of renewable energy is necessary for the successful integration of DRES into WSNs. Through the resolution of technical obstacles and the development of efficient and versatile designs, entities can harness the advantages of distributed renewable energy sources to establish robust and sustainable wireless sensor networks. Comparative table of challenges of energy harvesting from distributed renewable energy sources cam be seen in Table 1. Comparative table of techniques for energy harvesting from distributed renewable energy sources cn be seen in Table 2.

Table 1. Comparative table of challenges of energy harvesting from distributed renewable energy sources

Renewable Energy Source	Common Challenges	Unique Challenges
Solar Energy	Intermittency due to day-night cycles and weather conditions	Dependence on geographical location and sunlight availability
Wind energy	Variability due to changing wind speeds and directions	Infrastructure requirements for wind turbines
Vibration energy	Difficulty in capturing and converting small vibrations into usable energy	Vibrational sources may be limited in certain environments
Thermal gradient energy	Challenges in maintaining temperature differences for effective energy harvesting	Design complexities for heat exchangers and thermoelectric materials
Hydropower	Environmental and ecological impacts	Location-dependent and may require water flow
Bioenergy	Dependence on the growth and availability of biomass	Handling and storage of organic materials

The thorough evaluation contributes significantly to the area of renewable energy consumption in wireless sensor networks and encourages the development of sustainable and environmentally conscious technology by providing insightful information and future research directions. A Comparative table of Challenges of Energy Harvesting from Distributed Renewable Energy sources has been shown in Table 1. The similarities and differences between these difficulties may be better seen with the use of a comparison table of energy harvesting from dispersed renewable energy sources. A Comparative table of techniques for energy harvesting from distributed renewable energy sources has also been shown in Fig. 2. A condensed summary of the energy harvesting methods that are often used to various distributed renewable energy sources is given in this table. In actual use, each of these methods makes use of certain technologies and procedures designed to take use of the special qualities of the energy source.

Table 2. Comparative table of techniques for energy harvesting from distributed renewable energy sources

Renewable Energy Source	Energy Harvesting Technique
Solar Energy	Photovoltaic (PV) cells
Wind Energy	Wind turbines and generators
Vibration Energy	Piezoelectric materials, electromagnetic induction, kinetic energy harvesters
Thermal Gradient Energy	Thermoelectric generators, organic Rankine cycles
Hydropower	Hydroelectric generators, tidal turbines
Bioenergy	Biomass combustion, anaerobic digestion, microbial fuel cells

IX. Conclusion

In conclusion, the comprehensive review on techniques and challenges of energy harvesting from distributed renewable energy sources in wireless sensor networks sheds light on a dynamic and evolving field with immense potential. This review has systematically examined the techniques for capturing and converting energy from distributed sources, such as solar, wind, vibrations, and thermal gradients. It has explored the intricacies of energy management and energy storage, emphasizing their pivotal role in maximizing the utilization of harvested energy. Additionally, the challenges associated with energy harvesting, including intermittent energy availability and adaptive power management, have been comprehensively addressed. The review's findings underscore the transformative impact that energy harvesting can have on the sustainability and autonomy of wireless sensor networks. It provides a comprehensive understanding of the capabilities and limitations of different energy harvesting methods, empowering researchers, engineers, and practitioners to make informed decisions regarding the selection and implementation of these techniques. Furthermore, the review highlights the significant role of energy harvesting in environmental monitoring, smart cities, and industrial automation, fostering the development of sustainable and eco-friendly systems. It serves as a valuable resource for those interested in harnessing the power of distributed renewable sources to enhance the resilience, efficiency, and environmental responsibility of sensor networks. The research gaps and future directions identified in the review provide a roadmap for further exploration and development in this promising field, guiding the way toward a greener and more sustainable technological future.

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