International Journal of Intelligent Communication and Computer Science
Vol. 1, No. 1, 2023, Pages 1-11.

Enhancing Sustainability and Energy Efficiency in Wireless Sensor Networks through Solar Energy Harvesting

Anil Kumar Mishra [1], Neeraj Sharma[1]

Research Paper

Department of Physics, N.A.S. College, Meerut, INDIA
Email: anilmishranas@gmail.com
Received: 12 April 2023, Revised: 27 Jun 2023, Accepted: 10 July 2023

Abstract:

Wireless sensor networks (WSNs) have emerged as a crucial technology in various domains, including engineering and medical science. WSNs consist of small, low-power sensor nodes that gather and transmit data wirelessly. However, a significant challenge faced by WSNs is the limited lifespan of the node's batteries. Once the battery is depleted, it typically needs to be replaced, which can be impractical or even impossible in certain scenarios. To address this challenge, this work proposes the use of solar energy harvesting in WSNs, enabling the nodes to recharge and continue operating without solely relying on batteries. Solar energy harvesting involves integrating solar panels into the sensor nodes, allowing them to harness energy from the sun and convert it into electrical energy. In this study, the performance of the WSN nodes is evaluated by considering the residual energy of both normal nodes and energy harvested nodes. The residual energy represents the remaining energy or battery capacity of the nodes after a specific period of operation. By comparing the residual energy between normal nodes and energy harvested nodes, the effectiveness of the solar energy harvesting approach can be assessed.

Keywords: WSN, Solar Energy Harvesting

1. Introduction:

Wireless Sensor Networks (WSNs) have emerged as a powerful and versatile technology that enables the collection, processing, and communication of data from the physical environment. These networks consist of numerous small, autonomous sensor nodes that collaborate to monitor and transmit data about the surrounding environment. WSNs have gained significant attention and have found applications in various fields due to their scalability, low-cost nature, and ability to operate in diverse environments [1]. Wireless Sensor Networks typically comprise three main components: sensor nodes, a communication infrastructure, and a data processing system. Each sensor node is equipped with sensing, processing, and communication capabilities [2]. The sensing component allows the nodes to perceive and capture information from the environment, such as temperature, humidity, light intensity, or pressure [3]. The processing component enables the nodes to analyze and process the collected data, extract meaningful information, and perform local computations. The communication component facilitates the exchange of data between sensor nodes, allowing them to collaborate and share information. The communication infrastructure in WSNs can vary depending on the application requirements and network architecture. Nodes can communicate directly with each other in a peer-to-peer manner or utilize hierarchical communication structures [4]. In hierarchical structures, nodes are organized into clusters or groups, where data is aggregated and forwarded to a central base station or sink node for further processing and analysis. The communication protocols and algorithms employed in WSNs are designed to optimize energy efficiency, reliability, and scalability, considering the limited resources and dynamic nature of the network [5]. WSNs find applications in various domains due to their ability to provide real-time, continuous, and cost-effective data collection and monitoring. Some of the prominent application areas of WSNs include:

A. Environmental Monitoring

WSNs are extensively used for environmental monitoring, including air quality monitoring, water quality monitoring, forest fire detection, and climate monitoring [6]. They enable scientists, researchers, and environmental agencies to gather data on various environmental parameters, study patterns, and make informed decisions for resource management and conservation.

B. Smart Cities

WSNs play a vital role in building smart cities. By deploying sensor nodes throughout urban areas, WSNs enable the collection of data on traffic patterns, parking management, waste management, energy consumption, and public safety [7]. This data can be used to optimize resource allocation, enhance efficiency, and improve the quality of life for urban residents.

C. Healthcare

WSNs have transformative applications in healthcare, enabling remote patient monitoring, fall detection, medication adherence tracking, and ambient assisted living [8]. These networks facilitate continuous and personalized healthcare, allowing healthcare professionals to remotely monitor patient health, detect emergencies, and provide timely interventions.

D. Agriculture

WSNs are employed in precision agriculture for crop monitoring, irrigation management, pest control, and soil monitoring. Sensor nodes deployed in agricultural fields gather data on soil moisture, temperature, humidity, and nutrient levels [9]. This information enables farmers to optimize irrigation, fertilizer application, and overall crop health, leading to improved yields and reduced resource wastage.

E. Industrial Monitoring

WSNs are used in industrial settings for monitoring and controlling manufacturing processes, machinery conditions, and asset tracking. These networks enable real-time monitoring of critical parameters such as temperature, pressure, vibration, and energy consumption [10]. This data can be used for predictive maintenance, quality control, and optimization of industrial processes.

F. Structural Health Monitoring

WSNs play a vital role in monitoring the health and integrity of structures such as bridges, buildings, and infrastructure. Sensor nodes can detect structural abnormalities, measure vibrations, and monitor environmental conditions that may affect the structural integrity [11]. This information helps in early detection of potential failures, ensuring the safety and maintenance of infrastructure.

2. WSN Node Details

Wireless Sensor Networks have revolutionized data collection and monitoring capabilities in various fields. With their ability to collect real-time data, process information locally, and communicate wirelessly, WSNs have opened up new avenues for applications such as environmental monitoring, healthcare, smart cities, agriculture, industrial monitoring, and structural health monitoring. The advancements in sensor technology, communication protocols, and data processing techniques continue to expand the potential of WSNs, making them a vital tool in addressing complex challenges and improving decision-making processes.

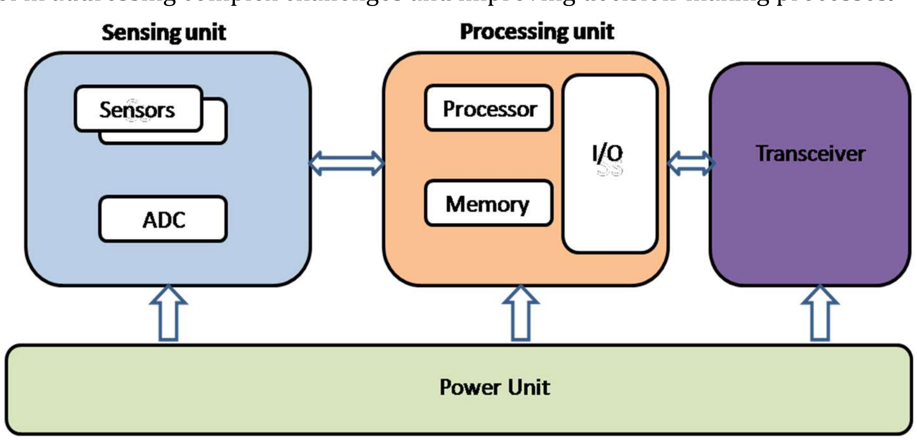

Figure 1: Sensor node units

Sensor nodes are fundamental components of wireless sensor networks (WSNs) used to collect and transmit data from the environment they are deployed in. Each sensor node typically consists of several units that work together to perform sensing, data processing, and communication functions. Here are the key units commonly found in a sensor node:

A. Sensing Unit

The sensing unit is responsible for measuring physical or environmental parameters. It includes one or more sensors that can detect various types of data such as temperature, humidity, light intensity, pressure, or motion.

B. Processing Unit

The processing unit, often a microcontroller or microprocessor, is responsible for processing the collected sensor data. It performs computations, data filtering, signal conditioning, and data fusion to extract meaningful information from the raw sensor measurements.

C. Memory Unit

The memory unit stores the program code for the sensor node's operation, as well as the collected sensor data. It typically includes non-volatile memory (e.g., flash memory) to store the program code and persistent data, and volatile memory (e.g., RAM) for temporary data storage during runtime.

D. Communication Unit

The communication unit enables wireless communication between the sensor node and the network infrastructure. It includes a transceiver that allows the node to send and receive data wirelessly using protocols such as Wi-Fi, Bluetooth, Zigbee, or LoRaWAN [12]. The communication unit facilitates data transmission from the sensor node to a gateway or a central server.

E. Power Unit

The power unit supplies the necessary electrical power to the sensor node. It typically includes a battery or energy harvesting module (e.g., solar panels or kinetic energy harvesters) to provide energy for the node's operation. Power management circuitry is often included to regulate and optimize power usage. In many applications, sensor nodes are deployed in locations where recharging or replacing batteries is challenging. Therefore, the power subsystem is a critical aspect to consider. It can be classified into two categories: rechargeable and non-rechargeable WSNs.

F. Non-Rechargeable WSNs

These WSNs utilize non-rechargeable batteries that have a limited lifespan. Once the battery depletes, the node ceases to function.

G. Rechargeable WSNs (rWSNs)

Rechargeable WSNs continue to operate as their batteries can be recharged using various renewable energy sources and wireless power transfer techniques. These techniques, such as solar energy harvesting or inductive power transfer, enable the replenishment of energy in the sensor nodes without the need for manual intervention. The use of rechargeable WSNs provides the advantage of prolonged operation and reduced maintenance requirements compared to non-rechargeable WSNs. By harnessing renewable energy sources and wireless power transfer technologies, rWSNs offer increased autonomy and sustainability in various applications [13]. The activation of nodes in rechargeable wireless sensor networks (rWSNs) is accomplished through energy harvesting techniques that extract energy from the surrounding environment and convert it into electrical energy [13]. When there is an abundant and accessible supply of harvested energy, it can continuously power the nodes, ensuring their sustained operation [14]. Energy harvesting presents a viable solution to enhance the lifespan of rWSNs that operate under limited energy conditions [12]. However, there are various challenges associated with the functioning of environmental monitoring nodes. These nodes are typically deployed in remote and uninhabited locations, making them disconnected from conventional power sources [13]. To ensure efficient operation of environmental wireless sensor networks (EWSNs), it is crucial to employ suitable network topologies and operational techniques [14] that effectively minimize power consumption [13]. The selection of an appropriate power source is a crucial step in designing an EWSN. Typically, EWSN devices rely on primary (non-rechargeable) batteries as their power source. However, the lifespan of EWSN devices can be significantly extended by incorporating energy harvesting devices as an alternative power option alongside primary batteries. This hybrid approach enables the utilization of harvested energy to supplement or even replace the primary batteries, thereby ensuring prolonged operation of the sensor nodes. By integrating energy harvesting devices into EWSNs, the reliance on finite primary batteries is reduced, enabling sustainable and autonomous operation. Energy harvesting technologies, such as solar panels, kinetic energy harvesters, or thermal energy converters, can be employed to capture and convert ambient energy into electrical power. These harvested energy sources can provide a continuous supply of energy to the nodes, reducing the need for frequent battery replacements or recharging. The combination of primary batteries and energy harvesting devices in EWSNs offers several advantages, including increased network lifespan, reduced maintenance costs, and improved reliability. The harvested energy serves as a supplementary power source, providing a buffer to ensure continuous operation even during periods of low battery levels. Additionally, energy harvesting can be particularly advantageous in regions with abundant and readily accessible ambient energy sources.

3. Introduction to Solar Energy Harvesting

Solar energy harvesting models involve the characterization of the energy generation potential of solar panels based on various factors, including solar radiation, panel specifications, and environmental conditions. Here are the key details to consider when discussing solar energy harvesting models:

A. Solar Radiation Data

Solar energy harvesting models rely on solar radiation data to estimate the amount of sunlight available for energy generation. Solar radiation data typically includes parameters such as global horizontal irradiance (GHI), direct normal irradiance (DNI), and diffuse horizontal irradiance (DHI). This data is collected from weather stations or satellite measurements and represents the solar energy incident on a horizontal surface.

B. Panel Specifications

The specifications of the solar panels used in the energy harvesting system are crucial for accurate modeling. Panel specifications include parameters such as efficiency, surface area, maximum power point voltage, and current. These specifications determine the energy conversion efficiency of the panels and their ability to generate electrical power from the incident solar radiation.

C. Environmental Factors

Environmental factors play a significant role in solar energy harvesting models. Factors such as temperature, shading, and panel orientation affect the performance of solar panels. Temperature influences the efficiency of solar cells, while shading from buildings, trees, or other objects can reduce the amount of solar radiation reaching the panels. Panel orientation, tilt angle, and tracking mechanisms can be considered to optimize energy generation based on the specific geographical location.

D. Mathematical Models

Various mathematical models are used to estimate the energy generation potential of solar panels. The most common model is the single-diode equivalent circuit model, which represents the electrical behaviour of a solar cell. This model considers factors such as the current-voltage (I-V) characteristics, series and shunt resistances, and the maximum power point (MPP) of the solar panel. Other models, such as the Lambertian model or the empirical models, may be used to estimate energy generation based on specific panel types and environmental conditions.

E. Solar Energy Harvesting

In majority of the cases, solar energy is taken as energy source for such nodes as it is quite economical and pure energy [15]. However, the availability of solar energy cannot be controlled; still weather predictions can be used to get better idea about it [15].

The main component of the harvesting module is the harvesting circuit, which controls energy storage, collects electricity from the solar panels, and delivers it to the target system. The circuit design focuses on maximizing efficiency to ensure optimal energy utilization. Solar panels have an ideal working position that generates the maximum power output. To achieve this, the harvesting circuit clamps the solar panel's output terminals to a predetermined voltage, ensuring operation at or close to the maximum power point. The effectiveness of a maximal power point tracker (MPPT) circuit is crucial in continuously tracking and operating at the ideal position, as the maximum power point changes throughout the day [16]. However, commercially available MPPT ICs designed for high-power applications like solar-powered water heaters are not suitable for low-power, solar collecting embedded systems.

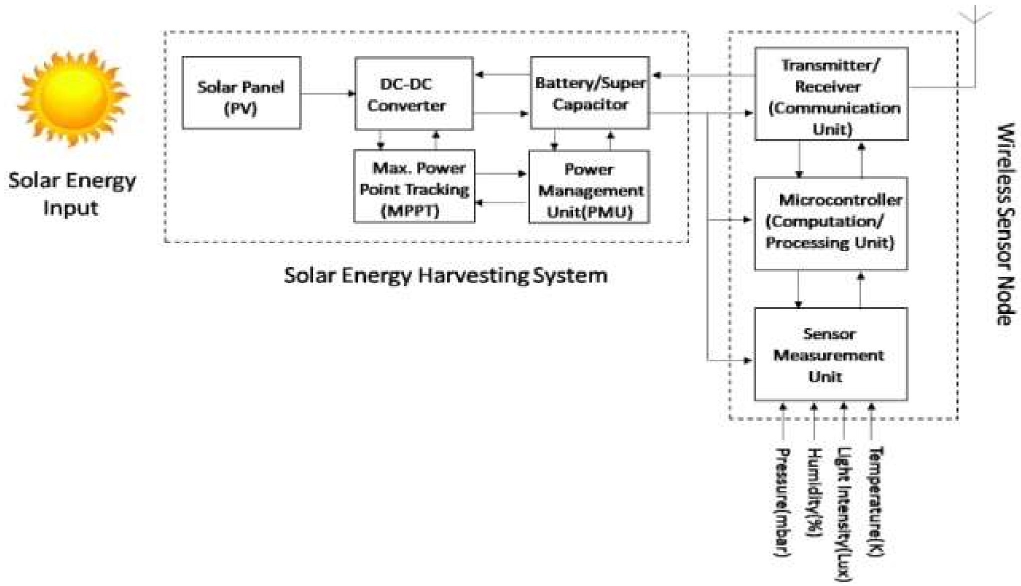

Figure 2: Schematic diagram of solar energy harvesting system

In embedded systems, a DC-DC converter is often employed to provide a stable supply voltage. The choice of the DC-DC converter depends on the operational voltage range of the specific battery being used and the supply voltage requirements of the target system [16]. A boost-buck converter is necessary when the desired supply voltage falls within the battery's voltage range, as the battery voltage needs to be adjusted according to its condition. On the other hand, if the supplied voltage exceeds the battery's operating range, a boost converter or buck converter can handle the situation, significantly improving power supply efficiency. Various modeling and forecasting techniques can be utilized to optimize the utilization of available solar energy. Harvested energy prediction, incorporating ambient shadow detection, enables changes in scheduling patterns for sensor nodes based on energy requirements and remaining battery levels [17]. Buchli et al. introduced a systematic approach for managing power capacity in integrated solar energy harvesting devices [18]. Their method employs an advanced astronomical framework to estimate the amount of energy that can be harvested and determine the required battery capacity. To enhance the lifespan of rechargeable batteries, systems incorporating solar panels, lithium batteries, and MPPT control circuits can fully harness solar energy [19]. These systems ensure efficient energy conversion, storage, and utilization, thereby maximizing the use of solar power and extending the battery's operational life. In summary, the harvesting circuit plays a critical role in collecting and storing energy from solar panels. By utilizing MPPT techniques, the circuit maximizes power extraction by operating at the optimal voltage. DC-DC converters are employed to provide stable supply voltages, and the choice of converter depends on the battery and system voltage requirements. Modeling and forecasting techniques, combined with efficient scheduling and management strategies, further enhance the utilization of solar energy. By integrating solar panels, lithium batteries, and MPPT control, the lifespan of rechargeable batteries can be extended, ensuring efficient utilization of solar power in embedded systems.

A. Modeling of a Solar PV Panel

Light energy is converted into electrical energy by a semiconductor device known as solar cell. The electron-hole pair (EHP) is produced when a photon of light energy (hv >Eg) is incident across a solar cell. The light created current, shown by the symbol, is made up in part by this newly produced EHP (I_L). The perfect solar cell's theoretical current-voltage (I-V) formula is expressed as
Solar cell current

$$(I) = I_L - I_0\left[\exp\left(\frac{qV}{kT}\right) - 1\right] \quad (1)$$

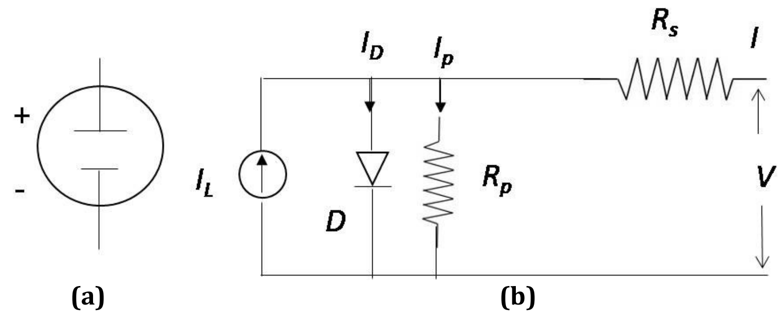

Figure 3: (a) Solar cell (b) Equivalent model

Here, I = total output current of solar cell, I_L = Light generated current by the solar cell, I_o = Reverse Saturation current due to recombination, q = charge of electron (1.6×10^{-19} C), V = open circuit voltage of solar cell, k = Boltzmann's constant (1.38×10^{-23} J/K), T = Temperature of Solar cell (300 K. In Figure 3b, Kirchhoff's current law (KCL) can give the characteristic current equation for this equivalent circuit:

Output Current of Equivalent Cell Model $(I) = I_L - I_D - I_p$ (2)

where, Ip = current in parallel resistance, I_L = Light generated current, and I_D = diode current.

Diode Current

$$(I_D) = I_0\left[\exp\left(\frac{V + IR_s}{nV_T}\right) - 1\right] \quad (3)$$

where, Rs = series resistance, n = diode ideality factor, (1 for ideal, 2 for practical diode), V_T = Thermal voltage (kT/q),. Current in parallel resistance

$$(I_p) = \frac{V + IR_s}{R_p} \quad (4)$$

Replacing the value of I_D and I_p in current Equation (2), we get the complete IV equation of the equivalent circuit of a single solar Cell, for which related all parameters with output current and voltage are given as [20]:

Solar cell current

$$(I) = I_L - I_0\left[\exp\left(\frac{q(V + IR_s)}{nkT}\right)\right] - \left(\frac{V + IR_s}{R_p}\right) \quad (5)$$

Perturb and Observe (P&O) MPPT Algorithm

Step 1: Measure the solar panel voltage (V) and current (I)
Step 2: Perturb the voltage slightly (e.g., by increasing or decreasing it)
Step 3: Measure the resulting power (P = V * I)
Step 4: Compare the new power with the previous power:

- If the new power is higher, continue perturbing in the same direction.
- If the new power is lower, reverse the perturbation direction.

Step 5: Repeat these steps until the maximum power point is reached or convergence criteria are met

The P&O algorithm aims to keep the operating point at the MPP by continuously adjusting the voltage based on the observed power change.

4. WSN Energy Model:

The above mentioned radio model assume that *d*, is the separation between transmitter and receiver and, d^2 represent the loss of energy because of the transmission channel.

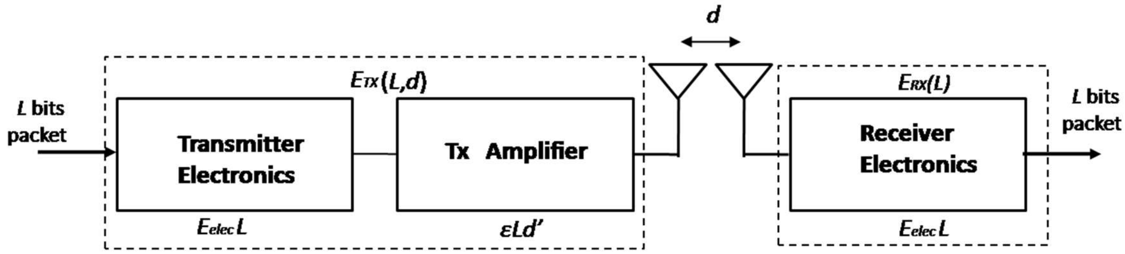

Figure 4: First order radio model

We can define the first order radio model equations as

$$E_{TX}(L,d) = E_{TX-elec}(L) + E_{TX-amp}(L,d) \quad (6)$$

$$E_{TX}^{fs}(L,d) = E_{TX-elec} \times L + E_{TX-amp} \times L \times d^2 \quad (7)$$

$$E_{TX}^{mp}(L,d) = E_{TX-elec} \times L + E_{TX-amp} \times L \times d^4$$

$$E_{RX}(L,d) = E_{RX-elec}(L) E_{RX}(L) = E_{RX-elec}(L) \times L \quad (8)$$

Where E_{TX} is the energy consumed at the time of transmission, E_{RX} is the energy consumed during reception, $E_{TX\text{-elec}}$ and $E_{RX\text{-elec}}$ are the energies needed for the operation of the electronic circuit of transmitter and receiver, respectively. E_{amp} is termed as the measure of energy needed for the amplifier circuit. On the other side, *L* denotes the size of the packet. Thus in each round of transmission and reception, energy of the sensor node battery deplete and after definite amount of rounds battery drains and sensor node fails to transmit and receive data.

A. Wireless Energy Transfer

The harvested solar energy is wirelessly transmitted to a set of "k" sensor nodes. This energy is then stored in rechargeable batteries within the nodes. To distribute the energy further, the rechargeable nodes utilize antennas to transfer power to other sensor nodes. In order to establish a successful power transfer, the omnidirectional antennas rely on a clear line of sight between the transmitter and receiver nodes. This means that the propagation channel model assumes the absence of any distortion along the signal path in the line of sight (LOS). Comparatively, when the LOS channel is compared to a non-line-of-sight (NLOS) channel, the overall route loss is lower in the LOS channel, especially when the distance remains the same [21]. The route loss in the free-space model is determined solely by the frequency and distance, and it is considered a theoretical model. The fundamental principle of the free-space concept is that there are no obstructions present beside or between the transmitter and receiver. Consequently, the transferred harvested energy to each individual node is calculated using Equation (9):

$$E_H^N(T) = \frac{\eta_s \eta_{RF} E_H(T)}{N_H}, \quad (9)$$

where η_s represents the efficiency of solar energy harvesting, η_{RF} denotes the efficiency of RF energy/power transfer, and N_H represents the total number of nodes that require energy harvesting.
The residual energy for node '*i*' in the j^{th} round is given by

$$E_{res}(i,j) = \min\left(E_{\max}(i), E_{res}(i,j-1) + E_H(i,j-1)\right) \quad (10)$$

where $E_{\max}$ is the initial energy of the particular node.
The amount of energy harvested in terms of harvesting rate ζ is given by

$$E_H(i,j-1) = \zeta_i \Delta t \quad (11)$$

where

$$\zeta_i = rand(W_{h,\min}(j-1), W_{h,\max}(j-1)) \quad (12)$$

where, '*W*' denotes the power.

5. Simulation Results

In Figure 5, a plot depicting the relationship between solar radiance (measured in W/m^2) and the hours of a day is shown. As anticipated, the plot illustrates a pattern that aligns with our expectations of solar radiation throughout the day. In the initial hours of the day, after 12 a.m., the sun has set, resulting in zero solar radiance. During this time, the plot reveals a flat line at the bottom, indicating the absence of sunlight and thus no measurable solar radiation. As the day progresses and the hours on the x-axis increase, the solar radiance gradually begins to rise. This upward trend demonstrates the gradual increase in sunlight as the sun rises in the sky. The rate of increase in solar radiance may vary depending on factors such as geographical location, time of year, and weather conditions. Reaching its peak, the solar radiance attains its maximum value around 12 p.m. to 3 p.m., as indicated by the highest point on the plot. This period represents the midday when the sun is positioned directly overhead, resulting in the most intense solar radiation of the day. The steep incline leading up to this peak reflects the rapid accumulation of solar radiance during the morning hours. Following the peak radiance period, the plot demonstrates a decline in solar radiance as the day progresses. This decline signifies the gradual decrease in sunlight as the sun begins to move lower in the sky towards the horizon. The rate of decline may vary depending on factors such as cloud cover, atmospheric conditions, and geographical location. It is worth noting that the plot depicts a relatively rapid fade in solar radiance as the sun approaches the horizon and approaches sunset. This fading speed is a result of the sun's angle becoming increasingly oblique, causing sunlight to traverse a larger portion of the atmosphere before reaching the Earth's surface. As a consequence, the intensity of solar radiation diminishes more rapidly during this period.

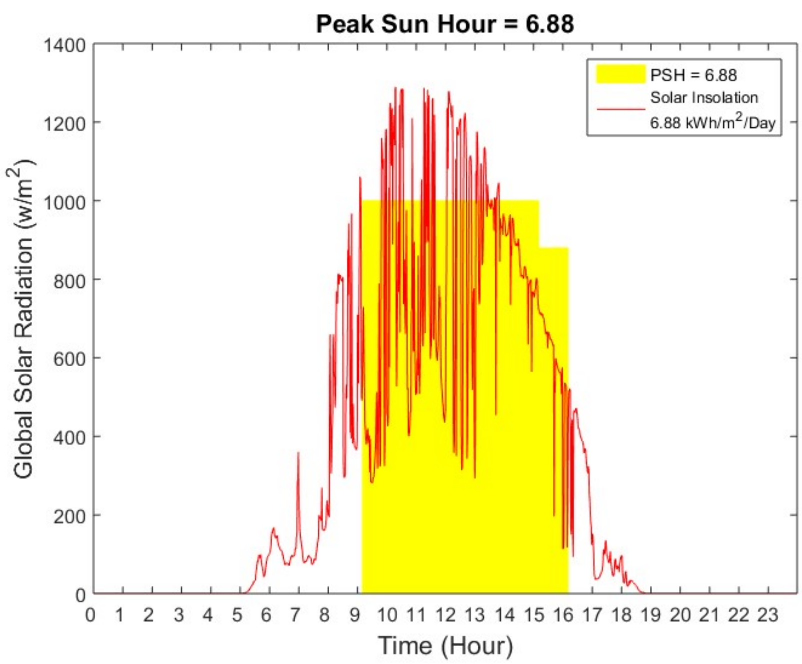

Figure 5: Solar Radiation vs. Time

The simulation parameters are detailed in Table 1. In a wireless simulation, a 100m ×100m area is considered as the geographical coverage for the network. Within this 100m×100m area, a total of 100 nodes are deployed. These nodes represent the individual devices or sensors that participate in the wireless network. The nodes are distributed throughout the area based on a random deployment scheme. Each node is equipped with wireless communication capabilities, allowing them to transmit and receive data wirelessly within the network. The communication range of the nodes defines the maximum distance over which they can establish direct communication links.

Table 1: Simulation Parameters

Parameters	Value
Initial Energy (E_{max})	0.5 J
Transmission energy and receiving energy	5 nJ/bit
Amplification energy (free space)	10 pj/bit/m^2
Amplification energy (multipath)	13 pj/bit/m^4
η_s(solar energy harvesting efficiency)	0.035
η_{RF}(RF energy/power transfer efficiency)	0.4
N_H	100

In Figure 6, a plot depicting the relationship between residual energy and the number of rounds is shown for a Wireless Sensor Network (WSN) considering both normal nodes and energy harvested nodes. The x-axis of the plot represents the number of rounds, indicating the progression of the WSN over time or operations. The y-axis represents the residual energy, which signifies the remaining energy or battery capacity of the nodes. The plot clearly illustrates that energy harvested nodes possess higher residual energy compared to normal nodes. This discrepancy in energy levels can be attributed to the additional energy obtained through harvesting mechanisms. The plot showcases a noticeable trend where the energy harvested nodes consistently exhibit higher residual energy compared to normal nodes as the number of rounds increases. This disparity arises from the additional energy acquired by the energy harvested nodes through solar panels. These nodes are capable of converting ambient energy sources into electrical energy, thus replenishing and maintaining higher energy levels.

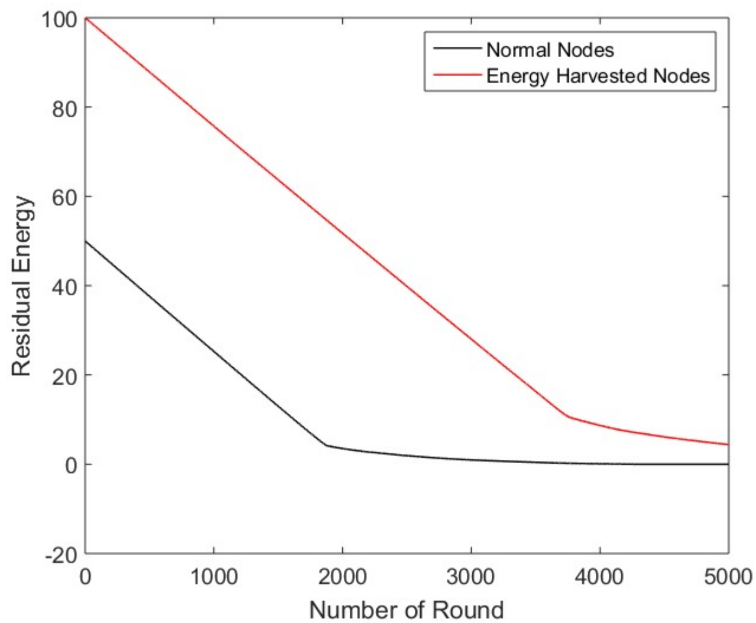

Figure 6: Residual Energy vs. Number of Rounds

6. Conclusions

In conclusion, this paper highlights the significance of incorporating solar energy harvesting techniques in wireless sensor networks (WSNs) to address the limited lifespan of node batteries and enhance overall system performance. WSNs play a vital role in various applications, including engineering and medical science. However, the reliance on batteries poses challenges in terms of battery replacement, especially in situations where it is impractical or impossible. To tackle this issue, we proposed a solar energy harvested

WSN system, where sensor nodes are equipped with solar panels to recharge and continue operating using renewable solar power. By harnessing solar energy, the nodes can extend their operational lifespan, reduce the need for frequent battery replacements, and improve the overall sustainability of the network. In this study, we specifically focused on evaluating the performance of WSN nodes in terms of residual energy for both normal and energy harvested nodes. By comparing the residual energy levels, we observed that energy harvested nodes consistently displayed higher residual energy compared to normal nodes. This discrepancy can be attributed to the additional energy obtained through solar energy harvesting, enabling the nodes to maintain higher energy levels over time. The adoption of solar energy harvesting in WSNs offers several benefits. It provides a renewable and sustainable power source, reducing the environmental impact associated with traditional battery-powered solutions. Additionally, the integration of solar panels enhances the autonomy and reliability of the WSN by mitigating the limitations of battery life.

References

1. Cecílio, José, Pedro Furtado, José Cecílio, and Pedro Furtado. "Wireless sensor networks: Concepts and components." *Wireless Sensors in Heterogeneous Networked Systems: Configuration and Operation Middleware* (2014): 5-25.
2. Prasad, Poonam. "Recent trend in wireless sensor network and its applications: a survey." *Sensor Review* 35, no. 2 (2015): 229-236.
3. Bloznelis, Mindaugas, Jerzy Jaworski, and Katarzyna Rybarczyk. "Component evolution in a secure wireless sensor network." *Networks: An International Journal* 53, no. 1 (2009): 19-26.
4. Zhou, Hai-Ying, Dan-Yan Luo, Yan Gao, and De-Cheng Zuo. "Modeling of node energy consumption for wireless sensor networks." *Wireless Sensor Network* 3, no. 1 (2011): 18.
5. Kanoun, Olfa, ed. *Energy Harvesting for Wireless Sensor Networks: Technology, Components and System Design*. Walter de Gruyter GmbH & Co KG, 2018.
6. Oliveira, Luís ML, and Joel JPC Rodrigues. "Wireless Sensor Networks: A Survey on Environmental Monitoring." *J. Commun.* 6, no. 2 (2011): 143-151.
7. Rani, Shalli, R. Maheswar, G. R. Kanagachidambaresan, and P. Jayarajan, eds. *Integration of WSN and IoT for smart cities*. Cham: Springer, 2020.
8. Ko, JeongGil, Chenyang Lu, Mani B. Srivastava, John A. Stankovic, Andreas Terzis, and Matt Welsh. "Wireless sensor networks for healthcare." *Proceedings of the IEEE* 98, no. 11 (2010): 1947-1960.
9. Jiber, Yassine, Hamid Harroud, and Ahmed Karmouch. "Precision agriculture monitoring framework based on WSN." In *2011 7th international wireless communications and mobile computing conference*, pp. 2015-2020. IEEE, 2011.
10. Aponte-Luis, Juan, Juan Antonio Gómez-Galán, Fernando Gómez-Bravo, Manuel Sánchez-Raya, Javier Alcina-Espigado, and Pedro Miguel Teixido-Rovira. "An efficient wireless sensor network for industrial monitoring and control." *Sensors* 18, no. 1 (2018): 182.
11. Farrar, Charles R., and Keith Worden. "An introduction to structural health monitoring." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 365, no. 1851 (2007): 303-315.
12. Mahmoud, Mahmoud S., and Auday AH Mohamad. "A study of efficient power consumption wireless communication techniques/modules for internet of things (IoT) applications." (2016).
13. Liu, Ying, Kwan-Wu Chin, Changlin Yang, and Tengjiao He. "Nodes deployment for coverage in rechargeable wireless sensor networks." *IEEE Transactions on Vehicular Technology* 68, no. 6 (2019): 6064-6073.
14. Tony, A., and Lely Hiryanto. "A review on energy harvesting and storage for rechargeable wireless sensor networks." In *IOP Conference Series: Materials Science and Engineering*, vol. 508, no. 1, p. 012120. IOP Publishing, 2019.
15. Sharma, Himanshu, Ahteshamul Haque, and Zainul A. Jaffery. "Solar energy harvesting wireless sensor network nodes: A survey." *Journal of Renewable and Sustainable Energy* 10, no. 2 (2018).
16. Hohm, D. P., and M. E_ Ropp. "Comparative study of maximum power point tracking algorithms." *Progress in photovoltaics: Research and Applications* 11, no. 1 (2003): 47-62.

17. Sharma, Amandeep, and Ajay Kakkar. "A review on solar forecasting and power management approaches for energy-harvesting wireless sensor networks." *International Journal of Communication Systems* 33, no. 8 (2020): e4366.
18. Buchli, Bernhard, Felix Sutton, Jan Beutel, and Lothar Thiele. "Dynamic power management for long-term energy neutral operation of solar energy harvesting systems." In *Proceedings of the 12th ACM conference on embedded network sensor systems*, pp. 31-45. 2014.
19. López-Lapeña, Oscar, Maria Teresa Penella, and Manel Gasulla. "A new MPPT method for low-power solar energy harvesting." *IEEE Transactions on industrial electronics* 57, no. 9 (2009): 3129-3138.
20. Hasan, Md Asif, and Sambit K. Parida. "An overview of solar photovoltaic panel modeling based on analytical and experimental viewpoint." *Renewable and Sustainable Energy Reviews* 60 (2016): 75-83.
21. Violette, Edmond J., Richard H. Espeland, Robert O. DeBolt, and F. K. Schwering. "Millimeter-wave propagation at street level in an urban environment." *IEEE Transactions on Geoscience and Remote Sensing* 26, no. 3 (1988): 368-380.