Impact Factor (SJIF): 6.092 E-ISSN: 2583-1615

International Journal of Research in Academic World

Received: 08/July/2024 **IJRAW:** 2024; 3(8):87-94 **Accepted:** 12/August/2024

Solar Energy Harvesting (SHE) for Low Power Internet of Things (IoT) Edge Devices

[*1]Mamatha Dhananjaya, [2]Dr. Manjunatha Reddy HS and [3]Ramya KV

[*1, 3]Assistant Professor, Department of ECE, Global Academy of Technology (VTU), Bangalore, India.

[2]Professor and Head, Department of ECE, Global Academy of Technology (VTU), Bangalore, India.

Abstract

This This work introduces an energy-efficient monolithic Power Management Unit (PMU) designed specifically for photovoltaic cells, capable of efficiently charging a large supply capacitor and managing stored energy to provide the necessary supply voltage and power for low-energy wireless sensor nodes, including sensors and actuators. The proposed system is self-sustaining, initiating operation with a light source luminosity of 500 lux or higher using only a 1.42 cm² solar cell. Additionally, it integrates an energy monitor, enabling the system to power autonomous sensor nodes operating in discontinuous modes. This PMU enhances energy efficiency, making it ideal for applications requiring low power consumption and reliable energy management in indoor environments.

Keywords: Solar energy harvesting, power management unit, DC-DC converter

1. Introduction

The Internet of Things (IoT) represents a transformative force in modern technology, interlinking physical devices, vehicles, buildings, and other objects, embedded with sensors, software, and network connectivity, enabling these entities to collect and exchange data. This network of connected devices offers unprecedented opportunities for automation, data-driven decision-making, and improved efficiency across various sectors. The concept of IoT is not new [1]; however, its rapid expansion in recent years has been fueled by advances in wireless communication, cloud computing, and the proliferation of smart devices. At its core, IoT leverages the power of the internet to extend the capabilities of everyday objects, allowing them to communicate with each other and with central systems without requiring human intervention. This connectivity enables real-time monitoring, control, and analysis, which can significantly enhance operational processes. For instance, in industrial settings, IoT devices can monitor machinery for signs of wear and tear, predict maintenance needs, and optimize production schedules, thereby reducing downtime and costs. Similarly, in smart homes, IoT devices such as thermostats, lighting systems, and security cameras can be controlled remotely, providing convenience, energy savings, and enhanced security.

One of the key components of IoT is data. The vast amount of data generated by IoT devices can be analyzed to extract valuable insights, leading to improved decision-making and the creation of new business models. For example, in the healthcare industry, IoT-enabled devices can monitor patients' vital signs in real time, allowing for timely interventions and personalized treatment plans. In agriculture, IoT systems can track soil moisture levels, weather conditions, and crop health, helping farmers to optimize irrigation and maximize yield. The ability to gather and analyze data on such a large scale opens up possibilities for innovation and efficiency that were previously unimaginable. However, the growth of IoT also brings significant challenges, particularly in terms of security and privacy [2]. With so many devices connected to the internet, the potential for cyberattacks increases, raising concerns about the vulnerability of critical systems and personal information. Ensuring that IoT devices are secure and that data is protected from unauthorized access is a major focus for developers and policymakers alike. Moreover, the sheer volume of data generated by IoT devices presents challenges in terms of storage, processing, and management. Advanced data analytics and machine learning techniques are being developed to address these issues, but the complexity of IoT ecosystems means that these solutions must be continuously refined.

Internet of Things is reshaping the way we interact with the world around us, offering new levels of connectivity, efficiency, and intelligence. From smart homes to industrial automation, healthcare, and agriculture, IoT is driving innovation across a wide range of industries. While the benefits of IoT are vast, the challenges, particularly related to security and data management, must be addressed to fully

***Corresponding Author:** Mamatha Dhananjaya

realize its potential [3]. As IoT continues to evolve, it is likely to play an increasingly central role in our lives, transforming not only how we live and work but also how we think about technology and its impact on society.

The paper is arranged as follows: Section 2 highlights the research motivation of the paper. Section 3 introduces an overview of IoT enabling technologies introduces in Section 3.1. A brief description of the WSNs technology that enabled the IoT revolution is provided in Section 3.2. Various sources of energy wastage and different solutions have been mentioned in the literature and are presented in Section 3.5. Section 5 identifies the gaps in the existing literature in terms of energy conservation measures that could be considered in future works. Finally, Section 6 is summarized the paper.

2. Motivation of the Research

Researching continuous power for edge IoT devices is critical due to the increasing reliance on these devices for real-time data processing in remote or resource-constrained environments. Edge IoT devices often operate in areas where reliable power sources are scarce, making uninterrupted operation a significant challenge [4]. Ensuring continuous power is essential to maintain the functionality of these devices, which are integral to applications like environmental monitoring, smart agriculture, and industrial automation.

Furthermore, continuous power solutions can enhance the lifespan and efficiency of edge devices, reducing downtime and maintenance costs. By exploring innovative energy-harvesting techniques, low-power design strategies, and efficient power management systems, researchers can develop sustainable solutions that support the growing demand for resilient and autonomous IoT networks. This research is vital for enabling the full potential of IoT technologies, particularly in critical and remote applications where consistent performance is non-negotiable.

3. Literature Review

The Internet of Things (IoT) technology, with its ability to connect a vast array of devices to networks, has revolutionized how organizations operate and interact with their environments. Leaders across industries recognize the immense potential of IoT to drive efficiency, innovation, and new revenue streams. By investing in IoT, companies are capitalizing on its ability to transform ordinary objects into smart, connected devices that can collect, analyze, and share data.

The applications of IoT are extensive and span across various sectors. In smart homes, IoT devices control lighting, heating, and security systems, offering enhanced convenience and energy efficiency. In healthcare, wearable IoT devices monitor patient health in real-time, enabling early diagnosis and personalized treatment. Industrial IoT (IIoT) applications improve manufacturing processes by monitoring equipment and optimizing production through predictive maintenance. In agriculture, IoT sensors track soil conditions and weather patterns, helping farmers maximize crop yields [5]. Understanding these common applications is essential for grasping the current impact of IoT. However, the future holds even more possibilities as IoT technology continues to evolve, offering new solutions for challenges in areas like urban planning, environmental monitoring, and beyond. As IoT expands, its role in shaping the future of technology and society will only grow.

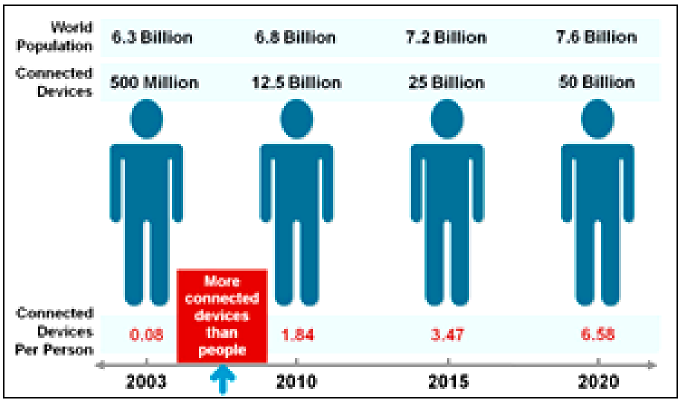

Fig 1: The number of people greater than the number of people [5]

The global number of IoT devices is expected to nearly double from 15.9 billion in 2023 to over 32.1 billion by 2030, with China projected to lead in 2033 with around 8 billion consumer devices. The consumer segment, accounting for 60% of all IoT devices in 2023, is anticipated to maintain this dominance over the next decade. Key industry verticals, each exceeding 100 million connected IoT devices, include electricity, gas, water supply, waste management, retail, transportation, and government. By 2033, IoT devices across all industries are expected to surpass eight billion [6]. The most significant use case in the consumer segment is internet and media devices, such as smartphones, with forecasts predicting over 17 billion devices by 2033. Additionally, other major use cases, including connected vehicles, IT infrastructure, asset tracking, and smart grids, are each expected to exceed one billion devices by the same year, underscoring IoT's growing impact across various sectors.

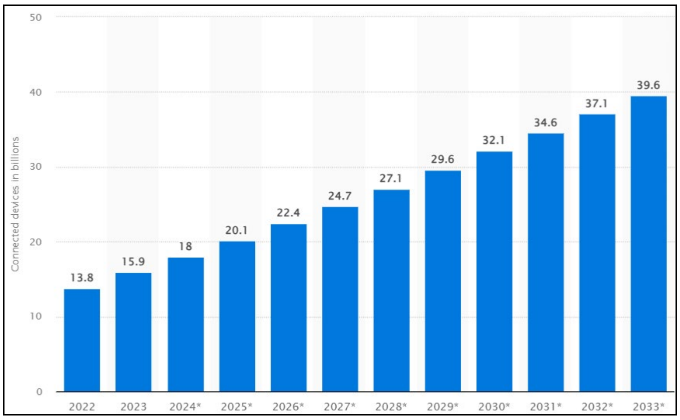

Fig 2: Number of IoT devices globally [6]

Applications of IoT as highlighted in recent studies [7], underscoring its broad impact across various sectors. Figure 3 showcases a comprehensive taxonomy of IoT applications, categorizing them into key fields such as healthcare, environmental monitoring, smart cities, commercial enterprises, industrial operations, and infrastructure management. These application areas are pivotal in driving the adoption and evolution of IoT, illustrating how this technology is shaping modern advancements and gaining widespread acceptance. The continuous exploration of IoT applications enhances our understanding of the technology, facilitating the design of innovative systems tailored to emerging needs. Essentially, IoT revolves around the concept of generating and transferring data between objects, thereby enabling seamless communication across devices. This capability expands the range of IoT applications, making them highly versatile and virtually limitless [8]. The dynamic nature of IoT ensures that its applications continue to grow, influencing various domains and contributing to the advancement of technology in the new world. The study of these applications is crucial for improving IoT technology and driving further innovation, ensuring its relevance in addressing both current and future challenges.

Power consumption is a critical challenge for IoT devices, particularly because many rely on small, non-rechargeable batteries [9]. Optimizing battery life is essential, not only to meet customer expectations for long-lasting devices but also to ensure the economic viability of IoT projects. In cases where sensors and actuators fail prematurely due to battery depletion, replacement costs can be prohibitively high. Manufacturers use various tools to conduct battery drain analysis to understand how IoT devices consume power. These devices often exhibit highly variable current waveforms, with rapid switching between operational modes that consume tens or hundreds of milliamps and low-power sleep modes that require only micro-or nano-amps. This variability makes accurate power management challenging, but essential for prolonging battery life.

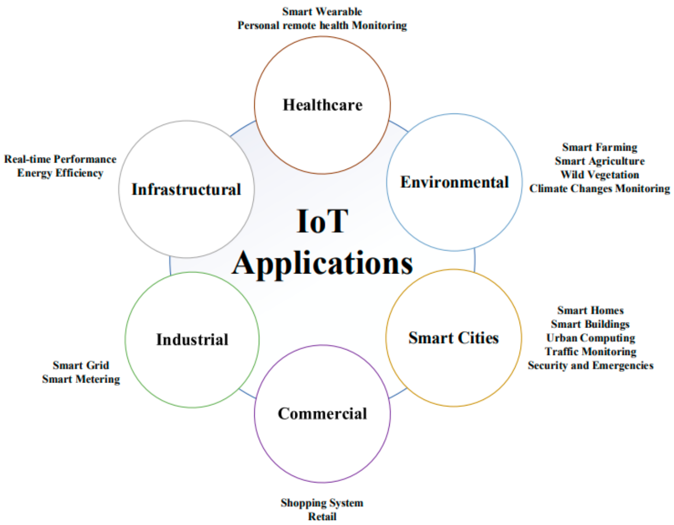

Fig 3: Taxonomy of IoT applications [8]

Proper design techniques can significantly extend the battery life of IoT devices. These techniques may include optimizing power consumption during active modes, minimizing power use in sleep modes, and employing energy-efficient components. By addressing these factors, manufacturers can ensure that IoT devices operate effectively over extended periods, reducing the need for frequent battery replacements and enhancing the overall sustainability of IoT networks.

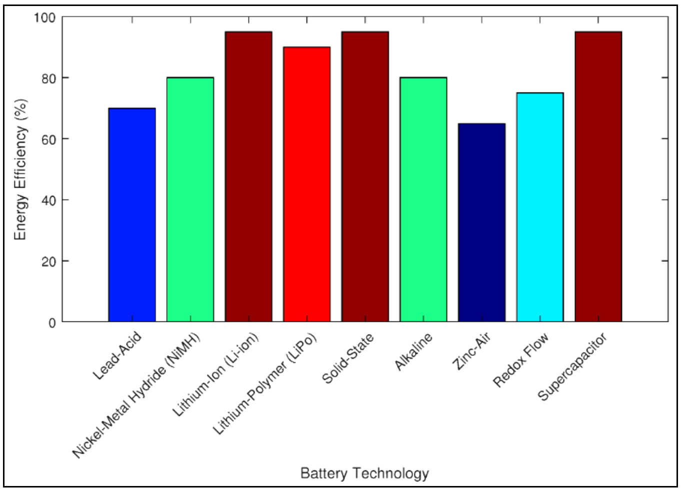

Fig 4: Average energy efficiency of different battery technologies [10].

Energy efficiency in batteries, defined as the ratio of discharged to charged energy, is crucial, with energy losses manifesting as heat that must be managed to prevent overheating. The safety of IoT devices, especially wearables that come into close contact with human skin, is a significant concern. Wearable batteries must avoid causing skin allergies or toxicity. Lead-acid batteries, due to their toxic components, rank lower in safety. Lithium-based batteries, though widely used, carry risks like thermal runaway if mismanaged. Alkaline and zinc-air batteries are safer alternatives, adhering to IEC 60086-2 standards for safety and medical compatibility.

Table 1: IoT network overview [10]

Technology	Power Consumption	Energy Density Requirements	Range	Battery Life Expectancy	Typical Applications
BLE	Very Low	Low	Short (up to 10 m)	Medium	Wearables, Beacons
LoRaWAN	Low	Medium	Long	Long	Remote Sensors, Agriculture Monitoring
IoT over Cellular Network	Low	Medium	Long	Long	Smart Meters, Asset Trackers
WiFi	High	High	Short	Short	Smart Home, Industrial IoT

When designing an IoT system with a wireless network, processing unit, and end nodes, several critical factors must be carefully evaluated. Energy density is a key consideration, requiring optimization to ensure efficient operation. Power consumption analysis is vital to prevent rapid battery depletion, ensuring the system functions effectively over an extended period. Long battery life is essential for minimizing the need for frequent replacements. Safety considerations are also paramount to avoid potential hazards to users and the environment.

Wireless networks such as BLE (Bluetooth Low Energy), LoRaWAN, GSM, and Wi-Fi are integral to IoT systems but vary significantly in their power demands. BLE is preferred for applications requiring long battery life due to its low power consumption, while LoRa offers low power use over longer distances [10]. Wi-Fi, although providing higher bandwidth, consumes more power, potentially shortening battery life. Cellular IoT networks like EC-GSM-IoT and NB-IoT balance long-range communication with energy efficiency, making them suitable for wide-area applications.

Providing continuous energy or power supply to IoT devices using renewable energy resources is a promising approach to ensure their uninterrupted operation. Renewable energy sources such as solar, wind, and kinetic energy can be harnessed to power IoT devices, particularly those deployed in remote or off-grid locations. Solar panels, for instance, can be integrated into IoT devices to convert sunlight into electricity, while small wind turbines or kinetic energy harvesters can generate power from environmental movements.

Using renewable energy not only enhances the sustainability of IoT systems but also reduces dependence on conventional batteries and the environmental impact associated with battery disposal. This approach is especially beneficial for IoT applications that require continuous monitoring and data transmission, such as environmental sensors, agricultural monitoring systems, and remote industrial equipment. By tapping into renewable energy sources, IoT devices can achieve longer operational lifespans, reduced maintenance costs, and greater reliability, all while contributing to a more sustainable and energy-efficient future.

4. Energy Harvesting

Energy harvesting refers to the process of capturing and converting energy from external sources like solar, wind, thermal, or kinetic energy into electrical power. This technique is particularly valuable for powering IoT devices, especially in remote or hard-to-reach areas where replacing batteries is impractical. By harnessing ambient energy, these devices can operate autonomously for extended periods, reducing the need for conventional power sources. Energy harvesting enhances the sustainability and efficiency of IoT systems, allowing them to function continuously without relying on grid power or frequent battery replacements, thereby supporting long-term and cost-effective deployments.

Wind energy and solar energy are two prominent methods of energy harvesting for powering IoT devices, each with its unique advantages and limitations.

Wind energy harvesting involves capturing energy from wind using small-scale turbines or piezoelectric materials. It is particularly effective in locations where wind is consistent and strong, such as coastal or mountainous regions. Wind energy can be harvested day and night, offering a continuous power supply, which is a significant advantage over solar energy. However, wind energy harvesting systems can be more complex due to the mechanical components involved, requiring maintenance and potentially being subject to wear and tear. Additionally, wind speeds may vary, leading to fluctuations in the power generated, which can affect the reliability of IoT devices.

On the other hand, solar energy harvesting utilizes photovoltaic cells to convert sunlight into electricity. Solar energy is widely accessible and easy to deploy, making it a popular choice for IoT devices, especially in areas with abundant sunlight. Solar panels are typically low-maintenance and have no moving parts, making them durable and reliable. However, solar energy harvesting is dependent on sunlight, which means power generation is limited to daylight hours and can be affected by weather conditions such as cloud cover or shading. This variability can be a drawback for IoT devices that require a consistent power supply.

Wind energy harvesting is advantageous for its ability to generate power continuously, especially in windy environments, but may involve more complex and maintenance-heavy systems. Solar energy harvesting is easier to implement and reliable in sunny areas, but its dependency on daylight can limit its effectiveness. The choice between wind and solar energy harvesting for IoT devices should be based on the specific environmental conditions and power requirements of the application, with some systems potentially benefiting from a hybrid approach that combines both energy sources to maximize reliability and efficiency.

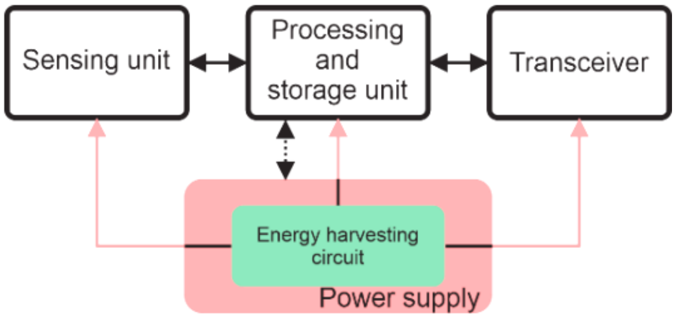

Fig 5: IoT device with Energy Harvesting Architecture: Harvest-Use

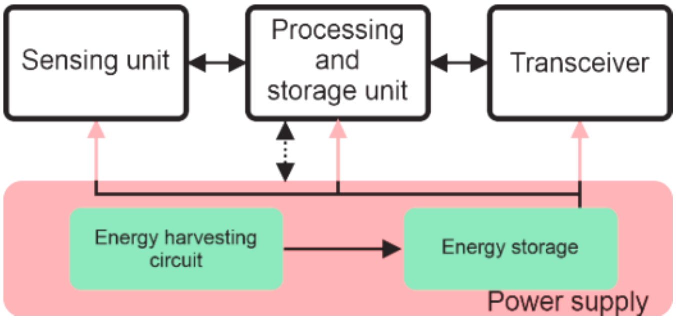

Fig 6: IoT device with Energy Harvesting Architecture: Harvest-Store-Use

Energy harvesting, or energy scavenging, involves capturing energy from external sources like mechanical loads, vibrations, temperature gradients, or light, and converting it into small amounts of power to supply electronic devices. This approach leverages ambient energy from the environment, providing a green energy source that can either replace primary batteries or charge secondary cells, offering a cost-effective and environmentally friendly solution for powering wireless devices. A typical energy harvesting system consists of three main components: the energy source (external energy collected), the harvesting architecture (mechanisms for conversion), and the load (the consumer of the energy) as shown in the two architecture Figure 5 and Figure 6 [11].

The harvested energy can be used immediately or stored for future use, leading to two primary architectures in energy harvesting systems. In systems configured for immediate use, energy is converted and directly consumed by the device. In systems designed for storage, energy is captured and stored in batteries or capacitors, allowing for continuous operation even when the external energy source is unavailable. Key components of these systems include energy harvesting circuits that convert ambient energy into Direct Current (DC) energy, power management units that optimize energy efficiency, and storage elements that ensure a reliable power supply. These components are the focus of ongoing research aimed at creating energy-autonomous wireless sensors for deployment in IoT environments, enabling sustainable and efficient operation in diverse applications.

5. IoT Edge Device

The Internet of Things (IoT) ecosystem is a complex network composed of several critical components, each performing distinct functions that collectively enable the seamless operation of smart systems. The Edge, a crucial part of this ecosystem, comprises Gateways, Devices, Sensors, and

Actuators, all of which interact to sense, process, connect, and execute tasks as shown in Figure 7 [12]. Understanding these components and their roles is essential to grasp the full potential and operation of IoT systems.

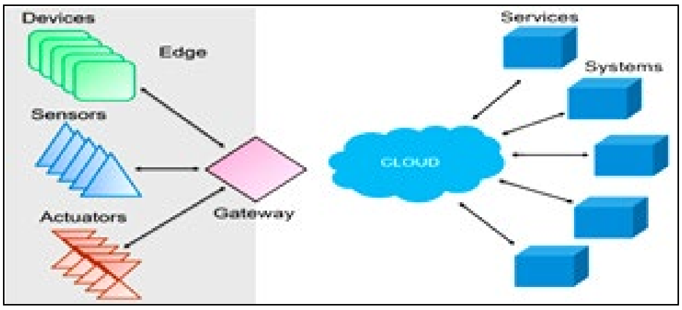

Fig 7: IOT System, Cloud and Edge.

A. Sensors and Actuators: "Sense and Execute"

Sensors and actuators are the foundational elements in any IoT system, responsible for interacting with the physical world. Sensors are designed to detect and measure various physical parameters such as temperature, humidity, pressure, light, sound, and motion, converting these into electrical signals or other measurable parameters that can be processed by the system. For instance, microphones capture sound waves and convert them into electrical signals, while accelerometers measure the rate of change in velocity.

In contrast, actuators perform the "execute" function, converting electrical signals back into physical action. This could involve opening a valve, moving a robotic arm, or producing sound through a speaker. Actuators are integral to IoT systems because they allow the system to interact with the environment based on the data received from sensors.

One of the key challenges in the design of sensors and actuators is power management. Depending on whether a node is mains-powered or battery-powered, the power requirements can vary significantly. Smart sensors are often required to operate with minimal power consumption, especially in battery-powered devices, to extend their operational life. This consideration can drive functional partitioning, where some processing might be done locally (at the edge) rather than sending all data to the cloud, thereby conserving energy and reducing latency.

B. Devices: "Process"

Devices in IoT systems act as the processing units. They are responsible for collecting, processing, and storing data in a more distributed fashion, closer to the endpoints. This decentralized approach reduces the need for constant communication with the cloud, thereby lowering latency and conserving network resources.

Advances in processing technology have significantly contributed to making these devices smaller and more powerful, enabling them to perform complex computations locally. This capability is crucial in scenarios where immediate processing is required, such as in autonomous vehicles or real-time monitoring systems. By handling data locally, devices can provide quicker responses to changes in the environment, enhancing the overall efficiency and functionality of IoT systems.

C. Gateways: "Connect"

Gateways serve as the bridge between edge devices and the cloud. They are essential for moving data from the edge of the network to central cloud-based systems where further processing and storage can take place. Gateways manage the communication between devices that may operate on different protocols and the cloud, ensuring seamless data flow across the network.

In addition to connecting devices to the cloud, gateways often perform data preprocessing to reduce the volume of data sent to the cloud, which conserves bandwidth and reduces costs. For example, a gateway might aggregate data from multiple sensors, filter out noise, or perform basic analytics before transmitting the data.

D. Cloud: "Process"

The cloud in IoT systems is where extensive data processing, storage, and analysis occur. Cloud platforms provide the computational power and storage capacity required to handle the vast amounts of data generated by IoT devices. The cloud also supports on-demand services, allowing users to access and analyze data from anywhere at any time.

In IoT, the cloud is not just a passive data repository; it often hosts advanced analytics and machine learning algorithms that can derive insights from the collected data. These insights can then be sent back to the devices for action or used to improve system performance over time. For instance, predictive maintenance algorithms running in the cloud can analyze data from industrial machines to predict failures before they occur, thereby reducing downtime and maintenance costs.

E. Systems: "Act"

The final component in an IoT system is the action layer, where the information processed by the cloud is used to perform specific tasks or services. This could involve sending a command to an actuator, such as a robot arm or an audio speaker, based on the data received. For example, a command issued to Amazon's Alexa might trigger a purchase or provide an answer to a query, demonstrating how IoT systems can interact with users in meaningful ways.

In some cases, the "act" function might involve more complex actions, such as driving machinery in an industrial setup, controlling home automation systems, or managing traffic in smart cities. The ability to act based on data is what makes IoT systems truly intelligent and autonomous, enabling them to perform tasks that improve efficiency, safety, and convenience across various applications.

The IoT ecosystem is a sophisticated network of interconnected components, each playing a vital role in sensing, processing, connecting, and executing tasks. Sensors and actuators form the interface with the physical world, devices process data locally, gateways connect the edge to the cloud, the cloud provides extensive processing and storage capabilities, and the system's "act" function uses this information to perform meaningful actions. Together, these components create powerful, intelligent systems that are transforming industries and improving our daily lives.

6. Proposed System

The proposed indoor solar energy harvester is designed shown in Figure 8 to provide continuous power to an autonomous sensor node, making it suitable for energy-limited environments. This system's architecture comprises several key components, each playing a crucial role in maintaining efficient and reliable operation. Among these, the Power Management Unit (PMU) is a central element that interfaces between the energy source (the solar harvester) and the load, which includes the microcontroller (MCU), sensors, and actuators.

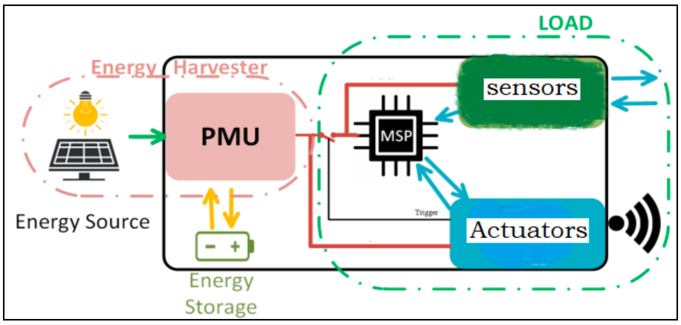

Fig 8: The Proposed system

The PMU is responsible for managing the energy harvested from indoor light sources, ensuring that sufficient power is supplied to the various components of the sensor node. It regulates the power distribution to the microcontroller, which processes data, and to the sensors and actuators that perform specific tasks such as sensing environmental parameters and communicating wirelessly with a reader or central system.

To optimize energy consumption, the system is designed to reduce power usage during periods of inactivity. Specifically, the microcontroller and sensors are switched off when not actively processing or transmitting data. During this time, only the low-power transceiver and the PMU remain active. The transceiver continuously listens for a trigger command from the reader, which signals the system to wake up and perform its tasks. This listening mode is energy-efficient but still consumes a small amount of power, which is why the design prioritizes minimizing consumption during these periods.

The PMU is tailored for these energy-limited loads, particularly in scenarios where the power budget is tight, such as in environments with minimal indoor lighting. It ensures that the sensor node remains operational by efficiently managing the small amounts of energy harvested. When the system is triggered, and the microcontroller and sensors are activated, the PMU handles the surge in power demand, ensuring that all components receive the energy they need to function correctly.

The proposed system integrates an indoor solar energy harvester with a well-designed PMU to maintain the operation of an autonomous sensor node under challenging power conditions. The PMU's ability to manage power distribution and minimize energy consumption during idle periods is crucial for extending the sensor node's operational life, making it a viable solution for sustainable, energy-efficient IoT applications.

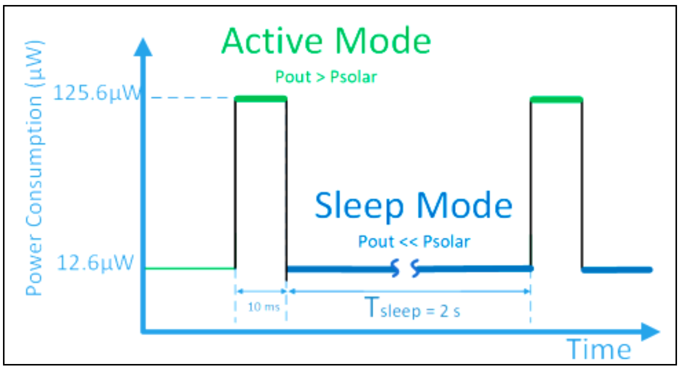

Fig 9: Power consumption pattern over time for the proposed wireless sensor node [13]

The power consumption dynamics of a wireless sensor node is shown in figure 9. are pivotal in determining the efficiency and sustainability of energy-harvesting systems, especially in IoT applications where the balance between power generation and consumption is crucial. A typical wireless sensor node operates in two primary modes: active mode and sleep mode, each with distinct power requirements.

The transceiver communicates with the reader or central node using backscattering techniques, complemented by a battery-assisted semi-passive operation. This setup achieves a sensitivity of -24 dBm, allowing a communication range of up to 21 meters [14]. In battery-assisted mode, the minimum energy required to power the chip is 12.6 µW, with a supply voltage specification ranging from 1 V to 3.3 V. Notably, a minimum of 1.4 V is necessary to wake up the system. This configuration ensures efficient communication while minimizing power consumption.

F. Active Mode: High Power Demand

During the active mode, the sensor node engages in tasks such as data collection, processing, and communication, which demand significantly higher power. This is the phase where the sensor actively interacts with its environment-sensing physical parameters, manipulating data, and transmitting information to other network components or the cloud. Due to these intensive activities, the power consumption during the active mode often exceeds the power that can be harvested in real-time from ambient sources like indoor solar energy.

The challenge in this phase is that the energy generator, such as a solar panel, typically provides insufficient power to meet the immediate needs of the sensor node during its active operations. This discrepancy necessitates a design strategy where the system can store excess energy harvested during periods of low activity or sleep mode, which can then be utilized during the high-demand active phases. Thus, energy storage components, like capacitors or batteries, play a critical role in bridging the gap between energy generation and consumption during active mode.

G. Sleep Mode: Energy Conservation

In contrast, during sleep mode, the sensor node significantly reduces its power consumption by deactivating non-critical functionalities. This mode is characterized by the shutdown of various components such as the microcontroller (MCU) core, sensor electronics, and interface logic peripherals. The node enters a low-power state, effectively conserving energy while waiting for a stimulus-such as a scheduled wake-up signal or an external event-to resume full operations.

The sleep mode is integral to the efficiency of low-power, duty-cycled sensor nodes, as it typically lasts much longer than active mode, often by an order of magnitude. This extended low-power period allows the system to accumulate energy from the harvester, making it available for the next active cycle. The stark difference in power requirements between active and sleep modes allows for strategic energy management within the sensor node, particularly through the use of power management units (PMUs).

H. Power-Limited Loads

Power-limited loads refer to scenarios where the power consumption during sleep mode is comparable to the power generated by the harvester. This situation is common in cases where the transceiver, which is responsible for maintaining communication, remains active even during sleep mode to continuously listen for incoming signals. The continuous operation of the transceiver, even at reduced power levels, leads to a non-negligible power drain during periods that would otherwise be low-consumption.

In such power-limited scenarios, maximizing the efficiency of the PMU is critical. This is often achieved through the implementation of Maximum Power Point Tracking (MPPT) modules, which dynamically adjust the power conversion process to ensure that the harvester operates at its maximum efficiency. MPPT modules optimize the energy transfer from the harvester to the storage elements or directly to the load by adapting to varying environmental conditions, such as changes in light intensity for solar harvesters. The goal is to maintain an optimal balance where the energy harvested closely matches the energy consumed, even in low-power scenarios.

I. Energy-Limited Loads

Energy-limited loads, on the other hand, are characterized by a significant difference between power consumption in active and sleep modes. In these systems, the average power consumption during active mode is much higher-often by an order of magnitude-than during sleep mode and exceeds the average power generated by the harvester. However, during sleep mode, the energy consumption is low enough to allow the system to store energy efficiently, which will later be used during active periods.

In energy-limited scenarios, while MPPT is still beneficial, it is not as critical as in power-limited loads. The system can rely on the relatively low power demands during sleep mode to build up an energy reserve in an external capacitor or battery. This stored energy is then available to power the sensor node during its high-demand active periods. The harvester in such systems often operates near the “open circuit” condition during stationary states, where the energy storage is maximized, and the energy recovery process is continuous and efficient.

Understanding the power consumption patterns of wireless sensor nodes, particularly the distinction between active and sleep modes, is essential for designing efficient energy-harvesting systems. Power-limited loads require careful management of continuous low-level energy consumption, often necessitating advanced MPPT techniques to maximize energy transfer efficiency. In contrast, energy-limited loads benefit from the ability to store energy during low-demand periods and utilize it during high-demand active phases, making them more flexible in terms of power management strategies. By tailoring the PMU and energy storage systems to the specific needs of the sensor node, designers can ensure reliable and sustainable operation, even in energy-constrained environments.

J. Power Management Unit

The charge pump (CP) or DC-DC converter which is shown in Figure 10. is designed to quadruple the output voltage of the energy generator. It achieves this by using two identical charge pump modules, CP1 and CP2, each with a fixed conversion ratio of 2×. [15] These modules work in tandem, and their outputs are combined through a conventional voltage adder, resulting in the final 4× voltage increase. This configuration efficiently boosts the voltage, ensuring sufficient power for the system's operation.

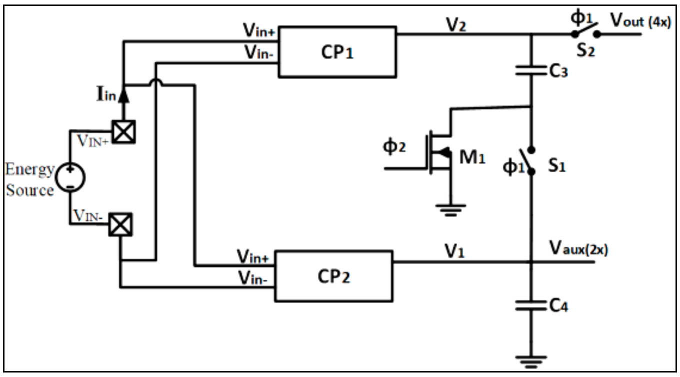

Fig 10: DC-DC Converter

K. Energy Source

The selected energy source is a small monocrystalline photovoltaic panel, specifically the KXOB25-05X3F shown in Figure 11a, with an active area of 1.42 cm² [16]. This solar cell's performance has been characterized under various indoor lighting conditions, examining light intensities ranging from 500 to 1000 lux. Different light sources, including fluorescent, LED, and halogen, were considered during the testing. The characterization results were then plotted to illustrate the cell's behavior under these varying conditions.

The energy generator, which is the photovoltaic panel, converts ambient light into a continuous voltage output. This output voltage is influenced by both the intensity of the external light and the power demands of the Power Management Unit (PMU) [17]. As the light intensity and the PMU’s power requirements change, the panel’s voltage output follows a specific power curve, which is depicted in Figure 11b of the reference. In the case of an LED light source, this curve demonstrates how the panel’s voltage output adjusts to meet the energy needs of the system under different indoor lighting scenarios.

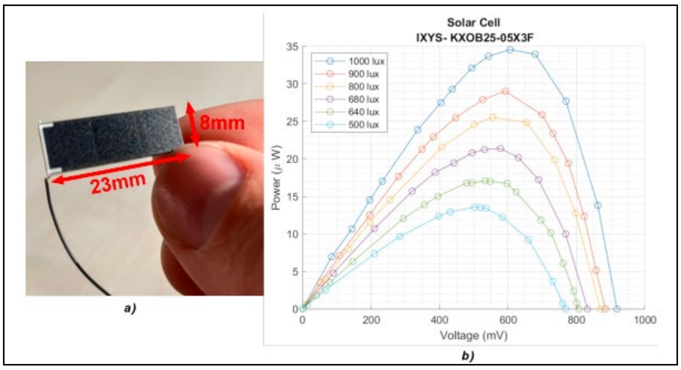

Fig 11: (a) Solar cell and dimensions; (b) output power from the solar cell vs. output voltage with LED light sources and different light intensities.

Here LED illumination was chosen due to its widespread use and high efficiency. According to the U.S. Department of Energy [18], LED lighting is expected to dominate most lighting installations by 2035. In a typical indoor setting with 680 lux from LED light, the solar cell previously discussed was tested, and it achieved a measured maximum power output of 21.38 μW. This demonstrates the potential of LED lighting as a reliable source for indoor energy harvesting, making it a critical factor in the design and optimization of such systems.

7. Conclusion

This work presents an innovative energy harvester that has been demonstrating high efficiency under low indoor lighting conditions. The proposed solar energy harvester is entirely self-sustaining, with the ability to cold start without external biasing signals. The solar power source is a commercial solar cell, the KXOB25-05X3F, with an active area of 1.42 cm^2. The system can initiate operation under indoor lighting as low as 500 lux without the need for external kick-off or control signals. It achieves a measured end-to-end Power Conversion Efficiency (PCE) of 60.54%, delivering a throughput power of 13.14 µW at 680 lux. Under higher indoor light conditions of 1000 lux, the maximum output power can reach up to 25 µW. When operating in an open-circuit scenario, the peak Voltage Conversion Efficiency (VCE) is 94.5%. Additionally, the integrated energy monitor enables the system to supply power to autonomous sensor nodes within a 1 V to 2 V operation range. This capability allows for discontinuous operation regardless of the sensor's power consumption during activity, achieved by adjusting the supply capacitor size and automatically modifying the measuring rate.

Conflicts of Interest

We confirm that there are no conflicts of interest related to this publication, and that no significant financial support was received that could have influenced its outcome. This statement ensures the integrity, impartiality, and transparency of the research, affirming that the results and conclusions are unbiased and solely based on the study.

References

1. Mouha RA. Internet of Things (IoT). *Journal of Data Analysis and Information Processing*, 9, 77-101. https://doi.org/10.4236/jdaip.2021.92006, 2021
2. AbdelRahman H. Hussein," Internet of Things (IOT): Research Challenges and Future Applications", *(IJACSA) International Journal of Advanced Computer Science and Applications*, 2019, 10(6).
3. Kinza Shafique, Bilal A. Khawaja, Farah Sabir4, Sameer Qazi, Muhammad Mustaqim," Internet of Things (Iot) For Next-Generation Smart Systems: A Review Of Current Challenges", Future Trends And Prospects For Emerging 5g-Iot Scenarios", DOI 10.1109/Access.2020.2970118,2020.
4. James Spehar, Adam Fuks, Marc Vauclair, Maurice Meijer, Joost van Beek, Bin Shao," Power Challenges Caused by IOT Edge Nodes: Securing and Sensing Our World", Proceedings of the 31st International Symposium on Power Semiconductor Devices & ICs, 2019.
5. Robin Chataut, Alex Phoummalayvane, Robert Ak, "Unleashing the Power of IoT: A Comprehensive Review of IoT Applications and Future Prospects in Healthcare, Agriculture, Smart Homes, Smart Cities, and Industry 4.0", 4.0. Sensors 2023, 23, 7194. https://doi.org/10.3390/s23167194.
6. Transforma Insights, Number of Internet of Things (IoT) Connected Devices Worldwide from 2019 to 2021, with Forecasts from 2022 to 2030 (in Billions). Statista. Available online: https://www.statista.com/statistics/1183457/iot-connected-devices worldwide/(accessed on 14 June 2023).
7. Rosilah Hassan, Faizan Qamar, Mohammad Kamrul Hasan, Azana Hafizah Mohd Aman, Amjed Sid Ahmed, "Internet of Things and Its Applications: A Comprehensive Survey", Symmetry 2020, 12, 1674; doi:10.3390/sym12101674
8. R. Ramakrishnan, Dr. K. Sasikala, Dr. A. Nagappan, "Challenges, Issues of Energy Efficiency in IoT devices and an analysis of batterylife power consumption in IoT devices and Applications.", *JETIR*, 2020, 7(11).
9. Kareeb Hasan, Neil Tom, Mehmet Rasit Yuce," Navigating Battery Choices in IoT: An Extensive Survey of Technologies and Their Applications", Batteries 2023, 9, 580. https://doi.org/10.3390/batteries9120580, 2023.
10. Teodora Sanislav, George Dan Mois, Sherali Zeadally, Silviu Corneliu Folea, " Energy Harvesting Techniques For Internet Of Things (Iot)", Special Section On Emerging Trends Of Energy And Spectrum Harvesting Technologies, Volume 9, 2021, DOI 10.1109/Access.2021.3064066.
11. Spehar J, Fuks A., Vauclair M, Meijer M, Van Beek J, Shao B. Power Challenges Caused by IOT Edge Nodes: Securing and Sensing Our World. 2019 31st International Symposium on Power Semiconductor Devices and ICs (ISPSD). doi:10.1109/ispsd.2019.8757597
12. Lopez-Gasso A, Beriain A., Solar H., Berenguer R, " Power Management Unit for Solar Energy Harvester Assisted Batteryless Wireless Sensor Node", Sensors 2022, volume 22, https://doi.org/10.3390/s22207908.
13. Beriain A, Solar H, Duroc Y, Tedjini S, "Voltage Multiplier Design for Harmonic Communication in Harvester Assisted Ultrahigh Frequency (UHF) Radio Frequency Identification (RFID) Systems. URSI Radio Sci. Lett. 2021.
14. Megahed M, Ramadass Y, Anand T, "A Sub 1 µW Switched Source Capacitor Architecture Free of Top/Bottom Plate Parasitic Switching Loss Achieving Peak Efficiency of 80.66% at a Regulated 1.8 V Output in 180 nm", In Proceedings of the 2019 IEEE Custom Integrated Circuits Conference (CICC), Austin, TX, USA, 14-17 pp. 1-4, April 2019.
15. Ys Ixolartm Datasheet: Kxob25-05x3f. Available Online: Https://Ixapps.Ixys.Com/Datasheet/Kxob25_05x3f.Pdf (Accessed On 14 December 2021).
16. Preto S, Caramelo Gomes C, 'Lighting in the Workplace: Recommended Illuminance (lux) at Workplace Environs", In Advances in Design for Inclusion; Springer: Cham, Switzerland, 2018._18.
17. Astigarraga A, Lopez-Gasso A, Golpe D, Beriain A, Solar H, del Rio D, Berenguer R, " A 21 m Operation Range RFID Tag for Pick to Light Applications with a Photovoltaic Harvester Micromachines", Volume 11, 1013, 2022.
18. US Department of Energy. LED Lighting Energy Saver. Available online: https://www.energy.gov/energysaver/led-lighting (accessed on 5 September 2022).