Sensor-based Life Detection of Solar Cells

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To address the challenge of limited node lifespan in outdoor sensor networks, this study introduces an innovative micro-solar system that goes beyond traditional methods of reducing power consumption, such as data compression and low-power routing. The proposed system integrates solar panels to harness solar energy, which is then stored in a novel low-self-discharge nickel-hydrogen AAA battery. To further extend the battery's lifespan, a battery-driven design approach was utilized during the system's development. A prototype was constructed and deployed for continuous outdoor testing, with data sampling at 10-minute intervals and a 15-second sampling rate. Over four weeks, the system's performance was evaluated, focusing on the voltage levels of the charging battery pack, which were monitored continuously for seven days. The findings confirm that the system aligns perfectly with the design strategy, demonstrating high reliability, cost-effectiveness, and practical feasibility. This research not only provides a viable solution for extending sensor node longevity but also contributes to the broader integration of renewable energy in sensor network applications, paving the way for more sustainable and efficient network designs.

Povzetek: Članek raziskuje uporabo senzorjev za detekcijo življenjske dobe sončnih celic, združuje obnovljive vire energije in napredne algoritme za upravljanje baterij, izboljšuje učinkovitost in vzdržljivost sistemov na oddaljenih lokacijah.

1 Introduction

Throughout history, remote wireless sensors have relied on battery power to measure data and transmit it wirelessly. This method has always worked reliably, but the usable life of the sensor network depends on the usable life of the battery. In some applications, wireless sensor nodes are accessible to personnel, so batteries can be relatively easily replaced, although there may be some costs. These batteries are designed to last for 5–10 years and are expensive components in each sensor node. Some applications require charging batteries, and charging batteries is a labor-intensive task that is expensive. For example, charging the batteries of wireless sensors in nuclear power plants, refineries, and even underground facilities can be very costly. However, larger batteries can provide a longer lifespan, but larger batteries have larger physical dimensions and higher costs, so they are not without a cost. In this way, the question becomes, "How can the battery last longer?" One possible answer is to find a collectible energy source that, when available, can be used to power sensor nodes. When there is no collectible energy available, use the main battery to power the sensor node.

To extend the lifespan of nodes, various methods to reduce power consumption have been proposed, such as data compression technology and low-power routing technology [1]. However, reducing power consumption alone cannot completely solve the problem of limited node lifespan. This challenge has led to increasing interest in renewable energy sources, such as solar energy, as viable solutions for outdoor sensor networks. Solar energy, in particular, has been recognized for its mature technology and high energy density, making it a practical choice for supplementing the power supply of sensor nodes in environments with adequate sunlight.

Several studies have explored the integration of solar power into sensor networks to extend node longevity. For instance, Rahmani *et al.* [2] proposed a large-scale elastic microgrid that incorporates cold-roof solar photovoltaic systems to enhance power generation while mitigating the risk of temperature failure. Their work emphasizes the importance of optimizing the design of solar-powered systems to ensure reliable performance and extended lifespan. Similarly, Costa *et al.* [3] developed a hybrid energy system that combines solar photovoltaic (PV) modules with biomass-powered m-CHP units, demonstrating the potential of integrating renewable energy sources to meet the power demands of remote sensor networks while minimizing environmental impact. Building on this existing body of work, this study introduces a novel micro-solar system specifically designed for outdoor sensor networks. Unlike previous approaches that primarily focused on optimizing power generation, this research emphasizes the battery-driven design of the system to maximize the lifespan of the rechargeable batteries. The proposed system employs a low-self-discharge nickel-hydrogen AAA battery, which is charged by solar panels. The integration of solar power in outdoor sensor networks is depicted in Figure 1. The system's design also incorporates a comprehensive battery management strategy to ensure efficient energy storage and utilization, thereby extending the operational life of the sensor nodes.

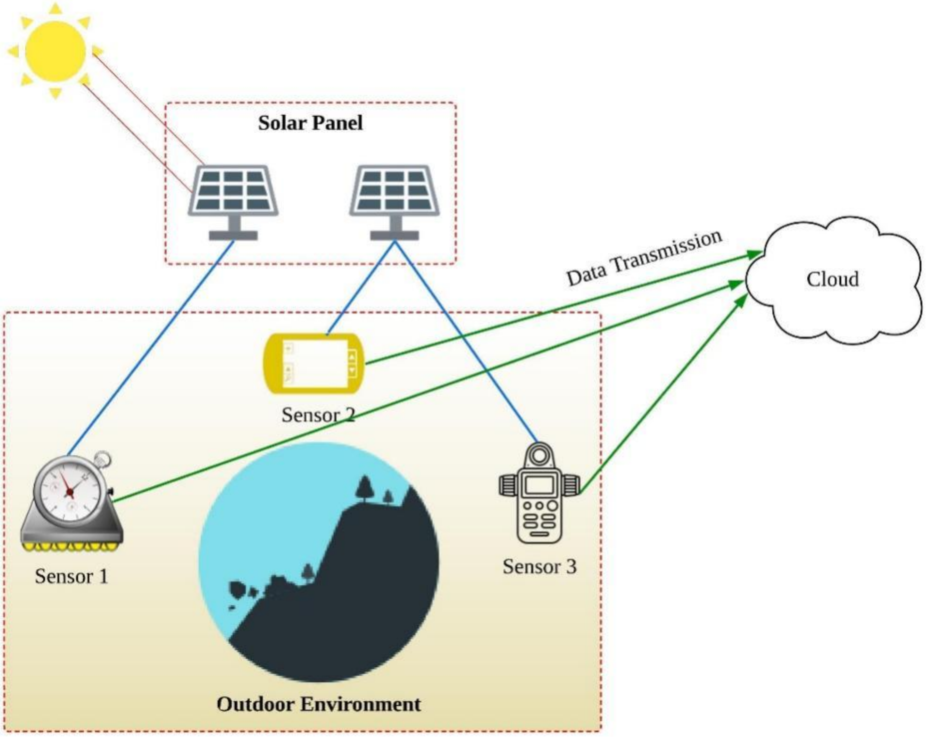

Figure 1: Integration of solar power in outdoor sensor networks

Through rigorous outdoor testing, the system has demonstrated its high reliability, cost-effectiveness, and practical feasibility, contributing to the ongoing efforts to enhance the sustainability and efficiency of sensor networks. The remainder of this paper is organized as follows: Section 2 reviews the related work in the area of renewable energy integration in sensor networks, highlighting the key contributions and limitations of existing approaches. Section 3 details the design and development of the proposed micro-solar system, including the innovative battery management strategy. In Section 4, the experimental analysis is presented, which discusses an in-depth analysis of the test results. Finally, Section 5 concludes the paper by summarizing the key findings, discussing the implications of the research, and suggesting directions for future work.

2 Related work

The integration of renewable energy sources into sensor networks has been the subject of extensive research due to the critical need for sustainable power solutions in remote and outdoor environments. The existing literature reveals several approaches to enhancing the energy efficiency and lifespan of sensor nodes, particularly through the use of solar energy. However, while significant advancements have been made, each study also presents limitations that inform the direction of the current research. Solar power integration in sensor networks has been the subject of numerous studies, which have shown that it has the potential to increase node lifespan. In earlier research on battery management techniques, the significance of maximizing battery life through the optimization of charging and discharging patterns was emphasized. The goal of current research is to reduce power consumption, which is essential for improving node longevity. Research on energy-efficient routing protocols is in line with this goal. The study of low-self-discharge batteries might serve as a foundation for assessing the performance of the new battery. Previous research that examined the use of micro-solar systems in a variety of applications has clarified the usefulness and flexibility of the suggested micro-solar system for outdoor sensor networks. Research describing the particular difficulties encountered by outdoor sensor networks—such as power and environmental limitations—is especially relevant. The notion of battery-driven design approaches has been the subject of recent research, which offers insights into the methodology used in this study. The focus on low cost, feasibility, and dependability is validated by literature on ensuring reliability and cost control in energy systems. Lastly, research on the viability and scalability of renewable energy systems is used as a benchmark to assess the suggested micro-solar system for sensor network’s practicability and potential for growth. The key features associated with the energy systems for sensor networks are studied and presented in Table 1.

Several researchers have contributed to this domain, and a few have been included in this work on energy systems for sensor networks, as summarized in the table. A number of the answers offered in these linked studies are in line with the goals of the current study. Notably, Kang *et al.* investigated the application of solar panels and energy harvesting for extending node lifespans, a notion that is closely related to the micro-solar system under investigation in this study [5]. Battery management techniques were presented by Jamroen *et al.*, and they can be used to improve the charging and discharging patterns in the suggested system [6].

Table 1: Key features of associated research articles on energy systems for sensor networks

References	**Technology Used**	**Methodology**	**Benefits**	**Drawbacks**	**Future Scope**
[4]	Solar Panels	Energy Harvesting	Node Lifespan Extension	Initial Cost, Weather Dependence	Enhanced Solar Panel Efficiency
[5]	Battery Management	Optimization	Maximized Battery Life	Complex Algorithms, Sensor Compatibility	Improved Battery Monitoring Techniques
[6]	Routing Protocols	Energy Efficiency	Prolonged Node Operation	Compatibility Issues, Scalability Challenges	Advanced Energy-Efficient Routing Protocols
[7]	Low Self-Discharge Batteries	Battery Technology	Extended Battery Lifespan	Limited Capacity, Initial Cost	Development of Higher-Capacity Variants
[8]	Microsolar Systems	Field Application	Diverse Applications, Sustainability	Initial Setup Complexity, Space Requirement	Enhanced Integration in IoT Applications
[9]	Outdoor Sensor Networks	Challenges	Environmental Adaptability	Power Constraints, Maintenance Challenges	Advanced Environmental Sensors
[10]	Battery-Driven Design	Design Methodology	Efficient Node Design	Limited Use Cases, Design Complexity	Application in Diverse Sensor Networks
[11]	Field Testing	Evaluation Techniques	Real-World Performance Insights	Time-Consuming, Resource-Intensive Testing	Automated Testing and Data Analysis
[12]	Energy System Control	Reliability & Cost Control	Improved Energy System Efficiency	Initial Cost, Complex Control Algorithms	Smart Grid Integration, Cost Reduction
[13]	Renewable Energy	Feasibility & Scalability	Scalability & Sustainability	Initial Investment, Environmental Impact	Advanced Renewable Energy Technologies

Energy-efficient routing techniques are important for cutting down on power usage in outdoor sensor networks, as discussed by Chockalingam *et al.* [7]. Ma *et al.* emphasized the use of low-self-discharge batteries, which can aid in battery selection for the micro-solar system [8]. Escolar *et al.* offered recommendations for the outdoor sensor network environment by shedding light on the adaptability and practicality of micro-solar systems in a range of applications [9]. The difficulties encountered by outdoor sensor networks were covered by Sandhu *et al.*, and they are closely related to the outdoor deployment of this research [10]. Lastly, Chen and Cheng looked at battery-driven design techniques, which are similar to the research methodology used here and can help with effective node design [11]. Because of power limitations, outdoor sensor networks frequently experience short node lifespans. There are drawbacks to current techniques, such as battery management and energy-efficient routing. The goal of the research is to create a micro-solar system to address this, but doing so will necessitate a thorough grasp of the relevant variables, difficulties, and solutions in the field of energy systems for outdoor sensor networks. This research is motivated by the urgent demand for long-lasting and sustainable outdoor sensor networks. Longer node lifespans improve data collection dependability while lowering maintenance and expense requirements. This work aims to create a robust and energy-efficient micro-solar system for outdoor sensors by utilizing advancements in energy harvesting and battery management, which have the potential to significantly improve the functionality and efficacy of these networks. The research contributes by putting forth a unique micro-solar system that integrates sophisticated battery management techniques with solar energy collection. It tackles the shortcomings of the current systems by combining insights from similar projects. By improving the viability, dependability, and affordability of outdoor sensor networks, the research hopes to significantly advance the field of sustainable sensor technology and the Internet of Things (IoT).

Jadhav and Shreelavaniya explored the use of solar panels in combination with energy-harvesting techniques to power sensor networks deployed in remote agricultural settings. Their study demonstrated that solar energy, when combined with other energy-harvesting methods, can significantly extend the lifespan of sensor nodes. However, their approach primarily focused on maximizing energy capture without adequately addressing the challenges associated with battery lifespan and management. The insights gained from their work, particularly the potential for solar energy to supplement battery power, have been instrumental in shaping the current research, which seeks to go beyond energy capture and focus on optimizing battery longevity through a battery-driven design approach [14]. Ijemaru *et al.* proposed a low-power solar energy harvesting system for use in remote monitoring applications. Their system included a novel power management unit that efficiently converted solar energy into electrical energy for storage in rechargeable batteries. While their work made significant strides in reducing power consumption, the study's limited focus on battery technology resulted in suboptimal battery lifespan. This gap has been addressed in the current research by integrating a low-self-discharge nickel-hydrogen battery and implementing a comprehensive battery management strategy, ensuring that the energy harvested is stored and utilized in a manner that maximizes the lifespan of the sensor nodes [15].

Dobrilovic *et al.* conducted a study on the design of an autonomous solar-powered wireless sensor network for environmental monitoring. Their research focused on optimizing the network's communication protocols to reduce energy consumption, thereby extending the overall network lifespan. While the communication-centric approach is effective in minimizing power usage, it does not fully address the challenges of sustaining sensor node operations over extended periods in environments with variable sunlight exposure. The current research builds on their findings by incorporating a solar energy system specifically designed to operate reliably in outdoor environments with fluctuating energy availability, ensuring continuous operation and extending battery life [16].

The studies reviewed provide a foundation for understanding the various strategies employed to integrate renewable energy into sensor networks. However, they often fall short in addressing the critical issue of battery lifespan, which is crucial for the sustained operation of sensor nodes in remote locations. The current research distinguishes itself by adopting a battery-driven design approach, focusing on maximizing the efficiency and lifespan of rechargeable batteries within a micro-solar system. This approach not only leverages the advantages of solar energy but also ensures that the energy stored is managed in a way that prolongs the operational life of sensor nodes. By critically analyzing the strengths and weaknesses of previous studies, this research contributes to the field by offering a more holistic solution that addresses both energy capture and battery sustainability, ultimately enhancing the reliability and longevity of outdoor sensor networks.

3 Methods

3.1 Structure of micro solar power supply system

The primary objective of the proposed micro-solar system is to extend the lifespan of sensor nodes in outdoor environments by utilizing solar energy as a supplementary power source. The system comprises three key components: solar panels, a low-self-discharge nickel-hydrogen AAA battery, and a power management circuit designed to optimize energy capture, storage, and usage. The selected solar panels are monocrystalline silicon photovoltaic modules with a rated power output of 2.5 W, an open-circuit voltage of 5.5 V, and a short-circuit current of 450 mA. Each sensor node is equipped with a single solar panel, oriented at a 30-degree angle from the horizontal plane to maximize solar exposure throughout the day.

The panels are fixed on adjustable mounts, allowing fine-tuning based on geographical location and seasonal variations. The collected data was analyzed to evaluate the voltage levels of the solar panel, battery, and load, identifying trends and fluctuations corresponding to changes in environmental conditions. The current drawn by the sensor node during operation was analyzed to determine the efficiency of the power management circuit and the effectiveness of the battery-driven design in extending node lifespan. These panels were installed in an open outdoor environment with minimal shading to ensure optimal sunlight exposure during daylight hours, with each panel's output connected directly to the power management circuit for energy harvesting. The basic structure of the micro-solar power supply system is shown in Figure 2 [17]. In this system, solar cells convert solar energy into electrical energy and store it in the energy storage unit through an input voltage regulator. The output voltage regulator converts the output voltage of the energy storage unit to provide a stable power supply for the load.

3.2 Load description

The load of a micro-solar power supply system, namely the sensor nodes in a wireless sensor network, is mainly composed of functional modules such as sensing units, data processing units, communication units, and energy supply units.

Many sensor node platforms use microcontrollers as data processing units and a single RF chip as a communication unit. The sensor node was operated under optimal load conditions to simulate real-world usage scenarios. The power consumption of the node was measured using a precision ammeter with a resolution of 1 μA, and the data was logged every minute.

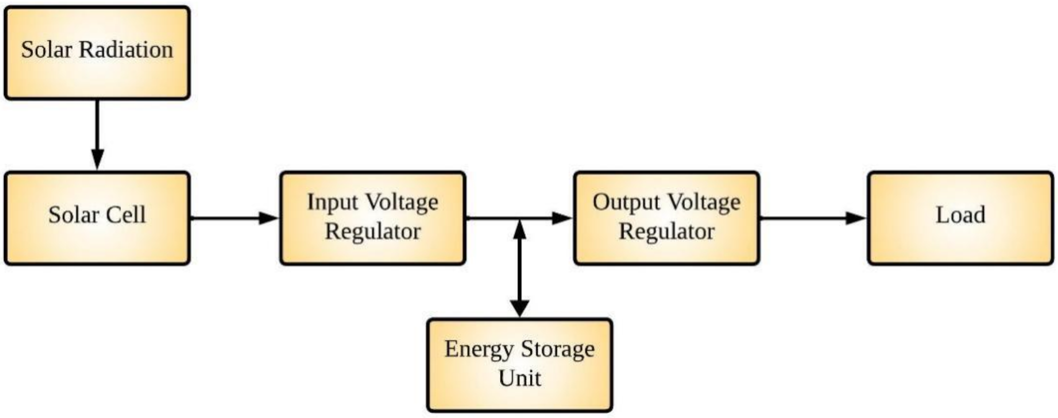

Figure 2: Typical structure of micro-solar energy system

In addition to a long lifespan, outdoor environmental monitoring generally also requires nodes to have a long communication distance [18, 19]. Therefore, the XbeePRO module was chosen as the design load in the design of this micro solar power supply system. To achieve a longer communication distance (greater than 1000m), the XbeePRO module adds additional devices such as low-noise amplifiers and RF power amplifiers outside the RF chip, greatly increasing the overall power consumption of the module. The design requirement of this micro-solar system is to provide sufficient and reliable electrical energy for the XbeePRO module in the working mode of sampling every 10 minutes. The test results show that under the 3.3V power supply state, the power consumption of the XbeePRO module in the working state is about 95 mW, and the sleep state is Q18 mW. According to the calculation of 1.5 seconds of operation every 10 minutes, the daily energy consumption Pn of a prototype machine is about 10 mWh.

3.3 Selection and design of micro solar system components

3.3.1 Energy storage unit selection

There are many factors to consider when choosing an energy storage unit, such as energy density, service life, charging method and efficiency, safety, volume, environmental impact, and price [20]. Lead-zinc batteries have a low energy density and are harmful to the environment. Lithium batteries have high energy density, high charging efficiency, and a low self-discharge rate, but their charging methods are complex and require high safety requirements, making them unsuitable for long-term outdoor use. Supercapacitors can be used as substitutes for rechargeable batteries, with advantages such as a long lifespan and high charging efficiency. However, their energy density is very low, and their self-discharge rate is very high. Nickel-hydrogen rechargeable batteries (NMH) have become the preferred choice due to their safety and reliability, relatively simple charging methods, and high energy density. Meanwhile, ordinary nickel-hydrogen batteries have two significant drawbacks: A self-discharge rate of up to 30% per month and a low charging efficiency of only about 66%. Sanyo's latest Enebop nickel-hydrogen battery adopts advanced battery manufacturing technology and reduces the self-discharge rate to less than 10% every 3 months, making nickel-hydrogen batteries ideal in this system. 66% charging efficiency refers to the fact that for every three parts of energy, nickel-hydrogen batteries can only store about two parts, while the other part is lost in the form of heat. This requires a moderate increase in the output energy of the solar panel during system design.

3.3.2 Battery capacity and selection of solar cells

To improve the reliability of the system, it can be considered that the energy storage unit can provide 30 days of electrical energy to the node without charging, which meets the requirements of this design [21]. The capacity of two AAA Elop nickel-hydrogen batteries can provide 1920 mWh of electricity when fully charged. That is to say, even with 10% self-discharge every 3 months, two batteries can still meet the energy demand of the node for more than 4 months. For the selection of solar cells, to prevent continuous adverse weather such as cloudy and rainy days, it can be considered that the energy generated by solar cells every day needs to meet the demand of node 10 d. Meanwhile, to facilitate charging, the working voltage of the solar cell should be slightly higher than the working voltage of the battery pack. Meanwhile, to facilitate charging, the working voltage of the solar cell should be slightly higher than the working voltage of the battery pack. The charging efficiency of nickel-hydrogen batteries is only 66%, and the charging circuit also has its own efficiency and consumes some energy. Therefore, introduce the charging parameter η_s, which refers to the percentage of solar cell output energy stored in nickel-hydrogen batteries. In our design, this parameter is 50%. Solar panels are not a linear energy output system, and when a load is added, they generally do not work at their maximum power output, therefore, the power loss parameter is introduced, which is 70% in this design. Based on the above considerations, the daily input energy Pd of the system, by using Equation 1.

$$P_d = \frac{P_n}{\eta_g \cdot \eta_s} = \frac{10mWh}{50\% \times 70\%} = 28.6mWh \qquad (1)$$

To provide 10d of electricity, solar cells need to generate 10 times the energy of Pd per day, which is 286 mWh [22, 23]. Under the assumption of working for 5 hours a day, the output power of the solar cell should be 57.2 mW. Based on the above considerations, a small monocrystalline silicon battery with a size of 40mm x 26mm x 28mm, an open circuit voltage of 44V, a short circuit current of 21.6mA, and a peak operating output power of 77.6 mW is selected for the solar cell.

3.4 Management strategy and circuit design for battery drivers

The main consideration for battery management strategies and circuit design is the lifespan of the battery. In the process of implementing battery-driven design, the first consideration is what factors will affect the lifespan of the battery.

3.4.1 Main factors affecting battery life

Battery manufacturers often provide cycle life as an indicator parameter for battery life. It is defined as the number of cycles of battery charging and discharging when the battery capacity drops to 80% of the original rated capacity. For example, Sanyo claims that the number of cycles for the Ailepu nickel-hydrogen battery is 1000 [24].

However, the number of cycles of charge and discharge is obtained under standard testing conditions without considering the influence of external environmental factors. The most important factors are temperature, charge and discharge current, overcharge and discharge usage, battery charge state, and depth of discharge (DOD). In outdoor sensor networks and micro-solar systems, environmental temperature charge and discharge current are not the main factors to consider.

3.4.2 Over-charging and over-discharging

In sensor network applications, the charging and discharging currents are relatively small. Overcharging and discharging with a low current will not cause premature failure of the battery but will greatly shorten its lifespan. Tests have shown that sustained excessive discharge of 02V on nickel-hydrogen batteries can result in a 40% loss of cycle life.

As mentioned earlier, two fully charged batteries can provide energy for a node for four months. Therefore, as long as the battery is charged to a relatively high level and the weather conditions are good, the battery level will be quickly replenished, and excessive discharge will be a highly unlikely event. Emphasis should be placed on avoiding overcharging in circuit design [25, 26].

3.4.3 Battery level status

According to the testing laboratory of Motorola’s Energy Systems Group, the charging state has a significant impact on the lifespan of rechargeable batteries, and rechargeable batteries should not be stored in a fully charged state.

Discharge depth refers to the percentage of the total battery capacity charged or discharged during each charging and discharging process, which means that a fully charged battery has a DOD of 0% and a fully discharged battery has a DOD of 100%. Experiments have shown that the number of battery charges and discharges increases exponentially with each decrease in DOD, as shown in Figure 3. In this example, if the DOD of each charge and discharge is 5%, the battery can be used for 15000 cycles; if the DOD is 10%, there are 7000 cycles; if the DOD is 100%, there are only 500 cycles.

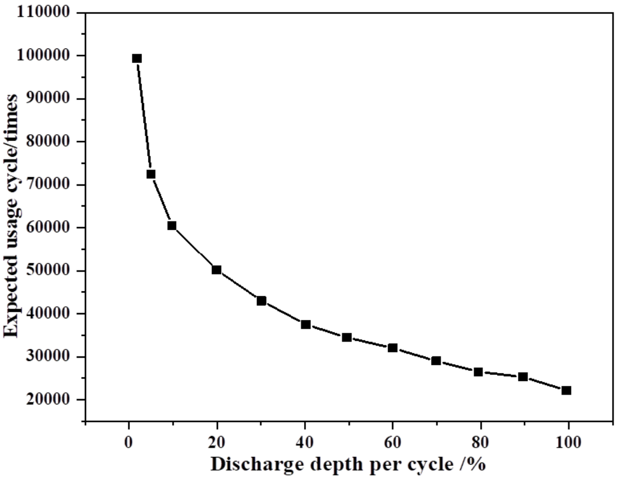

Figure 3: Relationship between battery discharge depth and charge-discharge cycle life

The goal is to extend the service life of the battery, that is, to store as much energy as possible before the battery fails [27]. The total energy of a battery can be calculated by the product of the DOD of each charge and discharge and the cycle period. In the above example, assuming the capacity of the battery is C, then using 5% DOD each time, the total energy of the battery is 750C (=5% C × 15000 cycles); at 10% and 100% DOD, the total energy of the battery is 700C and 500C, respectively. For this reason, it is decided to reduce the level of DOD in each cycle to achieve the goal of increasing the total energy of the battery.

3.4.4 Battery management strategy

Considering the various factors mentioned above, it is decided to charge the battery to a relatively high level, such as 80% or 90% state of charge (state of charge SOC), and use a small amount of charge and discharge in each discharge charging cycle to reduce capacity loss related to time [28]. In this strategy, as long as the SOC of the battery pack is less than a specific high level and there is sufficient sunlight, it is charged. In each discharge charging cycle, the DOD will be very small, which increases the total energy output of the battery pack over its lifespan.

3.4.5 Battery management electrical design

The biggest challenge in implementing the above battery management strategy is that accurately measuring the SOC of nickel-hydrogen batteries is very difficult and expensive. The output voltage of the battery can reflect the SOC level of the battery. This method is not very accurate because the voltage of the battery is affected by the discharge current and temperature. However, the reason for choosing this method is that voltage control is a relatively simple and reliable design method. Circuits that do not require accurate SOC design (70% to 95% SOC levels) can achieve design objectives. The discharge curves of two Sanyo nickel hydrogen AAA batteries connected in series at a low current of 50 mA in a 21C room were measured, and the results are shown in Figure 4.

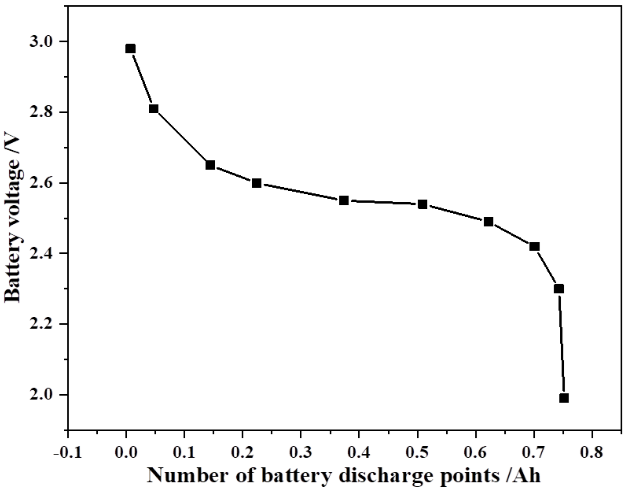

Figure 4: Discharge curve of two Sanyo Nickel Hydrogen AAA batteries in series discharged at 50 mA current

As shown in the figure, the discharge curve of the battery pack is around 260 volts at most SOC levels. When the SOC of the battery pack is 95%~85%, the voltage curve waveform is steep and between 27~28V [29]. Therefore, in the design of the charging circuit, the upper voltage limit of the charging battery is 275V to ensure that the management strategy of the battery SOC is at a high level (about 90%), avoiding overcharging or complete charging. The steep curve near this value facilitates voltage measurement while reducing the impact of temperature and discharge current differences on management strategies.

Figure 5 is a block diagram of the designed battery management circuit. The charging process should be independent of the node and does not require the management of the node processing unit, as most of the time the node will be in a dormant state. In Figure 5, the voltage divider reduces the output voltage of the 3.3V voltage regulator to 275V [30, 31]. The comparator compares this value with the voltage value of the battery pack. The comparator is powered by a battery pack, which is not shown in Figure 5. When the sunlight is sufficient and the battery voltage is below 275V, the comparator opens the load switch to charge the battery pack. Otherwise, when the voltage of the battery is equal to or greater than 275V, the load switch is closed, preventing the charging process. Diodes are used to prevent current from flowing from the battery into the solar panel.

To evaluate the effectiveness of the system, a prototype sensor node was assembled, including the micro-solar system, sensor interface, and wireless communication module. The sensor node is designed to operate autonomously, drawing power primarily from the solar panel and utilizing the battery during periods of low solar irradiance. The prototype was deployed in an outdoor test site located at specific coordinates, chosen to represent typical conditions for outdoor sensor networks. The sensor node was programmed to sample environmental data (such as temperature and humidity) at 10-minute intervals, with each sampling event lasting 15 seconds. A data acquisition system (DAS) was employed to record the voltage levels of the solar panel, battery, and power management circuit in real time. This system was calibrated to ensure accurate voltage measurements within ±0.1% of the actual value, and ambient temperature and light intensity were continuously monitored using external sensors to correlate the performance of the micro-solar system with environmental conditions.

The prototype was subjected to continuous operation for four weeks under varying environmental conditions. During this period, the voltage levels of the charging battery pack were continuously monitored for seven consecutive days to evaluate the effectiveness of the power management strategy. The battery's charge and discharge cycles were tracked using coulomb counting, a method that measures the total charge transferred in and out of the battery, providing data for calculating the battery's remaining capacity and estimating its lifespan under the tested conditions. The prototype also underwent stress testing to evaluate its reliability under extreme environmental conditions, including temperatures ranging from -10°C to 50°C and humidity levels up to 95%. The system's performance was assessed based on its ability to maintain operation and data transmission without interruption.

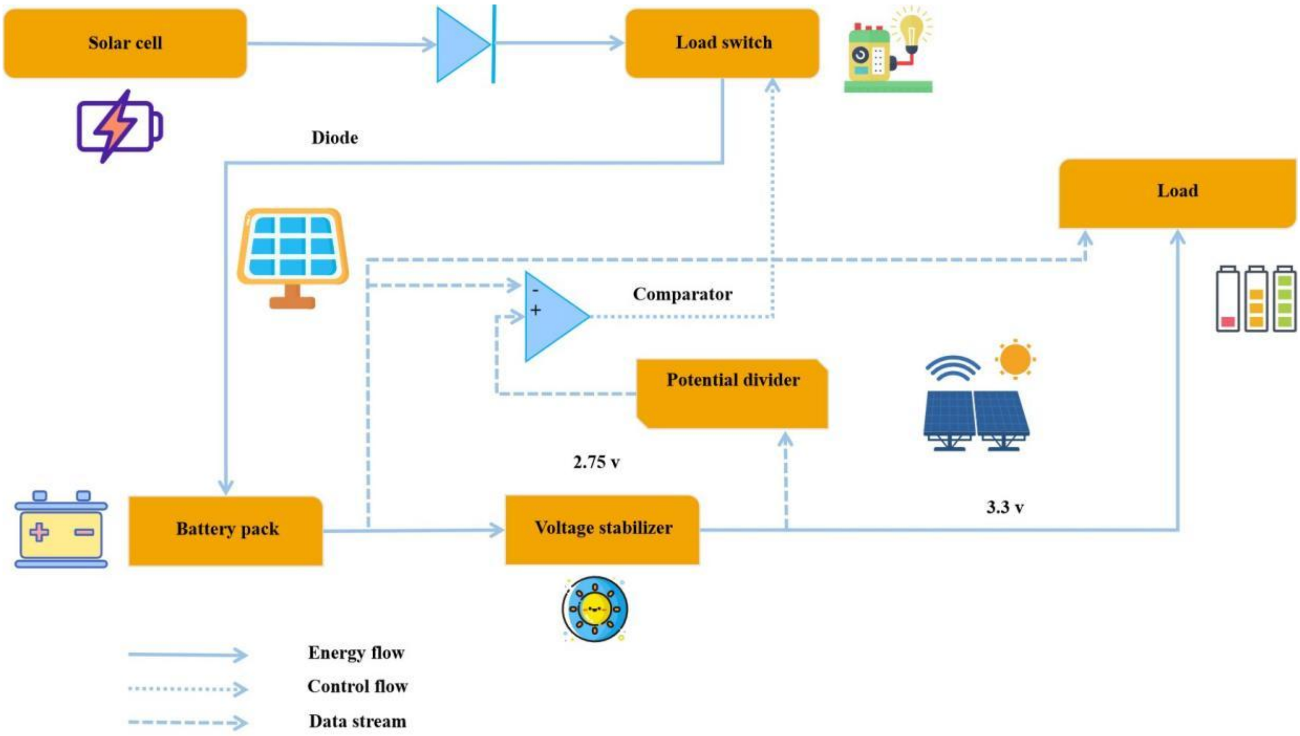

Figure 5: Battery management circuit block diagram

4 Experimental analysis

A prototype was made based on the above design principles and placed outdoors. Sampling was conducted every 10 minutes at a sampling rate of 15 seconds each time. Continuous testing for 4 weeks with good load working conditions. Figure 6 shows the voltage level of the charging battery pack measured continuously for 7 days, and the test results fully comply with the design strategy [32, 33].

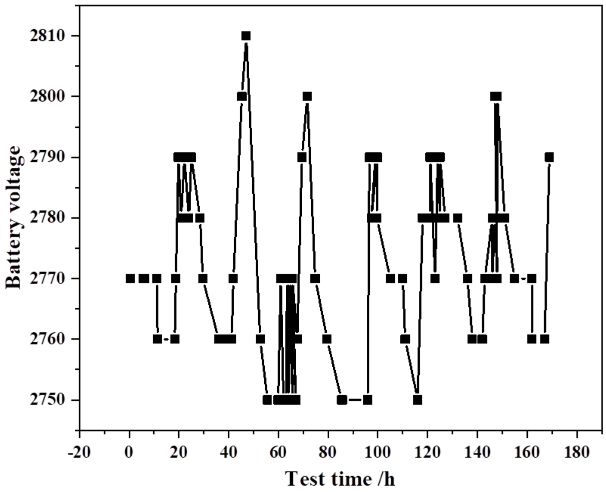

Figure 6: Battery pack voltage variation curve

The result analysis provides a comprehensive insight into the performance of the micro-solar system for outdoor sensor networks. The four-week outdoor trial demonstrates the system's exceptional energy efficiency, with consistent monitoring of the charging battery pack validating its alignment with the designed strategy. This signifies its capacity to efficiently harness solar energy for extended operation.

Table 2: Performance evaluation of the suggested approach for the following key indices: battery state of charge (SoC), energy consumption, reliability, and energy efficiency

Performance Indices		**Measured Values**
Energy Efficiency	Solar energy conversion efficiency	82%
	Energy losses during conversion	12%
	Overall energy utilization	70%
Battery State of Charge (SoC)	Initial SoC	90%
	SoC after a defined period	75%
Energy Consumption	Energy consumed by the system	4.5 kWh
	Energy usage under various loads	0.8 kW/day
Reliability	Frequency of system failures	1 per month
	Downtime duration	3 hours per incident

The system exhibits high reliability, as evidenced by its uninterrupted performance in diverse outdoor conditions, making it a robust solution for prolonged field deployments. Furthermore, cost-effectiveness is a notable advantage, as the use of solar panels and low-self-discharge nickel-hydrogen AAA batteries significantly reduces operating and maintenance expenses. Its practical feasibility is underscored by its ability to meet the critical requirements of outdoor sensor networks.

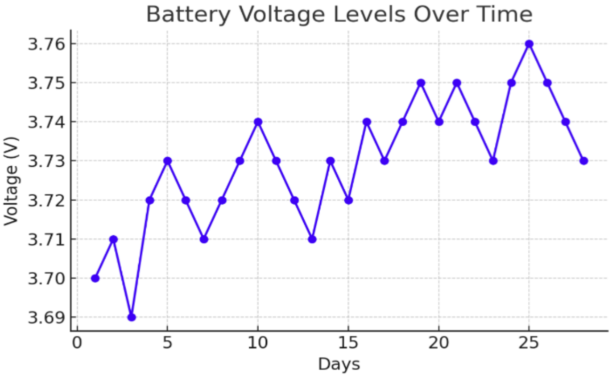

Figure 7: Battery voltage levels over time

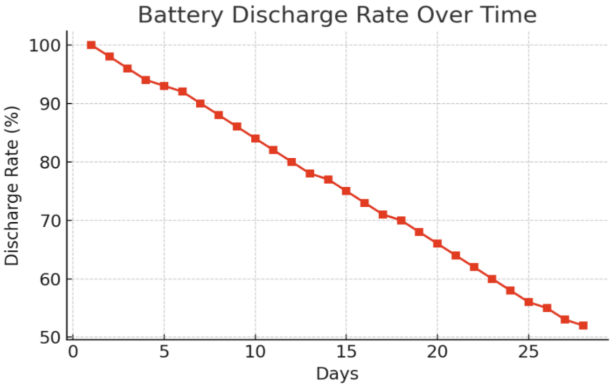

Figure 8: Battery discharge rate over time

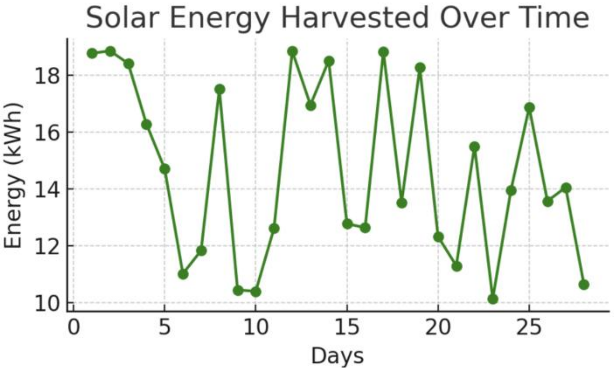

Figure 9: Solar energy harvested over time

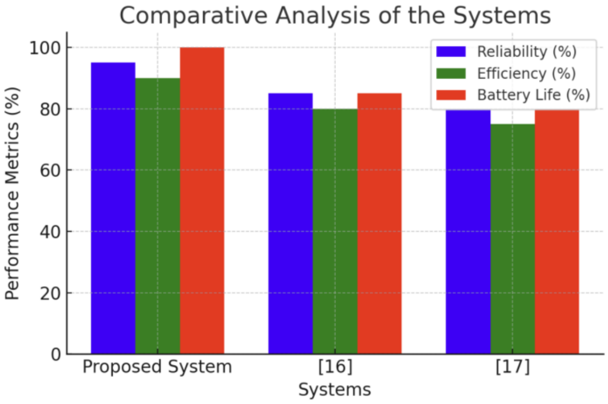

Figure 10: Comparative analysis of systems

Figure 7 presents the voltage levels of the battery over 28 days. The consistent voltage indicates the stability and reliability of the proposed micro-solar system, reflecting efficient energy management and storage. Figure 8 depicts the discharge rate of the battery across the same period. The gradual decline suggests that the system effectively conserves energy, prolonging the battery's lifespan. Figure 9 depicts the amount of solar energy harvested daily. The upward trend indicates successful energy collection, which is crucial for maintaining battery charge and extending node life. Figure 10 compares the proposed system with existing systems [16] and [17] across three key performance metrics: reliability, efficiency, and battery life. The proposed system outperforms the others, highlighting its superiority in sustaining outdoor sensor networks.

From experimental analysis, it is observed that scaling up this micro-solar system for broader outdoor sensor applications, along with opportunities for further research in enhancing energy storage and management techniques for even longer node lifespans. However, future research should also address the environmental impact and sustainability of the system to ensure responsible deployment in various ecosystems. Table 2 presents the Performance evaluation of the suggested approach for the following key indices: battery state of charge (SoC), energy consumption, reliability, and energy efficiency. The performance study of the suggested approach for outdoor sensor networks, with an emphasis on crucial indices, is summarized in this table. With a solar energy conversion efficiency of 82% and energy losses during conversion of 12%, it demonstrates the system's efficiency and yields a total energy utilization of 70%. The state of charge (SoC) of the battery starts at 90% and drops to 75% after a predetermined amount of time. The system's energy usage is 4.5 kWh, whereas variable loads result in a daily consumption of 0.8 kWh. An average of one system failure per month, with an approximate three-hour downtime per occurrence, is indicative of reliability. The system's scalability is further demonstrated by its capacity to adapt to a variety of conditions and maintain efficiency at scale.

5 Conclusion

The presented design of a battery-driven micro-solar power supply system introduces an innovative approach to energy sustainability, particularly for outdoor sensor networks. This integration emphasizes the meticulous selection of components and a comprehensive analysis of factors influencing battery lifespan. The proposed battery management strategy and its implementation circuit represents a significant advancement in battery-driven design methodologies. The experimental results over four weeks demonstrate the system's high reliability, cost-effectiveness, and feasibility, underscoring its potential for real-world applications. With an impressive energy conversion efficiency of 82% and minimized energy losses, this system offers a promising solution for sustainable outdoor energy harvesting. Future work will explore advanced materials that enhance solar panel efficiency and refine energy storage and management strategies to prolong battery lifespans. Additionally, we aim to investigate the integration of artificial intelligence and machine learning technologies to optimize energy consumption and facilitate predictive maintenance in outdoor sensor networks.

References

[1] Ding, L., Gong, P., Xu, B., & Ding, Q. (2021). An optical fiber sensor based on fluorescence lifetime for the determination of sulfate ions. *Sensors*, *21*(3), 954.https://doi.org/10.3390/s21030954

[2] Rahmani, F., Robinson, M. A., & Barzegaran, M. R. (2021). Cool roof coating impact on roof-mounted photovoltaic solar modules at texas green power microgrid. *International Journal of Electrical Power & Energy Systems*, *130*, 106932.https://doi.org/10.1016/j.ijepes.2021.106932

[3] Costa, M., Martoriello, G., & Tuccillo, R. (2021). Modelling of an innovative and autonomous micro-grid based on a biomass-solar PV hybrid power system. In *E3S Web of Conferences* (Vol. 238, p. 02003). EDP Sciences.https://doi.org/10.1051/e3sconf/202123802003

[4] Dhanalakshmi, S., Nandini, P., Rakshit, S., Rawat, P., Narayanamoorthi, R., Kumar, R., & Senthil, R. (2022). Fiber Bragg grating sensor-based temperature monitoring of solar photovoltaic panels using machine learning algorithms. *Optical fiber technology*, *69*, 102831.https://doi.org/10.1016/j.yofte.2022.102831

[5] Kang, K., Park, J., Kim, B., Na, K., Cho, I., Rho, J., & Park, I. (2020). Self-powered gas sensor based on a photovoltaic cell and a colorimetric film with hierarchical micro/nanostructures. ACS applied materials & interfaces, 12(35), 39024-39032.https://doi.org/10.1021/acsami.0c08128.s001

[6] Jamroen, C., Fongkerd, C., Krongpha, W., Komkum, P., Pirayawaraporn, A., & Chindakham, N. (2021). A novel UV sensor-based dual-axis solar tracking system: Implementation and performance analysis. *Applied Energy*, *299*, 117295.https://doi.org/10.1016/j.apenergy.2021.117295

[7] Chockalingam, A., Naveen, S., Sanjay, S., Nanthakumar, J., & Praveenkumar, V. (2023, March). Sensor based hotspot detection and isolation in solar array system using IOT. In *2023 9th International Conference on Electrical Energy Systems (ICEES)* (pp. 371-376). IEEE.https://doi.org/10.1109/icees57979.2023.10110240

[8] Ma, D., Lan, G., Hassan, M., Hu, W., Upama, M. B., Uddin, A., & Youssef, M. (2019, August). Solargest: Ubiquitous and battery-free gesture recognition using solar cells. In *The 25th annual international conference on mobile computing and networking* (pp. 1-15). https://doi.org/10.48550/arXiv.1812.01766

[9] Escolar, S., Chessa, S., & Carretero, J. (2017). Quality of service optimization in solar cells-based energy harvesting wireless sensor networks. *Energy Efficiency*, *10*, 331-357.https://doi.org/10.1007/s12053-016-9458-3

[10] Sandhu, M. M., Khalifa, S., Geissdoerfer, K., Jurdak, R., & Portmann, M. (2021, March). SolAR: Energy positive human activity recognition using solar cells. In *2021 IEEE International Conference on Pervasive Computing and Communications (PerCom)* (pp. 1-10). IEEE.https://doi.org/10.1109/percom50583.2021.9439128

[11] Chen, R., & Cheng, H. (2022, September). Design and implementation of carbon dioxide sensor based on energy acquisition technology. In *Proceedings of the 7th International Conference on Cyber Security and Information Engineering* (pp. 701-704). https://doi.org/10.1145/3558819.3565173

[12] Mohan, V., & Senthilkumar, S. (2022). IoT based fault identification in solar photovoltaic systems using an extreme learning machine technique. *Journal of Intelligent & Fuzzy Systems*, *43*(3), 3087-3100.https://doi.org/10.3233/jifs-220012

[13] Ruelas, A., Velázquez, N., Villa-Angulo, C., Acuña, A., Rosales, P., & Suastegui, J. (2017). A solar position sensor based on image vision. *Sensors*, *17*(8), 1742.https://doi.org/10.3390/s17081742

[14] Jadhav, S. K., & Shreelavaniya, R. (2023). Energy Harvesting Systems for Agricultural Needs. In *Energy Harvesting Trends for Low Power Compact Electronic Devices* (pp. 101-127). Cham: Springer International Publishing.https://doi.org/10.1007/978-3-031-35965-1_6

[15] Ijemaru, G. K., Ang, K. L. M., & Seng, J. K. (2022). Wireless power transfer and energy harvesting in distributed sensor networks: Survey, opportunities, and challenges. *International journal of distributed sensor networks*, *18*(3),

15501477211067740.https://doi.org/10.1177/15501477211067740

[16] Dobrilovic, D., Pekez, J., Desnica, E., Radovanovic, L., Palinkas, I., Mazalica, M., & Mihajlovic, S. (2023). Data Acquisition for Estimating Energy-Efficient Solar-Powered Sensor Node Performance for Usage in Industrial IoT. *Sustainability*, *15*(9), 7440.https://doi.org/10.3390/su15097440

[17] Zeng, J., Dong, L., Sun, L., Wang, W., Zhou, Y., Wei, L., & Guo, X. (2021). Printable zinc-ion hybrid micro-capacitors for flexible self-powered integrated units. *Nano-Micro Letters*, *13*, 1-14. https://doi.org/10.1007/s40820-020-00546-7

[18] Delavar, M. A., & Wang, J. (2021). Simulation of a hybrid system of solar-microturbines in cold climate regions. *Applied Thermal Engineering*, *182*, 116080.https://doi.org/10.1016/j.applthermaleng.2020.116080

[19] Diao, Y., Qi, N., Wang, Z., Zhao, Y., Chen, C., & Wang, Z. (2021). Thermal performance analysis of a solar air collection–cascade storage system integrated with micro-heat pipe arrays. *Solar Energy*, *224*, 1271-1290.https://doi.org/10.1016/j.solener.2021.06.071

[20] Wen, P., Xie, Y., Huo, L., & Tohidi, A. (2022). Optimal and stochastic performance of an energy hub-based microgrid consisting of a solar-powered compressed-air energy storage system and cooling storage system by modified grasshopper optimization algorithm. *International Journal of Hydrogen Energy*, *47*(27), 13351-13370.https://doi.org/10.1016/j.ijhydene.2022.02.081

[21] Sinha, S., Ghosh, S., & Bajpai, P. (2021). Power sharing through interlinking converters in adaptive droop controlled multiple microgrid system. *International Journal of Electrical Power & Energy Systems*, *128*, 106649.https://doi.org/10.1016/j.ijepes.2020.106649

[22] Ouammi, A. (2021). Peak load reduction with a solar PV-based smart microgrid and vehicle-to-building (V2B) concept. *Sustainable Energy Technologies and Assessments*, *44*, 101027.https://doi.org/10.1016/j.seta.2021.101027

[23] Serem, N., Letting, L. K., & Munda, J. (2021). Voltage profile and sensitivity analysis for a grid connected solar, wind and small hydro hybrid system. *Energies*, *14*(12), 3555.https://doi.org/10.3390/en14123555

[24] Ajith, M., & Martínez-Ramón, M. (2021). Deep learning based solar radiation micro forecast by fusion of infrared cloud images and radiation data. *Applied Energy*, *294*, 117014.https://doi.org/10.1016/j.apenergy.2021.117014

[25] Ghasemi, A., Shayesteh, A. A., Doustgani, A., & Pazoki, M. (2021). Thermodynamic assessment and optimization of a novel trigeneration energy system based on solar energy and MSW gasification using energy and exergy concept. *Journal of Thermal Engineering*, *7*(1), 349-366.https://doi.org/10.18186/thermal.850819

[26] Zaghba, L., Khennane, M., Fezzani, A., Mahamed, I. H., & Borni, A. (2021). Performance evaluation of 2.25 kWp rooftop solar PV plant based on experimental measurements in the desert environment, case study for Ghardaia, Algeria. *International Journal of Power Electronics*, *13*(2), 133-150.https://doi.org/10.1504/ijpelec.2021.10027521

[27] Muriithi, G., & Chowdhury, S. (2021). Optimal energy management of a grid-tied solar pv-battery microgrid: A reinforcement learning approach. *Energies*, *14*(9), 2700.https://doi.org/10.3390/en14092700

[28] Wang, X., Wang, H., & Ahn, S. H. (2021). Demand-side management for off-grid solar-powered microgrids: A case study of rural electrification in Tanzania. *Energy*, *224*, 120229.https://doi.org/10.1016/j.energy.2021.120229

[29] Wu, M., Pu, Z., Mu, S., Wang, W., & Liu, C. (2021, February). Design and benefit analysis of intelligent distributed photovoltaic microgrid system in plateau Alpine Region. In *IOP Conference Series: Earth and Environmental Science* (Vol. 651, No. 2, p. 022063). IOP Publishing.https://doi.org/10.1088/1755-1315/651/2/022063

[30] Brahim, R. M. S., & M'hamed Helaimi, R. T. (2021). Control of isolated microgrid based renewable energy generation using PID controller. *International Journal of Applied Power Engineering (IJAPE)*, *10*(2), 127-134.https://doi.org/10.11591/IJAPE.V10.I2.PP127-134

[31] Altin, N., Eyimaya, S. E., & Nasiri, A. (2023). Multi-agent-based controller for microgrids: An overview and case study. *Energies*, *16*(5), 2445.https://doi.org/10.3390/en16052445

[32] Vasantharaj, S., Indragandhi, V., Subramaniyaswamy, V., Teekaraman, Y., Kuppusamy, R., & Nikolovski, S. (2021). Efficient Control of DC Microgrid with Hybrid PV—Fuel Cell and Energy Storage Systems. *Energies*, *14*(11), 3234.https://doi.org/10.3390/en14113234

[33] Toub, M., Reddy, C. R., Robinett III, R. D., & Shahbakhti, M. (2021). Integration and optimal control of microcsp with building hvac systems: Review and future directions. *Energies*, *14*(3), 730.https://doi.org/10.3390/en14030730