Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 45 No. 4 (2024)

Developing Enhanced Battery Management Systems for Sustainable Energy Use in Namibia

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Abstract

This paper presents an innovative approach to developing enhanced Battery Management Systems (BMS) tailored for sustainable energy applications in Namibia. As the country transitions towards increased renewable energy integration, efficient energy storage solutions are crucial for maintaining system stability and reliability. We propose a comprehensive BMS framework that addresses the unique challenges posed by Namibia's climatic and infrastructural conditions. Our approach incorporates advanced algorithms for optimizing battery performance, predictive maintenance, and real-time monitoring, all while ensuring minimal energy losses and extended battery life. Through simulations and field trials, we demonstrate the system's effectiveness in improving energy management and reducing operational costs. The findings indicate that our enhanced BMS significantly contributes to the efficiency and sustainability of energy use in Namibia, paving the way for a more resilient and eco-friendly energy infrastructure.

Keywords: *Battery Management Systems, Sustainable Energy, Namibia, Renewable Energy Integration, Energy Storage Solutions, Optimization Algorithms, Predictive Maintenance, Real-time Monitoring, Energy Efficiency, Climate Adaptation*

I. INTRODUCTION

Globally, energy affordability and access to efficient and modern energy have continued to be a challenge. It was found that few countries have been able to reach sustainable energy sources, which increases the issues of energy affordability. It is a problem for poor households that find themselves with no other option but to spend a proportion of their income on purchasing energy sources that are not sustainable but restrain environmental development (Ucal, 2021). However, wind and solar energy embrace more efficient and renewable energy resources than fossil energy sources that create natural resource consumption (Mikhaylov, 2022). The integration of renewable energy technologies helps attain sustainable energy systems, which will have the least effects on the environment through the reduction of the adverse effects of conventional energy production (Ren et al., 2020).

In recent years, the global energy landscape has undergone significant transformations, driven by the imperative to address environmental concerns and meet the rising energy demands of an expanding population(Chinagorom et al., 2023). This transition is particularly crucial in regions like Namibia, where the energy sector faces distinct challenges that underscore the need for innovative solutions(Amesho et al., 2022). Central to these challenges is the dependence on traditional energy sources that are increasingly proving inadequate in terms of reliability, efficiency, and sustainability (Savela et al., 2020). The growing emphasis on renewable energy sources, such as solar power, highlights a critical shift in energy strategy aimed at mitigating the limitations of conventional systems and promoting a more resilient and eco-friendly energy infrastructure (Maradin, 2021).

One of the primary challenges in Namibia's energy sector is the seasonal variability of hydropower generation (Scholvin, 2021). Hydropower has long been a cornerstone of renewable energy, leveraging water flow to generate electricity (Suvitha et al., 2024). However, its effectiveness is heavily contingent on the availability of water resources, which can fluctuate significantly due to seasonal changes and climate patterns (Shadrina, 2020). During periods of drought or reduced rainfall, hydropower production can diminish substantially, leading to power shortages and instability in the energy supply (Ramião et al., 2022). This reliance on water availability underscores the need for supplementary energy sources that can provide consistent power regardless of seasonal variations.

In the United States, renewable energy from biomass, wind, and sunlight was evident. However, it is still reliant on imported oil and coal-derived electricity, which are harmful to the environment. The country also faces the challenge of being energy inefficient since 65% of its energy is lost while only around 31% of this amount is used to produce energy services (Varbanov et al., 2018). In Canada, research indicates that there is no sufficient usage of renewable energy sources, and there are no improvements to emissions(Benson et al., 2022).

Efficient energy sources, particularly solar energy, are essential for addressing the challenges faced by current energy systems(Ahmad et al., 2024). Seasonal variations in hydropower generation pose a significant problem, as hydropower's reliance on fluctuating water levels can lead to inconsistent energy supply, particularly during dry periods (Xiong et al., 2022). This variability creates a critical need for alternative energy sources that can provide a stable and reliable supply. In addition to hydropower variability, many coal-fired power stations suffer from poor maintenance, leading to decreased operational efficiency and higher rates of malfunction(Kock & Govender, 2021). These older facilities often face escalating maintenance issues and inefficiencies, further straining the energy infrastructure and contributing to unreliable power generation (Ebhota, 2021). The growing energy demands, driven by increasing population and economic development, exacerbate these issues by placing additional stress on existing power systems(Al-Badi &Al-Mubarak, 2019). As traditional energy sources struggle to keep pace with rising demand, the need for diversified and sustainable energy solutions becomes more pressing(Bănică et al., 2024). Solar energy presents a viable solution to these challenges (Maka & Alabid, 2022). Its abundance and relatively low operational costs make it a promising alternative to traditional energy sources(Novas et al., 2021). Solar power can offer a consistent and reliable energy supply, particularly in regions with high solar irradiance, and can help to stabilize the energy supply by mitigating the impacts of hydropower variability and reducing dependency on aging coal-fired power stations(Liu et al., 2023). Integrating solar energy into the energy mix is a critical step towards achieving a more sustainable and resilient energy system (Amesho et al., 2022).

As a result, efficient battery systems that are used in electric vehicles, solar panels, and smart power grids require a Battery Management System (BMS) that ensures efficiency, durability, and safety. The safe and efficient operation of a battery depends on BMS, which may consist of overcharging circuits, overvoltage, undervoltage barriers, thermal control, and balance problems (See et al., 2022). The State of Charge (SOC) estimator inside a typical Battery Management System (BMS) supports battery cell voltage balancing, which improves the performance of any battery system (Lee et al., 2021).

Despite the promising advancements in Battery Management Systems (BMS), several challenges persist, particularly concerning the efficiency and effectiveness of energy storage solutions (Habib et al., 2023). One of the notable issues is the failure to achieve optimal energy conversion rates in many existing BMS (Karkuzhali et al., 2020). Energy conversion efficiency is crucial in determining how effectively energy can be stored and subsequently, retrieved from batteries (Magsumbol et al., 2022). When energy conversion is inefficient, it not only impacts the overall performance of the battery system but also reduces the effective energy density, meaning that the amount of usable energy stored per unit of battery volume or weight is diminished(Fang et al., 2022).

Low energy conversion rates in traditional BMS can lead to several problems(Luo et al., 2023). For instance, if a significant portion of the energy is lost during the conversion process, the battery’s overall capacity and lifespan can be adversely affected(Schimpe et al., 2018). This inefficiency can result in shorter battery life and a higher frequency of maintenance or replacement, leading to increased costs and reduced reliability of energy storage systems (Rengasamy et al., 2021). Additionally, inefficiencies in energy conversion can impact the performance of the entire energy management system, especially in applications that demand high reliability and performance, such as renewable energy integration and electric vehicles(Kim et al., 2021).

In response to these challenges, recent advancements have introduced innovative solutions that leverage modern computational power to address the limitations of traditional BMS. The Cloud Battery Management System represents a significant leap forward in this regard (Naseri et al., 2023). By utilizing cloud computing, this approach enhances the computing power available for developing and implementing sophisticated digital models and algorithms(Al-Jumaili et al., 2023). These advanced models and algorithms can optimize battery performance in several ways(Wu et al., 2021).

Cloud-based BMS can facilitate the development of more accurate predictive models for battery behavior(Tran et al., 2022). These models can account for various factors such as temperature fluctuations, charge-discharge cycles, and aging effects, thereby providing more precise predictions about battery performance and lifespan(Yang et al., 2021). Improved predictions enable more effective management of battery health and performance, leading to enhanced efficiency and reliability (Xuan et al., 2020).

Cloud-based systems can implement advanced algorithms for real-time monitoring and control(Shi et al., 2023). These algorithms can dynamically adjust charging and discharging strategies based on real-time data, optimizing energy conversion and storage efficiency(Lee et al., 2023). For example, algorithms can adjust charging rates to minimize energy loss and balance the load more effectively, thereby improving the overall efficiency of the battery system(Krishna et al., 2023).

Moreover, cloud computing allows for continuous updates and improvements to BMS algorithms(García et al., 2023). As new data becomes available and computational techniques advance, cloud-based systems can quickly integrate these improvements, ensuring that the BMS remains at the forefront of technology and performance(Wang et al., 2022). This adaptability is particularly valuable in the rapidly evolving field of energy storage, where ongoing advancements are crucial for maintaining competitive performance(Zekrifa et al., 2024).

The integration of Smart Energy Storage Systems (SESS) into microgrid management exemplifies the crucial role that BMS plays in optimizing battery performance and enhancing the efficiency of energy storage solutions(Nasiri et al., 2022). As microgrids become increasingly prevalent in modern energy infrastructure, driven by the need for localized and resilient energy systems, the functionality of SESS and its associated BMS becomes pivotal in ensuring effective operation and management(Meena & Reddy, 2023).

Microgrids, which are localized grids that can operate independently or in conjunction with the main power grid, benefit significantly from the incorporation of Smart Energy Storage Systems(Micallef et al., 2023). SESS is designed to manage and optimize energy storage within these microgrids, ensuring that energy is available when needed and that it is used efficiently(Lyden et al., 2022). In such settings, the BMS is integral in overseeing the performance of the batteries used within the SESS(Meena & Reddy, 2023). Effective BMS implementation in microgrids not only enhances battery longevity but also improves overall system reliability and efficiency(Kıvrak et al., 2019).

Presented in Figure 1 is the approximate composition of exhaust gases from diesel engines. Greenhouse gases (GHGs) were the result of the higher atmospheric concentrations which affected the environment and caused climate change and global warming. In connection, some tractors used in farming had diesel engines which also contribute to the release of Greenhouse gases (GHGs), including the release of hydrocarbons (HCs), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2) and particulate matter (PM) (Da Silveira et al., 2023).

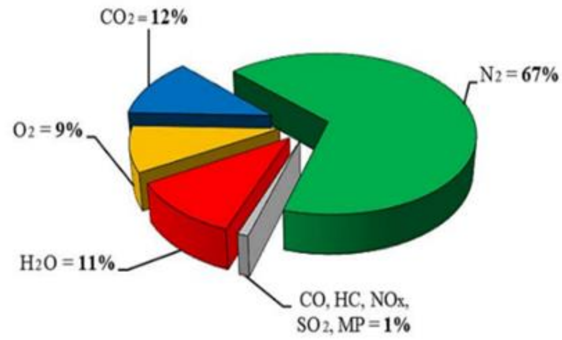

Figure 1. Approximate Composition of Exhaust Gases from Diesel Engines

Furthermore, the economy and environment have been affected because of the carbon dioxide (CO_2) emissions released by diesel-based mechanization in farming. The major sources of CO_2 emissions are diesel engines which are commonly found in agricultural machinery. The use of Diesel has contributed to global warming and climate change. For example, the carbon dioxide emissions from transportation facilities in China increased from 318 million tons in 2004 to 752 million tons in 2022 having an average annual growth rate of 4.9% (Li et al., 2024).

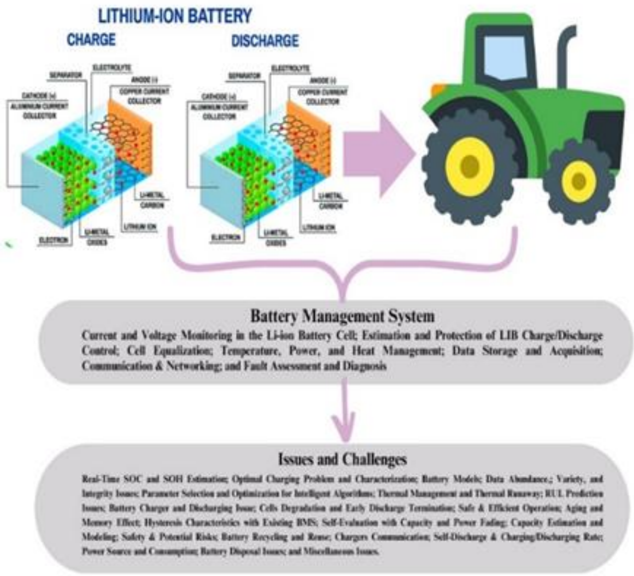

Figure 2. Overview of the Study

This study will help reduce the release of Carbon dioxide emissions from tractors that use diesel through the help of Enhanced Battery Management Systems (BMS). This innovation will help efficient energy usage and minimize wastage. By using a Battery Management System (BMS), the energy consumption for heating and electricity can be lower (Gaitan et al., 2022). The adoption of BMS using digital technologies like Battery Isolation Manager (BIM) can also help to improve energy efficiency. It can meet the requirements of digitalization and could help prevent climate change in the future(Santos et al., 2022).

In addition, this study will be seen through the Resource-Based View (RBV) theory of Barney (1991), who suggested that organizations can attain sustainable energy usage by having valuable, rare, inimitable, and non-substitutable resources. The theory highlighted the role of an organization in attaining and maintaining sustainable energy use. The Resource-Based View (RBV) theory can be applied to evaluate the strategic value of advanced Battery Management System (BMS) technologies in Namibia. Hence, creating an advanced Battery Management System (BMS) could help solve these sustainable energy issues within Namibia.

This study will be anchored on the Diffusion of Innovations Theory by Rogers (1962),which defines how, why, and at what rate innovations are adopted by cultures. The theory suggests several determinants that explain the importance of technology adoption in terms of perceived usefulness, compatibility with the prevalent paradigm, relative simplicity, experimenter control, and visibility. Thus, this theory can help the study to identify the factors that determine the acceptance and integration of advanced Battey Management System (BMS) technologies in Namibia.

A gap of knowledge can be noticed in the area concerning the improvement of these systems to improve the efficiency and sustainability of the process in Namibia. Namibia has somewhat faced challenges in that 90% of its electricity comes from coal imports even though the country has good solar resources(Mutede, 2024).

This dependency worsens the sustainability problem, which results in the necessity of specific BMS solutions that can help convert coal into renewable energy sources(Nunes et al., 2023).

Most Battery Management System (BMS) technologies that are being used today have failed to meet the needs of the developing regions, especially in terms of scalability and interoperability. Although there are emerging innovations like Continuous Battery Management System(CBMS) and Near Field Communication (NFC) technologies, their compatibility with digital tools like Battery Isolation Manager (BIM) is somewhat limited. If well integrated, there could be an enhancement in energy management and minimization of energy wastage. The development of a Battery Management System (BMS) could be of great help in minimizing the use of energy and can help achieve sustainable energy use in Namibia; thus, there is a need to conduct this study.

Research Questions

The primary purpose of this study is to determine the effectiveness of Enhanced Battery Management Approaches for Imminent Sustainable Energy Use. This will specifically answer the following questions:

1. What are the current challenges in the existing Battery charging technologies?
2. What are the impacts of technology on existing battery management systems?
3. In what ways can the existing Battery Management system be improved to provide efficient output?
4. In what way can the existing Battery Management system be improved to be sustainable?

II. LITERATURE REVIEW

Battery Management Systems

The critical components of a Smart Energy Storage System (SESS) are the Battery Management System (BMS) and State of Charge (SOC) estimator, cell balancer, and thermal management. The research identified the positives and negatives of the efficiency levels of Smart Energy Storage Systems (SESS), namely electrochemical, thermal, and mechanical energy storage systems, for their effective utilization. A study found that Battey Management System (BMS) design and implementation have been done in the past to increase efficiency and battery life (Meena & Reddy, 2023).

Srinivas and Prakash (2023) pointed out that in the integration of RES and the management of demand for power systems, the Smart Energy Storage System (SESS) is a significant factor. They asserted that the Battery Management System (BMS) is required for a Smart Energy Storage System (SESS) because it executes some of the needed operations, including State of Charge (SOC), Continuous Battery (CB), and Terminate Charge (TC). Based on the findings of this research, the integration of a Battery Management System (BMS) is important in the enhancement of the reliability and effectiveness of the Smart Energy Storage System (SESS).

Balasingam et al. (2022) discovered a Smart Energy Storage System (SESS)-that controlled the Renewable Energy Sources (RES) and peak load. Designing and testing battery systems increases performance and lifetime. The case suggests a Battery Management System (BMS)for a Smart Energy Storage System (SESS). The authors used unique battery-lifetime methods to manage a Smart Energy Storage System (SESS) with a Battery Management System (BMS).

Integration of Renewable Energy (RE) and Power Shield (PS) and their responsiveness on top of the Smart Energy Storage System was identified by Lohar et al. (2022). Their research on previously discussed batteries highlighted multiple interventions on modeling and simulation concerns that improve battery performance and life cycle. They defined smart energy storage and its differences. The researchers also discussed electrochemistry, thermal, and the positive and negative use of mechanical energy storage. They claimed that a Battery Management System (BMS) must be integrated into every Smart Energy Storage System (SESS) for sustainable energy consumption.

The work of Darwish et al. (2021) further elaborates on the advantages and disadvantages of energy storage systems. Furthermore, their research reveals that by bettering the Battery Management System (BMS) layout and its software using hardware, the ability and dependability of Smart Energy Storage System might be promoted. It was also known in this study that the Battery Management System (BMS) prevents potentially dangerous changes, and it works completely to improve its performance.

Impact of (BMS) Battery Management Systems to Sustainable Energy Use

The Li-ion batteries used in photovoltaic (PV) panels require a Battery Management System (BMS) as a safe mode of operation. Battery Management System (BMS) manages problems like overcharge, overvoltage, under-voltage, temperature changes, and variations in voltage balance, and this helps the battery life last longer. On top of that, the state of charge, the current or voltage, and the cell temperature of the battery pack should be managed by a Battery Management System (BMS), which makes it the most important factor in controlling the performance and capacity of the battery(Holey, 2023).

Meena and Reddy (2023b) elaborated on this by stating that since the BMS can be incorporated into the lithium-ion batteries used in PV systems, it becomes easy to prevent fires while increasing battery life and efficiency. They concluded that in PV systems, lithium-ion batteries when used with BMS, may enhance the safety, life, and efficiency of the batteries and help extend the use of renewable energy resources like solar energy.

Habib et al. (2023) developed an advanced hetero-architecture Energy Management System (EMS) for edge computing photovoltaic (PV) systems with lead-acid ESSs. Fuzzy algorithm operated grid-connected and islanding Energy Storage System (ESS). The study showed that edge technology would be vital for Energy Management System (EMS) strategies and photovoltaic(PV) and Energy Storage System (ESS) controllers in the future.

Sagar et al. (2022) showed how fuzzy logic islanded and regulated electricity to balance microgrids based on ESS decisions. This work promotes renewable energy management and sustainability by involving complex photovoltaic PV and Energy Storage System control approaches in edge computing. Real-time control could improve Renewable Energy Source (RES) and Energy Storage System (ESS) management systems through the Battery Ensemble ANN Modeler (BEAM) technique. These strategies may increase energy efficiency and sustainability (Hannan et al., 2021).

III. RESEARCH METHODOLOGY

The researcher will model, prototype, and field test battery management systems. The initial steps involve developing mathematical models to simulate BMS setup performance under various conditions. The simulations will enhance BMS design and function.

After modeling, the updated BMS will be designed and built into prototypes for testing. Next, the prototypes will be tested across multiple Namibian regions to ensure their efficiency and reliability in the country's operational setting.

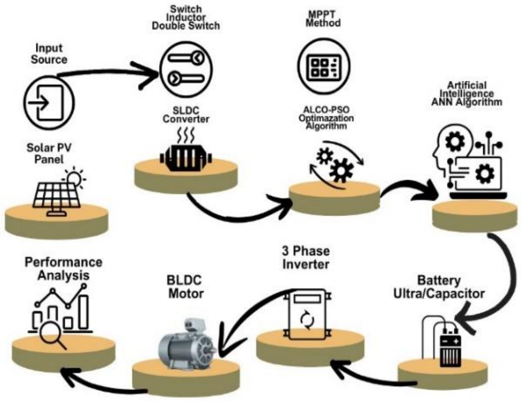

Figure 3. Battery Management System Model

Figure 3 illustrates the model of the battery management system. A solar source, electric batteries, and a power management algorithm make up the system. This paper proposes the Maximum Power Point (MPP) tracking technique to monitor the maximum power from the solar photovoltaic panel. The proposed method also demonstrates the utilization of the solar energy battery and ultra-capacitor energy storage system for the Brushless DC Electric Motor(BLDC) motors.

The total system comprises the boost converter, three-phase inverter, brushless direct current motor, the solar panel, the battery, and the ultra-capacitor. The boost converter is responsible for the Maximum Power Point Tracking (MPPT) process of charging the battery. The voltage of the battery does not change and is regulated by Maximum Power Point Tracking (MPPT) for charging. Depending on the voltage of the solar panel and the output current, the boost converter cycle will be changed. At the same time, the battery charges the Brushless DC Electric Motor(BLDC)and then supplies the power to the motor. The proposed system realizes the transfer from the battery to the motor without voltage drop; this enhances the motor's performance. Besides that, the lifespan of the battery is also enhanced. First, the Photovoltaic solar panel converts the light energy received from the sun into electrical energy. Then, the state load is removed from the centre converter, and the switched inductor is used to step up the voltage obtained from the solar photovoltaic (PV) panel.

The maximum power point tracking (MPPT) technique and the combination of other techniques like ant colony optimization with lion optimization and particle swarm optimization are used to control the voltage and current. Also, the energy conversion faults are diagnosed using an artificial neural network algorithm.

The electrical energy supply is given to the battery or ultra-capacitor, and the latter is charged with the former. After that, the power from the battery is supplied to a three-phase inverter to change the direct current. Next, the electrical energy is fed to the BLDC motor, and the moment that the current passes, the motor starts to rotate. During the process, solar power in the BLDC is efficient without loss as the motor used is brushless. Solar energy is usually abundant in nature in its availability. Therefore, the proposed work employs the solar panel to supply power to the BLDC motor. Then, the BLDC motor is tested in the light of the specific parameters, including torque, power density, operating life, and noise.

Ant Colony Optimization (ACO)

Ant Colony Optimization (ACO) is inspired by the natural foraging behavior of ants(Nurcahyadi & Blum, 2021). ACO algorithms simulate how ants find the shortest path to food sources(Li et al., 2022). By mimicking this process, ACO efficiently explores the solution space to identify the optimal operating point for maximum power output(Chen & Tan, 2022). The algorithm adjusts control parameters dynamically, allowing the MPPT system to adapt to varying environmental conditions and improve its accuracy and responsiveness(Li et al., 2023).

Lion Optimization Algorithm (LOA)

The Lion Optimization Algorithm (LOA) is based on the hunting strategies of lions(Masadeh et al., 2019). LOA models the cooperative and competitive behaviours observed in lion packs during hunting(Yassen et al., 2021). This optimization technique focuses on balancing the exploration of new solutions and the exploitation of known ones(Yazdani et al., 2022). By leveraging the social dynamics of lions, LOA enhances the convergence rates of MPPT systems and improves the precision of identifying the maximum power point, making it a robust tool for optimizing power output(Ali et al., 2017).

Particle Swarm Optimization (PSO)

Particle Swarm Optimization (PSO) draws inspiration from the social behavior of birds flocking or fish schooling(Shami et al., 2022). In PSO, a swarm of particles represents potential solutions that search the solution space collaboratively(Huang & Xu, 2023). Each particle adjusts its position based on its own experience and the information shared by other particles(Zhu et al., 2023). This collective approach allows PSO to navigate the solution space efficiently and converge on the optimal power point more effectively(Wang et al., 2017).

Fault Diagnosis Using Artificial Neural Networks (ANNs)

Artificial Neural Networks (ANNs) play a critical role in diagnosing faults within energy conversion systems(Kane & Andhare, 2016). ANNs are designed to analyze system performance and detect anomalies by learning from historical data(Rodríguez-Hernández et al., 2021). They identify patterns indicative of potential faults or inefficiencies, such as component failures or operational irregularities(Hagenauer & Helbich, 2021). By implementing ANN-based fault diagnosis, energy systems can achieve timely maintenance, prevent system downtime, and ensure overall reliability and longevity(Matel et al., 2019).

The electrical energy supply is given to the battery or ultra-capacitor, and the latter is charged with the former. After that, the power from the battery is supplied to a three-phase inverter to change the direct current. Next, the electrical energy is fed to the Brushless DC Electric Motor(BLDC)motor, and the moment that the current passes, the motor starts to rotate. During the process, solar power in the Brushless DC Electric Motor(BLDC) is efficient without loss as the motor used is brushless. Solar energy is usually abundant in nature in its availability. Therefore, the proposed work employs the solar panel to supply power to the Brushless DC Electric Motor(BLDC) motor. Then, the Brushless DC Electric Motor(BLDC) motor will be tested in the light of the specific parameters, including torque, power density, operating life, and noise.

Participants

The targeted participants of this study will comprise farmers who will be using the electrical water pumping system. The preferences and perspectives of these respondents will be analyzed through the use of survey questionnaires. The study population will be represented by ___ participants who will fill in the survey questionnaires. The purposive sampling method will be used to collect the data to conduct the statistical quantitative analysis. Hence, in this study, the purposive sampling method will be more appropriate since it enables the researcher to choose participants who hold specific attributes or information regarding the research objectives (Narayan et al., 2023).

Data Collection and Analysis

In this research study, the data will be gathered through the use of a semi-structured questionnaire. The study population will be farmers, who will be the target of this research survey. The researcher will examine and confirm if the respondents have answered all the questions. The sampling data obtained will be put in a tabular form called a worksheet for easy analysis. The demographic data of the respondents, together with their answers, will be quantitatively analyzed using the Statistical Package for the Social Sciences (SPSS).

IV.CONCLUSION

In conclusion, the development of Enhanced Battery Management Systems (BMS) for sustainable energy use in Namibia is essential to address the country's energy challenges, particularly the heavy reliance on imported coal-based electricity despite its significant solar energy potential. This study emphasizes the importance of optimizing BMS to improve battery efficiency, safety, and lifespan, which are crucial for integrating renewable energy technologies like solar power. By addressing current issues such as battery fault detection, thermal runaway, and sensor faults, and by incorporating advanced algorithms and models, the proposed BMS can enhance the performance of energy storage systems. The implementation of such systems will not only contribute to more reliable and durable batteries but also support Namibia's transition towards sustainable energy use. The study's focus on digital technologies and innovative methods like Maximum Power Point Tracking (MPPT) and artificial neural networks illustrates the potential for significant advancements in energy management. These improvements could lead to reduced energy wastage, lower environmental impact, and a more sustainable energy infrastructure in Namibia. Ultimately, the successful adoption of advanced BMS technologies could serve as a critical step toward achieving Namibia's energy sustainability goals, ensuring that the country maximizes its renewable energy resources and reduces its dependence on fossil fuels.

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