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Research Article

Comparative Assessment of Techno-Economic Performance of Battery Energy Storage for Solar Photovoltaic Systems; Sealed Lead-Acid and Nickel-Cadmium Batteries in Sierra Leone, Kenema Municipality

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Abstract

Introduction: This research focuses on the evaluation of battery energy storage systems, specifically examining the techno-economic performance of Sealed Lead-Acid and Nickel-Cadmium (NiCd) batteries in conjunction with Solar Photovoltaic (PV) systems. The research considered factors such as charging efficiency, temperature sensitivity, self-discharge rates, and cycle life, all of which impact the performance and economic viability of these battery types. *Objective:* The primary objective of this research was to conduct a comparative assessment of the techno-economic performance of Sealed Lead-Acid and Nickel-Cadmium (NiCd) batteries for energy storage within a Solar PV system in Kenema, Sierra Leone. This involves analysing their key characteristics and evaluating their suitability for the specific environmental and operational context. *Methods:* The research employed a comparative analysis, considering technical specifications, operational parameters (charging/discharging efficiencies, temperature effects, self-discharge rates, cycle life), and potentially, economic factors (initial cost, lifespan, maintenance costs) of both battery types. *Result:* The results highlighted the performance differences between Sealed Lead-Acid and Nickel-Cadmium batteries, considering the operational factors mentioned in the background. The result will discuss that Sealed Lead-Acid batteries have a typical charging efficiency of 95% compared to the 80% efficiency of Nickel-Cadmium (NiCd) batteries. The research also examined performance under various temperature conditions, as well as the self-discharge rates. The ideal temperature for lead-acid batteries was generally determined to be about 25°C. For every 8–10°C increase in temperature, the useful capacity of lead-acid batteries decreases by roughly 50%. Sealed Lead-Acid batteries have a self-discharge rate of 1-5% per month, whereas Nickel-Cadmium (NiCd) batteries have a self-discharge rate of 20–30% per month. Lead and its compounds make up roughly 65-75% (by weight) of the battery, while sulfuric acid makes up 14–20%. *Conclusion:* The conclusion provided insights into the relative advantages and disadvantages of each battery type in the context of a Solar PV system in Sierra Leone, considering both the technical and economic aspects. It aimed to provide recommendations based on the comparative assessment, offering guidance for selecting the most appropriate battery technology for such applications.

Keywords

Nickel-Cadmium, Sealed Lead-Acid, Performance, Photovoltaic, Solar, Energy

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1. Introduction

The integration of renewable energy sources, particularly solar photovoltaic (PV) systems, has gained significant momentum over the past decade, driven by the urgent need to address climate change and enhance energy security. Solar energy offers a sustainable alternative in regions like Sierra Leone, characterised by irregular power supply and high reliance on fossil fuels. However, one of the critical challenges to maximising the potential of solar PV systems was effective energy storage, as it ensures reliability and stability in energy supply, particularly during periods of low solar irradiance.

Battery energy storage systems (BESS) have emerged as vital components in deploying solar PV systems, facilitating the shift from intermittent electricity generation to a more reliable and consistent energy supply. Among various battery technologies, Sealed Lead Acid (SLA) and Nickel-Cadmium (NiCd) batteries were commonly used in off-grid and hybrid applications due to their maturity and relative cost-effectiveness [8, 12]. Nevertheless, the techno-economic performance of different battery technologies can significantly impact both the initial investment and long-term operational costs, which is crucial for decision-making in energy projects.

Recent studies indicate that while SLA batteries were often favoured for their lower upfront costs, NiCd batteries offer advantages regarding longevity and performance under extreme temperature conditions, which could be particularly relevant in the Sierra Leonean context [40]. As the country seeks to improve its energy landscape, there is a pressing need for comparative assessments that could inform stakeholders about the most suitable and economically viable battery technologies for solar PV systems.

Conducting a comparative assessment of SLA and NiCd batteries in Sierra Leone, specifically in the Kenema Municipality, presents an opportunity to evaluate the techno-economic viability of these technologies in a real-world context. This assessment will consider factors such as cost, lifespan, efficiency, scalability, and environmental impact. Such an analysis could ultimately guide energy policy decisions and investments that support sustainable energy development in Sierra Leone.

Problem Statement

The integration of solar photovoltaic (PV) systems with energy storage solutions was vital for improving energy access and reliability in developing areas like Sierra Leone, particularly in Kenema Municipality, where dependence on conventional energy sources was high [30]. The combination of solar PV with battery energy storage systems (BESS) offers a sustainable electrification method. However, the effectiveness of these systems can be hampered by the variability of solar energy and irregular power supply. Selecting suitable battery technologies—specifically sealed lead-acid (SLA) and nickel-cadmium (Ni-Cd) batteries, known for their reliability and cost-effectiveness—was essential for optimising performance [23]. Currently, there is a lack of comprehensive studies comparing these battery types within the context of solar PV in Sierra Leone, which creates knowledge gaps regarding their suitability and economic viability [19]. This absence of empirical data hinders effective policy-making and investment in renewable energy solutions. Additionally, considerations about environmental impact, lifecycle efficiency, and total cost of ownership require further exploration. This research aimed to conduct a comparative assessment of SLA and Ni-Cd batteries to enhance the performance of solar PV systems in Kenema Municipality, Sierra Leone, thereby supporting the transition to sustainable energy solutions.

2. Literature Review

2.1. Overview of Solar PV Systems

Solar photovoltaic (PV) systems have gained significant traction as a sustainable energy solution worldwide. These systems convert sunlight directly into electricity through photovoltaic cells, which are commonly made from silicon. Over the past decades, advancements in solar technology, policy incentives, and growing concerns over climate change have led to the increased deployment of solar PV systems, especially in regions with abundant sunlight like Sierra Leone.

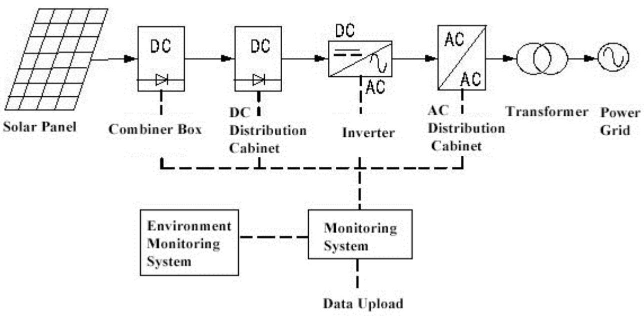

Figure 1. *Main elements of solar photovoltaic systems.*

2.2. Theoretical Framework

The integration of battery energy storage systems (BESS) with solar photovoltaic (PV) systems has gained significant attention in recent years, particularly in off-grid locations like Kenema, Sierra Leone [24]. Theoretical frameworks have been developed to assess the techno-economic performance of BESS for PV systems, considering factors such as energy storage capacity, depth of discharge, and charging/discharging efficiency.

In the context of this study, the theoretical framework focused on the comparative assessment of sealed lead-acid (SLA) and nickel-cadmium (Ni-Cd) batteries for PV systems in Kenema, Sierra Leone. The framework was drawn from existing research on the technical and economic performance of these battery technologies [7].

Technical Performance

The technical performance of SLA and Ni-Cd batteries was evaluated based on their energy storage capacity, cycle life, and self-discharge rate. SLA batteries have been widely used in PV systems due to their relatively low cost and high discharge capacity [35]. However, Ni-Cd batteries have been shown to offer higher cycle life and lower self-discharge rates, making them suitable for applications with high energy storage requirements [39].

Economic Performance

The economic performance of SLA and Ni-Cd batteries was evaluated based on their initial cost, operating cost, and lifespan. The levelized cost of energy (LCOE) was used to compare the economic viability of the two battery technologies (NREL, 2022). The LCOE was taken into account the initial investment, maintenance costs, and replacement costs over the lifespan of the batteries.

Environmental Performance

The environmental performance of SLA and Ni-Cd batteries was evaluated based on their environmental impact, including greenhouse gas emissions, toxic material content, and recyclability [10]. The study considered the environmental benefits of using renewable energy sources like solar PV and the potential environmental impacts of battery disposal and recycling.

Comparative Assessment

The comparative assessment of SLA and Ni-Cd batteries was based on a multi-criteria decision analysis (MCDA) framework, which considered technical, economic, and environmental factors [20]. The MCDA framework enabled the evaluation of the trade-offs between different criteria and the identification of the most suitable battery technology for PV systems in Kenema, Sierra Leone.

In conclusion, the theoretical framework for this study provided a comprehensive basis for the comparative assessment of SLA and Ni-Cd batteries for PV systems in Kenema, Sierra Leone. The framework drew on recent research to evaluate the technical, economic, and environmental performance of these battery technologies and provide insights into their suitability for off-grid PV applications.

2.3. Technological Components of Solar PV Systems

A typical solar PV system consists of several key components, including:

1) Solar Panels: Convert sunlight into electrical energy. The efficiency of panels has improved, with many modern panels achieving efficiencies of over 20% [29].
2) Inverters: Convert the direct current (DC) generated by solar panels into alternating current (AC), which is usable in homes and businesses. Recent developments have seen the rise of string inverters and microinverters, enhancing system efficiency [32].

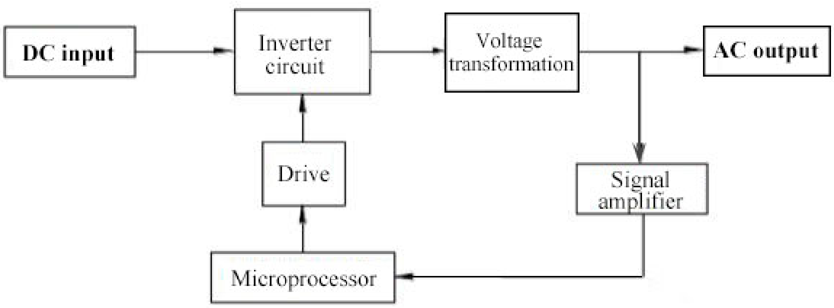

Figure 2. *Inverter block diagram.*

Primary Protection Measures for Solar PV Systems

Apart from earthing, primary protection measures were essential to safeguard solar photovoltaic (PV) systems from the adverse effects of electrical surges and lightning strikes. To combat these threats, two key protection methods were implemented.

While earthing provides fundamental lightning protection, surge arresters, such as metal oxide varistors (MOVs), offer additional defence against electrical surges caused by lightning strikes. These devices were commonly integrated into larger electrical systems to safeguard sensitive equipment.

Diodes serve two key functions: they prevent the reverse flow of current and can create a bypass path for current in situations like partial shading in photovoltaic (PV) systems.

In electrical systems, the term "load" refers to the appliances and equipment that draw power, encompassing both alternating current (AC) and direct current (DC) devices. Determining the load's energy requirements was crucial for the design and sizing of the overall system. Typically, a load assessment was conducted at the outset. For further information on this topic, consider consulting resources such as studies on "Comparative Assessment of Techno-Economic Performance of Battery Energy Storage for Solar Photovoltaic Systems" and analyses of "Sealed Lead Acid and Nickel-Cadmium Batteries in Sierra Leone, Kenema" [32, 39].

Mounting Structures: Allow solar panels to be installed at optimal angles. Tracking systems that move with the sun can significantly enhance energy capture [9].

Energy Storage: Battery storage systems, like sealed lead-acid (SLA) and nickel-cadmium (NiCd) batteries, store excess energy generated during the day for use during non-sunny periods. Battery storage has become essential for optimising the reliability and dispatchability of solar energy [22].

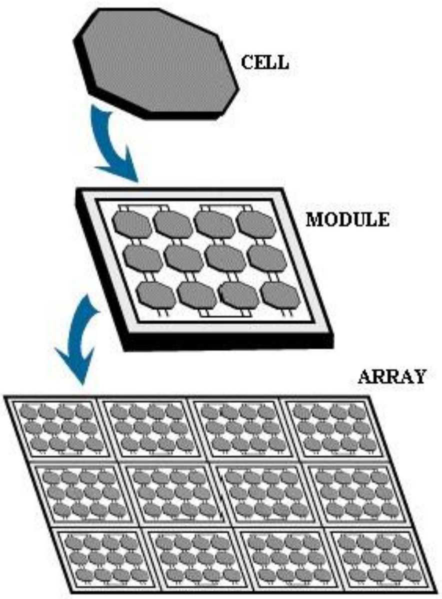

Figure 3. *Basic Components of a Solar Panel.*

2.4. Comparative Assessment of Battery Energy Storage

In areas like Kenema, Sierra Leone, selecting the appropriate battery storage technology was crucial for enhancing the efficiency and reliability of solar PV systems. The two prevalent battery technologies were sealed lead-acid (SLA) and nickel-cadmium (NiCd) batteries.

Sealed Lead-Acid Batteries (SLA): These batteries are widely used due to their low cost and ease of maintenance. They are well-suited for applications where space is limited and are typically rated for a cycle life of 500–1,000 cycles [1].

Nickel-Cadmium Batteries (NiCd): Known for their robustness and reliability, NiCd batteries perform well in extreme temperatures and have a longer cycle life (up to 2,000 cycles) compared to SLA batteries. However, they are generally more expensive and face environmental disposal concerns due to cadmium's toxicity [39]. A typical solar PV home system has the basic components, as shown in Figure 4 below.

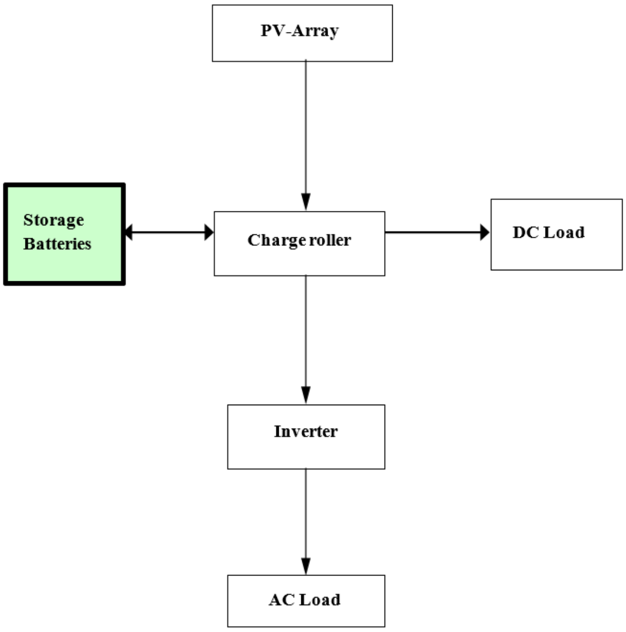

Figure 4. *Configuration of a PV system.*

A comparative analysis of these technologies in the context of Kenema could reveal significant insights into their techno-economic performance based on factors such as initial cost, life cycle cost, capacity, efficiency, and environmental impact. Early studies indicated that while SLA batteries may initially appear cheaper, the total cost of ownership could favour NiCd batteries due to their longer lifespan and lower replacement frequency [16].

Developments and Future Directions

As the renewable energy landscape evolves, ongoing research is focusing on improving battery technology through advancements such as lithium-ion batteries and new materials that offer enhanced performance and environmental sustainability. This is crucial for regions like Sierra Leone, where energy demand is expected to rise significantly, and reliable energy storage could play a vital role in energy accessibility [15].

2.5. Technical Characteristics

The comparative assessment of Sealed Lead-Acid (SLA) and Nickel-Cadmium (Ni-Cd) batteries for solar PV systems in Kenema, Sierra Leone, involves evaluating their Energy Storage Capacity, Cycle Life, Charging Efficiency, and Discharge Characteristics [1, 9].

Energy Storage Capacity: SLA batteries typically range from 84Wh to 4000Wh. Ni-Cd batteries typically range from 84Wh to 4000Wh.

Cycle Life: SLA batteries offer 250-500 charge/discharge cycles, while Ni-Cd batteries offer 400-1000 cycles [1, 8].

Charging Efficiency: SLA batteries typically have 80-90% efficiency, whereas Ni-Cd batteries can achieve 80-95% efficiency.

Discharge Characteristics: SLA batteries discharge at 5A-10A with a voltage drop from 12.7V to 10V. Ni-Cd batteries discharge at 2A-5A, with a voltage drop from 12.8V to 10.8V [8, 1, 9].

2.6. Economic Assessment and Maintenance Requirements

This section provides an overview of the economic assessment and maintenance requirements associated with Battery Energy Storage Systems (BESS), with a specific focus on the context of solar photovoltaic (PV) systems in Sierra Leone, particularly in Kenema. The discussion was to compare two common battery technologies: Sealed Lead Acid (SLA) and Nickel-Cadmium (Ni-Cd) batteries.

2.6.1. Economic Assessment of BESS for Solar PV Systems

The economic viability of integrating BESS with solar PV systems hinges on several factors, including the initial investment cost, operational expenses (including maintenance and replacement), system lifespan, energy arbitrage opportunities, and local electricity tariffs [17]. The cost of batteries has significantly decreased in recent years, making BESS more attractive for residential, commercial, and off-grid applications [14]. However, the specific economic benefits depend on the application and local market conditions.

Levelized Cost of Energy (LCOE): A key metric for economic evaluation, LCOE compares the total lifetime cost of the system to the total energy generated [27]. Integrating BESS can affect LCOE by improving the utilisation of PV-generated electricity, potentially reducing reliance on the grid or diesel generators.

Net Present Value (NPV) and Internal Rate of Return (IRR): These financial metrics help assess the profitability of a BESS investment over its lifespan. High upfront costs of BESS require careful consideration of these parameters [6].

Cost-Benefit Analysis (CBA): CBA helps to quantify the benefits of BESS, such as improved grid stability, reduced greenhouse gas emissions, and increased energy independence [21].

2.6.2. Comparative Assessment of Techno-Economic Performance in Sierra Leone (Kenema)

In the specific context of Sierra Leone, and particularly in Kenema, factors such as the availability and cost of grid electricity, the local climate (affecting PV generation and battery performance), and the availability of skilled technicians were crucial [38]. Off-grid or mini-grid applications were common in such regions, and BESS play a vital role in ensuring a reliable power supply, especially during periods of low solar irradiance or grid outages [28]. The following aspects must be compared when assessing SLA and Ni-Cd batteries in Kenema:

1) Capital Cost: SLA batteries are typically less expensive upfront than Ni-Cd batteries.
2) Lifespan and Cycle Life: Ni-Cd batteries typically have a longer lifespan and greater cycle life than SLA batteries.
3) Depth of Discharge (DoD): Ni-Cd batteries can generally handle a deeper DoD than SLA batteries without significant damage, which impacts usable energy storage.
4) Maintenance Requirements: SLA batteries are generally considered "maintenance-free" in sealed configurations; Ni-Cd batteries may require occasional electrolyte top-up.
5) Operating Temperature: Both battery types are sensitive to temperature extremes, which can affect their performance and lifespan. The hot and humid climate of Kenema needs to be taken into consideration.
6) Energy Efficiency: The round-trip efficiency of both battery types should be considered.
7) Environmental Impact: Both battery types have environmental considerations. SLA batteries contain lead, and Ni-Cd batteries contain cadmium, which are toxic and require careful handling and recycling.

2.6.3. Maintenance Requirements for SLA and Ni-Cd Batteries

Maintenance requirements significantly impact the long-term operational costs and reliability of BESS.

Sealed Lead Acid (SLA) Batteries

Minimal maintenance was generally required for sealed SLA batteries. Regular visual inspections to check for corrosion, leakage, and proper ventilation are critical. The battery charge controllers that prevent overcharging and over-discharging were essential to protect the battery and increase its lifespan.

Nickel-Cadmium (Ni-Cd) Batteries

Some Ni-Cd battery types, especially those used in older systems, may require regular electrolyte top-up. The electrolyte level must be maintained to prevent damage. Periodic equalisation charging helps to balance the cells within the battery bank, improving performance and lifespan [4]. Proper ventilation was important to avoid the buildup of hydrogen gas during charging. Regular monitoring of battery voltage, current, and temperature was essential to ensure optimal performance and identify potential problems.

Techno-Economic

The techno-economic study comparing Sealed Lead-Acid (SLA) and Nickel-Cadmium (Ni-Cd) batteries for off-grid solar PV systems in Kenema, Sierra Leone. The research aimed to address electrification challenges in remote areas with weak grid infrastructure by evaluating the technical (efficiency, lifespan) and economic (initial/operational costs, LCOE) performance of SLA and Ni-Cd batteries. SLA batteries were cheaper but had limitations; Ni-Cd offered better performance but was more expensive due to environmental concerns. The research determined the most suitable battery technology considering both technical and economic factors [29].

Environmental Impact Assessment (EIA)

The integration of battery energy storage systems (BESS) with solar photovoltaic (PV) installations, particularly in developing nations like Sierra Leone, presents a complex interplay of benefits and drawbacks regarding EIA. While solar PV inherently offers a cleaner energy source, the environmental consequences of BESS, especially considering the use of older battery technologies like sealed lead-acid (SLA) and nickel-cadmium (Ni-Cd) batteries, were critical to evaluate.

Raw Material Extraction and Manufacturing

The production of batteries, including SLA and Ni-Cd, requires the extraction of various raw materials (lead, cadmium, etc.). This process can lead to:*(1)* Mining activities often result in deforestation, soil erosion, and the disruption of ecosystems, particularly in resource-rich regions [3]. *(2)* Mining and manufacturing processes can release pollutants such as heavy metals (lead, cadmium) into the air, water, and soil, posing risks to human health and environmental quality [31]. *(3)* The extraction of finite resources raises concerns about sustainability and long-term availability, particularly for materials like lithium, nickel, and cobalt, which are commonly used in advanced battery chemistries [26].

Battery Use and Operation

The efficiency of energy storage and the lifespan of batteries directly influence the overall environmental footprint. Lower efficiencies and shorter lifespans (common with SLA and Ni-Cd compared to newer technologies) lead to more frequent replacement and increased material consumption.

The manufacturing of batteries requires energy, often sourced from fossil fuels. The use of electricity from the grid to charge batteries (especially in areas with a high carbon intensity in the electricity mix) could indirectly contribute to greenhouse gas emissions.

Batteries could pose safety hazards (e.g., acid spills in SLA, and cadmium toxicity in Ni-Cd) if not handled or maintained correctly. Such risks could be exacerbated in developing countries where safety standards might be less stringent [37].

End-of-Life Management and Recycling

Improper disposal of spent batteries was a significant environmental hazard. Lead and cadmium are toxic heavy metals that could leach into the soil and contaminate water sources [25]. Effective recycling programs are crucial to recovering valuable materials and reducing the environmental impact. The complexity of battery recycling and the availability of recycling infrastructure vary significantly across different regions. In Sierra Leone and specifically in Kenema, the capacity for safe and environmentally sound battery recycling may be limited [14].

The lack of formal recycling infrastructure can lead to informal recycling practices (e.g., burning batteries to extract metals) that pose serious risks to human health and the environment [11].

Specific Considerations for Kenema

Given the context of Kenema Municipality, a region in Sierra Leone, the environmental impact of battery choice was particularly relevant. The selection of SLA or Ni-Cd over more modern battery options requires scrutiny, accounting for the likelihood of lower recycling rates, the potential for informal disposal practices, and the environmental burdens of raw material supply chains.

The life cycle assessment (LCA) methodology provides a framework for evaluating the environmental impacts of BESS. LCAs consider the full lifecycle – from raw material extraction, manufacturing, transportation, use, and end-of-life management.

3. Methodology

This methodology outlines the approach for a comparative assessment of the techno-economic performance of Sealed Lead Acid (SLA) and Nickel-Cadmium *(Ni-Cd)* batteries for use in Solar Photovoltaic (PV) systems in Kenema, Sierra Leone. The research aimed to provide insights into the suitability and viability of each battery technology for off-grid electricity access, considering technical performance, economic feasibility, and environmental impact. These vendors were selected based on the requirements of the study, such as the availability of the two battery types under study and a reasonable sales history of each battery type.

3.1. Study Area and Data Collection

Kenema was selected due to its significant off-grid energy demand and reliance on diesel generators. It was also a representative location for studying the impact of energy storage technologies in a developing country context.

A survey was conducted to identify existing or planned solar PV systems in Kenema. This involves site visits to homes, businesses, and community facilities. The systems were categorised based on size (e.g., small household, medium-sized commercial, large community systems) and application (e.g., lighting, appliances, productive uses). Comprehensive data was collected for both *SLA* and *Ni-Cd* battery systems. This includes:

3.2. Technical Data

Voltage, capacity *(Ah and kWh)*, depth of discharge *(DoD)*, cycle life, charging/discharging rates, operating temperature range, and self-discharge rates from manufacturers' datasheets.

PV system characteristics, panel capacity (Wp), inverter capacity (VA or kW), and load profiles (power consumption patterns) through direct monitoring using data loggers and/or interviews with system owners and users. This includes measuring daily and seasonal variations in solar irradiance and energy demand. Operating parameters, charging and discharging voltage and currents.

3.3. Economic Data

Initial Investment Costs, Battery purchase price, including costs for transportation, installation, and any necessary accessories (e.g., battery management systems - BMS).

Operating and Maintenance Costs, Replacement costs, maintenance labour, and component replacements. Fuel and Electricity Costs**,** for systems that may operate as hybrid systems or backup energy. Financial Incentives, information on any existing subsidies, tax breaks, or financing schemes available.

Performance Data, measurements of key performance indicators *(KPIs)* such as Round-trip efficiency (ηRT) Depth of Discharge *(DoD)*, State of Charge *(SoC*, Energy throughput, and Battery lifetime. Environmental Impact Data was the data related to the materials used in battery manufacturing, potential for recycling, and disposal methods.

3.4. Battery Performance Analysis

The analysis of the *(SLA and Ni-Cd)* batteries using appropriate software like SPSS. The analyses simulated battery behaviour under varying load profiles, solar irradiance, and operating conditions to estimate battery performance [18].

The following performance metrics were evaluated and compared: Assess the effective storage capacity of each battery technology, considering DoD and other factors. Determine the expected number of charge-discharge cycles before the battery reaches its end-of-life. This was estimated using manufacturers' data and degradation models [33]. Evaluate the energy losses during charging and discharging cycles for each battery.

Analyse the impact of battery failure on the overall reliability of the PV system using appropriate metrics like Loss of Power Probability *(LPSP)* and reliability indices [15]. Analyse the effect of the local temperature profile on the battery performance.

3.5. Economic Analysis

The Levelized Cost of Energy *(LCOE)* was calculated for each battery technology. LCOE considers the total lifetime cost of the system, including initial investment, operation and maintenance costs, fuel costs (if applicable), and salvage value, divided by the total energy generated over the lifetime of the system [13].

$$\mathrm{LCOE} = \sum_{t=1}^{n} \frac{\frac{I_t+M_t+F_t}{(1+r)^t}}{(1+r)^t} \tag{1}$$

Where:

LCOE = Levelized Cost of Energy, I_t = Investment expenditures in the year *t*, M_t = Operations and maintenance expenditures in the year *t*, F_t = Fuel expenditures in the year *t*, E_t = Electricity generation in the year *t*, *r* = Discount rate, and *n* = System Lifetime.

Sensitivity Analysis performs a sensitivity analysis to examine how changes in key economic parameters (e.g., battery price, discount rate, fuel costs, and grid electricity prices) impact the LCOE and economic viability of each battery technology [5].

Payback Period and Return on Investment (ROI), calculated the payback period and ROI was to evaluate the economic attractiveness of each battery technology.

4. Result

4.1. Technical Performance

The characteristics compared were charging, discharging, Storage, and Cycling.

4.1.1. Charging Efficiency Comparison

Figure 5 illustrates the typical charging efficiency of two prevalent battery types: Sealed Lead-Acid and Nickel-Cadmium NiCd. The charging efficiency was presented as a percentage, denoting the proportion of energy successfully stored in the battery during the charging process (Car and Driver). The charging efficiency metrics for these battery types were as follows: (i) Sealed Lead-Acid batteries exhibit a typical charging efficiency of 95% (Car and Driver). (ii) Nickel-Cadmium NiCd batteries demonstrate a lower efficiency of 80% (Car and Driver).

These findings indicate that approximately 95% of the supplied energy was effectively stored in Sealed Lead-Acid batteries, whereas only 80% of the energy was stored in Nickel-Cadmium NiCd batteries.

It was essential to acknowledge that these values represent typical charging efficiencies and may vary based on multiple factors such as battery condition, charging method, and temperature. These values serve as a general indication of the efficiency levels for these battery types. The charging efficiency plays a crucial role in evaluating battery performance and selecting the most suitable battery for specific applications. Batteries with higher charging efficiencies were generally more desirable, as they could store a larger proportion of the supplied energy, leading to longer battery life and improved overall performance [34].

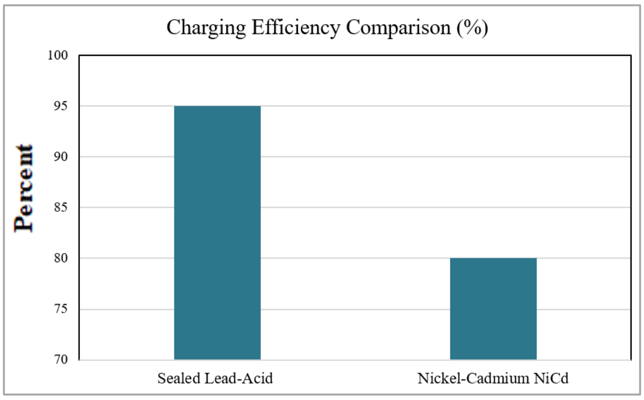

Figure 5. *Typical Charging Efficiency of Batteries.*

4.1.2. Battery Performance: Discharge, Retention, and Lifespan

This analysis explores the performance characteristics of Sealed Lead-Acid (SLA) and Nickel-Cadmium (NiCd) batteries, focusing on discharge rate, charge retention, and cycle life.

4.1.3. Temperature Dependence and Discharge Performance

Temperature significantly influences battery performance. Batteries can operate safely across a range of temperatures, though optimal performance varies based on design. Table 1 highlights the operating temperature ranges for both battery types. SLA batteries typically perform best around 25℃, with a reduction in usable capacity of approximately 50% for every 8−10℃ increase in temperature. NiCd batteries, however, exhibit superior low-temperature discharge characteristics. At −20℃, NiCd battery can deliver around 80% of its rated capacity, compared to approximately 60% for an immobilised electrolyte SLA battery under the same conditions. This indicates a greater resilience of NiCd batteries in cold environments.

4.1.4. Self-Discharge and Charge Retention

Self-discharge was a phenomenon inherent to batteries, wherein internal chemical reactions diminish stored charge even when the battery was disconnected from a circuit. This process reduces the battery's shelf life and results in a lower-than-full charge when put into use. The rate of self-discharge was affected by battery type, state of charge, charging current, ambient temperature, and other factors. The SLA batteries exhibited a self-discharge rate of 1-5% per month. NiCd batteries have a significantly higher self-discharge rate, ranging from 20-30% per month.

This comparison demonstrates that SLA batteries retain their charge for a considerably longer period compared to NiCd batteries, making them more suitable for applications where long-term storage is crucial.

4.1.5. Cycle Life and Battery Applications

SLA batteries typically offer a cycle life of 200-300 cycles, and NiCd batteries demonstrated a considerably longer cycle life, typically reaching 1500 cycles.

The cycle life of a battery signifies the number of charge-discharge cycles it can undergo before its capacity decreases to a specified threshold. The cycle life was influenced by factors such as battery type, depth of discharge (DoD), and operating temperature. SLA batteries, due to their lower cycle life, are frequently used in applications like uninterruptible power supplies (UPS), emergency lighting, and security systems. They were also employed in electric vehicles, wheelchairs, and golf carts (Corrosion Doctors). NiCd batteries, characterised by a high cycle life, were commonly found in portable electronic devices like cordless phones, power tools, and digital cameras.

Table 1. *Temperature Range, Self-discharge Rate, and Life-Cycle of Battery.*

Battery Type	Temperature Range Centigrade (℃)	Self–discharged Rate/Month Percentage (%)	Life–Cycle Number of cycles (Hz)
Sealed Lead-Acid	-40 to +60	1-5	200-300
Nickel-Cadmium NiCd	-40 to +60	20-30	1500

Source: Field Survey, 2024

Economic Evaluation

The economic viability of battery energy storage (BES) systems was a crucial factor in their adoption, especially in off-grid applications like those found in Sierra Leone. This analysis leverages detailed price data sourced from local suppliers and online resources, along with cycle-life information derived from the technical assessment. This data enables a comprehensive life-cycle cost (LCC) analysis for each battery technology considered.

Market Price of Batteries

Table 2. *Average Unit Cost for Electricity Storage in Battery Types.*

Battery Type	Cost Per Amp-Hour (Ah) (Le)	Cost Per Watt-Hour (Wh) (Le)
Sealed Lead-Acid	35.14	3.43
Nickel-Cadmium NiCd	100.45	10.41

Source: Field Survey, 2024

These figures highlight that SLA batteries exhibit a lower unit cost per Ah and Wh compared to NiCd batteries. This suggests that SLA batteries may be more cost-effective for electricity storage, at least based on initial capital expenditure. However, a thorough LCC analysis should consider factors such as lifespan, efficiency, maintenance costs, and potential environmental impacts to provide a holistic assessment. This analysis was consistent with the findings of [34], where the cost-effectiveness of different BES technologies was examined based on regional market prices.

4.2. Sealed Lead Acid (SLA) Battery

SLA batteries consist primarily of lead and lead oxide electrodes, immersed in sulfuric acid. During discharge, lead sulfate forms, with the amount varying based on the battery's state of charge. Lead and its compounds constitute approximately 65-75% (by weight) of the battery, while sulfuric acid makes up 14-20%.

Lead and its inorganic compounds pose health risks to humans. While skin absorption is unlikely, overexposure can lead to nausea, headaches, and chronic health issues, including kidney and central nervous system damage. The International Agency for Research on Cancer (IARC) classifies lead and inorganic lead compounds as a B2 hazard (probable/possible human carcinogen) based on animal and limited human evidence.

4.3. Nickel Cadmium (NiCd) Battery

Under normal operating conditions, inhalation of hazardous materials from NiCd batteries is unlikely due to their sealed design. However, extreme heat or pressure causing a breach in the battery casing could release cadmium fumes.

Inhaling cadmium fumes can cause various health problems, including throat dryness, respiratory irritation, headaches, nausea, and even death upon prolonged exposure to high concentrations (e.g., above 1 to 5 mg/m^3 over eight hours). Both cadmium and nickel are classified by the US National Toxicology Program (NTP) as reasonably anticipated carcinogens. Nickel is also considered toxic to aquatic organisms and may cause long-term adverse effects in aquatic environments. (See: Comparative Assessment of Techno-Economic Performance of Battery Energy Storage for Solar Photovoltaic Systems; Sealed Lead-Acid and Nickel-Cadmium Batteries in Sierra Leone, Kenema).

4.4. Environmental Considerations of Battery Technologies

Table 3 offers a comparative assessment of the potential environmental and human health risks associated with Nickel Cadmium (Ni-Cd) and Sealed Lead Acid (SLA) batteries in the context of Kenema City, Sierra Leone. The original analysis suggests that both battery types present a "high risk" to human health and the community. This assessment was corroborated by the absence of available recycling facilities for these batteries within Kenema City, highlighting a critical environmental vulnerability. The original analysis lacked specific quantitative data regarding the identified risks, but the implications of environmental damage from these batteries were apparent.

The environmental impact of battery technologies, including Ni-Cd and SLA batteries, extends beyond their immediate use and includes the extraction, manufacturing, and disposal phases. A broader consideration of battery technologies emphasises a wider range of concerns. The analysis, however, provided no details regarding the quantification of risk [36].

Furthermore, as noted in a recent publication, even Lithium-ion (Li-ion) batteries, increasingly prevalent in various applications such as laptops, smartphones, electric vehicles, and electric grids, are associated with considerable environmental and human costs. The extraction of raw materials like lithium and cobalt, essential components of Li-ion batteries, necessitates significant energy and water consumption and often involves hazardous working conditions in mining operations [2].

Table 3. *Human and Ecological Risks from Batteries.*

Battery Type	Risk to Human Health	Risk to Community	Recycle Availability in Kenema City.
Nickel Cadmium	High	High	Not Available

Battery Type	Risk to Human Health	Risk to Community	Recycle Availability in Kenema City.
Sealed Lead Acid	High	High	Not Available

Source: Field Survey, 2024

4.5. Battery Price Data in Kenema City, Sierra Leone (November 2024)

The increasing adoption of renewable energy technologies, particularly solar photovoltaic (PV) systems, necessitates robust energy storage solutions. Battery Energy Storage Systems (BESS) play a critical role in addressing the intermittent nature of solar power, enhancing grid stability, and expanding access to electricity in off-grid communities. Research on the techno-economic performance of different battery types is crucial for informed decision-making and investment in these technologies. This document presents recent price data for batteries available in Kenema City, Sierra Leone, collected in November 2024. This information is relevant for evaluating the economic viability of various BESS configurations for solar PV applications in the region. Comparative assessments, such as the one referenced below, highlight the importance of considering factors beyond just the initial price, including lifecycle costs, performance characteristics, and environmental impact.

The choice of battery technology significantly impacts the overall performance and cost-effectiveness of a BESS. Sealed Lead Acid (SLA) and Nickel-Cadmium (Ni-Cd) batteries represented common options, each with distinct advantages and disadvantages. Comprehensive techno-economic analyses, considering factors such as Depth of Discharge (DoD), cycle life, charge/discharge rates, and temperature sensitivity, are vital for optimising BESS design.

***Table 4**. Battery Price Data (Le) in Kenema City, Sierra Leone (November 2024).*

12V SLA Battery					12V NiCd Battery				
Cost (Le)	Capacity (AH)	Energy (Wh)	Unit Cost (AH) (Le)	Unit Cost (Wh) (Le)	Cost (Le)	Capacity (AH)	Energy (Wh)	Le/AH	Le/Wh
1100	35	420	31.43	2.62	78	1	12	78.00	6.50
1100	40	480	27.50	2.29	158	1.5	18	105.33	8.78
1100	45	540	24.44	2.04	41.475	1.3	15.6	31.90	2.66
1200	50	600	24.00	2.00	258	2.6	31.2	99.23	8.27
1200	55	660	21.82	1.82	328	3.5	42	93.71	7.81
1200	60	720	20.00	1.67	420	4.5	54	93.33	7.78
1200	65	780	18.46	1.54			Ave=	83.59	6.97
1500	70	840	21.43	1.79					
1600	75	900	21.33	1.78					
1600	80	960	20.00	1.67					
1700	100	1200	17.00	1.42					
2100	120	1440	17.50	1.46					
2300	150	1800	15.33	1.28					
3000	200	2400	15.00	1.25					
4100	250	3000	16.40	1.37					
		Ave=	20.78	1.73					

Source: Field Survey, 2024

Table 4 presents a detailed comparison of the prices of various battery technologies, specifically with a 12 V NiCd battery. The 12 V Sealed Lead Acid (SLA) battery offers a range of capacities, and this analysis examines the pricing trends across this spectrum. Both technologies demonstrated an inverse relationship between price and capacity in amp-hours (AH) and watt-hours (Wh): prices decrease with lower capacities and increase with higher capacities. This observation was grounded in research analysing the techno-economic performance of battery energy storage, including Sealed Lead Acid and Nickel-Cadmium batteries within the context of solar photovoltaic systems. This research includes data from Sierra Leone, specifically Kenema Municipality.

5. Discussion

The provided highlights key differences between Sealed Lead-Acid and Nickel-Cadmium (NiCd) batteries, particularly regarding their charging efficiency, temperature performance, and self-discharge rates. These characteristics have significant implications for their suitability in various applications, especially in the context of renewable energy systems and off-grid power solutions.

The higher charging efficiency of Sealed Lead-Acid batteries (95%) compared to NiCd batteries (80%) means that Lead-Acid batteries were more energy-efficient. They require less energy input to achieve the same level of charge, which translates to reduced energy waste and potentially lower operating costs.

The text indicates that Lead-Acid batteries have an optimal operating temperature of around 25℃, with a significant capacity reduction at higher temperatures. NiCd batteries, conversely, perform relatively well at low temperatures. This difference influences their suitability in different climatic conditions. For instance, NiCd batteries might be preferable in cold environments, while the performance of Lead-Acid batteries could be more predictable in more moderate climates.

The significantly lower self-discharge rate of Sealed Lead-Acid batteries (1-5% per month) compared to NiCd batteries (20-30% per month) was a major advantage. This allows Lead-Acid batteries to retain their charge for much longer periods during storage or periods of non-use. This was especially important in applications like backup power systems, where batteries need to be ready for use even after extended periods of inactivity. Both battery types have been found useful in a variety of applications. Sealed Lead-Acid batteries were commonly used in uninterruptible power supplies (UPS), emergency lighting, and electric vehicles because of their high energy density, relatively low cost, and long cycle life. NiCd batteries were less common than they once were due to the problems with cadmium's toxicity, but were still used in some portable power tools and emergency lighting systems due to their good performance at high and low temperatures and their long cycle life.

6. Summary

This compares Sealed Lead-Acid and Nickel-Cadmium (NiCd) batteries across several key performance indicators: Sealed Lead-Acid batteries have a higher charging efficiency (95%) than NiCd batteries (80%). Both battery types can operate under similar temperatures, but their optimal performance varies. Sealed Lead-Acid batteries perform best around 25℃, with reduced capacity at higher temperatures. NiCd batteries maintain good discharge characteristics at low temperatures.

Sealed Lead-Acid batteries have a significantly lower self-discharge rate (1-5% per month) compared to NiCd batteries (20-30% per month), allowing them to retain their charge for a longer time. NiCd batteries generally have a longer cycle life and can be recharged more times compared to Sealed Lead-Acid batteries. Sealed Lead-Acid batteries are more cost-effective in terms of both cost per Amp-Hour (Ah) and cost per Watt-Hour (Wh).

7. Conclusion

This research could be recommended for future research such as, long-term performance assessments of both Sealed Lead-Acid (SLA) and Nickel-Cadmium (NiCd) batteries in varying environmental conditions specific to Sierra Leone, extended to the regions in Sierra Leone, integration of battery energy storage systems with other renewable energy sources, such as wind or hydroelectric power, etc.

Abbreviations

PV	Photovoltaic
NiCd	Nickel-Cadmium
BESS	Battery Energy Storage Systems
SLA	Sealed Lead Acid
MCDA	Multi-criteria Decision Analysis
AC	Alternating Current
DC	Direct Current
MOVs	Metal Oxide Varistors
EIA	Environmental Impact Assessment

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Author Contributions

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Conflicts of Interest

The author declares no conflicts of interest.

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