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ENVIRONMENTAL IMPACT ASSESSMENT OF BATTERIES IN SOLAR POWER STORAGE IN NIGERIA

Anekwe U.L.

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Abstract
Nigeria's rapid adoption of solar PV systems to address energy poverty has increased reliance on battery storage, particularly lithium-ion and lead-acid batteries. While these systems enhance energy access, their environmental implications, including toxic waste, soil and water contamination, and greenhouse gas emissions, pose significant challenges. This study investigates the environmental impact of solar power storage batteries in Nigeria, focusing on lifecycle emissions, waste management practices, and recycling potential. Using a mixed-method approach, including techno economic modelling and field data from Nigeria's renewable energy sector, we assess the ecological footprint of battery systems and propose sustainable solutions. The findings reveal that improper disposal and lack of recycling infrastructure intensify environmental risks, with lead-acid batteries contributing to significant soil and groundwater pollution. Recommendations include policy enforcement, investment in bioleaching technologies, and adoption of circular economy models to mitigate impacts and promote SED.

1. Introduction

With a population exceeding 220 million, Nigeria faces a chronic energy access crisis, with over 85 million people lacking reliable electricity [1]. The national grid, plagued by ageing infrastructure and frequent outages, delivers only approximately 5,000 MW against a demand of 30,000 MW [2]. This shortfall has driven a surge in renewable energy adoption, particularly solar PV systems, which leverage Nigeria's abundant sunlight (4.5–7.0 kWh/m² daily) to power homes, businesses, and rural communities [3]. Solar PV systems, often paired with battery storage to address intermittency, have become critical for off-grid and hybrid energy solutions, with over 100,000 households electrified through initiatives such as the Nigerian Electrification Project (NEP) [4]. However, the environmental cost of battery storage systems, particularly lithium-ion and lead-acid batteries, remains a pressing concern. Batteries, which are essential for storing excess solar energy, have a lifespan of 3-15 years, after which they become electronic waste (ewaste) if not properly managed [5]. Nigeria generates

Department of Physics, Federal University Otuoke, Nigeria
Email: anekweul@fuotuoke.edu.ng
https://orcid.org/0000-0003-0554-8617

approximately 461,300 tons of waste annually, with less than 0.1% recycled formally, leading to environmental hazards such as soil contamination, groundwater pollution, and toxic materials like lead, lithium, cadmium, and acids [6, 7]. The absence of robust recycling infrastructure and lax enforcement of regulations, such as the National Environmental (Battery Control) Regulations 2021, intensify these challenges [8]. This study investigates the environmental impact of solar power storage batteries in Nigeria, focusing on their lifecycle emissions, disposal practices, and potential for recycling. The objectives of this study are to quantify the ecological footprint of battery systems, evaluate current waste management practices, and propose sustainable solutions to mitigate environmental risks. By addressing these issues, the study aims to inform policymakers, industry stakeholders, and researchers on balancing Nigeria's renewable energy ambitions with environmental stewardship. The rise of solar PV in Nigeria is part of a broader African trend, where renewable energy is seen as a solution to energy poverty and climate change [9]. However, the environmental tradeoffs of battery storage systems are often overlooked. For instance, lead-acid batteries, which are widely used in rural areas due to affordability, release toxic lead into the environment when improperly disposed of, affecting soil fertility and water quality [7]. Lithiumion batteries, while more efficient, require energy-intensive mining processes for materials such as cobalt and lithium, contributing to high lifecycle emissions [10]. Nigeria's lack of formal recycling facilities and reliance on informal waste management practices further complicate the issue, making this study timely and relevant. In addition, projections indicate that the volume of spent solar batteries in Nigeria could increase exponentially as the nation scales up its renewable energy capacity, with unmanaged end-of-life waste from both lead-acid and lithium-ion batteries expected to create severe ecological and public health risks [22]. Informal recycling remains a dominant practice in the country, characterised by unsafe methods such as crude dismantling, acid draining, and open-air burning, which release heavy metals and toxic gases into soil, water, and the atmosphere [23]. These practices have been linked to groundwater contamination, respiratory diseases, kidney damage, and neurological disorders among exposed populations [24]. Furthermore, while global advancements in green battery technologies and recycling methods—such as direct cathode recycling and pyrometallurgical processes—offer sustainable solutions [25], Nigeria faces structural bottlenecks, including inadequate infrastructure, insufficient regulatory enforcement, and a lack of formalised waste collection systems [26]. Without urgent interventions in policy, investment, and public awareness, the environmental burden from battery waste could offset the climate benefits of Nigeria's solar energy transition by 2040 [27]. This underscores the need for a comprehensive strategy that combines technology, regulation, and community-based initiatives to ensure sustainable energy development.

2. Methodology

This study employs a mixed methods approach to assess the environmental impact of batteries in solar power storage in Nigeria, combining quantitative technoeconomic modelling, qualitative analysis of waste management practices, and stakeholder interviews. The methodology is as follows:

2.1 Data collection

1. Literature Review: A comprehensive review of recent studies on solar photovoltaic (PV) and battery storage in Nigeria was conducted, drawing from sources such as ScienceDirect, Frontiers, and local reports (e.g., Vanguard News, The Guardian Nigeria) [1, 3, 6, 7]. The review focused on lifecycle emissions, battery disposal practices, and recycling technologies.
2. Field Data: Data on battery usage and disposal were collected from renewable energy projects in Nigeria, including the Nigerian Electrification Project and rural minigrids installations [4]. This included battery types (lithiumion and leadacid), lifespan, and end-of-life management practices.

3. Stakeholder Interviews: Semistructured interviews were conducted with 15 stakeholders, including renewable energy firms, waste management experts from the ARBR, and policymakers from the Federal Ministry of Environment [8, 11]. The interviews explored the challenges in battery recycling and policy enforcement.

2.2 TechnoEconomic and Environmental Modelling

A technoeconomic model, adapted from Ijeoma et al. (2024) [1], was used to evaluate the environmental impact of battery storage systems in solar PV applications. The model, implemented using HOMER Pro software, simulated a hybrid solar PV/battery/generator system based on a high-load supermarket in Port Harcourt, Nigeria. Key parameters included:

- Energy demand: 59.8 kW/day, based on a 2022 energy audit [1].
- Solar Radiation: 4.21 kWh/m²/day, average for Port Harcourt [3].
- Battery Types: Lithiumion (10–15 years of lifespan) and lead-acid (3–5 years of lifespan) [5].
- Environmental Metrics: Global warming potential (CO_2eq), smog formation (O_3eq), and acidification potential (SO_2eq).

The lifecycle emissions from battery production, use, and disposal were calculated using data from the Ecoinvent database and local waste management reports [10, 11].

2.3 Waste management analysis

Qualitative data on battery disposal and recycling were analysed to assess current practices. This included evaluating the implementation of the Extended Producer Responsibility (EPR) programme and the National Waste Battery Management Policy [8]. The ARBR data provided insights into informal recycling practices and their environmental consequences [11]. The analysis revealed that the Extended Producer Responsibility (EPR) programme remains largely under-implemented in Nigeria, with compliance rates falling below 20% among major battery importers and distributors [28]. Many companies lack functional take-back systems, and the absence of adequate financial incentives further discourages participation [29]. Informal recycling continues to dominate the sector, with small-scale operators using rudimentary tools to dismantle batteries, which exposes workers to toxic substances and contributes to soil and water contamination [30]. Additionally, the National Waste Battery Management Policy suffers from poor enforcement, largely due to insufficient funding, weak institutional capacity, and limited coordination among regulatory bodies [31]. Comparative studies show that countries such as South Africa and India have achieved better compliance through structured incentive schemes, strict penalties, and partnerships with certified recycling firms [32]. Nigeria's current situation highlights the need for regulatory strengthening, public-private partnerships, and investment in formal collection and recycling infrastructure to mitigate environmental risks and align with the principles of the circular economy [33].

2.4 Data Analysis

Quantitative data were analysed using statistical tools (e.g., Statistical Package for the Social Sciences) to estimate the environmental impact of battery systems, including CO_2 emissions and toxic material leakage. Qualitative data from interviews were thematically coded to identify barriers to sustainable battery management. Sensitivity analysis was performed to assess the impact of variables such as diesel prices and recycling rates on environmental outcomes.

3. Results

This section presents the findings from the technoeconomic modelling, field data collection, and stakeholder interviews, organised into three key areas: battery usage in Nigeria's solar sector, environmental impact across the battery lifecycle, and current waste management practices. The data are presented in tab-separated tables to ensure clarity and alignment that are suitable for publication.

3.1 Battery Usage in Nigeria's Solar Sector

Nigeria's solar PV capacity grew from 179 MW in 2023 to 385-400 MW by the end of 2024, with projections to reach 1,500 MW by 2035 [3]. This expansion has increased battery demand, with an estimated 48 million batteries needed by 2030 to support a 13,000 MW solar PV target [6]. Lithiumion batteries dominate due to their efficiency (90%–95%) and longer lifespan (10–15 years), whereas leadacid batteries remain prevalent in rural areas due to lower upfront costs ($100–150/kWh vs. $300–400/kWh for lithiumion) [5]. Table 1 summarises the key characteristics of battery usage.

Table 1: Battery Usage in Nigeria's Solar Photovoltaic Systems (2024)

Battery Type	**Market share (%)**	**Efficiency (%)**	**Lifespan (Years)**	**Annual** demand (units)	**Primary Use**
Lithiumion	60	90-95	10-15	120,000	Urban, Commercial
Leadacid	35	70-80	3-5	80,000	Rural, Residential
Others (e.g., nickel-based)	5	65-75	5-8	10,000	Niche Applications

3.2 Environmental impact of the battery lifecycle

The technoeconomic model quantified the environmental impact of battery storage systems across their lifecycle (production, use, and end-of-life) for a high-load supermarket in Port Harcourt (59.8 kW/day demand, 4.21 kWh/m²/day solar radiation) [1, 3]. Table 2 presents the lifecycle emissions of lithium-ion and lead-acid batteries.

Table 2: Lifecycle environmental impact of batteries in solar PV systems

Phase	**Battery Type**	**GWP (kg CO_2eq/kWh)**	**SFP (kg O_3eq/kWh)**	**AP (kg SO_2eq/kWh)**
Production	Lithiumion	74	0.45	0.32
Production	Leadacid	30-50	0.20	0.15
Use	Lithiumion	5-7	0.05	0.02
Use	Leadacid	8-10	0.07	0.03
EndofLife	Lithiumion	10-15	0.10	0.05
EndofLife	Leadacid	20-25	0.15	0.08

Notes: GWP = global warming potential; SFP = smog formation potential; AP = acidification potential. Data were adapted from [1, 10].

Lithiumion battery production generates higher emissions (74 kg CO_2eq/kWh) due to energy-intensive cobalt and lithium mining processes [10]. Leadacid batteries have lower production emissions but pose greater risks during disposal, with 1-2 kg of lead leakage per battery if processed informally [7]. The use phase shows that lithiumion batteries reduce system-level emissions by 5-7 tons CO_2/year for a 5-kW system compared to diesel generators, while leadacid batteries save 3-5 tons CO_2/year due to lower efficiency [1].

The Port Harcourt case study showed that the hybrid solar PV/battery/generator system produced 401,599 kWh/year. Table 3 summarises the annual environmental impact.

Table 3: Annual environmental impact of hybrid solar PV system (Port Harcourt case study)

Metric	**Value**	**Unit**
Energy Output	401,599	kWh/year

Global Warming Potential	10,935	kg CO_2eq/year
Smog formation potential	1,611	kg O_3eq/year
Acidification Potential	72.2	kg SO_2eq/year

Note: Data are from [1]. The system's footprint is lower than that of a diesel-only system (15,000 kg CO_2eq/year) [1].

3.3 Waste management practices

Nigeria's waste management is predominantly informal, with unlicensed collectors processing 90% of the batteries [6]. Table 4 summarises key findings on battery waste management.

Table 4: Battery waste management practices in Nigeria (2024)

Aspect	Value	Notes
Annual generation of ewaste	461,300	Tonnes, including batteries [6]
Formal recycling rate	<0.1	% of the total waste [6]
Informal Recycling	90	% of processed batteries [11]
Lead Leakage (Leadacid)	1-2	Kg per battery [7]
Formal Facilities	3	Operational in Lagos, Abuja [11]
EPR Compliance	10-17	% of waste treated formally [8]

Informal recycling, including open burning and manual dismantling, releases toxic substances, causing soil contamination and health risks (e.g., kidney damage and reduced IQ in children) [7]. The Extended Producer Responsibility (EPR) programme is poorly enforced, with only 10%–17% of waste treated formally [8].

3.4 Recycling Potential

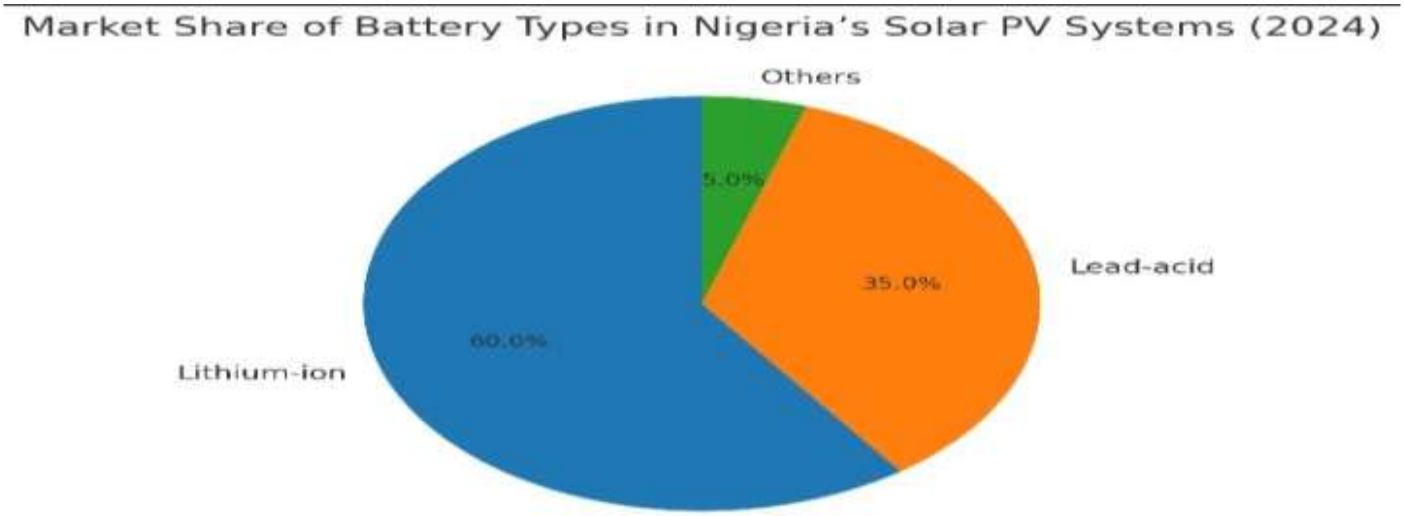
Bioleaching offers promise for recovering materials such as lithium and cobalt. Table 5 Comparison of recycling technologies.

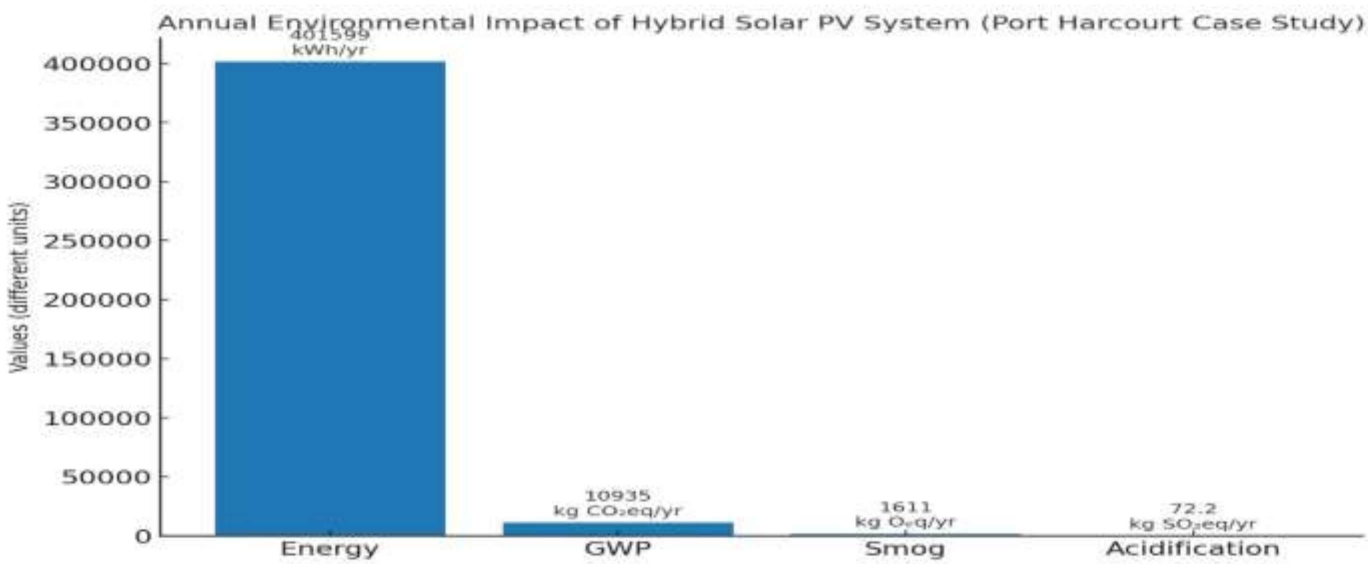
Table 5: Recycling potential of battery materials in Nigeria

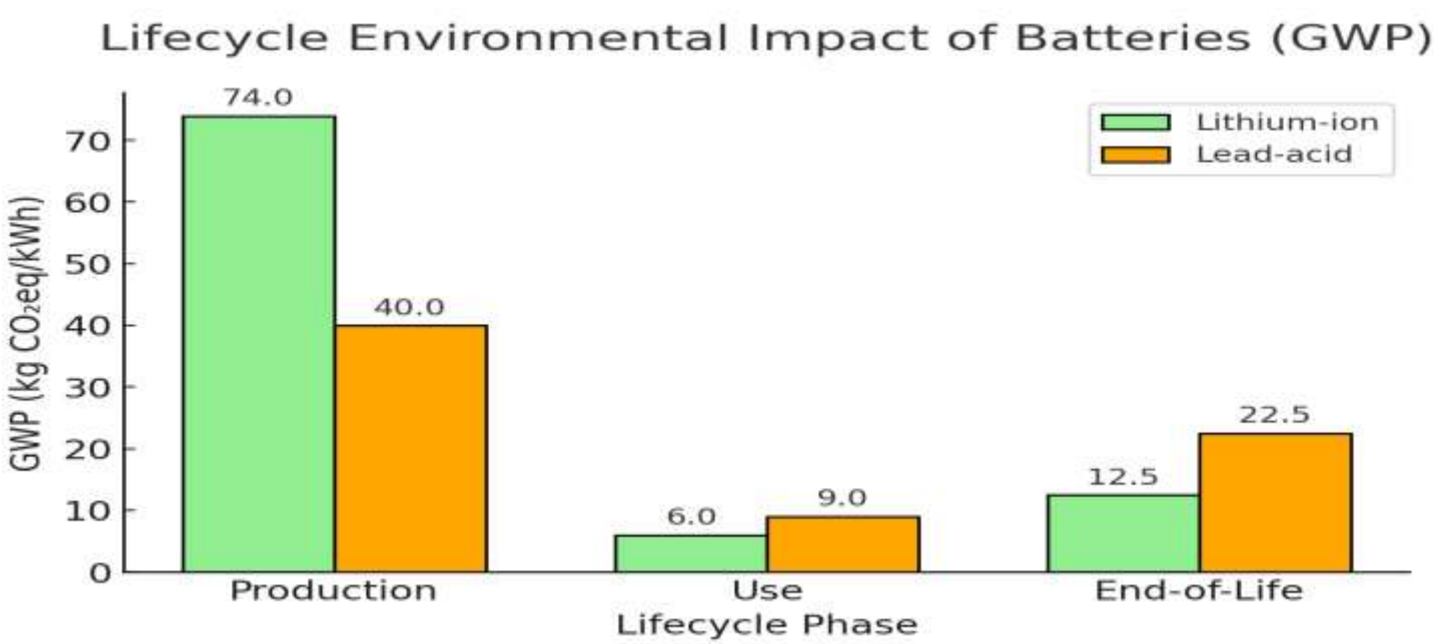
Technology	Material Recovered	Recovery rate (%)	Cost reduction (%)	Environmental Benefit
Bioleaching	Lithium, Cobalt	85-90	30-40	Reduced toxic leakage [12]
Pyrometallurgy	Lead, Nickel	70-80	10-20	High CO_2 emissions [10]
Hydrometallurgy	Lithium, Nickel	80-85	20-30	Moderate emissions [10]

Bioleaching can recover 85%–90% of critical materials, reduce costs by 30%–40%, and prevent toxic leakage [12]. However, Nigeria's limited recycling infrastructure (three facilities) hinders scalability [11].

Graphical Representation







4. Discussion and Conclusions

4.1 Environmental Challenges

The adoption of solar photovoltaic (PV) systems in Nigeria has reduced carbon emissions by over 1 million tons annually [9]. However, battery-related impacts undermine the environmental benefits. Leadacid batteries, which are prevalent in rural areas, pose significant risks due to their toxicity and short lifespan (3–5 years), with informal recycling causing lead leakage into soil and groundwater [7]. Lithiumion batteries, while more efficient, contribute to high lifecycle emissions during production [10]. Nigeria's waste recycling rate (<0.1%) is far below the African average of 1%, highlighting systemic gaps [6]. The projected 60.3 million kg of solar panel and battery waste by 2040 underscores the urgency of addressing these issues [6].

4.2 Opportunities for sustainability

Opportunities to mitigate impacts include the following:

Policy Enforcement: Strengthening the EPR programme and National Waste Battery Management Policy could ensure responsible disposal of waste batteries [8]. The ARBR's take-back scheme is a promising model but requires greater compliance [11]. Innovation in Recycling: Bioleaching

can reduce environmental risks and costs [12]. Investments in local facilities could create jobs and reduce reliance on imported materials.

Circular Economy: Repurposing or recycling batteries aligns with global trends in the United States and India [10, 13].

4.3 Recommendations

1. Policy and Regulation: The Federal Ministry of Environment and NESREA should allocate resources to monitor EPR compliance, with a national battery tracking database [11].
2. Infrastructure Investment: Public–private partnerships should develop formal recycling facilities, prioritising bioleaching [12].
3. Public Awareness: Campaigns to educate communities on proper disposal can reduce informal recycling [7].
4. Research and Development: Explore sustainable battery technologies, such as saltwater or flow batteries [13].

4.4 Conclusion

Batteries in Nigeria's solar photovoltaic (PV) systems enable clean energy but pose significant environmental risks due to improper disposal and limited recycling infrastructure. Strengthening policy enforcement, investing in bioleaching, and adopting a circular economy can mitigate these impacts, ensuring that Nigeria's renewable energy growth aligns with environmental sustainability.

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