



ORIGINAL RESEARCH ARTICLE

ENVIRONMENTAL AND PERFORMANCE ASSESSMENT OF LITHIUM-ION AND FLOW BATTERY IN HYBRID RENEWABLE ENERGY SYSTEMS

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ABSTRACT

Reliable and affordable electricity remains critical for rural development in regions where grid expansion is constrained by high costs, difficult terrain, and dispersed settlements. Hybrid Renewable Energy Systems (HRES) that integrate solar, wind, and energy storage provide a viable decentralized alternative, with rural Kenya offering representative deployment conditions. In this study, Imbirikani in Kajiado County, Kenya, was selected as a case site because of its alignment with typical off-grid microgrid contexts. This study compares lithium-ion (Li-ion) and vanadium redox flow battery (VRFB) energy storage technologies within HRES deployed in rural Kenya, using HOMER Pro for techno-economic simulations, and cradle-to-grave Life Cycle Assessment (LCA) following ISO 14040/14044, and Analytic Hierarchy Process (AHP), based multi-criteria decision analysis (MCDA) was used. The results indicate that Li-ion systems achieved a lower Levelized Cost of Storage (LCOS) of KSh. 23.17/kWh compared to KSh. 28.32/kWh for VRFBs, primarily driven by higher round-trip efficiency and lower upfront capital costs. However, Li-ion systems exhibit higher Global Warming Potential (GWP) impacts of 0.18 kgCO₂/kWh, relative to VRFBs' 0.10 kgCO₂/kWh, largely attributable to lithium-cobalt extraction and limited end-of-life recyclability. In contrast, VRFBs demonstrated longer cycle life, full depth-of-discharge capability, and electrolyte recyclability exceeding 80%, thereby supporting improved long term environmental performance. The study contributes an integrated techno-economic, environmental, and decision-analysis framework for evaluating energy storage technologies in rural African micro grids. Therefore, it is evident that, the multi-criteria evaluation highlights Li-ion batteries as the preferred option for near-term, cost-driven rural micro grid deployment in Kenya, while VRFB technologies are recommended for long-term sustainable energy planning where lifecycle, durability and environmental performance are prioritized.

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1.0 Introduction

Reliable and affordable electricity underpins global development, however, a substantial proportion of the population, majorly in Sub-Saharan Africa, continues to experience limited access to modern electricity services, particularly in rural and remote regions (Thango and Obokoh, 2024; Rezaee and Silva, 2025). In Kenya, last-mile grid expansion has progressed quite well, yet approximately 25% of households still lack access due to remoteness, challenging terrain, high extension costs making centralized grid solutions economically unattractive (Muchiri et al., 2023; Kebir et al., 2023). Lately, decentralized Hybrid Renewable Energy Systems (HRES) integrating solar photovoltaic (PV), wind, and Energy Storage Systems (ESS) are gaining traction for rural electricity provision (Chen et al., 2022; Thango and Obokoh, 2024; Manas et al., 2023). These systems

currently mitigate renewable intermittency, enhance energy security, and maximize renewable energy utilization (Ugwu *et al.*, 2022; Deguenon *et al.*, 2023).

Among available storage technologies, lithium-ion (Li-ion) batteries and vanadium redox flow batteries (VRFBs) are currently emerging as leading candidates for hybrid renewable microgrids. Li-ion batteries offer high energy density and declining costs but are sensitive to degradation, elevated temperatures, and reliance on critical minerals (Hemmati *et al.*, 2024; Zhao *et al.*, 2023; Zanoletti *et al.*, 2024). In contrast, VRFBs provide longer cycle life, decoupled power energy scalability, and high recyclability, though they are associated with higher upfront investment requirements and system complexity (Olabi *et al.*, 2023; Ezennaya *et al.*, 2023; S. Ahmed, and A. D'Angola. 2025).

Kenya presents a distinct operational context. With high ambient temperatures, Li-ion degradation is accelerated, irregular rural load profiles and grid instability also increase cycling stress, and limited recycling infrastructure heightens environmental risks (Zeng, 2025; Hemmati *et al.*, 2024). Limited battery recycling and end-of-life management infrastructure also heightens environmental risks which are associated with conventional battery technologies (Zanoletti *et al.*, 2024; Zhao *et al.*, 2023). VRFBs, by comparison, demonstrate robust performance in semi-arid regions such as Turkana and Kajiado but currently remain underutilized due to high initial cost and limited region-specific performance assessments (Muchiri *et al.*, 2023; Olabi *et al.*, 2023).

A critical research gap persists in the lack of integrated studies that simultaneously combine techno-economic modeling, full life cycle assessment (LCA), and multi-criteria decision analysis (MCDA) for rural microgrids in Kenya. Existing studies have often evaluated storage technologies in isolation or focused on a single assessment dimension, and this has limited their usefulness for informed decision-making (Manas *et al.*, 2023; Tomczewski *et al.*, 2024; Rozhdestvenskiy *et al.*, 2024). This study addresses this gap by developing an integrated assessment framework that combines HOMER Pro simulation, cradle-to-grave LCA, and MCDA to evaluate Li-ion and VRFB technologies in Kenyan rural HRES. The Rural Electrification and Renewable Energy Corporation (REREC), and the Energy and Petroleum Regulatory Authority (EPRA), to support optimized and sustainable energy storage deployment (Tomczewski *et al.*, 2024; Thango and Obokoh, 2024; Hemmati *et al.*, 2024

2. Materials and Method

Figure 1 illustrates how local energy conditions, system modeling, and multi-criteria evaluation are integrated to guide storage technology selection.

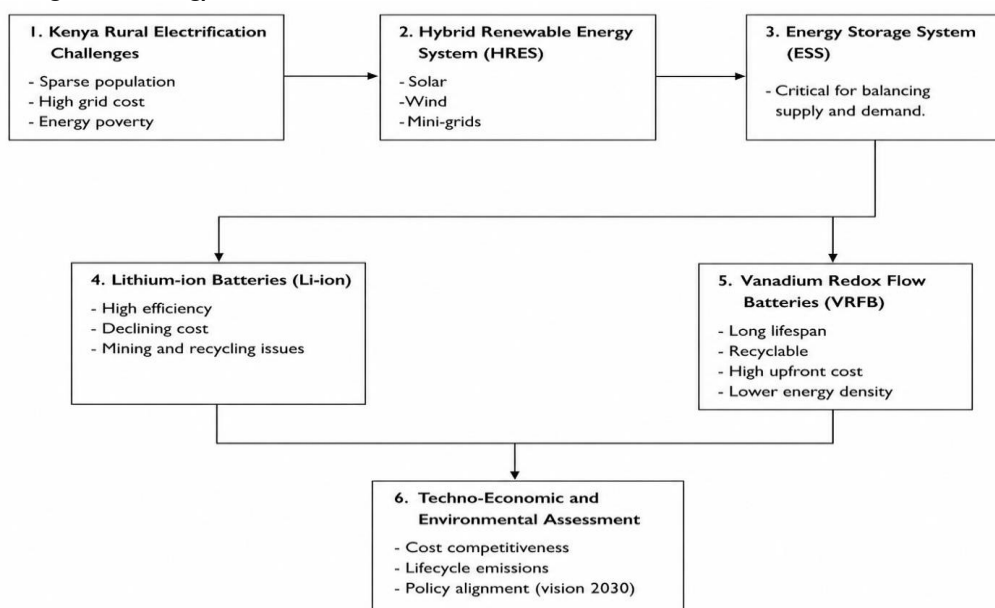


Figure 1: A holistic framework of the integrated study (Tomczewski *et al.*, 2024)

2.1 Study Area

Imbirikani, Kajiado County in Kenya, was selected as the representative case due to its high solar irradiance ranging from 5.5 to 6.5 kWh/m²/day, frequent power interruptions experienced, rising commercial and household electricity demand, and strong alignment with and similarity to conditions across Arid and Semi-

Arid Lands (ASAL) electrification clusters in Kenya (Muchiri et al., 2023). The site correlates well with typical Kenya Off-Grid Solar Access Project (KOSAP) which is targeted settlements and provides a suitable test environment for microgrid deployment.

2.2 Performance Modelling

With similar approaches having been successfully applied to HRES operating under high demand variability and cost sensitivity in African contexts, the applicability of the modeling framework adopted in this study is reinforced (Nkambule et al., 2023). The hybrid photovoltaic (PV)–wind–battery system was modelled using HOMER Pro, by employing hourly load profiles and annual energy demand representative of Kenyan rural mini-grids. PV arrays were configured at latitude optimized tilt angles with appropriate spacing to minimize shading losses, while wind generation complemented solar PV by supplying energy during evening periods and low solar availability. The residential and institutional electricity loads were simulated using parameters that reflect the consumption characteristics and climatic conditions of off-grid communities in Imbirikani, Kenya.

2.2.1 System configuration

The hybrid PV-wind-battery system was modelled and optimized in Homer Pro to evaluate Li-ion and VRFB storage performance under representative rural Kenyan conditions. The PV capacity within a range of 50-150 kW, wind generation using a 10-20 kW class turbine to compliment solar output, particularly during low irradiance periods, and battery storage within a range of 50-500kWh, were defined as decision variables and optimized to minimize NPC. Li-ion and VRFB technologies were parameterized using literature-based specifications for efficiency, lifetime, and degradation. VRFB was modelled with decoupled energy-power scaling, while Li-ion was treated as a fixed capacity unit. This approach ensured a consistent, least-cost basis for technology comparison.

2.2.2 Grid and operational assumptions

The system was modelled in Homer Pro as a fully off-grid hybrid renewable energy system with no grid import or export. A reliability constraint of not greater than 1% annual unmet load was imposed to ensure acceptable service levels, alongside a minimum renewable fraction of not less than 80% to reflect sustainability targets. Temperature effects were incorporated through ambient-based derating of Li-ion battery performance using site-specific data, while VRFB operation was assumed to be unaffected due to its thermal stability. These constraints were embedded within the optimization to ensure realistic system performance under local operating conditions.

2.2.3 Sensitivity analysis parameters

To characterize uncertainty, the following variables were varied:

- Battery CAPEX: 0.8×, 1.0×, 1.2× baseline
- Discount Rate: 6%, 10%, 14%
- Load Growth: 0%, 2%, 4% per year
- Diesel Fuel Price: (only for backup scenarios) ±25%

Robustness of LCOS and NPC outcomes across technologies were assessed using these sensitivity scenarios, which was consistent with established techno-economic evaluation and hybrid system optimization methodologies (Zhao et al., 2023; Thango and Obokoh, 2024; Manas et al., 2023).

2.2.4 LCOS calculation

The Levelized Cost of Storage (LCOS) was computed as follows:

$$LCOS = \frac{\sum_{t=0}^n \frac{C_t}{(1+r)^t}}{\sum_{t=0}^n \frac{E_t}{(1+r)^t}} \quad |$$

Where C_t = total annualized cost in year t (CAPEX amortization + OPEX + replacements), E_t = energy supplied in year t (kWh), r = discount rate, n = system lifetime (years).

A formulation consistent with standard LCOS definitions applied in HRES assessments (Hemmati *et al.*, 2024; Zhao *et al.*, 2023) was adopted.

Table 1: Literature-derived techno-economic input parameters for storage systems used in HOMER Pro modelling

Parameter	Unit	Li-ion (LFP)	VRFB	Data Source
Capital cost	KSh/kWh	57,924	90,104	Olabi <i>et al.</i> (2023), Thango and Obokoh (2024), Hemmati <i>et al.</i> (2024).
Replacement cost	KSh/kWh	25,744	45,052	Olabi <i>et al.</i> (2023), Hemmati <i>et al.</i> (2024).
O&M cost	KSh/kWh/year	1,287	1,931	Hemmati <i>et al.</i> (2024), Olabi <i>et al.</i> (2023).
Round-trip efficiency	%	92	75	Olabi <i>et al.</i> (2023), Hemmati <i>et al.</i> (2024), Rezaee and Silva (2025).
Lifetime	years	10	20	Olabi <i>et al.</i> (2023), Hemmati <i>et al.</i> (2024).
Cycle life	cycles	6,000	13,000	Olabi <i>et al.</i> (2023), Hemmati <i>et al.</i> (2024).

All parameters are synthesized from peer-reviewed literature and used as model inputs for techno-economic simulation; they do not represent primary experimental results of this study.

2.3 Environmental Assessment

A cradle-to-grave life cycle assessment (LCA) was conducted using Open LCA with the ecoinvent database v3.9.1 for background life-cycle inventory data (ecoinvent Association, 2022). The assessment quantified the environmental impacts which are associated with the energy storage technologies. The functional unit was defined as 1 kWh of electricity delivered over the system lifetime, thereby accounting for differences in round-trip efficiency, degradation behavior, and operational longevity between technologies (Hemmati *et al.*, 2024; Zhao *et al.*, 2023). The system boundary included raw material extraction, component manufacturing, international transportation through the Port of Mombasa followed by inland freight, operational deployment within the Imbirikani hybrid renewable energy system (HRES), and end-of-life processes such as recycling, material recovery, or final disposal.

Recycling processes were modeled using a mass allocation approach, with assumed recovery rates at 80% for VRFB electrolytes and 40 to 50% for Li-ion battery components, consistent with recent studies on battery recyclability and regional material recovery constraints (Olabi *et al.*, 2023; Zanoletti *et al.*, 2024). Kenya-specific parameters were incorporated to enhance contextual relevance, including a national grid carbon intensity of 0.0479 kg CO₂/kWh based on report by the regulator, Energy and Petroleum Regulatory Authority, (EPRA, 2024) and water scarcity characterization using the AWARE 2.0 methodology to reflect semi-arid conditions (Hemmati *et al.*, 2024).

The environmental impact categories assessed comprised global warming potential, water footprint, mineral resource depletion, and particulate matter emissions, which are widely recognized as critical indicators for evaluating energy storage sustainability in emerging economies (Hemmati *et al.*, 2024). These categories also align with international LCA best practices and policy-oriented sustainability assessments for decentralized energy systems.

2.4 MCDA: Analytic Hierarchy Process

2.4.1 Criteria structure and weighting

The Analytic Hierarchy Process (AHP) was employed as the primary multi-criteria decision analysis (MCDA) tool to assign relative weights to the techno-economic and environmental criteria used in evaluating lithium-ion and VRFB storage technologies within the HRES.

Expert elicitation was conducted involving four renewable energy engineers, three power system planners, two environmental analysts, and one policy and regulatory officer. This expert composition was deliberately

structured to ensure balanced representation and regulatory considerations, for enhanced robustness and credibility of the weighting process (Digkoglou et al., 2024).

Individual expert judgments were aggregated using the geometric mean method, generating a consolidated comparison matrix from which priority vectors, representing criteria weights, were derived. The evaluation framework was structured around three primary criteria groups, integrating techno-economic performance, environmental impacts, and system sustainability considerations. This methodological approach ensured consistency, transparency, and reproducibility of the decision-making process.

- Economic (LCOS, CAPEX, O&M) — 0.40
- Technical (Round-trip efficiency, lifetime, DoD) — 0.30
- Environmental (GWP, recyclability, water footprint) — 0.30

This justification for higher weighting on economic criteria reflects the cost-sensitivity of rural electrification projects and the capital constrained nature of Kenyan off-grid Mini-grids. Technical performance was then ranked second due to its influence on reliability and energy autonomy, while environmental metrics ranked last but remained significant because long-term climate and resource sustainability are increasingly embedded in national electrification pathways (Siksnylyte-Butkiene et al., 2022).

Expert Choice v11 was used for scoring computation then replicated in Microsoft Excel Solver MCDA add-in for transparency and replicability. The Consistency Ratio (CR) was then evaluated according to Saaty’s rule, with the final matrix yielding CR = 0.08, below the acceptable threshold of 0.10, confirming internal coherence of judgments across expert responses (Digkoglou et al., 2024). Following weight validation, normalized weighted scores were applied to Li-ion and VRFB performance attributes to compute overall technology suitability indices, enabling scenario-based sensitivity analysis under varying CAPEX, discount rate, and degradation trajectories.

2.4.2 Baseline composite scores

These were the baseline Technology Sustainability Index scores, after normalization of performance indicators and application of the derived weights: Li-ion: 0.62 and VRFB: 0.38 which sum to 1.00, satisfying AHP normalization requirements. Under baseline assumptions (CAPEX baseline, discount rate = 10%), Li-ion ranks higher due to lower LCOS, higher round-trip efficiency and lower initial capital cost. However, VRFB demonstrates stronger environmental performance and superior lifecycle durability, which improves its relative score under long-term sustainability emphasis.

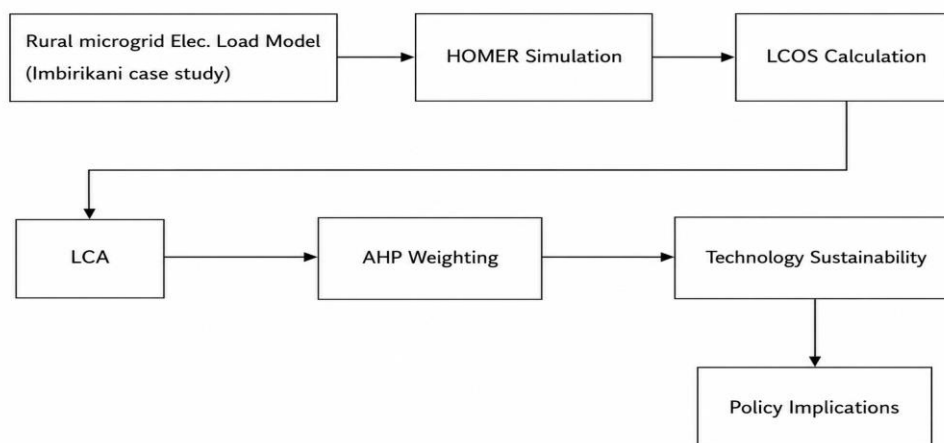


Figure 2: The sequential Flowchart

2.4.3 Sensitivity-adjusted MCDA results

To evaluate robustness, sensitivity analysis was conducted by varying Battery CAPEX ($\pm 20\%$), and Discount rate (6%, 10%, 14%). Relative LCOS values were normalized to a baseline index of 1.00 to ensure consistency with HOMER-derived absolute LCOS results. These normalized values were then incorporated into the MCDA recalculation.

Under reduced VRFB CAPEX (0.8× baseline) and lower discount rate (6%), the composite scores shifted to, Li-ion: 0.48 and VRFB: 0.52. This reversal indicates that VRFB becomes marginally preferable when capital cost barriers are reduced, and long-term planning horizons are emphasized. Under high discount rate and increased CAPEX (1.2× baseline; $r = 14\%$), Li-ion at 0.71 retains dominance over VRFB at 0.29, results confirm that cost

and financing structure remain the dominant determinants of storage technology selection in rural Kenyan microgrids. Overall, load profiles were modelled and simulated in HOMER Pro to compute the Levelized Cost of Storage (LCOS), followed by Life Cycle Assessment (LCA) for environmental impacts. AHP assigned weights to criteria, combining technical, economic, and environmental performance into a technology suitability index, which informed policy recommendations and deployment decisions and this is illustrated by the sequential workflow in Figure 2.

3. Results and Discussion

3.1 Techno-Economic Performance

Simulation results (table 2) indicate Li-ion systems achieve lower LCOS (KSh 23.17/kWh) compared to VRFB (KSh 28.32/kWh), primarily due to higher efficiency and lower upfront cost, this statistical analysis is further supported by the use of LCOS as a robust comparative metric for grid-scale and microgrid energy storage evaluations in the study by Bhattacharyya, (2024). VRFBs exhibit higher initial CAPEX but extended lifespans of 20 years and above hence reducing long term replacement costs.

Table 2: Comparative HOMER Pro Simulation Results for Li-ion and VRFB Storage Systems Over a 20-Year Analysis Period

Metric	Li-ion	VRFB
Capital Cost (KSh/kWh)	57,924	90,104
Net Present Cost (20 yrs)	669.34M	823.81M
Levelized Cost (KSh/kWh)	23.17	28.32
Round-trip Efficiency (%)	90–92	75–80
Lifetime (years)	10–12	20+

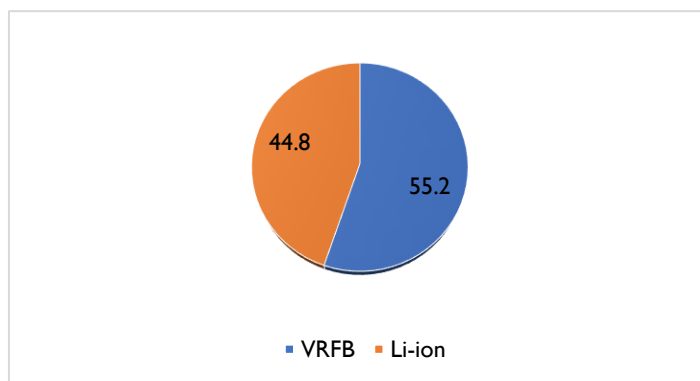


Figure 3: Net Present Cost share (derived from Table 2)

3.2 Environmental Assessment

These comparative LCA results presented in Figure 4 and summarized in Table 3 reveal distinct environmental performance profiles between Li-ion and VRFB technologies under the Kenyan HRES context. Whereas Figure 4 shows the relative impacts across key environmental categories, table 3 presents the numerical results. The values were generated from cradle-to-grave simulations conducted in OpenLCA then standardized to the functional unit of 1 kWh delivered over the system lifetime. The model incorporated Kenyan grid carbon intensity based on Energy and Petroleum Regulatory Authority (EPRA 2024) data and applies site-specific boundary conditions for the Imbirikani HRES configuration. The basis for subsequent analytical interpretation is therefore formed by these results which represent model-derived lifecycle performance outputs. Together, they highlight measurable trade-offs between climate burden, recyclability, mineral dependency, and water consumption.

3.2.1 Global warming potential (GWP)

The results highlight clear environmental trade-offs between Li-ion and VRFB technologies when applied in Kenyan HRES. Li-ion demonstrates a lower water footprint during manufacturing but exhibits a higher GWP

of 0.18kgCO₂/kWh, which is approximately 70–110% higher than that of VRFB systems. This elevated GWP is largely attributed to lithium brine extraction in Chile and Argentina, cobalt refining in DRC and high-temperature cathode sintering processes. VRFBs exhibit the opposite profile, higher water uses in electrolyte creation with a substantial record ranging 0.1 kgCO₂/kWh, primarily because vanadium electrolyte can be recovered, reused and does not require high-energy reprocessing, which then has two implications in Kenyan HRES deployment:

- i. Li-ion increases upstream emissions, meaning large-scale deployment expands embodied carbon despite Kenya’s clean grid mix.
- ii. VRFBs align better with Kenya’s long-term decarbonization strategy, especially as grid emission factors continue declining.

Within the context of rural Kenyan HRES, these findings underscore a critical trade-off between short-term environmental intensity and long-term sustainability, reinforcing the importance of technology selection that aligns with both climate mitigation and resource management objectives.

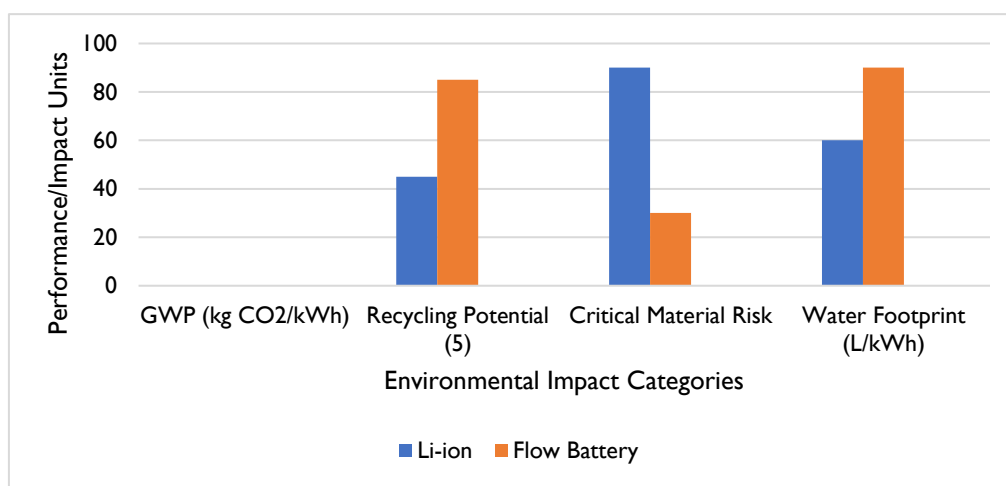


Figure 4: Comparative LCA results of Li-ion and VRFB in Kenyan HRES.

Table 3: Environmental Results of Li-ion vs. Flow Batteries

Metric	Li-ion	VRFB	Primary Data Source
Global Warming Potential (kg CO ₂ /kWh)	0.18	0.1	Hemmati <i>et al.</i> (2024); Zhao <i>et al.</i> (2023)
Recycling Potential (%)	40–50	Over 80 (electrolyte reusable)	Zanoletti <i>et al.</i> (2024); Olabi <i>et al.</i> (2023)
Critical Material Risks	High (Li, Co, Ni)	Low (vanadium recyclable)	Zhao <i>et al.</i> (2023); Olabi <i>et al.</i> (2023)
Water Footprint (L/kWh)	Moderate	High (electrolyte processing)	Hemmati <i>et al.</i> (2024); Zanoletti <i>et al.</i> (2024)

3.2.2 Recyclability and end-of-life circularity

While VRFBs demonstrated greater than 80% recyclable electrolyte recovery, enabling multiple life-cycles with minimal material loss, the Li-ion recycling stands at 40% globally, and Kenya currently lacks industrial recycling capacity often resulting in landfill disposal or informal sector handling. The observation, therefore, reveals that VRFBs reduce cumulative material demand by cycling electrolyte through generations of batteries, whereas Li-ion requires fresh mineral input for each replacement cycle, i.e. 12 years.

This means that Kenya could achieve fully circular VRFB loops if recycling and electrolyte recovery infrastructure is developed hence a major long-term environmental benefit.

3.2.3 Water footprint trade-offs

Table 4 shows a key trade-off that emerges between VRFB recyclability and water use.

Table 4: Environmental Trade-Off Summary.

Impact	Li-ion	VRFB
GWP	Higher	Lower
Recyclability	Moderate	High
Mineral scarcity risk	High	Low
Water footprint	Lower	Higher

3.2.4 Mineral scarcity and long-term sustainability

Li-ion relies on critical, geopolitically concentrated minerals like Lithium in Chile/China, Cobalt in DRC, and Nickel in Indonesia, meaning with accelerating global demand, there’s a likelihood of future price spikes and supply insecurity. VRFBs rely on vanadium, which is more geographically diverse from South Africa, Brazil, to China, recoverable at end-of-life and reusable without loss of chemical integrity. Therefore, over 20-to-30-year horizons, VRFBs offer superior materials security, which is crucial for Kenya’s long-term electrification strategy and independence from foreign supply shocks.

3.2.5 Kenya-Specific Performance Insight

Table 5: Environmental outcome summary.

Environmental Outcome	Li-ion	VRFB	Best Fit for Kenya
Hot-climate tolerance	Moderate (thermal degradation)	High	VRFB
Embodied emissions	High	Lower	VRFB
Recycling feasibility	Weak (no local capacity)	Strong potential	VRFB (future-ready)
Short-term carbon impact	Higher	Lower	VRFB

Li-ion remains suitable for immediate deployment, but VRFBs are clearly aligned with post-2030 sustainability, climate, and material circularity goals.

3.3 Multi-Criteria Trade-Offs by AHP Results

A Multi-Criteria Decision Analysis (MCDA) framework (weights: Economic 40%, Technical 30%, Environmental 30%) were used to produce the rankings. Sensitivity analysis (Table 6 and Figure 5) revealed that reducing VRFB CAPEX by 20% reverses ranking, underscoring cost sensitivity in technology adoption.

To ensure consistency with the absolute LCOS values earlier presented in table 2, the sensitivity results in Table 6 are expressed as a Relative LCOS Index rather than absolute cost values. The index is normalized to the baseline scenario (Baseline CAPEX, $r = 10\%$), which is assigned a value of 1.00. Values below 1.00 indicate proportional cost reduction relative to the baseline, while values above 1.00 indicate cost increase. This normalization enables comparison of directional sensitivity effects without altering the absolute LCOS values derived from HOMER Pro simulations.

Table 6: MCDA Composite Scores Under Baseline and Sensitivity Scenarios

Scenario	Li-ion relative LCOS index (KSh/kWh)	VRFB relative LCOS index (KSh/kWh)	Preferred Technology
Baseline	0.62	0.38	Li-ion
VRFB CAPEX -20%	0.48	0.52	VRFB

Figure 5 presents the normalized AHP composite scores for the two storage technologies under both baseline and selected sensitivity scenarios. The vertical axis represents the overall Technology Sustainability Index (ranging from 0 to 1), calculated by aggregating weighted economic (40%), technical (30%), and environmental (30%) criteria. Each bar reflects the final weighted score after normalization of individual performance indicators. Higher values indicate greater overall suitability within the defined decision framework. The figure therefore visualizes how changes in CAPEX and discount rate assumptions influence relative ranking between the two technologies. The AHP-based MCDA framework generated baseline composite scores of 0.62 for Li-ion and 0.38 for VRFB, indicating stronger near-term suitability of Li-ion under current cost structures. Sensitivity analysis revealed that reducing VRFB capital cost by 20% shifts the ranking in favor of VRFB (0.52 vs 0.48), highlighting the influence of financing conditions on technology preference. These results demonstrate that storage selection in Kenyan rural microgrids is highly sensitive to capital cost assumptions and planning horizon emphasis.

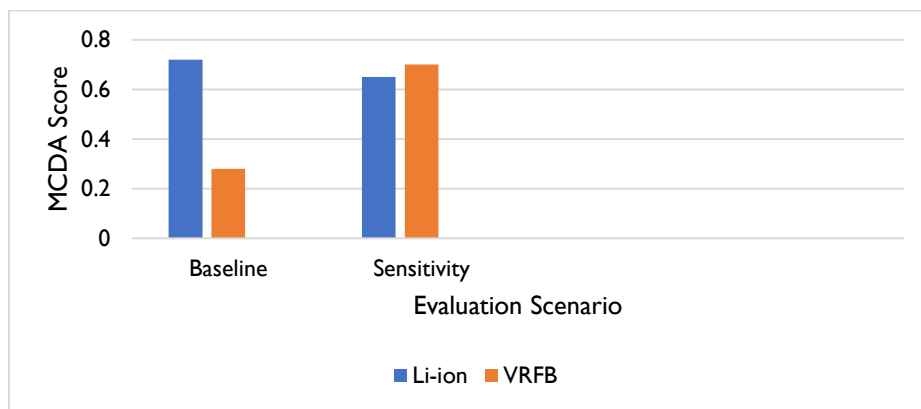


Figure 5: MCDA Ranking of Li-ion and Flow Batteries Under Baseline and Sensitivity Scenarios.

3.4 Global Context

In Lombok, Indonesia, Hemmati *et al.* (2024) reinforced the trends observed in this analysis by reporting a continued decline in the levelized cost of storage (LCOS) for lithium iron phosphate (LFP) batteries, reaching approximately Ksh 19.29/kWh by 2030, which closely aligns with the forward cost projections derived in this study. The findings demonstrated that economies of scale, manufacturing learning rates, and incremental efficiency improvements are key drivers of declining Li-ion storage costs in grid-connected and hybrid power systems (Hemmati *et al.*, 2024; Zhao *et al.*, 2023; Zeng, 2025).

Similarly, the studies conducted within African contexts indicate that VRFBs exhibit superior performance relative to Li-ion systems under long duration storage and high cycling operational regimes, particularly in microgrid and off-grid applications (Olabi *et al.*, 2023; Ezennaya *et al.*, 2023; Ahmed, S., and D'Angola, A. 2025). These studies showed that VRFBs benefit from extended cycle life, minimal capacity degradation, and operational robustness, which results in lower lifetime costs despite higher initial capital expenditures. The performance characteristics which are relevant for rural and remote power systems where daily deep cycling and extended discharge durations are common (Olabi *et al.*, 2023; Deguenon *et al.*, 2023). The cost convergence is projected between these two technologies at the global scale by 2030, this is driven by the reductions in vanadium electrolyte costs, improved recycling and reuse pathways, and large-scale deployment of VRFB systems (Zhao *et al.*, 2023; Zanoletti *et al.*, 2024; S. Ahmed, and A. D'Angola, 2025). From a Kenyan perspective, these global cost and performance trends suggest that a complementary deployment strategy, utilizing Li-ion batteries for near-term deployment and VRFBs for long-term, high-utilization storage can optimize both system affordability and sustainability. This dual-technology approach aligns with Kenya's rural electrification objectives and long-term energy transition goals, hence ensuring immediate energy access while supporting durable, low-degradation storage infrastructure (Muchiri *et al.*, 2023; Thango and Obokoh, 2024; Olabi *et al.*, 2023).

3.5 Policy and Strategic Implications

The results provide important insights for energy planning and policy development in Kenya's rural electrification context. The techno-economic analysis demonstrates that Li-ion batteries currently offer lower LCOS, higher round-trip efficiency and lower capital expenditure, which positions them as a practical option for near-term deployment in cost-constrained rural HRES. Conversely, the environmental assessment and lifecycle performance indicate that VRFBs offer superior durability, recyclability, and lower lifecycle emissions, making them more aligned with long-term sustainability objectives.

The findings suggest a time-dependent and context-specific deployment pathway rather than a single-technology solution. In the near term, the cost advantage of Li-ion systems supports their prioritization in ongoing rural electrification initiatives, particularly under programs such as KOSAP and REREC. However, the sensitivity analysis results indicate that reductions in VRFB capital costs or access to concessional financing could significantly improve their competitiveness, highlighting the importance of financial and policy interventions.

Strategically, the results underscore the need for policy frameworks that incorporate lifecycle performance metrics, including recyclability and environmental impact, alongside conventional cost-based criteria. The strong recyclability potential of VRFB systems further suggests opportunities for developing local circular

economy pathways, while the current limitations in Li-ion recycling infrastructure indicate a need for improved regulatory and waste management systems. Overall, this study demonstrates that optimal energy storage deployment in Kenyan rural microgrids depends on balancing short-term economic feasibility with long-term sustainability considerations, with policy and investment decisions playing a critical role in shaping this transition.

4. Conclusion

This study assessed Li-ion and VRFB technologies for deployment in the Imbirikani Hybrid Renewable Energy System using an integrated techno-economic, environmental, and multi-criteria decision framework.

Techno-economic simulations conducted using HOMER Pro showed that Li-ion systems achieve a lower Levelized Cost of Storage (LCOS) and Net Present Cost over a 20-year project horizon due to higher round-trip efficiency and lower initial capital costs, confirming their economic advantage for short- to medium-term rural mini-grid deployment in Kenya. Cradle-to-grave Life Cycle Assessment conducted in accordance with ISO 14040 and ISO 14044 revealed notable environmental trade-offs, with Li-ion systems exhibiting higher global warming potential, while VRFB technologies demonstrate superior lifecycle durability and recyclability, indicating stronger long-term sustainability potential. Multi-criteria decision analysis based on the Analytic Hierarchy Process further confirmed that Li-ion ranks higher under cost-constrained electrification scenarios, whereas VRFB performance improves when sustainability and system longevity are prioritized.

Overall, the results demonstrate that Li-ion currently represents the most economically viable storage option for rural mini-grids in Kenya, while VRFB technologies constitute a promising long-term sustainable alternative. Future research should incorporate stochastic battery degradation modelling, expanded lifecycle datasets for African supply chains, and operational data from pilot microgrids to further refine storage technology selection for decentralized energy systems.

This study is subject to the following limitations: Techno-economic modeling assumes ideal operational dispatch without accounting for unforeseen outages or component failures, LCA relies on global background datasets, which may not fully capture Kenya-specific industrial processes, VRFB deployment remains limited in Sub-Saharan Africa, and real-world performance data are sparse. Future research should therefore incorporate field-based performance monitoring, expanded Kenya-specific life cycle inventories, and stochastic degradation modeling.

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