© FEB 2021 | IRE Journals | Volume 4 Issue 8 | ISSN: 2456-8880

Energy Storage Systems for Off-Grid Communities: A Techno-Economic Evaluation

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Abstract- Energy storage systems (ESS) play a crucial role in enhancing energy access, particularly for off-grid communities that lack connection to centralized power grids. This presents a techno-economic evaluation of various energy storage technologies for off-grid applications, focusing on their technical suitability, economic viability, and operational sustainability. Off-grid communities, often located in remote or underserved regions, face significant challenges related to energy reliability, affordability, and system resilience. Integrating ESS with renewable energy sources such as solar photovoltaic (PV) and wind power can address these issues by mitigating supply intermittency and enabling stable, round-the-clock electricity access.The evaluation covers a range of ESS technologies, including lithium-ion batteries, lead-acid batteries, flow batteries, and mechanical storage solutions such as pumped hydro and compressed air energy storage (CAES). Each technology is assessed based on key performance indicators, including energy density, cycle life, efficiency, cost per kilowatt-hour (kWh), and maintenance requirements. Additionally, this considers contextual factors such as climate conditions, local technical capacity, and ease of deployment in off-grid environments.Results reveal that lithium-ion batteries offer superior energy density and efficiency but have higher upfront costs compared to traditional options like lead-acid batteries. However, their longer cycle life and declining costs make them increasingly competitive. Flow batteries and mechanical storage solutions, while technically promising, often face scalability and cost barriers in small-scale off-grid applications.This highlights the importance of a holistic, site-specific approach that balances technical performance, lifecycle costs, and local economic factors. It calls for targeted policy support, financing mechanisms, and community engagement to enable sustainable deployment of ESS in off-grid regions. This evaluation provides a strategic framework for decision-makers, developers, and investors seeking to advance energy access and resilience through optimized energy storage solutions.

Index Terms - Energy storage systems, Off-grid communities, Techno-economic evaluation

I. INTRODUCTION

Energy access remains a critical global challenge, with approximately 775 million people worldwide lacking access to electricity, primarily in sub-Saharan Africa, South Asia, and remote island regions (Mustapha *et al*., 2018; Oyedokun*et al*., 2019). Many of these populations reside in off-grid communities, where geographical barriers, low population density, and economic constraints make the extension of centralized grid infrastructure technically difficult and financially unfeasible (Olaoye *et al*., 2016; SHARMA *et al*., 2019). The lack of reliable electricity in these communities limits socio-economic development, access to healthcare, education, and economic opportunities, perpetuating cycles of poverty and exclusion. Addressing this challenge requires innovative, decentralized energy solutions that can sustainably meet local electricity needs (Oduola *et al*., 2014; Akinluwade*et al*., 2015).

In recent years, renewable energy technologies, particularly solar photovoltaic (PV) and small-scale wind turbines, have emerged as promising solutions for off-grid electrification (ADEWOYIN *et al*., 2020; OGUNNOWO *et al*., 2020). These technologies offer significant advantages, including scalability, declining costs, and minimal environmental impacts. However, their inherent intermittency—solar PV depending on sunlight availability and wind systems reliant on variable wind conditions—poses substantial operational challenges (Mgbame*et al*., 2020; ADEWOYIN *et al*., 2020). Without effective ways to store excess energy produced during peak generation periods, off-grid communities may face frequent supply interruptions, resulting in unreliable electricity access (FAGBORE *et al*., 2020; Akinrinoye*et al*., 2020).

Energy storage systems (ESS) play a pivotal role in addressing these challenges by enabling the reliable, continuous supply of electricity from renewable energy sources. ESS technologies store surplus electricity generated during periods of high renewable output and discharge it when generation is low or demand exceeds supply (Egbuhuzor*et al*., 2021; Adesemoye*et al*., 2021). This capability ensures that off-grid systems can deliver stable and predictable power, thereby enhancing energy security, supporting productive uses of electricity, and improving community resilience. Furthermore, ESS allows for better optimization of renewable energy assets, reducing the need for backup diesel generators and minimizing associated fuel costs and emissions (Adewoyin*et al*., 2021; Dienagha*et al*., 2021).

Despite the recognized importance of ESS in off-grid contexts, selecting the most suitable technology remains complex. Off-grid systems are highly diverse, varying in size, location, energy demand, and operational constraints (ADEWOYIN *et al*., 2021; Ogunnowo*et al*., 2021). A one-size-fits-all approach is unlikely to succeed, as the optimal solution depends on a range of factors such as energy needs, environmental conditions, lifecycle costs, and local technical capacity for installation and maintenance.

This aims to conduct a comprehensive techno-economic evaluation of various energy storage technologies suitable for off-grid communities. The analysis focuses on both technical performance—including energy density, cycle life, efficiency, and reliability—and economic viability, encompassing upfront capital costs, operation and maintenance expenses, and overall lifecycle costs. Technologies considered include lithium-ion batteries, lead-acid batteries, flow batteries, and mechanical storage systems such as pumped hydro storage and compressed air energy storage (CAES) (ADEWOYIN *et al*., 2021; Ogunnowo*et al*., 2021). Additionally, emerging technologies like hydrogen-based storage and hybrid systems are examined where applicable.

This objective is to provide energy planners, policymakers, and investors with actionable insights into the comparative advantages and trade-offs of different ESS technologies in off-grid settings. By identifying the most technically suitable and economically feasible storage options, this seeks to inform more effective energy access strategies and accelerate the deployment of resilient, low-carbon energy solutions in underserved communities worldwide.

II. METHODOLOGY

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology was applied to ensure a transparent and systematic approach to the literature review for the techno-economic evaluation of energy storage systems (ESS) in off-grid communities. The review process began with a comprehensive search across major academic databases, including Scopus, Web of Science, IEEE Xplore, and ScienceDirect. Keywords and Boolean operators were combined to identify relevant literature, including terms such as “energy storage systems,” “off-grid communities,” “techno-economic analysis,” “battery storage,” “renewable energy integration,” and “decentralized energy systems.”

The initial search yielded a total of 1,245 records. After removing duplicates, 980 unique articles were screened based on titles and abstracts to assess their relevance to the study’s focus on ESS technologies for off-grid energy applications. Studies that solely addressed grid-connected systems, large-scale centralized storage, or unrelated technical topics were excluded at this stage.

Following this preliminary screening, 305 articles were selected for full-text review. Each article was assessed according to pre-defined inclusion and exclusion criteria. Studies were included if they evaluated technical and/or economic aspects of energy storage technologies specifically in off-grid or isolated settings, discussed renewable energy integration with storage, or provided comparative analyses of storage technologies relevant to decentralized energy systems. Studies focusing only on theoretical models without practical relevance, or those lacking techno-economic metrics, were excluded.

After the full-text assessment, 112 articles were deemed eligible for inclusion in the systematic review. Data were systematically extracted from these studies, covering technical indicators such as energy density, round-trip efficiency, cycle life, and discharge characteristics, as well as economic metrics including capital costs, levelized cost of storage (LCOS), operation and maintenance expenses, and payback periods. The studies also provided contextual insights, such as local environmental conditions, maintenance requirements, and supply chain availability.

The selected studies were synthesized to provide a comparative assessment of different ESS technologies across diverse geographic and socio-economic contexts. The PRISMA methodology ensured rigor, reproducibility, and objectivity in the identification, selection, and analysis of the literature, allowing for robust conclusions regarding the techno-economic suitability of energy storage systems for off-grid communities.

2.1 Overview of Energy Storage Technologies

Energy storage systems (ESS) are essential components in modern decentralized energy infrastructures, particularly in off-grid communities where energy reliability, affordability, and sustainability are critical. These technologies enable the temporary storage of surplus electricity for later use, helping to balance supply and demand, especially in systems reliant on intermittent renewable sources such as solar photovoltaic (PV) and wind (Okolo *et al*., 2021; Ojika*et al*., 2021). This presents a detailed overview of various energy storage technologies categorized into electrochemical storage systems, mechanical storage systems, and emerging technologies.

Lithium-ion batteries are among the most widely deployed electrochemical storage technologies, known for their high energy density, lightweight design, and long cycle life. They offer excellent round-trip efficiencies, often exceeding 90%, and have fast response times, making them suitable for both short-term and long-term energy storage applications. Lithium-ion batteries are also scalable, from small residential systems to large community-level installations. However, their high initial capital costs and sensitivity to extreme temperatures pose challenges for off-grid deployment, particularly in harsh climates (Daraojimba*et al*., 2021; Orieno*et al*., 2021). Despite these drawbacks, ongoing cost reductions and improvements in battery chemistries, such as lithium iron phosphate (LFP), continue to enhance their viability for off-grid systems.

Lead-acid batteries represent a more traditional storage technology, commonly used in remote communities due to their low upfront cost and relative simplicity. They are easy to install and maintain, making them suitable for regions with limited technical capacity. However, lead-acid batteries suffer from low energy density and limited cycle life, often requiring frequent replacements in high-demand settings (Ding*et al*., 2019; Maddukuri*et al*., 2020). Their round-trip efficiency typically ranges from 70% to 85%, and their environmental risks associated with lead handling and disposal necessitate careful management. Despite their limitations, lead-acid batteries remain popular in low-budget off-grid systems, particularly where high energy throughput is not required.

Flow batteries, such as vanadium redox flow batteries (VRFB), offer promising features for off-grid energy storage, including scalability, long cycle life, and the ability to discharge fully without degradation. Flow batteries store energy in liquid electrolytes, allowing easy expansion of storage capacity by simply increasing electrolyte volume. They are particularly suitable for long-duration storage applications, such as overnight energy supply in solar-based systems (Onaghinor*et al*., 2021; Mustapha *et al*., 2021). While flow batteries have relatively low energy densities and higher initial costs compared to lithium-ion or lead-acid batteries, their durability and low maintenance requirements make them attractive for larger off-grid installations.

Pumped hydro storage (PHS) is the most established form of mechanical energy storage, involving the movement of water between two reservoirs at different elevations. During periods of surplus energy, water is pumped to a higher elevation and later released to generate electricity via turbines. PHS offers high efficiency, typically between 70% and 85%, and long operational lifespans. However, it requires significant geographic and environmental conditions, including suitable terrain and water availability, making it impractical for many off-grid communities, especially those in arid or flat regions (Yimen*et al*., 2018).

Compressed air energy storage (CAES) operates by compressing air and storing it in underground caverns or high-pressure tanks. When electricity is needed, the compressed air is heated and expanded to drive turbines and generate power. CAES systems are characterized by their large-scale capacity and relatively long-duration storage potential. However, they also face site-specific constraints, such as the need for specialized geological formations or high-pressure vessels, which limits their applicability in small or remote off-grid settings (Onifade *et al*., 2021; Onaghinor*et al*., 2021). Additionally, their round-trip efficiency is generally lower, ranging from 40% to 70%, though advanced adiabatic CAES technologies are under development to improve performance.

Hydrogen-based storage is gaining attention as an emerging solution for long-duration and seasonal energy storage. In such systems, surplus electricity is used to produce hydrogen via electrolysis, which can then be stored and later converted back into electricity through fuel cells or combustion engines. Hydrogen storage offers nearly unlimited scalability and can store energy for extended periods without degradation, making it suitable for off-grid regions with highly variable renewable energy resources. However, the technology remains expensive due to high costs associated with electrolyzers, fuel cells, and hydrogen infrastructure. Moreover, the round-trip efficiency is relatively low, generally between 30% and 45%, though improvements in electrolyzer and fuel cell technologies continue to advance.

Hybrid storage systems represent an innovative approach by combining multiple storage technologies to leverage their complementary strengths. For example, systems integrating lithium-ion batteries for high-power, short-duration applications with flow batteries or hydrogen storage for long-duration energy needs can deliver optimized performance across various timescales. Hybrid systems can improve overall system resilience, operational flexibility, and cost-effectiveness in off-grid settings (Onaghinor*et al*., 2021; Onifade *et al*., 2021). However, their complexity and higher initial integration costs require sophisticated control systems and skilled technical support, which may be challenging in some remote communities.

The diverse range of energy storage technologies offers varied technical and economic trade-offs for off-grid applications. Lithium-ion batteries lead in efficiency and energy density but are constrained by high costs and temperature sensitivity. Lead-acid batteries provide affordable, simple solutions but require frequent replacements. Flow batteries excel in durability and scalability but remain expensive for smaller-scale systems. Mechanical storage systems like pumped hydro and CAES offer long-term solutions but face significant geographic limitations. Emerging technologies such as hydrogen-based storage and hybrid systems present promising long-term options but still face cost and technical hurdles (Dincerand Acar, C, 2018; Gür, 2018). Selecting the optimal ESS for off-grid communities depends on carefully balancing these factors according to local energy needs, environmental conditions, and economic contexts.

2.2 Techno-Economic Assessment Framework

A rigorous and comprehensive techno-economic assessment framework is essential for evaluating the suitability of energy storage systems (ESS) in off-grid communities. The framework must systematically assess both the technical performance and economic feasibility of various storage technologies, while also accounting for local contextual factors that affect deployment and operation as shown in figure 1(Akpe*et al*., 2021; Abayomi *et al*., 2021). This structured evaluation enables informed decision-making regarding technology selection, investment, and long-term sustainability.

The technical assessment of ESS focuses on four key metrics: energy density, round-trip efficiency, cycle life and depth of discharge (DoD), and operational reliability and scalability.

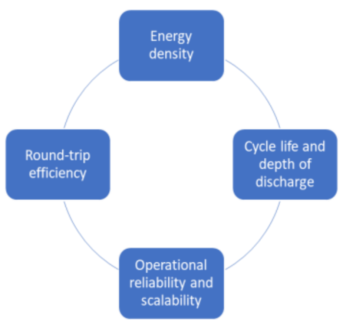

Figure 1: Technical Performance Metrics

Energy density, measured in watt-hours per kilogram (Wh/kg) or watt-hours per liter (Wh/L), is a critical parameter for determining the physical footprint and portability of a storage system. Higher energy density allows more energy to be stored in a smaller volume or weight, which is particularly important in off-grid communities where space is constrained or where systems need to be transported to remote locations (Kitson*et al*., 2018; Wallenius*et al*., 2018; Kaluthanthrige*et al*., 2019).

Round-trip efficiency refers to the ratio of energy output to energy input during a complete charge-discharge cycle, typically expressed as a percentage. Higher efficiency minimizes energy losses and improves the overall effectiveness of renewable energy systems. Technologies such as lithium-ion batteries generally achieve high round-trip efficiencies (90% or more), while mechanical systems like compressed air energy storage (CAES) often exhibit lower efficiencies.

Cycle life and depth of discharge (DoD) indicate the durability and usable capacity of the storage system. Cycle life refers to the number of charge-discharge cycles a system can endure before its performance degrades below a specified threshold. DoD measures the proportion of stored energy that can be utilized in each cycle without compromising battery longevity (Chianumba*et al*., 2021; ODETUNDE *et al*., 2021).

Higher cycle life and deeper DoD enable longer operational lifespans and better resource utilization, reducing the frequency of costly system replacements.

Operational reliability and scalability pertain to the ability of the system to function consistently under varying conditions and to be expanded as energy needs grow. Reliable systems minimize the risk of outages and maintenance-related disruptions, which is vital in off-grid communities where technical support may be limited. Scalability ensures that energy storage capacity can be increased to accommodate growing population and demand without requiring a complete system overhaul.

Economic assessment focuses on four critical metrics: capital costs, levelized cost of storage (LCOS), operation and maintenance (O&M) costs, and payback period or return on investment (ROI).

Capital costs, expressed in dollars per kilowatt-hour ($/kWh) of storage capacity, represent the initial expenditure for procuring and installing the storage system. These costs vary significantly by technology. For example, lithium-ion batteries have higher upfront costs than lead-acid batteries but may offer lower lifetime costs due to superior durability.

Levelized cost of storage (LCOS) is a comprehensive metric that accounts for all costs over the system's lifetime, including capital expenditures, operational costs, replacements, and efficiency losses, divided by the total energy delivered (SHARMA *et al*., 2021;

ODETUNDE *et al*., 2021). It allows a fair comparison of technologies with different lifespans, efficiencies, and maintenance needs, making it one of the most widely used indicators in energy economics. Operation and maintenance (O&M) costs include routine inspections, component replacements, labor, and repair activities. These costs can be particularly high in off-grid locations where skilled labor is scarce and spare parts must be transported over long distances.

Payback period and ROI evaluate the financial return from deploying the storage system relative to its costs. A shorter payback period or higher ROI enhances the attractiveness of an investment, especially in budget-constrained off-grid communities that prioritize fast returns.

Beyond technical and economic metrics, several contextual factors must be integrated into the assessment framework to ensure realistic and practical evaluations.

Local climate and geography have significant impacts on system performance. For example, extreme temperatures can degrade battery efficiency and lifespan, while mechanical storage systems like pumped hydro require specific topographical features. Remote locations may also pose transportation and installation challenges, adding to project costs.

Technical capacity for maintenance is another critical factor. Some ESS technologies, such as lithium-ion or flow batteries, may require specialized skills and diagnostic tools for maintenance and repairs, which may not be readily available in off-grid communities (Adewale *et al*., 2021; Nwabekee*et al*., 2021). Simpler systems, such as lead-acid batteries, may be preferred despite technical limitations if local technicians can maintain them with ease.

Availability of supply chains and spare parts affects long-term system sustainability. ESS technologies that rely on complex components or proprietary parts may face operational risks if supply disruptions occur. Technologies with widely available parts and local manufacturing options generally offer higher resilience and lower life-cycle costs.

The techno-economic assessment framework for energy storage systems in off-grid communities must balance detailed technical performance analysis with comprehensive economic evaluations and local contextual considerations. Technical metrics such as energy density, efficiency, cycle life, and scalability are essential for understanding system capabilities and limitations. Economic criteria, including capital costs, LCOS, O&M expenses, and financial returns, determine long-term affordability and feasibility. Crucially, local conditions—ranging from environmental factors to technical capacity—strongly influence the practicality of deployment. This integrated, multi-dimensional framework enables stakeholders to select the most appropriate energy storage technologies for enhancing energy access, reliability, and sustainability in off-grid settings.

2.3 Applications

The deployment of energy storage systems (ESS) in off-grid communities has gained momentum worldwide, driven by the need to improve energy access, enhance reliability, and integrate renewable energy sources. Diverse geographic, economic, and technical conditions across regions necessitate tailored solutions for off-grid electrification (Halliday, 2021; Adewale *et al*., 2021). This presents detailed case studies and applications from three regions—Africa, Asia-Pacific, and Latin America—highlighting the role of ESS in supporting sustainable energy systems in off-grid communities.

In sub-Saharan Africa, where more than 500 million people lack access to electricity, solar + storage microgrids have emerged as a leading solution for off-grid electrification. These systems combine solar photovoltaic (PV) arrays with battery energy storage systems (BESS), enabling continuous electricity supply even in the absence of sunlight.

One notable example is the Rural Electrification Agency (REA) solar microgrid projects in Nigeria. These microgrids utilize lithium-ion batteries alongside solar PV to provide electricity to remote villages and agricultural communities. Lithium-ion technology was chosen due to its high energy density, long cycle life, and ability to function under high temperatures common in the region. The microgrids typically range from 50 kW to 500 kW in capacity, serving households, schools, healthcare centers, and local businesses.

The systems have significantly improved community welfare by enabling lighting, refrigeration for vaccines, and productive uses such as milling and irrigation. Economically, the projects demonstrated rapid payback periods, often within 5 to 7 years, due to savings on diesel fuel and improved economic productivity. Maintenance is supported through local technicians trained under government-backed programs, ensuring long-term system sustainability.

Other African countries, such as Kenya and Tanzania, are also deploying similar solar + storage microgrids. In many cases, lead-acid batteries are still used in lower-budget installations despite their shorter cycle life, due to their low upfront costs and ease of maintenance (Akinrinoye*et al*., 2021; Kufile*et al*., 2021). However, there is a gradual shift toward lithium-ion and emerging flow battery technologies as costs continue to decline and technical performance improves.

Islanded communities in the Asia-Pacific region face unique energy challenges due to geographic isolation and vulnerability to climate change. Historically dependent on expensive diesel generation, many islands are transitioning to renewable energy microgrids integrated with ESS.

A prominent case is the Tonga Renewable Energy Project, which aims to achieve 70% renewable energy penetration by integrating solar PV, wind, and energy storage. The project deployed a combination of lithium-ion batteries and flow batteries to store surplus energy during the day for nighttime consumption. The energy storage systems were specifically designed to withstand the humid, saline environments typical of island regions.

The project has significantly reduced diesel fuel imports, cutting energy costs and lowering greenhouse gas emissions. It has also enhanced energy security by providing backup power during severe weather events. The combination of technologies was selected to balance high energy density for short-term needs with long-duration storage for extended cloudy or low-wind periods.

In the Philippines, the Isabela Island Microgrid Project provides another successful example. The community-operated microgrid uses solar PV, lithium-ion batteries, and backup diesel generators. Advanced battery management systems and predictive maintenance tools help maximize battery life and ensure reliability. Furthermore, training programs for local operators were included in the project design to build local technical capacity and promote community ownership.

These projects underscore the importance of robust energy storage solutions in islanded settings where grid extension is not feasible and highlight the growing relevance of hybrid systems combining multiple storage technologies for enhanced resilience and performance (Fredson *et al*., 2021).

Remote mountainous regions in Latin America often face severe challenges in achieving reliable electricity access due to difficult terrain, sparse populations, and harsh environmental conditions. Nevertheless, several innovative projects have demonstrated the successful application of ESS in such contexts.

In Peru, the “Energía para Todos” (Energy for All) initiative has brought solar + storage systems to remote Andean villages. These systems typically use lead-acid batteries combined with solar PV to provide basic lighting, mobile charging, and power for small appliances. Despite the lower technical performance of lead-acid batteries, their low cost and ease of repair made them suitable for initial deployments. However, the high altitude and cold temperatures led to faster battery degradation, prompting ongoing pilot projects with lithium-ion and flow batteries that offer better thermal tolerance and longer operational lifespans.

In Chile’s Atacama Desert region, known for its abundant solar resources but extreme temperature variations, solar microgrids equipped with lithium-ion and vanadium redox flow batteries have been deployed. These projects aim to provide consistent electricity to mining communities and indigenous settlements. The systems are designed with redundancy and thermal management technologies to handle large temperature swings between day and night. The vanadium redox flow batteries offer deep cycling capabilities and long lifespans, which are crucial for the harsh desert environment.

In Colombia's mountainous regions, the government and development agencies have supported hybrid microgrid systems combining solar PV, micro-hydro turbines, and energy storage to address both seasonal and daily variability in energy supply (Fredson *et al*., 2021). These projects often use a mix of lead-acid and lithium-ion batteries to optimize for cost and performance.

These case studies from Africa, Asia-Pacific, and Latin America demonstrate that there is no universal solution for energy storage in off-grid communities. The choice of ESS technology must consider local environmental conditions, technical capacities, and economic constraints. Lithium-ion batteries are gaining popularity due to their superior technical performance and declining costs, but lead-acid batteries remain relevant where simplicity and affordability are priorities. Flow batteries and hybrid systems show promise for long-duration and high-resilience applications, particularly in remote or challenging environments.

Each case highlights the importance of tailoring ESS technologies to specific regional needs, ensuring community involvement, and integrating maintenance training and local supply chains to maximize long-term project success. The growing portfolio of off-grid ESS applications offers valuable insights for replicating and scaling sustainable energy solutions in underserved regions worldwide.

2.4 Key Findings and Comparative Analysis

The techno-economic evaluation and regional case studies of energy storage systems (ESS) in off-grid communities reveal several critical findings regarding the performance, feasibility, and deployment strategies of different technologies. A comparative analysis across regions and application scales highlights the trade-offs between technical performance and economic feasibility, as well as the vital role of financing, subsidies, and regulatory support in determining project success as shown in figure 2(Sasseand Trutnevyte, 2019; Tröndle*et al*., 2020).

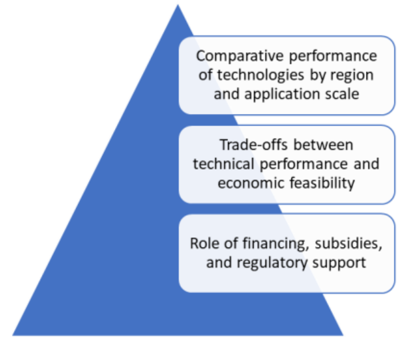

Figure 2: Key Findings and Comparative Analysis

The analysis shows that the choice of ESS technology is strongly influenced by regional characteristics and application scale. In Africa, particularly in sub-Saharan regions, lithium-ion batteries are emerging as a preferred option for solar + storage microgrids serving small to medium-sized communities. These systems, typically ranging from 50 kW to 500 kW, leverage the high energy density, long cycle life, and superior efficiency of lithium-ion batteries to deliver reliable power for lighting, refrigeration, and agricultural activities. Despite their higher capital costs, these batteries are increasingly attractive due to declining global prices and improved supply chains in African markets.

In contrast, lead-acid batteries still dominate in smaller, lower-income projects or where local technical expertise favors simpler technologies. Their affordability and ease of maintenance make them practical in regions where long-term financial planning and technical training remain challenging. However, they often require frequent replacements due to limited cycle life and lower depth of discharge, which can increase long-term operational costs.

In Asia-Pacific islanded communities, particularly in Tonga and the Philippines, hybrid systems that combine lithium-ion batteries with flow batteries or other long-duration storage technologies have shown success in balancing daily and seasonal variability. These projects, often larger in scale (over 1 MW), prioritize system resilience against severe weather and fuel supply disruptions. Flow batteries, such as vanadium redox, offer durability and deep cycling capabilities that complement lithium-ion batteries for short-term high-power needs.

In Latin America's mountainous regions, the choice of storage systems varies by community size and local conditions. Remote villages often start with lead-acid-based systems due to lower upfront costs, but pilot programs are increasingly integrating lithium-ion and flow batteries to address altitude- and temperature-related performance issues. In larger installations, such as those serving mining operations or entire villages, hybrid solutions incorporating solar PV, micro-hydro, and energy storage are deployed to optimize system performance under diverse energy supply profiles (Oladigbolu*et al*., 2020; Niyontreze*et al*., 2020).

A key finding from the comparative analysis is the trade-off between technical performance and economic feasibility. Lithium-ion batteries consistently deliver superior technical performance across all regions, with high energy density, long cycle life, and high round-trip efficiency (often above 90%). However, their higher upfront costs present challenges for small-scale or resource-constrained off-grid communities, despite their decreasing global prices.

Lead-acid batteries, on the other hand, remain economically accessible but suffer from poor technical attributes such as low cycle life and reduced efficiency (typically 70%–85%). Their shorter lifespans and higher maintenance requirements may offset initial cost savings, particularly in applications with high daily cycling or large energy demands.

Flow batteries and hybrid systems offer niche advantages, especially for large-scale projects requiring long-duration storage and resilience against harsh environmental conditions. While technically robust, these systems often entail high capital costs and complex operational requirements, limiting their widespread use to pilot or government-backed projects.

Ultimately, the optimal choice of technology depends on the specific energy demand profile, local resource availability, and project financing structure. Many successful projects blend technologies to leverage their respective advantages while minimizing their weaknesses.

Financial mechanisms, subsidies, and policy interventions play a decisive role in enabling ESS deployment in off-grid communities. The case studies reveal that most successful projects were supported by government subsidies, international development funds, or public-private partnerships.

In Africa, projects under Nigeria's Rural Electrification Agency and Kenya's Last Mile Connectivity initiative benefited from concessional financing and grants, which covered high upfront capital costs and provided incentives for private developers to deploy advanced storage solutions. Without these subsidies, many communities would have been unable to afford lithium-ion or hybrid storage systems (Faunce*et al*., 2018; Sani*et al*., 2020).

In the Asia-Pacific region, targeted government policies—such as Tonga's Renewable Energy Act and renewable portfolio standards in the Philippines—have driven investment in storage-enabled microgrids. Financial incentives for renewable energy integration and energy storage, combined with resilience-focused policies, have encouraged utilities and communities to adopt advanced systems.

Similarly, in Latin America, regulatory frameworks such as Peru's "Electrification for All" and Chile's distributed generation policies have facilitated microgrid deployment through technical assistance and subsidies. However, challenges remain in ensuring consistent financing streams and developing long-term operations and maintenance programs.

Additionally, innovative financing models such as pay-as-you-go (PAYG) schemes, community-based ownership models, and microfinance loans have proven effective in reducing financial barriers, particularly for small-scale systems. These models help spread the upfront costs over time and align payment structures with the income patterns of rural households.

The comparative analysis of energy storage systems across Africa, Asia-Pacific, and Latin America demonstrates that technology selection must account for a complex interplay of technical performance, economic feasibility, and local conditions. While lithium-ion batteries offer superior performance, their economic feasibility depends heavily on external financing and supportive policies. Lead-acid batteries continue to serve as a transitional technology where affordability and simplicity are prioritized. Flow batteries and hybrid systems represent specialized solutions for larger, more complex projects.

The analysis also underscores the importance of financing mechanisms, subsidies, and regulatory frameworks in scaling up ESS deployment in off-grid settings. Effective government policies, concessional funding, and innovative financing schemes are critical in bridging the affordability gap and enabling long-term sustainability. As technology costs continue to fall and policy environments evolve, the integration of advanced storage systems is expected to accelerate, enhancing energy access and resilience for off-grid communities worldwide (Hart*et al*., 2018; Rinaldi*et al*., 2019).

2.5 Policy and Investment Recommendations

The expansion of energy storage systems (ESS) in off-grid communities is essential for improving energy access, enhancing renewable energy integration, and promoting socioeconomic development (Pagliaro, 2019; Babatunde*et al*., 2020). However, despite their transformative potential, widespread deployment of ESS in such settings remains constrained by high upfront costs, technical capacity gaps, and limited financing options. To overcome these barriers, targeted policy measures and strategic investment approaches are necessary. This presents comprehensive policy and investment recommendations focused on three key areas: incentives for off-grid energy storage deployment, support for local manufacturing and technical training, and innovative financing models.

Incentives for Off-Grid Energy Storage Deployment
One of the most effective ways to accelerate ESS adoption in off-grid communities is through well-designed incentives that reduce financial risks and stimulate market growth. Governments and development agencies can play a catalytic role by offering capital subsidies, tax credits, and tariff exemptions for energy storage technologies used in off-grid projects. These incentives can lower the initial investment burden for project developers and community organizations, making advanced ESS technologies more accessible.

Performance-based incentives such as feed-in tariffs for renewable energy with storage or results-based financing (RBF) mechanisms can further encourage the integration of storage systems by linking financial support to operational outcomes, such as the number of households electrified or the amount of diesel fuel displaced. Such models have already shown success in several African and Asian markets.

Additionally, governments can introduce public procurement programs that prioritize off-grid ESS for remote schools, healthcare facilities, and public services. By creating predictable demand, these programs can drive economies of scale and attract private sector participation. Importantly, incentives should be technology-neutral, allowing a range of ESS solutions—including lithium-ion, flow batteries, and hybrid systems—to compete based on suitability and cost-effectiveness in specific contexts.

A key challenge in many off-grid regions is the lack of local capacity to manufacture, install, and maintain advanced ESS technologies (Faisal*et al*., 2018; Aberilla*et al*., 2020). To ensure the long-term success of off-grid storage projects, policies should prioritize support for local manufacturing and workforce development.

Governments can provide tax breaks, low-interest loans, and land grants to encourage local manufacturing of battery components, balance-of-system equipment, and ancillary technologies such as charge controllers and inverters. Establishing regional manufacturing hubs for battery assembly, particularly for lithium-ion and lead-acid batteries, can reduce supply chain bottlenecks, lower transportation costs, and enhance technology affordability.

Equally important is the development of technical training programs to build local expertise in the installation, operation, and maintenance of ESS. Partnerships between governments, technical institutes, universities, and industry stakeholders can help establish vocational training centers focused on renewable energy and storage technologies. These programs should cover not only technical skills but also business and financial management for community-based energy operators.

Community engagement is essential to these efforts. Programs that empower local entrepreneurs—particularly women and youth—can enhance social acceptance and ensure equitable access to job opportunities in the off-grid energy sector. Furthermore, such initiatives can strengthen local ownership and improve system reliability by ensuring that maintenance expertise is available within the community.

Given the high capital costs of ESS technologies, especially for advanced systems like lithium-ion and flow batteries, innovative financing models are critical to unlocking off-grid market potential (Marnell*et al*., 2019; Mongird*et al*., 2019). Three approaches stand out: microloans, pay-as-you-go (PAYG) systems, and grants.

Microloans provided by local microfinance institutions (MFIs) can help households and small businesses afford the upfront costs of energy storage systems. These loans can be tailored to the specific cash flow patterns of rural communities, with flexible repayment schedules aligned with seasonal income variations, such as agricultural harvests.

PAYG systems have proven particularly effective in Africa and parts of Asia for small-scale solar home systems and are increasingly being adapted for microgrid and storage projects. Under this model, users pay for electricity or storage services incrementally via mobile money or other digital payment platforms. This approach reduces the initial financial burden on users while allowing project developers to recover costs over time. PAYG systems also create strong incentives for service providers to ensure system reliability, as continued payments depend on customer satisfaction.

Grants and concessional financing remain essential for the most vulnerable and remote communities, where commercial financing may not be viable due to extreme poverty or high logistical costs. Donor agencies, development banks, and climate finance institutions can provide grants or low-interest loans to support feasibility studies, pilot projects, and infrastructure development for off-grid storage systems (Agupugo and Tochukwu, 2021). These funds can also be used to subsidize training programs, promote technology innovation, and de-risk private sector investments through credit guarantees or first-loss provisions.

Scaling up energy storage deployment in off-grid communities requires a multi-faceted policy and investment approach that addresses both supply- and demand-side barriers. Incentives such as capital subsidies, tax relief, and results-based financing can accelerate ESS adoption by reducing upfront costs and rewarding performance (Leimona*et al*., 2019; Walker*et al*., 2019). Support for local manufacturing and technical training is vital to build resilient supply chains, lower long-term costs, and empower communities to manage and maintain their systems independently. Meanwhile, innovative financing models—including microloans, PAYG schemes, and grants—are essential for making storage technologies accessible to low-income households and small enterprises.

By integrating these strategies, governments, donors, and private sector actors can create enabling environments that foster the rapid, sustainable, and inclusive expansion of ESS in off-grid regions. Such efforts not only improve energy access but also contribute to broader development goals, including poverty reduction, climate resilience, and economic empowerment.

CONCLUSION

The techno-economic evaluation of energy storage systems (ESS) for off-grid communities highlights the critical need for context-specific solutions that balance technical performance, cost-effectiveness, and local conditions. Lithium-ion batteries have emerged as the optimal choice for many off-grid applications due to their high energy density, long cycle life, and superior round-trip efficiency. They are particularly suited for medium- to large-scale systems in regions with technical support and declining battery costs, such as Africa's solar microgrids and Asia-Pacific islanded communities. However, their high initial investment and technical complexity may limit applicability in extremely resource-constrained settings.

In contrast, lead-acid batteries remain relevant for smaller-scale projects where affordability and simplicity outweigh concerns about shorter lifespan and lower efficiency. These systems are often deployed in remote mountainous regions of Latin America or in initial electrification efforts requiring minimal technical expertise. Flow batteries and hybrid storage systems offer promising options for larger, long-duration storage applications, particularly in environments requiring deep cycling and enhanced system resilience, though they remain costlier and require specialized infrastructure.

The findings emphasize the necessity of tailored, site-specific solutions that consider factors such as local climate, technical capacity, financing availability, and community energy needs. There is no universal solution; successful deployment requires aligning technology choice with local operational realities and long-term sustainability.

Future research should focus on improving the affordability, durability, and scalability of advanced ESS technologies for decentralized energy systems. Key priorities include developing novel battery chemistries, enhancing hybrid energy storage configurations, and creating robust predictive tools for system sizing and optimization. In addition, research into circular economy approaches—such as recycling and second-life battery applications—will be essential for ensuring the environmental sustainability of future off-grid energy storage deployments.

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