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The Role of Battery Energy Storage in Colombia's Sustainable Energy Transition: A Socio-Ecological and Economic Perspective

Fredy Martínez[1], César Hernández[2], Diego Giral[3]

Abstract

This paper explores the integration of Battery Energy Storage Systems (BESS) in Colombia's power grid as a socio- environmental solution for the country's renewable energy transition. Given Colombia's increasing reliance on solar energy, the intermittency of this source presents challenges that demand sustainable energy storage solutions. This study analyzes the role of BESS not only in technical terms but also from an eco-humanistic perspective, incorporating environmental, economic, and social justice dimensions. Through an interdisciplinary approach, we examine the potential for BESS to support energy democratization, reduce dependence on fossil fuels, and foster inclusive energy policies. Additionally, the paper discusses regulatory challenges, economic feasibility, and the environmental impact of BESS deployment in Colombia. Finally, we present policy recommendations to ensure a just and sustainable energy transition.

Keywords: *Battery Energy Storage (BESS), Ecohumanism, Energy Transition, Renewable Energy Policy, Sustainability.*

Introduction

Colombia is undergoing a significant transformation in its energy sector, aiming to diversify its traditionally hydroelectric-dependent energy matrix by incorporating renewable energy sources, particularly solar power (Giraldo et al., 2021; Pupo-Roncallo et al., 2019). This shift is driven by the country's abundant solar resources, especially in regions like the Guajira Peninsula, which boasts high solar irradiance levels (Granit, 2023). The government's commitment to this transition is evident in its ambitious plans to increase the share of unconventional renewable energy sources to 25% of the energy matrix by 2050, as outlined in the National Energy Plan (González-Dumar et al., 2024; Pinedo-López et al., 2024).

However, the integration of solar energy into the national grid presents challenges due to its intermittent nature, which can lead to grid instability (Khalid, 2024; Mlilo et al., 2021; Shafiullah et al., 2022). Solar power generation is subject to daily and seasonal variations, as well as weather fluctuations, making it less predictable than traditional energy sources (Yang et al., 2022). This intermittency necessitates the development of effective energy storage solutions to ensure a stable and reliable electricity supply (Jafarizadeh et al., 2024).

Battery Energy Storage Systems (BESS) have emerged as a viable solution to address these challenges by storing excess energy generated during peak production periods and releasing it during times of high demand or low production (Hannan et al., 2021; Rana et al., 2022; Saldarini et al., 2023). In Colombia, the deployment of BESS is still in its early stages, with pilot projects such as Celsia's 2 MWh lithium iron phosphate battery system at the Solar Palmira 2 facility in Valle del Cauca. This project aims to enhance the plant's generation capacity and contribute to grid stability (Filho et al., 2023; Gonzalez et al., 2021; Graham et al., 2021).

The successful integration of BESS into Colombia's energy infrastructure requires an interdisciplinary approach that considers not only the technical aspects but also environmental sustainability, economic feasibility, and social justice (S. Ahmed et al., 2024). Environmental considerations include the lifecycle impacts of battery production, use, and disposal, as well as the sourcing of raw materials (Silvestri et al., 2024). Economically, the high initial investment costs and the need for supportive regulatory frameworks

[1] Facultad Tecnológica, Universidad Distrital Francisco José de Caldas, Bogotá, Colombia, Email: fhmartinezs@udistrital.edu.co
[2] Facultad Tecnológica, Universidad Distrital Francisco José de Caldas, Bogotá, Colombia, Email: cahernandezs@udistrital.edu.co.
[3] Facultad Tecnológica, Universidad Distrital Francisco José de Caldas, Bogotá, Colombia, Email: dagiralr@udistrital.edu.co

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are critical factors (Akinsooto et al., 2024). Socially, ensuring that the benefits of energy storage technologies are equitably distributed, particularly to underserved and rural communities, is essential for a just energy transition (Guan et al., 2024).

This paper aims to explore the multifaceted role of Battery Energy Storage Systems in Colombia's sustainable energy transition. The objectives are to assess the technical potential of BESS in enhancing grid reliability, evaluate the environmental and economic implications of large-scale deployment, and analyze the social dimensions related to energy equity and access. By adopting a comprehensive perspective, this study seeks to provide insights that inform policy decisions and strategic planning for integrating BESS into Colombia's renewable energy landscape.

The remainder of this paper is structured as follows: Section 2 presents the theoretical and conceptual framework, defining key concepts such as ecohumanism and energy justice. Section 3 delves into the role of BESS in Colombia's energy future, covering technical overviews, regulatory landscapes, socioeconomic impacts, and environmental considerations. Section 4 discusses the challenges and barriers to BESS implementation, including regulatory, financial, and infrastructural obstacles. Section 5 offers policy recommendations and explores future outlooks for BESS in Colombia. Finally, Section 6 concludes the study by summarizing the key findings and emphasizing the importance of an interdisciplinary approach to Colombia's energy transition.

Theoretical and Conceptual Framework

The deployment of BESS within Colombia's evolving energy landscape requires a multidisciplinary analysis that extends beyond technical feasibility. The integration of energy storage into national grids must be examined through a lens that incorporates environmental sustainability, economic viability, and social justice considerations. This section provides a structured theoretical foundation by defining ecohumanism in energy policy, exploring energy storage as a tool for environmental justice, analyzing the sustainability and life cycle of battery technologies, and reviewing existing literature on BESS and sustainable energy transitions in Latin America. These perspectives collectively inform a holistic framework for evaluating the role of BESS in Colombia's energy transformation.

Ecohumanism in Energy Policy

Ecohumanism in energy policy represents a paradigm shift that acknowledges the intrinsic relationship between ecological well-being and human prosperity. This approach challenges conventional energy policies that prioritize short-term economic gains over long-term environmental and social stability. Instead, ecohumanism advocates for an ethical framework wherein energy policies are designed to ensure that technological advancements and resource utilization align with the principles of sustainability, inclusivity, and intergenerational equity (Albaqami, 2025). Within the context of Colombia's energy transition, this perspective necessitates policies that safeguard ecosystems while simultaneously fostering equitable access to clean energy.

A critical aspect of ecohumanism is the recognition that energy is not merely a commodity but a fundamental enabler of human development. In energy policy, ecohumanism translates into practices that mitigate the socio-environmental costs of large-scale energy infrastructure projects, ensuring that affected communities (particularly indigenous and rural populations) are active stakeholders in decision-making processes. As the country expands its renewable energy portfolio, integrating ecohumanism into policy frameworks will be crucial for balancing energy security with ecological preservation. The integration of BESS, therefore, must not only support grid stability but also uphold environmental integrity and the well-being of the communities impacted by energy developments.

Energy Storage as a Tool for Environmental Justice

Environmental justice in the energy sector refers to the fair distribution of environmental benefits and burdens across different social groups, ensuring that historically marginalized populations are not

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disproportionately affected by energy-related externalities. The deployment of BESS plays a crucial role in promoting environmental justice by facilitating decentralized and resilient energy systems that empower underserved communities. By enabling the integration of intermittent renewable energy sources such as solar and wind, BESS reduces dependence on fossil fuel-based generation, mitigating localized pollution and its associated health risks, particularly in urban and industrialized areas (M. Ahmed et al., 2024).

In Colombia, where energy access remains uneven (especially in remote and conflict-affected regions) energy storage solutions present an opportunity to bridge disparities in electricity reliability. Rural areas, which often rely on costly and polluting diesel generators, could significantly benefit from microgrid systems that incorporate solar energy with battery storage. Beyond technical deployment, environmental justice also demands scrutiny of the material and supply chain implications of BESS technologies. The extraction of lithium, cobalt, and nickel, essential components of many battery chemistries, raises ethical concerns regarding labor exploitation and environmental degradation in mining regions. Therefore, ensuring environmental justice requires policies that regulate responsible sourcing, promote circular economy strategies, and invest in battery recycling technologies to minimize long-term ecological footprints.

Sustainability and Life Cycle Analysis of Battery Technologies

The sustainability of battery technologies is a multidimensional challenge that requires consideration of raw material extraction, energy-intensive manufacturing processes, operational efficiency, and end-of-life management. Life Cycle Analysis (LCA) provides a comprehensive assessment of the environmental impact of BESS across these stages, identifying areas where improvements can enhance overall sustainability.

Research indicates that the production of lithium-ion batteries is associated with significant greenhouse gas emissions, water consumption, and land degradation, largely due to intensive mining operations and chemical processing (Mousavinezhad et al., 2024). Additionally, battery disposal poses substantial risks if effective recycling systems are not in place, leading to potential contamination of soil and water sources.

One strategy to mitigate these impacts is the development of alternative battery chemistries with lower ecological footprints. Emerging technologies such as sodium-ion and solid-state batteries offer promising advancements in reducing reliance on scarce minerals while improving energy density and cycle life (Nekahi et al., 2024). Moreover, circular economy principles advocate for the repurposing of used electric vehicle batteries for stationary energy storage applications, extending their operational lifespan and reducing waste generation. Implementing comprehensive sustainability policies in Colombia's BESS sector will require regulatory frameworks that mandate responsible material sourcing, incentivize research into next-generation battery technologies, and enforce robust recycling infrastructure to minimize the environmental burden of large-scale energy storage deployments.

Battery Energy Storage Systems and Sustainable Energy Transitions in Latin America

Latin America is experiencing an accelerated shift towards renewable energy adoption, with BESS emerging as a pivotal technology for enhancing energy resilience and sustainability. The region's abundant solar and wind resources create an ideal environment for integrating battery storage solutions to mitigate the variability of renewable generation. Countries such as Chile and Brazil have initiated large-scale energy storage projects to complement their expanding solar and wind capacity, demonstrating the feasibility and economic advantages of grid-scale BESS (Shadman et al., 2023). These developments provide valuable insights into best practices for Colombia's energy transition, highlighting the importance of policy incentives, investment in energy infrastructure, and technological innovation.

Colombia's reliance on hydropower, historically a cornerstone of its electricity generation, presents both opportunities and challenges for BESS implementation (Durvasulu et al., 2024). While hydropower provides a stable baseload supply, climate variability and extended drought periods, exacerbated by El Niño events, underscore the need for complementary storage solutions to maintain grid stability. The adoption of BESS can facilitate greater flexibility in the national grid, allowing for more effective utilization of solar

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and wind resources while reducing vulnerability to hydrological fluctuations. Furthermore, investment in distributed energy storage could enable local energy autonomy, reducing transmission losses and enhancing energy security, particularly in off-grid and underserved areas.

Existing Literature on BESS and Sustainable Energy Transitions

A growing body of research underscores the transformative potential of BESS in supporting global sustainable energy transitions. Studies have examined the optimization of battery life cycle costs, the techno-economic feasibility of large-scale storage deployments, and the socio-environmental trade-offs associated with different battery technologies (Demirci, 2023; Sarfraz et al., 2024; Wohlschlager et al., 2024). In Latin America, academic discourse has increasingly focused on the role of policy frameworks in accelerating BESS adoption, with emphasis on tariff structures, regulatory incentives, and grid modernization strategies (Bulut & Ozcan, 2024). These studies offer critical insights that can inform Colombia's approach to integrating energy storage into its energy transition strategy.

Recent analyses have also explored the intersection of BESS with climate resilience planning, demonstrating how storage solutions can mitigate the risks associated with extreme weather events and grid disruptions. Research in this domain highlights the necessity of incorporating storage technologies into national energy policies to enhance system reliability and adaptation capabilities in the face of climate change (Suman, 2021). As Colombia continues to develop its renewable energy sector, leveraging these scholarly contributions will be essential for designing policies that maximize the benefits of BESS while addressing economic, environmental, and social considerations.

Implications for Colombia's Energy Policy

For Colombia to fully realize the benefits of BESS within its renewable energy strategy, energy policies must integrate ecohumanistic principles, prioritize environmental justice, and adopt sustainability-driven regulatory frameworks. Policymakers must address challenges related to resource extraction, supply chain ethics, and end-of-life battery management while ensuring equitable access to energy storage solutions. The formulation of incentive mechanisms, research funding, and infrastructure investments will be key determinants in shaping a resilient and inclusive energy system. By aligning BESS deployment with broader sustainability objectives, Colombia can position itself as a regional leader in energy innovation, fostering a transition that is both technologically advanced and socially responsible.

The Role of Battery Energy Storage in Colombia's Energy Future

The integration of BESS is pivotal in advancing Colombia's renewable energy agenda, particularly in enhancing solar power utilization, ensuring grid stability, and reducing reliance on hydroelectric power during periods of water scarcity. This section delves into the technical, regulatory, socioeconomic, and environmental dimensions of BESS deployment within the Colombian context.

Technical Overview

BESS in Solar Power Integration

The intermittency of solar energy, characterized by fluctuations due to diurnal cycles and weather variability, poses challenges to consistent power supply. BESS addresses this issue by storing excess energy generated during peak sunlight hours and releasing it during periods of low production or high demand, thereby smoothing out supply inconsistencies.

The integration of renewable energy sources, particularly solar photovoltaic systems, introduces significant variability in net load patterns throughout the day. This phenomenon, commonly referred to as the "Duck Curve", arises due to the misalignment between peak solar generation and peak electricity demand. Fig. 1 illustrates this effect by comparing the low-renewables scenario, where conventional power generation dominates, against a high-renewables scenario, where a significant share of solar energy leads to midday net

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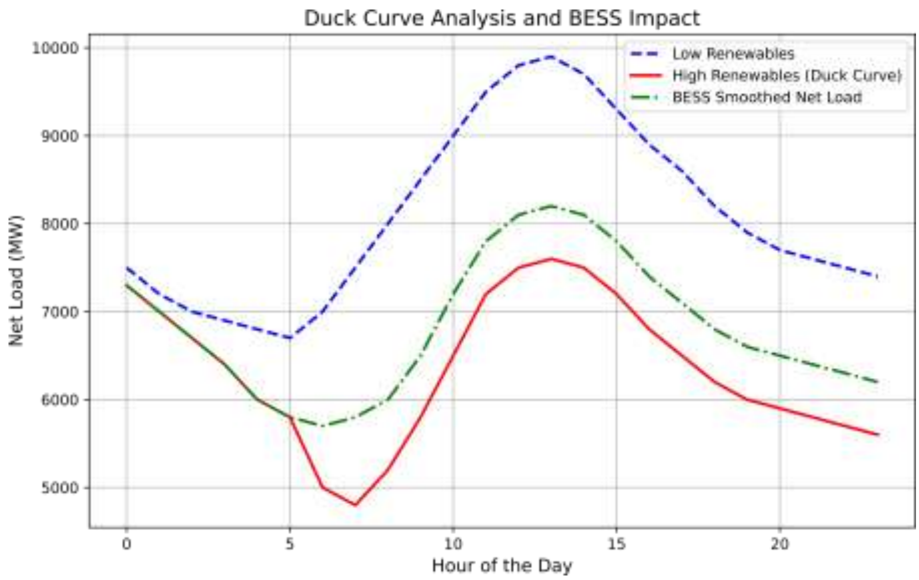
load reductions and steep evening ramp-ups (González-Dumar et al., 2024). The characteristic dip observed in the net load curve around midday demonstrates the displacement of conventional generation due to high solar output, followed by a steep incline in the late afternoon and evening as solar generation diminishes while demand remains high.

Figure 1



Impact of renewable energy penetration on net load variations throughout the day. The low-renewables scenario (blue dashed line) exhibits a relatively stable net load profile, whereas the high-renewables scenario (red solid line) demonstrates the characteristic Duck Curve, highlighting the midday dip due to increased solar generation. The BESS-adjusted net load (green dash-dotted line) illustrates how battery energy storage systems (BESS) mitigate these fluctuations by redistributing excess solar energy, thereby reducing ramping requirements and enhancing grid stability.

Battery Energy Storage Systems (BESS) offer a practical solution to mitigate these fluctuations by storing excess solar energy during peak generation hours and discharging it during periods of high demand. The BESS-smoothed net load profile, also depicted in Fig. 1, highlights how energy storage can effectively reduce the magnitude of net load fluctuations, leading to a more balanced grid operation. By absorbing surplus energy that would otherwise lead to curtailments and strategically discharging during peak hours, BESS plays a crucial role in enhancing system stability, minimizing reliance on fast-ramping fossil fuel plants, and optimizing the efficiency of renewable energy utilization. This underscores the necessity of integrating large-scale energy storage solutions into Colombia's power infrastructure to ensure the reliability and sustainability of its energy transition.

In December 2024, Colombia operationalized its first solar energy storage system, featuring a 1 MW/2 MWh lithium ferro-phosphate battery energy storage system (BESS) at the Celsia Solar Palmira 2 photovoltaic farm in Valle del Cauca. This system autonomously manages energy storage and discharge, ensuring operational safety and efficiency. Such advancements underscore the technical feasibility of integrating BESS with solar installations to bolster energy reliability.

Grid Stabilization and Energy Security

Beyond facilitating renewable integration, BESS plays a critical role in enhancing grid stability and energy security. By providing rapid response capabilities, BESS can mitigate frequency and voltage fluctuations, manage peak loads, and serve as a contingency during grid disturbances. The Andes Solar IIB project exemplifies this application; it incorporates advanced energy storage solutions to address the intermittency of solar energy, thereby stabilizing the grid and ensuring a continuous power supply (Graham et al., 2021).

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The deployment of similar systems in Colombia can enhance the resilience of the national grid against both supply-side and demand-side uncertainties.

Reducing Hydroelectric Dependency During Droughts

Colombia's energy matrix has traditionally been dominated by hydroelectric power. However, hydroelectric generation is susceptible to climatic variations, particularly during droughts induced by phenomena such as El Niño, which can lead to significant reductions in water availability and, consequently, power shortages. Integrating BESS with solar energy systems offers a viable solution to this challenge by diversifying the energy mix and providing a reliable alternative during periods of reduced hydroelectric output. This strategic shift not only enhances energy security but also mitigates the risks associated with over-reliance on a single energy source.

Integration of BESS in Latin America's Energy Landscape

Latin America has witnessed a significant surge in the adoption of BESS to complement its renewable energy initiatives. Countries such as Chile and Brazil have pioneered large-scale BESS projects, setting precedents for energy storage solutions in the region. For instance, the Andes Solar IIB project in Chile integrates a 180 MW photovoltaic system with a 116 MW/560 MWh BESS, effectively enhancing grid stability and reliability (Graham et al., 2021). This project exemplifies how coupling renewable energy sources with substantial storage capacities can mitigate intermittency issues and ensure a consistent energy supply.

Case Study: Celsia Solar Yumbo - Colombia's Foray into BESS Integration

In Colombia, the Celsia Solar Yumbo project stands as a testament to the country's commitment to integrating BESS with renewable energy sources. Commissioned in 2024, this project features a 9.9 MW solar photovoltaic plant complemented by a 2 MWh lithium iron phosphate (LFP) battery storage system (Ramirez-Tovar et al., 2022). The primary objective of this integration is to manage energy dispatch effectively, ensuring a steady supply during peak demand periods and enhancing the overall reliability of the grid. The technical specifications of the Celsia Solar Yumbo project are outlined in Table 1. The integration of the BESS has yielded notable improvements in the plant's performance metrics. As depicted in Table 2, there has been a significant enhancement in energy dispatch reliability and a reduction in grid fluctuations post-BESS implementation (Zuñiga-Cortes et al., 2023).

Table 1. Technical Specifications of Celsia Solar Yumbo Project

Parameter	Specification
Solar PV Capacity	9.9 MW
Battery Storage Capacity	2 MWh
Battery Technology	Lithium Iron Phosphate (LFP)
Commissioning Year	2024
Location	Yumbo, Valle del Cauca, Colombia

Table 2. Performance Metrics Before and After BESS Integration

Metric	Before BESS	After BESS
Energy Dispatch Reliability	85	98
Grid Fluctuations (Events/Month)	15	3
Peak Demand Support (MW)	0	2
Renewable Energy Utilization (%)	70	90

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Implications for Colombia's Energy Strategy

The success of the Celsia Solar Yumbo project underscores the potential benefits of integrating BESS into Colombia's energy infrastructure. By enhancing the reliability and efficiency of renewable energy plants, BESS can play a pivotal role in reducing dependence on traditional energy sources and promoting a sustainable energy future. Furthermore, the positive outcomes from such projects can serve as a blueprint for scaling up BESS applications across the nation, particularly in regions with high renewable energy potential.

Recommendations for Future Implementations

To capitalize on the advantages of BESS, it is imperative to address existing challenges such as high capital costs and regulatory hurdles. Policymakers should consider implementing financial incentives, such as tax credits and subsidies, to attract investments in energy storage solutions. Additionally, establishing clear regulatory frameworks that define the operational parameters and market participation of BESS will provide the necessary clarity and confidence for stakeholders. Collaborative efforts between the government, private sector, and research institutions can further drive innovation and facilitate the widespread adoption of BESS in Colombia.

Regulatory Landscape

Current Policies

The Colombian government has recognized the strategic importance of energy storage in modernizing its power sector. In 2019, the Energy and Gas Regulation Commission (CREG) issued Resolution 098, which formally incorporated grid-scale battery storage projects into the national transmission system. This regulation outlines the framework for identifying storage needs, project implementation protocols, selection processes, remuneration mechanisms, and quality assurance standards (Filho et al., 2023). By establishing clear guidelines, Resolution 098 aims to address existing grid challenges and facilitate the seamless integration of renewable energy sources.

Legal Barriers and Financial Incentives for BESS

Despite progressive policies, several legal and financial barriers impede the widespread adoption of BESS in Colombia. The lack of market-based regulatory incentives, such as dynamic pricing models and time-of-use tariffs, diminishes the economic attractiveness of energy storage investments. Additionally, complexities in grid connection procedures and the absence of tailored financial support mechanisms further deter potential investors. To overcome these obstacles, it is imperative to develop comprehensive incentive structures, streamline regulatory processes, and establish financial instruments that reduce the capital expenditure burden associated with BESS projects.

Socioeconomic Impact

Job Creation and Economic Potential

The deployment of BESS is poised to generate significant socioeconomic benefits, including job creation across various sectors such as manufacturing, installation, operation, and maintenance of energy storage systems. The burgeoning energy storage market also presents opportunities for local industries to engage in the production of battery components, thereby stimulating economic growth and technological innovation. By fostering a domestic energy storage industry, Colombia can enhance its energy independence and position itself as a regional leader in renewable technologies.

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Implications for Energy Access and Rural Electrification

BESS has the potential to revolutionize energy access in remote and underserved regions of Colombia. By enabling the development of off-grid and microgrid systems powered by renewable energy, BESS can provide reliable electricity to communities previously reliant on diesel generators or lacking access altogether. This transformation not only improves the quality of life but also promotes economic development by facilitating the operation of businesses, schools, and healthcare facilities. Ensuring equitable access to energy storage technologies is thus a critical component of Colombia's broader social and economic development goals.

Environmental and Ethical Considerations

Impact of Mining for Battery Materials

The environmental footprint of BESS extends beyond their operational phase to include the extraction and processing of raw materials such as lithium, cobalt, and nickel. Mining activities associated with these materials can lead to habitat destruction, water contamination, and adverse impacts on local communities. Therefore, it is essential to implement stringent environmental regulations, promote responsible sourcing practices, and invest in research focused on alternative materials with lower ecological impacts.

Potential for Circular Economy Solutions

Adopting a circular economy approach in the energy storage sector involves designing batteries for longevity, facilitating reuse and repurposing, and establishing efficient recycling processes. Second-life applications, where batteries retired from electric vehicles are repurposed for stationary energy storage, exemplify this strategy. By extending the lifecycle of battery components and reducing waste, circular economy practices can mitigate environmental impacts and enhance the sustainability of BESS deployments. Developing robust policies and infrastructure to support these initiatives is crucial for realizing their full environmental and economic benefits.

Challenges and Barriers

The integration of BESS into Colombia's energy infrastructure is pivotal for enhancing renewable energy utilization and ensuring grid stability. However, this endeavor is fraught with multifaceted challenges encompassing regulatory and financial obstacles, environmental concerns, and deficiencies in technical expertise and infrastructure. A comprehensive understanding of these barriers is essential for formulating effective strategies to facilitate the large-scale deployment of BESS in Colombia.

Regulatory and Financial Obstacles

Regulatory Framework Limitations

Colombia's regulatory landscape for energy storage is still evolving, with existing policies not fully addressing the unique operational characteristics of BESS. The Energy and Gas Regulatory Commission (CREG) has initiated efforts to incorporate grid-scale battery storage projects into the national transmission system. However, the current regulations do not fully accommodate the dual nature of BESS, which can function both as a load and a generator. This ambiguity complicates the classification and remuneration of BESS within the electricity market, potentially deterring investment and hindering large-scale deployment. Moreover, the absence of a clear framework for behind-the-meter (BTM) energy storage systems further exacerbates regulatory uncertainties, as there is no established protocol to facilitate their integration into the existing grid infrastructure.

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Economic Viability and Market Incentives

The financial feasibility of BESS projects in Colombia is challenged by high capital expenditures and the absence of robust economic incentives. Although the costs of lithium-ion batteries have decreased globally, they remain substantial, and the current pricing structures in Colombia's energy market do not sufficiently incentivize large-scale energy storage deployment. The lack of dynamic pricing models, such as time-of-use tariffs, and limited access to ancillary service markets reduce the potential revenue streams for BESS operators, thereby undermining the economic attractiveness of such investments. Additionally, the fixed pricing model prevalent in the Colombian energy sector undermines storage profitability, as it fails to account for the value-added services that BESS can provide, such as peak shaving and load leveling.

Grid Connection and Permitting Processes

The procedural complexities associated with grid connection and the acquisition of necessary permits pose significant barriers to BESS implementation. Lengthy approval timelines, coupled with a lack of standardized interconnection guidelines, create uncertainty and increase project development costs. Streamlining these processes through clear, transparent, and efficient regulatory pathways is essential to facilitate the timely and cost-effective integration of BESS into Colombia's energy infrastructure. Furthermore, the absence of a cohesive policy framework for distributed renewable energy exacerbates these challenges, as it leads to inconsistencies in the application and enforcement of regulations across different jurisdictions.

Environmental Concerns

Resource Extraction and Ecological Impact

The production of batteries for energy storage necessitates the extraction of raw materials such as lithium, cobalt, and nickel. These mining activities have been associated with environmental degradation, including habitat destruction, soil and water contamination, and significant water consumption. For instance, lithium extraction in arid regions can lead to unsustainable water usage, adversely affecting local ecosystems and communities. Such environmental ramifications necessitate the adoption of responsible mining practices and the exploration of alternative materials with lower ecological footprints. In Colombia, while lithium mining is not prevalent, the importation of lithium-ion batteries implicates the country in the global supply chain, thereby associating it with the environmental impacts of lithium extraction in other regions.

Waste Management and Recycling Challenges

The end-of-life management of batteries presents a critical environmental challenge. Inadequate recycling infrastructure and the absence of standardized protocols for battery disposal can lead to the accumulation of hazardous waste, posing risks to both human health and the environment. Developing efficient recycling processes and promoting a circular economy approach, where materials are recovered and reused, are vital steps toward mitigating the environmental impact of BESS. This includes establishing policies that incentivize recycling initiatives and the development of technologies for material recovery. In Latin America and the Caribbean, it is estimated that between 6.6 and 7.5 million tonnes of lithium-ion batteries will reach end-of-life between 2024 and 2050, underscoring the urgency of developing robust recycling and reuse strategies.

Technical Expertise and Infrastructure Deficiencies

Skill Gaps in the Workforce

The successful deployment and operation of BESS require a workforce equipped with specialized skills in areas such as system design, installation, maintenance, and safety management. Currently, there is a paucity of professionals in Colombia with the requisite expertise to support large-scale BESS projects. Addressing this skills gap through targeted educational programs, vocational training, and capacity-building initiatives

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is essential to develop a competent workforce capable of advancing the country's energy storage ambitions. Collaborative efforts between academic institutions, industry stakeholders, and government agencies are necessary to develop curricula and training programs that align with the specific needs of the energy storage sector.

Infrastructure and Technological Readiness

The integration of BESS into the existing power grid necessitates upgrades to infrastructure and the adoption of advanced technologies. This includes the development of smart grid systems, enhancement of grid flexibility, and implementation of sophisticated energy management systems to effectively coordinate storage assets. The current state of Colombia's grid infrastructure may require significant investments to accommodate these advancements, posing financial and logistical challenges. Collaborative efforts between the government, industry stakeholders, and international partners are crucial to mobilize the necessary resources and expertise for infrastructure development. Additionally, the development of local manufacturing capabilities for BESS components could reduce dependency on imports and enhance the resilience of the supply chain.

Safety Standards and Risk Management

Ensuring the safety and reliability of BESS installations is paramount. The absence of comprehensive safety standards and risk management protocols can lead to operational hazards, including thermal runaway events and fire risks. Developing and enforcing stringent safety regulations, along with continuous monitoring and maintenance practices, are imperative to safeguard both personnel and assets. This also involves educating stakeholders about best practices and emerging technologies that enhance the safety profiles of BESS. Implementing international safety standards and adapting them to the local context can provide a framework for developing robust safety protocols tailored to Colombia's specific needs.

Policy Recommendations and Future Outlook

Drawing from successful policies and business models implemented across Latin America, this section provides comprehensive policy recommendations and explores sustainable business models to accelerate BESS adoption in Colombia, ensuring social and environmental responsibility.

Policy Initiatives to Accelerate BESS Adoption

Development of a Comprehensive Regulatory Framework

Establishing a robust regulatory framework is fundamental to facilitate the deployment of BESS in Colombia. This framework should clearly define the operational parameters of BESS, recognizing their dual role as energy consumers and suppliers. The National Energy Commission (CNE) of the Dominican Republic serves as a pertinent example, having issued Resolution CNE-AD-0005-2024, which integrates battery storage systems into renewable energy projects to enhance the stability of the National Interconnected Electric System (SENI). Colombia can draw from this approach to develop standardized interconnection guidelines and streamline permitting processes, thereby reducing bureaucratic hurdles and fostering investor confidence.

Implementation of Financial Incentives and Support Mechanisms

To address the high capital expenditures associated with BESS projects, Colombia should consider implementing financial incentives such as tax credits, subsidies, and concessional loans. These measures can lower economic barriers and attract private sector investment. The Global Energy Alliance for People and Planet (GEAPP) exemplifies this strategy through its Battery Energy Storage Systems Consortium, a multi-stakeholder partnership aimed at expanding battery storage capacity in low- and middle-income countries (Stanczyk, 2022). By participating in such consortia or developing similar national initiatives, Colombia can leverage international support and mobilize resources for large-scale BESS deployment.

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Promotion of Social and Environmental Responsibility

Ensuring that BESS deployment aligns with social equity and environmental sustainability is paramount. Policies should mandate comprehensive environmental impact assessments and enforce the responsible sourcing of raw materials. Additionally, it is crucial to engage local communities, particularly Indigenous populations, in decision-making processes. Embracing Indigenous leadership and respecting their rights can lead to shared prosperity and sustainable development. Successful projects, such as Canada's Okikendawt Hydro Project and New Zealand's Tauhara North II Geothermal Project, demonstrate the benefits of equitable partnerships with Indigenous communities (Islam & Vodden, 2023). Colombia can adopt similar approaches to ensure that energy projects are inclusive and culturally sensitive.

Policy Analysis and Regulatory Challenges

Regulatory Framework and Market Structure

Colombia's regulatory environment for energy storage is still in its nascent stages. The existing policies primarily focus on traditional energy generation and lack specific provisions that address the unique operational characteristics of BESS. This regulatory ambiguity creates uncertainty for investors and hinders the development of a robust energy storage market. A comparative analysis with other Latin American countries reveals that nations like Chile and Uruguay have made significant strides in establishing comprehensive regulatory frameworks for energy storage, thereby attracting substantial investments in this sector.

Economic Incentives and Financial Barriers

The financial viability of BESS projects in Colombia is challenged by the absence of tailored economic incentives. Unlike other countries in the region that offer tax benefits, subsidies, or favorable tariff structures to promote energy storage, Colombia's incentive mechanisms are underdeveloped. This deficiency, coupled with high capital expenditure requirements, deters private sector participation and slows the adoption of BESS technologies. To bridge this gap, it is imperative to design and implement financial instruments that can mitigate investment risks and enhance the attractiveness of energy storage projects.

Grid Access and Infrastructure Limitations

Access to the national grid remains a significant bottleneck for BESS deployment in Colombia. Regulatory delays and a moratorium on new grid connection requests, as observed in 2024, have exacerbated this issue, leading to project backlogs and increased uncertainty among developers. Additionally, the existing grid infrastructure may require substantial upgrades to accommodate the bidirectional energy flows associated with BESS operations. Addressing these challenges necessitates a coordinated effort to streamline grid connection procedures and invest in modernizing the grid to support advanced energy storage solutions.

Policy Recommendations

To overcome these challenges, the following policy recommendations are proposed:

- Establish a Dedicated Regulatory Framework for BESS: Develop and implement regulations that specifically address the operational, financial, and technical aspects of energy storage systems. This framework should define the roles and responsibilities of BESS within the energy market, including guidelines for grid integration, safety standards, and performance metrics.

- Implement Financial Incentives: Introduce tax incentives, subsidies, or low-interest financing options to reduce the initial capital burden on investors. Learning from regional counterparts, such as the incentives provided in Chile, can offer valuable insights into structuring these financial mechanisms effectively.

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- Streamline Grid Connection Processes: Simplify and expedite the procedures for BESS projects to connect to the national grid. This includes revising existing policies to eliminate unnecessary bureaucratic hurdles and establishing clear timelines for approval processes.

- Invest in Grid Modernization: Allocate resources towards upgrading the grid infrastructure to handle the dynamic interactions introduced by energy storage systems. This investment is crucial for ensuring the reliability and efficiency of the grid as it adapts to the evolving energy landscape.

- Enhance Institutional Capacity: Strengthen the capabilities of regulatory bodies by providing training and resources focused on the technical and economic aspects of BESS. A well-informed regulatory authority is essential for the effective oversight and promotion of energy storage technologies.

Future Outlook

The successful integration of BESS into Colombia's energy system holds the promise of increased resilience, sustainability, and energy security. By addressing the current policy and regulatory challenges, Colombia can pave the way for a more flexible and reliable grid that effectively incorporates renewable energy sources. The experiences of neighboring countries underscore the importance of proactive policy-making and regulatory reforms in achieving these objectives. As such, a concerted effort from policymakers, industry stakeholders, and the broader community is essential to realize the full potential of BESS in Colombia's energy transition.

Sustainable Business Models for BESS

Deployment Public-Private Partnerships (PPPs)

Collaborative ventures between government entities and private companies can effectively mobilize the necessary resources and expertise for BESS projects. Public-Private Partnerships (PPPs) facilitate risk-sharing and can expedite project implementation. For instance, the World Bank's engagement in Uzbekistan's Solar and Renewable Energy Storage Project, which includes the construction of a 250 MW solar power plant and a 63 MW/126 MWh BESS, underscores the efficacy of such partnerships in scaling renewable energy infrastructure (Shadrina, 2024). Colombia can replicate this model by creating favorable conditions for private investment and establishing clear contractual agreements that delineate the responsibilities and benefits of each party.

Community-Led Energy Storage Initiatives

Empowering local communities to lead BESS projects fosters energy autonomy and ensures that the benefits of renewable energy are equitably distributed. Business models such as energy cooperatives and utility-community partnerships have demonstrated success in enhancing local energy resilience. A study analyzing community energy storage (CES) projects in Europe and India highlights the potential of these models to improve grid integration and provide economic benefits to community members. By supporting community-led initiatives through technical assistance and financial support, Colombia can promote grassroots participation in the energy transition.

Integration with Renewable Energy Developers

Strategic alliances between BESS providers and renewable energy developers can optimize energy generation and storage solutions. Companies like Grenergy, with a portfolio of 15.9 GW of solar PV and 21.7 GWh of storage in various stages of development across Latin America, exemplify the potential of integrating BESS with renewable energy projects to enhance grid stability and energy reliability (Kvist & Vera-Valdés, 2024). Colombia can encourage such integrations by offering incentives for projects that

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combine renewable energy generation with storage solutions, thereby maximizing the utilization of intermittent renewable resources.

Future Research and Development Trajectories

Advancement of Local Battery Production

Investing in the research and development of domestic battery manufacturing capabilities can reduce dependence on imports and stimulate local economies. This involves exploring alternative materials that are abundant locally and have a lower environmental footprint. Bolivia's initiative in developing small-scale energy storage systems, leveraging its lithium resources, serves as a pertinent example of aligning local resource availability with energy storage solutions. Colombia can assess its mineral resources and invest in technologies that utilize these materials, fostering a sustainable and self-sufficient energy storage industry.

Enhancement of Recycling and Reuse Mechanisms

Developing efficient recycling processes and promoting a circular economy approach are vital for the sustainable management of BESS. This includes establishing policies that incentivize recycling initiatives and the development of technologies for material recovery. Addressing the challenges associated with battery waste management will mitigate environmental impacts and contribute to resource conservation. Implementing certification programs, such as the Responsible Cobalt Initiative and the Responsible Minerals Initiative, can ensure the ethical sourcing and recycling of materials used in battery production.

Capacity Building and Technical Training

Establishing educational programs and vocational training focused on BESS technologies will cultivate a skilled workforce capable of supporting the burgeoning energy storage sector. Partnerships with academic institutions and international organizations can facilitate knowledge transfer and the development of specialized curricula. The National Renewable Energy Laboratory (NREL) has provided technical assistance in Latin America and the Caribbean, supporting the deployment of grid-interactive solar photovoltaics with battery energy storage systems and developing workforce strategies for priority energy sectors. Colombia can collaborate with such organizations to enhance local expertise and ensure the availability of qualified professionals to drive the energy transition.

Conclusion

The integration of BESS in Colombia represents a pivotal milestone in the country's energy transition, serving as a bridge between intermittent renewable energy sources and a stable, reliable power grid. As the nation seeks to diversify its hydroelectric-dependent energy matrix by incorporating greater shares of solar and wind power, BESS has been identified as a critical enabling technology to address the inherent variability of these sources. This study has provided a comprehensive analysis of the technical, regulatory, economic, and environmental dimensions of BESS deployment in Colombia, offering insights into both the opportunities and challenges associated with its large-scale implementation.

From a theoretical and conceptual standpoint, the role of BESS extends beyond technical feasibility to encompass broader socio-environmental and economic considerations. The application of ecohumanistic principles to energy policy underscores the necessity of aligning technological advancements with ethical, inclusive, and sustainable energy development goals. The study highlights that BESS, when implemented with a focus on environmental justice, has the potential to democratize energy access, particularly in rural and underserved communities, by enabling decentralized and resilient energy systems. However, this requires careful planning to ensure equitable access to energy storage technologies and to prevent the exacerbation of socio-economic disparities.

Technically, the analysis of BESS integration in Colombia demonstrates its effectiveness in mitigating grid instability, enhancing the efficiency of solar power plants, and providing backup capacity during peak

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demand or grid failures. The case study of Celsia Solar Yumbo illustrates how lithium iron phosphate (LFP) batteries can improve energy dispatch reliability and reduce grid fluctuations, leading to enhanced overall system performance. Additionally, the growing adoption of BESS in Latin America, particularly in countries such as Chile and Brazil, provides valuable lessons for Colombia regarding best practices in system design, market participation, and regulatory adaptation. The study also emphasizes that for BESS to effectively support Colombia's renewable energy goals, investments in smart grids, predictive control algorithms, and advanced energy management systems will be necessary.

Despite its benefits, the widespread adoption of BESS in Colombia is constrained by several regulatory and financial challenges. The study identifies a significant gap in the current regulatory framework, where existing policies lack clear provisions for the remuneration and market participation of energy storage assets. While the Energy and Gas Regulation Commission (CREG) has taken initial steps to incorporate BESS within the national grid through Resolution 098, further refinements are required to address behind-the-meter applications, ancillary service markets, and time-of-use pricing structures. Furthermore, financial barriers persist due to the high capital costs associated with BESS deployment and the absence of tailored incentive mechanisms such as tax credits, concessional loans, and energy storage auctions. Overcoming these barriers will require a combination of regulatory reforms, investment strategies, and targeted fiscal policies to de-risk BESS investments and promote market development.

Beyond regulatory and financial constraints, environmental and ethical considerations surrounding BESS deployment remain critical. The extraction and processing of lithium, cobalt, and nickel, key materials used in battery manufacturing, pose significant environmental and social risks, including habitat destruction, water scarcity, and human rights violations in mining regions. The study highlights the importance of establishing a circular economy approach to mitigate these risks, advocating for second-life applications of retired batteries, investments in recycling technologies, and the exploration of alternative battery chemistries with lower ecological footprints. Additionally, long-term sustainability requires stringent regulatory oversight to ensure responsible material sourcing, waste management, and end-of-life disposal of batteries.

The socioeconomic implications of BESS adoption further reinforce the need for a structured, strategic approach to its deployment. By fostering a local energy storage industry, Colombia can stimulate job creation in multiple sectors, including battery manufacturing, system integration, and maintenance services. Moreover, the expansion of BESS in off-grid and microgrid applications presents a viable solution for electrifying remote and Indigenous communities that remain disconnected from the national grid. However, for these benefits to be realized, capacity-building initiatives must be prioritized, ensuring that a skilled workforce is available to support the scaling of energy storage technologies. The study suggests that public-private partnerships, industry-academia collaborations, and vocational training programs will be essential in bridging the technical expertise gap and fostering a robust energy storage ecosystem.

Based on these findings, the study presents the following key recommendations for accelerating BESS adoption in Colombia:

- Regulatory Framework Development: Establish a dedicated and comprehensive regulatory framework that defines the technical, operational, and economic roles of BESS within the Colombian electricity market. This framework should clarify market participation rules, tariff structures, and remuneration mechanisms for both grid-scale and distributed storage assets.

- Financial Incentives and Market Instruments: Implement policy-driven financial mechanisms such as tax exemptions, grants, low-interest financing, and performance-based incentives to mitigate the high upfront costs of BESS projects. Additionally, the introduction of demand response programs and time-of-use tariffs could enhance the economic viability of storage investments.

- Grid Modernization and Infrastructure Investment: Allocate resources for upgrading grid infrastructure to support the integration of energy storage systems, particularly in regions with

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high renewable energy penetration. Investments in smart grid technologies, digital monitoring tools, and AI-driven energy management platforms will be crucial for optimizing BESS operations.

- Sustainability and Circular Economy Strategies: Develop policies that promote battery recycling, second-life applications, and research into alternative battery chemistries. Encouraging domestic innovation in energy storage technologies can position Colombia as a leader in sustainable battery production while reducing dependence on imported storage solutions.

- Workforce Development and Capacity Building: Establish training and certification programs to develop a skilled workforce capable of supporting the growing BESS industry. Collaborations between government agencies, universities, and industry stakeholders can facilitate knowledge transfer and technical skill development in energy storage technologies.

- Community-Led and Decentralized Energy Storage Models: Support the development of community-driven energy storage projects, particularly in rural and off-grid areas, through cooperative ownership structures and microfinance programs. This approach ensures that the benefits of BESS deployment are equitably distributed across all socioeconomic groups.

Future research should focus on optimizing BESS operational strategies, integrating machine learning algorithms for predictive analytics, and exploring hybrid energy storage configurations that combine batteries with alternative storage technologies such as pumped hydro and hydrogen storage. Additionally, ongoing policy analysis will be necessary to assess the effectiveness of regulatory interventions and adapt frameworks to evolving technological advancements and market dynamics.

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