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The Technology of Lithium-Ion Batteries: An Alternative and Future Option to Meet Pakistan's Energy Demands

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ABSTRACT

Pakistan faces persistent challenges of electricity shortfalls, over-dependence on imported fuels, grid instability, and ever-increasing electricity demand. At the same time, the country has significant wind and solar energy potential. However, these sources are intermittent, and a stable supply requires efficient and reliable energy storage. This study uses a qualitative literature review and policy analysis to assess the potential of lithium-ion (Li-ion) battery energy storage systems (BESS) as an effective and future-oriented solution to meet the country's energy needs. The article contributes to the literature on energy sustainability in Pakistan by linking Li-ion BESS to national energy needs, storage applications, implementation barriers, lessons from international experience, and supply-chain resilience options. The assessment draws on official Government of Pakistan statistics for FY2024-25 to compare electricity generation and consumption and to evaluate the applicability and utility of Li-ion BESS in the current scenario. The study is limited in scope, as it does not include techno-economic modeling or project-specific surveys; instead, it relies on reports from international organizations and peer-reviewed studies on Li-ion BESS, solar–wind– energy storage systems, and international experience. The analysis compares Li-ion BESS with alternative technologies, including pumped-hydro storage, flow batteries, and emerging sodium-ion batteries, and proposes a needs-based approach to implementing such systems in Pakistan, grounded in financial and technological suitability. The study also examines the experiences of China, the United States, and South Korea to show how these countries have integrated battery storage into their energy sectors. At present, Pakistan lacks the domestic industry to support Li-ion BESS deployment, leaving it dependent on international supply chains for batteries and their components. The study therefore recommends a strategic, needs-specific, and phased adoption of the technology. The findings suggest that Li-ion BESS is a promising solution for distributed solar-plus-storage, backup supply, and electric mobility; however, it is not a standalone solution to Pakistan's energy challenges. Deployment should be guided by site-specific feasibility studies, grid readiness, affordability, life-cycle costs, and diversified supply-chain mechanisms.

Keywords: *Lithium-ion battery, Battery energy storage system, Pakistan energy landscape, Energy alternatives for Pakistan*

1. Introduction

Pakistan's energy sector faces acute, interconnected challenges including reliability issues, reliance on fuel imports, structurally weak generation capacity, transmission and distribution losses, and limited grid capacity. According to the Pakistan Economic Survey 2024-25 published by the Finance Division, Government of Pakistan, total electricity generation during July-March FY2024-25 stood at 90,145 GWh, comprising 46.3% thermal, 30.4% hydropower, 19.1% nuclear, and 4.2% renewable generation [1]. Pakistan remains heavily dependent on conventional sources, including hydropower and fossil fuels, which together make up a large share of the generation mix. This over-reliance has exposed the national economy to volatility in international fuel prices and contributed to circular debt, which has surpassed Rs 2.6 trillion [2]. Additionally, tariff pressures further complicate planning and investment [3].

Beyond these factors, Pakistan's energy policy has not adequately accounted for alternative energy sources or energy storage infrastructure, leaving the system unable to fully benefit from renewable energy. Pakistan has a major opportunity to diversify its electricity generation through these resources; however, generation variability, limited flexibility, grid constraints, and funding issues limit their effectiveness. Assessments by the International Renewable Energy Agency (IRENA) highlight the need for strategic planning, investment, and policy development for renewable energy [4]. Integration of such storage systems provides more options for grid support services, decentralized backup, and sustainability.

In this context, lithium-ion (Li-ion) battery technology offers a forward-looking solution for bridging the gap between energy supply and demand in Pakistan. Li-ion batteries are widely used in portable electronics, vehicles, and stationary storage because of their higher energy density compared with traditional lead-acid batteries, fast response, long cycle life, modular deployment, and better efficiency [5, 6]. These batteries are being used globally and play a vital role in integrating renewable energy systems. Their portability enables electric mobility, and their modularity supports decentralized power generation and storage. Additionally, these technologies have contributed, directly and indirectly, to reducing carbon emissions [5]. These advantages make the technology attractive for developing economies such as Pakistan.

As Pakistan transitions towards renewable energy sources to achieve a resilient and clean energy future, Li-ion BESS offer a dual advantage. First, they enable the use of renewable energy systems; second, through their storage capabilities, they can help both rural and urban areas move toward energy self-sufficiency and support sustainable development and climate goals. Because Li-ion BESS is not a universal solution, other alternatives, such as pumped-hydro storage and sodium-ion batteries, may be used as part of a more technology-neutral strategy, depending on the requirements.

This study develops a Pakistan-focused analytical framework that links the challenges facing Pakistan's energy sector to battery storage applications, international experience, implementation barriers, supply-chain risks, and policy adaptations. It contributes by synthesizing these factors into context-specific assessments that identify where Li-ion batteries are of the greatest practical value in addressing Pakistan's challenges. The analysis provides a structured basis for prioritizing battery storage applications and does not advocate the technology as the single remedy for Pakistan's energy problems.

The study addresses four main questions: (i) Which of Pakistan's energy challenges can battery storage realistically help to address? (ii) How does Li-ion BESS compare with relevant alternatives? (iii) What transferable lessons can Pakistan learn from the experiences of China, the United States, and South Korea? (iv) What policy measures related to infrastructure development, recycling, and procurement are needed to ensure the safe and resilient implementation of storage technology?

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1.1 Limitations of the Study

The study is not all-inclusive and is limited by several factors. First, no independent techno-economic modeling was performed; instead, the references and findings are based on official statistics and reports from international organizations and Pakistani official sources. Second, variations in the scope and reporting periods of data from different institutions limit direct comparisons of costs, deployment levels, and relative performance. Third, although international case studies provide indicative lessons, they cannot ensure that the proposed interventions would produce similar results in Pakistan, owing to differences in capabilities and capacities. Finally, the study does not quantitatively compare Li-ion battery storage with alternative technologies for application in Pakistan; therefore, its conclusions should be interpreted as a policy assessment only.

1.2 Research Methodology

The study adopts a qualitative approach that combines a focused literature review with an analysis of policy documents. It draws on official reports from international energy organizations, including the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA), and on Pakistan's official sources, including the National Electric Power Regulatory Authority (NEPRA) and the Ministry of Finance, Government of Pakistan, together with peer-reviewed research articles. Sources were selected based on their relevance to Pakistan's energy conditions, Li-ion battery technology and its economic and technical aspects, international experience, and policy implications. They were identified through targeted searches of the official websites of relevant institutions and scholarly publication platforms, using search phrases such as 'Pakistan battery energy storage', 'Li-ion batteries', 'renewable energy integration', 'solar-storage system', 'critical mineral supply chain', and 'recycling technology for Li-ion batteries. The publications were prioritized from 2018–2026, while retaining earlier references for their relevance to foundational battery technology.

Sources were included based on their relevance to Pakistan's energy sector, battery integration, and official statistics; sources not specific to Pakistan or the technology were excluded. The analytical process is structured around five factors: (i) energy sector needs, (ii) potential applications of battery systems, (iii) implementation barriers, (iv) lessons from international experience, and (v) policy priorities. This study analyzes transferable lessons from China, the United States, and South Korea in relation to Pakistan's economic, institutional, and industrial capabilities. This qualitative study does not involve primary quantitative data collection or modeling.

2. Energy Landscape of Pakistan

In recent years, Pakistan's energy landscape has expanded and diversified. However, it still depends on imported fuels and faces structural inefficiencies. Finance Division data on actual power generation for FY2025 (July 2024-March 2025) indicate that Pakistan produced 90,145 GWh, with 46.3% from thermal power plants, 30.4% from hydropower, 19.1% from nuclear, and 4.2% from renewable sources [1].

The report also notes a difference between total installed capacity and total generation because of seasonal conditions, operating routines, and plant availability. Therefore, generation shares alone cannot establish that one source is more reliable than another. For example, hydropower generation varies with water availability, whereas thermal generation depends on fuel supply, cost, and dispatch decisions [1, 2]. Similarly, consumption varies by sector and season.

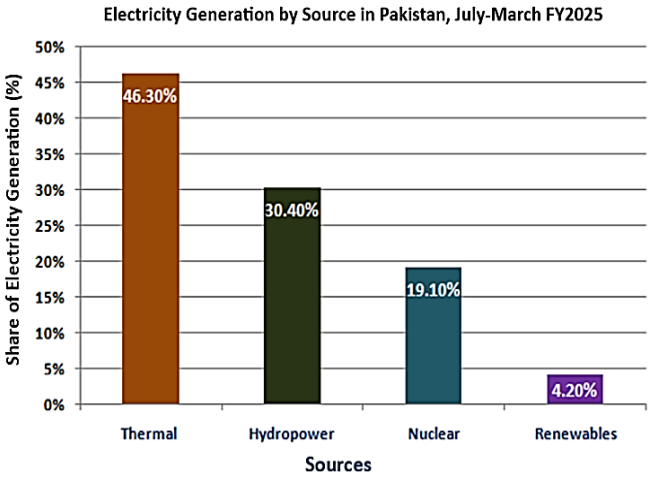


Fig. 1: Electricity Generation by Source in Pakistan, July–March FY2024–25. Source: Pakistan Economic Survey 2024–25 [1].

Fig. 1 represents that thermal sources have the largest share of generation (46.3%), followed by hydropower (30.4%) and nuclear (19.1%). Renewables account for the smallest share (4.2%), which shows that renewable sources have not yet been fully integrated into the national energy mix [1].

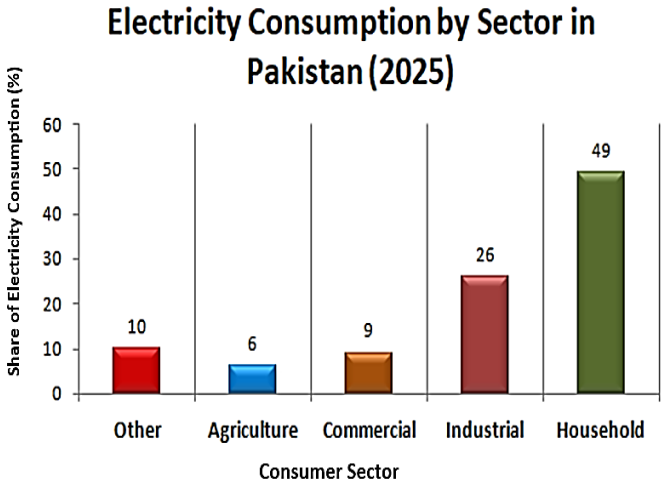


Fig. 2: Electricity Consumption by Sector in Pakistan, July–March FY2024–25. Source: Pakistan Economic Survey 2024–25 [1].

Fig. 2 shows that households consume nearly half (49%) of electricity, while industry uses 26% [1]. The remaining quarter is consumed by the agricultural, commercial, and other sectors. Sectoral demand patterns matter for this assessment because household evening peaks, industrial load profiles, and agricultural pumping schedules create different storage needs.

Pakistan's energy sector faces sustainability challenges owing to structural weaknesses and financial constraints. First, overreliance on fossil fuels has exposed the country to the financial burden of global oil price volatility, which strains its foreign exchange reserves and contributes to circular debt. Second, system inefficiencies and capacity underutilization persistently affect the sustainability of energy generation. Some thermal power plants operate at lower capacity because of maintenance issues, higher input costs, and grid limitations [2]. Additionally, transmission and

distribution losses exacerbate the financial impact and aggravate operational inefficiencies.

Third, governance and regulatory inefficiencies have also contributed to the failure to integrate renewable sources effectively into the energy mix. Delays and inconsistencies in policies and tariff adjustments, together with a lack of investment in energy storage infrastructure, have hampered the adoption of new technologies and diversification towards renewable energy sources [7]. Finally, seasonal variations affect hydropower generation, which fluctuates with river flows and rainfall [8]. Similarly, weather conditions are an important factor for wind and solar energy.

These challenges contribute to grid instability and lead to periodic load shedding. An adequate storage system is necessary to cover power shortages in such situations. To pursue the Sustainable Energy for All (SE4All) goals [9] of clean, low-carbon production from renewable sources and to achieve a resilient energy future for Pakistan, transformational policies are necessary, including grid modernization, a focus on renewables, and the development of sustainable storage systems to maximize the benefits of renewable sources.

2.1 Renewable Energy Potential in Pakistan

Pakistan has strong renewable energy potential that, if effectively harnessed, could reduce its over-dependence on thermal energy and transform its energy landscape. Pakistan is among the most solar-rich countries in South Asia, with an average solar potential of 5-7 kWh/m² per day [10]. In Balochistan and Sindh alone, the estimated potential exceeds 2,900 GW, and vast unutilized land enables large-scale photovoltaic installations [10]. Similarly, the area between Karachi and Hyderabad, stretching through Gharo–Jhimpir, is known as the Sindh wind corridor and has strong wind-power potential, estimated at up to 50 GW [7]. In addition, biomass-based power generation, largely from sugarcane residue (bagasse) in the sugar industry, is being used in localized waste-to-energy generation programs [11].

The Pakistan Economic Survey indicates that renewable energy sources contribute only 4.2% of the total generation mix, primarily because of limited grid capacity, lack of financing, and inadequate policies for these sources [1]. However, the growing number of rooftop solar installations and incentives such as net metering have expanded renewable energy use in Pakistan, bringing its total share to 12.1% [1]. To tap this potential effectively, Li-ion BESS can play an important role by substantially boosting storage capacity and helping to address the country's energy shortages through decentralized, stable, and clean energy. Deploying Li-ion BESS will not only enhance energy independence but also support climate resilience [12].

3. Li-ion Battery Technology

Li-ion battery technology has gained significance as a modern energy storage innovation and is considered a foundation of the global transition to sustainable, clean energy.

A Li-ion battery is a rechargeable device that stores (charges) and releases (discharges) electricity by moving lithium ions between the positive and negative electrodes. The lithium ions travel through the electrolyte, while electrons travel through the external circuit. This ion movement between the anode and cathode is reversible and constitutes the charging and discharging cycles. Because of their highly reversible electrochemical reactions, Li-ion batteries can sustain many charge–discharge cycles with relatively slow degradation [13]. Li-ion batteries are preferred over conventional batteries because of their higher energy density, light weight, superior efficiency, and long cycle life [14]. They are widely used in electric vehicles, portable electronic devices, and large-scale energy storage, especially in solar- and wind-based energy systems [5].

The working principle of a Li-ion battery is based on intercalation and de-intercalation, in which lithium ions move between the negative and positive electrodes without significantly changing the host materials' crystal structure. This movement allows the battery to store energy during charging and release it during discharging.

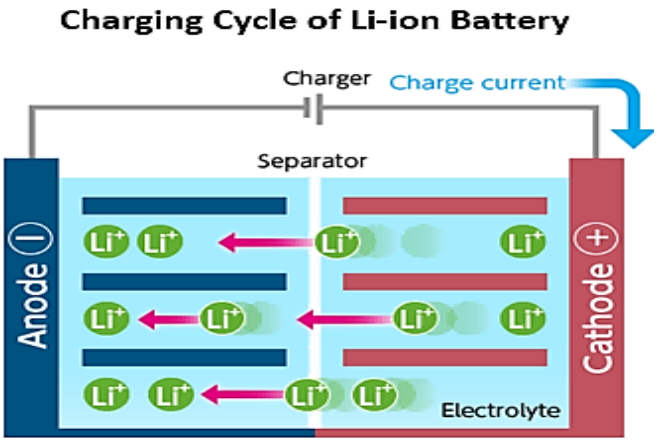


Fig. 3: Simplified schematic illustration of the charging process in a lithium-ion battery. Source: Adapted from [15].

Fig. 3 shows that during charging, when a charging source is connected, lithium ions are extracted (de-intercalated) from the cathode and move through the electrolyte to the anode, where they are inserted (intercalated) between the graphite layers.

The ions become embedded in the anode, and this transition from a low-energy state to a high-energy state corresponds to electrical energy storage. The more Li ions that are embedded in the anode, the more energy the battery stores [15].

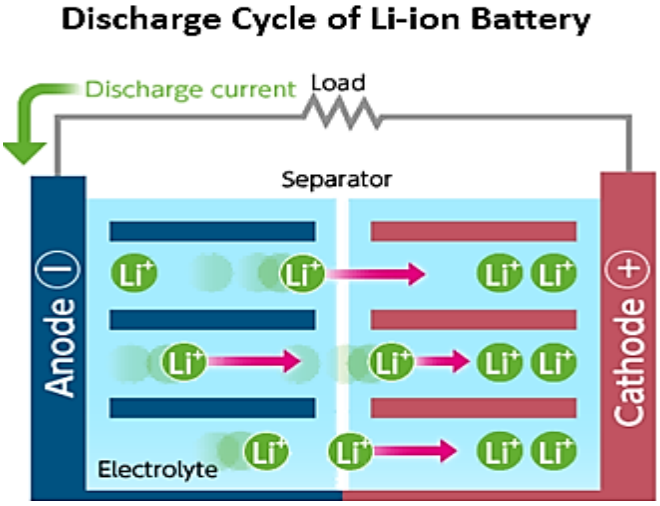


Fig. 4: Simplified schematic illustration of the discharging process in a lithium-ion battery. Source: Adapted from [15].

Fig. 4 shows the discharge cycle of a Li-ion battery. When a load is connected, the Li ions embedded in the anode are released (de-intercalated) and return through the electrolyte to the cathode,

where they are re-inserted (intercalated). This process releases energy that powers the connected load. The more ions that move to the cathode, the more charge the battery delivers [15].

A Li-ion battery consists of four main components:

1. Anode

The anode is typically made of graphite, whose layered structure retains lithium ions between its layers. It serves as the negative electrode. During charging, Li ions from the cathode travel to the anode and embed between the graphite layers; this process is called intercalation. Graphite can host Li ions repeatedly with limited degradation and is also used for its structural stability and good electrical conductivity. Research into silicon-based anodes is ongoing because of their much higher specific capacity; however, significant challenges related to volume expansion and durability still limit their widespread use [16].

2. Cathode

The cathode functions as the positive electrode and uses a lithium-containing compound that hosts Li ions. It is the active material on which the battery's energy density, voltage, capacity, and thermal stability largely depend. It is the primary source of Li ions in the battery [15]. Common materials include lithium iron phosphate (LFP), lithium cobalt oxide (LCO), lithium nickel cobalt aluminum oxide (NCA), and lithium nickel manganese cobalt oxide (NMC), which are selected based on the battery's intended use.

3. Electrolyte

The electrolyte is the medium that conducts ions between the electrodes during charging and discharging. It is usually a lithium salt, such as lithium hexafluorophosphate ($LiPF_6$), dissolved in organic solvents. A key characteristic of the electrolyte is that it allows ions to move between the electrodes while blocking direct electron flow, which instead travels through the external circuit [16]. It also contributes to the battery's chemical stability.

4. Separator

The separator acts as a barrier between the anode and cathode, preventing physical contact. It is a porous polymer membrane placed between the electrodes. The pores allow ions to pass through while preventing short-circuiting [16]. The separator plays an important role in the battery's safety, operational stability, and reliability.

Li-ion BESS provide a reliable option for small-scale electricity storage to power local businesses, educational institutions, and agricultural facilities, and to provide backup power in emergencies [17]. Their usage and importance depend on the utility they offer.

3.1 Comparison with Alternative Energy Storage Technologies

In addition to Li-ion batteries, several other technologies support electricity storage. However, because of their high energy density, modularity, rapid response, and high efficiency, Li-ion battery systems support diverse applications, such as solar-system compatibility, peak shaving, power backup, and grid support [6]. Other alternatives include the following: (i) pumped-hydro storage can provide large-scale, long-duration storage, but it requires suitable geography and water availability, as well as greater infrastructure investment and longer development periods [18]; (ii) flow batteries are a viable option for stationary applications requiring long discharge durations [17], their application is project-specific, and costs vary depending on the technology and required output; and (iii) sodium-ion batteries may become feasible as the technology matures and its performance and costs evolve, since their wider application is currently being assessed in terms of cost reduction, performance improvement, and supply-chain establishment [19].

Accordingly, while Li-ion batteries suit modular and distributed applications, other technologies may be considered based on project-specific requirements, cost, storage, and local conditions. Comparative assessments of grid storage technologies indicate that Li-ion batteries should be considered alongside flow batteries and pumped-hydro storage, as they are not a universal stand-alone replacement.

4. Pakistan's Energy Challenges and the Role of Li-ion Batteries

Pakistan depends on imported fossil fuels for electricity generation, which places a heavy burden on the government's foreign exchange reserves. Inadequate grid infrastructure also undermines a sustainable energy supply for households and the country's underdeveloped industry.

Growing electricity demand and shortages in supply stem from insufficient generation capacity and grid instability; infrastructure gaps stem from financial constraints; high energy costs stem from dependence on imported fossil fuels; and increased use of fossil fuels increases Pakistan's vulnerability to climate change. Policy gaps, limited institutional capacity, and policy inconsistencies further compound these challenges.

Li-ion batteries offer a strategic pathway to energy sustainability, resilience, and energy security for Pakistan by enabling renewable energy systems and improving grid reliability.

a. Renewable Resource Integration

Pakistan has great solar and wind energy potential. However, because these sources are intermittent and grid support is inadequate, Pakistan has not used this potential effectively. While expanding grid capacity for renewable sources that are not available round the clock is costly, Li-ion batteries can store excess energy produced during peak solar and wind generation periods and support the national grid during shortfalls [20]. Moreover, utility-scale solar and wind projects coupled with Li-ion BESS in Punjab and Sindh can supply electricity locally during low-generation periods and at night.

b. Grid Stability and Reduction in Load Shedding

Despite an overall increase in the country's generation capacity, Pakistan still faces load shedding and voltage fluctuations that affect industries and households. The main causes include aging infrastructure, transmission constraints, insufficient reserve capacity, and supply-demand mismatches [2]. To meet evening demand peaks, when commercial and domestic activities increase, the system relies on expensive thermal power plants that burn fossil fuels.

Li-ion batteries offer load shifting (storing electricity when demand is low and supplying it to the grid when demand is high), peak shaving (discharging during peak hours to reduce maximum demand), and frequency regulation (rapidly injecting or absorbing power to stabilize the grid during fluctuations) [21]. Li-ion batteries can instantly supply stored power to prevent outages and ensure grid stability [22]. Installing batteries near city centers and industrial zones can reduce transmission losses. This will reduce load shedding and improve grid resilience.

c. Use in Electric Vehicles

According to the Pakistan Economic Survey [1], the petroleum import bill amounted to US$8.9 billion, as the country imported 13.8 million metric tons of petroleum products during FY2024–25.

The transportation sector is the largest consumer of imported petroleum, which not only affects foreign exchange reserves but also causes greenhouse gas emissions and pollution. National policy, therefore, focuses on reducing dependence on imported fuels and encouraging electric vehicles (EVs).

Li-ion batteries offer long life and high energy storage capability, making them suitable for EVs. Modern EVs use Li-ion batteries, which have improved their economic competitiveness with fossil-fuel vehicles. The Ministry of Industries and Production launched the New Energy Vehicles (NEV) Policy 2025–30, which aims for 30% of new vehicle sales to be focused on electric vehicle by 2030 to promote electric transportation and reduce reliance on fossil fuels [23]. The Government of Pakistan also launched the Pakistan Accelerated Vehicle Electrification (PAVE) scheme in 2025, under which it conducted e-balloting for 40,000 electric two-wheelers and 1,000 three-wheelers [24]. The transition to EVs can help reduce dependence on fossil fuels.

d. Decentralization of Energy

Many communities in Balochistan, the mountainous areas of Khyber Pakhtunkhwa, and other rural areas face long hours of power outages and supply disruptions. Unreliable supply also stems from line losses and disruptions along long expansions of centralized supply lines. Moreover, extending traditional infrastructure to these areas has been economically challenging [25]. Li-ion batteries provide an effective alternative through decentralized Li-ion BESS installations that do not rely entirely on the national grid. Community-level micro-grids based on Li-ion BESS can provide reliable energy to villages, schools, small industries and businesses, hospitals, and irrigation systems, similar to small hydropower micro-grids [25]. Another major advantage of decentralized energy systems is their resilience to grid failures during natural disasters.

5. Challenges to Adoption

According to an Institute for Energy Economics and Financial Analysis (IEEFA) report, Pakistan imported 1.25 GWh of battery energy storage in 2024 [3], indicating a significant increase in deployment at different levels. However, despite Pakistan's immense renewable potential, Li-ion technology faces several adoption barriers.

First, because of limited local manufacturing, Li-ion BESS remain dependent on imported equipment, resulting in high upfront deployment costs as well as high operation and maintenance costs. Government taxes and customs duties further add to these costs, which have been a major source of reluctance towards large-scale investment [7].

Targeted fiscal incentives, including customs duty concessions, tax adjustments, and concessional financing facilities, are essential to encourage investment in localized Li-ion battery production [26]. Such incentives would help reduce dependence on imports, save foreign exchange reserves, and improve the country's green energy profile.

Second, most of the critical minerals used in Li-ion battery manufacturing, such as lithium, cobalt, nickel, manganese, copper, and graphite, are concentrated in a small group of countries, including Chile, Australia, China, Argentina, Indonesia, and the Democratic Republic of the Congo [27]. Pakistan lacks a substantial domestic supply of the basic raw materials needed to support Li-ion battery production. It also lacks commercial-scale recycling technology to recover these materials; without proper recycling, used batteries become an environmental liability and contribute to pollution. Investment in battery recycling technology is therefore important for mineral supply-chain management and for reducing dependence on imported raw materials [28].

Third, despite several policies promoting solar energy adoption, comprehensive regulations for battery storage systems remain unadopted. Current policies do not address battery energy storage, either for integration with the national grid or for use as a stand-alone backup system [3]. This policy gap has slowed investment in utility-scale energy storage, particularly in Li-ion battery systems. National policy has not defined regulatory issues such as tariff structures, ownership, licensing procedures, grid interconnection, and compensation mechanisms, creating uncertainty for investors about financial returns [29].

Battery storage systems are not incentivized through tax exemptions, investment subsidies, concessional financing, or subsidized loans to support residential, industrial, and commercial investment. Additionally, national technical expertise and standards remain underdeveloped, which affects consumer confidence, system stability, and the safe deployment of these systems across the country [29].

Fourth, a major technical challenge facing Pakistan is effectively integrating battery storage systems with the national grid. Inadequate substations, an outdated transmission structure, transmission and distribution losses, and limited grid flexibility hamper electricity supply efficiency [2]. The country's traditional grid was designed as a centralized transmission system; therefore, establishing battery storage systems and integrating them with the national grid requires serious investment in smart grids, digital substations, monitoring systems, and grid management automation [2]. Furthermore, because of limited planning and implementation experience, utility companies have not developed the necessary technical expertise through workforce training, international partnerships, and research collaboration.

Fifth, although Li-ion BESS produce low greenhouse gas emissions during operation, their production and disposal present certain environmental challenges [30]. Mining lithium, nickel, and cobalt consumes energy and water and can cause land degradation, pollution, and biodiversity loss [31]. Additionally, disposal requires specialized handling to avoid groundwater pollution and soil contamination. Pakistan lacks expertise in battery production, transportation, disposal, and recycling, which poses a serious environmental risk.

Finally, supply-chain concentration and geopolitical risks may become a major barrier. China largely dominates battery supply chains and has developed capabilities in processing key materials and producing battery components and cells [28]. This poses a significant risk, as reliance on imported materials and management systems can expose Pakistan to price fluctuations, trade restrictions, shipping delays, and shifts in geopolitical relations. If most of the value chain remains overseas, technology deployment may deliver fewer benefits than anticipated [3].

6. International Experience and Lessons for Pakistan

Pakistan can learn several lessons from countries that have developed battery storage technologies, including China, the United States, and South Korea. China has sustained industrial development and investment in battery manufacturing, renewable energy deployment, and electric vehicle production, making it a world leader. According to IEA assessments [6], China produces approximately 80% of the world's battery cells.

The United States' experience shows that public support for domestic manufacturing and financial incentives for research and development stimulate investment in battery based storage technology [32]. The key lesson for Pakistan from the U.S. experience is to build public support for adopting Li-ion BESS and incentivize small, localized projects through public–private partnerships. The government should attract private financing for micro-grids based on Li-ion BESS or other storage technologies to reduce the burden on the centralized power supply. However, unlike the United States, Pakistan does not need to develop the full Li-ion industrial value chain; instead, it should encourage a phased approach involving foreign investment and private industry. This will not only develop an industrial base for Li-ion batteries but also create jobs and skilled human resources [26].

South Korea established collaboration between the government and battery manufacturers, illustrating the importance of technological innovation [33]. The South Korean experience is a classic example of technology development through research institutions and local industry. Pakistan can utilize its research institutions to partner with local battery manufacturers and support the industry through joint research and development ventures. The government needs to streamline and incentivize procurement procedures for importing base technologies and to encourage private investment in projects through public–private partnerships. Through its research institutes and local manufacturing companies, Pakistan should also collaborate with South Korean and Chinese companies for joint battery manufacturing ventures in Pakistan.

Pakistan is in a very different position from these countries in terms of technological research and development, economic investment potential, and the industrial base for material processing. These experiences suggest three priority areas for Pakistan: establishing a realistic investment framework, building a minimum domestic industrial base to indigenize technology, and developing integrated research partnerships with universities and private companies.

A phased approach, rather than full-scale deployment, suits Pakistan's transition. It should begin with needs-based imports and deployment to address energy challenges [26], followed by technical training programs in collaboration with international institutes, attracting foreign investment in technology development, and developing local assembly and recycling capabilities.

7. Policy Recommendations for Pakistan

The analysis shows that Li-ion battery technology offers a strong option for addressing Pakistan's energy challenges by integrating renewable energy into the national energy mix. However, to realize this potential, Pakistan needs a policy framework to deploy Li-ion BESS, introduce energy reforms, electrify the transport system, develop an industry to support Li-ion battery production, and manage environmental impacts. Internationally, batteries have been used successfully as a key component of electricity systems, providing flexibility and sustainability while integrating renewable energy.

The following policy recommendations are proposed to help Pakistan derive maximum benefit from Li-ion battery energy storage systems:

a. National Li-ion BESS Policy

A dedicated BESS policy is essential for Pakistan to clearly outline objectives, investment incentives, technical standards, regulatory terms, and implementation targets. Pakistan should devise a comprehensive national policy that considers the nature and utility of different storage facilities and includes clear assessment criteria for Li-ion BESS [7]. The policy should distinguish among industrial, residential, and utility-scale storage and set out specific incentives and regulations to encourage public–private cooperation. Clear regulations on grid integration, ownership, licensing, operation, end-of-life management, and safety should be developed to avoid implementation discrepancies and promote transparency [7].

b. Integration of Battery Storage into Renewable Energy Planning

Power sector planning should include battery energy storage as a fundamental part of Pakistan's renewable energy strategy.

Planned solar and wind projects should be evaluated by generation capacity and classified as grid-integrated, battery-supported, or utility-scale systems. Planning based on needs assessments may be followed by competitive bidding for wind-plus-storage, solar-plus-storage, and hybrid renewable energy projects. This can provide greater predictability and round-the-clock electricity availability [34].

c. Incentive-Based Adoption of Battery Storage Systems

Incentivizing adoption through tax reductions, easier financing, and targeted subsidies can help manage the high initial cost of battery storage systems. These incentives should encourage solar-plus-storage systems using Li-ion BESS to supply power outside peak generation hours, and they should be extended to schools, hospitals, agricultural units, and small industries to reduce the load on the grid [35].

d. Upgradation of the National Grid

Transmission and distribution infrastructure must be upgraded regularly to meet growing electricity demand. Since Li-ion BESS cannot resolve the electricity system's structural weaknesses on their own, regular grid modernization that enables their future integration is necessary. Automated controls play an important role in modern energy management systems, and grid automation can facilitate future BESS integration. For system stability, battery storage systems can be deployed in areas facing voltage instability or transmission congestion, and at utility sites where peak generation capacity is unreliable [3].

e. Indigenization of Li-ion Battery Manufacturing

Gradual progress toward full Li-ion battery manufacturing is quite a viable option, not only to build an industrial base for modern storage systems but also to provide a potential platform for exporting these technologies to other countries [26]. Pakistan should adopt a phased industrial development strategy that evolves from research and assembling imported battery components to domestic manufacturing, building capabilities in cell manufacturing, material processing, and Li-ion battery recycling.

f. Development of Recycling and Material Processing Capabilities

A circular economy framework covering battery production, material processing, and effective recycling is essential to reap the full benefits of the technology [31]. Research on second-life applications can help repurpose used batteries that are no longer suitable for their original purpose.

g. Integration of Electric Vehicles in Transportation Sector

The transportation sector should be encouraged to adopt Li-ion battery-powered electric vehicles, and the government should

incentivize this transformation. Smart charging infrastructure must be established to complement this strategy [32, 33].

h. Solar-Plus-Storage Strategies

In rural areas, solar-plus-storage systems using batteries can help overcome load shedding by providing a reliable backup electricity supply. Total reliance on centralized electricity supply to rural areas is not only costly to establish but even more costly to maintain, given the need to balance supply and demand.

i. Supply Chain Diversification

Pakistan should pursue supply-chain diversification through transparent procurement, developing domestic expertise in cell and battery component processing, and partnering with diverse suppliers [29]. These measures may not eliminate import dependence entirely, but they could substantially reduce the risk of supply disruptions.

8. Conclusion

The study concludes that Li-ion BESS offer a valuable option to complement Pakistan's energy transition and to tap renewable sources, especially through solar-plus-storage systems. Li-ion batteries provide a diversified, sustainable, and resilient energy system option that can help Pakistan overcome electricity shortages, rising energy costs, dependence on fossil fuels, grid instability, and ever-increasing energy demand. It is a future-oriented technology with the potential to support Pakistan's energy sustainability. It can improve renewable energy integration, reliability, and energy security by storing electricity generated during peak generation periods and providing vital supply when demand increases or generation declines.

The analysis indicates that Li-ion battery storage systems offer a near-term deployment option that supports solar and other renewable electricity systems while providing reliable backup and grid support. However, these benefits depend on affordability, grid integration capacity, technical expertise, and the risks associated with international supply-chain dependencies.

The study's main finding is that battery-based storage is not a standalone solution to Pakistan's energy challenges and should be deployed according to specific needs and potential. Policymakers should adopt a phased approach to support integration into the national energy mix and progressively reduce dependence on international supply chains.

This phased approach involves, first, prioritized deployment according to needs and applications, considering other energy storage options in tandem; second, strengthening domestic capabilities through investment in training, promotion of foreign investment, and indigenization of processes; third, developing recycling expertise to meet environmental responsibilities and sustainable development commitments; and finally, avoiding undifferentiated expansion in order to maintain supply-chain resilience.

Pakistan needs to develop a policy for the strategic deployment of Li-ion BESS across the country based on supply–demand gaps. This deployment should be based on site-specific studies to assess the feasibility of appropriate storage systems. Although Li-ion BESS offer an immediate, rapidly deployable option, decision-making must be based on site-specific assessments of economic and technical viability.

Pakistan can reduce its dependence on imported fuels by integrating suitable energy storage systems to benefit from renewable energy sources. This will not only support Pakistan's socio-economic development but also help it meet its environmental commitments and sustainable development goals.

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