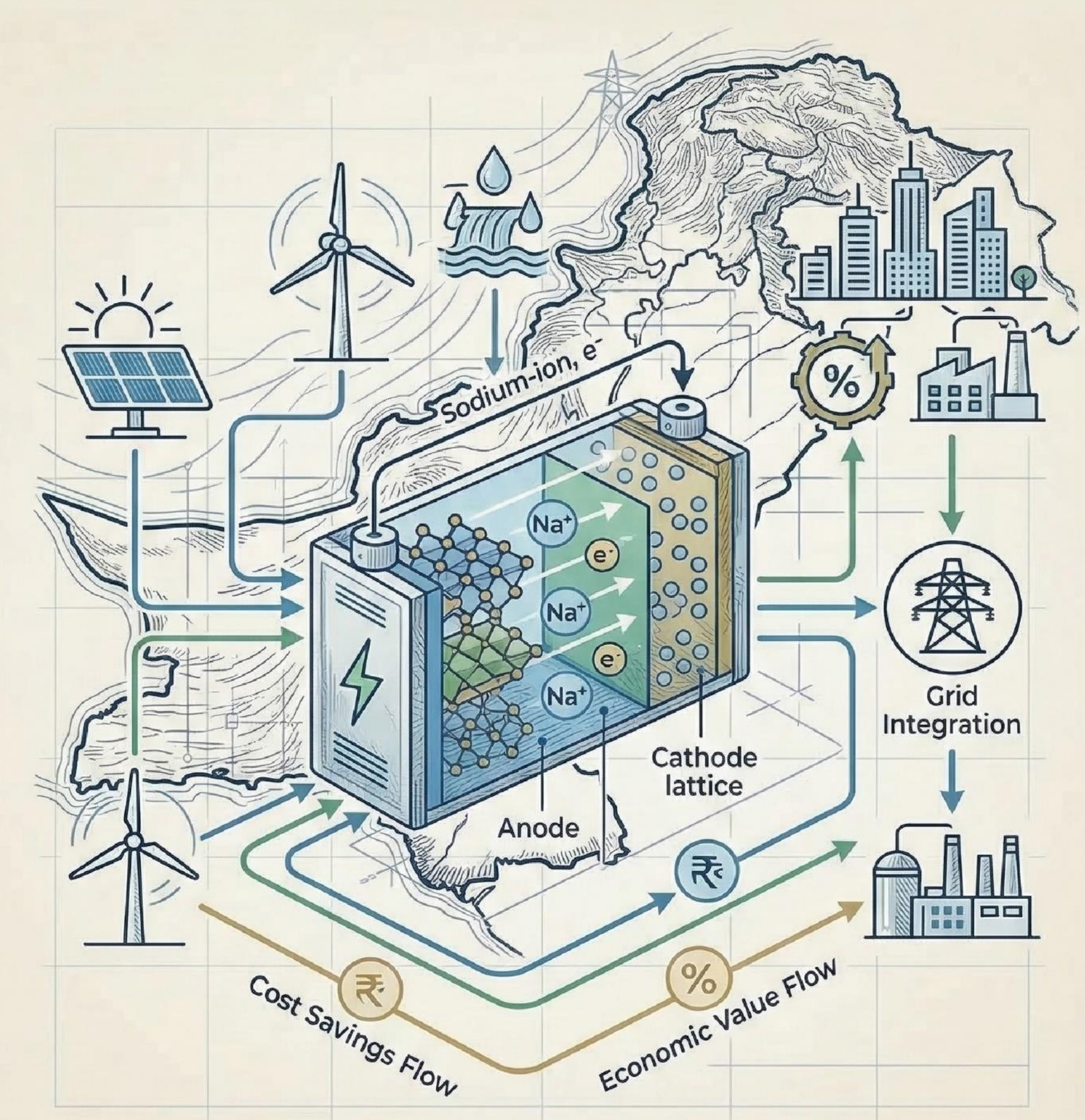
Sustainable Development Policy Institute

ANALYSIS OF SODIUM ION BATTERY STORAGE

A Technical and Economic Blueprint to Resolve Pakistan's Power Crisis



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Executive Summary

The global energy transition has entered a critical phase where affordable and sustainable energy storage solutions are paramount. Though Lithium-ion batteries are gaining dominance in the market largely due to the high energy density and capacity, their supply chain dependence on the rare mineral inputs and their environmental impact are reducing the supply chain resilience and driving the prices up. On the contrary, the Sodium-ion batteries (SIBs) have emerged as a promising strategic option utilizing low-cost, and safer materials while offering strong performance in terms of stationary storage and decentralized applications.

In case of Pakistan, the energy storage capacity remains at a premature stage due to the dilemma of meeting energy demand and managing over capacity which can be transitioned to a green-industrial opportunity of localizing sodium-ion battery (SIB) value chains and deploying them where they are more vulnerable, such as for grid firming in renewable corridors, peak management in cities, coal-to-storage repurposing, and rural microgrids. Pakistan has abundant biomass resources, a large reserve of rock salt, and chemical industry facilities. Thus, the country is ideally placed to localize the value chain in sodium-ion. The potential of domestic production of sodium metal and biomass-derived hard carbon could put cell costs at USD 60/kWh. It would offer an up to 30-40 per cent system-level cost advantage over imported lithium-ion systems. When installed along the renewable corridors in Pakistan, SIBs employ widely accessible cheap and thermally stable resources (sodium, iron, manganese, hard carbon) and do not need rare and geopolitically concentrated materials.

Beyond this, the climate and market conditions in Pakistan, their safety, high-temperature tolerance, and reduced thermal requirements all combine to result in reduced capex and opex compared to similar-sized systems using lithium in a stationary application. The study estimates a total system cost of about USD 152/kWh SIB versus around 200/kWh for lithium-ion batteries at grid scale - a 24 per cent reduction due to lower prices of input and simpler thermal management. This cost advantage can be realized domestically. The presence of rock-salt deposits means that metallic sodium can be produced using the Downs process at a cost of PKR 275-375/kg (USD 1.0-1.45/kg), which is much lower than international market prices of USD 2.5-3.0/kg, since both electricity and feedstock are locally available nearby at a large-scale at a low cost.

Agricultural by-products, including 80 Mt/year bagasse, rice husk, wheat straw, and cotton stalks, can be used as raw materials via pyrolysis, in the form of hard-carbon anodes. On the system side, priority deployments can quickly help alleviate renewable-caused curtailment and capacity-payment oversights. In this study, modeling illustration indicates a 5-10 MW/20-40 MWh SIB blocks at 10 strategic nodes that would cost ~USD 60.8 million (vs ~USD 80 million for Li-ion), with 2 to 4 hours of the dispatched value to cover the 18:00-22:00 peak and substitute ~100 MW of the thermal capacity.

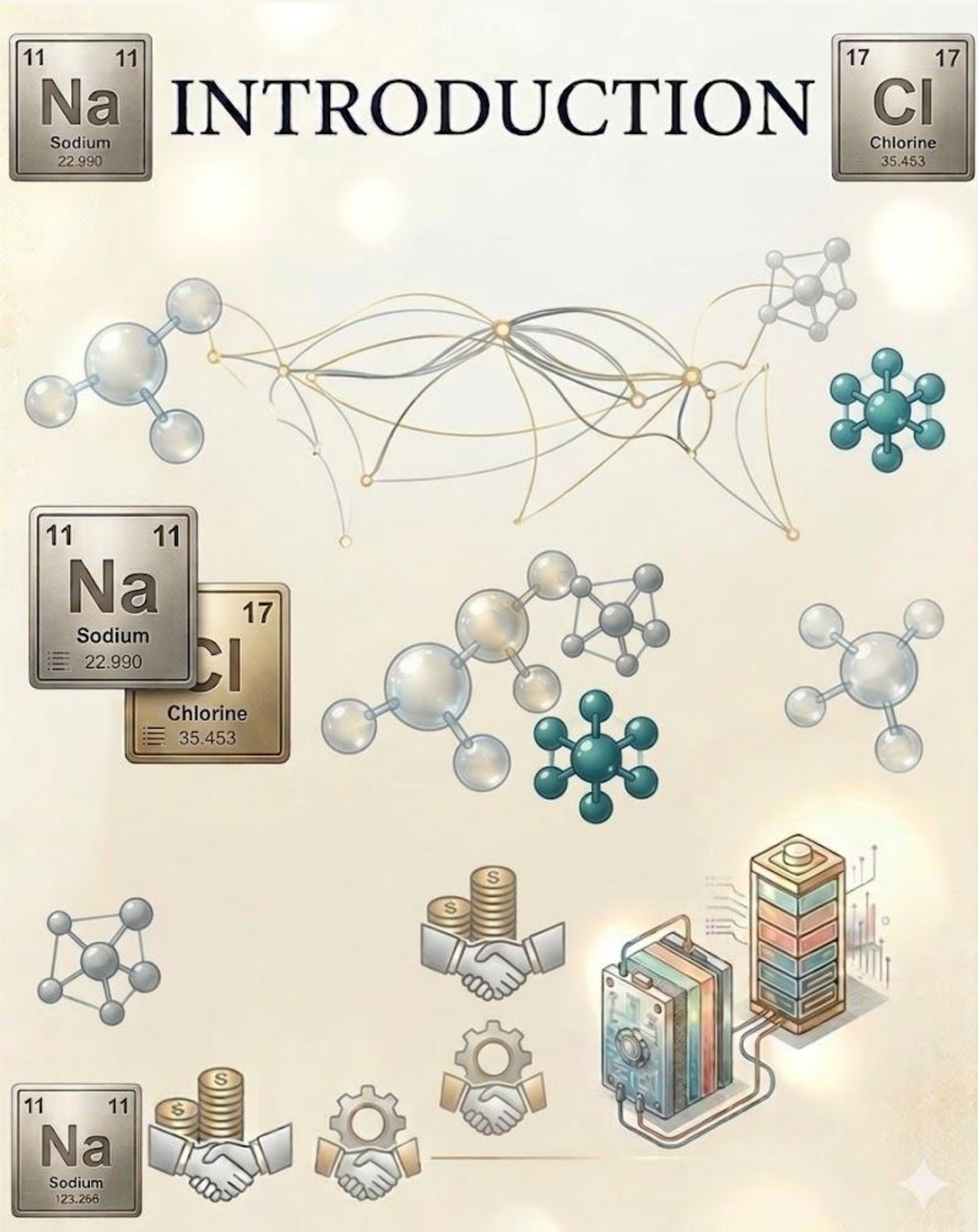
At distribution level, 2 MW / 8 MWh units at 11/33 kV substations open tariff arbitrage opportunities and transformer relief, at simple paybacks less than eight years in your tariff example. In the case of rural access, a 20 kW PV + 100 kWh SIB microgrid costs USD 35-40 k (share of the battery costs USD

15.2 k), and it can illuminate 1,000 sites and provide power to 100-120k households at LCOE 0.12-0.15 USD/kWh, which is significantly lower than the one that diesel can provide. A key transition pathway involves repurposing underutilized coal plants into solar-plus-storage hubs. For example, Sahiwal has experienced a >70 per cent generation reduction due to high fuel and generation costs. In this context, a 100 MW/400 MWh to 200 MW/800 MWh SIB could be activated for approximately USD 60-120 million using existing grid interconnections — thereby avoiding imported fuel risks and reducing capacity-payment pressures.

The curtailment cost signal already ensures that it is quite strong. The NPMV payments on un-evacuated RE increased by an order of magnitude to PKR 39.5 bn (FY24) in Jhimpir and other wind corridors, where SIB blocks could substitute the expected cost to PKR 11.8 (FY23) and PKR 1.9 bn (FY22). Under CPEC Phase II, Special Economic Zones (SEZs) such as Allama Iqbal Industrial City, Rashakai & Dhabeji) offer anchor sites to establish sodium refining, cathode precursors, cell assembly and export-pack integration that can leverage the really already established chlor-alkali, fertilizer complexes, port access and access to the 132-500 kV grid. That makes Pakistan well-positioned to sell products regionally to the Middle East, Central and South Asia, and Africa where there is an emerging demand in robust, hot-climate storage.

To unlock investment, Pakistan should (i) integrate storage, including SIB, into NDC delivery, IGCEP, and DISCO planning, (ii) establish MRV protocols so that SIB projects might qualify for Article 6 transactions, blended climate finance, and concessional gridside pilots, and (iii) adopt a national battery roadmap with SEZ-based fiscal incentives, domestic-content milestones, and technology-partnership pathways (CATL/HiNa/Reliance-Faradion).

The strategic implications extend beyond energy security. Under CPEC Phase II, SEZs provide an enabling environment for sodium refining, cathode synthesis, and cell assembly, positioning the country as a regional hub for affordable storage exports to South Asia, the Middle East, and Africa. Repurposing under-utilized coal plants as battery hubs, integrating SIBs into rural microgrids, and embedding seasonal storage for peak demand management. Therefore, sodium-ion technology has progressed beyond the experimental phase and is becoming increasingly viable for industrial applications. For Pakistan, they represent a rare convergence of natural resource advantage, industrial capacity, and strategic geography.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1. Introduction

1.1. Strategic Context of Pakistan's Energy System

Grid stability is linked to the ability of a power system to maintain the continuous and reliable supply of electricity even if supply and demand fluctuate. It is generally jeopardized by the increasing presence of intermittent renewable energy sources as well as the decommissioning of centralized thermal generation units. Historically, enormous thermal and hydro power facilities provided grid stability, due to the intermittent nature of wind and solar resources, the required decentralized generation, and reservations against pumped hydro construction, the grid is becoming increasingly complex. Within this changing environment, Battery Energy Storage System (BESS) provides the basis for renewable energy convergences around the world (Horzela-Miś & Semrau, 2025).

BESS has been introduced as a vital means of modernizing grid operation, allowing for faster and more adaptable support to preserve grid consistency. It can react in milliseconds, altering the grid frequency to compensate for fluctuations in power supply and demand, keeping the frequency close to standard values (typically 50 or 60 Hz). It provides reactive power to change voltage levels, which is a particularly important function in high-penetration renewable parts (Smith, Cattell, Farcot, O'Dea, & Hopcraft, 2022). They are also particularly significant in load balancing and peak shaving, where energy is stored off-peak and released when demand is high to relieve grid stress and reduce the utilization of expensive peaker plants.

Figure 1: Types of energy storage technologies with distinct characteristics

Figure 1 highlights the most significant problems that are presented by renewable intermittency and peak demand as well as integration of variable sources such as wind and solar. Lithium-ion (Li-ion) batteries are the most common that have powered the energy storage market today. However, rising concerns in the environmental, regulatory, and supply chain safety-related issues concerning high costs, thermal safety, threats of supply chain bottlenecks because of critical minerals are creating a market breakthrough in using alternative chemistries, especially in sodium-ion (Na-ion) batteries.

These incorporate sodium (Na+) ions as charge carriers rather than lithium, and although they can provide a lower specific energy level without lithium, they are thermally more stable, much safer, and far less costly to manufacture. Their raw materials, such as sodium, iron, and manganese, are much more readily available and easily accessible than lithium, cobalt, and nickel and confer on them a strategic position when it comes to large-scale stationary storage.

As prices of lithium in the international markets continue to fluctuate and as the demand follows suit, sodium-ion batteries have risen as the next significant advancement in the field of batteries. By 2035, global sodium-ion battery production capacity is projected to reach at least 90 GWh, driven by major players in China, India, and the EU. Sodium-ion R&D efforts have concentrated first on commercializing a battery by a small number of companies, such as CATL, HiNa Battery and Reliance Industries, which are aiming to have products available in a matter of years (Nekahi et al. 2024). These advancements make sodium-ion batteries more promising within grid-scale storage and low-speed electric mobility, where the cost and safety and supply of materials are of greater importance than portability or high power-to-weight ratios (ATGE Plus Ltd., 2025).

1.2. Peak Load Balancing

Pakistan is currently facing a growing power crisis despite a generation surplus, with decades of above-required supply-side investments failing to resolve power outages, soaring electricity prices, and an escalating circular debt now nearing PKR 1.8 trillion (and continuing to rise) (NEPRA, 2024). The root of this issue lies in Peak Load Management and the country's seasonal demand patterns. As shown in the graph, electricity demand peaks during the evening hours, with 15.8 GW reached between 18:00 and 22:00, while tapering off in off-peak hours. This generation pattern, along with the growing need for flexibility in managing high and low demand periods, presents a major challenge as the country transitions to higher shares of renewable energy sources like solar and wind, which are intermittent and cannot consistently meet peak demand.

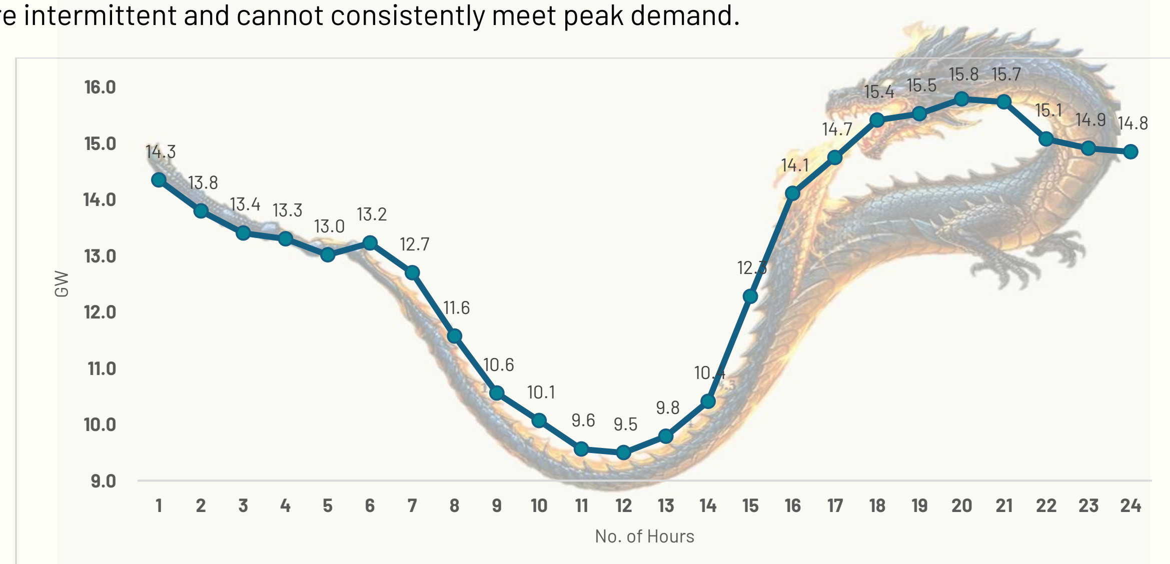


Figure 2: Generation Pattern – GWh (15th Oct 2025)

Although Pakistan has ambitious targets to achieve 60% renewable energy generation by 2030 under its Nationally Determined Contributions (NDCs), current policies, such as the Indicative Generation Capacity Expansion Plan (IGCEP) 2024-30 and the Alternative Renewable Energy Policy 2019, fail to sufficiently address the integration of energy storage solutions. This creates a gap between aspirations and action, especially when managing the daily and seasonal fluctuations in demand.

This is where sodium-ion technology offers a strategic advantage for Pakistan. Sodium, an abundant and cost-effective resource compared to the rare and expensive lithium, can be leveraged for BESS. Sodium-ion batteries are an ideal solution for Peak Load Management, allowing excess energy to be stored during periods of low demand (such as midday) and released during peak hours in the evening, ensuring grid stability and minimizing price volatility. These batteries are also well-suited to address Pakistan's seasonal demand patterns, where high electricity usage in the summer for cooling contrasts with the need for reliable backup during winter peaks.

Integrating sodium-ion energy storage into national energy planning would not only alleviate pressure on existing transmission systems but also enable more effective demand-side management and reduce transmission losses. Given Pakistan's vast sodium resources, this technology presents a more economic and sustainable alternative to lithium-based solutions, especially in the context of renewable energy integration. Moreover, as the demand for renewable energy grows, sodium-ion batteries can complement solar and wind generation, which will help smooth out the fluctuations.

Abundant Natural Resources

Khewra Salt Mine: The second-largest salt mine in the world and the largest in Pakistan, producing more than **350,000 tons** of high-purity halite salt per year.

Vast Tunnel Network: The mine has a tunnel network **730 meters** deep and about **40 kilometers** of tunnels, providing a solid foundation for establishing a sodium-ion battery industry.

Economic and Fiscal Benefits

Low-Cost, Domestic Energy: By utilizing locally produced sodium from the Khewra Salt Mine, Pakistan can ensure **low-cost sources** for grid stability, eliminating dependency on imported fuels.

Reduction in Energy Import Costs: Investing in sodium-ion battery manufacturing would allow Pakistan to reduce reliance on expensive imported fuel for energy generation, creating long-term cost savings.

Sustainable Industrialization

Energy-Efficient Manufacturing: Unlike energy-intensive processes such as crypto mining, which consume large amounts of electricity without contributing to industrialization.

Environmental Benefits: Sodium-ion battery production has a **lower environmental impact** compared to traditional energy-intensive industries, supporting a greener energy transition.

Figure 3: Strategic Advantage of SIBs in Pakistan

1.3. Clean Energy Transition with Sodium-Ion Technology

Nevertheless, Pakistan has yet to recognize the importance of power of energy storage — specifically in the context of sodium-ion technology — in its NDCs or energy sector strategies.

Adoption of Na-ion in national energy and climate strategies would be needed to facilitate Pakistan reach its targets of renewable energy and electric vehicles (60% RE and 30% EV penetration by 2030). In the absence of a strong storage network, uncertainty in renewable power availability will remain a destabilizing risk on the grid, increase curtailment, and undermine the viability of decarbonization objectives. Integrating energy storage into long-term policy plans, such as the NDC implementation roadmap, would also open climate financing.

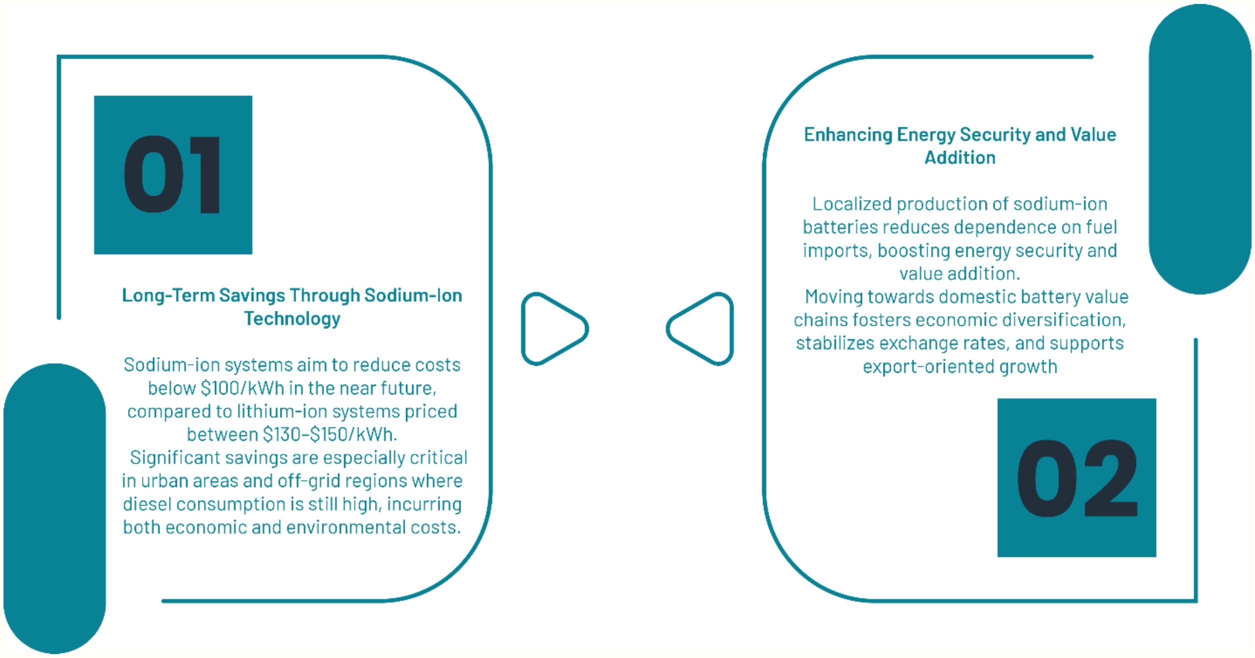


Figure 4: Opportunity in Clean Energy Transition with Sodium-Ion Technology

This interest in sodium-ion batteries is compounded by the geographical location: Pakistan is a country located at an ideal place. The developing countries such as Afghanistan, Central Asia, and the Middle East also seek to explore decentralized energy systems based on renewables and need affordable and thermally stable battery designs. With a smart investment in sodium-ion research and development, production, and bilateral collaborations, Pakistan might emerge into a leading exporter of green battery technologies in the agreed energy corridor of the South and Central Asia. This would not only accommodate domestic grid stability and energy security but also form part of the national green industrialization and equitable energy transition - a just energy transition where access to energy is democratized. It creates job opportunities and makes Pakistan a viable energy marketplace in the future.

1.4. Significance and Objectives

This study aims to initiate energy and industrial policy debate in Pakistan by repositioning the country's mineral and agricultural endowments not as passive commodities, but as strategic resources for technological transformation. Unlike extractive and energy-intensive processes such as crypto mining, which have little to no fiscal benefit, and limited appropriate job creation as well as the production of no products contributing to a more energy-resilient system, the research sees sodium-ion battery development as a high-leverage structural-change opportunity. Through the realization of the potential of abundant deposits of sodium chloride in Pakistan and the use of agricultural wastes as battery materials for locally produced battery production, the study emphasizes to shift the trend of speculative digital economies (mining bits) to value-added green industrialization (mining salt) based on indigenous resources. This transition not only better aligns with national development ambitions, including energy security, decarbonization, and the provision of employment opportunities, but also places Pakistan in a global market that is in the ascent in terms of affordability, security and scalability of battery storage.

The study further addresses a disintegrating policy gap by informing why Pakistan should have energy storage as part of its NDCs, IGCEP and SEZs. It also presents a workable roadmap towards climate-aligned economic diversification and regional export leadership. In such a way, the study not only offers the technical but also the political economy rationale as to why sodium-ion batteries might prove instrumental in a fair, inclusive, and sovereign energy transition in Pakistan.

GLOBAL LANDSCAPE

2. Global Landscape

2.1. Role of Energy Storage

The global energy storage market is experiencing remarkable growth, driven by the rapid expansion of BESS, which is becoming a critical component of the global energy transition. As countries strive to decarbonize their energy systems and meet ambitious climate goals, energy storage technologies are increasingly seen as essential for ensuring grid reliability, flexibility, and stability. The installed capacity of energy storage is expected to increase ninefold by 2040, reaching an impressive 4 terawatts (TW) globally (Anadolu Agency, 2023). This growth is largely attributed to the widespread adoption of BESS, which hit a record high in 2024, marking a milestone in the sector with the addition of 200 GWh of new storage capacity. As a result, the total global battery storage capacity reached 375 GWh (Berbatović 2025), highlighting the growing role of energy storage in balancing electricity supply and demand, particularly in response to the surge in renewable energy generation.

One of the main challenges in integrating renewable energy sources like solar and wind into power grids is their inherent intermittency. These renewable sources, while essential for achieving a cleaner energy future, are variable and cannot always meet demand when it is at its peak. As renewable energy generation continues to rise, energy storage will become critical in stabilizing the grid and providing the flexibility needed to ensure a reliable power supply. Energy storage systems help balance supply and demand in real-time by storing excess energy during periods of high renewable generation and releasing it during peak demand periods. This function is vital in reducing price volatility in power markets and maintaining a stable electricity supply.

Also, global power demand is expected to keep growing, with low-carbon energy sources increasingly filling the gap in meeting this demand. Energy storage will be pivotal in the provision of necessary flexibility to handle intermittent renewable energy and support the integration of these sources into the grid. As energy storage technologies continue to evolve and scale, they will play a crucial role in mitigating the challenges posed by renewable energy intermittency and will be essential in ensuring a reliable, low-carbon, and sustainable energy future.

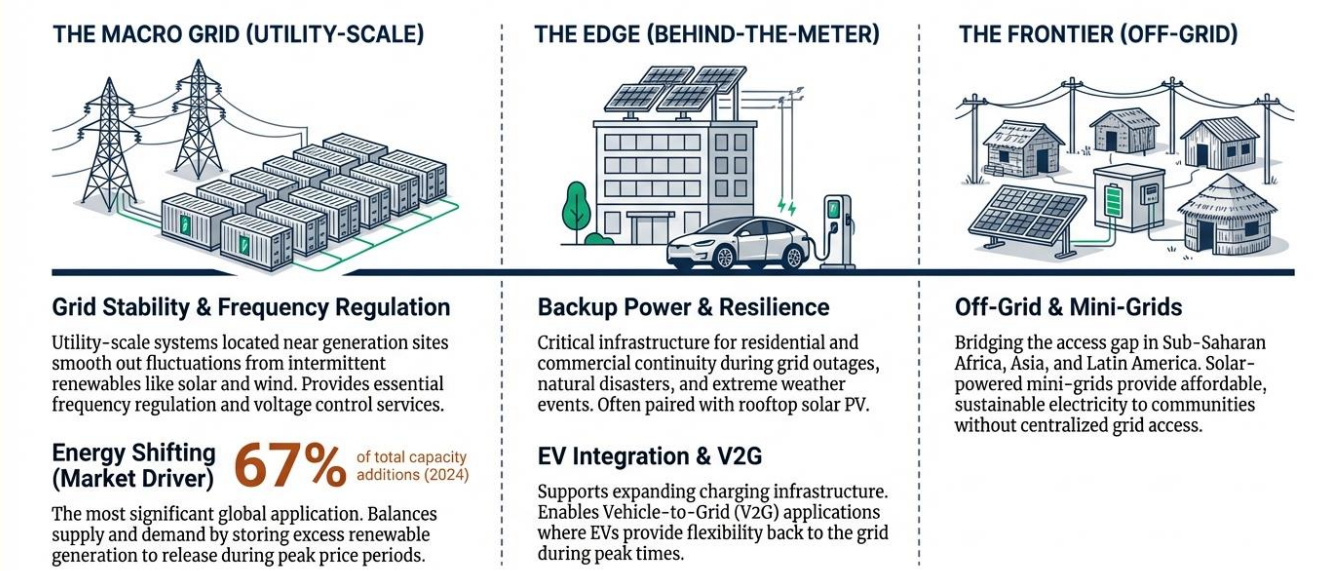


Figure 5: Five Pillars of Energy Storage

2.2. Technological Advancements and Cost Reductions in Battery Energy Storage Systems

Over the past decade, technological advancements have significantly reduced the cost of energy storage systems. By 2024, the global average cost of BESS has fallen to under USD 300 per kWh, a sharp decline from previous years. This trend is expected to continue, with prices potentially dropping to USD 250 per kWh, allowing electricity storage costs to reach as low as USD 60 per MWh (Colthorpe 2025). This reduction is driven by economies of scale, improvements in manufacturing processes, and innovations in battery chemistry, which have led to higher energy densities and longer cycle life. Manufacturers now guarantee more than 10,000 charge-discharge cycles, maintaining at least 80% battery health throughout the lifespan, increasing both reliability and cost-effectiveness (SmartPropel, 2023).

Over the last 10 years, installed costs have fallen by 20% per year on average, from USD 1,742/kWh to USD 192/kWh, while deployment has increased by around 80% per year (IRENA, 2025).

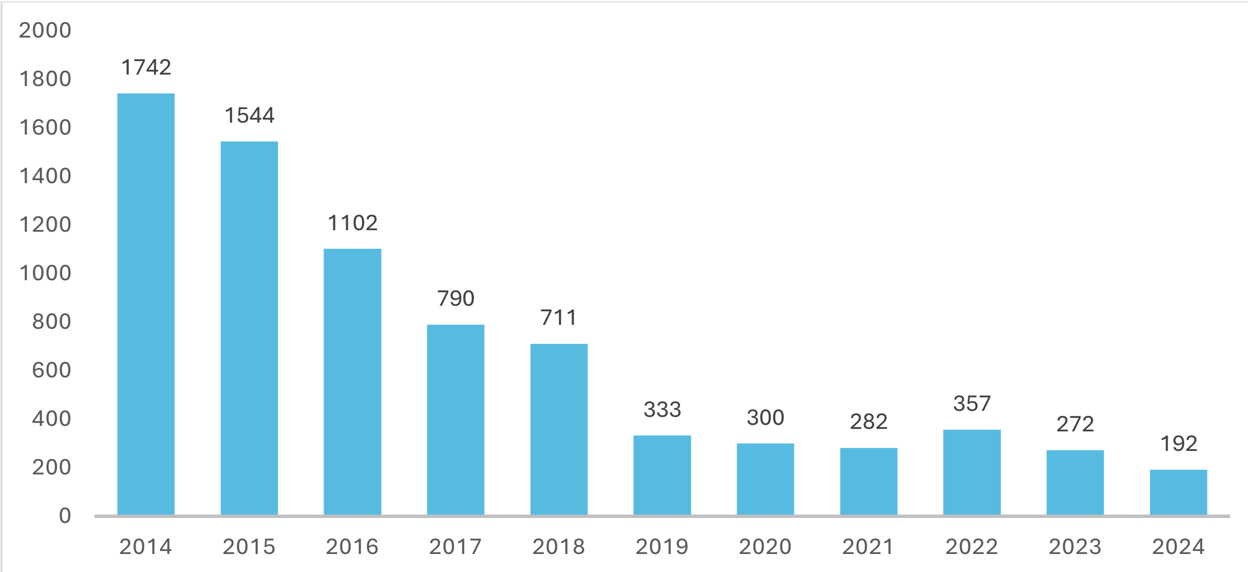


Figure 6: Cost trend of Battery Storage at project level ($/kWh)

This sharp decline is due to improvements in battery technology, increased manufacturing capacity, and more energy storage systems being used worldwide. As a result, energy storage is becoming more affordable and competitive with other power sources. For example, in 2024, the cost of a 2-hour battery storage system fell by 38%, and a 4-hour system dropped by 32% compared to 2023 (IRENA, 2025). These price reductions make energy storage a more appealing option for utilities, especially in areas with high renewable energy generation, where flexible and scalable solutions are needed for grid stability.

Categories of Battery Energy Storage System (BESS)

BESS falls into two main categories, i.e. utility-scale batteries and behind-the-meter batteries. Utility-scale batteries are typically large-scale systems connected to distribution or transmission networks or power-generation assets. These systems, with storage capacities ranging from several megawatt-hours to hundreds of megawatt-hours, are primarily used for grid applications like frequency regulation, energy shifting, and balancing supply with demand.

On the contrary, behind-the-meter systems are connected directly to electricity meters for commercial, industrial, and residential customers. Often paired with rooftop solar photovoltaics (PV) systems, these batteries are mainly used for purposes such as reducing electricity bills, managing demand, and providing backup power during outages. The variety in battery technologies reflects the diverse needs of different applications, whether requiring quick energy delivery for grid stability or long-duration storage for cost savings and reliability.

2.3. Regional Breakdown of Energy Storage Additions

The global energy storage market is experiencing rapid growth due to an increasing shift towards renewable energy and the need for more flexible power grids. The demand for BESS is expected to grow significantly as the cost of renewable energy continues to drop and the share of intermittent energy sources like solar and wind in the energy mix increases.

In 2024, the world saw 200 GWh of new BESS projects come online, increasing the total global operational capacity to 375 GWh. China remains the dominant market, accounting for over 100 GWh of new capacity, followed by the United States, which added 35 GWh. Germany, Australia, and the United Kingdom were also among the top five contributors. Looking ahead to 2025, global energy storage capacity additions are expected to reach a record 92 GW, representing a 23% increase from the previous year. By 2035, cumulative energy storage installations are expected to exceed 2 TW (approximately 7.3 TWh), driven by the accelerating pace of battery storage deployment across key markets (BloombergNEF, 2023).

2.3.1. China and the US Lead the Charge

Both China and the United States are expected to continue to dominate the energy storage market through 2035. Despite recent policy challenges, such as the removal of storage mandates in China and tariff-related uncertainties in the US, both countries are ramping up their energy storage deployments due to favourable market dynamics.

- **China:** As the largest market for energy storage, China is making concerted efforts to meet its ambitious renewable energy targets. The country aims to accelerate its transition from mandates to market-driven growth through the introduction of spot market mechanisms and provincial compensation schemes for energy storage.
- **United States:** The US market continues to expand despite recent shifts in federal energy policy, including changes to import tariffs and restrictions on Chinese equipment. However, with strong domestic battery manufacturing initiatives and the potential for higher battery demand in the stationary storage market, the US is set to remain a major player in the global energy storage race.

Both China and the US are benefiting from supportive policies, such as subsidies for energy storage systems that provide incentives for utilities to invest in storage technologies. Additionally, market-driven factors, such as the need to balance intermittent renewable energy and provide grid stability, make energy storage a crucial solution for meeting future power demands.

2.3.2. Europe's Growing Energy Storage Market

The European Union (EU) has set ambitious climate targets that are expected to drive demand for energy storage across the region. Several European countries, including Germany, the United Kingdom, and Spain, have implemented policies and incentives that support the deployment of energy storage systems, particularly battery storage and pumped hydro projects.

- In Germany, the transition to renewables (Energiewende) has necessitated the need for energy storage solutions that can provide grid stability and integrate renewable energy into the national grid. The EU is also working on expanding grid interconnectivity between member states to enhance energy security and balance supply and demand (Thimet & Mavromatidis, 2023).

- The UK, with its aggressive renewable energy targets and commitment to net-zero emissions by 2050, is also expanding its energy storage capacity (Solar Energy UK, 2023). This is primarily driven by the integration of offshore wind and solar energy projects, which require energy storage solutions to manage their intermittent nature.

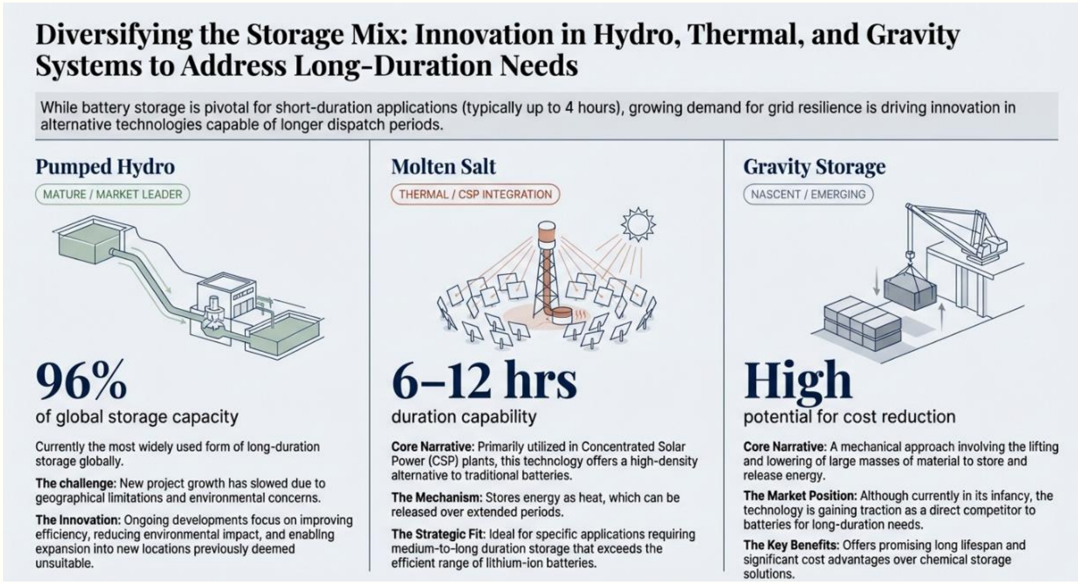
As countries are transitioning towards a low-carbon energy future, energy storage is expected to play a central role in balancing supply and demand, improving grid resilience, and enabling the widespread integration of renewable energy sources.

2.4. Global Trends in Technological Advancements in Energy Storage

Technological advancements in energy storage are driving the market's expansion, particularly with developments in battery chemistry, storage duration, and system integration. Among these, lithium-ion (Li-ion) batteries remain the dominant technology in the energy storage sector. Their cost-effectiveness, high energy density, and long lifespan have contributed to a dramatic price drop of over 90% since 2010, from USD 1,400 per kWh to less than USD 200 per kWh. This substantial price reduction has positioned Li-ion batteries as one of the most affordable solutions for integrating renewable energy into the grid.

In parallel, lithium iron phosphate (LFP) batteries are gaining significant traction in both electric vehicle (EV) and stationary storage markets due to their cost advantages, longer cycle life, and improved safety. By 2023, LFP batteries accounted for 80% of new battery storage installations and 40% of global EV sales, highlighting their growing prominence (Guerra 2025). Looking forward, solid-state and sodium-ion batteries are expected to play an increasingly important role in the future of energy storage. Solid-state batteries are anticipated to offer higher energy densities and enhanced safety features, while sodium-ion batteries present a more affordable alternative with lower material costs compared to lithium-ion batteries. Both technologies are poised for commercial deployment in the coming years, with solid-state batteries promising to revolutionize energy storage for both grid and transportation applications.

In response to the rising demand for long-duration storage, innovations in pumped hydro, compressed air, and gravity-based energy storage are gaining attention. Although these technologies are not as widespread as lithium-ion battery storage, they are seen as complementary solutions for addressing storage needs that require extended durations, ranging from 6 to 12 hours. As the demand for long-duration storage rises, these technologies could provide essential alternatives for grid stability and renewable energy integration.



A closer look at sodium-ion batteries reveals their significant market presence. As of 2024, 72% of the sodium-ion battery market is attributed to stationary energy storage, underscoring the dominant role of this sector in the sodium-ion battery landscape. The remaining 28% of the market is divided among other applications such as transportation, consumer electronics, and emerging sectors (Mordor Intelligence, 2025).

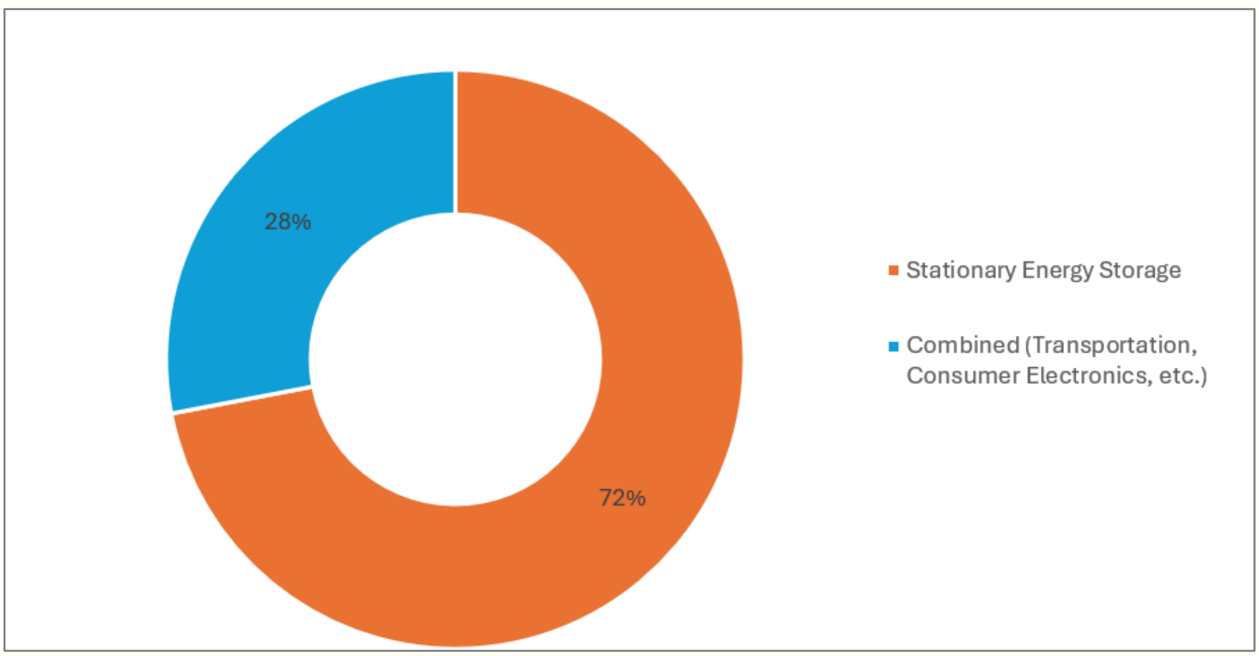


Figure 7: Sodium-Ion Battery Market Share by Application (2024)

Notably, sodium-ion batteries are increasingly being adopted for grid applications, renewable energy integration, and backup power solutions. According to Mordor Intelligence (2025), the utility sector holds 55% of the sodium-ion battery market share, signalling a strong demand for sodium-ion batteries in energy storage solutions.

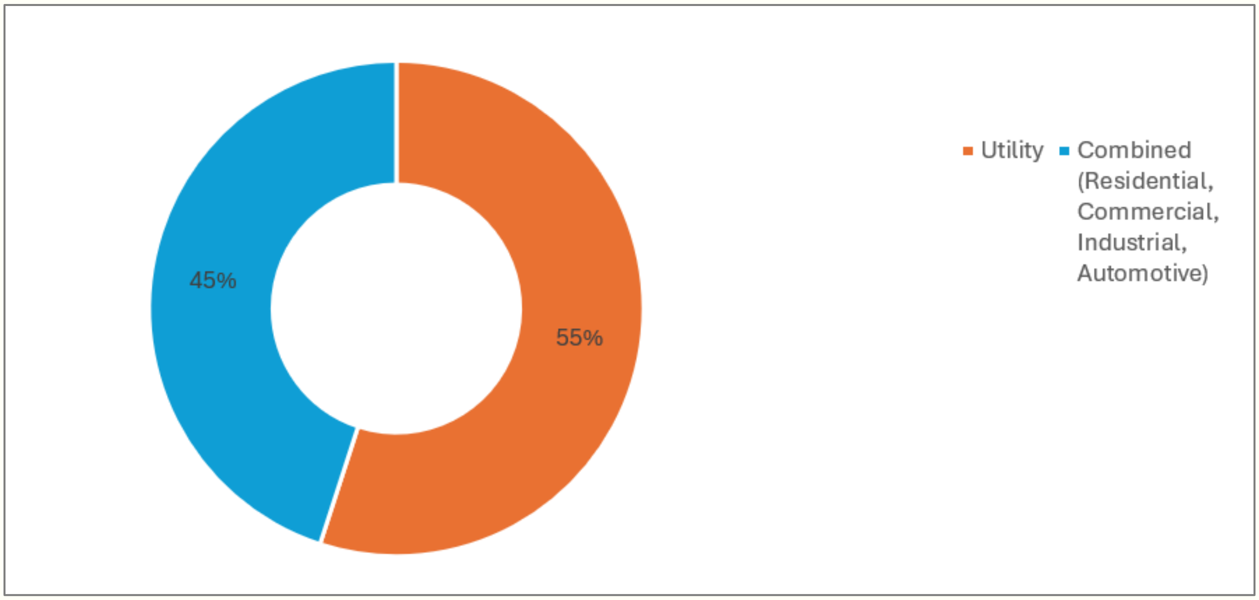


Figure 8: Sodium-Ion Battery Market Share by End-User Industry (2024)

2.5. Resource Availability, Innovation and Future Growth Projections

The global push for energy storage and clean energy transition is intricately tied to the availability of critical natural resources. As BESS becomes the cornerstone of modern energy infrastructure, the role of lithium, cobalt, nickel, and graphite, key materials in battery production, has gained increasing importance. As countries race to decarbonize their energy systems and meet ambitious climate goals, having access to indigenous resources and innovating with alternative storage technologies will be pivotal in shaping the future of energy storage.

Energy storage, particularly in the form of BESS, is set to experience unprecedented growth. According to projections from Rystad Energy and BloombergNEF, global energy storage capacity is expected to increase ninefold by 2040, reaching over 4 terawatts (TW). By 2025, annual energy storage installations are expected to hit an all-time high of 92 GW (equivalent to 247 GWh), a 23% increase over 2024 levels. Much of this growth will be driven by the continued expansion of lithium-ion battery technologies, which remain the dominant storage solution, owing to their efficiency and energy density.

However, this rapid growth is not without challenges. The materials required for lithium-ion batteries, such as lithium and cobalt, are relatively rare and expensive. Lithium is subject to geopolitical volatility and environmental concerns, making its supply chain prone to disruption. As global demand for energy storage and electric vehicles (EVs) surges, the need for alternatives to lithium-ion batteries has become more pressing.

Sodium-ion batteries, a promising alternative, are attracting significant attention due to their potential to provide a more affordable and abundant solution. Sodium, unlike lithium, is widely available and significantly cheaper. Sodium-ion batteries could help reduce dependency on lithium and cobalt, easing the supply constraints and environmental impact associated with these materials. However, while sodium-ion technology holds great promise, it currently lags behind lithium-ion in terms of energy density and cycle life, which means it still has some catching up to do in terms of commercial adoption.

The debate between lithium-ion and sodium-ion is crucial as the world faces a potential shortage of critical minerals needed for lithium-based batteries. While lithium remains the preferred option due to its high energy density and performance in energy storage, its high cost and limited availability make it an unsustainable long-term solution. Conversely, while sodium-ion technology provides a highly accessible and economical alternative, overcoming existing performance barriers remains necessary for widespread commercial adoption.

As energy storage systems continue to scale up, the global demand for critical materials like lithium will only intensify, raising concerns about supply chain security, environmental impact, and cost. Countries with abundant indigenous resources of these materials will be in a favourable position to strengthen their energy storage markets and energy security. However, a diversified approach to energy storage — incorporating both lithium-ion and sodium-ion technologies — will be essential to ensure resilience in global energy systems.

By 2035, cumulative energy storage capacity is expected to reach 2 terawatts (7.3 TWh), with China and the United States continuing to lead the global market. The increasing integration of renewable energy, especially in regions with high solar and wind potential, will accelerate the need for advanced storage solutions. As such, energy storage will play a critical role in balancing intermittent renewable energy generation and providing flexibility necessary for grid stability. In the long-term, to meet the targets set by the Net Zero Emissions (NZE) by 2050 scenario and the Paris Agreement, energy storage capacity must grow rapidly. By 2030, global energy storage capacity needs to increase to 1,500 GW to accommodate the expanding share of renewables and achieve the goal of limiting global warming to 1.5°C by 2100.

COMPARATIVE ANALYSIS OF SODIUM-ION BATTERIES

3. Comparative Analysis of Sodium Ion Batteries

3.1. Performance Comparison

As the global demand for energy storage continues to rise, especially with the shift towards renewable energy and electric mobility, the choice of battery technology becomes increasingly critical for a sustainable and equitable energy future. Both sodium-ion batteries (SIBs) and lithium-ion batteries (LIBs) are the key players in this space, thus they present distinct advantages and challenges depending on their applications, environmental impact, and resource availability. The growing interest in sodium-ion technology stems from its potential to address the limitations of lithium-ion batteries, especially concerning resource scarcity and cost in regions that rely heavily on decentralized energy access.

Table 1 below compares the key differences between sodium-ion and lithium-ion batteries, focusing on factors such as resource availability, environmental impact, cost, and suitability for various applications. It highlights the strengths of sodium-ion batteries in terms of safety, temperature performance, and cost while also addressing the higher energy density and established market presence of lithium-ion batteries (Nayak et al. 2018). This framework serves as a basis for critically assessing sodium-ion roadmaps and the future scenarios necessary for achieving techno-economic parity with lithium-ion batteries (Yao et al. 2025).

Table 1: SIBs vs. LIBs for a Just Energy Transition

Dimension	Sodium-Ion Batteries (SIBs)	Lithium-Ion Batteries (LIBs)
Resource Availability	Uses abundant, globally distributed sodium—reduces reliance on geopolitically sensitive supply chains and supports resource equity.	Dependent on geographically concentrated lithium and cobalt reserves (e.g., Chile, Bolivia, DRC), leading to potential geopolitical tensions and resource extraction inequalities.
Environmental Impact	Lower life-cycle GHG emissions (43–57% reduction projected by 2050); lower water and ecological footprint; no cobalt use.	High carbon and water footprint due to energy-intensive mining; concerns over habitat disruption and unethical practices (especially with cobalt).
Cost and Affordability	Projected to be 10–30% cheaper in the long-term; fewer safety and thermal management requirements; better total cost of ownership in remote or rural applications.	Currently cheaper upfront due to scale but higher lifecycle costs; requires expensive BMS and cooling in high-demand or outdoor environments.
Charging	Faster charging times	Slower charging time
Safety	Inherently safe with no thermal runaway; ideal for low-income, off-grid communities; no need for complex fire suppression.	Safety risks exist (e.g., overheating, thermal runaway); safer variants like LiFePO4 still require managed environments and BMS integration.
Temperature Performance	Operates between −20°C to +60°C without efficiency loss—ideal for	Sensitive to temperature extremes; requires active thermal management

	harsh, off-grid, or disaster-prone settings.	in cold or hot climates, adding cost and complexity.
Energy Density	Lower (typically 90–150 Wh/kg), but acceptable for stationary storage, grid support, or short-range mobility.	Higher (150–250 Wh/kg); ideal for portable electronics and long-range electric vehicles.
Cycle Life & Deep Discharge	High tolerance to deep discharge; supports long lifespans with minimal degradation; ideal for variable renewable energy storage.	More sensitive to deep discharges; frequent cycling reduces capacity over time without robust BMS.
Recycling and Circularity	Easier recycling potential due to simpler, less toxic chemistry; lower material value currently limits economic incentive.	Growing recycling efforts, but limited efficiency and scale; complex chemistries hinder cost-effective material recovery.
Industrial Policy and Localization	Uses non-strategic, widely available materials—greater potential for local manufacturing in developing countries.	Strong global market integration but less scope for domestic value chain development without heavy investments.
Suitability for Remote/Rural Use	Ideal for rural electrification, microgrids, off-grid applications, and RV/caravan systems due to affordability, safety, and temperature tolerance.	Better for urban, controlled, high-performance environments; not optimized for off-grid or harsh settings without additional systems.
Relevance to SDG7 and NDCs	Not yet integrated in Pakistan's NDCs, but aligns with SDG7 goals for clean, affordable energy; can complement Article 6 implementation for inclusive mitigation.	Widely used in mobility and grid-scale projects; integral to current NDC pathways but not ideal for decentralized energy justice applications.
Gender and Social Equity Impact	Enables clean energy access in remote communities, empowering women (e.g. lighting, cold chains, clean cooking); lower barriers to adoption.	Limited reach without subsidies or infrastructure; less accessible for informal or rural sectors due to cost and safety limitations.
Market Readiness and Innovation	Emerging but growing (CATL, Faradion, Natron, Tiamat); suitable for public investment, localization, and targeted R&D; especially promising for developing countries.	Market mature with large-scale investment; dominant in EVs and electronics; innovation focus is now on solid-state variants and reducing supply chain vulnerabilities.
Flexibility for R&D	Raw material available – Inexpensive R&D process	Imported – Expensive / Limited

3.2. Case Studies on Energy Storage through Sodium-Ion Batteries

The use of sodium-ion batteries in energy storage projects is growing globally. There are several case studies that demonstrate SIOs potential to support transition to renewable energy. Notable examples include the Baochi Station, Fulin Station, and Shanxi Project, each focusing on different aspects of sodium-ion technology, such as grid stabilization, energy smoothing, and the transformation of traditional coal-based industries (Energy News, 2025). These projects highlight the diverse applications of sodium-ion batteries, from hybrid grid-forming solutions to standalone storage systems. They also showcase the advancements in efficiency, cost reduction, and environmental benefits that sodium-ion technology can offer (SodiumBatteryHub, 2025). Table 2 below outlines the key differences in project type, capacity, innovation highlights, and economic impact across these case studies, providing a detailed comparison of their contributions to the energy storage landscape.

Table 2: SIBs Case Studies: Overview and Impact

Dimension	Baochi Station (Yunnan)	Fulin Station (Guangxi)	Shanxi Project (Huayang Group)
Project Type	World's first grid-forming hybrid sodium-lithium battery plant	China's first standalone sodium-ion battery energy storage station	Coal-based sodium-ion battery industrial chain transformation
Capacity	200 MW / 400 MWh; 580 GWh/year output	Initial: 10 MWh → Scalable to 100 MWh	1 GWh of cell annually
Deployment Date	Commissioned May 2025	Commissioned May 2024	Industrial chain established since 2019
Grid Function	Grid-forming: autonomous voltage/frequency control	Stationary storage; grid-scale energy smoothing	Potential for grid storage; focus on manufacturing innovation
Innovation Highlights	3× higher output & 6× faster response than traditional Na-ion; integrates Li-ion for high-frequency response	210 Ah cells; charges to 90% in 12 minutes; 92% energy efficiency	Uses hard carbon from anthracite coal for anodes; wide operating temp (−20°C to +60°C); 90% efficiency
Carbon/Climate Impact	98% renewable energy use; avoids RE curtailment (~120 GWh/year); supports 270,000 households	Avoids 50,000 tonnes CO_2/year; powers 35,000 households	Converts carbon-intensive coal value chain into low-carbon battery material production
Economic Impact	Estimated 30% cost reduction over sodium-only systems; market-based electricity services	Potential 20–30% cost reduction via structural and process improvements	Industrial revitalization of a legacy coal enterprise; job retention and upskilling
Location Strategy	Western China (Yunnan) with high RE penetration	Southern China (Guangxi) with growing demand and solar potential	Northern China (Shanxi) — traditional coal hub transitioning into clean-tech manufacturing center
Strategic Role	Flagship for hybrid storage and grid stabilization under RE transition	Pilot model for rapid-deploying, efficient sodium-ion storage infrastructure	Just transition model for fossil fuel regions; vertical integration for national battery sovereignty
Technology Readiness	Advanced hybrid integration; grid-forming tech under standardization	Utility-scale pilot; showcases Na-ion	First in China to develop complete Na-ion

		parity with Li-ion on efficiency & speed	battery production chain
Policy Implications	Influences 40% of projected new storage capacity by 2030 (grid-forming)	Demonstrates fast deployment and sodium-ion maturity; encourages RE-linked storage rollouts	Supports national goal of clean coal utilization; enhances strategic raw material independence

3.3. Key Drivers and Use Cases of Sodium-Ion Batteries in Energy Storage

The sodium-ion battery market is seeing rapid development, driven by a range of factors that highlight its potential across various applications. One of the key drivers is China's policy-backed grid tenders, which are boosting the demand for large-scale energy storage systems, particularly in regions with high renewable energy penetration. This growth is expected to have an immediate impact, particularly for grid stabilization and energy storage projects. Furthermore, the breakthrough in Prussian-Blue cathodes is enabling faster charging capabilities, making sodium-ion batteries an attractive solution for applications such as electric two-wheelers in India and Southeast Asia. Another major use case for sodium-ion batteries is in cold-climate resilience, where they are being deployed in Nordic residential storage systems. This is due to their ability to operate efficiently in low temperatures, making them an ideal choice for energy storage in regions with extreme weather. These advancements position sodium-ion batteries as a versatile solution for stationary energy storage, with applications spanning grid stabilization, residential storage, and off-grid systems. Table 3 below outlines these key drivers, their geographic relevance, and the projected impact timelines for each use case.

Table 3: SIBs Applications

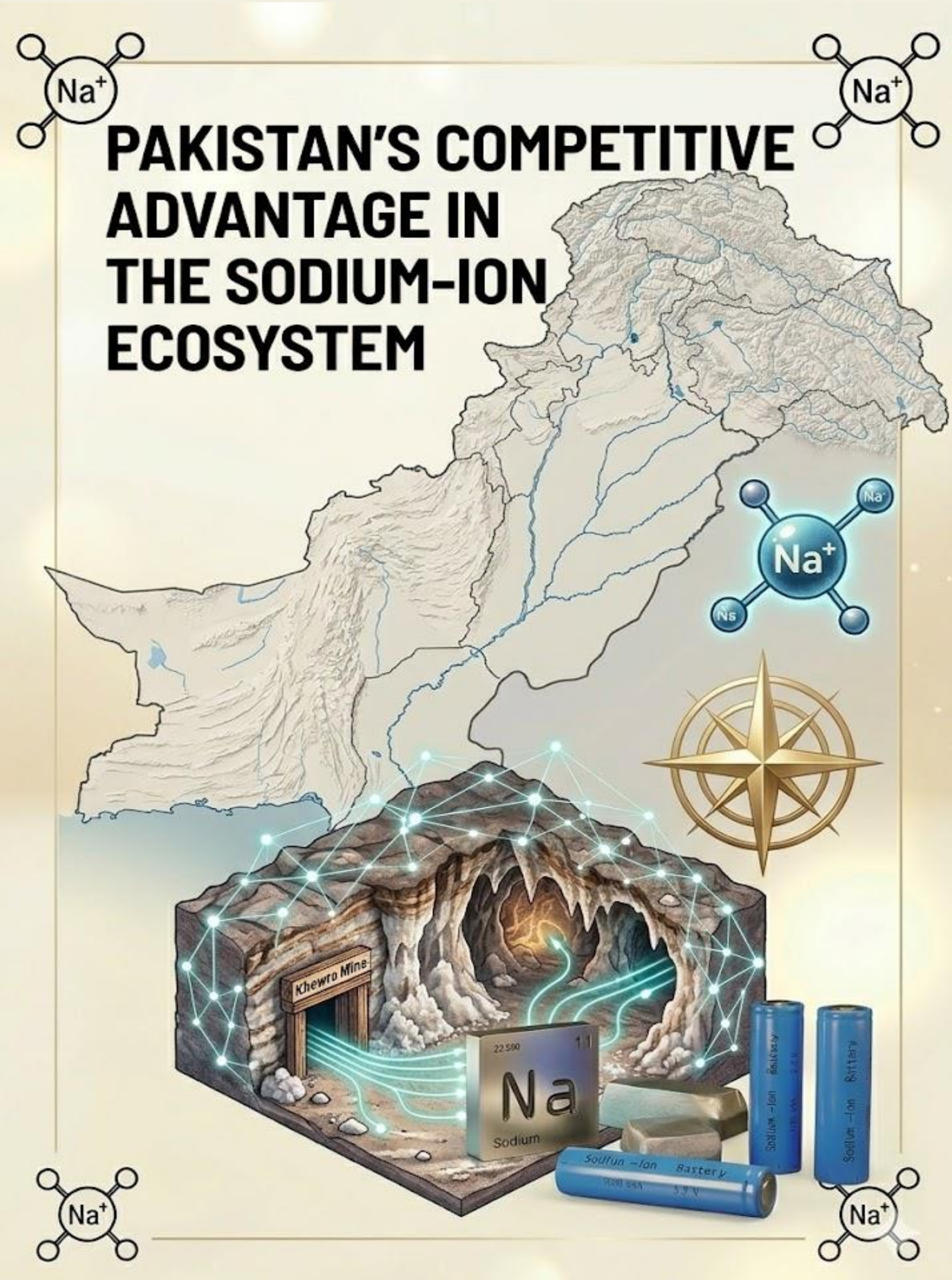
Applications	(~) % Impact on CAGR Forecast	Geographic Relevance	Impact Timeline
China's policy-backed 100+ MWh grid tenders accelerate domestic demand	+4.20%	China, wider Asia-Pacific	Short term (≤ 2 years)
European EV OEMs switch low-range models to sodium-ion to meet EU Battery Regulation	+3.80%	Germany, France, UK	Medium term (2–4 years)
LFP cathode cost inflation narrows pack-level cost gap below USD 70/kWh	+3.10%	Global focus on China and North America	Short term (≤ 2 years)
Prussian-Blue breakthrough enables 15-minute charge for India two-wheelers	+2.50%	India, Southeast Asia	Medium term (2–4 years)
Cold-Climate Resilience Spurs Nordic Residential Storage Subsidies	+1.80%	Nordic Countries, with potential expansion to Canada and Russia	Medium term (2–4 years)
CATL-Utility Joint-Venture Plants Secure Vertical Supply Chains	+1.10%	China, with expansion to Europe and North America	Long term (≥ 4 years)

3.4. Sodium-Ion Battery Projects: Innovations and Strategic Applications

Building on the growing momentum of sodium-ion battery adoption, several international projects are showcasing the potential of this technology in diverse applications. In the US, Peak Energy's 3.5 MWh pilot project marks the country's first grid-scale sodium-ion battery energy storage system (BESS), with plans for expansion and a 24 GWh giga-factory. This project emphasizes backup power and peak shaving for industrial and grid users, highlighting its role in stabilizing the energy supply. Similarly, Reliance Industries in India is making strides with its sodium-ion R&D-to-commercial transition, with a planned 5 GWh capacity aimed at renewable integration, rural microgrids, and EV charging. These initiatives demonstrate the broad applicability of sodium-ion batteries in addressing both energy storage challenges and climate concerns, while also promoting energy independence (Environment & Energy Leader, 2025). Table 4 below outlines these case studies, showcasing their capacity, innovation, environmental impact, and strategic role in advancing sodium-ion battery technology.

Table 4: SIBs Project: Capacity, Innovation, and Impact

Dimension	Peak Energy (USA)	Reliance Industries (India)
Project Type	The US first grid-scale sodium-ion BESS	Sodium-ion R&D-to-commercial scale transition project
Capacity	3.5 MWh pilot (expandable); 24 GWh giga-factory in planning	5 GWh (planned); initial deployment for EV + stationary applications
Deployment Date	Commissioned July 2025	Announced 2023; pilot lines operational by 2024
Grid Function	Backup + peak shaving for industrial/grid users	Renewable integration, rural microgrids, EV charging
Innovation Highlights	Passive cooling; no fans/pumps; fire-safe; 33% lower degradation	India's first sodium-ion dry cell tech (via Faradion acquisition); focus on localized R&D
Carbon/Climate Impact	Avoids 10,000–20,000 tons CO_2/year; >85% system efficiency	Reduces dependence on lithium; avoids 60,000 tons CO_2/year (proj.)
Economic Impact	$1M annual savings/GWh; built from US domestic soda ash supply	Import substitution; job creation in Giga factory + supply chain
Location Strategy	North Carolina (domestic battery corridor)	Gujarat/Maharashtra (RE industrial clusters + SEZs)
Strategic Role	Clean, scalable, fire-safe storage for hot/dry industrial zones	National battery independence; rural/urban storage integration
Technology Readiness	TRL 8–9 (commercial pilot + expansion underway)	TRL 6–7; moving toward commercial scale
Policy Implications	Supported under U.S. IRA + DOE incentives; avoids China risk	Backed by India's National Battery Mission + Production Linked Incentive (PLI) schemes


PAKISTAN'S COMPETITIVE ADVANTAGE IN THE SODIUM-ION ECOSYSTEM
Na+
Khewra Mine
11
Na
Sodium

4. Pakistan's Competitive Advantage in Sodium-Ion Ecosystem

4.1. Geological Endowment

Pakistan possesses a significant geological advantage in the development of a sodium-ion battery ecosystem, rooted primarily in its vast and high-quality rock salt reserves. These reserves, located at major sites such as Khewra, Warcha, Kalabagh, and Bahadurkhel offer an abundant supply of sodium chloride (NaCl), which is the fundamental input for sodium metal production. This availability provides a critical upstream resource for domestic sodium-ion battery manufacturing. The sodium contained in these deposits can be converted into metallic sodium through the Downs process, an electrochemical technique involving molten NaCl electrolysis. The feasibility of using this process in Pakistan is enhanced by the country's lower industrial electricity rates and proximity to raw material source, which together create a cost-effective supply chain for sodium-ion technology (Slater et al. 2013; Pervez et al. 2018).

To convert sodium chloride into metallic sodium suitable for battery-grade applications, the Downs process is used. This method involves molten salt electrolysis and is highly scalable, energy-intensive, and well-established. Domestic production costs are estimated to be in the range of PKR 275–375 per kilogram, which equates to approximately USD 1.00–1.45 per kg, compared to global prices of USD 2.50–3.00 per kg (Pervez et al. 2018; Pan et al. 2018; Slater et al. 2013). This favorable economics of sodium refining are summarized in Table 5, which presents the component-wise cost structure based on local inputs and utility rates.

Table 5: Estimated Local Cost of Metallic Sodium Production (PKR/kg)

Input Component	Estimated Cost (PKR/kg)
Raw NaCl (mined)	20–25
Electricity (6–7 kWh/kg)	250–350
Total	275–375

Moreover, Figure 8 provides a visual representation of the material composition differences between sodium-ion and lithium-ion batteries. Sodium-ion systems utilize aluminum and hard carbon in the anode, and more accessible metals like iron and manganese in the cathode, whereas lithium-ion systems often rely on expensive and critical minerals such as cobalt and nickel. This underscores the geopolitical and economic benefits of adopting sodium-ion technologies in a resource-rich but import-dependent country like Pakistan.

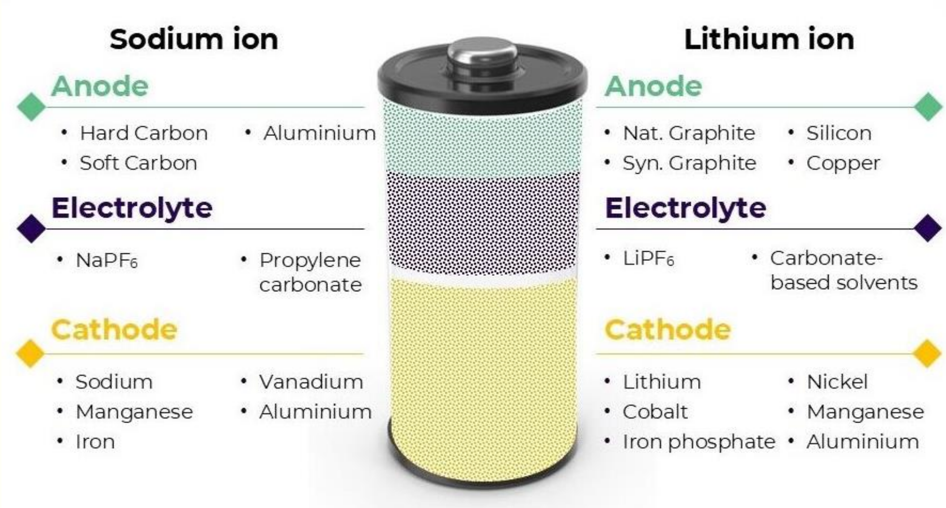


Figure 9: SIBs vs. LIBs components.

Given the scale of Pakistan's natural NaCl reserves and the potential for low-cost, localized sodium production, the country is positioned to play a pivotal role in regional sodium-ion battery manufacturing. When combined with supportive industrial policies and infrastructure investments, this geological foundation forms the cornerstone for developing a cost-competitive and resilient battery supply chain aligned with Pakistan's broader energy transition objectives.

4.2. Manufacturing Architecture of Sodium Ion Battery

Transitioning from a mineral-rich economy to a high-tech manufacturing hub requires a clear understanding of the complex chemical and mechanical processes involved in battery production. The following figures illustrate the end-to-end manufacturing architecture. Figure 11 provides a granular mapping of the chemical precursors and processing steps, from the synthesis of layered oxide cathodes and biomass-derived hard carbon anodes to the final assembly of battery packs.

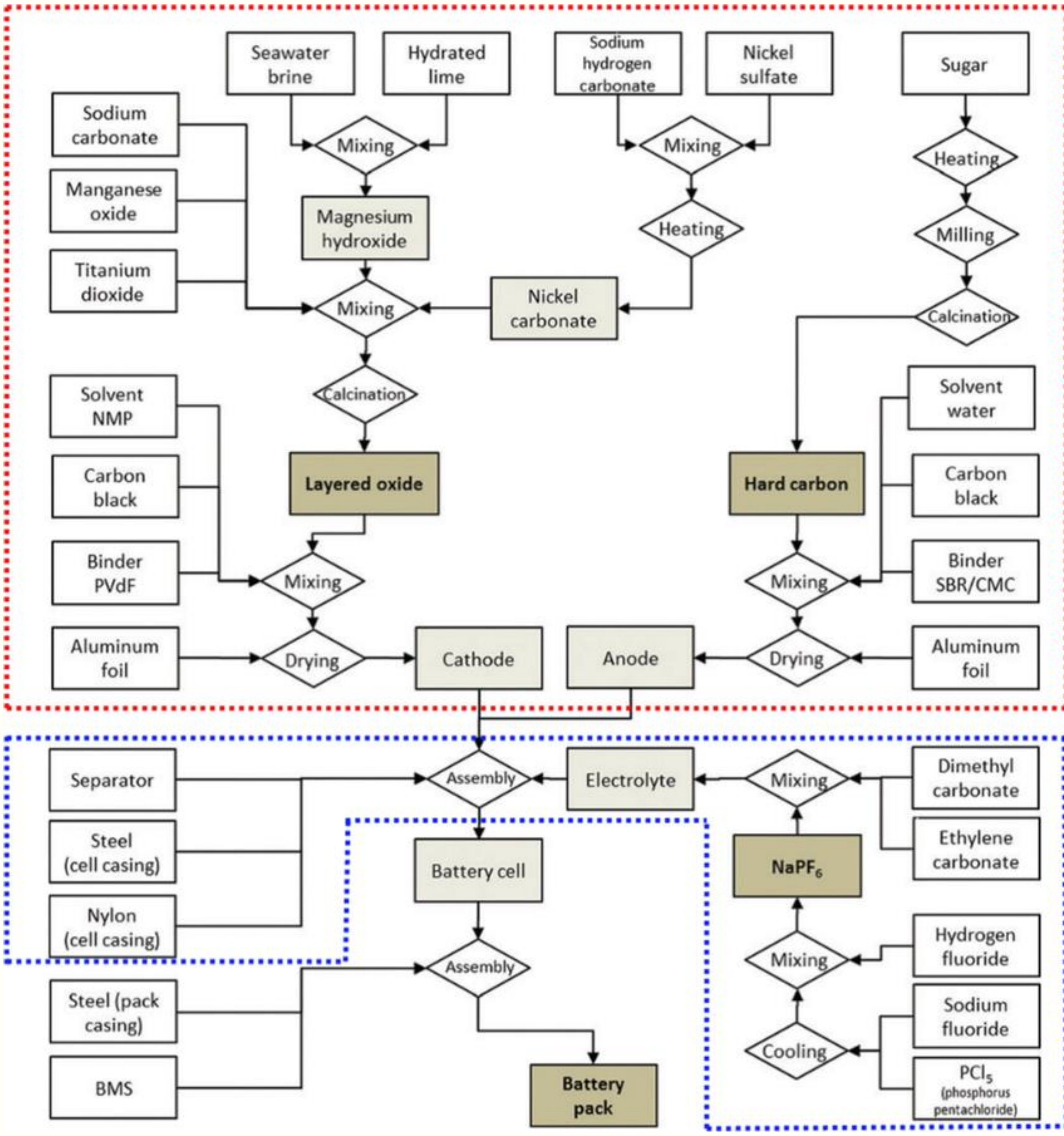


Figure 10: SIB Manufacturing Flowchart

4.3. Sodium-Ion Value Chain in Pakistan

The transition from mineral occurrence to battery-grade material requires a granular assessment of Pakistan's existing industrial base against global quality standards. On the cathode side, Pakistan possesses a significant strategic advantage in its established soda ash industry centered at Khewra, with an installed capacity of approximately 560,000 tons per annum (tpa). Sodium salts represent one of the few battery-critical commodities where Pakistan can be regionally competitive in cost and supply, provided that battery-grade purification processes are implemented to control iron and moisture levels. While manganese and titanium occurrences exist along the ophiolite belts and the Makran coast respectively, the primary challenge remains scaling chemical upgrading and beneficiation to reach battery-grade purity. Furthermore, any near-term strategy involving nickeldoped layered oxides will remain import-dependent, as evidenced by Pakistan's 2023 imports of approximately 92,000 kg of nickel sulfate.

Regarding the anode, Pakistan's advantage is uniquely anchored in its massive agricultural sector, which provides diverse feedstocks for hard carbon such as bagasse, rice husk, and molasses. While the domestic feasibility of a rural-based value chain is high, the industrial bottleneck lies in the precise process control of temperature and atmosphere during pyrolysis to ensure first-cycle efficiency. Beyond active materials, the manufacturing process faces shared bottlenecks in the form of electrode inputs. While aluminum foil is produced locally, it must be upgraded to meet strict battery-grade tensile and surface cleanliness specifications. To mitigate the high costs and regulatory overhead of specialized solvents, Pakistan should prioritize water-based cathode processing using CMC/SBR binders rather than the imported NMP/PVDF route. Finally, the "import wall" remains most significant for electrolyte salts ($NaPF_6$), carbonate solvents, and microporous separator films, which are the most quality-sensitive blocks of the value chain and are likely to remain import-anchored for the initial years of localization

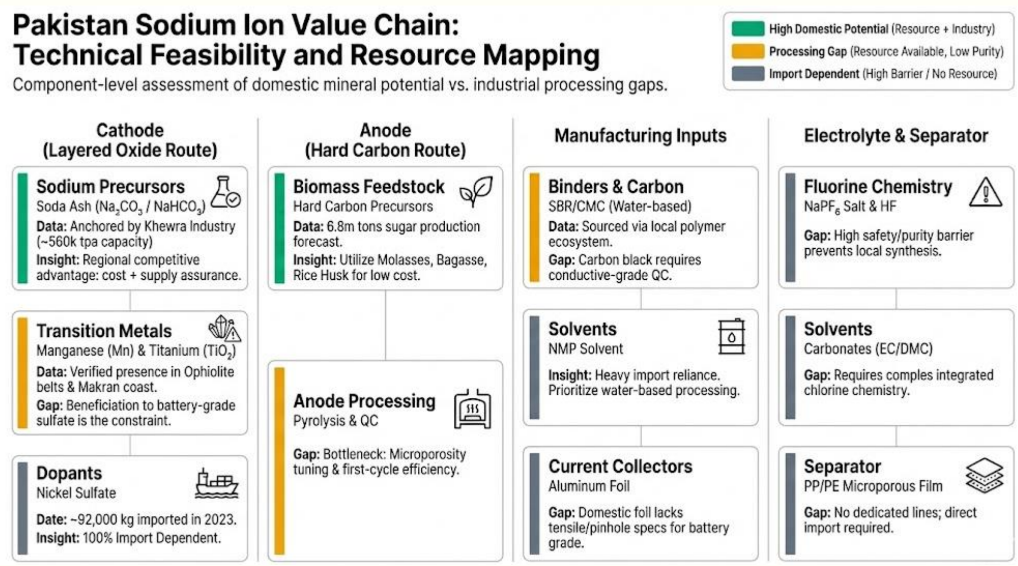


Figure 11: Technical Feasibility and Resource Mapping of SIBs Value Chain

4.4. Local Manufacturing and Supply Chain Readiness

Pakistan's industrial landscape presents a strong foundation for the development of a vertically integrated sodium-ion battery manufacturing ecosystem. Key industrial corridors such as the Faisalabad Special Economic Zone (SEZ), Dhabeji SEZ, and Rashakai SEZ offer the infrastructure, utility support, and logistical connectivity necessary for assembling a localized supply chain. These zones are also strategically situated near existing chemical clusters and metallurgical operations, which can be retrofitted to support battery component manufacturing with minimal capital investment. A critical pillar of localization lies in the refining of battery-grade sodium metal. As discussed in Section 4.1, Pakistan's salt reserves can be processed using the Downs process at significantly lower costs. Industrial co-location of sodium refining plants within SEZs, particularly in

Faisalabad and Dhabeji, would reduce raw material transport costs, benefit from shared infrastructure, and support efficient integration into the battery manufacturing workflow.

In addition to sodium production, cathode material synthesis offers high localization potential. Pakistan's reserves of iron and manganese, particularly in northern Punjab and Balochistan, can be used as precursors for cathode active materials such as sodium iron phosphate ($NaFePO_4$) and sodium manganese oxide ($NaMnO_2$). These chemistries are gaining global traction due to their non-toxic, earth-abundant composition and their compatibility with renewable energy storage applications. For instance, $NaFePO_4$-based chemistries accounted for over 60% of global sodium-ion cathode deployment in the first half of 2025 (Lechner et al. 2024). Setting up pilot-scale cathode synthesis labs in collaboration with universities and private sector firms will be instrumental for scaling.

Hard carbon anodes, essential to sodium-ion technology, can be manufactured from agricultural waste using thermal pyrolysis. Pakistan's annual biomass output of over 80 million tons, including bagasse, wheat straw, rice husk, and cotton stalks, provides a robust feedstock for decentralized anode production, which will be discussed in detail in Section 4.3. To better understand the feasibility of full-scale sodium-ion battery production, it is crucial to examine the estimated cost structure of the battery components. As presented in Table 6, the total cell-level cost for sodium-ion batteries in Pakistan is estimated at USD 60/kWh, while the complete system-level cost, including thermal management and inverters, reaches approximately USD 110/kWh. These figures indicate a 30–40% cost advantage over lithium-ion batteries, which are currently priced between USD 150 and 180/kWh (Adrian et al. 2025; Liu et al. 2024).

Table 6: Estimated Cost Structure of SIB Components (USD/kWh)

Component	Estimated Cost	Notes
Cathode ($NaFePO_4$, $NaMnO_2$, PBA)	15	Local iron/phosphate supply
Anode (Biomass-derived hard carbon)	10	Sugarcane, wheat straw, rice husk
Electrolyte ($NaPF_6$ + solvent)	8	Less flammable, lower cost
Separator	5	Polypropylene or cellulose base
Current Collectors (Aluminum)	4	Replaces costly copper
Cell Casing & BMS	6	Onboard safety & communication
Cell Assembly	12	Welding, forming, integration
Total Cell Cost	60	
System-Level Cost	110	Includes housing, HVAC, PCS

These localized cost advantages arise not only from abundant raw material inputs, but also from a simplified system design. Sodium-ion cells, due to their high thermal stability and non-flammable electrolytes, require less-intensive cooling and protective hardware than lithium-ion batteries (Slater et al. 2013).

Beyond the component-level production, Pakistan's industrial base also provides opportunities for Small and Medium Enterprises (SMEs) to drive innovation in subsystems such as electrolyte formulation, separator membranes, and thermal control units. SME-led initiatives can be supported through university incubators in Lahore, Karachi, and Islamabad, as well as through public-private R&D programmes. In conclusion, the industrial localization of sodium-ion battery supply chain in Pakistan is not only technically viable but also economically advantageous. By leveraging the synergies between raw materials, existing industrial infrastructure, and SEZ policy incentives, Pakistan can position itself as a competitive manufacturer in the global energy storage market.

4.5. Biomass Resources for Hard Carbon

An equally strategic advantage for Pakistan in developing a sodium-ion battery ecosystem lies in its abundant agricultural biomass, which serves as a primary source for hard carbon anodes. Unlike lithium-ion batteries that rely on synthetic graphite or expensive natural graphite imports, sodium-ion batteries can utilize hard carbon derived from biomass, a material that performs effectively as an anode due to its disordered structure and favourable sodium intercalation characteristics (Liu et al. 2024; Hu et al. 2024).

Pakistan produces over 80 million tons of agricultural biomass annually. This includes sugarcane bagasse, rice husk, wheat straw, and cotton stalks. These materials can be thermochemically processed via pyrolysis and activation into hard carbon, yielding a stable, low-cost material for battery anode production. Table 7 outlines the estimated availability and carbon yield of key biomass types in Pakistan. Bagasse, the fibrous by-product of sugarcane processing, represents the most abundant source with over 60 million tons available per year and a high carbon yield ranging from 25% to 30%. Other sources like rice husk and wheat straw also contribute meaningfully to the feedstock pool, with moderate yield and good structural properties for anode fabrication (Hu et al. 2024; Palomares et al. 2018).

Table 7: Biomass Availability and Carbon Yield for Anode Production of SIBs

Biomass Type	Availability (MT/year)	Carbon Yield (%)	Comments
Bagasse (sugarcane)	60+	25–30%	High-purity, low ash
Rice Husk	6–8	20–25%	Good porosity
Wheat Straw	8–10	20–25%	Stable yield
Cotton Stalks	3–5	15–20%	Secondary resource

Through pyrolysis and subsequent activation processes, these biomass sources can be converted into hard carbon with yields ranging between 15% and 30%, depending on the input material and processing parameters. Notably, rice husk and wheat straw exhibit favourable pore distribution and moderate carbon yield, while cotton stalks, though less abundant, provide higher energy density when optimized. According to recent findings (Hu et al. 2024), the cost of producing hard carbon anode material from these sources in Pakistan ranges from USD 300 to 500 per ton, a figure that compares favourably to global import prices of hard carbon, which currently average USD 800 to 1000 per ton.

The localized availability of these raw materials also aligns with Pakistan's broader sustainability goals, particularly in fostering circular economy practices. Rather than treating agricultural waste as a disposal burden, the sodium-ion battery value chain offers a pathway to upcycle biomass into high-value energy storage components. Moreover, the geographic distribution of feedstock sources, primarily across the Punjab and Sindh, overlaps with industrial hubs, reducing transport costs and enabling regionally dispersed manufacturing clusters.

This linkage between circular economy and battery manufacturing is illustrated in Figure 6, which shows how key input elements from agriculture and industry, such as sodium, carbon, and iron, can be converted into battery components and ultimately serve end-use applications in consumer electronics, EVs, and stationary energy storage. The figure 9 highlights the flow of materials from feedstock to application, supporting the case for a vertically integrated and environmentally responsible battery manufacturing model in Pakistan

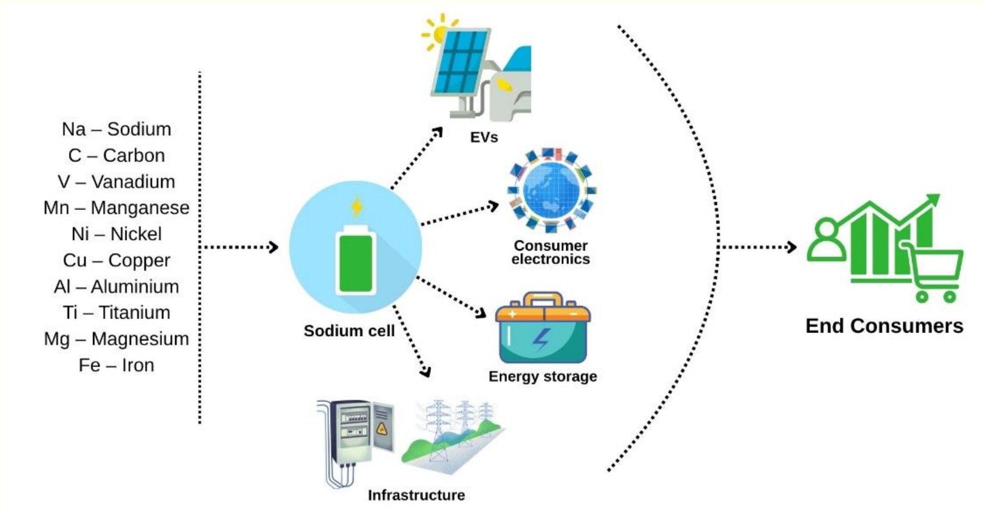


Figure 12:Key elements powering SIBs

From a technical perspective, biomass-derived hard carbon offers a disordered microstructure that accommodates sodium ions effectively, especially in cells operating at moderate energy density levels. While performance lags behind synthetic graphite in lithium-ion systems, innovations in temperature-controlled pyrolysis and template-based activation have closed much of this gap. Several studies highlight that optimized biomass-based hard carbon can support reversible capacities of 250 to 350 mAh/g with stable cycling beyond 4,000 cycles, figures that are well-suited for grid-scale and stationary storage (Slater et al. 2013; Liu et al. 2024).

As the sodium-ion battery industry matures globally, and as companies like Faradion and CATL integrate biomass-derived anode materials into commercial products, Pakistan is well-positioned to serve not only domestic demand but also participate in global supply chains. Investments in modular pyrolysis infrastructure, combined with targeted R&D in biomass material optimization, could anchor a vibrant, rural-based value chain that enhances energy access while boosting farm-level incomes.

4.6. Existing Chemical Industry Base

Pakistan's existing chemical and metallurgical industry offers a strong foundation for the development of a localized sodium-ion battery manufacturing ecosystem. Central to this opportunity is the widespread presence of chlor-alkali plants, primarily in the Punjab and Sindh, which already utilize electrolysis technology to convert sodium chloride (NaCl) into sodium hydroxide and chlorine. These facilities, currently operating within the industrial clusters of Faisalabad, Lahore, and Karachi, can be feasibly upgraded or retrofitted to produce battery-grade metallic sodium using the Downs process. This process involves molten NaCl electrolysis and is a mature, globally accepted method for producing high-purity sodium metal. Given Pakistan's affordable electricity tariffs and large-scale salt deposits, domestic sodium refining through this approach can achieve a production cost advantage, enabling the supply of one of the most critical inputs for sodium-ion batteries at a cost well below international benchmarks (Slater et al. 2013; Pan et al. 2018). Table 5, provided earlier, highlighted that metallic sodium production in Pakistan could range between USD 1.0 and 1.45 per kilogram, compared to global prices exceeding USD 2.5 per kilogram, thereby ensuring competitive input economics.

In addition to chlor-alkali units, Pakistan's well-established fertilizer industry offers further synergies. Plants engaged in the production of phosphate and nitrogen fertilizers regularly handle phosphoric acid, ammonia, and other compounds closely related to cathode precursor synthesis. These existing capabilities can be adapted to support the synthesis of sodium iron phosphate ($NaFePO_4$) and sodium manganese oxide ($NaMnO_2$), the primary cathode materials used in sodium-ion batteries. Recent research underscores the growing commercial viability of these chemistries due to their cost-effectiveness, thermal stability, and compatibility with abundant minerals such as iron and manganese (Palomares et al. 2018; Hu et al. 2024). Leveraging fertilizer sector infrastructure for cathode production can, therefore, significantly reduce initial capital investment and facilitate the creation of upstream battery material supply chains with domestic linkages.

The metallurgical sector, with an extensive presence in Balochistan, Karachi, and the northern Punjab industrial belt, complements this opportunity by providing beneficiation and processing capabilities for iron and manganese ores. This is particularly relevant for cathode production, where the purity of precursor metals plays a critical role in determining battery performance and stability. By upgrading or repurposing existing mineral processing plants to meet battery-grade material specifications, Pakistan can localize the entire upstream segment of sodium-ion battery materials. This would not only reduce reliance on imported cathode materials but also enable the development of cost-efficient and resilient supply chains.

Figure below illustrates the spatial distribution of Pakistan's chemical and metallurgical industrial base, showcasing the proximity of chlor-alkali units, fertilizer factories, and metallurgical processing zones to Special Economic Zones (SEZs). This geographic overlap provides a natural alignment between upstream feedstock production and downstream battery manufacturing, facilitating the co-location of sodium refining, cathode synthesis, and electrode preparation within integrated industrial clusters. These SEZs, already benefiting from fiscal incentives and infrastructure under

CPEC, can serve as anchor points for battery manufacturing hubs, reducing logistics costs and enabling economies of scale

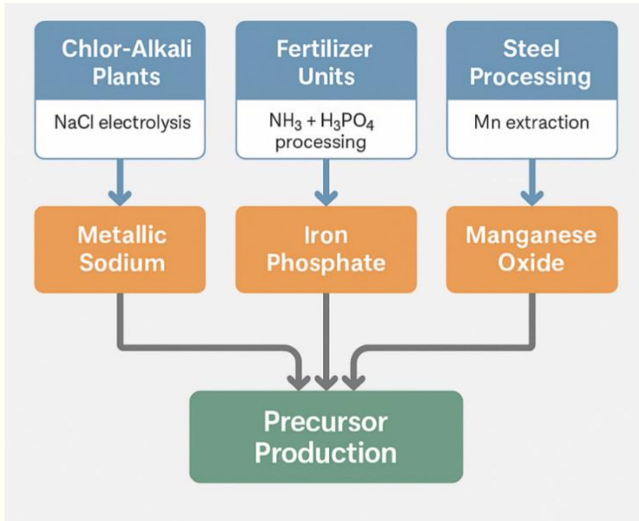


Figure 13: Mapping Pakistan's Existing Chemical and Metallurgical Industrial Base

When viewed holistically, Pakistan's existing industrial base provides not only the technical infrastructure but also the human capital and logistical frameworks necessary to support the early stages of sodium-ion battery localization. With appropriate policy alignment, technology transfer agreements, and concessional financing mechanisms, these industries can be repositioned to produce battery-grade sodium, cathode precursors, and ancillary chemicals, ultimately forming the core of a robust, integrated value chain for sodium-ion energy storage solutions.

4.7. Integrated Value Chain and Export Potential

The development of a cohesive sodium-ion battery value chain in Pakistan holds immense potential for domestic energy resilience and regional economic integration, provided the transition from mineral extraction to battery-grade processing is strategically managed. By aligning upstream resource extraction with midstream materials processing and downstream system integration, Pakistan can establish itself as a cost-effective manufacturing base and a key exporter of energy storage solutions. This final phase of localization converges the geological abundance of the Salt Range, the industrial readiness of the chemical sector, and the biomass availability of the Indus plains into a vertically integrated framework. However, this integration must account for the "import wall" in specialized components like separators and electrolyte salts, prioritizing the localization of the cathode and anode, where Pakistan's competitive advantage is strongest

A robust value chain begins with sodium extraction and high-purity refining of soda ash from domestic mines, complemented by the production of hard carbon anodes from agricultural residues such as bagasse and rice husk. Cathode synthesis leverages indigenous iron and manganese reserves, though initial phases may rely on imported dopants to bridge the gap in domestic chemical upgrading. These midstream activities feed into final cell assembly and battery pack integration within SEZs such as Allama Iqbal Industrial City, where proximity to chemical clusters reduces logistics costs. Such integrated ecosystems are critical; as highlighted by Lechner et al. (2024), they reduce transaction costs, supply delays, and price volatility, thereby improving the overall competitiveness of domestic manufacturing.

Importantly, the cost advantage offered by sodium-ion batteries is substantial. When comparing system-level costs for grid-scale installations, sodium-ion batteries are approximately 24 per cent cheaper than lithium-ion counterparts. As shown in Table 8, the estimated total system cost for sodium-ion storage is USD 152/kWh, compared to USD 200/kWh for lithium-ion. These savings arise primarily from lower input material costs (sodium, aluminum, and biomass-derived carbon), simpler thermal management systems, and the elimination of cobalt and nickel dependencies (Adrian et al. 2025).

Table 8: Sodium-Ion vs. Lithium-Ion Grid-Scale System Cost (USD/kWh)

Component	Sodium-Ion	Lithium-Ion
Battery Pack (Cells)	85	115
BMS & Control Systems	10	15
Power Conversion System (PCS)	25	25
Thermal Management	7	10
Installation & Housing	15	20
O&M (5-Year NPV)	10	15
Total System Cost	152	200

Note: sodium-ion batteries offer a clear pathway towards 75% localization by leveraging Pakistan's indigenous salt and biomass resources, lithium-ion technology remains almost entirely import-dependent. Consequently, continuing a lithium-centric strategy forces the national economy to expend significant foreign exchange on critical mineral imports, whereas transitioning to a localized sodium-ion value chain provides a strategic opportunity to reduce this fiscal pressure.

This cost profile makes sodium-ion technology especially attractive for large-scale deployments in Pakistan's renewable corridors, including Jhimpir and Bahawalpur, as well as for urban substations in Lahore, Faisalabad, and Karachi. The advantages of sodium-ion chemistry, such as high thermal tolerance, safer electrochemical profiles, and stable cycle life, allow systems to operate in extreme temperatures with reduced fire risk, an essential feature for semi-arid and high-temperature environments prevalent across Pakistan and neighboring countries (Liu et al. 2024).

Beyond domestic use, Pakistan's sodium-ion value chain is well-positioned to serve emerging markets in South Asia, the Middle East, and Africa. These regions are experiencing surging demand for affordable and robust energy storage, particularly for off-grid solar hybrid systems, telecom backup, and rural electrification. Commercial forecasts indicate that battery markets in the Middle East and Africa will grow from USD 7.55 billion in 2025 to USD 10.60 billion by 2030, expanding at a CAGR of ~7%. Sodium-ion chemistries, prized for low cost, thermal tolerance, and safety, are gaining traction in solar-hybrid and telecom use cases across these regions. Emerging energy procurement initiatives, such as Pan-African and SAARC solar alliances, are increasingly prioritizing modular storage technologies, creating demand for localized assembly hubs. Pakistan's geographic proximity, port access, and developing SME capacity align well with these regional dynamics, offering export pathways grounded in tariff advantages, shorter logistics chains, and locally tailored deployment models.

Market projections position the sodium-ion sector to grow robustly from a baseline of USD 270 million in 2024 towards multi-billion-dollar scales by 2030, with CAGRs ranging from 16% to over 24% depending on forecast models. Pakistan's location at the confluence of mineral resources, biomass availability, manufacturing potential, and growing regional battery demand yields substantial opportunity. A value chain that integrates electrode fabrication, sodium refining, cell assembly, and export logistics, utilizing strategic SEZ infrastructure, positions the country to capitalize on regional storage needs while developing a competitive, export-ready battery ecosystem.

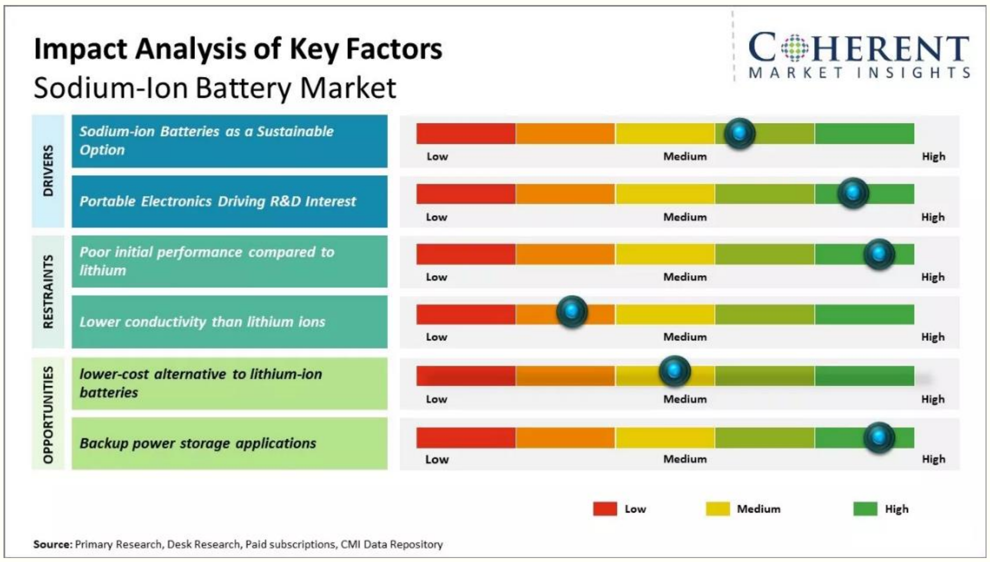
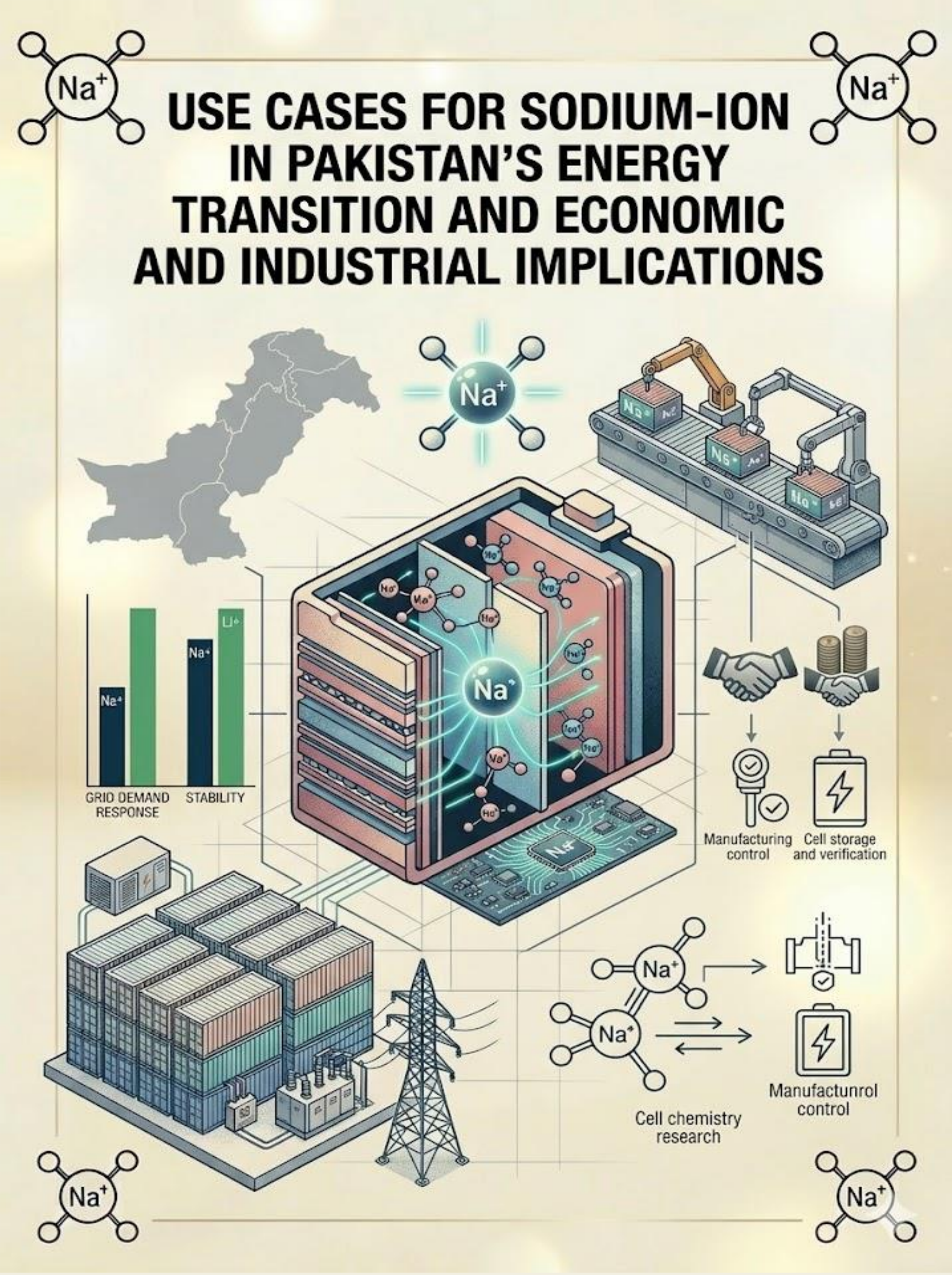


Figure 14: Key factors driving the SIB market


USE CASES FOR SODIUM-ION IN PAKISTAN'S ENERGY TRANSITION AND ECONOMIC AND INDUSTRIAL IMPLICATIONS
GRID DEMAND RESPONSE
STABILITY
Manufacturing control
Cell storage and verification
Cell chemistry research
Manufactunrol control

5. Use Cases for Sodium-Ion in Pakistan's Energy Transition and Economic & Industrial Implications

Sodium-ion batteries (SIBs) have emerged as a frontrunner for stationary applications due to their unique electrochemical properties, which offer distinct advantages over traditional chemistries in terms of safety, cost, and environmental sustainability. Unlike lithium-based systems, which are constrained by rare mineral supply chains and thermal sensitivity, sodium-ion technology leverages earth-abundant materials and maintains high efficiency across a wide temperature spectrum, making it particularly suitable for the diverse climatic conditions of regions like South Asia and the Middle East. By integrating these batteries into the grid, utilities can effectively manage the temporal mismatch between energy generation and demand, thereby ensuring stability while reducing reliance on fossil-fuel-based peaking plants.

5.1. Grid-Level Storage: Renewable Firming and Peak Management

The integration of renewable energy into Pakistan's grid infrastructure has accelerated significantly over the past decade, with solar and wind accounting for an increasing share of installed capacity. However, intermittency and temporal mismatches between generation and demand pose a critical bottleneck. Sodium-ion batteries provide a compelling solution due to their operational safety, cost-efficiency, and robust thermal profile, especially for grid-level storage supporting renewable energy corridors in Jhimpir (wind) and Bahawalpur (solar), and urban substations in Lahore and Faisalabad where demand spikes sharply during early evening hours.

Each identified site is evaluated for deployment of 5–10 MW battery systems with energy capacities ranging from 20–40 MWh, enabling 2–4 hours of continuous discharge. The sodium-ion system-level capital expenditure, calculated at USD 152/kWh (refer to Table 8), results in a site-wise deployment cost.

40 MWh × USD 152 / kWh = USD 6.08 million per site PKR 1.7 billion per site

Assuming a rollout across 10 strategic locations, the national CAPEX stands at:

USD 6.08 million × 10 = USD 60.8 million ≈ PKR 17 billion

In contrast, a lithium-ion alternative priced at USD 200/kWh would require an investment of USD 8 million per site, totaling USD 80 million for the same rollout. This highlights a capital savings margin of nearly USD 20 million, demonstrating the economic feasibility of localizing the sodium-ion value chain to reduce the initial financial burden of the energy transition. (Lechner et al. 2024).

From a technical perspective, each 5 MW / 20 MWh battery system can provide 20 MWh of energy per day. Across 10 sites, this totals 200 MWh/day. When strategically dispatched during the 6:00 pm to 10:00 pm peak period, this would offset up to 100 MW of thermal capacity, thereby reducing reliance on imported RLNG and high-sulfur furnace oil-based peaking plants. Sodium-ion batteries' capacity to operate without complex active cooling further enhances their viability for hot climates, where average summer temperatures routinely exceed 40°C (Pan et al. 2018). These characteristics make sodium-ion batteries especially well-suited for deployment within urban substations and transmission bottlenecks.

5.2. Distribution-Level Load Management and Demand Shifting

Distribution Companies (DISCOs) in Pakistan, such as LESCO, FESCO, and K-Electric, are under increasing pressure due to load variability across residential and commercial feeders. Sodium-ion battery storage offers a decentralized method for evening load leveling, transformer protection, and tariff arbitrage at 11kV or 33kV substations, particularly in industrial estates with night-time operations (e.g. Sundar Industrial Estate in Lahore, SITE in Karachi).

A typical substation deployment would involve a 2 MW / 8 MWh sodium-ion system, providing backup or peak shaving for 1–2 feeders. Based on the previously established cost (Table 4), the site cost becomes:

8 MWh × USD 152 = USD 1.216 million ≈ 340 million PKR

From a technical standpoint, sodium-ion's non-flammable electrolyte chemistry and wide thermal operating window (–20°C to +60°C) (Slater et al. 2013; Pan et al. 2018) eliminate the need for active cooling or specialized housing, reducing O&M expenses by up to 20% versus lithium-ion. These systems can also serve backup roles during feeder faults, improving SAIFI and SAIDI scores for utilities.

5.3. Microgrids and Rural Electrification Initiatives

Pakistan's off-grid population in areas such as Chitral, Kohistan, and South Waziristan continues to rely on expensive, polluting diesel generators. The sodium-ion battery offers a cleaner and safer alternative, especially when coupled with community solar mini-grids or rooftop solar arrays. Owing to their ability to safely ship at zero-voltage and perform in high ambient temperatures, sodium-ion batteries are uniquely suitable for deployment in such remote, infrastructure-poor regions.

A village microgrid for approximately 100 households would include:

- 20 kW of solar PV
- 100 kWh of sodium-ion storage
- Inverters, smart metering, control logic, and cabling

Based on our cost model (Table 8), the battery cost alone is:

100,000 Wh × USD 152 = USD 15,200 ~ PKR 4.3 million
Full microgrid system = USD 35,000–40,000

Deploying 1,000 such microgrids across the country yields a total investment requirement of USD 35–40 million, enabling electrification of 100,000–120,000 rural households. These systems displace diesel, which typically costs USD 0.30–0.35/kWh, with solar + storage systems offering LCOEs between USD 0.12–0.15/kWh (Liu et al. 2024).

Additionally, the cycle life of modern sodium-ion batteries, which ranges between 4,000 to 6,000 cycles with minimal capacity degradation (Hu et al. 2024), ensures more than 10 years of service in microgrid operations, particularly with partial cycling and proper charge control.

These systems are also aligned with Sustainable Development Goal 7 (SDG-7), which emphasizes universal access to affordable, reliable, and sustainable energy. Community-based O&M models can further reduce operational costs and create rural employment pathways, while sodium-ion's safety profile makes it ideal for decentralized deployment without the need for highly trained technicians.

5.4. Transforming Under-Used Coal Plants into Energy Storage Hubs

As Pakistan's power system evolves towards cleaner and more flexible energy sources, some of its traditional baseload coal plants are becoming increasingly misaligned with current and future needs. One such example is the Sahiwal Coal Power Plant, a 1,244-megawatt facility that was once expected to be a cornerstone of reliable baseload generation. However, in recent years, its performance and relevance have significantly declined.

Between 2020 and 2024, the plant's generation fell by over 70 per cent. The load factor dropped from nearly 67 per cent in 2020 to only 19 per cent in 2024, despite the plant remained technically available for operation. This means that while the infrastructure remains in place and capable of running, it is now being used for only a fraction of its potential. The reasons are both economic and structural. With its reliance on imported coal, the plant has become exposed to unpredictable international prices and the instability of currency exchange rates. In 2022–2023, its average fuel cost rose to over 27 rupees per kilowatt-hour, and the total cost of generation exceeded 34 rupees per unit, making it among the most expensive sources of electricity in the country.

This situation provides a clear opportunity to rethink how such large-scale energy infrastructure can be repurposed to serve the future. Rather than letting the plant continue to operate inefficiently or sit idle, the existing site could be transformed into a clean energy hub using battery storage and solar energy. For example, installing a sodium-ion battery system with a capacity of 100 megawatts and 400 megawatt-hours would cost around 60 million US dollars. A larger setup of 200 megawatts and 800 megawatt-hours would require roughly 120 million dollars. These systems do not require fuel to operate, which means they are immune to the risks of global commodity markets and exchange rate fluctuations. Most importantly, sodium-ion battery technology can be produced using local resources such as rock salt and agricultural waste, which gives Pakistan a natural advantage in reducing its reliance on imports.

By combining solar power with these batteries, the repurposed Sahiwal site could continue to play an important role in the national grid. During daylight hours, solar energy would generate power, and the battery systems would store it for use during the evening peak or periods of high demand. The site already has transmission infrastructure and grid access in place, which makes this transition not only feasible but also cost-effective. In addition to energy benefits, repurposing the plant could help reduce Pakistan's growing burden of capacity payments. These are contractual payments made to power producers regardless of how much electricity they deliver. If underutilized plants like Sahiwal continue to operate in their current form, they will contribute to rising circular debt without delivering meaningful value. Transforming such assets into renewable energy storage sites would allow these financial resources to be redirected towards building a more secure, cleaner, and efficient energy system.

Repurposing coal plants in this way is more than a technical solution. It is a strategic opportunity to realign legacy infrastructure with national goals related to climate change, energy affordability, and industrial development. Sahiwal can become a blueprint for how Pakistan transitions away from expensive, imported fossil fuels toward a resilient and self-sustaining energy future

5.5. Seasonal Energy Storage: Managing Peak Demand Through Seasonal Shifting

In Pakistan, the seasonal fluctuations in both energy generation and demand present an opportunity for utilizing sodium-ion battery storage to optimize grid stability and efficiency. The ability to store excess energy during times of low-cost production and discharge it during high-demand periods offers a viable solution to reduce reliance on expensive fuel-based peaking plants, helping to better manage the grid throughout the year.

During the summer, Pakistan sees a significant increase in solar generation due to the long daylight hours and high solar radiation. This period is particularly advantageous for energy storage, as energy from cheaper sources, like solar, is abundant. By deploying sodium-ion batteries to store the surplus energy generated during these hotter months, Pakistan can build up a reliable energy reserve that can be tapped into during the winter months when energy demand surges due to heating needs and increased consumption. By releasing this stored energy during the winter, when generation from renewable sources like solar is limited, the country can reduce its reliance on high-cost thermal power plants or imported fuels, ensuring that the grid remains stable while minimizing energy costs.

During the winter months, when energy consumption is typically lower, Pakistan can take advantage of cheaper power plants and surplus generation to store energy for use in the summer. By charging sodium-ion batteries in winter, when demand is low and more energy is available from lower-cost sources, this stored energy can be used to meet the increased demand for cooling during the hot summer months. This seasonal storage approach helps smooth out the variations in demand between seasons, ensuring that high-demand periods, such as those experienced during the summer, are supported by stored, cheaper energy, thereby reducing the need for expensive peaking plants that operate during times of extreme demand.

This strategy of utilizing seasonal energy storage ensures that energy production costs are optimized, and the system's reliance on expensive fuel imports is minimized. By leveraging Pakistan's abundant renewable energy during off-peak seasons, such as solar power in the summer, and storing it for future high-demand periods, the country can enhance its energy security, reduce its environmental footprint, and create a more efficient and resilient energy system. This seasonal shifting of energy production and storage not only helps balance supply and demand but also promotes economic stability by avoiding the high costs of importing fuel during peak demand times, making the entire grid system more sustainable.

Table 9: Use Cases and Implications of SIBs

Use Case	Primary Purpose	Strategic Implication for Pakistan	Key Parameter
Grid-Level Firming	Balancing intermittent wind/solar in corridors like Jhimpir and Bahawalpur.	Reduces "Non-Project Missed Volume" (NPMV) payments and renewable curtailment.	5–10 MW / 20–40 MWh blocks per site
Peak Load Management	Discharging stored midday solar energy during the 18:00–22:00 evening peak.	Offsets expensive thermal generation and reduces circular debt.	~100 MW thermal capacity offset
Coal-to-Storage Repurposing	Transforming under-used assets like Sahiwal into solar+storage hubs.	Avoids imported fuel risk and utilizes existing grid infrastructure.	100 MW / 400 MWh typical setup
Rural Microgrids	Providing 24/7 power to off-grid communities in remote regions.	Replaces expensive diesel ($0.35/kWh) with clean storage ($0.15/kWh).	20 kW PV + 100 kWh battery units
Industrial Load Leveling	Managing high-demand industrial feeders and preventing transformer overload.	Provides tariff arbitrage and improves utility reliability (SAIFI/SAIDI).	2 MW / 8 MWh at 11/33 kV substations
Seasonal Shifting	Storing surplus summer solar for winter heating or vice versa.	Maximizes utilization of low-cost generation across all seasons.	High thermal tolerance (–20°C to +60°C)

Use Cases and Business Models for Sodium-Ion Storage in Pakistan

The largest near-term use case for sodium-ion storage in Pakistan lies in utility-scale deployment to support renewable energy (RE) integration in key corridors such as Jhimpir (wind) and Bahawalpur (solar). These RE zones often face curtailment or under-utilization due to the grid's inability to absorb intermittent generation during off-peak hours. As a result, the energy that could have been produced is frequently wasted.

This issue has precise financial consequences, as payments made to Renewable Energy (RE) power producers for energy that could not be evacuated—referred to as Non-Project Missed Volume (NPMV) — have surged dramatically in recent years. In FY 2021–22, NPMV payments totaled approximately Rs 1.9 billion, a figure that rose to Rs 11.8 billion in FY 2022–23 and skyrocketed to nearly Rs 39.52 billion in FY 2023–24. According to the latest NEPRA State of Industry Report 2025, the cost associated with NPMV was recorded at Rs 13.285 billion for FY 2024–25. While this represents a decrease from the peak seen in the previous year, it remains a multi-billion rupee drain on the national exchequer. Much of this lost generation continues to be concentrated in high-potential wind zones like Jhimpir where grid bottlenecks persist despite increased RE capacity additions, making the deployment of sodium-ion storage a strategic necessity to absorb and shift this otherwise wasted energy.

Sodium-ion batteries offer a targeted and economically viable solution to this challenge. These systems enable time-shifting of RE generation through 2 to 4 hours of flexible discharge capacity, absorbing excess supply during midday and dispatching it during peak demand in the evening.
For example, deploying a 50 MW / 200 MWh sodium-ion battery system in Bahawalpur would allow solar plants to store excess energy instead of curtailing output. At a system-level capital cost of USD 152/kWh, this installation would cost approximately USD 30.4 million. In contrast, a similar lithium-ion system at USD 200/kWh would require USD 40 million, indicating a direct savings of USD 9.6 million. These funds could instead be used for grid upgrades or further RE capacity expansion (Lechner et al. 2024; Adrian et al. 2025).

Importantly, sodium-ion batteries do not rely on imported fuel, eliminating foreign exchange risk. They can also be manufactured locally using domestic sodium reserves, biomass-derived hard carbon, and widely available metals such as iron and aluminum, offering long-term cost stability and strategic resilience. Business models for such deployments could include Power Purchase Agreements (PPAs) with time-of-day tariff structures, where the battery operator is compensated not only for stored energy delivery but also for grid-balancing and curtailment avoidance. By preventing energy waste and reducing dependency on imported fossil fuel-based peaking plants, sodium-ion batteries offer both economic and operational value to Pakistan's evolving grid.

POLICY AND INVESTMENT OPPORTUNITIES

6. Policy and Investment Opportunities

In Pakistan, the development of a robust sodium-ion battery (SIB) ecosystem hinges not only on technological readiness and local resource availability, but also equally on an enabling policy environment and strategic investment. As the country navigates its energy transition, industrial decarbonization, and SDG commitments, sodium-ion battery manufacturing presents a unique convergence point for climate finance, regional trade, and domestic energy security. This section outlines the key opportunities for policy support, foreign direct investment, and institutional alignment across public and private sectors.

Under the second phase of the China–Pakistan Economic Corridor (CPEC), the strategic focus has shifted from energy infrastructure to industrial cooperation. This pivot offers a high-leverage window for Pakistan to localize sodium-ion battery (SIB) manufacturing within its developing Special Economic Zones (SEZs). Three SEZs— Allama Iqbal Industrial City (Faisalabad), Rashakai SEZ (Khyber Pakhtunkhwa), and Dhabeji SEZ (Sind — are prime contenders for integrated battery value chains due to their proximity to raw materials, port and grid infrastructure, and policy support.

6.1. CPEC Phase II and Strategic Role of SEZs

Allama Iqbal Industrial City (AIIC) spans over 3,200 acres and is located adjacent to the M-3 Motorway and major gas pipeline corridors. The zone already hosts several chlor-alkali and fertilizer firms capable of supporting precursor processing for sodium refining and cathode materials like $NaFePO_4$. Moreover, it is directly connected to the 132 kV grid, ensuring uninterrupted power supply for industrial-grade electrolysis plants. The AIIC is positioned just 60 km from major biomass clusters in Jhang and Chiniot, enabling parallel hard carbon production from bagasse and wheat straw.

Rashakai SEZ, which became operational in late 2023, spans 247 acres and benefits from its location along the M-1 Motorway and proximity to the Tarbela hydropower grid. It is already attracting interest in electronics, electric two-wheeler assembly, and battery housing facilities. With a focus on light engineering, this zone is suited for cell assembly and battery pack integration, leveraging local PCB and inverter manufacturers such as RASTECH and Premier Electronics.

Dhabeji SEZ, located 40 km from Karachi Port, offers direct export access via Port Qasim. This is critical for reaching markets in the Middle East and East Africa, where off-grid sodium-ion solutions are gaining traction due to lower thermal management needs. Dhabeji is served by a 500 kV high-voltage grid line, ensuring scalable energy access for energy-intensive refining units.

A comparative analysis of site attributes is presented in Table 9, which summarizes the suitability of these SEZs for different parts of the sodium-ion value chain.

Table 10: Comparative Suitability of SEZs for SIB Manufacturing

SEZs	Key Features	Most Suitable Value Chain Segment	Strategic Advantage
Allama Iqbal Industrial City (Faisalabad)	3,200+ acres, grid-connected, adjacent to biomass zones	Sodium refining, cathode precursor synthesis	Integration with fertilizer, chlor-alkali and agro-processing
Rashakai SEZ	247 acres, M-1 corridor, electronics cluster	Cell assembly, BMS integration	Proximity to Tarbela hydropower and EV pilot programmes
Dhabeji SEZ	Near Port Qasim, 500 kV grid, chemical industries	Sodium refining, export-pack assembly	Access to GCC/African markets, NaCl proximity

In terms of international investment opportunity, joint ventures with global SIB leaders like CATL (China), HiNa Battery (China), and Reliance-Faradion (India/UK) are increasingly viable. CATL launched its "Naxtra" sodium-ion platform in early 2025, offering 175 Wh/kg energy density, sub-zero operation, and over 10,000 cycles besides making it ideal for Pakistan's hot and off-grid geographies. HiNa Battery has already commercialized 140–155 Wh/kg sodium-ion cells for electric vehicles and grid storage in China. Reliance, through its acquisition of Faradion, is setting up manufacturing lines in Gujarat (India) and evaluating export-oriented assembly hubs abroad. These firms are seeking regional bases that offer:

- **Labour cost savings** (Pakistan's manufacturing labour cost is ~USD 130/month vs. ~USD 250 - 300 in China)
- **SEZ-based tax exemptions** (up to 10 years under Pakistan's SEZ Act)
- **Preferential trade access** to the Middle East and Central Asia

In summary, if CPEC Phase II is to catalyze new industrial sectors, sodium-ion batteries offer a converging point for local resource utilization, foreign technology absorption, and regional market penetration. The SEZs provide a geographic and institutional framework for assembling a complete battery value chain, from refining sodium and biomass carbon to exporting modular energy storage systems.

6.2. Article 6 and Climate Finance Pathways

Pakistan's strategic pivot towards sodium-ion battery (SIB) localization aligns strongly with emerging international climate finance mechanisms, particularly under Article 6 of the Paris Agreement, which governs voluntary carbon markets and cooperative approaches. Article 6 enables countries to trade carbon reductions across borders and supports the development of Mitigation Outcome Units (MOUs) that can be monetized or used to meet Nationally Determined Contributions (NDCs). This makes Pakistan's battery manufacturing ecosystem an attractive candidate for climate-linked investment and results-based financing.

The sodium-ion battery value chain has a low lifecycle carbon footprint, especially when hard carbon is derived from agricultural waste like bagasse or rice husk and cathode precursors are synthesized locally using renewable power or low-carbon energy. According to Liu et al. (2024), sodium-ion batteries can achieve up to 40% lower embedded CO_2 emissions per kWh compared to conventional lithium-iron phosphate (LFP) systems when produced with biomass-sourced anodes and recycled aluminum current collectors.

Given these advantages, there is a strong case for Pakistan to seek MRV-ready (Measurement, Reporting, and Verification) support for sodium-ion R&D and pilot deployments under Article 6.2 bilateral cooperation or 6.4 carbon crediting mechanisms. For instance, a sodium-ion deployment of 100 MWh across 10 distributed sites could displace roughly 30,000 tons of CO_2 equivalent per year compared to diesel-based peaker plants or imported lithium systems powered by fossil-heavy grids. These mitigation outcomes can be bundled as carbon credits to attract international buyers seeking high-impact, SDG-aligned offsets.

Several climate finance channels can be mobilized:

- **Green Climate Fund (GCF)**: Pakistan has already accessed funding through GCF for renewable energy integration. Sodium-ion systems linked to rural electrification, disaster-resilient energy access, or industrial decarbonization could be packaged under GCF's mitigation and readiness pipelines.
- **SDG-Aligned Innovation Funds**: Programmes such as UNDP's Climate Promise, the Climate Investment Funds (CIF), and Clean Technology Fund (CTF) support storage innovations with co-benefits in employment, energy access, and emissions reduction.
- **Blended Finance Instruments**: Instruments such as the Private Infrastructure Development Group (PIDG) and InfraCo Asia are actively funding energy projects in Pakistan and could co-invest in sodium-ion manufacturing or mini-grid deployment models where returns are modest but socio-environmental gains are high.[1]

To be eligible for such climate-linked capital, Pakistan must develop a sector-specific MRV protocol for sodium-ion battery lifecycle emissions, aligned with international standards like ISO 14064 or the GHG Protocol Product Standard. This involves collaboration between the Ministry of Climate Change, NEECA, and technology developers, possibly with technical support from ADB, or the World Bank.

Crucially, Article 6 cooperation enables technology-transfer tied to emissions outcomes, allowing Pakistan to forge bilateral offset agreements with countries seeking cost-effective decarbonization solutions. Countries like Switzerland, Japan, and Sweden have shown interest in South–South Article 6 cooperation. By positioning sodium-ion storage as a mitigation-enabling technology, Pakistan could monetize these partnerships to de-risk R&D, localize production, and finance distributed battery systems in off-grid or industrial zones.

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[1] https://pidg.org/eaaif-invests-in-usd-141-9-million-sustainable-aviation-fuel-facility-in-pakistan-marking-funds-first-asia-investment/

6.3. Role of Private Sector in Market-Led Adoption

The successful localization of a sodium-ion battery (SIB) ecosystem in Pakistan is fundamentally dependent on the active engagement of the private sector to bridge the gap between policy intent and commercial execution. This sector acts as the primary engine for Immediate-Term Industrial Anchoring, where private groups, particularly within the Commercial and Industrial (C&I) segment—function as early adopters of peak-shaving storage to mitigate rising grid tariffs.

Beyond consumption, the private sector is the critical driver of the Upstream Value Chain, specifically in the high-purity refining of soda ash (sodium carbonate) and sodium bicarbonate from the Salt Range. Private-sector-led R&D, in collaboration with academic institutions, is essential for the thermal tuning of biomass-derived hard carbon from agricultural residues like bagasse and rice husk, as well as the chemical refining of manganese (Mn) and iron (Fe) ores into battery-grade precursors.

In the Midstream Technical Localization segment, local engineering firms and automotive assemblers are uniquely positioned to lead Hardware Integration. This includes entering joint ventures for the domestic assembly of Battery Management Systems (BMS) and the fabrication of specialized steel/aluminum cell housings and current collectors, which can reduce total system costs by up to 15%. By leveraging Financial De-risking tools like Article 6.2 carbon finance, the private sector can advance toward Long-Term High-Tech Sovereignty, establishing Pakistan as a regional hub for affordable storage. Unlike the lithium-ion model, which remains entirely import-dependent, this private-led strategy enables a 75% localized value chain, significantly reducing the drainage of foreign exchange reserves while achieving the strategic goal of reducing lithium dependence to less than 20%.

6.4. Policy and Institutional Ecosystem

The successful development of a domestic sodium-ion battery (SIB) ecosystem in Pakistan will require a robust, coordinated institutional and policy framework. This framework must align energy storage localization with national climate, energy, and industrial strategies such as the Integrated Generation Capacity Expansion Plan (IGCEP 2047), Pakistan's Nationally Determined Contributions (NDCs), the CPEC Phase II industrial cooperation agenda, and the Sustainable Development Goals (SDGs), particularly Goals 7 (Affordable and Clean Energy), 9 (Industry, Innovation, and Infrastructure), and 13 (Climate Action).

6.4.1. Institutional Framework

At the institutional level, NEPRA (National Electric Power Regulatory Authority) plays a central role in enabling storage adoption by defining tariff structures, dispatch protocols, and ancillary services compensation. NEPRA's recent regulatory framework for BESS, published in late 2024, provides a key opening to formally include sodium-ion technology in energy market planning. It allows storage systems to participate in grid balancing, frequency control, and demand-side management. With proper classification under "energy assets," sodium-ion systems deployed by DISCOs or Independent Power Producers (IPPs) could qualify for capacity payments and wheeling incentives.

The Alternative Energy Development Board (AEDB) and the Ministry of Energy (Power Division) are responsible for integrating renewable energy and grid-scale storage into national energy planning. In the IGCEP 2047 update, released by NGC (formerly NTDC) in Q1 2025, storage is now identified as a critical enabler for achieving the 60% non-fossil power target by 2030. This creates a strategic entry point for sodium-ion batteries, particularly for applications like solar peak-shifting, wind firming, and rural microgrids.

Additionally, the Petroleum Division under the Ministry of Energy, which oversees the broader industrial value chain, including mining and chemical processing, must streamline policy for sodium refining and cathode material development. Clear regulatory pathways for licensing, waste disposal, and power access for energy-intensive refining units will reduce project uncertainty for battery manufacturers.

6.4.2. Policy Toolkit

From a policy toolkit perspective, the government has multiple levers to catalyze investment and technology adoption across the sodium-ion battery value chain:

- **Tax and Tariff Exemptions**: Duty-free import of battery-grade materials and components (e.g. $NaPF_6$ salt, separators, battery management systems) should be extended to sodium-ion systems, like those provided for lithium-ion under SRO 575(I)/2006. Tariff harmonization between upstream (chemicals, materials) and downstream (battery packs, electronics) imports is also essential.
- **Pilot Deployment Financing**: Storage projects within SEZs or under public-private partnerships (PPPs), such as a proposed 10×100 MWh sodium-ion deployment programme, can be supported through blended finance mechanisms with State Bank of Pakistan's green banking window, Pakistan Sovereign Wealth Fund, or International Finance Corporation (IFC). Integration into the Renewable Energy Risk Mitigation Facility (RE-RMF) can further de-risk storage investments.
- **National Battery Roadmap Inclusion**: Pakistan currently lacks a comprehensive national battery policy. A draft roadmap must include sodium-ion as a priority chemistry for grid-level, industrial, and rural applications. This roadmap should define domestic content requirements, investment thresholds, and technology transfer incentives aligned with CPEC Phase II goals.
- **Institutional Cohesion**: A dedicated inter-agency task force, possibly modeled on India's National Mission on Advanced Chemistry Cell Battery Storage, should be created to steer Pakistan's sodium-ion strategy. It can include representation from Ministry of Science and Technology , Ministry of Energy , National Electric Power Regulatory Authority, Board of Investment, and Pakistan Standards and Quality Control Authority , ensuring convergence of industrial, academic, and regulatory objectives.

6.4.3. Strategic Execution

To transform these policy levers into industrial reality, a phased implementation approach is required. The following blueprint provides a 10-year strategic horizon, mapping the transition from initial assembly and indigenous resource anchoring to full energy sovereignty. This roadmap prioritizes segments where Pakistan holds a comparative resource advantage, such as biomass-derived anodes and refined sodium salts, before moving towards high-tech joint ventures for electrolytes and separators.

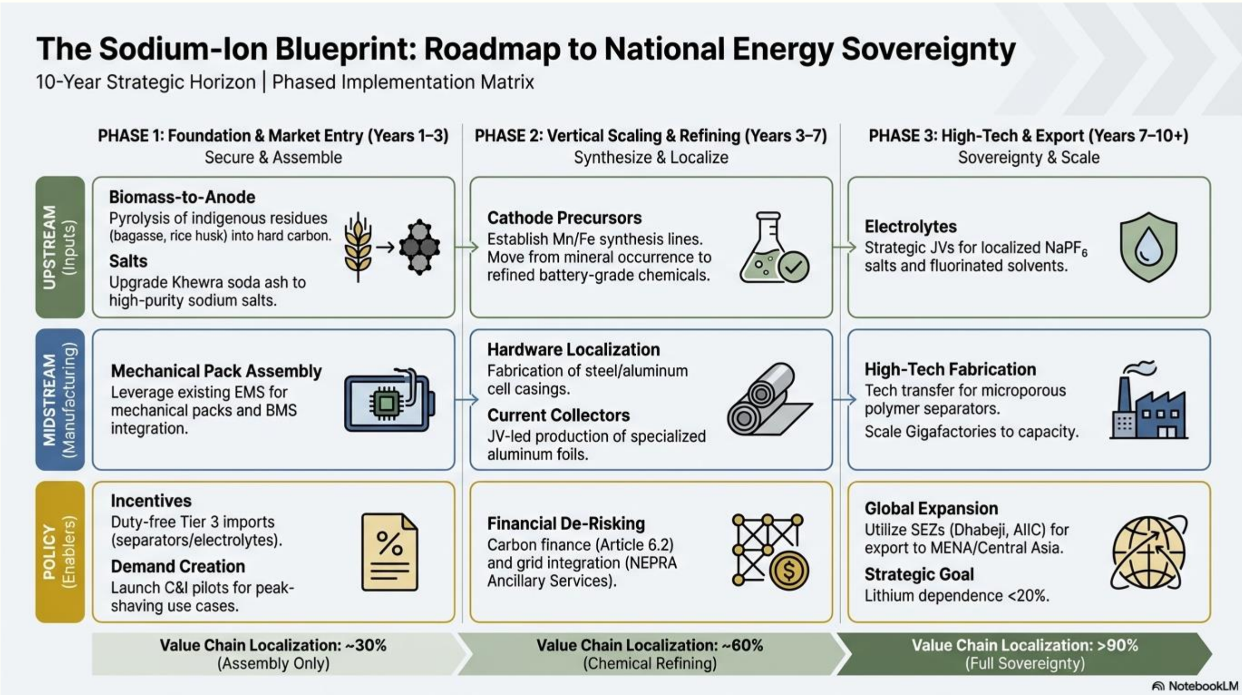

Figure 15: National SIB Roadmap

By adhering to this tiered maturity framework, Pakistan can transition from an import-dependent model to a 75% localized value chain. This shift is critical for preserving foreign exchange reserves and achieving the strategic target of reducing lithium dependence to less than 20% by 2035.

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