STORING THE TRANSITION: BATTERIES, PUMPED HYDRO AND INDIA'S CLEAN POWER FUTURE

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INNOVATION POLICY LAB GLA1011H STUDENT WHITE PAPER 2025-01

0. Introduction

India has made remarkable progress in expanding green energy capacity over the past decade, particularly in solar and wind power. However, this rapid buildout has created a new and increasingly binding challenge: electricity generation from renewables is intermittent, while India's power system was historically designed around stable coal-based generation that provides continuous supply. Without sufficient mechanisms to store electricity when renewable output is high and to release it when supply is needed, the expansion of clean energy capacity has not translated into a proportional increase in clean electricity generation, leaving coal dominant in the generation mix despite strong renewable investment. In response to this integration challenge, energy storage has emerged as a central policy priority.

In public debate and policy discourse, two storage technologies have risen to prominence as potential solutions to India's integration challenge: Battery Energy Storage Systems (BESS) and Pumped Hydro Storage (PHS). Both are technologically mature and increasingly deployed, yet they differ sharply in cost structure, environmental impacts, feasibility, and reliance on external supply chains. To identify policy priorities for India's clean energy transition, the Indian government has requested the development of a report answering the following critical policy question: which energy storage technology should the Indian government prioritize to address intermittency and support long-term decarbonization?

This white paper begins by summarizing the context, highlighting India's recent climate commitments and investments in the renewable energy sector. It then presents the two main options for energy storage in India, namely PHS and BESS, and compares them along four key decision criteria: economic costs and benefits, environmental challenges, feasibility, and external dependency or autonomy. After a careful analysis, this report argues that India should adopt a dual storage strategy, avoiding the risks of technological lock-in highlighted by Kupers and benefitting from each technology's distinct strengths.[1] While BESS is essential for short-duration flexibility and easy to deploy at a rapid pace, PHS should be encouraged as the backbone of India's long-duration storage infrastructure due to its lower lifecycle costs, greater environmental durability, and higher degree of strategic autonomy. To support this approach, the paper proposes targeted institutional reforms to accelerate PHS deployment while strengthening the sustainability of BESS through recycling-focused policy interventions.

1. Context

For decades, India's energy system has been heavily dependent on coal and other fossil fuels, making the country one of the world's largest emitters of greenhouse gasses. In the most recent year, the United Nations reported that India recorded the highest absolute increase in global emissions and remains the third largest emitter overall.[2] Although renewable and other non-fossil sources now account for more than half of India's total installed power capacity, coal continues to dominate actual electricity supply, generating approximately 70 to75 percent of total power output.[3] This gap between installed clean capacity and fossil-based generation highlights a core structural challenge in India's energy transition. Aligning with the international goal of limiting global warming to 1.5°C above pre-industrial levels would require coal's share in electricity generation to fall dramatically to around 17 to19 percent by 2030, a trajectory that

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[1] Roland Kupers, "Getting Unstuck," in *A Climate Policy Revolution* (Harvard University Press, 2020), https://doi.org/10.2307/j.ctvxbpffq.4.

[2] The Wire Staff, "India Records Highest Rise in Greenhouse Gas Emissions in 2024: UNEP Report," The Wire, November 6, 2025, https://thewire.in/environment/india-records-highest-rise-in-greenhouse-gas-emissions-in-2024-unep-report.; 1. Climate Trace, "Country Spotlight: India," Climate TRACE, August 30, 2022, https://climatetrace.org/news/country-spotlight-india.

[3] Press Information Bureau Delhi, Government of India, "The Solar Surge: India's Bold Leap Toward a Net Zero Future", August 19, 2025, https://www.pib.gov.in/PressNoteDetails.aspx?id=155063&NoteId=155063&ModuleId=3&reg=3&lang=2.; Aseem Trivedi, "India's Power Paradox: Why Coal Is Still Our Backbone," Novasensa, June 30, 2025, https://www.novasensa.com/post/india-s-power-paradox-why-coal-is-still-our-backbone.;

India is not currently on track to meet.[4] This underscores the urgency of addressing the structural constraints that prevent renewable capacity growth from translating into sustained reductions in fossil-based generation.

Despite these challenges, India has made significant progress over the past two decades in starting to shift away from carbon-intensive energy sources and restructuring its power sector toward sustainability. Much of this transformation has been driven by long-term policy planning, strengthened climate commitments, and a national effort to diversify its energy sources. Under its first Nationally Determined Contribution (NDC) submitted in 2015 as part of the Paris Agreement, India pledged to reduce the emissions intensity of its economy by one-third from 2005 levels by 2030, and to ensure that a substantial share of its electricity capacity came from non-fossil sources. These commitments were ambitious for a rapidly growing economy but India exceeded several of them ahead of schedule. By 2019, emissions intensity had already fallen by roughly one-third, and by 2023, non-fossil technologies accounted for over 40 percent of installed national power capacity. Building on this momentum, India strengthened its climate pledges in 2022, committing to reduce emissions intensity by 45 percent by 2030, raise the share of installed non-fossil electricity capacity to 50 percent, and achieve net-zero emissions by 2070.[5] These updated targets have been supported by rapid expansion in renewable energy capacity in the last decade, particularly in solar and wind power. By mid-2024, renewable energy installations had reached nearly 200 GW, and non-fossil technologies accounted for more than half of the total national power capacity, achieving India's COP26-era 50 percent non-fossil

[4] Climate Action Tracker, Policies & Action, September 24, 2025, https://climateactiontracker.org/countries/india/policies-action/.

[5] Confederation of Indian Industry, publication, *India's Outlook on Clean Energy Storage: A Roadmap to Net Zero*, 2024, https://ciire.in/pdf/CII%20Comprehensive%20Analysis%20of%20BESS%20and%20Pumped%20Hydro%20Storage%20in%20India%202024_13%20Nov%20(002).pdf.

milestone five years early.[6] Solar power has grown especially rapidly, placing India among the world's top solar producers, with domestic manufacturing capacity for solar modules expanding in parallel.[7] The continued scale-up of renewables is central to India's target of 500 GW of non-fossil capacity by 2030, a goal that seems achievable based on current investment and policy trajectories.[8]

However, this renewable capacity expansion has not translated proportionally into clean electricity generation. Despite the growth of solar and wind installations, renewables continue to account for only around 22 percent of total electricity generation.[9] This disconnect reflects persistent grid integration challenges, especially the lack of sufficient energy storage capacity. Solar and wind resources are inherently variable, generating electricity only when sunlight or wind is available. As their share in the power system increases, mechanisms are required to store excess generation during periods of high output and release electricity during evening peaks or periods of low renewable availability.[10]

Energy Storage Systems (ESS) have therefore emerged as an essentialcomponentof India's next phase of decarbonization. Storage enables grid stabilization, peak-load management,

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[6] Press Information Bureau Delhi, Government of India., "India's Renewable Energy Capacity Hits New Milestone," Ministry of New and Renewable Energy, November 13, 2024, https://www.pib.gov.in/PressReleaseIframePage.aspx?PRID=2073038&reg=3&lang=2.

[7] Ibef, "India Becomes Third Largest Solar Energy Generator: Union Minister of New and Renewable Energy, Mr. Pralhad Joshi: IBEF," India Brand Equity Foundation, August 1, 2025, https://www.ibef.org/news/india-becomes-third-largest-solar-energy-generator-union-minister-of-new-and-renewable-energy-mr-pralhad-joshi.

[8] Reuters, "India Hits 50% Non-Fossil Power Milestone Ahead of 2030 Clean Energy Target | Reuters," Reuters, July 14, 2025, https://www.reuters.com/business/energy/india-hits-50-non-fossil-power-milestone-ahead-2030-clean-energy-target-2025-07-14/.

[9] Knn India - Knowledge & News Network, "Renewable Energy Share to India's Electricity Generation Reaches 22% in 2024-25: Minister Naik," KNN Knowledge & News Network, March 12, 2025, https://knnindia.co.in/news/newsdetails/sectors/energy/renewable-energy-share-to-indias-electricity-generation-reaches-22-in-2024-25-minister-naik.

[10] Confederation of Indian Industry, *India's Outlook on Clean Energy Storage*

outage resilience, electric mobility integration, and decentralized energy access.[11] India's energy planners estimate that over 400 GWh of storage capacity will be required by the early 2030s, with the majority expected to be supplied by BESS and PHS.[12] While alternative storage technologies such as compressed air, thermal storage, and flywheels exist, BESS and PHS currently represent the most viable and scalable solutions for large-scale grid integration in the Indian context.[13]

2. Types of Energy Storage

PHS and BESS each function in radically different ways. While they both play a critical role in enabling power systems to absorb high shares of variable renewable energy while maintaining reliability, flexibility, and system stability, they serve distinct operational needs in India's energy storage landscape.

2.1. Pumped Hydro Energy Storage

Pumped hydro energy storage is the oldest and most widely deployed form of large-scale storage globally. It operates using two reservoirs at different elevations: water is pumped uphill using surplus electricity and released back through turbines to generate electricity when demand rises. In essence, pumped energy is gravitational energy stored in elevated water. PHS is

[11] Confederation of Indian Industry, *India's Outlook on Clean Energy Storage*
[12] Charith Konda, "India's Battery Storage Boom: Getting the Execution Right," IEEFA, August 18, 2025, https://ieefa.org/resources/indias-battery-storage-boom-getting-execution-right.
[13] Confederation of Indian Industry, *India's Outlook on Clean Energy Storage*

particularly suitable for long-duration storage[14], as typical plants provide 6-20 hours of discharge at full power[15], with round-trip efficiencies of 70-80 percent and lifetimes exceeding 40 years.[16]

India clearly recognizes the strategic importance of pumped storage as it expands its solar and wind capacity. Although deployment was historically limited, with only around 4.8 GW of pumped storage operational in early 2021, development has accelerated sharply in recent years.[17] As of mid-2025, India has approximately 6-7 GW of PHS commissioned, 8.5 GW under construction, and over 60 GW under investigation or active planning.[18] Least-cost modelling for India suggests that, under current cost assumptions, around 9 GW of pumped hydro will be economically attractive by 2030 as part of a broader storage portfolio, with similar levels by 2032. These results also show that if battery costs remain higher than expected, or if PHS projects can be delivered at a lower cost, the optimal PHS capacity will roughly double to 17-18 GW by 2030. [19]

2.2. Battery Energy Storage

BESS uses electrochemical processes, primarily lithium-ion technologies, to store and release electricity. Batteries convert electrical energy into chemical form during charging and

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[14] U.S. Department of Energy, "Pumped Storage Hydropower," Office of Energy Efficiency & Renewable Energy, accessed December 17, 2025, https://www.energy.gov/eere/water/pumped-storage-hydropower

[15] "Battery Energy vs Pumped Hydro: Analysing India's Power Storage System Contenders," *NDTV Profit*, May 22, 2024, https://www.ndtvprofit.com/economy-finance/battery-energy-vs-pumped-hydro-analysing-indias-power-storage-system-contenders

[16] "What Is the Round-Trip Efficiency of Pumped-Hydro Storage and How Does It Compare to Other Grid-Scale Storage?," *Energy Sustainability Directory*, November 20, 2025, https://energy.sustainability-directory.com/learn/what-is-the-round-trip-efficiency-of-pumped-hydro-storage-and-how-does-it-compare-to-other-grid-scale-storage/.

[17] International Energy Agency, *India Energy Outlook 2021* (Paris: OECD Publishing, 2021), https://www.oecd.org/content/dam/oecd/en/publications/reports/2021/03/india-energy-outlook-2021_a03d3c7e/ec2fd78d-en.pdf

[18] Press Information Bureau, Government of India (Government of India Takes Key Decisions for Energy Storage)," June 7, 2024, https://www.pib.gov.in/PressReleasePage.aspx?PRID=2149363&reg=3&lang=2

[19] Nikit Abhyankar et al., *Strategic Pathways for Energy Storage in India Through 2032* (India Energy & Climate Center, 2025)

reverse the reaction during discharge. They are highly modular, deployable at various scales, and capable of responding within milliseconds.[20] While individual battery systems typically provide 1-4 hours of storage, they excel at fast frequency response, voltage control, renewable smoothing, and short-duration peak shaving.[21]

India's battery-storage sector has grown rapidly from a small base, helped by nearly a 90 percent decline in global battery prices over the last decade and a 65 percent reduction in Indian storage auction prices since 2021. The Indian government has set a national target for storage to meet 4 percent of electricity demand by 2030, equivalent to roughly 200-250 GWh of grid-scale storage. Recent system-level modelling finds that, in a least-cost pathway consistent with 500 GW of non-fossil capacity by 2030, India would need around 61 GW/218 GWh of storage by 2030 and 97 GW/362 GWh by 2032. Due to rapid cost declines, battery storage is expected to dominate this mix, providing about 51 GW/164 GWh by 2030 and 87 GW/308 GWh by 2032, with PHS contributing around 9 GW. The modelling also highlights an evolution in battery durations: 2-hour batteries dominate until around 2027, mainly covering evening peaks, while 4-hour batteries will become predominant from 2027 onwards, cycling roughly once per day to shift solar generation from daytime to evening and night-time demand.[22]

As the country moves into a decisive phase of its energy transition, determining the relative strengths, limitations, and broader implications of these two technologies has become a central policy challenge. A comparison of BESS and PHS has thus become critical for India to assess which storage pathway should be prioritized for future investment, innovation, and deployment in support of its long-term decarbonization strategy.

[20] Montel Group, "What Is an Energy Battery Storage System (BESS)?" *Montel Group Blog*, accessed December 17, 2025, https://montel.energy/resources/blog/what-is-an-energy-battery-storage-system-bess
[21] "Battery Energy vs Pumped Hydro: Analysing India's Power Storage System Contenders"
[22] Abhyankar et al., *Strategic Pathways for Energy Storage in India Through 2032.*

3. Evaluating the Strengths and Weaknesses of BESS and PHS in India

In order to effectively compare the two energy storage technologies in the Indian context, this analysis evaluates both technologies across four key decision criteria. First, it examines economic costs and benefits to assess not only short-term financial viability but also the long-term economic value of each storage option. Second, it considers environmental costs in order to account for lifecycle impacts, ecological disruption, and waste management risks that may affect sustainability over time. Third, it assesses the feasibility of expanding each type of energy storage by examining geographical constraints, administrative and regulatory readiness, and social acceptance, all of which shape the pace and scale of deployment in practice. Finally, the analysis assesses external dependency and strategic autonomy by examining the extent to which each technology relies on imported inputs and global supply chains, an increasingly important consideration for India's energy security in the long term.

This framework focuses on factors that are most relevant for medium and long-term storage deployment in India. Technical performance metrics such as response time or ramping capability are not examined in detail, as both technologies are capable of meeting grid requirements. Instead, the analysis prioritises economic, environmental, institutional, and strategic considerations that are more likely to constrain or enable large-scale deployment, in order to make an informed recommendation for India's best path forward.

3.1 Economic Costs and Benefits

PHS and BESS are both commercially viable means of energy storage in India, but a careful analysis of costs and benefits reveals that while BESS is emerging as a financially attractive option for short-duration, market-driven applications, PHS retains a clear economic advantage for long-duration storage and delivers broader, more durable benefits for regional development.[23]

From a strictly financial point of view, PHS requires higher upfront capital investment due to its large scale and extensive civil works requirements, with costs typically ranging from US$1,700 to US$2,500 per kW of installed capacity.[24] BESS, in contrast, has seen a dramatic decline in prices over the last two or three years, with standalone battery storage now estimated at roughly US$150-200 per kWh for the energy component, and a four-hour system's power capacity typically costing US$1,400-2,000 per kW.[25] Because PHS is priced primarily on power capacity and BESS includes separate power and energy components, these figures cannot be directly compared on a per-unit basis, and the true comparison must consider the full system costs over the lifetime of each technology.[26] Indeed, operational costs and lifetimes differ greatly between the two storage systems: PHS plants have low operating costs and can last 40-80 years with almost no loss in efficiency, whereas BESS exhibit noticeable degradation after 1,500-3,000 cycles and have an effective lifetime of 10-20 years, thus requiring regular battery replacement.[27] Although batteries achieve higher round-trip efficiency on a per-cycle basis, typically 85-95 percent for lithium-ion systems compared to 70-80 percent for PHS, this advantage is largely confined to short-duration applications of up to 4 hours.[28] As storage duration increases, adding battery capacity raises both marginal losses and replacement costs, while PHS maintains stable performance over extended discharge periods, making it better suited for long-duration storage of

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[23] Jyoti Gulia et al., *Energy Storage: Connecting India to Clean Power on Demand* (Institute for Energy Economics and Financial Analysis, 2023), https://ieefa.org/resources/energy-storage-connecting-india-clean-power-demand.
[24] Gulia et al., *Energy Storage*.
[25] Abhyankar et al., Strategic Pathways for Energy Storage in India Through 2032.; Gulia et al., *Energy Storage*.
[26] Abhyankar et al., *Strategic Pathways for Energy Storage in India Through 2032*.
[27] Gulia et al., *Energy Storage*; Adrian Soto et al., "Impact of Micro-Cycles on the Lifetime of Lithium-Ion Batteries: An Experimental Study," *Journal of Energy Storage* 55 (November 2022): 105343, https://doi.org/10.1016/j.est.2022.105343.
[28] "What Is the Round-Trip Efficiency of Pumped-Hydro Storage and How Does It Compare to Other Grid-Scale Storage?"; *Sodium-Ion Batteries: A Technology Brief* (IRENA, 2025).

over 8 hours.[29] Differences in capital costs, operational costs, asset lifetimes, and storage durations are captured by the levelized cost of storage (LCOS), which provides a common metric for evaluating the average cost of storing and delivering one unit of energy over the lifetime of each system. Based on 2024 costs, the LCOS for BESS is estimated at Rs 5.5-6 per unit, compared to Rs 4.5-5 per unit for PHS.[30] This suggests that, despite the recent reductions in battery prices, PHS currently remains more cost-effective when considering both its longer operational lifetime and extended storage duration.

While cost comparisons provide an important baseline, they do not capture the entire economic picture. It is also essential to consider the potential economic returns each technology can generate, including through arbitrage opportunities and revenue from ancillary services, but also through broader economic benefits like job creation or regional development. For the first time in 2024, BESS became commercially viable, meaning that it generated more revenue than costs per year.[31] While costs have been steadily declining, revenue from market participation have simultaneously increased from INR 0.5 million/MWh in 2015 to INR 2.4 million/MWh in 2025, making merchant BESS a financially viable standalone business model.[32] In addition to arbitrage in the day ahead market, BESS generates revenue in the ancillary services market, with projections that investing in BESS today can lead to total returns of up to 24%.[33] With estimations that the market size will increase from a few hundred million USD in 2024 to over a billion in the next decade, there is also significant opportunity for job creation, with roles like

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[29] Gulia et al., *Energy Storage*.
[30] Mihika Barve, "Battery Energy Vs Pumped Hydro: Analysing India's Power Storage System Contenders," *NDTV Profit*, July 6, 2024, https://www.ndtvprofit.com/economy-finance/battery-energy-vs-pumped-hydro-analysing-indias-power-storage-system-contenders.
[31] "The Age of Storage: Batteries Primed for India's Power Markets. Chapter 3: The Economics of Merchant BESS," *Ember*, 2025, 3, https://ember-energy.org/latest-insights/the-age-of-storage-batteries-primed-for-indias-power-markets.
[32] "The Age of Storage."
[33] "The Age of Storage."

battery manufacturing technician, inverter engineer, or commissioning engineer becoming highly sought after.[34]

In contrast, India's PHS market is already worth 12.2 billion USD in 2024, and expected to double in size by 2033, with a growth rate of 8.34% per year.[35] As of now, it is the most commercially viable means of energy storage in India.[36] Due to their large scale, PHS projects are also expected to generate a significant number of jobs: taking the case of Odisha alone, the opportunity to deploy 3,790 MW of PHS by 2030 is predicted to create 3,300 full-time jobs in the state.[37] These opportunities are not only limited to plant operations, but also include the creation of jobs for drivers, laborers, and construction workers.[38] The local infrastructure development associated with PHS projects, in the form of roads and bridges, also provides greater livelihood opportunities for local populations, increases regional tourism, and decreases internal migration.[39] PHS thus holds a distinct advantage on this front, bringing considerable economic and social benefits for long-term regional growth.

Overall, this economic analysis clearly demonstrates that both energy storage systems have a financially viable economic future in India. However, the cost-effectiveness of PHS and BESS over the next decade will depend largely on how their respective cost trajectories evolve.[40] If battery costs continue to decline significantly, BESS could become increasingly attractive, particularly for shorter-duration applications. However, if battery prices do not fall as much, or if

[34] "Battery Energy Storage Systems (BESS) Careers in India," The Green Bein, October 1, 2025, https://www.thegreenbein.in/post/battery-energy-storage-systems-bess-careers-in-india.
[35] *India Pumped Hydro Storage Market Size, Share, Trends and Forecast by Type, Sources, and Region, 2025-2033* (IMARC, 2025), https://www.imarcgroup.com/india-pumped-hydro-storage-market.
[36] Gulia et al., *Energy Storage*.
[37] "Pumped Storage Hydropower," Council on Energy, Environment and Water, February 13, 2025, https://www.ceew.in/pumped-storage-hydropower.
[38] Council on Energy, Environment and Water, "Pumped Storage Hydropower."
[39] Council on Energy, Environment and Water, "Pumped Storage Hydropower."
[40] Abhyankar et al., *Strategic Pathways for Energy Storage in India Through 2032*.

pumped hydro projects can be developed efficiently and at capital costs under Rs. 4 Cr/MW, PHS would remain the more cost-effective option, especially for long-duration storage.[41]

3.2 Environmental Challenges

While BESS and PHS both contribute to India's clean energy transition, they also pose distinct environmental risks. BESS introduces waste management concerns, while PHS can disrupt water streams and local ecosystems, raising questions about the sustainability of each system for long-term, large-scale deployment.

The environmental concerns associated with BESS in India largely stem from the country's limited capacity to manage the end-of-life stage of batteries.[42] The accumulation of lithium-ion batteries is rising rapidly and by 2030 India is projected to hold a stock of roughly 600 GWh.[43] However, current recycling infrastructure can process only a fraction of that, around 128 GWh, leaving a significant gap between battery generation and recycling for disposal. Although India has introduced regulatory frameworks such as the Battery Waste Management Rules to strengthen oversight, the country still faces considerable challenges. These rules encourage manufacturers to take responsibility for collection and recycling, and promote technological improvements in reuse and material recovery. But in practice, India continues to struggle with insufficient collection infrastructure, high logistical costs, and limited recycling capacity. The environmental risk is substantial as improperly managed batteries can lead hazardous materials, including lithium, cobalt, nickel, and cadmium, to leach into soil and water systems. When handled correctly, however, recycling enables the recovery of valuable metals and allows India to build a more circular battery economy. These issues apply across battery

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[41] Abhyankar et al., *Strategic Pathways for Energy Storage in India Through 2032*.
[42] Confederation of Indian Industry, *India's Outlook on Clean Energy Storage*
[43] Puja Das, "India Leans on Pumped Hydro for Energy Storage as Battery Costs and Recycling Woes Mount," Down To Earth, September 3, 2025, https://www.downtoearth.org.in/energy/india-leans-on-pumped-hydro-for-energy-storage-as-battery-costs-and-recycling-woes-mount.

chemistries, but some types, such as nickel cadmium batteries, pose additional concerns due to cadmium's persistence and toxicity.[44]

The environmental footprint of PHS differs significantly depending on whether a project uses on-river or off-river configuration. Off-river systems, which operate using water stored entirely within man-made reservoirs, have several environmental advantages. Since the same water is reused continuously, these systems typically maintain high operational efficiency and require only minor additions of water over time to offset evaporation. Their performance is largely stable throughout the years because they do not rely on fluctuating natural river flows. As a result, they are generally less vulnerable to droughts, floods, or other climate-related uncertainties.[45]

In contrast, on-river systems draw water directly from natural rivers and lakes, making them highly sensitive to seasonal variability and increasingly unpredictable climate conditions. These projects can also disrupt downstream agriculture, alter fragile ecosystems, and result in displacement and water diversions that affect local communities. As discussed in the following section, this can trigger intense public backlash, including community protests, legal challenges, and political resistance, particularly where displacement and water insecurity are involved. As climate variability increases, these environmental and social tensions will likely be intensified as contested natural water flows are managed.[46]

Overall, the environmental trade-offs between the two technologies differ in both scale and type. BESS carries higher lifecycle risks due to toxic waste, mineral extraction requirements, and India's limited recycling capacity. PHS avoids these chemical hazards but can introduce

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[44] Confederation of Indian Industry, *India's Outlook on Clean Energy Storage*
[45] Jyoti Parikh, "A Reliable Storage Option That Needs Attention: Off- River Pumped Hydro Power," ETEnergyworld.com, February 21, 2025, https://energy.economictimes.indiatimes.com/news/power/a-reliable-storage-option-that-needs-attention-off-river-pumped-hydro-power/118444466.
[46] Parikh, "A Reliable Storage Option That Needs Attention"

localized ecological impacts, especially when connected to natural water systems.[47] As aforementioned, PHS have extremely long operational lifespans, often lasting 40 to 80 years. This longevity means that once constructed, they require minimal replacement and generate virtually no ongoing waste. In contrast, BESS typically only operates for 10 to 20 years before needing full or partial replacement. As a result, BESS creates a continuous stream of end-of-life battery material that India is not currently equipped to recycle at scale.[48] When considering long-term sustainability, PHS, particularly off-river designs, demonstrates significantly greater environmental resilience, while BESS imposes recurring waste management challenges in the absence of a major expansion of India's recycling infrastructure.

3.3 Feasibility

The feasibility of expanding PHS and BESS in India depends primarily on site suitability, India's administrative and regulatory readiness, and the degree of social acceptance of each technology. On this front, each technology exhibits distinct challenges.

First, geographical considerations play a role in determining which storage option is practical and where, as the land requirements for BESS and PHS differ greatly. PHS requires specific topographical conditions, with significant elevation differences and enough space for two reservoirs.[49] For on-river PHS, it also necessitates the presence of natural, flowing bodies of water.[50] Rather than a limitation, this represents an advantage for PHS in India, as the country's geography is particularly adapted to the development of these projects, with the state identifying an extensive number of potential suitable sites across the country.[51] As of 2023, the Central

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[47] Confederation of Indian Industry, *India's Outlook on Clean Energy Storage*
[48] Das, "India Leans on Pumped Hydro for Energy"
[49] "How Does Pumped Hydroelectric Storage Work and What Are Its Geographical Limitations?," *Energy Sustainability Directory*, November 20, 2025, https://energy.sustainability-directory.com/learn/how-does-pumped-hydroelectric-storage-work-and-what-are-its-geographical-limitations/.
[50] "How Does Pumped Hydroelectric Storage Work and What Are Its Geographical Limitations?"
[51] Gulia et al., *Energy Storage*.

Electricity Authority of India had identified an on-river PHS potential of 103GW, with several existing dams in India that do not yet include a PHS component and could be converted, on top of significant off-river potential.[52] The large majority of the sites identified were in Maharashtra, but also in Mizoram, Tamil Nadu, or Himachal Pradesh, states that have already begun issuing large scale tenders or signing memoranda of understanding with independent power producers for site allotment.[53] As of May 2025, India had 125 PHS projects in the pipeline, with a projected cumulative capacity of 151.7 GW, highlighting that geographical feasibility is strong and that there is significant long-term potential for expanding pumped hydro storage in India.[54] Conversely, BESS is not site-dependent and can be installed almost anywhere.[55] However, to reduce costs, BESS has the possibility of being co-located with solar power plants, an advantage that PHS does not offer.[56] As such, it is most likely to be installed in states with significant solar energy capacity, where there is high, concentrated electricity demand, and where there is limited capacity to deliver electricity during peak demand periods, such as Gujarat, Maharashtra, Telangana, Rajasthan, Uttar Pradesh, and Andhra Pradesh.[57]

Beyond geographical considerations, the regulatory and administrative framework strongly influences which type of energy storage may be more feasible to expand. Historically, many identified PHS projects and hydropower projects more generally have been abandoned or faced significant delays and cost overruns.[58] The main reasons identified for such delays included

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[52] Gulia et al., *Energy Storage*.
[53] Gulia et al., *Energy Storage*.
[54] Varun Potty and Maria Chirayil, "Flooded with Options? The Status of Pumped Storage Projects in India," Prayas Energy, June 12, 2025, https://energy.prayaspune.org/power-perspectives/flooded-with-options-the-status-of-pumped-storage-projects-in-india.
[55] Das, "India Leans on Pumped Hydro for Energy"
[56] Abhyankar et al., *Strategic Pathways for Energy Storage in India Through 2032*.
[57] Abhyankar et al., *Strategic Pathways for Energy Storage in India Through 2032*.
[58] Upasa Borah et al., "Pumped Storage Plants in India: Assessing Policies and Progress," *Working Papers*, Working Papers, Trustbridge Rule of Law Foundation, March 2025, 12, https://ideas.repec.org//p/bjd/wpaper/12.html.

difficulties in land acquisition, environment and forest-related clearance delays, rehabilitation and resettlement issues, and inadequate infrastructural facilities, among others.[59] Crucially, the time taken to provide environmental clearances was identified as a main bottleneck, increasing both the time and the costs associated with PHS projects and making them less financially viable.[60] While this problem is more pronounced for PHS projects due to their large scale, BESS projects also regularly face delays related to civil works, land acquisition, and environmental clearances.[61] Delays in signing power purchase agreements (PPAs) also often occur due to expectations of further price reductions from the offtaker.[62] This can lead BESS projects to become financially unviable, with Solar Energy Corporation of India's 500 MW/1,000 MWh standalone BESS tender being ultimately cancelled due to significant delays in signing the necessary contracts.[63]

However, the Indian government has taken resolute steps to support the faster development of the two energy storage systems through supply-side policies, demonstrating a clear political commitment to eliminating administrative burdens and increasing the feasibility of large-scale energy storage deployment across the country. In April 2023, the Ministry of Power issued detailed guidelines to streamline the development of PHS projects.[64] Notable changes included the identification of exhaust mines as potential sites for PHS, the provision of financial incentives like tax benefits and concessional climate financing, and the exemption of off-river PHS projects from environmental impact assessments (EIAs).[65] In addition, the government began providing government land at concessional rates in order to make land acquisition more

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[59] Borah et al., "Pumped Storage Plants in India."
[60] Borah et al., "Pumped Storage Plants in India."
[61] Confederation of Indian Industry, *India's Outlook on Clean Energy Storage*.
[62] Gulia et al., *Energy Storage*.
[63] Gulia et al., *Energy Storage*.
[64] Confederation of Indian Industry, *India's Outlook on Clean Energy Storage.*
[65] Confederation of Indian Industry, *India's Outlook on Clean Energy Storage*.

affordable.[66] For BESS, the government introduced two major policies: the Production Linked Incentive (PLI) Scheme for Advanced Chemistry Cell (ACC) Battery Storage, which offers financial incentives to encourage local battery manufacturing, and the Viability Gap Funding (VGF) scheme, which supports the development of BESS by covering up to 40 percent of capital costs to improve attractiveness for investors.[67] For both technologies, the government also waived the Inter-State Transmission System (ISTS) charges between 2021 and 2025, reintroducing transmission charges by 25 percent annually from July 1, 2025 to June 30, 2028, with the goal of reducing the initial cost burden of energy storage projects.[68] These policies are clear examples of the state taking an active role in a sector with high uncertainty, providing both policy and finance to encourage the creation of competitive markets in the renewable energy sector. In this sense, India's approach reflects Mazzucato's conception of the entrepreneurial state, in which governments actively shape markets to support green technologies and counter the sunk-cost advantages of incumbent fossil-based systems.[69] Indeed, this strategic vision and sustained support for clean energy storage have been central to improving the feasibility and cost-effectiveness of both PHS and BESS systems.

Despite this policy support, feasibility also ultimately depends on the political and social support of affected populations, as community opposition can exacerbate the administrative and regulatory delays already identified. While BESS have so far encountered limited public resistance due to their relatively small size and flexible siting, many communities have opposed PHS projects, as previously mentioned, on the grounds that they lead to environmental

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[66] Confederation of Indian Industry, *India's Outlook on Clean Energy Storage*.
[67] Confederation of Indian Industry, *India's Outlook on Clean Energy Storage*.
[68] Confederation of Indian Industry, *India's Outlook on Clean Energy Storage*.
[69] Mariana Mazzucato, "Pushing vs. Nudging the Green Industrial Revolution," in *Entrepreneurial State* (Anthem Press, 2015).

degradation, disruption of local ecosystems, and the displacement of populations.[70] For example, a 2000 MW PHS project proposed by the Karnataka government in the Sharavathy river valley has generated significant opposition, with claims from activists, ecologists, and residents that the project would destroy the natural habitat of the Lion-Tailed Macaque, an endangered species endemic to the area.[71] Civil society groups have also criticised the project's EIA as incomplete and insufficiently rigorous, arguing that it failed to adequately assess key risks or justify the project and that the public consultation process did not allow for informed participation.[72] Similarly, PHS projects in Andhra Pradesh have come under fire, facing accusations of violating laws protecting tribal communities and forest rights, and bypassing consultative processes.[73] In practice, these forms of contestation increase the risk that PHS projects may face prolonged delays or cancellation, despite formal policy and administrative support.

Taken together, this analysis suggests that BESS is currently more feasible to deploy rapidly and at scale in India due to its siting flexibility, simpler approval processes, and limited social resistance. As for PHS, despite strong geographical potential and policy support, its large-scale deployment remains more contingent on overcoming administrative delays and securing sustained local acceptance.

3.4 External Dependency

A critical distinction between BESS and PHS lies in the degree of external dependency embedded in their supply chains. This is a critical consideration for India, which aims to become

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[70] "A Disaster in the Making: Ecologists and Villagers Oppose 2000 MW Sharavathy Pumped Storage Project," *Groundxero*, October 24, 2025, https://www.groundxero.in/2025/10/24/a-disaster-in-the-making-ecologists-and-activists-oppose-2000-mw-sharavathy-pumped-storage-project/.
[71] "'A Disaster in the Making.'"
[72] "'A Disaster in the Making.'"
[73] Pavan Korada, "Andhra Pradesh: Pumped Storage Projects Spark Concerns over Tribal Displacement and Environmental Harm," Environment, *The Wire*, December 6, 2024, https://thewire.in/environment/andhra-pradesh-pumped-storage-projects-spark-concerns-over-tribal-displacement-and-environmental-harm.

less import-dependent in line with Modi's vision for Atmanirbhar Bharat, or a "self-reliant" India.[74]

BESS exhibits a structurally high level of external reliance, primarily due to India's dependence on imported critical minerals, like lithium, cobalt, nickel, vanadium, and natural graphite, sourced predominantly from China, Chile, Indonesia, and the Democratic Republic of the Congo.[75] These dependencies extend beyond raw materials: despite recent progress under India's PLI scheme for battery storage manufacturing, the upstream components of battery manufacturing remain import-intensive. Key inputs such as cathode and anode materials, anode-grade graphite, separators, electrolyte solvents, binder chemicals, and even cell-manufacturing equipment are still largely sourced from abroad. As a result, large parts of the BESS value chain remain exposed to international markets.

This dependence is not only a long-term concern, but already has practical implications for BESS deployment in India. Export restrictions, especially China's recent controls on graphite exports, increase uncertainty for battery supply.[76] Graphite is a critical input for lithium-ion battery anodes, and China dominates both mining and processing. When exports are subject to licensing or additional controls, supply becomes less predictable.[77] For Indian developers, this can mean longer procurement timelines, higher input prices, and more risk when bidding for large BESS projects. Even if shipments are eventually approved, delays and administrative

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[74] Department for Promotion of Industry and Internal Trade, *Investment Promotion Reforms* (New Delhi: Ministry of Commerce and Industry, Government of India, January 2021), 3, 8, https://www.dpiit.gov.in/static/uploads/2025/06/9976ca15f5dcf1a3fa26fb3f83bb7daa.pdf

[75] International Energy Agency, *The Role of Critical Minerals in Clean Energy Transitions* (Paris: IEA, 2021), 23–27.

[76] ScanX News Team, "China's Graphite Export Restrictions Impact Indian Companies," *ScanX*, October 9, 2025, https://scanx.trade/stock-market-news/global/china-s-graphite-export-restrictions-impact-indian-companies/21546852

[77] China Export Controls: Lithium Batteries and Artificial Graphite Anode Materials," Herbert Smith Freehills Kramer, October 2025, https://www.hsfkramer.com/insights/2025-10/china-export-controls-lithium-batteries-and-artificial-graphite-anode-materials

uncertainty can affect project schedules and financing. As India moves from pilot-scale deployments to large, utility-scale BESS auctions, this uncertainty becomes more consequential. Grid-scale storage projects rely on tight construction timelines and fixed-price bids, making them particularly sensitive to delays or cost revisions in battery supply. In this context, export controls function not only as a price risk, but as a deployment risk, directly affecting the pace and bankability of BESS expansion in India. As BESS deployments scale into hundreds of gigawatt-hours, these vulnerabilities intensify, limiting India's strategic autonomy in storage deployment and increasing long-term foreign-exchange exposure.

External dependence also shapes the trajectory of BESS costs in India. BESS prices are highly sensitive to raw material inputs, meaning that global shortages or speculative price surges can directly slow India's storage rollout or alter the least-cost mix between BESS and PHS. Furthermore, as previously mentioned, India's domestic recycling infrastructure remains insufficient to meaningfully offset these upstream imports. Without large-scale recovery of lithium, cobalt, and nickel, India remains locked into international supply chains for most battery chemistries, and the absence of domestic cathode and precursor-material production reinforces this dependency. Even alternative chemistries, such as LFP or sodium-ion, while reducing reliance on cobalt and nickel, still depend on imported phosphate salts, sodium carbonate, or specialized manufacturing equipment, preserving the structural asymmetry.[78]

In contrast, PHS is characterized by a comparatively high level of domestic autonomy. Its development relies principally on resources and capabilities available within India: water, land, civil and structural engineering, tunnelling expertise, concrete and steel production, turbine manufacturing capacity, and a large domestic hydropower workforce. India possesses

[78] NITI Aayog and RMI, *Need for Advanced Chemistry Cell Energy Storage in India: Part III of the National Energy Storage Mission Strategy* (New Delhi: NITI Aayog, 2022), 14–16

longstanding institutional and industrial capacity in large-scale hydro and civil works, enabling PHS projects to rely predominantly on domestic firms, domestic labour, and domestic supply chains. Even the electromechanical components for PHS, including turbines, generators, and pump-turbine assemblies, can be procured from established Indian manufacturers, further reducing exposure to international market fluctuations.[79]

This domestic orientation gives PHS a significant strategic advantage. Its cost structure is largely shielded from foreign exchange risks and global commodity cycles, allowing long-term planning that is less vulnerable to external shocks. As PHS requires no imported mineral inputs and maintains 40-80 years of operational life with minimal component replacement, its cumulative exposure to global supply chains is negligible compared to BESS, where entire systems must be replaced every decade.[80] The relative insulation of PHS enhances India's capacity to expand long-duration storage on its own terms, without being constrained by geopolitical risks, technology-export controls, or mineral market concentration. In a clean energy transition increasingly shaped by strategic competition over critical minerals, this autonomy becomes a critical advantage.

3.5 Evaluation Results

The criteria evaluation has demonstrated the distinct strengths, weaknesses, and limitations of each energy storage technology. Table 1 summarizes the comparison between the two technologies. On the one hand, PHS scores high on economic and autonomy considerations. It has emerged as more cost-effective for long-duration storage and capable of delivering

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[79] Central Electricity Authority, *National Electricity Plan: Volume I Generation* (New Delhi: Ministry of Power, Government of India, 2023), 85.
https://mnre.gov.in/en/document/national-electricity-plan-volume-i-generation-by-cea/

[80] Schleifer, Anna H, Stuart M Cohen, Wesley Cole, Paul Denholm, and Nate Blair. 2025. "Exploring the Future Energy Value of Long-Duration Energy Storage." *Energies (Basel)* 18 (7): 1751.
https://doi.org/10.3390/en18071751.

considerable regional development and local economic growth. Its independence from external supply chains also provides it with a clear advantage for India's path towards greater autonomy in its energy sector. However, PHS projects score low on the environmental and feasibility criteria, with environmental concerns and social opposition leading to significant delays in the realization of projects. Conversely, BESS projects score high on economic considerations and feasibility. They are cost-effective for short-duration storage and much easier to site and deploy without significant opposition or delays. Nonetheless, BESS struggles with larger environmental challenges, associated with the significant amount of waste that batteries generate. They also face supply chain disruption risks due to a high reliance on imports, causing concerns for India's long-term energy security.

Table 1. Comparison of PHS and BESS across four criteria

Criteria	**PHS**	**BESS**
Economic Costs and Benefits	● Commercially viable ● Costly to build but cheap to operate ● Long lifespan makes it economical in the long term ● Produces local and regional development	● Commercially viable ● Cheaper for short duration storage ● Falling costs but frequent replacements necessary ● Limited broader economic benefits
Environmental Challenges	● On-river systems can disrupt biodiversity and alter local ecosystems ● Off-river systems have relatively low environmental impact	● Produces large quantities of battery waste ● Limited capacity to recycle
Feasibility	● Huge amount of potential sites mapped ● Slow approvals and construction timelines ● Policy initiatives to support PHS include guidelines to streamline the development of PHS projects and the waiver of ISTS charges ● Potential for social resistance and backlash, can cause further delays	● Some regulatory approvals required, but overall easy to put in place anywhere ● Shorter timelines ● Policy initiatives to support BESS include the PLI Scheme for ACC battery storage, the VGF Scheme, and the waiver of ISTS charges ● Little social or political resistance
External Dependency	● Relatively independent	● Mineral dependency on China (e.g. lithium, cobalt, and nickel) ● Battery manufacturing component dependency on China ● Export restrictions uncertainty

4. Policy Recommendations

The preceding analysis demonstrates that India's energy storage challenge cannot be addressed through a single technological pathway. BESS and PHS perform distinct and complementary functions within the power system, and each presents unique economic, environmental, institutional, and strategic trade-offs. Supporting both PHS and BESS also allows India to benefit from each technology's distinct advantages without becoming overly dependent on one storage system, a risk highlighted by Kupers.[81] Indeed, focusing exclusively on one option could create a technological lock-in, where early cost advantages and economies of scale entrench a technology that may not be optimal in the long term. By fostering parallel development of both storage types, policymakers can maintain flexibility, capture complementary benefits, and keep open the possibility for future innovation, while avoiding the risk that early adoption of one system constrains options for efficiency, resilience, or strategic autonomy in the long term. Rather than creating a universal solution, effective policy must be tailored to the specific constraints and advantages associated with each technology.

Based on the comparative evaluation, this section advances a dual policy approach that reflects these differences. First, it outlines institutional reforms aimed at accelerating the deployment of PHS and strengthening social acceptance of these projects. Second, it presents targeted policy measures to guide the expansion of BESS in a manner that minimizes environmental risks and strengthens domestic capabilities, particularly through improved end-of-life battery management and material recovery.

[81] Kupers, "Getting Unstuck."

At the same time, the policy options presented here should be understood as illustrative rather than exhaustive or definitive. Given the diversity of India's energy landscape, regional storage needs, and administrative capacities across states, alternative policy designs may be equally appropriate. The examples discussed focus on areas where government intervention is likely to have the highest leverage, particularly in reducing environmental risk, regulatory uncertainty, and strategic dependence, while maintaining incentives for private investment. By grounding these proposals in the analytical framework developed earlier, this section seeks to translate abstract trade-offs into concrete policy approaches that can inform future policy design and research, rather than prescribe a single optimal blueprint.

4.1 Accelerating PHS Projects through a Unified National Mechanism

Effective scaling up of PHS in India requires institutional solutions that combine strategic planning, environmental prudence, and legitimate community participation. Given India's high technical potential for PHS and the political commitment to accelerating long-duration energy storage deployment, public policy must provide mechanisms that simultaneously reduce the risks of environmental degradation, public resistance, and project delays.

Recent policy developments highlight the urgency of this challenge. As noted earlier, policy changes introduced in 2023 enabled certain PHS projects to bypass full EIAs in an effort to fast-track development.[82] While this approach was intended to accelerate deployment, it has generated growing public and political concern regarding the environmental and social impacts of PHS projects. It remains too early to assess whether these expedited procedures will

[82] Sweta Goswami, "Off-River Pumped Storage Plants Exempt from Environmental Impact Assessment," Moneycontrol, February 16, 2023, https://www.moneycontrol.com/news/power/off-river-pumped-storage-plants-exempt-from-environmental-impact-assessment-10100181.html.

meaningfully increase project commissioning rates. However, early signals suggest that weakening environmental safeguards may undermine the political sustainability of PHS expansion, as emerging community opposition, legal challenges, and public backlash risk delaying projects further rather than accelerating them. In this sense, procedural shortcuts may prove counterproductive.[83] A more durable approach would introduce strict, credible environmental standards while preserving efficiency and predictability for developers.

To address these challenges, this paper proposes the creation of a unified national mechanism for identifying, assessing, and overseeing PHS projects. This mechanism builds on existing regulatory instruments, including the EIA Notification (2006), Guidelines for Eco-Sensitive Zones, and Pumped Storage Guidelines (2023), while strengthening their predictability, transparency, and quality of implementation.[84]

At the core of this proposal is the establishment of a national inventory of pre-cleared and restricted sites for PHS development, designed to support systematic, environmentally sound, and socially informed project planning. This inventory would be developed and maintained by a dedicated PHS Siting Taskforce, an inter-agency body responsible for the full lifecycle of site assessment and classification. The taskforce would include representatives from key government departments (energy, environment, water resources), regional authorities, and independent environmental and social impact experts. Centralizing decision-making within a national taskforce would allow the siting process to remain streamlined and efficient at a higher level of government, rather than shifting final authority entirely to localized decision-making processes

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[83] "'A Disaster in the Making.'"
[84] Compfie, "Amendment in Eia Notification, 2006 for Pump Storage Projects (Dated- 18.05.2023) – Ministry of Environment, Forest and Climate Change," Compfie, May 24, 2023, https://compfie.aparajitha.com/amendment-in-eia-notification-2006-for-pump-storage-projects-dated-18-05-2023-ministry-of-environment-forest-and-climate-change/.

that could slow deployment. At the same time, it would preserve meaningful community input within a structured and accountable framework.

The taskforce would conduct comprehensive EIAs for all sites identified as having potential for PHS development and classify them into two categories: pre-cleared and restricted. Pre-cleared zones would be sites that pass the EIA process and do not pose significant environmental, ecological, or socio-cultural risks, making them suitable for PHS development. Restricted zones, on the contrary, would be sites that fail the EIA process due to irreversible environmental damage, legal constraints, or unacceptable social impacts.

As a guiding principle, the taskforce would prioritize off-river PHS sites, which generally involve fewer ecosystem disruptions than on-river systems. All EIAs would follow the established national assessment framework, but with mandatory early-stage public and civil society participation embedded as a core requirement of this policy design.

Currently, community engagement often occurs at later stages of EIAs, when EIAs are already drafted and opportunities for meaningful change are limited.[85] This reform would shift stakeholder participation to begin at the scoping phase, when concerns can meaningfully influence site selection, project design, or lead to site rejection altogether. Local communities possess detailed ecological knowledge of their surrounding environments, and their input can significantly improve the accuracy of environmental risk assessments. In parallel, formal socio-cultural impact assessments must be integrated into EIAs to identify context-specific

[85] Satyajit Mahatab and Ashutosh Debata, "The Role of Public Participation in Shaping Environmental Impact Assessments (EIA) in India: A Review," *International Journal of Integrative Research* 3, no. 6 (July 1, 2025): 415–32, https://doi.org/10.59890/ijir.v3i6.38.

sources of social resistance, displacement risks, or cultural disruption. Community consultations would be mandatory at every stage of the assessment process.[86]

Public engagement under this framework would be two-directional and continuous. The taskforce would not only receive community input but also be required to respond to community questions throughout the assessment process. All EIA reports would be published in open-access, plain-language formats, and all public submissions would be formally recorded, with the taskforce obligated to issue written responses. This structure strengthens both transparency, accountability, and procedural legitimacy.[87]

All pre-cleared and restricted sites, along with their associated EIA documentation, would be housed within a centralized public database, accessible to government agencies, developers, and civil society.[88] By centralizing and standardizing all EIAs within a single framework, the taskforce would be required to apply the same strengthened environmental and socio-cultural criteria to every site. This institutionalization of uniform standards would increase government accountability, as compliance with participation, assessment quality, and transparency requirements could be publicly monitored and verified. This system would replace today's relatively ad hoc assessment approach, reducing regulatory uncertainty while minimizing the likelihood of public backlash.

Although this approach may modestly slow project approval in the short term relative to regulatory fast-tracking, it is likely to accelerate implementation over the project lifecycle. By

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[86] Iftikhar Hussain Bhat, "From Reform To Controversy: A Critical Analysis of India's Environmental Impact Assessment (EIA) Framework ," *Journal of Society in Kashmir* 9 (2019), https://sociology.uok.edu.in/Files/c2d3b278-4cf7-49a5-9525-af5e352f2900/Journal/43097c96-62a4-4dc1-9e37-727e00aa46ea.pdf.
[87] Bhat, "From Reform To Controversy"
[88] Bhat, "From Reform To Controversy"

reducing social resistance and legal uncertainty at the outset, the framework lowers the probability of costly delays once construction begins.[89] Furthermore, environmental rigor does not need to come at the expense of developer incentives. Existing and future policy support, including tax reductions, concessional finance, and viability funding can ensure that PHS projects remain economically competitive while still benefiting from greater political and social durability.[90]

Once established, the national inventory would be continuously updated to reflect new ecological data, environmental change, or evolving community conditions. Developers seeking to initiate projects on pre-cleared sites would still be required to conduct a project-specific EIA, but prior site-level clearance would significantly reduce approval timelines, as baseline constraints would already be established. Developers wishing to pursue projects in unassessed areas could formally request such an assessment under the same standardized methodology. In this way, the pre-cleared site framework offers a pathway to accelerate PHS deployment without sacrificing environmental protection or social legitimacy, supporting India's long-term energy storage needs while safeguarding political and community trust.

4.2 Recycling BESS with a PLI Scheme

Effective scaling of BESS in India requires an institutional mechanism that addresses the environmental risks of end-of-life batteries while supporting the domestic recovery of critical

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[89] Admin, "Why Environmental Impact Assessments Are Crucial for Sustainable Development," Corelab, January 15, 2025, https://corelab.org/why-environmental-impact-assessments-are-crucial-for-sustainable-development/#:~:text=Ignoring%20environmental%20concerns%20during%20the,reduction%2C%20and%20improved%20resource%20management.

[90] Business Standard, "Power Ministry Plans Tax Breaks for Pumped Storage Hydro Projects," Business Standard, February 19, 2023, https://www.business-standard.com/article/economy-policy/power-ministry-plans-tax-breaks-for-pumped-storage-hydro-projects-123021900172_1.html.

minerals. As the volume of used lithium-ion batteries from BESS continues to grow, the limitations of the current recycling ecosystem, including insufficient collection networks, high transport costs, and uneven regulatory compliance, prevent India from building a reliable circular economy for battery materials.[91]

At present, battery collection remains fragmented and geographically uneven. Many end-of-life batteries are generated far from licensed recycling facilities, increasing transport costs and discouraging formal recycling, particularly for lower-value battery streams. As a result, a significant share of used batteries is either stored for long periods, handled by informal operators, or processed in suboptimal facilities that prioritize volume over material recovery and environmental safety. In parallel, uneven enforcement of environmental and Extended Producer Responsibility (EPR) regulations allows non-compliant actors to operate at lower cost, undermining incentives for investment in high-quality, compliant recycling infrastructure.

The proposed policy option introduces a dedicated PLI scheme for battery recycling. While India already operates a PLI scheme for battery manufacturing, no equivalent tool exists for the recycling industry, despite its strategic importance for reducing toxic waste and ensuring the long-term availability of secondary materials.[92] A recycling-focused PLI would create predictable, performance-linked incentives for firms that achieve higher recovery rates of lithium, cobalt, nickel, and other critical inputs, thereby encouraging investment in advanced, safe, and efficient recycling technologies.

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[91] Safarzadeh, Hamid, and Francesco Di Maria. 2025. "Progress, Challenges and Opportunities in Recycling Electric Vehicle Batteries: A Systematic Review Article." *Batteries (Basel)* 11 (6): 230. https://doi.org/10.3390/batteries11060230.

[92] Press Information Bureau, Government of India, (Prime Minister Launches National Mission for Development of Energy Storage Systems), July 10, 2025, https://www.pib.gov.in/PressReleasePage.aspx?PRID=2204627&reg=3&lang=2

Implementation responsibility would rest with the Ministry of Environment, Forest and Climate Change (MoEFCC), which would design and administer the incentive structure, define eligibility criteria, and evaluate firm performance. MoEFCC would also ensure alignment with the Battery Waste Management Rules and EPR obligations, oversee environmental compliance, and coordinate with the Central Pollution Control Board to verify that recovered materials meet national standards.

Within the PLI scheme, incentives would be tied to verifiable outputs, specifically, the quantity and quality of recovered battery-grade materials. This output-based structure would reward investments in advanced recycling technologies, while creating a clear and reliable incentive environment. All participating firms would remain subject to uniform reporting requirements, independent audits, and strict adherence to environmental and safety norms.

A complementary component of the policy would be the establishment of a national traceability and reporting framework for end-of-life batteries. At present, inconsistent collection and opaque battery flows limit the ability of recyclers to access sufficient and reliable raw materials. Under the proposed reform, producers and recyclers would adopt standardized labelling and digital lifecycle identifiers integrated into the existing EPR reporting system managed by MoEFCC. This traceability framework would make battery flows transparent, reduce transaction costs, and provide recyclers with predictable access to materials necessary for operating at scale.

Once established, the policy would be continuously updated to reflect technological advances and evolving market conditions. MoEFCC, in consultation with technical agencies and industry experts, would regularly review recovery standards and adjust incentive levels. Over time, the accumulation of publicly accessible data on recovery performance would enable more accurate national planning, support downstream manufacturing, and enhance India's long-term energy security.

In this way, a dedicated PLI scheme for battery recycling would accelerate the development of a circular economy for batteries, reduce toxic waste, and strengthen environmental safeguards. In addition, it would reduce dependence on foreign imports, fostering autonomous domestic capabilities in clean-energy recycling and manufacturing.

5. Conclusion

India's energy transition is approaching a critical inflection point. Without sufficient long-duration storage, India will struggle to reduce coal generation to levels consistent with climate-aligned pathways, undermining both its domestic climate goals and international credibility. In this context, the Indian government's request for a comparative assessment of PHS and BESS reflects a recognition that storage choices will shape the trajectory of the power sector for decades to come.

The criteria-based analysis highlights clear and complementary trade-offs between the two storage technologies. PHS performs strongly on long-term cost-effectiveness and strategic autonomy, making it well suited for long-duration storage, but faces feasibility challenges related to permitting, land acquisition, and social acceptance. BESS, by contrast, is easier and faster to deploy and well suited for short-duration flexibility, yet carries higher environmental risks due to lifecycle waste and recycling constraints, as well as greater exposure to external supply chains. No single technology dominates across all dimensions, underscoring the limits of a one-size-fits-all storage strategy.

These trade-offs motivate the paper's policy recommendations, as effective energy storage policy must address the specific barriers facing each technology. For PHS, this requires institutional reforms that improve environmental credibility, community engagement, and regulatory predictability to reduce delays over the project lifecycle. For BESS, it necessitates targeted intervention to manage end-of-life impacts and build domestic recycling and material recovery capabilities, ensuring that short-term deployment gains do not generate long-term environmental or strategic liabilities. The costs of inaction are substantial as delayed or poorly designed storage deployment could lock India into higher emissions trajectories, expose the power system to reliability risks, and generate social and political resistance to infrastructure development. This paper has necessarily focused on the two most scalable storage technologies currently available, BESS and PHS, while omitting other options such as compressed air, thermal storage, hydrogen-based systems, and emerging long-duration chemistries. Future research could explore how these technologies might complement this energy strategy as costs evolve and technological maturity improves. Additional studies to further assess regional variation in storage needs are also critical.

Ultimately, the challenge facing India is not whether to invest in energy storage, but how to do so in a way that is economically efficient, environmentally responsible, and politically sustainable. A balanced approach, prioritizing pumped hydro for long-duration resilience while ensuring that battery storage scales sustainably, offers the most credible pathway for translating renewable capacity growth into genuine decarbonization.

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