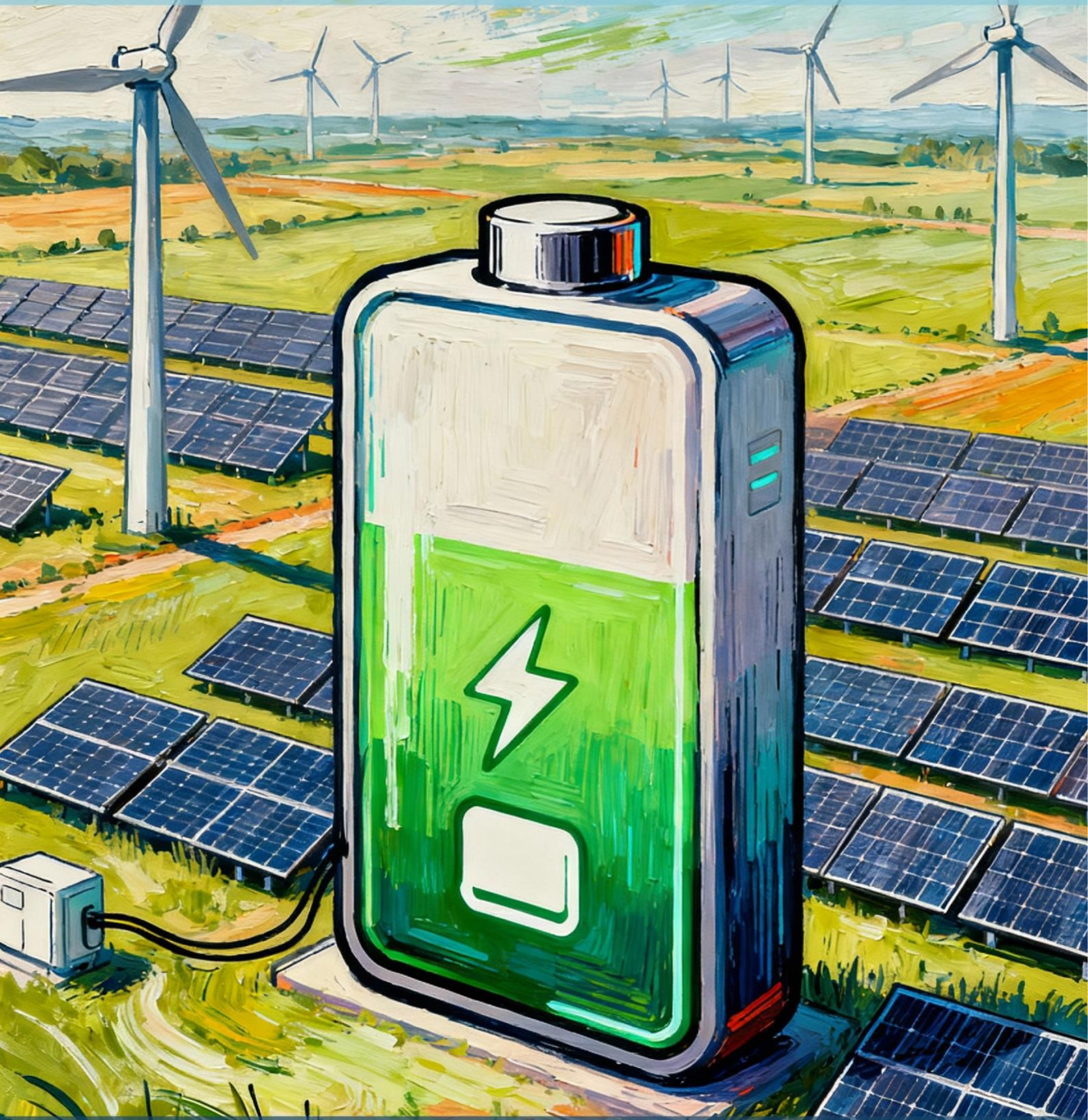
Submitted to Rajasthan Electricity Regulatory Commission | November 2025

SUBMISSION ON DRAFT RERC BATTERY ENERGY STORAGE SYSTEM (BESS) REGULATIONS, 2025



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1. Introduction

Rajasthan Electricity Regulatory Commission (RERC) has issued the Draft Battery Energy Storage System (BESS) Regulations, 2025, inviting public comments.

This submission is being made by the Centre for Energy, Environment & People, Jaipur (CEEP) with the objective of strengthening the proposed regulatory and procedural framework for the deployment of BESS in Rajasthan. The submissions are divided into following sections:

i. General Comments
ii. Section-wise Comments

We request the Commission to accept this submission on record and give us an opportunity to submit our oral submissions during the public hearing processes.

2. General Comments

2.1. Prudent Planning and Other Pre-requisites in BESS Deployment

We submit that the integration of energy storage in the grid is a complex activity that not only involves numerous technology options but also necessitates assessment of capacity requirements, value streams, and appropriate locations within the grid where the storage systems may be located. In the absence of detailed procedures and frameworks, and a functional ancillary services market, the present regulations may result in only a partial step toward ensuring prudent integration of BESS.

In this context, we submit CEEP's report on Regulatory Framework for Energy Storage Integration with the Electricity Grid along with this submission (attached as ***ANNEXURE – I***). The report analyses India's evolving regulatory and policy landscape for integrating energy storage systems into the electricity grid and outlines planning approaches, value streams, and technology options needed to enable large scale and economically viable deployment of energy storage across generation, transmission, and distribution. We request the Commission to consider this report and develop functional frameworks for planning battery storage across the power sector value chain, ensuring prudent and effective integration of battery energy storage as best suited.

2.2. Absence of Supporting Frameworks and Procedural Depth

The Draft Regulation is largely declarative, outlining broad objectives and roles without providing the procedural or technical details necessary for implementation. Several key concepts are introduced, such as Aggregators, ancillary service participation, and multi-use BESS applications, without specifying the operational frameworks that would govern them.

For example, **Clause 7** introduces Aggregators but leaves their registration process, technical obligations, and commercial responsibilities undefined. Similarly, **Clause 14** assigns SLDC responsibilities for scheduling, metering, accounting, and settlement, yet the regulation does not outline the technical parameters, data protocols, or reporting structures within which these procedures are to be developed.

Across the document, essential elements such as performance measurement criteria, metering hierarchies, dispatch principles, and data submission formats are either absent or deferred without any reference to a guiding framework. As a result, entities will be required to interpret core provisions independently, leading to inconsistent implementation and undermining regulatory certainty. Given the capital-intensive and system-critical nature of BESS, the absence of supporting operational frameworks makes several provisions difficult to apply in practice.

We request that the Commission issue, or explicitly reference, a supporting operational framework that defines the technical standards, data formats, and procedural requirements necessary for the uniform implementation of these Regulations.

3. Section-wise Comments

3.1. Planning and Cost Justification Not Anchored in Resource Adequacy Requirements

Clause 5.2 of the Draft Regulations provides for planning of energy storage capacity requirement to be conducted by Distribution Licensees and the State Transmission Utility (STU) keeping in view parameters such as the technical considerations, system reliability, and load requirements. However, the Ministry of Power (MoP), in consultation with Central Electricity Authority, has already notified 'Guidelines for Resource Adequacy Planning Framework for India' which specifies role of various entities in the sector.

In order to align the proposed regulations with these guidelines, it is suggested to incorporate or at least refer the provisions of the said guidelines in the regulations. Any disconnect may result in BESS being added without clarity on its accredited contribution to peak support or its role in meeting identified adequacy gaps, increasing the risk of oversizing or misallocation.

Under the current resource adequacy framework, CEA prepares the national resource adequacy methodology and assessment, and the states are required to develop their own state-level resource adequacy plans. By now, the CEA has undertaken resource adequacy on behalf of the states (until the states develop their own plans), and its plans show heavy reliance on BESS for meeting short-term and long-term demand and reliability. BESS, given its firming and flexibility characteristics, must therefore be evaluated explicitly in terms of its capacity contribution within this RA framework, lest they are deployed in a manner that is not optimal for the gird's requirement.

Moreover, the Draft does not mandate Licensees to demonstrate why BESS is the optimal solution for the identified need or whether alternative interventions such as network upgrades, demand-side initiatives, or flexible generation were evaluated before initiating procurement. In the absence of a system-level justification based on the resource adequacy plans, BESS proposals may proceed without establishing the reliability benefits or cost efficiency of the proposed configuration. This approach bears the risk of BESS additions being mere high-cost asset creation without genuinely strengthening state's adequacy position.

We therefore request that the Commission require BESS planning and procurement to be explicitly linked to resource adequacy plans and supported by a structured cost-optimisation analysis before their regulatory approval is sought.

3.2. Minimum size requirement without a clear rationale

Clause 5.3 prescribes that BESS projects must have a minimum power rating of one megawatt and an energy duration of at least two hours, except for distribution transformer level and behind-the-meter systems. It does not provide any technical reasoning or system-specific justification for the criteria.

As the Draft or the appended explanation does not offer justifications for these criteria, it creates ambiguity as to whether smaller distributed units, DTR-level storage, or localised applications are intentionally excluded or omitted due to oversight.

We therefore request the Commission to clarify the basis for the one megawatt/two-hour minimum criteria and explain how these thresholds align with Rajasthan's system needs.

3.3. Role of Aggregators

Clause 7 introduces the concept of "Aggregators" who may combine services such as demand response, distributed generation, and energy storage from multiple sites to provide ancillary services to the SLDC or Licensees. The Draft does not, however, define the scope of the role, responsibilities, or liabilities of an Aggregator. It is also unclear whether an Aggregator is intended to function as a commercial intermediary or as an operational entity responsible for real-time dispatch conformity, telemetry integrity, performance delivery, and deviation settlement. Without these minimum definitions, the regulatory foundation is incomplete, and the operational boundaries between Aggregators, BESS developers, Licensees, and the SLDC remain indeterminate.

Further, the clause delegates the task of specifying eligibility criteria and registration requirements to the SLDC, an operational entity with neither the institutional mandate nor the adjudicatory competence to define commercial, contractual, and liability obligations. Allowing SLDC to determine eligibility criteria without a Commission-level framework on the legal and operational obligations of Aggregators results in sub-delegation of the Commission's core regulatory functions to an entity empowered only for technical and real-time system operations. Such sub-delegation, where not authorised by statute, weakens the Commission's regulatory authority.

We therefore request the Commission to first outline, through its supporting documentation, an explanation containing the rationale behind the introduction of Aggregators. Further, we request the Commission to define their regulatory scope and accountability framework before empowering the SLDC to prescribe the eligibility criteria for these Aggregators.

3.4. Ambiguity Regarding Charges

Clause 9.1 of the Draft requires Licensees to procure BESS capacity and services through tariff-based competitive bidding. However, the Draft does not explain how charging costs will be treated across different use-cases or how they relate to the tariff discovered through bidding. Since BESS operation can involve multiple usages, such as peak shaving, congestion relief, arbitrage, and ancillary services, the entity bearing the charging cost varies depending on the application and the agreement between the licensee and the BESS developer.

The Draft also does not provide a framework for contractual structures between Licensees and developers. In the absence of a defined model, arrangements could emerge under which the Licensee funds the charging of the BESS while the developer retains the right to market the stored energy when the Licensee is not using the asset. This exposes the Licensee to clear financial asymmetry: if market prices are lower than the Licensee's charging cost, the Licensee books a loss; if market prices are higher, the developer may retain the upside unless explicitly required to share it. Such asymmetry amounts to transferring market-risk to consumers without Commission oversight.

To avoid this, the regulations must establish two baseline principles:

a. First, the Licensee should recover the cost it incurred for charging the BESS.
b. Second, any market revenue earned from energy or ancillary-service sales that derive from Licensee-funded charging must be allocated in a manner that protects tariff neutrality and prevents the developer from monetising energy paid for by consumers.

Concerns of this nature arise when charging-cost responsibilities, minimum sale value conditions, and revenue-allocation rules are not specified in the parent regulations or in any accompanying framework. The absence of these elements creates uncertainty about how charging costs will be compensated across different operational modes and whether the resulting arrangements will remain cost-reflective. The Commission should therefore define the allocation responsibilities and the cost-setting mechanism, and clarify the regulatory treatment of charging costs and any market-based revenues, so that cost-recovery discipline and tariff neutrality are preserved. The Commission may also indicate that supporting procedures, frameworks, and model documents will be issued subsequently to operationalise these principles.

3.5. SLDC Responsibilities Stated Without Timelines or Technical Criteria

Clause 14 sets out several responsibilities for the SLDC, including annual assessment of reserve requirements (**Clause 14.1**), publishing eligibility criteria for BESS participation within three months (**Clauses 14.2 and 14.3**), developing procedures for scheduling, metering, accounting, and settlement within six months (**Clause 14.4**), and ongoing performance monitoring (**Clause 14.5**). Although these timelines provide a broad implementation structure, the regulation does not define the technical or operational basis on which SLDC is expected to perform these tasks.

For instance, **Clause 14.1** requires SLDC to verify governor settings and assess PRAS, SRAS, and TRAS requirements from BESS. However, the regulation does not specify the standards or data protocols needed for such an evaluation. **Clauses 14.2 and 14.3** require SLDC to publish eligibility criteria for BESS and ancillary service providers, but they do not specify the performance thresholds, response-time requirements, or metering specifications that should form the basis of these criteria. Similarly, **Clause 14.4** mandates the development of scheduling and settlement procedures without outlining the principles that must govern the treatment of charging energy, discharge energy, round-trip losses, or deviation handling.

Where the Commission delegates operational procedure-making to the SLDC without defining the standards, data requirements, or decision-making criteria that constrain that discretion, the delegation risks becoming unguided. Such unguided discretion can result in inconsistency across entities, procedural uncertainty, and an uneven application of obligations that affect both system security and tariff outcomes.

We request that the Commission should define the key operational principles that SLDC must incorporate when drafting eligibility norms, reserve-assessment methodologies, and scheduling and settlement procedures.

3.6. Inconsistency with Battery Waste Management Rules, 2022

Clause 11.3 states that the "*responsibility of disposal shall lie with the owner of the BESS*." This provision does not align with the Battery Waste Management Rules, 2022 (BWM Rules) notified under the Environment (Protection) Act, 1986, which establish an Extended Producer Responsibility (EPR) framework for all categories of batteries, including stationary storage. Under Rule 4 of the BWM Rules, the legal obligation for collection, recycling, and environmentally sound disposal of end-of-life batteries lies with the *Producer* (the manufacturer or importer placing batteries on the market) and not with the *Consumer* or end-user. The owner of a BESS is only required to hand over waste batteries to an authorised entity, and they are not responsible for disposal or compliance with EPR targets.

Assigning disposal responsibility to the BESS owner contradicts the national rules created specifically for battery-waste management and hence will not pass legal scrutiny. Under Indian jurisprudence, where both the Centre and the State are competent to legislate on a subject, the central law prevails in the event of conflict. Battery-waste management is already governed by a central framework that allocates responsibility through the Extended Producer Responsibility mechanism. A state regulation cannot reassign that responsibility to another entity in a manner inconsistent with the central scheme. Any such deviation would be repugnant to the central rules and therefore unenforceable.

We request the Commission to revise **Clause 11.3** to align with the Battery Waste Management Rules, 2022, by clarifying that disposal obligations rest with the Producer under the EPR framework, while the owner's responsibility is limited to handing over the waste batteries to authorised channels.

ANNEXURE – I

CENTRE FOR ENERGY,
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Regulatory Framework for Energy Storage Integration with the Electricity Grid

September 2023

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List of Abbreviations

APERC	Andhra Pradesh Electricity Regulatory Commission
BESS	Battery Energy Storage System
CAES	Compressed Air Energy Storage
CAGR	Cumulative Annual Growth Rate
CEA	Central Electricity Authority
CERC	Central Electricity Regulatory Commission
CUF	Capacity Utilisation Factor
DAM	Day Ahead Market
DEA	Department of Economic Affairs
DG	Diesel Generator
DOD	Depth of Discharge
DSM	Deviation Settlement Mechanism
DSM	Demand Side Management
EMS	Energy Management System
ESO	Energy Storage Obligation
ESS	Energy Storage System
GDP	Gross Domestic Product
GOI	Government of India
GW	Giga Watt
HFC	Hydrogen Fuel Cell
IEX	Indian Electricity Exchange
IR	Inertial Response
Li-ion	Lithium Ion
LOLP	Loss Of Load Probability
MERC	Maharashtra Electricity Regulatory Commission
MNRE	Ministry of New and Renewable Energy
MoP	Ministry of Power
Na-S	Sodium Sulphur
NDC	Nationally Determined Contributions
NENS	Normalised Energy Not Served
NHPC	National Hydroelectric Power Corporation
Ni-Cd	Nickle Cadmium
NPV	Net Present Value
PFC	Primary Frequency Control
PHES	Pumped Hydro Energy Storage
PLI	Production Linked Incentive
PSP	Pumped Storage Projects
RAP	Resource Adequacy Plan
RE	Renewable Energy
RES	Renewable Energy Sources

RFB	Redox Flow Battery
RMI	Rocky Mountain Institute
ROCOF	Rate of Change of Frequency
RTM	Real Time Market
SMES	Superconducting Magnetic Energy Storage
SOC	State of Charge
TRAS	Tertiary Reserve Ancillary Services
UC	Ultra-Capacitor
UREDA	Uttarakhand Renewable Energy Development Agency

1. Introduction

India is amid energy transition across multiple sectors, including agriculture, transportation and mobility, and power. While transitions are integral part of development, the current energy transition is happening at an unprecedented pace, the need for which has stemmed from the urgency for climate action.

India has demonstrated the characteristics of a responsible sovereign by declaring ambitious Nationally Determined Contributions (NDCs). It has committed to reduce the emission intensity[1] of its GDP by 45% from 2005 level by 2030 (GOI, India NDCs 2030, 2022). An integral element of this is development of 500 GW electricity generation capacity from non-fossil fuel-based sources by 2030. 84% of this is likely to come from variable renewable energy resources (Das, 2022).

As on May 2023, 126.76 GW of renewable energy capacity is commissioned in India (Energy, 2023). This capacity has been added at a CAGR of 15.92% between 2016 - 2022 (IBEF, 2023). Furthermore, a CAGR of 19.85%[2] is desired for the period 2023 - 2030 for India to achieve 450 GW of RE generation capacity. This presents a scenario of unprecedented transition in the power sector.

Disruptive transitions pose a series of systemic challenges, including capability of institutions to manage transitions and a wide policy gap (Frank W. Geels, 2018). Legacy policy ecosystem often throttle innovation, deaccelerating the pace of transition and increasing its costs (Utpal Bhattacharya, 2017). In the context, agencies and actors are unlikely to leverage the opportunities presented by a transition process; reducing its social, political and economic appeal. At an early stage of its clean energy transition, Indian power sector also struggles from these challenges.

According to the Grid Controller of India Ltd, India experienced its highest-ever peak power demand on August 17th, 2023, reaching 234 GW (GCI Ltd, 2023). Increasing energy demand and share of renewables have a direct impact on grid security, reliability, and electricity tariffs. Energy storage is emerging as a viable solution to address these growing concerns supported by unit-cost reduction over last decade. As per BloombergNEF, the overall unit-cost of Lithium-ion battery pack has dropped by 37.6% in last five years (BloombergNEF, 2022). The Government of India has introduced multiple initiatives to promote energy storage system and their grid integration. This includes R&D initiatives such as Materials for Energy Storage[3] (DST, 2016), policy level support such as draft Energy Storage Policy (2021), CERC Ancillary Service Regulations 2022 and market facilitation steps such as PLI scheme National Programme on Advanced Chemical Cell (ACC) Battery Storage (Department of Heavy Industries, 2021).

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[1] Emission Intensity is expressed in metric tons of CO2 equivalent emissions per unit of GDP

[2] Author's Analysis: $CAGR_{2023\text{-}30}$ = ((450/126.769)^(1/7)-1) = 19.85%

[3] Materials for Energy Storage was launched in May, 2016 to support research and development for entire spectrum of energy storage technologies

While energy storage offers to play a critical role in ensuring grid flexibility and reliability, the sector struggles from multiple barriers associated with this nascent technology. This research paper studies the evolving regulatory landscape of energy storage in the Indian context. While acknowledging the unique characteristics of ESS and different value streams that it serves, it also evaluates a broad framework for determining the macro energy storage requirements for electricity grid based on systems costs optimisation, and a supportive regulatory framework for ESS integration in India.

2. Energy Storage Systems and Value Streams

Energy Storage Systems (ESS) is defined as devices that convert electrical energy from power systems into a storable form, which can then be converted back into electrical energy when needed (Wang et al., 2020). CERC, in its staff paper on *Introduction of Electricity Storage Systems in India*, identifies pumped hydro storage as the most prevalent type of grid-scale energy storage (CERC, 2017). However, technological advancements like Lithium-ion and redox flow batteries, due to their ability to rapidly regulate power in both directions, have led to the emergence of various value streams that ESS can now cater to.

In 2017, CERC recognised several grid-scale applications of energy storage systems: Load Shifting, Intermittent RE Control, decongestion, DSM, and frequency regulation. As renewable energy integration has grown and the imperative for energy transition has intensified, stakeholders have increasingly explored a wide array of services that ESS can provide. The Economics of Battery Energy Storage by RMI, categorizes thirteen distinct services that BESS can deliver at different levels: grid-level, utility-level, and customer-level. The table below presents a comprehensive yet extensive range of services that ESS can offer. Behind-the-meter i.e. Customer Services applications are not included within the scope of this report.

Grid-level Services	Energy Arbitrage - This stores energy when the price is low and sells energy during peak demand when the price is high.
	Frequency Regulation - ESS helps in correcting frequency deviations, maintaining frequency within limits.
	Voltage Support - ESS helps to maintain grid voltage within specified limits, to help manage reactive power.
	Spinning Reserve - Standby generation stations utilised during unexpected power shortage. ESS with longer discharge durations can be used as spinning reserves.
	Black Start - ESS help in energising part of the grid during unplanned blackouts
Utility-level Services	Transmission & Distribution Deferral - This involves using ESS to either defer or avoid the need of T&D equipment upgrade to meet demand growth.
	Resource Adequacy - Tying up sufficient capacity to reliably serve expected demand.
	Transmission Congestion Relief - ESS charging during off-peak hours and discharging during peak load helps in reducing the congestion in transmission network.
Consumer-level Services	Power Quality - ESS will help in protecting consumers from high variations in voltage.
	Power Reliability - The ESS installed close to consumer load aids customer during an unplanned interruption from the utility.
	Demand shifting and Peak reduction - ESS supports by reducing peak demand and shifting the demand to non-peak hours.

Table 1: Value Streams offered by ESS (Source: Smart Grid and Energy Storage in India)

3. Governance Landscape for Energy Storage Systems in India

India's steadfast emphasis on integrating RE into its grid has led to a growing recognition of ESS for ensuring reliable power supply. The staff paper on *Introduction of Electricity Storage System in India* by CERC recognises potential grid-level applications of ESS and corresponding ownership model (CERC, 2017). It suggests operational framework for the identified ESS applications and devises a cost recovery mechanism for them. While acknowledging the inherent challenges associated with ESS, such has high capital cost, environmental issues and safety aspects, it ascertains the imperative role of ESS deployment in ensuring grid reliability. At policy level, to speed up the adoption of ESS system, *draft Comprehensive Energy Storage Policy* was released (EnergyWorld, 2022). It invited industry stakeholders to discuss Regulatory, Financial & Taxation, Demand Management and Technological components of the policy. While this policy was never officially implemented, it served as a shared platform that facilitated participation from all stakeholders. Year 2022 was instrumental in legalising ESS under the purview of the Electricity Act, 2003 and was classified as an integral component of the power system, as defined in section 2 (50) (MoP, Clarifications on status of ESS, 2022). Various agencies, at national and sub-national level, have introduced policy measures to promote energy storage integration. These policy measures may be broadly classified as supply-side and demand-side interventions. The former includes measures to reduce cost of energy storage and facilitate viable business models for ESS integration in the electricity grid. The latter includes measures that shall create a market demand for energy storage systems. Following section outlines the supply-side and demand-side interventions aimed at adoption of ESS. Table 2 presents all policy interventions around ESS in a chronological manner and same are referred in section 3.1 and 3.2.

3.1. Supply-side Policy Interventions

The supply-side interventions can further be classified into four sub-categories which are (1.) Business Models, (2.) Manufacturing and R&D, (3.) Technical Standards and (4.) Incentives.

Business-model focused interventions primarily aim to incorporate ESS into commercial operations, enabling them to enhance RE integration and ensure grid reliability. Interventions [1], [2], [6], [10] introduce ESS in different business models by providing a framework for ESS participation in ancillary markets and coupling them with hybrid RE projects to combat renewable energy intermittency. MoP’s guidelines for procurement and utilisation of BESS [13] also conceptually recognises different value streams of BESS and outlines eight different business cases for energy supply, RE integration and grid resilience. Policy interventions such as tariff regulation and grant of connectivity streamline the bidding procedures and connectivity rules, bolstering its market participation [3], [4], [23]. Additionally, by allowing various entities to develop/own/operate the ESS and classifying standalone ESS operation as a delicensed activity, policy [14], [15] aims to increase the availability and integration of energy storage systems within the electricity infrastructure. Furthermore, [20] sets ambitious targets for PSP and BESS capacity additions by FY2032.

Manufacturing and R&D interventions like the PLI scheme [11] aims to attract investments in battery production, stimulating research, development, and manufacturing capabilities . The Scheme on Viability Gap Funding for development of BESS incentivises the growth of large-scale energy storage infrastructure [17]. Intervention of establishing **technical standards** [5] provides consistent and standardized technical requirements to ensure seamless integration of energy storage systems with the grid. Finally, [8], [18] and [22] provide financial incentives, making energy storage projects like PSP and BESS more economically attractive, thereby advancing their adoption and supporting a more resilient energy supply landscape. These comprehensive supply-side interventions partly contribute to ESS recognition and adoption in the electricity grid.

3.2. Demand-side Policy Interventions

Demand-side policy interventions play a pivotal role in driving the uptake of ESS by shaping preferences and behaviour of power sector entities. The Energy Storage Obligation (ESO) 2029-30 (2022) stands as a key policy, compelling the procurement of power from ESS, thereby fostering heightened demand. Complementing this, the Electricity Rights of Consumer Amendment Rules, 2022, mandates consumers who rely on Diesel Generator (DG) sets for backup power to transition to cleaner alternatives such as renewable energy paired with Battery Energy Storage Systems (BESS) within a specified timeframe.

Table 3 added below outlines energy storage policies and projects by some of the Indian states. While the supply and demand-side interventions outlined in the table 2 have encouraged adoption of energy storage systems, the existing planning guidelines and framework do not encompass those within planning scope. This gap in the existing governance landscape poses significant challenges in realising full potential of ESS.

3.3. The Crucial Role of Planning

The fundamental premise of energy storage's successful assimilation is its seamless integration into **the planning processes of key stakeholders**. Chief among these stakeholders is the Distribution Companies (Discoms), who are the primary procurers of power in the electricity sector. However, one glaring shortcoming in the current landscape is the absence of energy storage considerations in the planning processes of Discoms and other key stakeholders. The current guidelines for assessing Resource Adequacy Plan (RAP) haven't been evolved to include ESS in its planning which can potentially enhance the planning efficiencies. Without the integrated planning approach, the demand for energy storage systems remains handicapped.

While some demand-side policy interventions have been introduced, such as the Energy Storage Purchase Obligation, they provide a limited recognition to the nuanced needs of individual power sector entities. This limitation highlights the pressing need for a more holistic planning approach that recognises the diverse requirements of stakeholders and the value streams offered to them by ESS.

Planning for energy storage hinges on the recognition of the value streams it can provide to the energy ecosystem. However, a significant obstacle persists in the absence of robust pricing mechanisms. Present revenue compensation mechanisms are oriented towards computing traditional power system value streams. At grid-level, the regulatory landscape must enable ESS to provide multiple, stacked services and vetted revenue streams for them. For example, while frequency regulation might be paid through a wholesale market, transmission deferral could be covered as part of the cost of service. Therefore, it's important to assess and validate different services through different compensation methods to ensure the economic feasibility of ESS. The inability to assign a price to these value streams within the current governance framework hampers the effective integration of energy storage into the planning process, leaving a critical gap.

Beyond the planning stage, ensuring the resilient operation of the power system requires careful consideration of standing capacity. For power procurement and planning, standing capacity of the energy storage should be calculated to serve variability in the system while ensuring its reliability.

While the supply-side mandates may contribute to making energy storage more economically viable, they alone are insufficient to develop a conducive ecosystem. The absence of a market for services that ESS provides could potentially dissuade utilities from incorporating ESS into their business strategies. Recently, IEX activated trading platform for TRAS (Tertiary Reserve Ancillary Service) DAM and RTM from the delivery date of 1st June 2023. But lack of recognition and appropriate compensation for ancillary services provided by ESS has led to no market participation in TRAS bidding (IEX, 2023). Without integration into the planning process and a clear understanding of the distinct services provided by energy storage, the envisioned ecosystem would remain elusive.

Regulation	Policy	Guidelines	Order/Notification

Year	No.	Development	Key Inferences	Institution
2015	[1]	CERC Roadmap for ancillary services (CERC, Ancillary Service Operations, 2015)	Provides framework for participation of un-requisitioned capacity for providing ancillary services for assets whose tariff is either determined or adopted by regulatory commission. Notifies NLDC and RLDCs as nodal agencies for inter-state, and SLDC for intra-state implementation of ancillary services. Focuses only frequency regulation and decongestions.	CERC
2018	[2]	National Wind-Solar Hybrid Policy (MNRE, 2018)	Recommends addition of Battery for hybrid projects to reduce RE integration issues.	MNRE
2019	[3]	CERC Tariff Regulation 2019 (CERC, Tariff Regulagtion, 2019)	Detailed procedure for determination of tariff for Pumped Storage Hydro projects	CERC
	[4]	CERC Grant of Connectivity, Long-term Access and Medium-term Open Access Regulations, 2019 (CERC, Grant of Connectivity, 2019)	Defines energy storage and allows for standalone storage system of installed capacity 50MW and above as an applicant eligible for grant of connectivity	CERC
	[5]	CEA Technical Standards for Connectivity to the grid regulations, 2019 (CEA, Connectivity Regulations, 2019)	Defines connectivity standards for hybrid systems with energy storage and standalone energy storage systems.	CEA
2020	[6]	Guidelines for Tariff Based Competitive Bidding Process for Procurement of Round-The Clock Power from Grid Connected Renewable Energy Power Projects (MoP, RTC Power from RE, 2020)	Provides guidelines for Round-The-Clock (RTC) power procurement by DISCOMs from grid connected RE Sources complemented/balanced from any other source or storage.	MoP
2021	[7]	Draft Energy Storage Policy	Advocates for energy storage development across the value chains of power sector. It proposes transmission cost waiver both at the time of	NA

			charging the storage using RE as well as at the time of selling the stored energy.	
	[8]	Waiver of Inter-State Transmission Charges (Power, 2021)	Waiver of ISTS Charges on Hydro Pumped Storage Projects (PSP) and BESS Projects, commissioned up to 30.06.2025, is provided. The waiver shall be applicable for a period of 25 years for Hydro PSP and for a period of 12 years for BESS, or for a period subsequently notified for future projects by the Central Government from the date of commissioning of the power plant.	MoP
2022	[9]	"Classification of ESS under Electricity Act 2003" (MoP, Clarifications on status of ESS, 2022)	Included energy storage as a part of power system defined under sub section (50) of section 2 of the Electricity Act	MoP
	[10]	CERC Ancillary Service Regulations, 2022 (CERC, Tariff Regulations, 2019)	Aimed to enable energy storage to participate in ancillary service markets. Defined procedure for secondary and tertiary ancillary service mechanisms.	CERC
	[11]	PLI Scheme for Advanced Chemical Cell Battery Storage (MHI, 2021)	Incentivizes potential investors, both domestic and overseas, to set- up Giga-scale ACC manufacturing facilities with emphasis on maximum value addition and quality output	Ministry of Heavy Industries
	[12]	Electricity Rights of Consumer Amendment Rules, 2022 (MoP, Electricity Amendment Rules, 2022)	Mandates consumers, who are utilising Diesel Generator (DG) sets for backup power, to transition to cleaner technologies like renewable energy with BESS within five years, or in accordance with timelines determined by the State Commission.	MoP
	[13]	Guidelines for Procurement and Utilization of Battery Energy Storage Systems as part of Generation, Transmission and Distribution assets, along with Ancillary Services (MoP,	The guidelines conceptually recognise different value streams of BESS and 8 different business cases for energy supply, RE integration and grid resilience. It outlines the standardised process for BESS capacity procurements for intra- and inter-state BESS projects of over 1MW and 50MW respectively.	MoP

		Guidelines for Procurement and Utilization of BESS, 2022)		
	[14]	Electricity (Amendment) Rules (MoP, Electricity (Amendment) Rules, 2022)	Energy Storage Projects may be developed/owned/leased/operated by a generator/transmission company/distribution entity/system operator/load despatch centre or on standalone basis. Operation of standalone ESS would be delicensed activity at par with a generating company	MoP
	[15]	Updated Harmonized Master List of Infrastructure (DEA, 2022)	**Energy Storage Systems (ESS)** is included in the **Harmonized Master List of Infrastructure** subsectors by insertion of a new item in the category of 'Energy', with a footnote defining Energy Storage Systems (ESS)	DEA
	[16]	Energy Storage Obligation 2029-30 (MoP, ESO, 2022)	Mandate storage obligation to accommodate any new promising, commercially viable ESS technologies and reduction in costs of BESS. The prescribed storage obligation is 1 per cent in 2023-24 and increases up to 4 per cent in 2029-30	MoP
2023	[17]	Scheme on Viability Gap Funding for development of Battery Energy Storage Systems with capacity of 4,000 MWh (Power, Viability Gap Funding for development of BESS, 2023)	In the Union Budget 2023-24, customs duty exemption has been extended to import of capital goods and machinery required for manufacture of lithium-ion cells for batteries used in electric vehicles up to 31.03.2024	MoP
	[18]	Guidelines to promote development of Pump Storage Projects (PSP) (MoP, 2023)	1. Directs state commissions to ensure monetisation of ancillary services such as spinning reserves, faster start-up and shutdown etc. which help in supporting grid stability. The appropriate commission will notify peak and off-peak tariffs for generation to provide appropriate pricing signal to peak and base load generating plants.	MoP

			2. Additionally, electricity duty and cross-subsidy duty will not be applicable on pumping power for charging of PSPs. 3. Budgetary support for the creation of infrastructure facilities that have alternate developmental value for PSP projects up to Rs 1.5 crore/MW for projects up to 200 MW and up to Rs 1 crore/MW for projects above 200 MW.	
	[19]	Guidelines for Formulation of Detailed Project Reports for Pumped Storage Schemes (CEA, Guidelines for Formulation of Detailed Project Reports for PSP, 2022)	1. These guidelines have reduced the preparation timelines for Detailed Project Reports (DPRs) for Pumped Storage Power (PSP) projects in Himalayan and non-Himalayan Regions from 900 days to 840 and 690 days, respectively, based on geological factors. 2. For PSP projects allocated through Tariff-Based Competitive Bidding, integrated Renewable Energy Projects, or as captive plants, the timeline for CEA concurrence has been shortened to 50 days. For other PSPs, the concurrence timeline is 90 days.	CEA
	[20]	National Electricity Plan Vol 1 Generation (CEA, National Electricity Plan - Generation, 2023)	Confirms that ESS can be seen as efficient resource for energy arbitrage and transmission deferment applications. Issued FY2032 plan for storage capacity addition of 27GW/175 GWh for Pumped storage and 48GW/236 GWh for BESS	CEA
	[21]	Guidelines for Resource Adequacy Planning Framework for India (Power, 2023)	The resource adequacy framework lays down the optimal capacity mix required to meet the projected demand at minimum system cost. The framework is a function of energy storage, intermittency of RE sources, and new generation capacity which would timely assess required capacity to reliably meet future demand growth at optimal cost (least cost and secure manner) to the system.	MoP

	[22]	Waiver of ISTS Charges and losses for Renewable Power projects (MoP, ISTS Waiver, 2023)	100% transmission charge waiver for the following: 1. BESS projects commissioned by June 2025 for 25 years 2. Pumped storage projects awarded by June 2025 for 25 years 3. Green Hydrogen projects with min 51% annual power consumption from ESS utilising RE	MoP
	[23]	Competitive Bidding Guidelines for RE coupled with Storage (MoP, Bidding Guidelines for RE with Storage, 2023)	Issued bidding guidelines for procurement of peak, RTC, fixed-hour based or seasonal power from RE projects coupled with storage. Specified a penalty of 1.5 times tariff for shortfall in power supply.	MoP
	[24]	Draft Electricity (Amendment) Rules, 2023 (MoP, Draft Electricity (Ammendment) Rules, 2023)	Establishing, operating, and maintaining a dedicated transmission line shall be a delicensed activity for ESS (Not less than 25 MW in case of inter-state and 10 MW in case of state transmission system)	MoP

Table 2: Evolution of Energy Storage Landscape in India

State	Development	Key Inferences	Institution
Maharashtra	Draft MERC RPO (First Amendment) (MERC, Regulations, 2023)	The ESO is considered met if at least 85% of the energy stored in the system comes from renewable sources each year. The prescribed storage obligation is 1.5% in 2024-25 and increases up to 4% in 2029-30	MERC
	NHPC has signed MoU with Maharashtra Energy Dept	The MoU envisages development of four PSP aggregating to a total capacity of 7,350 MW, namely Kalu – 1,150 MW, Savitri – 2,250 MW, Jalond – 2,400 MW and Kengadi -1,550 MW.	NHPC and Department of Energy
Andhra Pradesh	Andhra Pradesh PSP Promotion Policy-2022 (Dept of Energy, 2022)	Policy is aimed at maximising the utilization of the state's 33 GW PSP capacity and declares NREDCAP as the nodal agency to facilitate developments of PSP	Department of Energy
	AP State Electricity Plan FY2023-23 FY2033-34 (APERC, 2023)	1350 MW Pumped storage capacity are projected to be added from FY 2023-24 to FY 2028-29.	APERC
Madhya Pradesh	Madhya Pradesh Renewable Energy Policy 2022 (GoMP, 2022)	For RE sourced ESS projects: Policy listed incentives (as below) for ESS when sourced with RE. To avail these incentives, the RE power project of "X" MW shall have minimum storage capacity of "X/10" MWh. Min CUF to be 35% A) Exemption of 20% payment of registration cum facilitation fees B) Exemption of payment of Electricity Duty for 10 years from COD C) 15% reimbursement on stamp duty on purchase of private land	MP Renewable
Uttarakhand	Uttarakhand State Solar Policy, 2023 (UREDA, 2023)	a) For Utility Scale Solar - 100% reimbursement of custom duty on input required for manufacturing battery storage for a period of 5 years b) Manufacturing – 50% exemption on stamp duty and 100% reimbursement of custom duty on input required for manufacturing the solar modules and battery storage for a Period of 5 years c) UERC shall introduce time-of-the-day solar energy feed-in tariffs	UREDA (Uttarakhand Renewable Energy Development Agency)

Table 3: State level Energy Storage Policy in India

The next chapter identifies secondary research to map methodologies for estimating energy storage requirements across the power sector infrastructure. This shall include relevant data points, boundary condition variables and constraints and limitations of the approaches.

4. Modelling Approaches to Energy Storage Planning and Integration

At system level and utility level, it is pertinent to outline various modelling approaches used to estimate sizing of ESS. This ensures that selection of the ESS is carried out agnostically. Below sections elaborates on literature of modelling approaches which include key input-outputs parameters with limitations and boundary conditions of the model. This includes literature at system and utility levels.

4.1. Systems Level Planning

Systems-level planning in the power sector involves a comprehensive and integrated approach to plan, develop, and manage the entire power system to ensure reliable, efficient, and sustainable electricity supply. The key outcomes of system level planning include optimisation of infrastructure costs while expanding capacity and planning the proportion of electricity generated from different sources. This is achieved by simulating different scenarios of load and supply. Simulation at system level allows policymakers to test different scenarios and evaluate the potential impact of different policies on production and pricing (Kahn, 1995). In the Indian context (Ministry of Power, India, 2023) also mandates the use of “least cost generation optimisation” method in its resource adequacy framework guidelines for optimal systems planning. For the context of this study, review of literature that has utilized system level planning methodologies to estimate energy storage system is conducted.

There are several methodologies that have been used for system level modelling. (Booth, 1972) has one of the earliest mentions of system level analysis for power system. The paper utilizes probability distribution scenarios to describe the system loads, and the results are combined to evaluate the energy generated by each unit in the system. Numerous studies over the past decades have also extensively explored sizing of energy storage using systems level design. (Nassar & Gruber, 1983) present a **system analysis model which reduces production costs** for a power system with storage. The study takes into account the **stochastic[4] nature of the load** and helps find the optimum energy storage device to minimise the expected production cost of meeting demand. Mazumdar & Kapoor (1995) use an advanced stochastic method to determine energy production costs at systems level. While this study does not mention energy storage, the paper is highly cited within the purview of ESS sizing at system level.

Researchers have also applied different methodologies of system level analysis to estimate energy storage requirements for a certain region. Conducting a real life simulation in Japan, (Esteban et al., 2012) estimated a total of 41 TWhr of battery energy storage to accommodate for a future 100% renewable energy scenario. Similarly, (Harsh Thacker et al., 2023) have also used production cost modelling to estimate energy storage requirements for Rajasthan grid

[4] having a random probability distribution or pattern that may be analysed statistically but may not be predicted precisely

in 2030. In order to build a regulatory framework, it is crucial to understand the value stream being served by ESS, inputs and constraints that are utilised to build system level analysis models.

To project long term capabilities with energy storage, an optimal mix of power generation sources and capacities to meet the projected demand is calculated, (Harsh Thacker et al., 2023). This involves considering inputs such as **current and forecasted demand** and **supply data**, in **both capacity and energy terms**. It also includes **plant technical details** such as **ramp rate, technical minimums, generator ratings**. Additionally, ESS at system level are also designed based on grid **reliability metrics** such as **LOLP**[5], **NENS**[6] and **Capacity Credits**[7] (Ministry of Power, India, 2023). In most cases, cost parameters such as investment cost, operation and maintenance costs, amortisation cost, interruption cost, and replacement cost for power plants are used as constraints to estimate financial feasibility while sizing ESS. (Sheibani et al., 2018).

The value streams that energy storage serves at system level can be categorised into infrastructure optimisation, energy arbitrage and grid reliability. System level studies were conducted by (Hozouri et al., 2015) and (Zhang et al., 2013) for maximising wind integration through pumped-hydro storage system. In (Hozouri et al., 2015), one of their key objective functions was to **maximise energy arbitrage** performed by ESS for the system. Whereas for (Zhang et al., 2013), maximising **Deviation Settlement Mechanism (DSM) savings** were key objectives. Both these studies included investment cost of ESS, operating and maintenance costs, fossil fuel generator costs as constraints. Total load curtailment cost is used as an additional constraint to evaluate energy arbitrage revenue in (Hozouri et al., 2015). Historic load shedding costs were additionally used as an input to evaluate grid balancing ability of the ESS by (Zhang et al., 2013).

Approach	Critical Input/Output Data	Constraints or Limitations
Minimise system level costs through production cost modelling for infrastructure optimization.	**Input data:** Current and Forecasted Demand, Current and Forecasted Supply, Long-term contracted capabilities, Plant wise technical details such as ramp rate, technical minimums, generator ratings, RE generation data, RE Expansion Plans, Intra-State Transmission Capabilities and Capacity Expansion Planning **Output data:** Daily generation data, Generation Cost, Energy Storage operational parameters including	• Cost parameters such as investment cost, operation and maintenance costs, amortisation cost, interruption costs are overall system constraints. • Congestion and other transmission/network related constraints have not been modelled.

[5] LOLP: It is defined as the measure of probability that a system load may exceed the generation.
[6] NENS: The total expected load shed due to supply shortages (MWh) as a percent (%) of the total system energy.
[7] Each generator can provide a "firm capacity", which represents the amount of power the generator can reliably provide. Capacity credit expresses firm capacity as a percentage of the installed nameplate capacity.

	charging and discharging. In addition, projection of optimal fuel mix which includes conventional and RE generators can also be studied.	• Reliability metrics have not been modelled. • Most model inputs are majorly supply side, demand side inputs are minimal/missing.

Table 4: Estimation Study Approaches at System level

4.2. Estimating Energy Storage System for Generation

Much of the literature for estimating size and capacity of ESS at generation level involves serving two value streams which are **Primary Frequency Control** and **Infrastructure optimisation.** The first part of this section examines literature for ESS that serves infrastructure optimisation.

In an empirical case study for Germany conducted by (Steffen & Weber, 2013), the authors state that "efficient storage capacity is the level of storage capacity that minimizes the total system cost, including investment and operating costs". It is inferred by (Steffen & Weber, 2013) that an increase in investment or operating costs of alternate energy technologies that are used to serve peak-load triggers higher storage capacity. In contrast, the investment costs of the baseload serving energy resources have no influence on efficient storage capacity. Additionally, the impact of CO_2 prices on storage capacity is also discussed in the paper. The study highlights inefficiency in the use of storage in scenarios where RES[8]-levels are below 60%. In the national framework released by MoP promoting energy storage systems, reduction in carbon emissions is considered an important objective.

In the studies conducted by (Ghofrani et al., 2013) and (Kargarian & Hug, 2016), total system costs for increasing wind integration are considered. (Ghofrani et al., 2013) propose a **probability-based framework** to enhance the performance and reliability of wind integration by minimising operation and load-interruption costs using ESS. Power, energy and investment cost of the storage system are considered as critical inputs. The planning horizon, however, has not been specified. The study in (Kargarian & Hug, 2016) highlights the two planning perspectives: hourly and intra-hourly intervals. Minimisation of system level costs is a key objective for both, but the **cost associated with demand response** and **ramping capabilities** of energy storage have a significant impact on the sizing of the ESS in (Kargarian & Hug, 2016).

While a majority of research estimating ESS at generation is focused on minimising total system cost, there are studies such as (Xiong & Singh, 2016), (Fallahi et al., 2014) and (Pudjianto et al., 2014) which focus on minimising daily/hourly operation and maintenance cost. It is observed in (Xiong & Singh, 2016) that **"operating cost curve flattens when the investment budget of ESS is quite high, implying that the reduction of daily operating cost is diminishing as the investment on ESS rises"**. (Fernández-Blanco et al., 2017) while also

[8] RES – Renewable Energy Sources

focusing on minimising ESS operating cost, states the importance of "**identification of sites where energy storage systems should be located to perform energy arbitrage**" to effectively determine the optimal size of ESS. In all the literature reviewed, there were no insights on whether transmission costs have been considered.

The integration of renewable energy sources in generation mixes have also led to a decrease in overall frequency support to the grid (Tielens & Van Hertem, 2012). The study suggests additional frequency control mechanisms such as energy reserves, kinetic energy of solar farms and demand-side management (DSM) interventions. With ESS, the sizing parameters for frequency and inertial control are different as PFC (Primary Frequency Response) require fast response time and high-power rating.

A BESS sizing estimation study conducted by (Dawei & Zhen, 2021) for frequency regulation emphasises on considering **rate**[9] **characteristics** as a critical sizing parameter. The study concludes that capacity estimation considering the rate characteristics can **"effectively reduce the configuration capacity, and this helps to realize the economic potential of BESS".** A different approach for estimating BESS size for primary frequency control has been presented by (Aghamohammadi & Abdolahinia, 2014), in which **overloading characteristics**[10] and **limitations of the state-of-charge (SOC)** are critical parameters. The simulation results in this study reaffirms a low-capacity BESS can also respond to frequency mismatch if the sizing studies are value-stream specific.

In addition to frequency control, ESS can also provide synthetic inertial control to the grid. The authors in (Delille et al., 2012) state, "synthetic inertia can mitigate the impact of wind and solar generation on the dynamic performance of isolated power systems in the case of a major generation outage". The key parameters of a ESS sizing study for PFC and inertial response conducted by (Alves et al., 2021) are system parameters such as **maximum and minimum output of generating source**, **maximum and minimum power demand of the load** and **maximum and minimum SOC** of the ESS. Similarly, the estimation model in (Knap et al., 2016) use **system size**, **system inertia**, **power/frequency characteristic** and **ROCOF**[11] as input parameters. The study by Knap et al. (2016) concluded that PFC requires more power and energy than Inertial Response (IR) since the IR is active only for a few seconds while PFC requirements are for longer time blocks. As the higher power requirement for sizing is considered, **same ESS can be used for both the services**. (Moon et al., 2017) conduct a real-life analysis of ESS in Korea, and their frequency-regulation abilities. The study states the advantages of using ESS over conventional generators citing their dynamic response.

[9] Charge/Discharge Rate for Battery Energy Storage System.
[10] The overloading capacity of the BESS refers to its ability to inject or absorb power to the grid for restoration of load-generation balance in a short time.
[11] ROCOF: Rate of Change of Frequency- it refers to the measurement of how quickly the system frequency is changing over time.

Approach and Associated Value Streams	Critical Input/Output Data	Constraints or Limitations
Sizing of ESS for **Primary Frequency Control** or **Optimising DSM charges** may be carried out through 1. mapping rate and power characteristics 2. through numerical simulation methods 3. ability to fulfill target limits of rate of change of frequency and minimum frequency required in the system.	**Input Data:** System Size, System Inertia, Basic profile of regional power grid, frequency regulation evaluation index, Target p-f characteristics, ROCOF, ESS cost function, output of generating source, Maximum and minimum power demand of load, SOC limits, CO2 Pricing, location of BESS, **Output Data:** Required Capacity for PFC, Sold Energy, Recharge Energy, NPV of Profits	• Overloading characteristics and ability for the ESS to charge/discharge are important parameters to size ESS for Primary Frequency Control • Addition of Inertial Response (IR) as a service would impact the sizing of the ESS • ESS for primary frequency control can be more effective with a grid with weak inertial response and slow primary frequency response • Planning horizon (time-of-use) is not specified as an input in sizing studies.

Table 5: Estimation Study Approaches at Generation level

4.3. Estimating Energy Storage System for Transmission

ESS sizing for transmission systems primarily serves the transmission capacity expansion/deferral, decongestion/grid resilience and black start.

In the case of transmission congestion relief, (Hemmati et al., 2017) state the importance **stochastic planning and scheduling** to account wind and solar uncertainty. This planning approach includes reliable forecast of energy supply and demand, which aids in better congestion management in the grid. While investment cost of ESS and penalties for decongestion are critical parameters, the study in (Hemmati et al., 2017) also require several other inputs. System topology and parameters such as **transmission line capacities, bus voltage** and **generator capacity and marginal production cost** are critical boundary conditions for the study. ESS parameters such **as rated power**, **capacity and point of coupling** are also critical inputs for the model.

(Aguado et al., 2017) emphasise the need of using ESS for transmission network expansion planning. The study conducted in the paper uses a mathematical optimisation model which maximises the "total social welfare". In addition to the critical input parameters mentioned in the above paragraph, market parameters such as **electricity prices**, **transmission tariffs** and **demand elasticity** are included in the model. The results are evaluated against metrics such as total social welfare, the quantum of benefits at generation and transmission and changes in demand.

Network expansion planning costs can also be saved through transmission deferral by ESS. An analysis conducted by (Eyer et al., 2005) highlights the need of considering **load growth and uncertainty** while estimating sizing for ESS. However, one critique of the analysis is that all sizing studies have been done without taking the storage system cost into consideration. The sizing considerations in (Bhandari et al., 2021) are done by a simulation tool developed by EPRI which determines the "amount of MW injection required from a BESS to eliminate MW overload". Critical inputs include **information on the contingencies to be studied**, **point-of-coupling** of the ESS and **generators to be dispatched to balance load generation**.

While increasing hosting capacities and transmission deferral are important value streams, grid resilience and supporting black start through ESS have also been studied. The authors in (Halwany et al., 2022) state technical inputs from transmission operators such as **service availability**, **block loading capability**, **resilience of supply** are critical to the optimisation model. The subsequent ESS results are then validated by simulating the dynamic behaviour of the wind farm during the black start operation. Similarly, (Yoon et al., 2019) propose using **RoCoF** as a critical input parameter to estimate ESS sizing for large scale transmission system for frequency and voltage regulation. **Fault location** and **clearing time** are additional input parameters for the model suggested by (Ortega & Milano, 2018) for transient stability of transmission systems.

Approach	Critical Input/Output Data	Constraints or Limitations
• Screening and contingency analysis through numerical optimisation models, and stochastic planning and scheduling may be carried out to size ESS for de-congestion and grid resilience. Additional investment deferral and infrastructure optimisation related to transmission may be carried out through either iterative optimisation or linear programming simulations.	**Input Data:** Description and definition of contingencies to be studied, Point-of-interconnection (PoI) for BESS, Generators to be dispatched through Point-of-interconnection, base year peak load, load growth over planning period, congestion index, T&D equipment ratings like nominal and emergency rating, financial inputs on augmentation cost and cost of energy storage integration, cost of finance, black start technical requirements like service availability, block loading	• Ageing effects of BESS have been modelled as a function of cost. • Out of scope constraints such as tradeoffs between nominal v/s peak rating, storage system modularity and storage technology costs can also be studied as a separate exercise to evaluate transmission deferral accurately. • Cost-benefit is extremely sensitive to load growth. • Power Plant efficiencies are not considered

• An analytical hierarchy process with worst case scenario modelling may be carried out to estimate sizing for ESS for black/cold start. Additionally, probabilistic methods can be used to integrate RE farms with ESS for black start operations.	capability, resilience of supply **Output Data:** Optimal value of BESS across system contingencies, cost-benefit analysis, and sensitivity analysis.	while sizing ESS for black start.

Table 6: Estimation Study Approaches at Transmission level

4.4. Estimating Energy Storage System for Distribution

At distribution level, the value stream that ESS can serve can be majorly categorised into infrastructure optimisation through investment deferral, voltage regulation and peak shaving.

Studies conducted by (Holjevac et al., 2019) and (Li et al., 2020) evaluate ESS for distribution infrastructure deferral. Although different optimisation models have been used in both, common critical input parameters are **transformer data**, **overhead line** and **cable data**, **consumption** and **peak load data, energy storage ramping capabilities** are same. Additionally, (Li et al., 2020) also use photovoltaic efficiency and charging interval of electric vehicles as critical inputs for their model. (Holjevac et al., 2019) however emphasis on inputs of power quality requirements such as voltage and loading limits to optimally determine the capacity of ESS.

An important value stream that ESS serves at distribution level is voltage regulation. This generally is stacked with other value streams. An example of this is the sizing strategy study conducted by (Yang et al., 2014) which presents a cost-benefit analysis for BESS for peak shaving and voltage regulation. On the basis on inputs such as **annual load**, **temperature** and **PV profiles**, an initial subsystem computes desired BESS control parameters such as **EMS, Bus Voltage Control** and **Battery Power Control**. This data is then fed into a cost-benefit analysis subsystem to calculate composite costs of different size of BESS for the associated value stream. In addition to this, (Nazaripouya et al., 2015) also considered the **location of BESS** as an important constraint by applying the minimum BESS size for desired voltage regulation at maximum solar penetration.

Often, while dealing with multiple value streams at distribution level, planners do not have access to methods or tools to appropriately assess true value of ESS. A novel method proposed in (Dugan et al., 2016) categorises six different sequential time-power flow simulation methods for BESS based on the value stream they are serving. These simulations mainly address peak shaving, time specific energy discharge[12], load following[13], load shape following mode[14] and dynamic mode[15]. These simulations are categorised in 15 minutes to one hour time frames, while 0.2-0.3 secs for dynamic mode of simulation.

At all the coupling points demand data and load data are almost always an input required to size an ESS. It becomes pertinent for the DISCOMs to accurately assess future load and demand growth as incorrect or bloated demand growth would have a significant impact on the economic viability of ESS.

Most simulation and optimisation methods concentrate on supply side parameters such as generation capacity, energy mix, plant efficiency, T&D losses, etc. However, demand side parameters such as energy savings, demand response participation, behavioural insights, social welfare and load flexibility are missing.

Manufacturers of ESS should include/supply planning software. Standard software interface can be used for conducting sizing estimation studies. This software can be integrated in the planning process at utility level and not be constraint to manufacturers. This would ensure repeatability of capacity of ESS for given inputs and boundary conditions.

Approach	Critical Input/Output Data	Constraints or Limitations
• Sizing of ESS for **decongestion** related to distribution may be carried out through direct search-based methods like mathematical or heuristics modelling, which also allow for **infrastructure optimisation and investment deferral** • Sizing for **Voltage and frequency** support may be achieved through probabilistic models and historical analysis.	**Input Data** Load data, Generation data, energy storage parameters like maximum power for charging and discharging, evaluation index parameters like annual availability hours of generation[16], equivalent annual investment cost[17], annual CUF of transformer, Bus Voltage reference, DOD, EMS software parameters based on function **Output Data:** Daily Energy storage power output, Income generated by reducing network loss, arbitrage	• Cost of the ESS is a function of deployment strategy i.e., constant power or economic dispatch. • Cost of fixed and O&M costs of ESS are assumed to be known. • Environmental impact constraints are yet to be measured/modelled • Time-of-use energy utilization cost can act as a constraint for energy arbitrage value stream

[12] Trigger the storage element at a specified time of day to discharge or charge at a specified constant level.
[13] The storage element is triggered to discharge at a specified time predicted through a short-term load forecast when it will be necessary to offset load demand.
[14] The storage charge and discharge cycle is determined by a predefined shape
[15] Advanced mode of analysis for modelling fast-changing phenomena such as frequency control
[16] The hours of generation operation at rated capacity, that is, the ratio of the annual actual generation of DG to the rated capacity of DG
[17] Defined as the ratio of the difference between the investment cost and the operating income of the equipment and the service life of the equipment.

	income, BESS annualized life cycle cost, shaved peak power	

Table 7: Estimation Study Approaches at Distribution level

5. Technology Selection Guide for ESS

Creating a regulatory framework necessitates an agnostic approach to technology selection of Energy Storage System. Selecting appropriate technology of an energy storage system (ESS) involves considering factors such as technical parameters, technology maturity, it's impact on the environment and storage duration. However, it is important to map these factors based on the value stream that ESS serve. The section presented below gives a brief description of the quantitative parameters of different ESS technologies.

i) **Specific Energy:** It represents the energy content of a material relative to its weight and is typically measured in watt-hours per kilogram (Wh/Kg). A higher specific energy value indicates that the material can store more energy per unit mass.

ii) **Volumetric Energy Density:** It represents the energy content of a material relative to its volume and is typically measured in watt-hours per litre (Wh/L). A higher volumetric energy density indicates that the material can store more energy within a given volume, directly impacting sizing and packaging consideration in ESS.

iii) **Round Trip Efficiency:** This is a measure of how efficiently a system can store and later release the energy. It is generally represented as a percentage of the ratio of energy output while the system is discharging to the energy input when system is charging. A higher percentage indicates that the energy storage system is more capable of storing and retaining energy.

iv) **Self-Discharge:** It refers to the gradual loss of stored energy over a given time. Self-discharge is a critical consideration when storing energy for long periods.

v) **Response Time:** It refers to the speed at which ESS can change its state from charging to discharging. It is a critical performance parameter in applications where rapid and precise energy flow is required.

vi) **Lifetime (Thousand Cycle):** Lifetime is typically expressed in terms of the number of charge-discharge cycles an ESS can undergo before its capacity or performance deteriorates to a specified level. Lifetime in cycle has a direct impact on economic viability and reliability of the overall system.

vii) **Lifetime (Years):** In addition to cycle life, calendar life is an important consideration. It represents the ESS's lifespan in terms of time, regardless of the number of cycles. It accounts for the natural aging of components over time.

Tables below outlines different ESS technologies and their quantitative and qualitative parameters which shall be referred in the next section to identify suitable ESS technology for identified value streams at system and utility level.

Technology	Specific Energy (Wh/Kg)	Vol. Energy Density (Wh/L)	Efficiency (%)	Self-Discharge (%/day)	Response Time(min/sec/ms) (ms – milli sec)	Lifetime (Thousand Cycles)	Lifetime (Years)	Unit Energy Cost (USD/kWh)
PHES	0.5-1.5	0-2	70-80	0-0.02	min	12-100	30-100	5-100
CAES	30-214	2-6	54-70	0-1	min	10-100	20-40	2-84
Flywheel	5-100	20-200	90-95	20-100	ms	100-1000	15-25	1,500-6,000
RFB	25-85	15-70	vary	0-33.6	ms	0.3-14	5-20	315-1,050
Lead Acid	30-40	80-90	80-82	0.09-0.4	ms	0.25-2.5	3-15	105-473
Ni-Cd	50-75	60-150	72	0.2-0.6	ms	2-2.5	10-20	800-1,500
Li-ion	100-265	177-676	92-95	0.09-0.36	ms	0.5-20	5-20	200-1260
Na-S	150-240	140-300	80	0.05-1	ms	1-10	10-25	263-735
HFC	0.8-100k	0.5-3k	20-50	-	sec	1-1.3	5-15	1,500
UC	1-20	10-30	85-98	40	ms	>50	10-30	~ 6000
SMES	0.5-5	0.2-2.5	85-98	10-15	ms	100+	30	1,000-10,000

Table 8: Quantitative Guide Mapping ESS to their parameters, (Liu et al., 2020)

Technology	Type of Technology	Storage Duration	Technological Maturity	Impact on Environment
PHES	Mechanical	Hours-Months	Matured	Significant huge areas of natural landscapes is required
CAES	Mechanical	Hours-Months	Developed	Emissions from combustion of natural gas
Flywheel	Mechanical	Seconds-Minutes	Commercial	Negligible, only for production, construction
RFB	Electro-chemical	Hours-Months	Demonstration/Commercial	Toxic remains after use
Lead Acid	Electro-chemical	Minutes-Hours	Commercial	Lead- Highly poisonous, soil and water contamination
Ni-Cd	Electro-chemical	Minutes-Hours	Commercial	Cadmium- Toxic for health and environment
Li-ion	Electro-chemical	Minutes-Days	Commercial	Rather low, impact through emission in manufacturing
Na-S	Electro-chemical	Seconds-Hours	Commercial	Significant due to higher reactivity of liquid Sodium
HFC	Chemical	Hours-Months	Developing	Negligible, byproduct is H_2O and minor CO_2
UC	Electrical	Seconds-Hours	Developed	Negligible, no heavy metal or disposal issue
SMES	Electrical	Minutes-Hours	Demonstration	Harmful due to strong magnetic field

Table 9: Qualitative Guide for Technology Selection of ESS

Coupling Stage	Applications	Parameters	ESS Selection
System Level	Infrastructure Optimisation	1. **Capacity:** Sufficient energy capacity to meet energy needs during peak demand periods, outages or when RE generation is low. 2. **Scalability:** The ESS should be scalable to accommodate future infrastructure expansion plans. 3. **Long Cycle Life:** To minimize replacement and maintenance cost as well as disruptions to grid operations. 4. **High Round Trip Efficiency:** To reduce energy costs and minimise losses during charge and discharge cycles. 5. **High Reliability and Availability:** To ensure uninterrupted operations of critical infrastructure components.	• Lithium Ion
	Peak Shaving	1. **Capacity:** Sufficient energy capacity to store surplus energy during off-peak periods and discharge it during peak demand periods. 2. **Power Rating**: Adequate power rating to deliver the required amount of energy quickly when demand surges, ensuring that the peak load is effectively shaved. 3. **Cycle Life:** A long cycle life to minimize degradation, as peak shaving may involve frequent charge and discharge cycles. 4. **Cost-Benefit Analysis:** To ensure that the potential energy cost savings outweigh the initial investment and operational costs of the ESS	• Lead Acid • Lithium Ion
	Grid Reliability	1. **Fast Response Time:** Rapid response time in milliseconds to quickly inject or absorb power in response to frequency or voltage deviations on the grid. 2. **Power Rating**: Sufficient power rating to deliver or absorb the required amount of energy within the response time frame to correct grid frequency deviations 3. **Cost Effectiveness:** a cost-effective business model that considers initial investment, operational costs and potential revenue from deviation settlement	• Lithium Ion

Generation Level	Renewable Energy Integration	1. **<u>Energy Capacity:</u>** Sufficient energy capacity to store surplus energy generated during periods of high renewable energy production. 2. **<u>Scalability:</u>** Scalability to expand the ESS capacity as renewable energy generation capacity grows or as grid integration requirements increase. 3. **<u>Cycle Life:</u>** A long cycle life to endure frequent charge and discharge cycles, as renewable energy sources often operate intermittently.	• Lead Acid • Sodium-Sulphur • Lithium Ion
	Primary Frequency Control	1. **<u>Power Rating:</u>** Sufficient power rating to deliver or absorb the required amount of energy within the response time frame. 2. **<u>Fast Response Time:</u>** Rapid response time in milliseconds to quickly inject or absorb power in response to frequency deviations on the grid. 3. **<u>Cost Effectiveness:</u>** a cost-effective business model that considers initial investment, operational costs and potential revenue from deviation settlement	• Lithium Ion
Transmission Level	Transmission Deferral	1. **<u>Capacity and Power Rating:</u>** Sufficient energy capacity to store excess electricity during periods of low demand or in cases of over-generation. 2. **<u>High Reliability and Availability:</u>** To ensure uninterrupted operations of critical infrastructure components. 3. **<u>Cycle Life:</u>** A long cycle life to endure frequent charge and discharge cycles associated with daily grid operations. 4. **<u>Scalability:</u>** Scalability to expand the ESS capacity as needed to accommodate growing transmission deferral requirements or changing grid conditions	• Lead Acid • Sodium-Sulphur • Lithium Ion
	Black Start	1. **<u>Rapid Response Time:</u>** To provide immediate power injection for the critical equipment needed to restart the grid. 2. **<u>Power Rating:</u>** Sufficient power rating to supply initial surge of electricity required to restart generators and essential grid components.	• Lithium Ion

		3. **High Reliability and Availability:** To ensure uninterrupted operations of critical infrastructure components. This including ESS having parameters like low self-discharge and high storage duration.	
	Decongestion	1. **Power Rating:** Adequate power rating to release stored energy during peak demand periods to alleviate congestion on transmission lines. 2. **Cycle Life:** A long cycle life to endure frequent charge and discharge cycles that may be required to address congestion on an ongoing basis. 3. **High Energy Efficiency:** High charge and discharge efficiency to minimize energy losses during the storage and retrieval process	• Lithium Ion • Lead-Acid
Distribution Level	Distribution Deferral	1. **Capacity and Power Rating:** Sufficient energy capacity to store excess electricity during periods of low demand or in cases of over-generation. 2. **High Reliability and Availability:** To ensure uninterrupted operations of critical infrastructure components. 3. **Cycle Life:** A long cycle life to endure frequent charge and discharge cycles associated with daily grid operations. 4. **Scalability:** Scalability to expand the ESS capacity as needed to accommodate growing transmission deferral requirements or changing grid conditions	• Lead Acid • Sodium-Sulphur • Lithium Ion
	Voltage Regulation	1. **Power Rating:** Sufficient power rating to deliver or absorb the required amount of power quickly to regulate voltage levels effectively. 2. **Fast Response Time:** Rapid response time in milliseconds to provide immediate adjustments to voltage levels and maintain grid stability. 3. **Cost Effectiveness:** a cost-effective business model that considers initial investment, operational costs and potential revenue from deviation settlement. 4. **Voltage Control Range:** The ability to regulate voltage levels within a defined range, ensuring compliance with grid voltage standards and guidelines.	• Lithium Ion

	Peak Shaving	1. **Capacity:** Sufficient energy capacity to store surplus energy during off-peak periods and discharge it during peak demand periods. 2. **Power Rating**: Adequate power rating to deliver the required amount of energy quickly when demand surges, ensuring that the peak load is effectively shaved. 3. **Cycle Life:** A long cycle life to minimize degradation, as peak shaving may involve frequent charge and discharge cycles. 4. **Cost-Benefit Analysis:** To ensure that the potential energy cost savings outweigh the initial investment and operational costs of the ESS	• Lead Acid • Lithium Ion

Table 10: Qualitative guide mapping value streams to technology characteristics

6. Recommendations

Overall, the policy developments have showcased a shift in recognition, from primarily supporting renewable energy integration to acknowledging ESS as a flexible resource capable of providing grid stability. However, to build an ecosystem for energy storage systems, below are some of the key recommendations.

1. Discoms shall be mandated to undertake comprehensive planning exercises that account for the integration of energy storage systems. These exercises should be conducted in collaboration with relevant regulatory authorities and follow a structured framework.
2. In guidelines for Resource Adequacy Plan, the long-term capacity contracts shall include energy storage requirements during assessment. Its input-output parameters and overall characteristics shall be considered as a part of optimisation constraints to arrive at optimal capacities in the long-term and fulfil resource adequacy.
3. The Central Electricity Authority and Central Transmission Utility shall include ESS in inter-state transmission planning. The State Transmission Utility shall also include ESS in its intra-state transmission planning.
4. Guidelines for calculating the standing capacity of energy storage systems to address grid variability and ensure system reliability shall be developed. Factors like demand fluctuations, renewable energy intermittency, and grid stability needs shall be considered when determining these capacity requirements.
5. There shall be a prerequisite to map unique characteristics and associated value streams of ESS to supplement the planning process. For example, a storage system, which is identified to serve energy arbitrage, would require energy capacity as prominent evaluation criteria. Whereas, for a frequency control value stream, ESS' ramping up or down capacities should be considered as the primary selection criteria. Thus, it is inefficient to use same yardstick for each value stream served by ESS. Understanding different input characteristics would be useful in optimal sizing of ESS in turn navigating towards its improved economic viability.
6. The regulatory framework shall be enabled to identify the value streams served by ESS at system levels and at utility level i.e. at generation, transmission and distribution level. It shall also outline approaches for optimal sizing of ESS for the identified value streams.
7. The regulatory authorities shall establish robust pricing mechanisms that accurately reflect the value streams provided by energy storage. It shall consider technical input and outputs of the identified value streams. These mechanisms should enable energy storage to offer multiple, stacked services and vetted revenue streams within the current regulatory framework.
8. To realise full potential of ESS, its market shall be developed through regulatory and policy tools. ESS operators and other market agencies shall be permitted to experiment innovative business models such as energy arbitrage, ancillary services to the grid, storage as a service to Discoms and other utilities, etc.
9. ESS operators may procure power from state generators at variable energy charge during non-peak hours, subject to availability of generator(s) and availability of transmission infrastructure.

10. Along with regulatory and market barriers to adoption of ESS, its high capital cost is one of the major barriers. A life-cycle cost instead of CAPEX approach, for instance demands a support from government, manufacturers and researchers. Government can play a role in incentivising stakeholders for initial capital cost through policies whereas researchers can strengthen the analytical and modelling capabilities of utilities to facilitate the integration of life-cycle cost considerations.

7. Concluding Remarks

Energy storage systems need to be valued beyond their functionality of storage and dispatch of power. Their modulatory and scalability allows integration across the power sector value-chain of generation, transmission, and distribution. Priority shall be given to create regulatory frameworks which enable integration of ESS across the three verticals through open market opportunities. This shall incentivise the private investors shall begin to monitor the opportunities as the ESS market matures, ensuring scalability at the inflection point.

In the meanwhile, mechanisms for price discovery through competitive bidding or cost-plus basis is perhaps the best plausibility to seed the nascent market. Integration with transmission and distribution networks is likely to create more value, as ESS are likely to leverage multitude of value-creation opportunities here. We recommend a technology neutral approach which enables generation of maximum value for the sector and the consumers.

Bibliography

1. PIB. (2022). *India's Stand at COP-26 .* Retrieved from Press Infromation Bureau: https://pib.gov.in/PressReleasePage.aspx?PRID=1795071
2. MoEFCC, G. (2022). *India's Long-Term Low-Carbon Development Strategy.* Retrieved from https://unfccc.int/sites/default/files/resource/India_LTLEDS.pdf
3. 2022, J. B. (2022). *India's renewable energy goals: Facts about progress made till 2022.* Retrieved from Centre for Science and Environment: http___cdn.cseindia.org_attachments_0.92441100_1647325277_indias-renewable-energy-goals-factsheet.pdf
4. Das, J. B. (2022). *India's renewable energy goals.* Retrieved from Centre for Science and Environment: http___cdn.cseindia.org_attachments_0.92441100_1647325277_indias-renewable-energy-goals-factsheet.pdf
5. Energy, M. o. (2023, May). *Programme wise Cumulative Physical Progress as on May, 2023*. Retrieved from www.mnre.gov.in: https://mnre.gov.in/the-ministry/physical-progress
6. IBEF, 2. (2023, Feb). Retrieved from https://www.ibef.org/industry/renewable-energy
7. SYR, I. A. (2023). *IPCC.* Retrieved from https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_LongerReport.pdf
8. DST, G. (2016). *Department of Science and Technology*. Retrieved from https://dst.gov.in/clean-energy-material-initiative-cemi
9. Department of Heavy Industries, G. (2021, June 09). *Department of Heavy Industries, GoI.* Retrieved from Department of Heavy Industries, GoI: https://heavyindustries.gov.in/writereaddata/UploadFile/ACC%20Scheme%20Notification%209June21.pdf
10. Frank W. Geels. (2018). Disruption and low-carbon system transformation: Progress and new challenges in socio-technical transitions research and the Multi-Level Perspective,. *Energy Research & Social Science,, 37*(ISSN 2214-6296), Pages 224-231.
11. Utpal Bhattacharya, P.-H. H. (2017, Oct). What Affects Innovation More: Policy or Policy Uncertainty? *JOURNAL OF FINANCIAL AND QUANTITATIVE ANALYSIS, 52*, 1869–1901. Retrieved from Cambridge.org: https://www.cambridge.org/core/services/aop-cambridge-core/content/view/FB21593CFF8551F9204850EFA896658B/S0022109017000540a.pdf/div-class-title-what-affects-innovation-more-policy-or-policy-uncertainty-div.pdf
12. CERC. (2019, Jan 09). *CERC Grant of Connectivity, Open Access Regulations, 2019.* Retrieved 06 2023, from CERC: https://cercind.gov.in/2019/regulation/Connectivity%20Regulations%20(7th%20Amendment).pdf
13. PIB. (2023, March 16). *Promotion of Clean Energy*. Retrieved June 2023, from PIB: https://pib.gov.in/PressReleseDetailm.aspx?PRID=1907698

14. CEA. (2023, March). *National Electricity Plan.* Retrieved June 2023, from Central Electricity Authority: https://cea.nic.in/wp-content/uploads/irp/2023/05/NEP_2022_32_FINAL_GAZETTE-1.pdf
15. GOI. (2010, January). *JNNSM.* Retrieved from https://www.seci.co.in/upload/static/files/mission_document_JNNSM(1).pdf
16. CERC. (2016). Retrieved from https://cercind.gov.in/2015/draft_reg/Ancillary_Services.pdf
17. NITI Aayog, R. M. (2017, Nov). *INDIA'S ENERGY STORAGE MISSION.* Retrieved from https://e-amrit.niti.gov.in/assets/admin/dist/img/new-fronend-img/report-pdf/India-Energy-Storage-Mission.pdf
18. MNRE. (2018, May 14). *National Wind-Solar Hybrid Policy.* Retrieved from https://mnre.gov.in/img/documents/uploads/2775b59919174bb7aeb00bb1d5cd269c.pdf
19. CERC. (2022, January 31). *Ancillary Service Regulations.* Retrieved from CERC: https://cercind.gov.in/Regulations/Ancillary-Service-Regulations-2022.pdf
20. CERC. (2019, March 7). *Tariff Regulations.* Retrieved from https://cercind.gov.in/2019/regulation/Tariff%20Regulations-2019.pdf
21. Regulators, F. o. (2022, November). *Framework for Energy Storage and EV.* Retrieved from http://www.forumofregulators.gov.in/Data/study/FOR-Report-Framework-Energy-Storage_and_EV.pdf
22. MERC. (2019). *MYT regulations.* Retrieved from https://www.mahadiscom.in/wp-content/uploads/2019/08/33.-01.08.2019-MYT-Regulation-2019_English.pdf
23. MHI. (2021, June 09). *ACC Scheme.* Retrieved from https://heavyindustries.gov.in/writereaddata/UploadFile/ACC%20Scheme%20Notification%209June21.pdf
24. Power, M. o. (2023, March). *Viability Gap Funding for development of BESS.* Retrieved from https://pib.gov.in/PressReleseDetailm.aspx?PRID=1907698
25. CEA. (2023, May 18). *National Electricity Plan - Generation.* Retrieved from https://cea.nic.in/wp-content/uploads/document_upload/2023/06/NEP_2022_32_FINAL_GAZETTE.pdf
26. MoP. (2022, March 11). *Guidelines for Procurement and Utilization of BESS.* Retrieved from https://powermin.gov.in/sites/default/files/webform/notices/BESS.pdf
27. Power, M. o. (2021, June). Retrieved from https://powermin.gov.in/sites/default/files/Waiver_of_inter_state_transmission_charges_Order_dated_21_June_2021.pdf
28. Power, M. o. (2022, Jan 29). *Clarification regarding usage of Energy Storage Systems (ESS) in various applications across the entire value chain of Power Sector-Reg.* Retrieved from https://energystoragepro.com/wp-content/uploads/2022/02/Clarification_regarding_usage_of_Energy_Storage_SystemESS_in_various_applications_across_the_entire_value_chain_of_power_Sector.pdf

29. MoP. (2022, January). *Clarifications on status of ESS.* Retrieved from https://energystoragepro.com/wp-content/uploads/2022/02/Clarification_regarding_usage_of_Energy_Storage_SystemESS_in_various_applications_across_the_entire_value_chain_of_power_Sector.pdf
30. CERC. (2019, March). *Tariff Regulagtion.* Retrieved from https://cercind.gov.in/2019/regulation/Tariff%20Regulations-2019.pdf
31. CEA. (2019, February 06). *Connectivity Regulations.* Retrieved from https://cea.nic.in/wp-content/uploads/2020/02/notified_regulations.pdf
32. MoP. (2020, November 03). *RTC Power from RE.* Retrieved from https://mnre.gov.in/img/documents/uploads/file_f-1604558525803.pdf
33. CERC. (2019, Jan). *Grant of Connectivity.* Retrieved from https://cercind.gov.in/2019/regulation/Connectivity%20Regulations%20(7th%20Amendment).pdf
34. MoP. (2023, June 09). *ISTS Waiver.* Retrieved from https://powermin.gov.in/sites/default/files/Waiver_of_Inter_State_Transmission_Charges_on_transmission_of_the_electricity_generated_from_solar_and_Orders.pdf
35. MoP. (2023, June 09). *Bidding Guidelines for RE with Storage.* Retrieved from https://powermin.gov.in/sites/default/files/Guidelines_for_Tariff_Based_Competitive_Bidding_Process_for_Procurement_of_Firm_and_Dispatchable_Power_from_Grid_Connected_Renewable.pdf
36. MoP. (2023, June 29). *Draft Electricity (Ammendment) Rules.* Retrieved from https://powermin.gov.in/sites/default/files/Seeking_comments_on_draft_electricity_amendment_rules_2023.pdf
37. CERC. (2015, August 13). *Ancillary Service Operations.* Retrieved from https://cercind.gov.in/2016/regulation/16.pdf
38. MoP. (2022, July 22). *ESO.* Retrieved from https://www.recregistryindia.nic.in/pdf/REC_Regulation/Renewable_Purchase_Obligation_and_Energy_Storage_Obligation_Trajectory_till_2029_30.pdf
39. RMI. (2015). *The Economics of Battery Energy Systems.* Retrieved from https://rmi.org/wp-content/uploads/2017/03/RMI-TheEconomicsOfBatteryEnergyStorage-FullReport-FINAL.pdf
40. RMI. (2015, October). *The Economics of Battery Energy Storage.* Retrieved from https://rmi.org/wp-content/uploads/2017/03/RMI-TheEconomicsOfBatteryEnergyStorage-FullReport-FINAL.pdf
41. IEX. (2023, May 28). *TRAS - DAM & RTM.* Retrieved from https://www.iexindia.com/Uploads/CircularUpdate/28_05_2023Circular%20No.%20819%20Intr[…]20(TRAS)%20Market%20Segment%20in%20DAM-AS%20and%20RTM-AS.pdf
42. MERC. (2023, August). *Regulations.* Retrieved from https://merc.gov.in/wp-content/uploads/2023/08/Draft-RPO-Regulations-1st-Amendment.pdf

43. MoP. (2023, April 10). Retrieved from https://powermin.gov.in/sites/default/files/Guidelines_to_Promote_Development_of_Pump_Storage_Projects.pdf
44. BloombergNEF. (2022, December 06). *Lithium-ion Battery Pack Prices.* Retrieved from https://about.bnef.com/blog/lithium-ion-battery-pack-prices-rise-for-first-time-to-an-average-of-151-kwh/
45. CERC. (2017, January). Retrieved from https://cercind.gov.in/2017/draft_reg/SP.pdf
46. EnergyWorld. (2022, Jan). Retrieved from https://energy.economictimes.indiatimes.com/news/power/draft-policy-on-energy-storage-systems-to-penalise-renewable-energy-curtailment/89169056?utm_source=linkedin_web&utm_medium=social&utm_campaign=socialsharebuttons
47. MoP. (2022, December 29). *Electricity (Amendment) Rules.* Retrieved from https://powermin.gov.in/sites/default/files/webform/notices/Draft_ectricity_Amendment_Rules_2022_organized.pdf
48. GoMP. (2022, August 18). *MP RE policy 2022.* Retrieved from https://www.mprenewable.nic.in/uploads/2022/RE%20Policy%202022.pdf
49. UREDA. (2023, April 23). Retrieved from Uttarakhand State Solar Policy: https://ureda.uk.gov.in/department2/library_file/file-08-05-2023-13-00-55.pdf
50. Dept of Energy, A. (2022). *AP PSP Promotion Policy.* Retrieved from https://nredcap.in/PDFs/Pages/GO_Ms_No_25_PSP_Policy.pdf
51. APERC. (2023, May). *AP State Electricity Plan.* Retrieved from https://aperc.gov.in/admin/upload/StateelectricityPlan07062023.pdf
52. GOI. (2022, August). *India NDCs 2030.* Retrieved from https://unfccc.int/sites/default/files/NDC/2022-08/India%20Updated%20First%20Nationally%20Determined%20Contrib.pdf
53. *GCI Ltd.* (2023, 08 17). Retrieved from https://timesofindia.indiatimes.com/business/india-business/indias-electricity-demand-hits-record-highs-in-august/articleshow/102933164.cms?from=mdr.
54. MoP. (2022, April). *Electricity Amendment Rules.* Retrieved from https://powermin.gov.in/sites/default/files/Electricity_Rights_of_Consumers_Amendment_Rules_2022.pdf
55. CEA. (2022, June). *Guidelines for Formulation of Detailed Project Reports for PSP.* Retrieved from https://cea.nic.in/wp-content/uploads/hpa/2023/06/Guidelines_for_Formulation_of_Detailed_Project_Reports_for_Pumped_Storage_Schemes_version_2.pdf
56. DEA. (2022, October 11). *Harmonized Master List of Infrastructure.* Retrieved from DEA: https://taxguru.in/corporate-law/data-centres-energy-storage-systems-included-harmonized-master-list-infrastructure-sub-sectors.html

57. MoP. (2023, August). *National Framwork for promoting ESS.* Retrieved from MoP: https://powermin.gov.in/sites/default/files/webform/notices/National_Framework_for_promoting_Energy_Storage_Systems_August_2023.pdf
58. Power, M. o. (2023, June 28). Retrieved from https://static.pib.gov.in/WriteReadData/specificdocs/documents/2023/jun/doc2023628218801.pdf
59. Kleinberg, M., Mirhosseini, N. S., Farzan, F., Hansell, J., Abrams, A., Katzenstein, W., Harrison, J., & Jafari, M. A. (2014). Energy Storage Valuation Under Different Storage Forms and Functions in Transmission and Distribution Applications. *Proceedings of the IEEE*, *102*(7), 1073–1083. https://doi.org/10.1109/JPROC.2014.2324995
60. *MoP_Procurement of RTC power*. (n.d.). Retrieved July 7, 2023, from https://mnre.gov.in/img/documents/uploads/file_f-1604558525803.pdf
61. *Renewable_Purchase_Obligation_and_Energy_Storage_Obligation_Trajectory_till_2029_30.pdf*. (n.d.). Retrieved July 7, 2023, from https://powermin.gov.in/sites/default/files/Renewable_Purchase_Obligation_and_Energy_Storage_Obligation_Trajectory_till_2029_30.pdf
62. Aghamohammadi, M. R., & Abdolahinia, H. (2014). A new approach for optimal sizing of battery energy storage system for primary frequency control of islanded Microgrid. *International Journal of Electrical Power & Energy Systems*, *54*, 325–333. https://doi.org/10.1016/j.ijepes.2013.07.005
63. Aguado, J. A., De La Torre, S., & Triviño, A. (2017). Battery energy storage systems in transmission network expansion planning. *Electric Power Systems Research*, *145*, 63–72. https://doi.org/10.1016/j.epsr.2016.11.012
64. Alves, E. F., Mota, D. dos S., & Tedeschi, E. (2021). Sizing of Hybrid Energy Storage Systems for Inertial and Primary Frequency Control. *Frontiers in Energy Research*, *9*. https://www.frontiersin.org/articles/10.3389/fenrg.2021.649200
65. Bhandari, A., Ramasubramanian, D., Singhvi, V., & Gaikwad, A. (2021). Considerations for Electric Utilities to Determine Energy Storage Size for Transmission Deferral to Increase Hosting Capacity. *2020 52nd North American Power Symposium (NAPS)*, 1–6. https://doi.org/10.1109/NAPS50074.2021.9449689
66. Booth, R. R. (1972). Power System Simulation Model Based on Probability Analysis. *IEEE Transactions on Power Apparatus and Systems*, *PAS-91*(1), 62–69. https://doi.org/10.1109/TPAS.1972.293291
67. Dawei, S., & Zhen, L. (2021, October 6). *Optimal configuration of battery energy storage system in primary frequency regulation—ScienceDirect*. https://www.sciencedirect.com/science/article/pii/S2352484721006648
68. Delille, G., Francois, B., & Malarange, G. (2012). Dynamic Frequency Control Support by Energy Storage to Reduce the Impact of Wind and Solar Generation on Isolated Power System's Inertia. *Sustainable Energy, IEEE Transactions On*, *3*, 931–939. https://doi.org/10.1109/TSTE.2012.2205025

69. Dugan, R. C., Taylor, J. A., & Montenegro, D. (2016). Energy Storage Modeling for Distribution Planning. *2016 IEEE Rural Electric Power Conference (REPC)*, 12–20. https://doi.org/10.1109/REPC.2016.11
70. Esteban, M., Zhang, Q., & Utama, A. (2012). Estimation of the energy storage requirement of a future 100% renewable energy system in Japan. *Energy Policy*, *47*, 22–31. https://doi.org/10.1016/j.enpol.2012.03.078
71. Eyer, J., Butler, P., & Iannucci, Jr., J. (2005). *Estimating electricity storage power rating and discharge duration for utility transmission and distribution deferral :a study for the DOE energy storage program.* (SAND2005-7069, 876523; pp. SAND2005-7069, 876523). https://doi.org/10.2172/876523
72. Fallahi, F., Nick, M., Riahy, G. H., Hosseinian, S. H., & Doroudi, A. (2014). The value of energy storage in optimal non-firm wind capacity connection to power systems. *Renewable Energy*, *64*, 34–42. https://doi.org/10.1016/j.renene.2013.10.025
73. Fernández-Blanco, R., Dvorkin, Y., Xu, B., Wang, Y., & Kirschen, D. S. (2017). Optimal Energy Storage Siting and Sizing: A WECC Case Study. *IEEE Transactions on Sustainable Energy*, *8*(2), 733–743. https://doi.org/10.1109/TSTE.2016.2616444
74. Ghofrani, M., Arabali, A., Etezadi-Amoli, M., & Fadali, M. S. (2013). Energy Storage Application for Performance Enhancement of Wind Integration. *IEEE Transactions on Power Systems*, *28*(4), 4803–4811. https://doi.org/10.1109/TPWRS.2013.2274076
75. Halwany, N., Pagnani, D., Ledro, M., Idehe, O. E., Marinelli, M., & Kocewiak, L. (2022). Optimal sizing of battery energy storage to enable offshore wind farm black start operation. *21st Wind & Solar Integration Workshop (WIW 2022)*, *2022*, 232–240. https://doi.org/10.1049/icp.2022.2759
76. Harsh Thacker, Sandhya Sundararagavan, & Simran Grover. (2023). *Estimating Energy Storage Requirements for Rajasthan Grid*. WRI, CES, CEEP. https://ceep.co.in/wp-content/uploads/2023/05/SET-Report_CEEP_WRI_CES.pdf
77. Hemmati, R., Saboori, H., & Jirdehi, M. A. (2017). Stochastic planning and scheduling of energy storage systems for congestion management in electric power systems including renewable energy resources. *Energy*, *133*, 380–387. https://www.sciencedirect.com/science/article/pii/S036054421730957X
78. Holjevac, N., Zidar, M., & Kuzle, I. (2019). Techno-economic assessment and optimization of the energy storage unit in the distribution network. *IEEE EUROCON 2019 -18th International Conference on Smart Technologies*, 1–6. https://doi.org/10.1109/EUROCON.2019.8861996
79. Hozouri, M. A., Abbaspour, A., Fotuhi-Firuzabad, M., & Moeini-Aghtaie, M. (2015). On the Use of Pumped Storage for Wind Energy Maximization in Transmission-Constrained Power Systems. *IEEE Transactions on Power Systems*, *30*(2), 1017–1025. https://doi.org/10.1109/TPWRS.2014.2364313
80. Kahn, E. (1995). Regulation by Simulation: The Role of Production Cost Models in Electricity Planning and Pricing. *Operations Research*, *43*(3), 388–398. https://doi.org/10.1287/opre.43.3.388

81. Kargarian, A., & Hug, G. (2016). Optimal sizing of energy storage systems: A combination of hourly and intra-hour time perspectives. *IET Generation, Transmission & Distribution*, *10*(3), 594–600. https://doi.org/10.1049/iet-gtd.2015.0031
82. Knap, V., Chaudhary, S. K., Stroe, D.-I., Swierczynski, M., Craciun, B.-I., & Teodorescu, R. (2016). Sizing of an Energy Storage System for Grid Inertial Response and Primary Frequency Reserve. *IEEE Transactions on Power Systems*, *31*(5), 3447–3456. https://doi.org/10.1109/TPWRS.2015.2503565
83. Li, C., Zhou, H., Li, J., & Dong, Z. (2020). Economic dispatching strategy of distributed energy storage for deferring substation expansion in the distribution network with distributed generation and electric vehicle. *Journal of Cleaner Production*, *253*, 119862. https://doi.org/10.1016/j.jclepro.2019.119862
84. Liu, J., Hu, C., Kimber, A., & Wang, Z. (2020). Uses, Cost-Benefit Analysis, and Markets of Energy Storage Systems for Electric Grid Applications. *Journal of Energy Storage*, *32*, 101731. https://doi.org/10.1016/j.est.2020.101731
85. Mazumdar, M., & Kapoor, A. (1995). Stochastic models for power generation system production costs. *Electric Power Systems Research*, *35*(2), 93–100. https://doi.org/10.1016/0378-7796(95)00993-0
86. Ministry of Power, India. (2023). *Guidelines for Resource Adequacy Planning Framework for India*. Ministry of Power, India. https://static.pib.gov.in/WriteReadData/specificdocs/documents/2023/jun/doc2023628218801.pdf
87. Moon, H.-J., Yun, A.-Y., Kim, E.-S., & Moon, S.-I. (2017). An Analysis of Energy Storage Systems for Primary Frequency Control of Power Systems in South Korea. *Energy Procedia*, *107*, 116–121. https://doi.org/10.1016/j.egypro.2016.12.143
88. Nassar, M., & Gruber, S. (1983). Probabilistic production cost model for a power system with storage. *International Journal of Electrical Power & Energy Systems*, *5*(2), 87–93. https://doi.org/10.1016/0142-0615(83)90012-1
89. Nazaripouya, H., Wang, Y., Chu, P., Pota, H. R., & Gadh, R. (2015). Optimal sizing and placement of battery energy storage in distribution system based on solar size for voltage regulation. *2015 IEEE Power & Energy Society General Meeting*, 1–5. https://doi.org/10.1109/PESGM.2015.7286059
90. Ortega, A., & Milano, F. (2018). Stochastic Transient Stability Analysis of Transmission Systems With Inclusion of Energy Storage Devices. *IEEE Transactions on Power Systems*, *33*(1), 1077–1079. https://doi.org/10.1109/TPWRS.2017.2742400
91. Pudjianto, D., Aunedi, M., Djapic, P., & Strbac, G. (2014). Whole-Systems Assessment of the Value of Energy Storage in Low-Carbon Electricity Systems. *IEEE Transactions on Smart Grid*, *5*(2), 1098–1109. https://doi.org/10.1109/TSG.2013.2282039
92. Sheibani, M. R., Yousefi, G. R., Latify, M. A., & Hacopian Dolatabadi, S. (2018). Energy storage system expansion planning in power systems: A review. *IET Renewable Power Generation*, *12*(11), 1203–1221. https://doi.org/10.1049/iet-rpg.2018.0089

93. Steffen, B., & Weber, C. (2013). Efficient storage capacity in power systems with thermal and renewable generation. *Energy Economics*, *36*, 556–567. https://doi.org/10.1016/j.eneco.2012.11.007
94. Tielens, P., & Van Hertem, D. (2012, January 1). *Grid Inertia and Frequency Control in Power Systems with High Penetration of Renewables*. Young Researchers Symposium in Electrical Power Engineering , Date: 2012/04/16 - 2012/04/17, Location: Delft, The Netherlands. https://lirias.kuleuven.be/1731030
95. Xiong, P., & Singh, C. (2016). Optimal Planning of Storage in Power Systems Integrated With Wind Power Generation. *IEEE Transactions on Sustainable Energy*, *7*(1), 232–240. https://doi.org/10.1109/TSTE.2015.2482939
96. Yang, Y., Li, H., Aichhorn, A., Zheng, J., & Greenleaf, M. (2014). Sizing Strategy of Distributed Battery Storage System With High Penetration of Photovoltaic for Voltage Regulation and Peak Load Shaving. *IEEE Transactions on Smart Grid*, *5*(2), 982–991. https://doi.org/10.1109/TSG.2013.2282504
97. Yoon, M., Lee, J., Song, S., Yoo, Y., Jang, G., Jung, S., & Hwang, S. (2019). Utilization of Energy Storage System for Frequency Regulation in Large-Scale Transmission System. *Energies*, *12*(20), Article 20. https://doi.org/10.3390/en12203898
98. Zhang, N., Kang, C., Kirschen, D. S., Xia, Q., Xi, W., Huang, J., & Zhang, Q. (2013). Planning Pumped Storage Capacity for Wind Power Integration. *IEEE Transactions on Sustainable Energy*, *4*(2), 393–401. https://doi.org/10.1109/TSTE.2012.2226067