Distribution Utilities Forum

Energy Storage at the Distribution Level – Technologies, Costs and Applications

(A study highlighting the technologies, use-cases and costs associated with energy storage systems at the distribution network-level)

SHAKTI SUSTAINABLE ENERGY FOUNDATION

teri THE ENERGY AND RESOURCES INSTITUTE
Creating Innovative Solutions for a Sustainable Future

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Prepared for
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For more information

The Energy and Resources Institute
Darbari Seth Block
IHC Complex,
Lodhi Road New Delhi-110 003
India

Tel. 2468 2100 or 2468 2111
E-mail pmc@teri.res.in
Fax 2468 2144 or 2468 2145
Web www.teriin.org
India +91 • Delhi (0)11

MESSAGE FROM

GIREESH B PRADHAN,

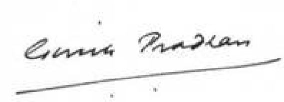
HONORARY CHAIRMAN, DISTRIBUTION UTILITIES FORUM

Aiming to reduce the dependency on fossil fuel for power generation; India has taken several path-breaking initiatives for faster adoption of renewable energy (RE) sources in the electricity sector, and consequently, the ambitious, yet the quite achievable target has been set up to install 175 GW RE by 2022. Recently, India has achieved a 100 GW milestone of installed renewable energy capacity which complements to aforesaid target. This shows a steady transition and commitments of the country towards clean energy-based power generation. Though, the higher penetration of renewable energy in the electricity network creates various technical issues such as voltage rise, reverse power flow, etc. It is therefore essential to have a balancing source like energy storage in the power portfolio of DISCOMs/ network operators.

DISCOMs need to prepare for smooth transitioning of the power sector since these advancements are likely to bring certain challenges alongside opportunities. The eighth Distribution Utilities Forum (DUF) meeting, on the theme of Energy Storage, was virtually held on 28th January 2021. It saw the involvement of a diverse set of stakeholders such as nodal ministries, DISCOMs, developers, and system operators that have a key role to play in the development of the energy storage supply chain across the country. I am glad to note that the stakeholders have had an extensive discussion and deliberation on key aspects of energy storage such as regulatory & policy measures, operational challenges, and their cost implications.

Discussions at the meeting along with responses from preliminary discussions with DISCOMs and other stakeholders on the subject and proposed suggestions have been captured in this report.

I trust that you will find the report to be an interesting read.



Gireesh B Pradhan

MESSAGE FROM
DR. VIBHA DHAWAN,
DIRECTOR GENERAL, TERI

With the increasing penetration of renewable energy in the electricity network, India is gradually becoming one of the global leaders in clean energy eco-space. The Government of India (GoI) has scaled up the target for installed capacity of renewable energy from 175 GW by 2022 to 450 GW by 2030. This is bound to bring more opportunities for new technologies like Energy Storage. Since power generation from RE sources such as solar PV and Wind is variable and intermittent, the role of energy storage for balancing becomes crucial for smooth and secure operation of grid. Energy storage with its quick response characteristics and modularity provides flexibility to the power system operation which is essential to absorb the intermittency of RE sources. In addition to maintaing demand and supply balance at in real time, energy storage systems (ESS) have a number of applications such as black start, backup power, ancillary services, energy arbitrage etc.

On the distribution level, ESS can manage distribution network congestion, minimize overloading of distribution transformer, act as back-up power source, perform energy arbitrage, and reduces peak power purchase requirements as well. However, lack of regulatory framework for ESS, high capital cost and limited ground-level experience hold back DISCOMS from investing in this technology. Moreover, India's strong commitment towards RE generation is backed by series of policy schemes such as the Production Linked Incentive (PLI) schemes for manufacturing high efficiency solar PV modules and advanced chemistry cell/batteries to boost the local manufacturing of solar PV modules and cells/batteries within the country. Given the progression in this sector, it is crucial to gauge the outlook of DISCOMs towards upcoming energy storage technologies and its applications, and understand their concerns.

The eighth DUF meeting on Energy Storage held on 28th January 2021, attended by a record number of DISCOMs as well as government and industry stakeholders. Their presence gave a comprehensive perspective that is captured in this report and the recommendations were shared with all the concerned stakeholders.

I am sure that you will find the report to be an interesting read.

Vibha Dhawan

Dr.Vibha Dhawan

MESSAGE FROM

DR. ANSHU BHARADWAJ,

CEO, SHAKTI SUSTAINABLE ENERGY FOUNDATION

The Distribution Utility Forum (DUF), an independent platform for the electricity distribution companies (Discoms) in India, is instrumental in bringing together distribution sector stakeholders to debate, discuss and deliberate the present and emerging challenges pertaining to the sector. Shakti Sustainable Energy Foundation (henceforth referred to as Shakti) has supported the forum since its inception in May 2018 to identify and deliberate on key thematic areas.

In recent years, energy storage has gained momentum because of the need to integrate a higher quantum of renewable energy (RE) in the grid to meet India's climate goals. In line with this aspiration, India set a target of 175 GW of RE to be installed by 2022 and the integration of such a large scale RE into the power system. However, the intermittency of RE can cause operational challenges, necessitating flexibility support to the grid operation. These intermittency issues can be resolved with Power-to-X pathways with energy storage facilities being a promising solution. The adoption of energy storage systems can help discoms develop an optimum power purchase stratergy. They can also contribute to meeting renewable purchase obligations, promoting decentralized distribution, and improving the reliability and quality of power.

After seven meetings of the Forum on five thematic topics viz. Rural Electrification, the Impact of Solar Rooftop on Discoms, Cost of Supply, Open Access, and Electric Vehicles, the eighth meeting held on 28th Januaray, 2021, focused on this thematic area of energy storage systems for Discoms.

This report is an outcome of the robust pre and post discussions that occurred on pertinent issues for energy storage at the distribution level. The views, one-on-one interaction, and suggestions given by DISCOMs, developers, and system operators have been considered in the preparation of this report.

I trust that Discoms will be able to glen useful insights from the report to boost energy storage in the country.

I take this opportunity to acknowledge the efforts made by TERI, by the DUF secretariat and members of Shakti who organized this productive and successful eight DUF meeting.

Dr. Anshu Bharadwaj
CEO, Shakti Sustainable Energy Foundation

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List of **Abbreviations**

A-CAES	Advanced Compress Air Energy Storage
AC	Alternating Current
BESS	Battery Energy Storage Systems
BNEF	BloombergNEF
BMS	Battery Management System
BOP	Balance of Plant
BTM	Behind-the-meter
C&I	Commercial-and-industrial
CAES	Compressed Air Energy Storage
CBA	Cost-benefit Analysis
CSP	Concentrated Solar Power
DERs	Distributed Energy Resources
DG	Diesel Generator
DR	Demand Response
DT	Distribution Transformer
DSM	Deviation Settlement Mechanism
EMS	Energy Management System
ES	Energy Solutions
ESS	Energy Storage Systems
ETES	Electric Thermal Energy Storage
EV	Electric Vehicle
FES	Flywheel Energy Storage
FOM	Front-of-meter
GHG	Greenhouse Gas
HTF	Heat Transfer Fluid
IOU	Investor-owned Utility
ISO	Independent System Operator
kW	Kilowatt
kWh	Kilowatt-hour
LCoE	Levelized Cost of Electricity
LFP	Lithium Ferro-phosphate
Li-ion	Lithium-ion
LNG	Liquefied Natural Gas
LT	Low Tension
MSES	Molten Salt Energy Storage

NaS	Sodium-sulfur
NMC	Nickel Manganese Cobalt
P2G	Power-to-gas
PCS	Power Conditioning System
PHS	Pumped Hydro Storage
PNNL	Pacific Northwest National Laboratory
PPA	Power Purchase Agreement
PV	Photovoltaic
RD&D	Research, Design & Development
RE	Renewable Energy
RPO	Renewable Purchase Obligation
SMES	Superconducting Magnetic Energy Storage
SOC	State of Charge
SRPV	Solar Rooftop Photovoltaic
TSO	Transmission Service Operator
VRE	Variable Renewable Energy

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We are extremely thankful to all the officials representing a diverse set of stakeholders such as nodal ministries like Ministry of New & Renewable Energy, central government agencies - mainly Energy Efficiency Services Limited (EESL) who spared time and provided valuable inputs during the virtual meeting of DUF.

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About the Authors

This report has been authored by: Mr. Ashish Kumar Sharma, Research Associate (up to February 2021), Mr. Ram Krishan, Associate Fellow, Er. Alekhya Datta, Fellow & Area Convenor (up to April 2021), Dr. Shashank Vyas, Associate Fellow (up to Februrary 2021), Mr. Neshwin Rodrigues, Associate Fellow, Ms. Jyoti Sharma, Project Consultant (up to June 2021), Mr. Nilesh Hadiya, Project Associate (up to June 2021), and Mr. Ashish Rawat, Project Associate of Electricity & Fuels Division, TERI.

Executive **Summary**

Globally, through various initiatives such as the Paris Agreement, several countries have taken cognizance that the paradigm shift towards renewables is an inevitable event. There have been global commitments for controlling greenhouse gas (GHG) emissions to arrest global warming and ensuring a slow pace of climatic changes. However, after a certain level of penetration of renewable energy, there would be a need of balancing fleets such as energy storage to continue the resilient and desired operations of power systems. The countries worldwide have initiated various pilot projects of energy storage systems to understand the multiple dimensions associated with energy storage technologies such as multiple technologies, different applications and corresponding revenue streams, environmental sustainability, possible ownerships as per the potential point of connections throughout the power evacuation chain.

India has also been in its early stages of understanding the applicability of energy storage in power systems. A few pilot projects have already been initiated here. There are multiple developments, compelling research, and policy interventions that have been undertaken by respective nodal agencies to assess the operational use cases of energy storage in Indian power systems, and consequently, it is being considered as an integral part of the power systems planning exercise. There are various types of energy storage technologies that exist for distribution network applications such as mechanical, electrochemical, electrical, chemical, thermal, etc. Since, battery storage, one of the electrochemical energy storage technologies that come with the flexibility of phased installation and is the only storage technology that can be installed as a balancing source within the distribution grid to relieve local grid operational challenges, is touted to be significant from the perspective of the distribution-level planning exercise.

Energy Storage at the Distribution Level: technologies, costs, and applications produce an assessment of operational-use cases and application-wise evaluation of economic feasibility of energy storage systems in the Indian context. The high cost of battery storage technologies is being foreseen as a major impediment to the large-scale adoption of such systems; therefore, the report covers the cost trends as claimed by relevant entities. The report also presents the global scenario of energy storage deployment vis-à-vis their global commitments, geographical location, economic prospects, and other local conditions.

Structure of *Energy Storage at the Distribution Level: technologies, costs, and applications* have been divided into five sections: Section I covers a broad-level introduction to energy storage systems enclosing the definition of key terms, an overview of various energy storage technologies and their relevance, cost trends as per PNNL and BNEF price survey to broadly gauge the economic prospects over the years. The section qualitatively evaluates six different characteristics relevant to energy storage attractiveness: 1) National targets and global commitments, 2) Current generation mix, 3) Manufacturing conduciveness for six different countries, namely i) Germany, ii) USA, iii) China, iv) Japan, v) Australia, and vi) India, policy support and subsidies, 4) Power market structure, and5) Miscellaneous factors. Section II briefly covers major pilot projects in India, followed by key applications of energy storage and their economic impact on electricity distribution utilities and key lessons learned. Section III takes into account policy and regulatory developments that are directly or indirectly impacting the adoption of energy storage systems in India and broad-level regulatory interventions. Section IV presents the views of different stakeholders including electricity distribution utilities, central agencies, and system developers and integrators and the last Section V covers way forward and broad-level recommendations in swift adoption of energy storage systems, pertinent to India.

All-dimensional view of energy storage system from the perspective of Indian power systems will enable distribution utilities to develop an understanding regarding the suitability of a particular energy storage technology to the local distribution grid, in line with geographical location and lagging areas in terms of distribution network operation, economic viability, and other local conditions. The report will not only help distribution utilities to understand the best practices in terms of energy storage technologies integration and operational-use cases followed by other distribution utilities in India but will also present the view of developers and system integrators to bring all stakeholders to a common platform to promote the large-scale adoption of such technologies from the standpoint of distribution utilities.

1. Introduction to Energy **Storage Systems**

Energy storage is expected to play a vital role in shaping up the developments in the power system. This responsibility becomes more pronounced with the advent of renewable energy (RE) systems. The undergoing transition in the electricity sector in India is witnessing a steady integration of a large quantum of RE, both at the bulk power system level and the distribution network level. The intermittent nature of RE-based power generation requires an adequate amount of flexibility in the power system to address the sudden changes in power. The issues are more complex at the distribution network level where increasing load growth and newly emerging consumption patterns coupled with an influx of distributed energy resources such as rooftop solar plants and electric vehicles (EVs) pose operational challenges. These broad issues have shifted the focus towards energy storage which is being seen as an enabling technology for power system flexibility and stability. This chapter discusses various energy storage technologies including the applications at the power system level.

1.1 Overview of Various Energy Storage Technologies

Energy storage can be categorized based on the involved process of energy conversion, as shown in Figure 1. Some of the storage technologies such as compressed air energy storage are based on thermodynamic processes involved in the compression and expansion of fluids like air and are still under technology trials.

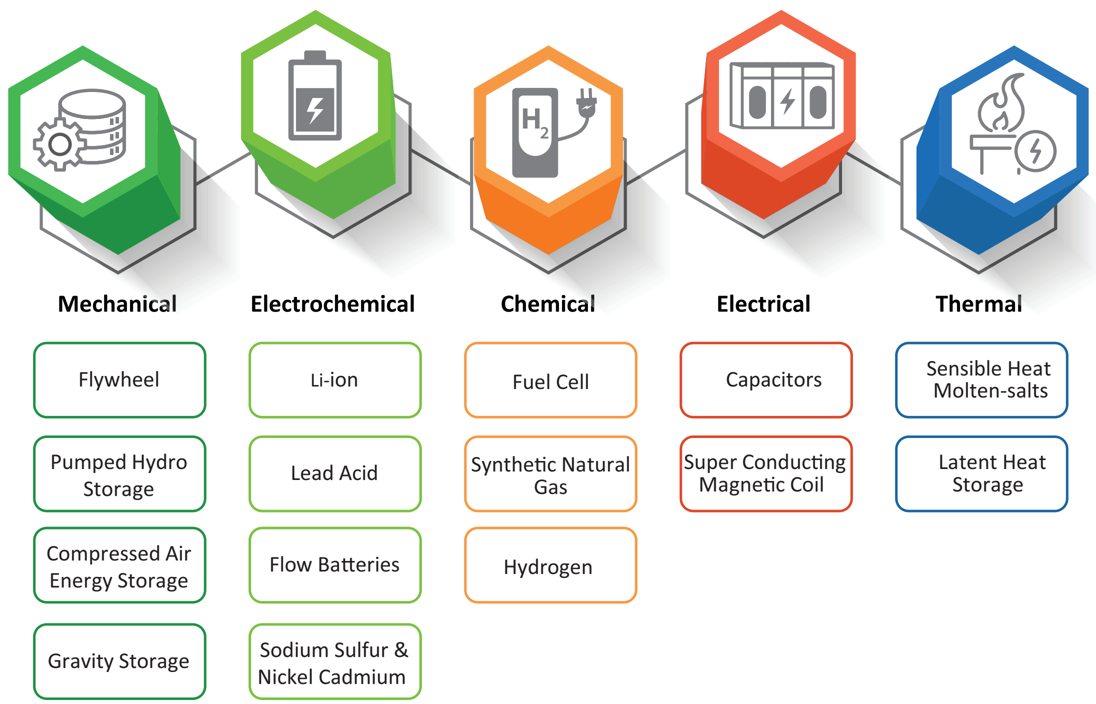


FIGURE 1: Classification of grid-scale energy storage

The other form of energy storage includes electromagnetic energy storage which can be further categorized into supercapacitors and superconducting magnetic energy storage (SMES). However, practically there are very limited cases for utility-scale applications for these technologies, in terms of ticket size. Supercapacitors, though, can be found in small-scale and Distributed Energy Resources (DERs) based integration. Hydrogen storage for stationary power applications is considered to be a key enabler for long or mid-term electricity storage, which can be utilized during the hour of the need for various applications. The potential role of hydrogen as energy storage in the power sector has been briefly discussed below in Box 1.

Box 1: Potential role of hydrogen as energy storage in the power sector

The viability of hydrogen-based energy storage is being explored now a days for stationary power applications, especially for medium and long-duration storage since it offers the highest gravimetric density amongst all available storage technology and its capacity does not degrade over time, unlike battery storage. It is a prominent technology that is predominantly used in chemical industries and refineries. Though, it's relevance for stationary power is still at a nascent stage due to certain challenges associated with the traditional way of hydrogen production, storage, and transportation, which requires extreme safety measures in place across the value chain. Green hydrogen, which is generated through renewables is gaining prominence now a days due to the increasing share of renewables in the total energy mix and is considered to be a technically viable option for hydrogen production. Green hydrogen will also play a crucial role in GHG emission curtailment and will pave the pathway for moving away from fossil fuel-based hydrogen production. The economic competitiveness of green hydrogen is also slowly being achieved due to the falling price of RE sources. The focus has now been to reduce the cost of electrolyzers, which is a major component of the green hydrogen value chain. Therefore, policy and regulatory support will be essential initially to foster green hydrogen adoption across the electricity sector. To accelerate the growth of hydrogen as an energy carrier in the country, the Government of India (GoI) had announced, under the Union Budget 2021-2022[1], to come up with a 'National Hydrogen Energy Mission (NHEM)' which will primarily focus on generating hydrogen from green power sources. This will also help India to lower the carbon intensity by 33-35% from the 2005 levels by 2030, a Nationally Determined Contribution (NDC) target set under the Paris agreement. In addition to this, the Department of Science & Technology (DST), GoI had launched a compilation report on the current status of hydrogen energy, covering the ongoing research activities in the country that are being carried out by various research organizations, academic institutions, and relevant stakeholders[2]. Whereas, TERI has also released a report titled 'The Potential Role of Hydrogen in India' which presents a cross-sector assessment of how hydrogen technologies can support the transition to a zero-carbon energy system in India[3]. In this report, few literature surveys have been carried out which describe the technical feasibility of hydrogen power for medium or long-duration electricity storage. The studies confirm that the green hydrogen as a balancing source is only viable for medium or long-term seasonal storage, while batteries are found to be cost-effective for short-term storage.

[1] https://pib.gov.in/PressReleasePage.aspx?PRID=1693898

[2] https://static.pib.gov.in/WriteReadData/userfiles/India%20Country%20Status%20Report%20on%20Hydrogen%20and%20Fuel%20Cell.pdf

[3] https://www.energy-transitions.org/publications/the-potential-role-of-hydrogen-in-india/

Amongst the types of technologies shown in Figure 1, two major types are being deployed on a commercial scale across the world while others have been used in pilot projects and are being experimented with. Pumped hydro storage (PHS) and Battery Energy Storage Systems (BESS) are relatively more mature at the technology-readiness level and have experienced successful commercial deployment in a variety of use-cases at the power-system level. Globally, the share of pumped hydro storage systems which are installed in the grid is found to be maximum compare to other available energy storage technologies. However, most of the recent installations are battery-based, primarily lithium-ion. This is mainly attributable to the fact that batteries have a broad range of applications, and can be installed in a phased manner. It thus becomes important to analyze these technologies in terms of their energy and power densities, discharge duration, and response times which are pertinent to grid-scale applications. The Ragone plot shown in Figure 2 helps in carrying out a comparative analysis of various energy storage technologies. As it can be seen from the Ragone plot, chemical energy storage (batteries) covers a wide range of areas under the plot which signifies that battery storage is suitable for most of the applications. On this ground, PHS and BESS will be the technologies under focus in this report. Characteristics of PHS and BESS are discussed in detail in the subsequent section.

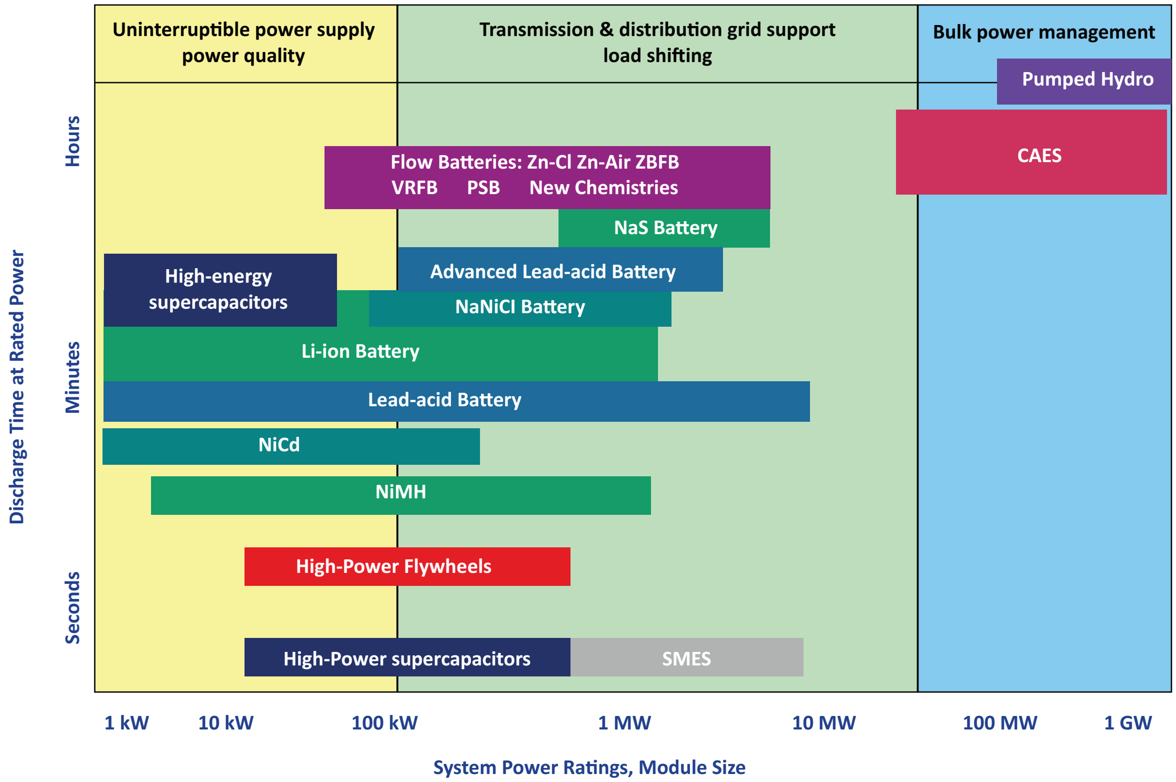


FIGURE 2: Ragone Plot

Source: US DOE/EPRI (2015)

1.1.1 Pumped Hydro Storage

A PHS system works on the principle of electromechanical energy conversion. PHS facilities are large-scale energy storage plants that use gravitational force to generate electricity. Water is pumped to a higher elevation for storage during low-cost energy periods and high-renewable energy-generation periods. When electricity is needed, water is released back to the lower pool, generating power through turbines. A closed-loop PHS operates without being connected to a continuously flowing water source, unlike traditional pumped hydro storage, making pumped hydro storage an option for more locations. Reservoirs, if available naturally, are required to pump water from a low-lying water source during motoring mode to a high-altitude reservoir to store the energy in potential energy at height. The water is then released during the generating mode to run a turbine-generator set to generate electricity to be fed into the bulk-transmission network.

In India, the state of West Bengal is amongst the front runners of utilizing PHS in its power network to manage system demand. The geographical location of West Bengal provides the edge to West Bengal State Electricity Distribution Company Limited (WBSEDCL) over other distribution utilities in terms of favorable sites for such storage systems. The Purulia Pumped Storage Project (PPSP) is one of the largest in the country. Based in the Purulia district, it is a-225 MW × 4 system. This project utilizes excess available power in the system during off-peak times to flatten the load curve. The project works in four operational modes: (i) generation, (ii) pumping, (iii) synchronous condenser, and (iv) line-charging (up to 400 kV bus) mode. The generation voltage is 16.5 kV. Figure 3 shows the plant and one of the tunnels.

FIGURE 3: Site images of PPSP in West Bengal[4]

The major issues associated with such an energy storage technology are the long-gestation period, high-upfront capital required including extensive civil works. It is worth mentioning, the cost of generation, including its storage, is very low, however, the round-trip efficiencies are a bit low.

[4] https://portald.wbsedcl.in/irj/go/km/docs/documents/WBSEDCL_DOCUMENTS/INTERNET/Website_28FEB2011/Puruliwa_Pumped_Storage_Project_2.html

Pumped hydro storage is more than 80% energy efficient through a full cycle, and the facilities can typically provide 10 hours of electricity, compared to about 6 hours for lithium-ion batteries. Despite these advantages, the challenge of PHS projects is that they are long-term investments – permitting and construction can take 3-5 years. This issue can be a major stumbling block for investors who would prefer short-term investment, especially in dynamic power markets which are evolving on a day-to-day basis.

1.1.2 Battery Energy Storage Technologies

A Battery Energy Storage System (BESS) converts electrical energy into chemical energy and stores a certain amount of energy considering the electrochemical conversion efficiency. The most commonly used battery chemistries for grid-level applications in the current scenario are based on lead, sodium, nickel, transition metals(vanadium, chromium, and iron), and lithium electrochemistry. The BESS is gaining wide acceptance for grid-level applications due to falling prices, and their unique features like quick response time, distributed energy/power-balancing capabilities, and phased installation. Moreover, the batteries can be used for both power and energy applications. On the contrary, capacitors and flywheels are used only for power applications. Suitable selection needs to be done for specific grid-level applications since each chemistry has distinct characteristics, such as charge/discharge rate capability, energy-power ratio, electrochemical conversion efficiency, depth of discharge, and life cycle. Some key definitions in the context of battery energy storage systems (BESS) are given here:

1. **Battery cycle life:** is defined as the number of charge-discharge cycles a battery can complete before its nominal capacity falls below 80% of its initial rated capacity.
2. **Energy density:** is the amount of energy that can be stored in a given mass of a substance or system.
3. **Round-trip efficiency:** Energy storage captures electricity in some manner and based on requirement transfers it to the grid. The ratio of energy put in (in megawatt hour or MWh) to energy retrieved from storage (in MWh) gives round-trip efficiency (also called AC/AC efficiency), expressed in percentage (%).
4. **Energy capacity:** The amount of energy that can be stored in a battery per MWh refers to the total energy that can be stored in a battery and the amount of energy that can be extracted in an hour. Energy capability is measured in terms of C. Higher is the C value, more current can be drawn from the battery, for example, lead-acid batteries have very high C values (up to 10C) while the value of C in lithium-ion batteries is significantly low (up to0.01C).
5. **Energy to power ratio:** It is defined as the rate of discharge or discharge time. Rated power (in MW) and capacity (the amount of energy the battery can deliver over time) are reported in MWh. Mathematically, the division between capacity and rated power gives discharge time.
6. **Power rating:** The use of MW denotes the power rating of a battery; this means, how fast power can be charged or discharged from a battery.
7. **C and E rates:** In describing the battery's technical specifications, discharge current is often expressed as C-rate, to normalize against battery design capacity, which is often varied based on battery chemistries. The C-rate is a measure of the rate at which a battery is discharged,

relative to its maximum capacity. A 1C rate means that the discharge current will discharge the entire battery in 1 hour. For a battery with a capacity of 100 Ampere hours (A-h), this equates to a discharge current of 100 A. A 5C rate for this battery would be 500 A, and a C/2 rate would be 50 A. Similarly, an E-rate describes the discharge power. A 1E rate is the discharge power to discharge the entire battery in 1 hour.

8. **Response time:** It is defined as the time taken by a storage system to reach nominal power after a standby period.
9. **Usable capacity:** The amount of electrical energy (in kWh) that can be discharged from a storage system as per the manufacturer's specifications, although sometimes also referred to in percentages as a ratio of usable capacity-to-installed capacity.

Lead-acid batteries

Lead-acid batteries have been one of the most prominent rechargeable electrochemical devices, predominantly used in uninterrupted power sources (UPS) for providing backup supply to various consumer categories during power outages. Lead-acid batteries are generally designed in two forms, namely, (i) vented lead-acid (VLA) and (ii) valve-regulated lead-acid (VRLA), with a power range up to a few megawatts and energy range up to 10 MWh. The VRLA requires lower maintenance as compared to VLA. Lead-acid batteries, a mature technology, are relatively cheaper than other battery technologies and have decent reliability and performance; however, low specific energy and cycle life pose a barrier in their large-scale deployment. To overcome these challenges, more recent advancement in lead-acid batteries involves the use of carbon in one or both of the electrodes. The introduction of carbon material in the form of ultra-capacitors enables the battery to operate for a longer duration and more effectively in a partial state of charge application than traditional lead-acid batteries. The composition of hybrid lead-acid and ultra-capacitor design has given the battery the ability to operate continuously in the highest efficiency region and avoid the corrosion and sulphation of active electrode material.

Flow batteries

The flow batteries are designed with two separate tanks which consist of electrolytic solutions, one tank act as a cathode material while the second tank is represented as an anode material. The electrolytic solution is passed through a membrane to generate electricity during discharging while in the case of charging the energy is stored in the form of chemical energy. Flow batteries exhibit unique features in a way that the power and energy capacity of the battery pack is completely decoupled. The flow batteries are typically an aqueous-based solution. Their cell voltage ranges from 1.0 to1.8 V, this prevents hydrolysis of water. Non-aqueous electrolyte flow batteries have high-open circuit voltage, so they have the potential for high energy density; however, these batteries are still under the development phase. The temperature range of flow batteries in an operating window is – 10°C to 50°C. Owing to the aqueous electrolyte (non-flammable), flow batteries are safe and have long cycle life (does not depend on the depth of discharge (DOD), energy depends on tank volume and electrolyte concentration and power determined by stack area. These batteries are most cost-effective for longer duration applications, besides, can provide fast ramp rates. Flow batteries' cycle life range is 2,000-20,000 cycles, and round-trip efficiency of 65%–85%. These batteries have certain drawbacks such as high-maintenance requirements, the large space requirement for large-sized batteries, the non-modular nature of the installation, and complex monitoring and control mechanisms for battery operation. Vanadium redox flow batteries are primarily commercialized by a few companies, for example, the US-based UniEnergy Technology (UET) and Vionx Energy, the German-based Gildemeister, and Sumitomo Electric from Japan.

Sodium-sulfur batteries

Sodium-sulfur battery is a molten salt-based battery that is constructed from liquid sodium and sulfur, is known to exhibit high-energy-density, longer cycle life, and high-round-trip efficiency. The composition of the material used to construct this particular battery is relatively inexpensive than the material used in other batteries. Sodium–sulfur battery has found a wide range of applications in an electricity distribution network such as grid support, solar photovoltaic (PV)/wind plant integration, and high-value proposition for different applications on islands. The technology has a great potential for grid services since it has a long discharge time and can respond precisely to improve power quality issues in the grid. It is a reliable technology, and the largest installed capacity of a single unit of 34 MW/245 MWh has been deployed in Aomori, Japan. The system was installed for wind stabilization. The technology is only suitable for stationary applications. The major drawback of this battery is the high-operating temperature which rangesfrom300–350°C. Japan has been considering this battery technology as an alternative to lithium-ion to reduce the imports of rare earth metals from the countries that control supply chains, extraction, and reserves of metals used in the manufacturing of lithium-ion batteries.

Lithium-ion batteries

Lithium-ion batteries are a well-known technology for portable electronic devices because of their unique features like high energy density and relatively low weight. In the past few years, lithium-ion batteries are being considered to be the most attractive for grid-level applications due to their several advantages over other chemistries like high-specific energy density, high charge/discharge rate capabilities, a large number of cycles, lower self-/cycle degradation, and higher round-trip efficiency. Owing to the increasing demand for lithium-ion batteries in the automotive industry and consumer electronics, in addition to the grid-level application, the cost is expected to fall in the coming years. In most of the commercially available lithium-ion batteries, the anode is lithiated graphite or lithium-titanate while the cathode is made up of either lithium metal oxide or lithium phosphate. The different chemistries of lithium-ion which are commercially available for different applications include $LiCoO_2$ (LCO), Li_2MnO_3 (LMO), $LiFePO_4$ (LFP), $LiNiMnCoO_2$ (NMC), $Li_4Ti_5O_{12}$ (LTO), and $LiNiCoAlO_2$ (NCA). These different chemistries showcase different performance, cost, and safety features that can be utilized for a variety of applications. As an example, LCO batteries are predominantly used in handhold electronics devices due to their high energy density and low weight. On the other hand, LFP, NMC, NCA, and LMO offer low-energy-density, but longer cycle life and inherent safety, thus these batteries, especially NMC and LFP are being utilized for grid-level applications. Moreover, LTO batteries offer high performance, higher cycle life, excellent safety feature, and higher charge/discharge rate (up to 10 C) however; their specific energy is low as compared to other lithium-ion batteries. Despite several technological advantages of LTO batteries over other lithium batteries, the higher cost of LTO has been a primary hurdle in their large-scale deployment. Table 1 gives the comparison between different battery chemistries to understand the drawbacks and benefits of available technologies in the market.

TABLE 1: Comparison of different battery chemistries

Battery technology	Advantage	Drawback	Application
Sodium Sulfur (NaS)	» High energy and power density[5] » High-round-trip efficiency » Fast response » Long life cycle » Fast-discharge capabilities » No self-discharge	» Low-cycle stability[6] » Rapid capacity fading in the initial cycle » Safety concern due to high working temperature	» Power quality » Renewable integration » Congestion relief
Vanadium redox flow batteries	» No energy to power ratio constraint » Extreme design flexibility » High-life cycle which does not depend on DoD[7] » Adjustable power rating » Limited self-discharge » Rapid response time	» Poor energy-to-volume ratio » Heavy weight » Limited for stationary storage application	» Ramping requirement » Peak shaving » Time shifting » Frequency regulation » Power quality
Lead-acid or advanced lead-acid	» High maturity » Low cost » High efficiency » Excellent safety feature[8]	» Low power and energy density » Less reliable » Lower cycle life » Sustained degradation due to sulphationon electrode plates	» Load leveling and regulation » Grid stabilization » Back-up power » Energy time shift

5 Details available at <https://www.energy.gov/sites/prod/files/2014/09/f18/Grid%20Energy%20Storage%20December%202013.pdf>

6 Details available at <https://www.mdpi.com/2079-9292/8/10/1201/htm>

7 Details available at <https://www.researchgate.net/publication/267571532_Vanadium_redox_flow_batteries_A_technology_review>

8 Details available at <https://www.sciencedirect.com/science/article/pii/S2352152X17304437>

TABLE 1: Comparison of different battery chemistries

Battery technology	Advantage	Drawback	Application
Li-ion batteries	» High efficiency » High-energy density » High-cycle life » High-DoD capabilities » Fast-response time » Resilience to irregular discharging	» Relatively expensive » Lack of standard recycling practices » High-safety requirements » Extremely sensitive to over temperature, over charge and internal pressure build-up » Intolerance to deep-discharge » Micro-level monitoring is required for battery cells	» Power quality » Frequency regulation » Peak shaving » Voltage support » Black start » Energy time shift

1.2 Cost Trends of Various Energy Storage Technologies – A Case Study of Grid-scale Energy Storage Cost Assessment by PNNL

The high cost of energy storage technologies, specifically battery storage is seen as the major impediment in the adoption of large-scale storage systems. There has always been ambiguity around the prices of battery storage systems, unlike pumped hydro energy storage systems which is an established technology. This mainly attributed to different costs associated with different applications, mainly due to different power and energy requirements for the particular operational use case, the ticket size of the project, domestic manufacturing efficiencies and competitiveness, the different components, and region-specific ease of availability of integration equipment such as Energy Management System (EMS), Battery Management System(BMS), etc.

The landed cost of installation of large-scale BESS in China could be lower than that in India for the same application. There are multiple applications of BESS, the horizon of applications widens when battery storage systems are coupled with smart inverters, solar PV, wind turbines, etc. Thus, the standardization of the cost of battery storage technologies may not be possible at this stage.

BNEF's 2020 Battery Price Survey, which considers passenger electric vehicles (EVs), e-buses, commercial EVs, and stationary storage, predicts that the average pack prices will be $101/kWh by 2023. It is at around this price point that the automakers should be able to produce and sell mass-market EVs at the same price (and with the same margin) as comparable internal combustion vehicles in some markets. This assumes no subsidies are available, but actual pricing strategies will vary by automaker and geography. However, in general, the ticket size of the project and power and energy requirement can be a reasonable basis to estimate the total cost and the Levelized cost of energy. One such storage cost and performance research that has been carried out by PNNL, funded by the US Department of Energy (DOE), is the HydroWIRES initiative. Figure 4 presents technology-wise energy storage cost estimates with varying ticket sizes of the projects in terms of both power and energy ratings for 2020 and 2030.

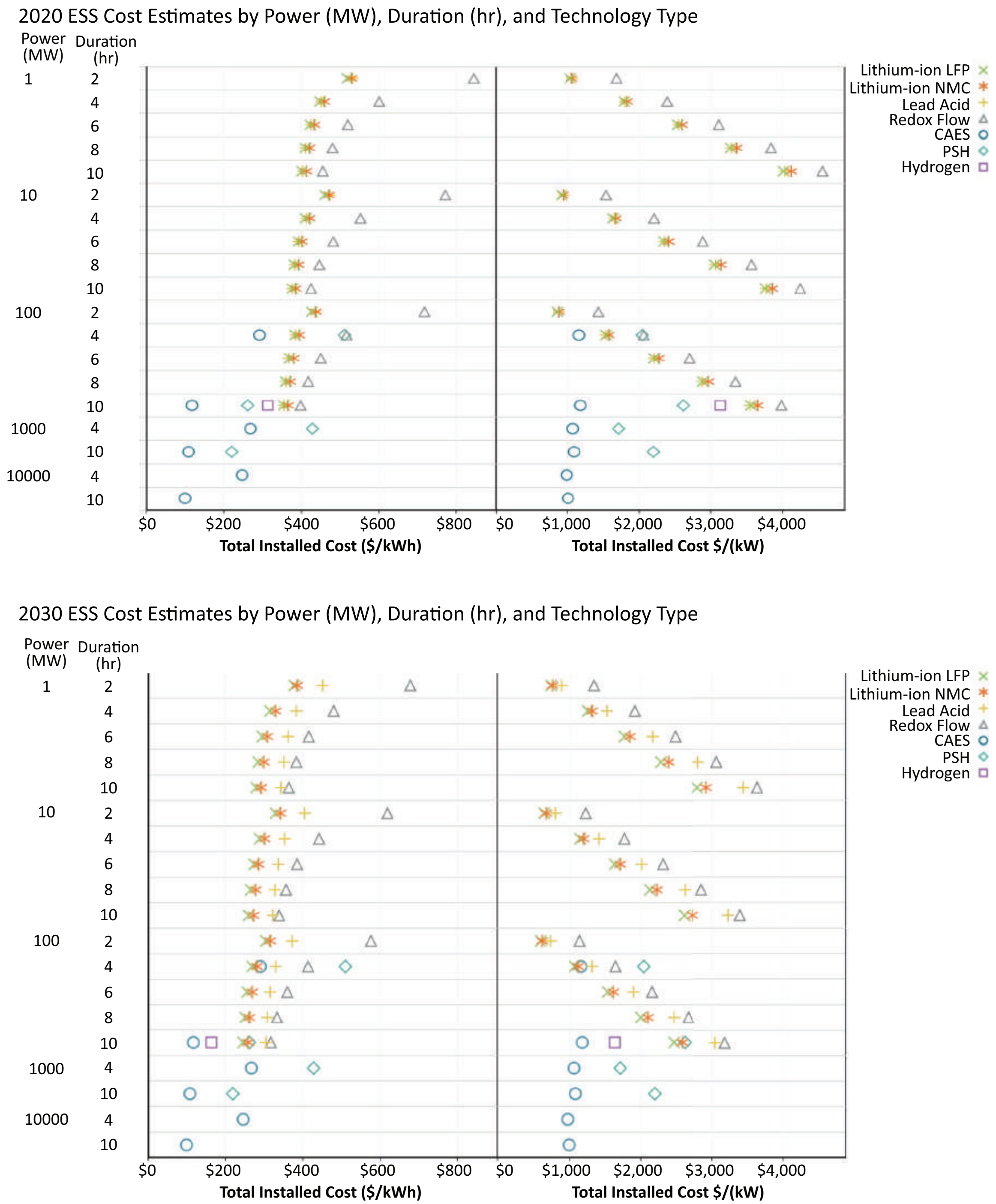


FIGURE 4: Technology-wise energy storage cost estimates

[9] https://www.pnnl.gov/sites/default/files/media/file/Final%20-%20ESGC%20Cost%20Performance%20Report%2012-11-2020.pdf

The work aims to: 1) update cost and performance values and provide current cost ranges; 2) increase the fidelity of the individual cost elements comprising a technology; 3) provide cost ranges and estimates for storage cost projections in 2030, and 4) develop an online website to make energy storage cost and performance data easily accessible and updatable for the stakeholder community.

The detailed tool is available at <https://www.pnnl.gov/ESGC-cost-performance>. The web tool not only helps to understand the cost trajectories of different energy storage technologies based on the ticket size of the project but also helps in visualizing the proportion of component-wise costing of associated equipment, which is equally important. The tool also reckons the LCOE which can be used to assess the economic viability of each technology, based on the size of the project.

Figure 5 presents the battery technology-wise cost ranges for four project sizes:

- 1 MW 2h
- 1 MW 10h
- 100 MW 2h
- 100 MW 2h

Lithium Iron Phosphate is emerging as an economical option with an average LCOE of $244 per MWh in 2030. However, the steepest fall in the prices is seen in the case of NMC almost 30%. PSH, Hydrogen, and CAES technologies stand applicable to large-scale requirements. The PNNL recognizes the fact that, with further developments, the web tool may require updating. Thus, the research effort will periodically update the tracked performance metrics and cost estimates as the storage industry continues its rapid pace of technological advancement.

1.3 Global Scenario on Grid-scale Energy Storage

Energy storage is being globally recognized as one of the prominent technologies in power systems. Though, energy storage deployment in some countries is only entering the pilot phase while in others commercialization is the next step. The country-wise share of energy storage capacity is illustrated in figure 6. Consequently, the top five countries based on the share of installed capacity were selected to make a fair comparison with scenarios in India. The key ESS technologies are pumped hydroelectric storage (PHS), compressed air energy storage (CAES), flywheels, batteries, and capacitors. According to the International Renewable Energy Agency's (IRENA) Renewable Energy Roadmap 2030, 475 gigawatts (GW) of ESS would be required to meet the target of 45% power from renewable energy sources in the energy mix by 2030. Recently, Lithium-ion has gained prominence as the leading battery technology because of its several technological advantages compared to other battery technologies such as high cyclic efficiency, larger energy density, etc. Moreover, EV batteries which are predominantly based on Lithium-ion technology can be utilized for balancing the grid and smoothly integrating renewable energy with the distribution network by enabling vehicle-to-grid (V2G) technology. V2G also opens new opportunities for energy trading between prosumers and consumers, and smart energy management. Other promising battery technologies for the future include sodium-ion (NIB) batteries and redox flow batteries. The most established form of energy storage is pumped storage with over 80% of the total capacity, as indicated below in Figure 6.

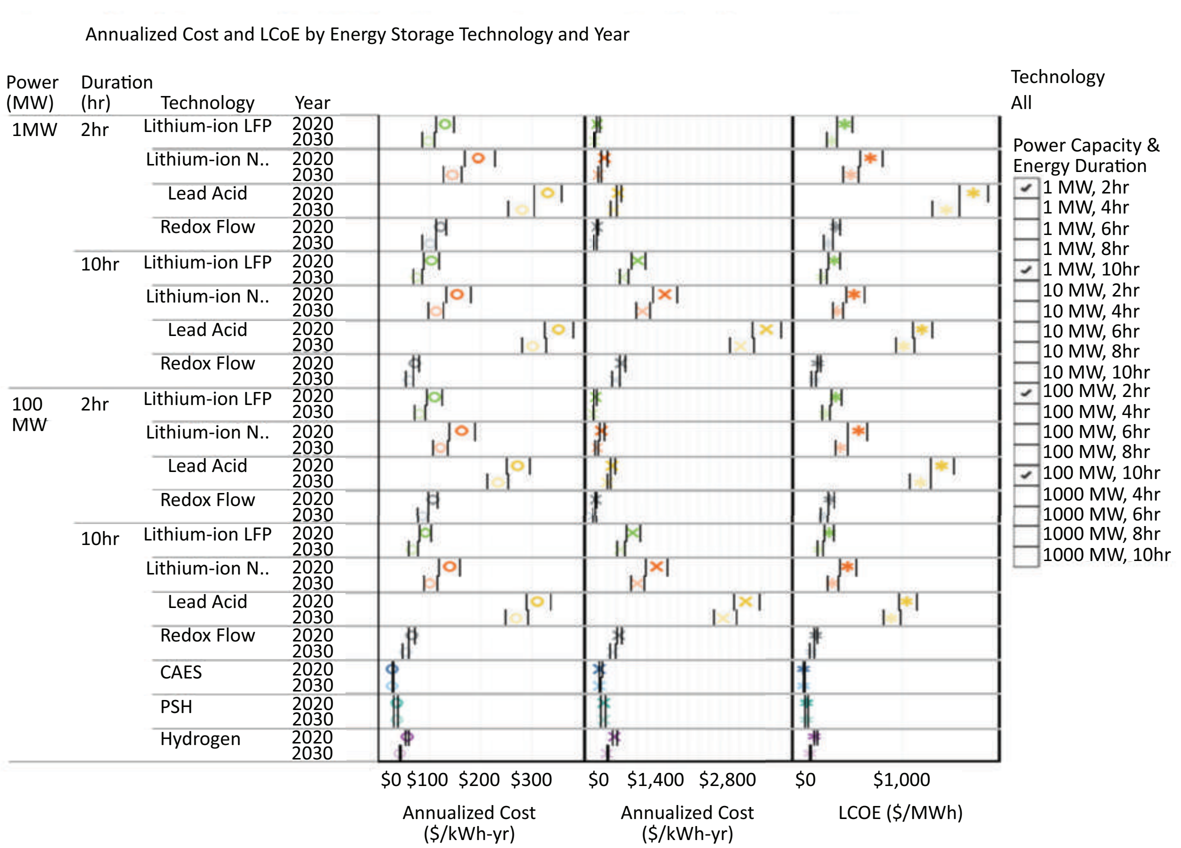
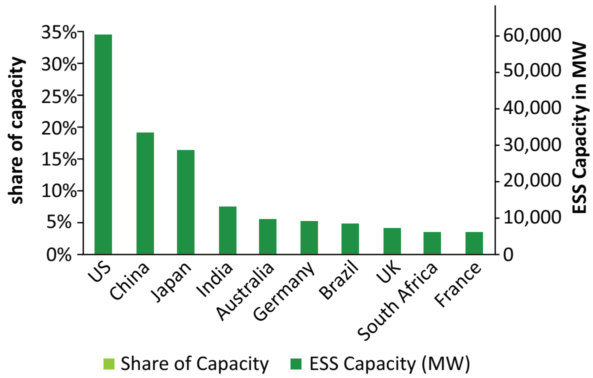


FIGURE 5: Battery technology-wise cost ranges



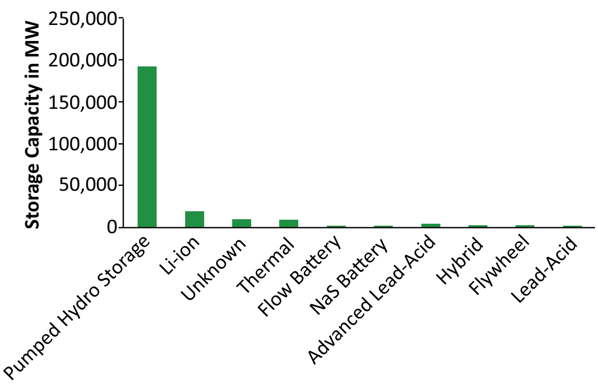


FIGURE 6: Country-wise energy storage technology landscape

Compared to markets for other technologies such as solar and wind, the storage market potential depends majorly on the structure of power markets; price signals, generation mix, electricity demand, interconnection with neighboring countries, T&D grid resiliency, priorities, region-specific pain areas, and country-specific targets. To understand these forces by region, this section qualitatively evaluates the following six different characteristics relevant to energy storage attractiveness:

» National targets and global commitments

» Current generation mix

» Manufacturing conduciveness for six countries: i) Germany, ii) USA, iii) China, iv) Japan, v) Australia, and vi) India, policy support and subsidies

» Power markets structure

» Miscellaneous factors

The manufacturing conduciveness considers ease of doing business; hold on supply chains to make rare earth metals available for manufacturing and miscellaneous factors include country-specific pain areas, ability to bank leveraging interconnections with neighboring countries, R&D, and industry experience. Each characteristic has been discussed in detail in the context of listed countries.

1. **National Targets and global commitments:** The national targets carve the way to a proliferation of new technologies and the landscape of the future, for example, India's aggressive move towards RE and EVs. With the increase in RE penetration, demand and supply variability is bound to increase. Even at the times, the sun is in the sky; RE generation is asymmetric to the actual demand for electricity, creating the need for a balancing source in power systems. Table 2 enlists the country-specific RE targets that are pushing the envelope of energy storage as a balancing source in different regions of the world.

   Table 2 briefly showcases an overview of country-wise targets in terms of RE along with EVs. Further, Britain has been urged to increase its renewable electricity target from 50% to 65% by 2030 after new research was carried out for the National Infrastructure Commission (NIC), which advises the government on national investment priorities. Australia has already met the set targets in September 2019. With increasing RE penetration resource adequacy planning is bound to become a more complex process. Every country has devised its ways to deal with asymmetry between RE generation and demand; the way of dealing with such asymmetry depends on local strengths and weaknesses which are discussed in the next section.

2. **Current generation mix:** The generation mix of each country is one of the significant factors to determine the flexibility needs of the power systems. Figure 7 indicates the current proportion of solar PV and wind installed capacities as a percentage of total installed capacity, as of the year 2018. The intermittency and variability are bound to increase with increasing RE penetration as per the national targets set by the respective governments.

TABLE 2: Country-specific RE targets

China	United States of America	Japan	Germany	United Kingdom	Australia	India
35% RE of total energy by 2030[10]	32% CO_2 reduction by 2030	Energy efficiency	80% GHG reduction by 2050	To bring all GHG emissions to net-zero by 2050[11]	20% RE by 2020[12]	100 GW solar by 2022
Potential of 86% RE of electricity by 2050[13]	30% RE by 2025	Minimize import of fossil fuels	80% RE by 2050	40 GW offshore wind by 2030[14]	Car fleet could be fully electric by 2050[15]	60 GW wind by 2022
25% of overall vehicle sales by 2025[16]	State-wise targets such as100% by 2045 (Hawaii)	Nuclear phase-out	Nuclear phase-out	Allowing sales of only zero-emission vehicles (ZEV) from 2035[17]	33,000 GWh of electricity from renewable sources by 2020	The government's target of 30%, 70%, 40%, and 80%EVsales penetration in private cars segment, commercial cars segment, buses, and 2W & 3W respectively by 2030[18]
–	–	30% renewables by 2030	–	50% RE by 2030	–	Non-fossil fuel target of 450 GW by 2030

10 China's National Development and Reform Commission Policy

11 https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law

12 Australian Energy Market Commission

13 World wild life, China's future generation assessing the maximum potential for RE power sources to China to 2050

14 https://www.gov.uk/government/news/new-plans-to-make-uk-world-leader-in-green-energy

15 CSIRO

16 Chinese Ministry of Industry and Information Technology

17 https://www.gov.uk/government/news/government-takes-historic-step-towards-net-zero-with-end-of-sale-of-new-petrol-and-diesel-cars-by-2030

18 https://pib.gov.in/PressReleseDetail.aspx?PRID=1570107

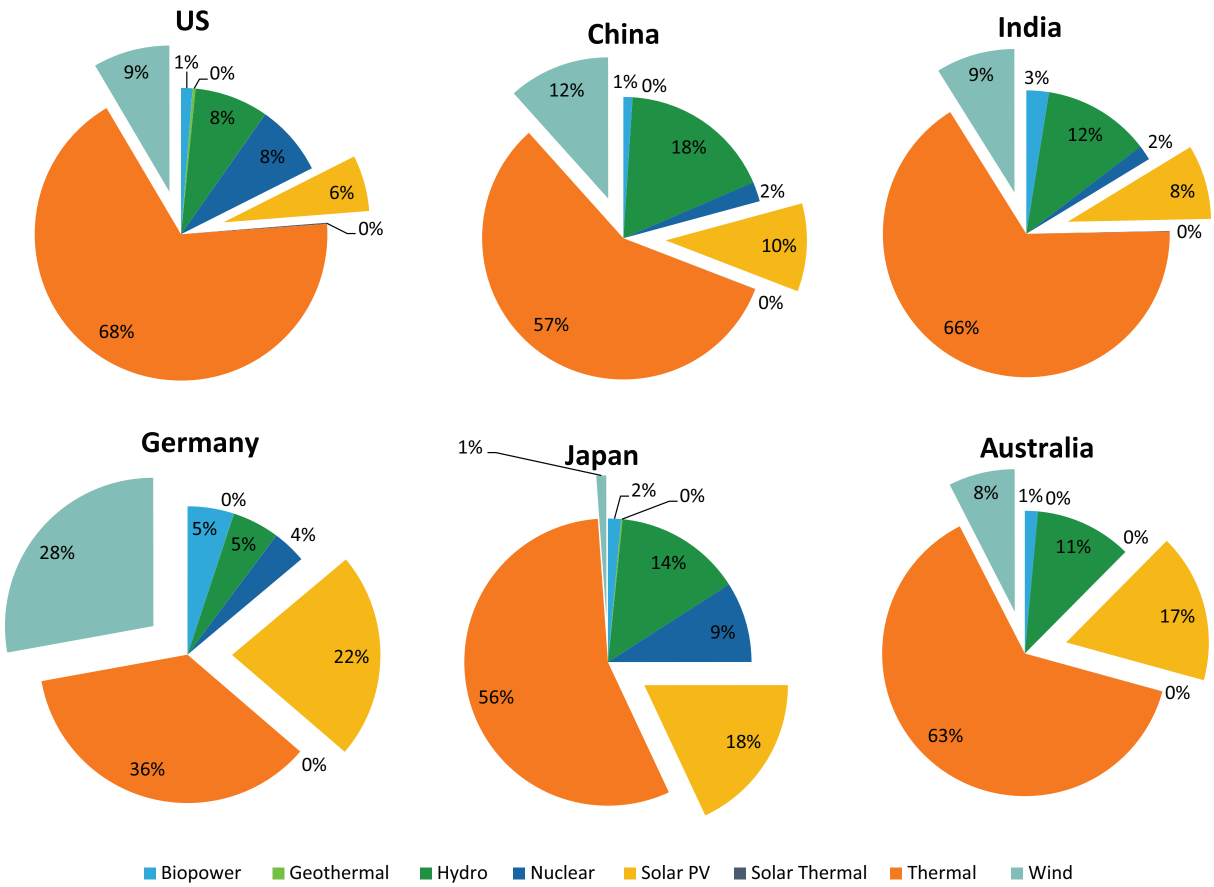


FIGURE 7: Current proportion of solar PV and wind installed capacities

Germany has the highest RE penetration as a result of the support of resolute interconnections with Nordic countries and the comparatively higher paying capacity of the residential consumers. United States of America (USA) is dependent on thermal power for meeting its base load requirements, at the same time, has aggressive state-specific targets.

3. **Manufacturing conduciveness, policy support, and subsidies:** For the 'Economic Battery Case' to happen, battery system costs would need to decline much more quickly than the recent pace of cost reductions. This would be possible if improved battery chemistries enter the market, further lowering the floor costs of batteries. Also, economies of scale in manufacturing and learning-by-doing would be essential to further drive down costs. Providing an initial push to achieve economies of scale with the help of subsidies could also provide front runner advantage. Though, supporting energy storage by coupling with RE or without RE is a question for policymakers since subsidy disbursement only for the projects coupled with RE may hold back on the real possibilities, linking storage subsidies to solar might lead to inefficiencies, with storage being installed in places where it doesn't serve an important role, or being installed simply for the subsidy, hardly the most efficient use of resources.

In India, energy storage technologies do not enjoy direct subsidies and financial incentives but coupling energy storage technologies with solar or wind may offer the projects the same benefits as offered to renewables such as wind and solar. Though, there has been a policy push towards renewables which would ultimately require a greater amount of flexibility to the Indian power grid. The government has set a target of 175 GW RE by 2022, staff paper on energy storage was introduced by Central Electricity Regulatory Commission (CERC), solar wind hybrid policy has been introduced and a couple of pilots have been demonstrated at distribution and transmission level. Solar Energy Corporation of India Limited (SECI) has already floated tenders of RE projects, coupled with storage to supply round the clock and firm power. The major driving factor propelling the growth of the lithium-ion battery manufacturing industry in India is the government's plan to boost electric mobility. The Indian government has envisioned the conversion of two- and three-wheelers into 100% electric by 2030. Consequently, the Department of Heavy Industry, Government of India launched Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles in India (FAME-India) Schemes (both Phase-1 & Phase-2) to provide budgetary support through demand incentives to create demand for EVs in the country, and major thrust is being given to electrification of public transport systems such as buses and 3-wheelers. To scale up the deployment of EVs through appropriate policy measures and an enabling electricity-related regulatory framework, 15 States/ UTs have published their respective EV policies, and 20 States/ UTs so far have issued tariff orders for EV charging, as of September 2020.The key policy initiatives in India that have directly or indirectly impacted the markets of battery storage are listed in Table 3.

TABLE 3: Key policy initiatives in India

Year	Policy
2001	Battery (Management and Handling) Rules; amended in 2010
2009	MNRE subsidy for EVs
2012	National Electric Mobility Mission Plan 2020
2014	National Smart Grid Mission
2014	Committee on Energy Storage and Hybrid Solutions
2014	Report on energy storage for ancillary services published
2015	FAME incentive scheme launched
2015	Smart Cities Mission
2016	Report on large-scale integration of renewable energy and deviation settlement mechanism
2016	Draft National Policy on Renewable Energy based Micro-grids and Mini-grids
2017	Staff paper on Introduction of Electricity Storage in India
2017	Formed the committee to create standards for battery energy storage systems
2018	National Wind-Solar Hybrid Policy
2018	National Energy Storage Mission
2019	Phase-II of the FAME Scheme launched with an outlay of INR 10,000 Crores for three years
2020	MNRE Issued Guidelines for Procurement of Round the Clock Power
2020	Green term ahead market in electricity

At present, the USA is likely to continue its lead the market at the country level. The grid in the USA is aging and it resulted in large-scale power interruptions, forcing the government and utilities to adopt measures to diversify and strengthen the country's power network. The market for storage in the USA is largely influenced by state policies, wholesale market rules, and retail rates. Several states such as California, Hawaii, Ohio, Illinois, and Texas are prominent markets for battery deployment. Other states such as Utah, Oregon, Massachusetts, and New York have introduced mandates and targets related to energy storage, which is expected to aid growth in the market. Despite strong projections, the USA market faces several challenges. The deployment of batteries is highly concentrated in a few states and 24 states have mandates for storage. California State is moving ahead of all other states in the USA through massive deployments. The State is the home of the largest lithium-ion batteries, in Tehachapi CA (8MW/32MWh battery). Recently, the government extended the subsidy program for energy storage and is also planning to introduce a new mandate, increasing the storage capacity deployed in the State. The Tesla and Panasonic giga-factory in the USA has been drawing global attention for its massive scale, as the plan is to manufacture 35 GWh of cells and 50 GWh of battery packs annually by 2020. There is a growing requirement for longer-duration storage systems, which provide capacity and load shifting in front of the meter. The residential and commercial sectors are also increasing their utilization of storage, particularly in states with high retail tariffs and poor grid infrastructure. California and Hawaii are two states with the largest market for residential battery storage. New York, New Jersey, Arizona, Nevada, Colorado, and Texas, among other states, have targeted new capacity construction for storage to meet their renewable energy target commitments.

The USA pioneered the extensive utilization of battery technologies on a large scale. As of 2018, 24 states and the District of Columbia introduced policies related to energy storage related to utility-scale including transmission, distribution, and utility-scale generation. Table 4 outlines relevant policies within the USA market.

TABLE 4: Policies within the USA market

Policy	Policy source	Effective date
Texas Senate Bill 943	Texas Legislature	Sep 2011
Self-Generation Incentive Program	California Public Utilities Commission	Jan 2010
California Assembly Bill 1150	California Legislature	Jan 2012
California Assembly Bill 2514	California Legislature	Jan 2011
Federal Energy Regulatory Commission Order 719	Federal Energy Regulatory Commission (FERC)	Dec 2008
Frequency Regulation Compensation in the Organized Wholesale Power Markets	Federal Energy Regulatory Commission (FERC)	Dec 2011
Storage Act of 2011	US Congress	
Project Number 39657	Federal Energy Regulatory Commission (FERC)	Dec 2011

TABLE 4: Policies within the USA market

Policy	Policy source	Effective date
Project Number 39917	Public Utility Commission of Texas	
Project Number 39917	Public Utility Commission of Texas	
Project Number 39764	Public Utility Commission of Texas	
Project Number 40150	Public Utility Commission of Texas	
Long-Term Procurement Planning: Rulemaking 12-03-014	California Public Utilities Commission	
Energy Storage Technology Advancement Partnership	Department of Energy	
Smart Grid Investment Grant Program	Department of Energy	Feb 2010
Smart Grid Demonstration Program	Department of Energy	
Storage OIR Proceeding	California Public Utilities Commission	
MLP Parity Act	US Senate	
Con Edison Load Reduction Incentives	Con Edison/ NYSERDA	May 2014
Modernization of the Hawaii Electric System	Hawaii Legislature	Jun 2014
HB 2193 - Relating to Energy Storage	Oregon Public Utility Commission	Jun 2015
Massachusetts House Bill 4568	House of Representatives - Commonwealth of Massachusetts	Aug 2016
Electric Program Investment Charge	California Public Utilities Commission	
Frequency Regulation Compensation in the Wholesale Energy Markets	Federal Energy Regulatory Commission (FERC)	

Source: DoE

According to the United States Geological Survey (USGS), 2018 the USA imported 78% of its cobalt and 100% of its graphite. For the foreseeable future, the country is likely to depend on Chinese supply chains to produce the batteries that help power America's economy.

China is increasing its portfolio of renewables, reducing coal consumption, and improving efficiency to curb emissions. According to data released from Benchmark Mineral Intelligence, a London-based research firm for the lithium-ion battery industry, in 2019, Chinese chemical companies accounted for 80% of the world's total output of raw materials for advanced batteries. The firm claimed, "Of the 136 lithium-ion battery plants in the pipeline to 2029, 101 are based in China". China controls the processing of pretty much all the critical minerals, whether it is rare earth, lithium, cobalt, or graphite. For three consecutive years ending in 2019, South Korea's market tracker SNE Research has ranked China's Contemporary Amperex Technology Company Limited (CATL), as number one in the EV battery production, with a 27.9% market share. This has been a result of China's early planning and policy push. China has focused on building capacity at every stage of the battery supply chain.

At the end of 2017, China released a national energy storage policy document, providing a framework for policies and an outline for the development tasks related to energy storage. Regional provinces issued their storage policies, which are expected to drive the battery storage market in China. The government also initiated several measures that promoted strong battery manufacturing intending to dominate the global battery market. The aim is to push for large-scale energy storage capacity, to solve the problem of stranded power in the west of the country. Storage technology such as batteries can help store renewable power when demand is low and provide additional capacity when demand increases. Sufficient storage would prevent power generation from being curtailed, in case of excess generation. The government launched pilot projects to test advances in energy storage technology, such as pumped hydro storage, compressed air energy storage, superconducting magnetic energy storage, and bulk storage with batteries using substances like lead-acid and lithium-ion. The programs are expected to be completed by the end of 2020, to put the projects into large-scale production five years later.

In the first half of 2018 alone, China had energy storage of 340.5 MW capacity under various stages of development. Four provinces, namely, Jiangsu, Henan, Qinghai, and Guangdong led the battery storage market in 2018. Currently, five companies in China are constructing Gigafactories to become global leaders in battery production. Encouraging government policies, a large manufacturing base, protectionist measures, and demand for batteries bode well for the Chinese battery market. Tianqi Lithium, a Chinese company, bought stakes in prominent mining companies in Chile and Australia, giving it substantial control over the global production of lithium. The country is making moves to dominate and consolidate its position as a global powerhouse in lithium battery manufacturing, which augurs well for the domestic stationary storage options.

According to the 13th financial year plan, energy storage has been designated to help strengthen the peaking capacity of the power grid, implement projects to improve demand response capacity, implement electrification projects, and implement technology innovation demonstration projects. The Energy Technology Revolution Innovation Action Plan (2016–2030) analyzed the state of energy storage development and applications in China and abroad, included advanced energy storage technologies amongst 15 major initiatives in the innovation action plan, and laid out an innovation action roadmap for energy storage technologies. The Made in China 2025 – Energy Equipment Implementation Plan included energy storage as one of its 15 categories of energy equipment and highlighted the need for continued development in PHS, CAES, flywheels, superconducting energy storage, supercapacitors, flow batteries, NaS batteries, and lithium-ion batteries. Table 5 illustrates the key initiatives that have been taken by relevant nodal agencies in China.

TABLE 5: Key Policy and Initiatives in China

Years	Policy	Organization
2005-09	"Renewable Energy Law of China and its amendment"	NPC of China
2005	Catalog for the guidance of the renewable energy industry development	NRDC of China
2006	"The national medium and long term Development plan for science and technology 2006–2020"	State Council of China
2010	12th Five-year Plan for intelligent network	State Grid Corporation of China
2010	Certain opinions of South Power Grid Corp. supporting new energy development"	China Southern Power Grid
2011	National standards of grid-connected wind power	NRDC of China
2011	Guiding catalog of Industrial Structure Adjustment	NRDC of China
2011	Decentralized energy power generating management method(draft)	National Energy Administration of China
2011	National "12th five-year plan for science and technology development"	Ministry of Science and Technology of China
2011	12thFive-YearPlanforNationalEnergyTechnology (2011–2015)	National Energy Administration of China
2012	12th five-year development plan for the New materials industry	Ministry of Industry and Information Technology of China
2012	Development plan for Energy-saving and new energy automotive industry (2012–2020)	Government of China
2017	China National Development and Reform Commission Policy19	NRDC of China
2020–24	Action Plan for the Development of Energy Storage Technology20	National Development and Reform Commission (NDRC)

[19] http://en.cnesa.org/latest-news/2020/5/28/development-outlook-for-energy-storage-in-chinas-fourteenth-five-year-plan-period

[20] http://en.cnesa.org/latest-news/2019/7/31/china-releases-2019-2020-action-plan-for-the-guiding-opinions-on-promoting-energy-storage-technology-and-industry-development

Japan faces challenges with self-sufficiency and is prone to severe natural disasters, which have reoriented the energy policy of the country. The government also established storage-manufacturing targets to help sustain its strong domestic industry and support it seco-towns and smart cities initiatives. Japan established several policies and initiatives that facilitate the utilization of battery energy storage, as illustrated in table 6. The country is a strong advocate of energy efficiency and conservation, which have been the critical aspects of its energy strategy. Gains in energy efficiency would help the government reduce its reliance on fuel imports. Japan has significant policy support for energy storage, resulting in a large base of commissioned energy storage projects in the country. The allocation of $779millionsubsidiesto help factories and small businesses would improve energy efficiency and encourage ESS deployment. The Ministry of Economy, Trade, and Industry (METI) announced a lithium-ion battery subsidy program worth $100 million, which was well-received by the public.

In 1974, following the oil crisis, the government launched the Sunshine Project, which focused on renewable energies, coal gasification, and liquefaction. Later in 1978, the government-sponsored research and development with a focus on heat pumps, energy storage, and gas turbine technologies. In the following years, the government established the Moonlight Project and New Sunshine Project, which promoted the development of different battery technologies such as sodium-sulfur, lead-acid, flow, and zinc bromide battery technologies. In 2012, METI

TABLE 6: Key Policy and Initiatives in Japan

Governing organization	Regulations and initiatives
METI	Technical Requirements Guidelines for Grid Interconnection to Secure Electricity Quality (2004, revised in 2013)
Japan Electric Association	Grid Interconnection Code (JEAC 9701-2006)(superseded by JEAC 9701-2012)
METI	Electricity Business Act: Required approval for large electricity storage system more than 80,000kWh
Fire and Disaster Management Agency, Ministry of Internal Affairs and Communications	Fire Service Act and Fire Prevention Ordinance
Ministry of Land, Infrastructure, Transport, and Tourism	Building Standards Act:
METI	Government support of energy storage projects to demonstrate the ability to time-shift demand by 10% in conjunction with expanded use of renewable generation resources. METI funding up to 75% of storage system cost to drive down the total cost METI has set aside JPY81 billion to resolve grid-related issues and to increase renewable energy. Additionally, the Ministry provides incentives for energy storage systems, which can be implemented onto solar power stations or substations.

established a Storage Battery Strategy Project Team to formulate and implement strategic policies for storage batteries, create battery markets, enhance industrial competitiveness, and aim at the international standardization of relevant technologies. In the fourth and fifth Basic Energy Plan, provisions were made for the increased adoption of renewables and energy storage. Subsidies such as the stationary lithium-ion battery program, renewable energy in local area plan, and the storage battery for renewable energy generation program offered subsidies to projects with energy storage technologies. Other programs such as the smart community program and local production and subsidies for the construction of zero-energy houses; and deployment of emergency response in areas with significant solar and wind power generation also contributed to the adoption of battery technologies.

Australia: Australia is one of the most exciting markets for battery energy storage in Asia-Pacific. The growth of renewable energy and distributed energy resources changed the operational and market dynamics of the electricity system in the country. State governments proposed investments in battery storage, which will enable the market to grow. The national large-scale renewable energy target is split into two schemes: The Small-scale Renewable Energy Scheme (SRES) and the Large-scale Renewable Energy Target (LRET). The LRET for large-scale generation of 33,000 GWh in 2020 indicates that almost 23.5% of electricity generation in Australia in 2020 will likely be from renewable sources. SRES incentivizes behind-the-meter installations of distributed generation technologies, which is expected to be the largest market for battery storage in the future. The key policy and initiatives that have taken place so far in Australia are tabulated in Table 7.

TABLE 7: Key Policy and Initiatives in Australia

State	Policy	Renewable energy target
ACT (Australia Capital Territory)	AUD 25 million Next Generation Battery Storage scheme aims at providing subsidized battery storage for 5,000 Canberra homes and businesses by 2020.	100% by 2020
New South Wales	No current policy. The closure of a generous feed-in tariff for solar PV is likely to stimulate investment in household batteries.	National renewable energy target
Northern Territory	No current policy. Home Improvement Scheme previously offered up to $4,000 vouchers for purchases including solar and batteries. Participants were required to make at least 50%of funds.	50% by 2030
Queensland	No interest loans and rebates to be provided in 2018 to drive uptake of batteries. 100 MW reverse auction for energy storage, which forms part of 400 MW renewables auction. $50 incentive for owners who register their storage system with a new State database.	50% by 2030

TABLE 7: Key Policy and Initiatives in Australia

State	Policy	Renewable energy target
South Australia	100 MW/129 MWh lithium-ion battery operational. Proposed a $100 million grant program to facilitate batteries in 40,000 homes. Solar Thermal plant in Port Augusta to supply state government electricity. $150 million Renewable Technology Fund to support a range of dispatchable renewable energy projects is fully allocated.	National renewable energy target
Tasmania	The battery of the nation pumped hydro feasibility study. Proposed $200,000 micro-grid pilot.	100% by 2022
Victoria	Building two large-scale battery storage plants: Tesla 25 MW/50 MWh battery integrated with Edify Energy's Gannawarra Solar Farm; and Fluence 30 MW/30 MWh system at Ballarat. Supported by a $25 million grant from ARENA and a $25 million grant from the Victorian Government.	25% by 2020 40% by 2025
Western Australia	No specific policy	National renewable energy target

4. **Power Markets:** Market-based reforms have been promoted since the 1990s to improve the performance of the power sector. After the early experience in the UK, the World Bank became a prominent advocate of a set of standard reform prescriptions that involved four distinct measures: the creation of independent regulatory bodies which would hold utilities accountable for financial and operational performance; unbundling of vertically integrated state-owned entities into distinct generation, transmission, and distribution entities; increasing private sector participation and investment; and enhancing competition. The idea behind reforms was that by making electricity a commodity, market forces and competition would lead to efficiency and productivity gains. This would allow consumers to access electricity at, or near, cost-reflective prices, reduce transmission and distribution losses, improve billing and collection efficiencies, and increase the adoption of efficiency measures.[21]

   Operating a power system requires making decisions on time scales covering fifteen orders of magnitude before real-time dispatch, as shown below in figure 8.

[21] Retail competition in power distribution, TERI

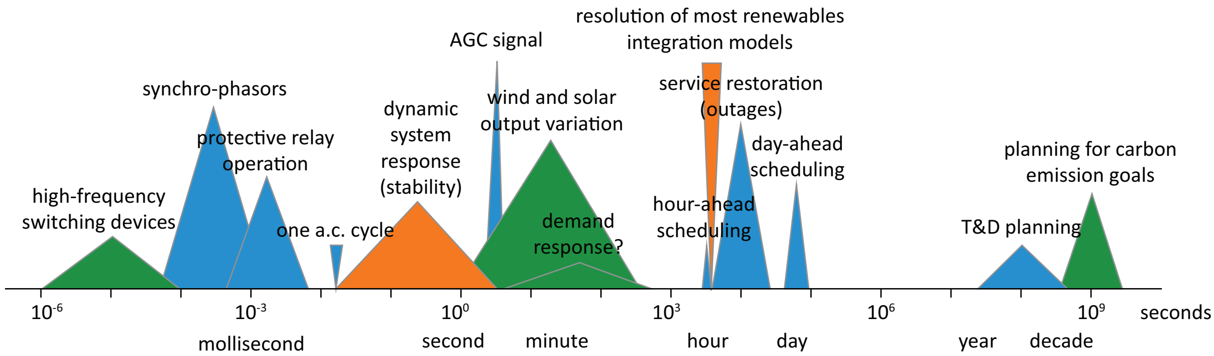


FIGURE 8: Fifteen orders of magnitude before real-time dispatch[22]

So, there could be three types of market contracts possible ancillary, energy, and the capacity market as shown below in figure 9.

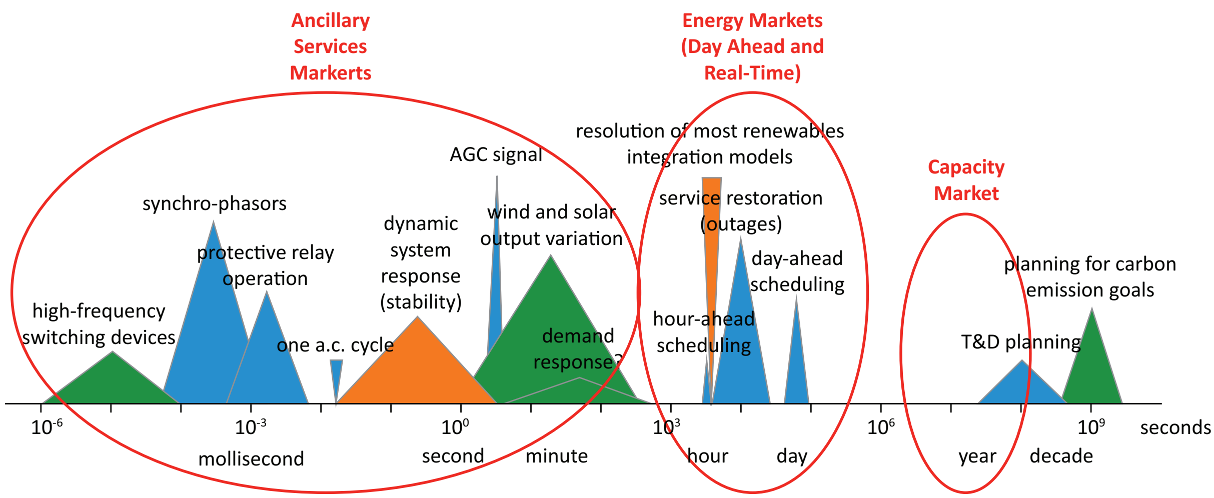


FIGURE 9: Classification of market contracts

Most of the countries such as the US, some parts of Europe, Canada, etc., have developed ancillary services markets and recognize battery storage as an asset to participate in the power markets improving the economic prospects of battery storage projects. Some ISO's in the US such as CAISO offer an opportunity to participate in both charging and discharging modes where market participation signals are bidirectional. The same is not the case for markets like China, India, and Japan. However, Japan is gradually moving towards deregulated structure opening more opportunities for participation for energy storage in power markets.

22 https://www.researchgate.net/figure/Time-scales-in-electric-grid-operation_fig1_228854029

5. **Miscellaneous factors:** Every country has its landscape, availability of conventional sources of energy, geospatial advantages such as higher solar irradiance, interconnections with neighboring countries, distance between regions of consumption and generation. Such factors also decide the quantum of balancing fleets required in the power system.

For example, Germany can import power that can also be used to bridge a gap between supply and demand in a renewable power system. Germany can import electricity from neighbors with large hydropower storage capacities. The grid interconnections of Germany with Nordic countries allow better management of power by providing banking opportunities. Figure 10 depicts the country-wise miscellaneous factors that can escalate the storage deployment in the power system.

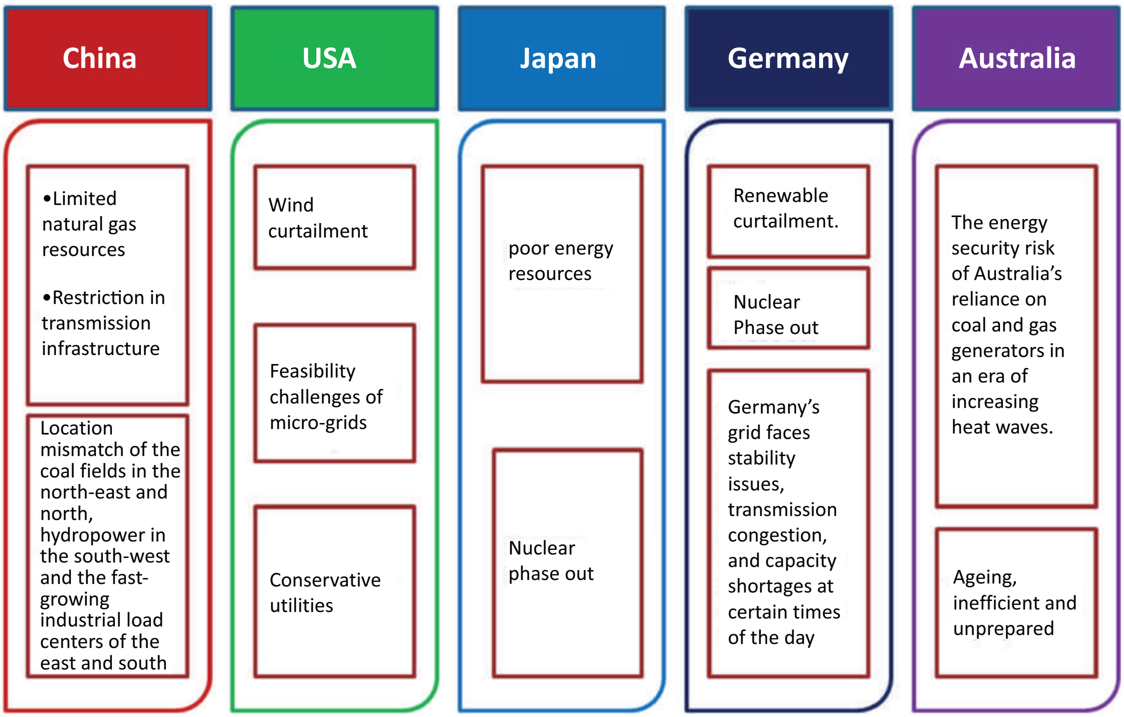


FIGURE 10: Country-wise miscellaneous factors

The power grid in China is one of the largest networks in the world, in terms of installed generation capacity, transmission length span, and total electricity produced. With the government advocating renewable power generation, projects of large scale were constructed in China. However, the aggressive deployment of renewable capacities resulted in curtailment and wasted power, due to a lack of sufficient transmission capacity to carry power to the demand centers in the east. For instance, in Italy, sodium-sulfur (NaS) batteries have been deployed to resolve bottlenecks in the grid caused by an oversupply of solar PV in the south that needs to be transported to the north. The batteries provide ancillary services. The national grid operator, Terna, received permission to own and operate the batteries, as energy storage is generally considered to be generation capacity that transmission system operators (TSOs) are not allowed to own under unbundling.

On the other hand, Japan an island nation is investing heavily in the R&D of NAS batteries to avoid future dependency on metals to manufacture lithium-ion batteries.

India is on the cusp of making important investment decisions over the next two decades. According to the 19th Electric Power Survey, the Central Electricity Authority (CEA) estimates that the peak electricity demand in India will grow at the rate of 6.32% per year and will touch 300 GW by 2026–27 as compared to 162 GW in 2016–17. According to India's National Electricity Plan, 123 GW of additional capacity will be required to meet the peak demand, because the contributions of renewable sources in meeting the peak demand are assumed to be minimal. The main reason behind this is that India's peak demand occurs during the evening, and even though wind energy is available during the evening, it is highly seasonal. As PHS is also limited by multiple factors such as seasonality, location and rehabilitation constraints, high upfront investments, long-gestation periods, etc., India looks forward to BESS as one of the flexibility sources and an integral part of the power system planning exercise.

2. Case Studies on Energy Storage Systems **Covering Electricity Distribution Sector**

2.1 BESS Pilot Projects in India

A battery energy storage system (BESS) has multiple dimensions to consider, at the same time, being beneficial to multiple stakeholders (Figure 11). To assess the true value of BESS in the Indian context, multiple pilot projects, demonstrating a combination of different technologies and different applications are required. A BESS, at the distribution level, could provide cumulatively more benefits to the power system as a whole than explicit benefits visible from DISCOM's perspective. There have been pilot projects in India to demonstrate different BESS technologies, different operational use cases at a different level of the grid, and identify cost recovery mechanisms.

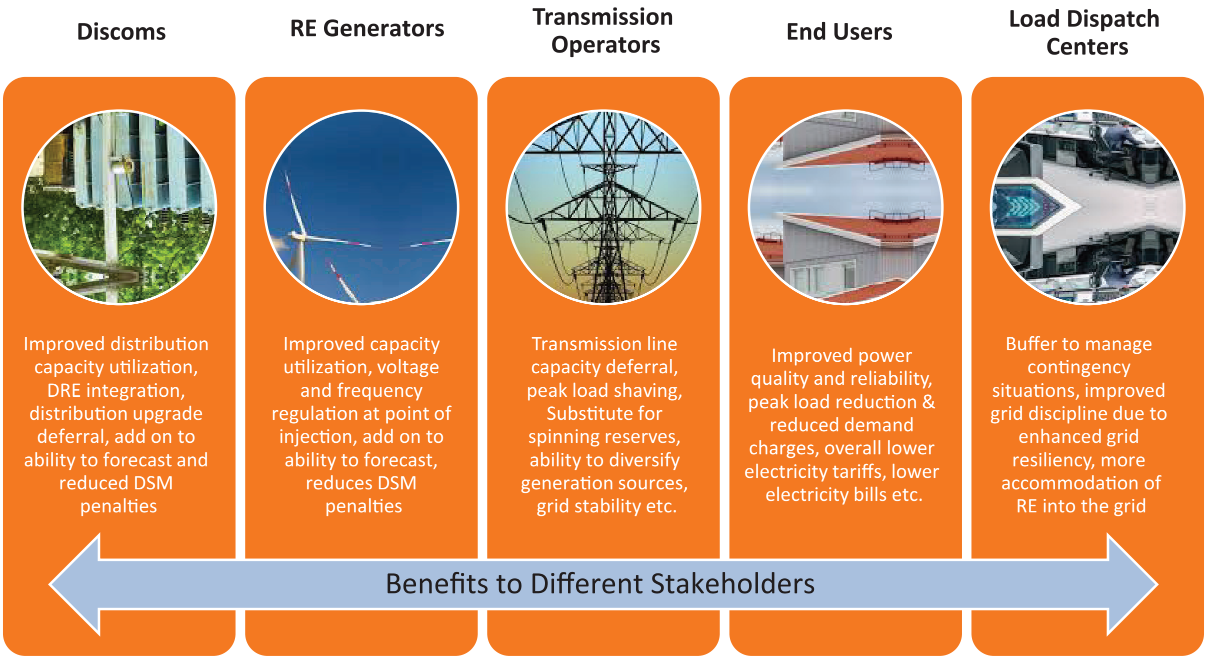


FIGURE 11: Benefits of BESS to stakeholders

2.1.1 10 MW/10 MWh Grid-connected Battery Energy Storage System in Rohini, Delhi

AES India, a subsidiary of AES Corporation and Mitsubishi Corporation, has commissioned a utility-scale battery storage system, a-10 MW solution for 1 hour that is serving the electric grid operated by Tata Power Delhi Distribution Limited (Tata Power-DDL). Fluence, a market leader of energy storage technology suppliers, jointly owned by AES Corporation and Siemens has designed control of the system on its state-of-the-art Advancion energy storage platform. The Advanced Control System provides flexibility into the control of the BESS to serve multiple applications by integration with an energy management system (EMS). The project was completed in 2 years, and the system has been successfully operating since April 2019. The project includes a lithium-ion battery, and to demonstrate this advanced technology, the specific battery technology which has been deployed is Lithium Nickel Manganese Cobalt oxide or commonly termed as NMC battery technology. LG Chemical is the manufacturer of battery packs/modules. The project is situated at Rohini, New Delhi, a 66-/11-kV substation operated by Tata Power-DDL (site images are shown in Figure 12). The 10-MW size of the project is divided into four BESS transformers (each with a rating of 2.5 MVA). Each of these transformers is connected to the two cores of BESS, thus making 8 cores in total. Each core is divided into 31 racks for battery nodes. The capacity of one battery module is 6.5 kWh with a voltage rating of 51.7 V. There are 14 modules connected in one node, in series, thus making each node with a rating of 85 kWh. For maintaining the temperature of batteries, there are individual battery fans for each module and it starts operating when the temperature reaches above 40°C. Each battery module also has individual BMS which communicates the battery status with each other and also with central BMS. As per the balance of the plant, the C-rate for the battery is fixed at 1 C. The BMS of the battery module helps in maintaining the state of charge (SOC) in the range of 45–55%, against the prescribed levels of SOC from the manufacturer which states that SOC of the battery can vary between 10% and 99%. The auxiliary energy consumption for the whole system ranges in 1–2% of the battery capacity.

FIGURE 12: Grid-connected BESS in Rohini, Delhi

The inverters are connected at 415 V (L-L) to switchgear with individual switch-breaker and this voltage level is being stepped up to 11 kV by an isolation transformer (which is used to physically isolate the BESS from the grid to ensure safety to the system), injecting the power at the secondary end of substation transformer. The charging of the system takes place from the grid supply by reversing the direction of power flow through the BESS transformer (that is, HT to the LT side). The different levels of the interconnection of BESS with the grid along with the control hierarchy are shown in Figure 13.

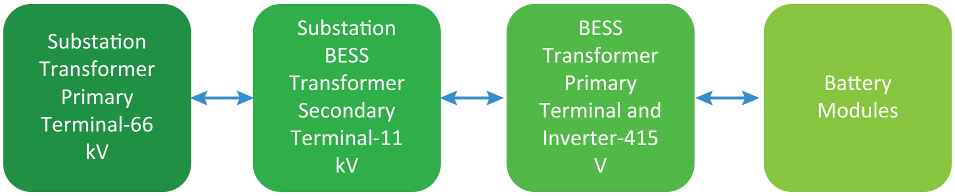


FIGURE 13: Interconnection of BESS with the grid

Application of Project

Being a pilot project, the system is being tested to observe which application it can best cater to. The system can be utilized for frequency regulation, energy arbitrage, deviation settlement mechanism (DSM), peak shaving, reactive power control, and many more. It is beneficial to utilize the BESS system for multiple applications, rather than restricting it to just one application. However, the current system is primarily being utilized for DSM application since utility has paid the heavy penalty as DSM charges in recent years (approx. INR 6.3 crore in FY 2018/19 and INR 6.69 crore in FY 2019/20). Besides this, as a secondary application, the system will cater to peak shaving, frequency regulation, and reactive power control for a few months in a year since these applications may not persist for the whole year. As an example, peak demand occurs only in summer, thus BESS will be used to manage the overload during this period while reactive power control applications can be tested in winter. In this view, the user, herein TATA Power-DDL has made certain plans for testing the system for various applications under the demonstration phase of the project (which is 2 years from commissioning time), and consequently, the benefits earned from corresponding use-cases have been elaborated in the subsequent section. The applications which will be tested under the demonstration phase are depicted in Figure 14.

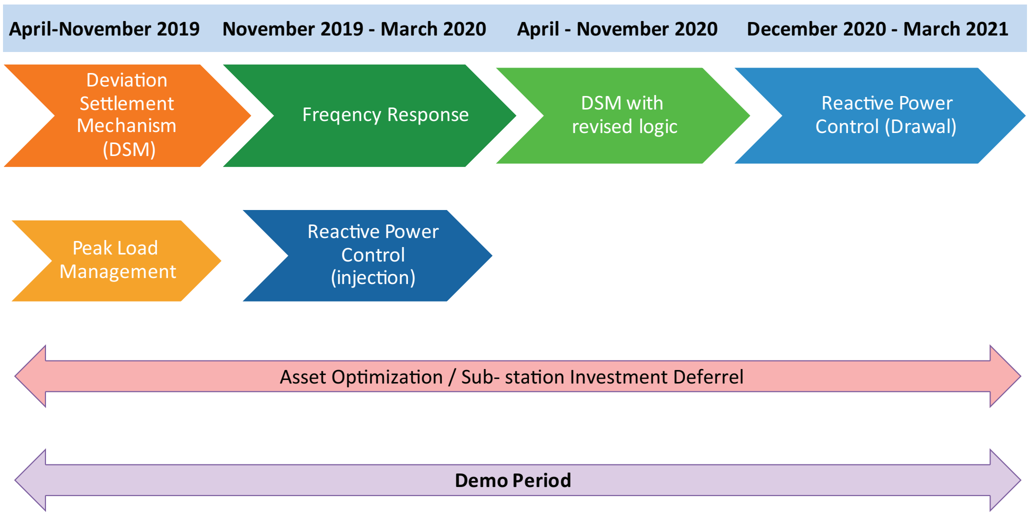


FIGURE 14: Various applications of BESS to be tested under demonstration phase

Results obtained from BESS operations under frequency response mode are shown in Figure15. The system is operated in automatic control mode, and the control action for charge/discharge operation is performed based on real-time monitoring of supply frequency. BESS injects power to the grid when the supply frequency is below 49.85 Hz while the charging is performed in case the frequency value is observed to be more than 50.05 Hz. The frequency gain for the operation of the system has been considered as 2 MW/0.01 Hz. Moreover, as a DSM management, the system had been operated for almost 1.2 cycles/per day from May 2020 to August 2020.

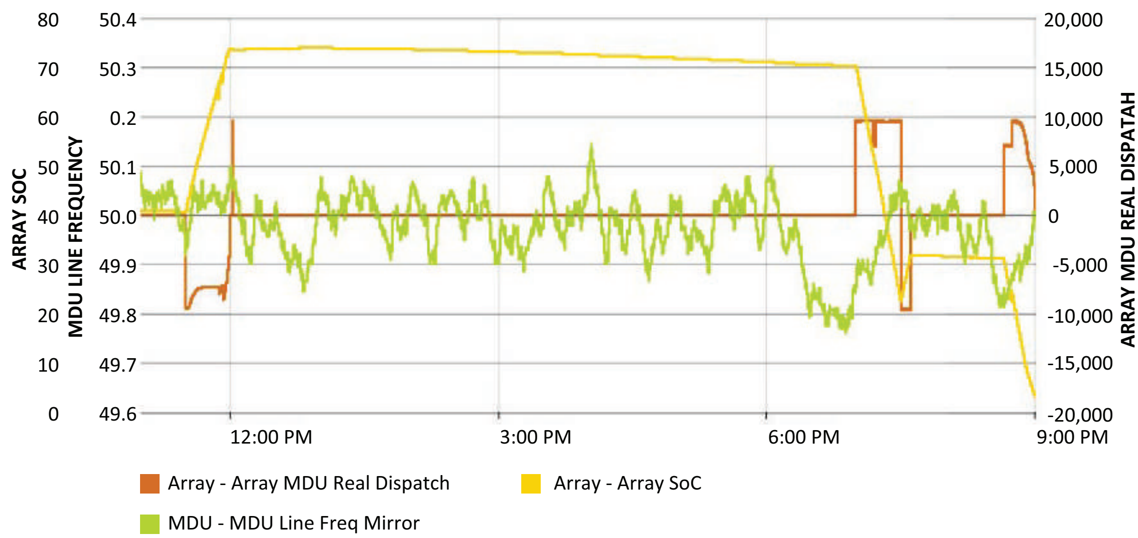


FIGURE 15: Response of BESS under frequency control mode of operation

Generally, based on application, a project's life is assessed. It is estimated that if the system is operated in frequency regulation mode only, then the project life would be more than 15 years, with one cycle taking place over three days. Roughly, it is being assumed that the project life would not be less than 15 years.

Financial Aspects

The project has been set up for 6.5 million USD (without taxes) in 2018. Batteries constitute only 30% of the overall project cost; it is the rest of the things involved which consume most of the capital share, such as power-conditioning units, EMS, isolation transformers, the foundation for the project, construction, and many more. It has been observed that other major costs include inverters, which constitute 10–15% of the project cost, and communication and electronic devices, which assume one of the biggest shares of the capital cost.

For the project, there are no commercial benefits from the BESS for a specified duration as per the agreement between TPDDL and AES. The financial benefits of utilizing the system would depend on the application it is being used for. There is work that needs to be done in analyzing the same, as Table 8 envisaged the revenue streams under different applications for which the system will be used.

TABLE 8: Revenue streams under different applications

Application	Revenue streams envisaged
Frequency response	Need of developed ancillary markets
Reducing deviation settlement charges	Savings in terms of deviation settlement charges
Reliability improvement	Yet to be quantified
Peak shaving	Savings in peak power purchase

Key Findings

It was observed by the utility that the penalty due to DSM charges has significantly increased, particularly in FY 2019 and FY 2020 after the fourth amendment in DSM regulation which came into effect in January 2019. The operation of BESS for DSM application has saved a considerable amount (approx. INR 22 lakh) during FY 2020/21 (till august 2020). In addition to this, the reactive power control mode of operation has resulted in voltage improvement by 2.51% by operating the system for 13 instances, though the reactive power draw mode has not been tested yet and the same will be tested during winter.

2.1.2 Battery Energy Storage System Pilot Project in Puducherry

Power Grid Corporation of India Limited (PGCIL) has already deployed two different battery technologies, namely advanced lead-acid and lithium-ion chemistry demonstration projects in its grid sub-station in Puducherry. In addition to this, PGCIL is proactively moving towards the installation of flow batteries in their facility, and consequently, the tender has been awarded for the same. The project which constitutes three distinct chemistries was differentiated into three work packages, listed in Table 9. The technical specifications of three different chemistries of BESS are provided in Table 10.

TABLE 9: Three different packages in Puducherry Pilot

Package	Technology	Capacity
Package I	Advanced lead–acid	500 kW-30 Min (250 kWh)
Package II	Lithium–ion	500 kW-30 Min (250 kWh)
Package III	Flow	250 kW-4 hours (1000 kWh)

TABLE 10: Technical characteristics of three different battery technologies

Parameters	Lithium–ion battery	Advanced lead–acid battery	Flow battery
Charging rate	3 hours from rated DoD to full capacity	3 hours from rated DoD to full capacity	5 hours from rated DoD to full capacity
DC-DC round-trip efficiency	>90%	>80%	>75%
Service life	10 years	10 years	10 years
Life cycle	4000 cycles (900 MWh)	3000 cycles (675 MWh)	3000 cycles (2,700 MWh)

System Configuration

Advance lead-acid battery is composed of lead and carbon in the anode material and lead oxide as cathode material. The architecture constitutes of two strings that are connected in parallel, and each string comprises 300 cells connected in a series configuration. While in the case of the lithium-ion battery, the anode is the composition of carbon and electrolytes and the cathode is made up of lithium iron phosphate. The two cells (which are rated with 3.2 V, 80 Ah) are initially connected in parallel, followed by a series connection of six such units which constitute one module having a rating of 19.2 V, 150 Ah. Afterward, 36 such modules are connected in series to make one string, and finally, four such strings are connected in parallel which brings the node voltage up to 691.2 V with a capacity of 600 Ah. The systems are interfaced with the grid through interconnection at LT terminal of 22/0.433 kV, 2 MVA transformer, as shown in Figure 16.

Battery packs are generally designed at more than the required usable energy from the system since various factors are taken into consideration while sizing the pack, like depth of discharge, DC-DC round-trip efficiency, PCS efficiency, and auxiliary consumption. All of these factors contribute to some amount of losses in the energy delivery at inverter AC terminals. As a key finding of the project, the technical specifications alongside the cost of two technologies are compared in Table 11.

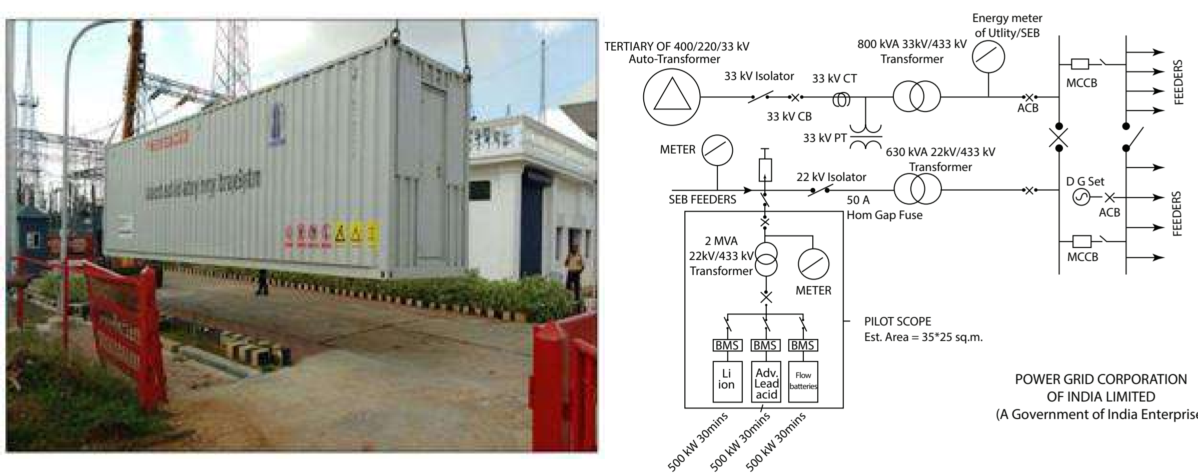


FIGURE 16: SLD and site configuration of the pilot at Puducherry

TABLE 11: Techno-economic comparison between Advanced lead-acid and Li-ion batteries installed at PGCIL premises

Parameters	Advanced lead–acid	Lithium–ion
Design capacity	691.2 kWh	398 kWh
Usable capacity	384 kWh @ 2C discharge rate	357 kWh @ 2C discharge rate
Delivered size	250 kWh/500 kW	250 kWh/500 kW
Number of cells	600	1728
Rated DoD	65.1%	70%
Battery footprint	One 40 feet and one 20 feet container Area footprint: 45 sq. metre	One 40 feet container Area footprint: 30 sq. metre
Cost	--	1.5 times advanced lead–acid

Application of the Project and Further Improvement Strategy

The systems have been designed to serve distinct grid-level applications since the utilization rate is an important factor while envisaging the revenue streams from BESS operation. Therefore, in this view, the technologies which have already been deployed under packages I and II, are serving primarily for energy time shift and frequency regulation. Moreover, a few other applications are to be added in the control topology of battery energy management systems (BEMS) to broadly cover all the possible financial implications in revenue generation. In this regard, USAID joined hands with PGCIL, and under its Greening, the Grid (GTG)-RISE initiative, the overall staked value of BESS for providing various services to the grid and the local Transmission &Distribution network will be assessed[23]. This collaborative effort is aimed at leveraging the investments and enhances the coverage of the pilot project alongside testing various functionalities. As an initial step in this direction, the GTG-RISE team has examined the existing control mechanism, and consequently, the scope of further improvement in hardware/software has been proposed. The pilot for the said work is being implemented by KEC International under a grant agreement funded by USAID. The pilot is focused on the enhancement of the existing control scheme to broadly cover the various plausible applications, and consequently, the work is to be carried out in the following order:

1. Hardware/software and telemetry retrofits across the three battery technologies
2. Development, implementation, and demonstration of control logics for the following distinct grid applications:
    - Dynamic frequency regulation
    - Voltage/reactive power support
    - Load following
    - Peak shaving
    - RE capacity firming
    - RE time shift
    - Integrated applications (combination of two or more of the above applications)

Since the system has been primarily operating under frequency control mode, the results obtained for a particular day of operation are shown in Figure 17. As it can be seen from the result, the discharge operation is triggered when the system frequency falls below 49.95 Hz while the charging is performed through the grid if the system frequency is found to be more than 50 Hz. If frequency lies in the dead band zone (that is, 49.95–50.05 Hz), the BESS will charge or discharge according to the status of battery SoC.

[23] Details available at <https://www.gtg-india.com/grid-connected-battery-energy-storage-system-bess/#sc_tab_1551086411_2_22>

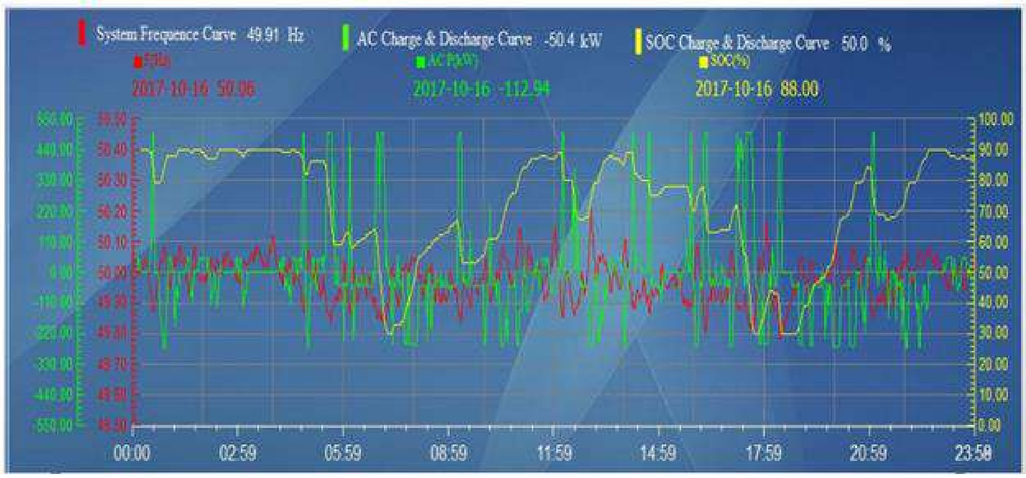


FIGURE 17: BESS charge/discharge operation under frequency control mode

2.1.3 Battery Energy Storage System Pilot Project at Multiple Locations in New Delhi in BRPL License area

The Energy and Resources Institute (TERI) in collaboration with BSES Rajdhani Power Limited (BRPL) has recently released a tender for supply, installation, and commissioning along with 5 years of comprehensive AMC of BESS (with a cumulative usable capacity of 410 kWh) which is to be installed at three different locations to serve distinct applications under licensee area of BRPL. The pilot demonstration is being carried out under UI-Assist which is a multilateral consortium of more than 30 collaborative entities, both from the USA and India. The project, jointly funded by the Department of Science and Technology, Government of India (DST, GoI), and United States Department of Energy (USDOE) is aimed at state-of-the-art technology demonstration for the smart energy distribution system and storage integration. The consortium is conducting cutting-edge collaborative research that will allow a continued increase of renewable energy penetration into our electric distribution grid.

The model tender document covers multi-dimensional aspects related to BESS for grid-level application and, consequently, different battery technologies (such as advanced lead-acid, NMC, LFP, and LTO) were considered initially for the selected applications. However, the LFP was identified as the best suitable technology for all three selected applications, as per the assessment carried out during the tender evaluation process since it requires lesser space for installation in comparison to advance lead-acid and exhibits better thermal stability as compared to NMC, and most importantly the cost was lowest amongst all mentioned lithium-ion technologies. Further, the tender was awarded to M/S Bharat Heavy Electricals Limited (BHEL) for providing turn-key solutions, and it is expected to be commissioned by January 2021. BESS will be serving distinct applications under three different consumer categories: (1) at a DT level for congestion relief, (2) institutional campus, and (3) gated housing society. The detailed specifications of BESS and applications are listed in Table 12.

TABLE 12: Specifications of BESS and applications

Pilot location	Power converter rating	BESS design capacity as per BHEL quote	Type of battery technology	Applications	Usable capacity and active power requirement
Category A (New Friends Colony, Taimur Nagar)	140 kVA	368.64 kWh	Lithium–ion (NMC/LFP*) or Adv. Lead Acid	Overload management of DTR and Energy arbitrage	230 kWh/125 kW
Category B (Ispatika Society, Dwarka, Sector 4)	270 kVA	201.6 kWh	Lithium–ion (NCM/ LFP*)	Back-up power and demand response	120 kWh/ 240 kW
Category C (TERI School of Advanced Studies, VasantKunj)	56 kVA	96 kWh	Lithium–ion (NCM/ LFP*)	Energy time shift and RE smoothening	60 kWh/ 50 kW

**Suitable battery technology identified during the tender evaluation process*

Key features and findings

As the project is focused on technology demonstration and carrying out further research, the customizable EMS is one of the important features of this pilot which will leverage distribution utility to demonstrate more than one application at each site to maximize the utilization of BESS and increasing the benefits earned from the system. The system will be interconnected with the existing SCADA system of utility through appropriate communication protocol which will enable the system to monitor and control from both central and locally placed (at site) control stations. In addition to this, more emphasis was given on technical specification (70% weightage) as compared to financial (30% weightage) while evaluating the bid. Moreover, instead of upfront cost, per unit cost (INR/kWh) of desired output (total throughput) was taken as the basis of financial evaluation, therefore, encouraged bidders to bid for most techno-commercially suitable technology. The major cost was observed for the battery pack (in the range of 40–50%) while the cost of PCS and AMC was also considerable (20% and 16%, respectively), as shown in Figure 18.

2.1.4 Battery Energy Storage System Pilot Project of 1 MWh Capacity in Bharat Heavy Electricals Limited's R&D Centre, Hyderabad

BHEL has deployed 1 MWh of containerized BESS solutions (distributed in three segments with different battery chemistry) which are being used for ramp-rate control and capacity-firming

01 Lithium iron phosphate (LFP) emerged as techno-commercially suitable technology for all the three applications

02 A major chunk of capital cost falls under the segment of battery packs and power electronics which are 40% and 20% respectively

03 AMC cost (for 5 years) approximately stands in range of 13% to 16% of total cost.

04 Median Price is the best estimate of Market cost which is 3.5 Crores.

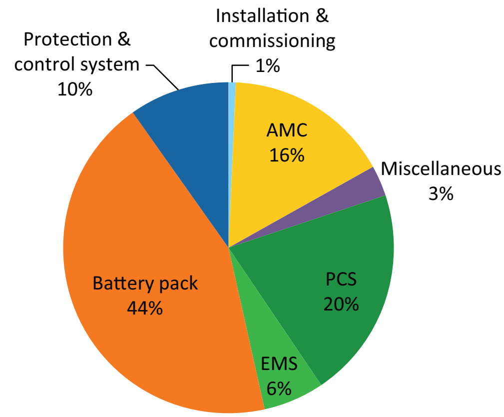


FIGURE 18: Key findings of TERI's tender

applications. The reason behind the selection of different battery chemistries is to analyze the performance of distinct chemistries since each battery technology exhibit some merits and demerits over other technologies. The system is designed for renewable integration; thus, the BESSs are integrated with a 500-kWp solar photovoltaic plant (SPV) installed at BHEL corporate R&D, Hyderabad. Since the system is configured to operate in ramp-rate control mode, a predefined ramp-rate limit of 10% per minute of SPV capacity (that is, ± 50 kW/minute) has been set. Accordingly, the control commands for charge/discharge operation are prompted by central EMS, if any excursion in generation (more/less than the predefined limit) from the SPV plant is observed. Besides this, the system is configured to operate for capacity firming, thus a predefined limit for power flow has been ensured at common interconnection points irrespective of solar generation patterns. Consequently, the power flow (as a set point for BESS operation) at 6.6 kV bus has been set at 250 kW from 07:00 AM to 06:00 PM. The battery will be charged when SPV generation is more than 250 kW while discharging of BESS takes place in case generation is lesser than 250 kW, thereby a constant power will be supplied to the grid during this period from the system (either from SPV or through BESS).

System Configuration

The systems which include 500 kWh of lithium–iron phosphate, 300 kWh of advanced lead-acid, and 200 kWh of flow battery are integrated with 500 kWp solar PV plant at common 6.6 kV AC bus through three separate power-conditioning systems with ratings of 500 kW, 100 kW, and 50 kW, as shown in Figure 19. The PCS was indigenously developed by BHEL which complies with all the relevant standards. The aforementioned energy rating of battery packs illustrates the usable energy requirement from the system. The system can be scaled up further, depending upon the size of SPV plant since the batteries are modular, and modules can be added either in series or parallel to get desired DC voltage at the inverter DC terminal.

The battery parameters such as cell voltage, Ah capacity alongside design capacity are listed in Table 13. The design capacity of the battery pack is slightly higher for lithium-ion and flow batteries than the usable energy requirement whereas, in the case of advanced lead-acid, it is much higher since the DoD and round-trip efficiency of this particular chemistry is on the lower side. One module of lithium-ion battery constitutes 6 series-connected cells, followed by 2 parallel connections. Further, 42 such modules are connected in series to make a rack, and 4

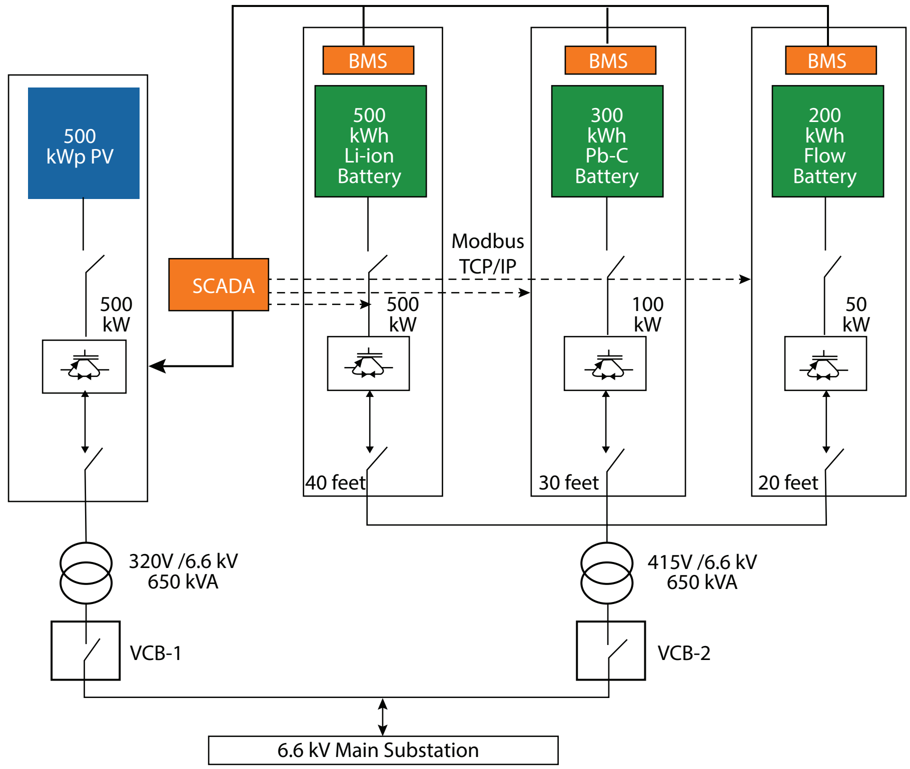


FIGURE 19: Inter-connection of BESS at 6.6 kV distribution line

such racks are configured in parallel to make a pack. On the other hand, an advanced lead-acid battery is configured by connecting 10 cells in series (to make a module), followed by 36 series-connected modules. In the case of a flow battery, 39 cells are connected in series to make one stack. Afterward, 4 such stacks are connected in a parallel configuration to make a 273 kWh pack.

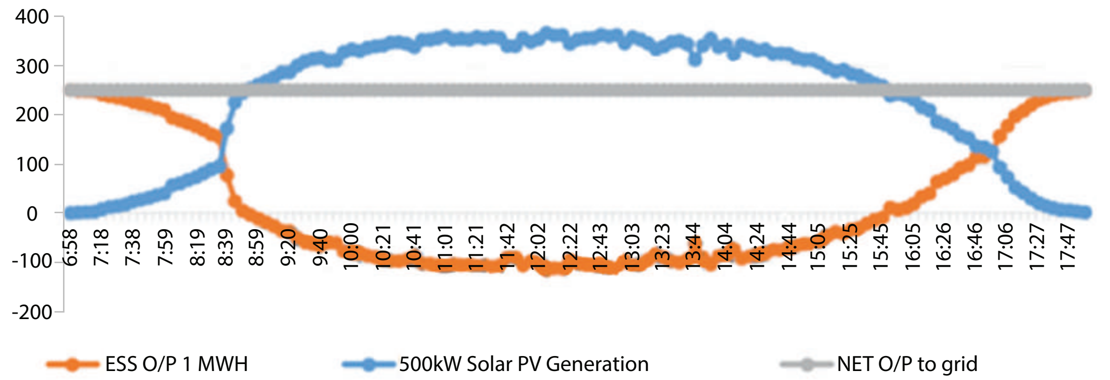
TABLE 13: Technical specifications of three different battery technologies installed at BHEL's R&D

Cell chemistry	Nominal cell voltage and Ah ratings	Design capacity and voltage rating	Usable energy
Lithium-iron phosphate	3.2 V, 80 Ah	516 kWh/ 806.4 V	500 kWh
Advanced lead-acid	2.0 V, 810 Ah	584 kWh/720 V	300 kWh
Vanadium redox flow battery	1.35 V, 1300 Ah	273 kWh/ 52.5 V	200 kWh

Key Findings

The developed BESS meets all the compliance as per relevant national/international standards such as anti-islanding protection, grid harmonics, grid interconnectivity, and the safety of the whole system. The system is also designed to operate in other grid-level applications such as reactive power control mode, peak load shaving, load leveling, frequency regulation, and power quality improvement through proper configuration of EMS. However, the performance validation was done only for capacity firming and ram-rate control applications.

The BESS operation under capacity firming and the ramp-rate control mode are shown in Figure 20. It can be seen from the result which is shown in figure 20 that the power flow through the 6.6 kV common bus remains constant for solar generating hours (that is, from 07:00 AM to 06:00 PM), and BESS operation is determined based on solar generation. Similarly, the operation of BESS under ram-rate control mode presents the fast-responsive behavior of BESS, and accordingly charge/discharge is performed based on intermittent generation of SPV plant. The response of the system has been less than 20 milliseconds.



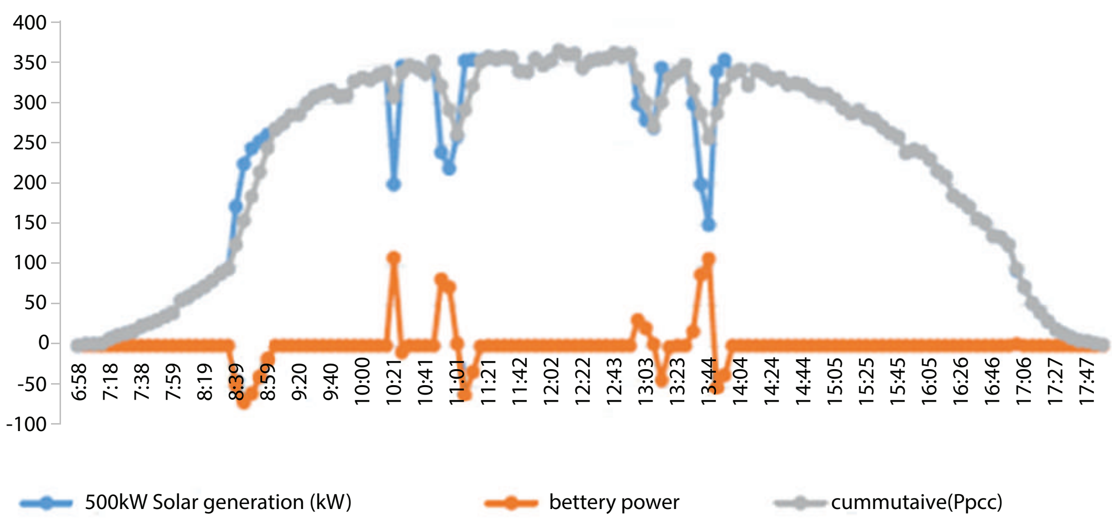


FIGURE 20: (a) BESS operation under capacity firming and (b) BESS operations in ramp-rate control mode

2.1.5 Summary and key findings of the pilot projects

Table 14 below illustrates the key features of the pilot projects that have been discussed in the previous section.

TABLE 14: Summary of the pilot projects and key learning

Pilot locations	Applications	Battery chemistries	Technical characteristics	Key findings
10 MW/10 MWh BESS in Rohini, Delhi	DSM, Frequency regulation, Peak shaving and Reactive Power Control	Lithium Nickel Manganese Cobalt Oxide (NMC)	Design capacity: 10 MWh/ 10 MW Maximum discharge rate: 1 C SOC range: 10-99%	DSM penalty savings during FY 2020-21: INR 22 lacs (approx.) Voltage improvement: 2.13% by operating the system for 13 instances Total project cost: INR 47.3 Crore approx.(30% for battery packs and 10-15% for converters)
500 kWh BESS at PGCIL facility in Puducherry	Energy time shift, Frequency regulation	Lithium ferro-phosphate (LFP) and Advanced Lead Acid	Design capacity: 398 kWh (LFP); 691.2 kWh (Adv. Lead-acid) Usable capacity: 357 kWh (LFP); 384 kWh (Adv. Lead-acid) Discharge rate: 2C	The cost of LFP is 1.5 times of Adv. Lead-acid Area footprint: 30 sq. meter (LFP), 45 sq. meter (Adv. Lead-acid)
410 kWh BESS pilots at multiple locations under BRPL licensee area in Delhi	Peak shaving (cat.-A), Reliability improvement (cat.-B), Energy time shift (cat.-C)	Lithium ferro-phosphate (LFP)	Design capacity: 288 kWh (cat.-A), 216 kWh (cat.-B), 72 kWh (cat.-C). Discharge rate: 1C (cat.-A), 2C (cat.-B), 1 C (cat.-C). SOC range: 15-95%	LFP emerged out to be a techno-commercially suitable technology for all three applications Total project cost: INR 2.5 Crore (40% of total cost for battery packs, 20% for PCS and 16% for 5 year AMC)

TABLE 14: Summary of the pilot projects and key learning

Pilot locations	Applications	Battery chemistries	Technical characteristics	Key findings
1 Mwh BESS pilot at BHEL's R&D center in Hyderabad	Ramp rate control, Capacity firming	Lithium ferro-phosphate (LFP), Advanced Lead-acid and Vanadium redox flow battery	Design capacity: 516 kWh (LFP), 584 kWh (adv. Lead-acid) and 273 kWh (flow battery) Discharge rate: 1C (LFP), 0.3 C (Adv. Lead acid), 0.25 C (flow battery)	System response: < 20 milliseconds PCS is indigenously developed by BHEL which comply with all the relevant standards

2.2 An Overview of Pumped Hydro Storage Development in India

Pumped hydro storage, which comes under a bulk energy storage system is generally utilized in power system domains for a variety of applications such as load following, peak shaving, surplus power absorption, spinning reserves, backup reserve, frequency regulation, voltage support, etc. As of October 2020, India has nine PHS plants with a combined installed capacity of 4785 MW, and the plants with the capacity of 1580 MW are under construction[24]. Out of these nine plants which are already operational, six plants are operated in both pumping and generation mode with a combined capacity of 3305 MW while three plants are only operating in generation mode having a combined capacity of 1480 MW. PHS was initially developed in the country to balance the thermal power station and had been used primarily to meet peak power demand and, as an emergency reserve to meet demand during catastrophic failure of conventional power plants. In the past, the operational efficiency of PHS plants had been quite low due to the unavailability of surplus off-peak power in most regions of the country (except the north-eastern region) to pump the water from the lower reservoir to the upper reservoir. Also, the grid frequency had been kept varying between 47.8 Hz and 50.5 Hz most of the time until 2003, which was causing poor operational efficiency for PHS plants since the pump turbines are designed to operate under a specific frequency band, especially during pumping mode. Table 15 illustrates the detailed description of major PHS plants in India.

24 https://cea.nic.in/old/reports/monthly/hydro/2020/pump_storage-10.pdf

TABLE 15: Major PHS plants in India

Location	State	Installed capacity (No. of units* unit size)	Year of commissioning	Mode of operation	Capital cost (million rupees)
Kadamparai	Tamil Nadu	4*100 MW	1987	Pumping and generation	2,250
Srisailam	Telangana	6*150 MW	2003	Pumping and generation	26,200
Ghatghar	Maharashtra	2*125 MW	2008	Pumping and generation	19,280
Purulia	West Bengal	4*225 MW	2008	Pumping and generation	26,388
Nagarjuna Sagar	Telengana	7*100.8 MW	1985	Pumping and generation	-----
Bhira	Maharashtra	1*150 MW	1995	Pumping and generation	2,570

2.2.1 Case study – Kadamparai pumped hydro storage plant

Kadamparai PHS plant with the capacity of 400 MW (4 units of 100 MW) is located in the state of Tamil Nadu, which was commissioned in the year 1987 at a capital cost of INR 2,250 million. The plant is operated as per the requirement of the state power system to meet the peak demand of the grid. The surplus off-peak power, especially from Wind generating stations of the state is utilized to store the water in the upper reservoir, and consequently, the Kadamparai PHS contributes to improved power output to the state grid during peak demand and emergency period. The increasing penetration of wind generating stations has contributed to the elongated off-peak duration for water pumping, which eventually leads to improved performance of the PHS plant after 2008-09, as shown in figure 21.

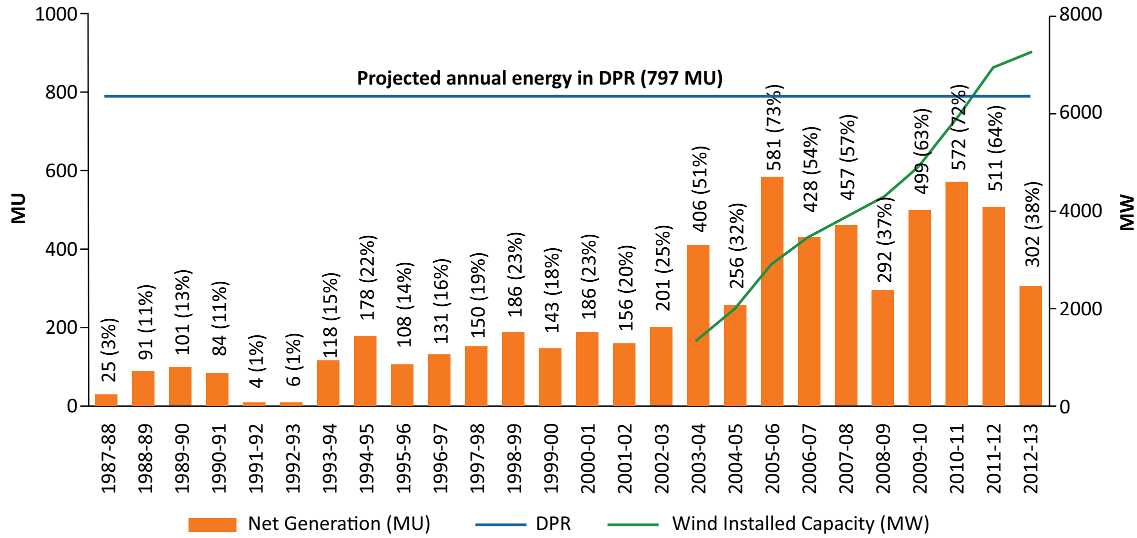


FIGURE 21: Year-wise performance of Kadamparai PHS plant until 2012-13

[25] https://www.sciencedirect.com/science/article/abs/pii/S0196890414007468

Economic aspects

The annual net benefit of the Kadamparai PHS plant has been calculated by considering several variables such as annual energy generation (MU), annual pump energy consumption (MU), the energy cost for pumping & generation (INR/kWh). Consequently, the annual net benefits for the years 2002-03 to 2011-12 have been calculated, as indicated in figure 22. It is the fact that the benefits from PHS plant majorly depends on the natural inflow of water in the upper reservoir due to rainfall, which is quite evident from the benefits shown in the year 2002-03 and 2003-04. Moreover, during 2004-05, major rehabilitation work had taken place in that region which resulted in poor profit.

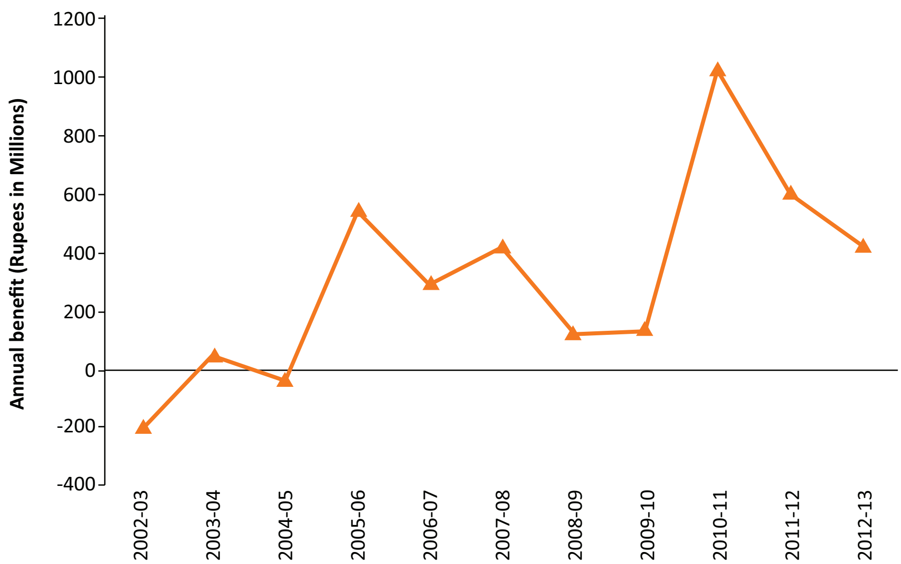


FIGURE 22: Annual benefits of Kadamparai PHS plant

2.2.2 Recent developments in India

To meet the ambitious target of RE penetration, particularly solar and wind, the Government of India (GoI) and relevant nodal entities have identified the need for flexible resources such as battery storage and PHS to absorb the variability and ensure the stabilized grid operation. In this view, in March 2019, GoI declared that the large hydropower plants with a capacity of more than 25 MW will be considered as RE resources. This move will enable larger projects to avail the benefits under the non-solar Renewable Purchase Obligation which mandates the utilities to purchase a portion of their electricity from hydropower stations. To further explore the technical feasibility of hydropower plants, in particular PHS, the Indian government has solicited World Bank to carry out a study to determine the flexibility of PHS and examine the appropriate market and regulatory framework[26]. Furthermore, MNRE has amended the National Wind-Solar Hybrid

[26] ET Energy World. "India to have 70,000 MW of hydropower capacity by 2030: Official - ET Energy World." ETEnergyworld. https://energy.economictimes.indiatimes.com/news/power/india-to-have-70000-mw-of-hydropower-capacity-by-2030-official/75859241 (accessed July 9, 2020)

Policy which included the pumped storage as an integral part of the hybrid system. This move will complement the large-scale integration of grid-connected Wind-Solar PV hybrid system deployment and efficient utilization of energy resources.

2.3 Application(s) and Economics of Grid-scale Energy Storage

Fundamentally, energy storage provides a medium to convert one form of energy to another. Since energy can neither be created nor destroyed, it can only be transformed from one form to another at some conversion efficiency. As per the Second Law of Thermodynamics, high-entropy energy cannot be transformed to low-entropy energy at 100% efficiency. Accordingly, to store energy for later use, low entropy or high-quality forms such as chemical energy is chosen (as in battery storage), however, for short-time applications requiring, the quicker release of energy, mechanical energy in the form of kinetic energy (flywheels) or potential energy (pumped-hydro storage), for a relatively long period, is also used.

Electrical energy can be converted into chemical energy and mechanical energy at relatively better conversion efficiencies. It gets stored in different forms for a certain period before being discharged. Considering the storage of electricity, several grid-connected or grid-scale energy storage systems exist and are being used for different applications in power grids across the world. Some forms of energy storage technologies like BESS are also more suited for off-grid applications such as microgrids for ensuring the supply of power to critical/common loads. However, with the increasing penetration of renewable energy sources that provide intermittent power and the emergence of the smart-grid paradigm, the importance of grid-connected energy storage is becoming significant. At the power-system level, energy storage can be connected at transmission grid-level for large-scale balancing of power and for providing flexibility and other ancillary services, and, at the distribution-network level for utility load-curve flattening, peak-power clipping, reducing overload on distribution assets, and a host of possible applications. Energy storage is thus assuming an important role as an integral component of the modern-day power grid.

In the past few years, electrochemical storage, which includes several batteries' chemistries, is considered to be the most appropriate technology for providing a range of services to the electricity sector. The application suitability of lithium-ion batteries stands prominent amongst the other technologies and applications, as shown in Figure 23. Though lithium-ion batteries can technically perform most of the applications but in general do not make economic sense due to the high cost of grid-interactive batteries and associated components.

The sharp decline in the cost of batteries, particularly for lithium-ion batteries and their high-performance factors such as higher cycle life, lower self-degradation, and fast discharge/charge capabilities have been the major drivers for their fast adoption across the globe.

Some of the applications for energy-storage technologies at the power-system level, specifically at the distribution-system level have been discussed in this section. Only those applications that have been implemented or are being considered for commercial applications have been reported.

Applications Technology	Bulk Energy Application		Ancillary Services Application					End use Energy Application		RE Integration	Transport Application	Off grid Application	Application Suitability Score
	Energy Arbitrage	Peak Shaving	Load Following	Spinning Reserve	Voltage Support	Black Start	Frequency Regulation	Power Reliability	Power Quality				
Mechanical Energy Storage													
PHES	1	1	0	0	0	1	1	0	0	1	0	0	42%
CAES	1	1	1	1	0	1	1	1	0	1	0	0	67%
FES	0	0	1	1	1	0	0	1	1	0	0	0	42%
Electro-chemical Energy Storage													
Lead Acid	1	1	1	1	1	1	0	1	1	1	1	1	92%
Nas	0	1	1	1	1	1	1	1	1	1	1	1	92%
Li-ion	1	1	1	1	1	1	1	1	1	1	1	1	100%
Flow Battery	1	0	1	0	1	1	0	1	1	1	0	1	67%
Electric Energy Storage													
DLC	0	0	0	0	0	0	0	0	1	0	1	0	17%
SMES	0	0	0	0	0	0	0	0	1	0	0	0	8%
Hydrogen Energy Storage													
Hydrogen Fuel Cell	1	0	0	0	0	0	0	0	0	0	1	1	25%
Thermal Energy Storage													
Thermal	1	1	1	1	0	0	0	0	0	0	0	0	33%

FIGURE 23: Application suitability of different storage technologies

2.3.1 Renewable Energy Grid Integration

Amongst the first and foremost applications of grid-scale energy storage is facilitating the smooth integration of renewable energy (RE) sources with the power system. The broad-based interest in energy storage has largely been driven by the growth in RE-based generation whose participation at the power-system level has been rising. As the penetration of RE generation increases, the variability and intermittent generation of these sources and the fact that RE is not always available when needed called for a controllable entity to match generation with demand. Energy storage can provide a superior solution to the variability problem when compared to fossil-based generation, whose operating reserves are being used to ensure reliability. Energy storage is a flexible resource for grid operators that can deliver a range of grid services quickly and efficiently.

Energy storage can 'firm' up or smoothen the variable output of RE sources. It can reduce the effects of fluctuations in wind or solar generation so that renewable resources become comparable to conventional generation options that have a fixed electricity supply rating and can provide more reliable operation. In this context, PHS with some technological advancements such as variable speed turbines has enabled fast and flexible ramping capabilities, which essentially provide flexibility to the generator to increase or decrease its power output according to forecasted net load. The intermittent generation of RE resources such as solar PV and Wind which are mainly dependent on weather conditions can be counteracted by PHS, thereby improving the system stability and resiliency. The location of the storage for firming renewable sources is not fixed. The storage may be co-located with the RE generation system, where the facility operator is paid more for power that can be dispatched when needed; or it may be closer to the consumer to avoid congested transmission lines. Storage may be carried out in the form of a single large system or may consist of several smaller systems, such as residential batteries.

Coupled with market-enabling mechanisms like ancillary markets, RE integration can act as a market-based application. However, this application is generally not market-based and has to be justified in an engineering and economic sense as compared to traditional T&D solutions. For example, improving the ability of the grid to accommodate solar photovoltaic (PV) by using storage to smoothen the PV generation and to mitigate high voltages caused by high PV penetration at peak. The RE integration can be understood as an umbrella with multiple applications such as supplying firm RE power, RE smoothening, microgrids in both urban and rural set-ups, load shifting, voltage regulation, etc. The load shifting of RE generation and microgrids concerning urban setup has been briefly discussed in the subsequent section.

Load Shifting and Renewable Energy Curtailment Reduction

The load shifting services provided by energy storage are proven to be flexible technological options for power system operators to make the RE power dispatchable by storing the excess power when the generation is surplus, and discharging the same when demand is higher than the generation. The PHS and BESS, in this regard, are being considered as the most viable option which can be utilized to store and discharge energy for a certain period depending upon the technical limitations of these technologies. BESS is generally utilized for continuous discharge up to 6 hours, while PHS can provide continuous supply starting from minutes, to even months to arrest the intra-day or seasonal variability.

It has been assumed that a solar plant of 500 MW installed capacity is supplying firm power for 4 hours in the evening (6:00 PM to 10:00 PM). In peak hours the plant is expected to supply 250 MW of power at all instances for four hours and for remaining hours deemed generation is supplied to the grid. The BESS was accordingly sized to receive the output of 1000 MWh (250 MW X 4 h). The typical operation for the project is illustrated in Figure 24.

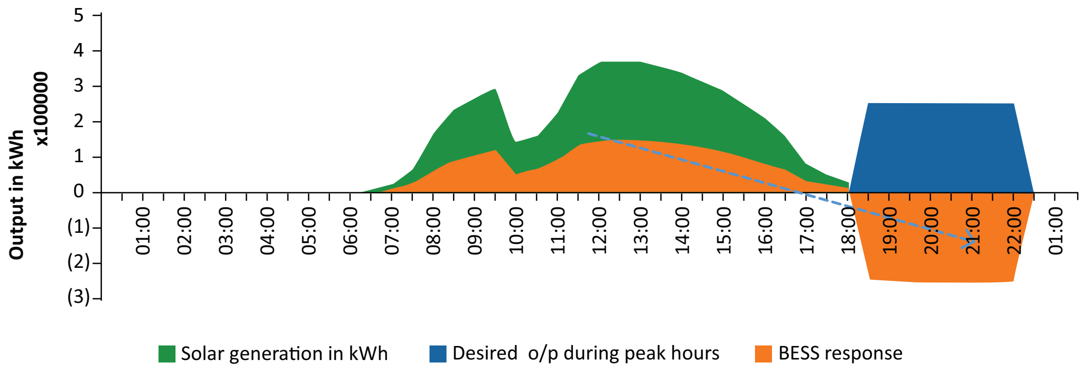


FIGURE 24: Illustration of Load Shifting

The positive BESS response denotes charging and the negative BESS response denotes discharging of BESS.

Battery Energy Storage System Sizing Overview

- Required BESS output: Maximum area under the curve of any typical day with the constraint of sufficient charging instances available
- Required kW rating: Maximum overshoot of demand at any instance
- BESS Technology: LFP as suitable to operational use case
- BESS Size: 1334 MWh/250 MW
- Total cycles: 4000 with 1 cycle per day for 365 days a year

Examining this project from an economic perspective is very important as the cost of battery packs (usually mentioned in the literature) is only 30% to 50% of the total cost of the BESS, depending on the ticket size of the project and other local factors such as weather condition. Thus, analyzing the cost of other parts of BESS is equally important. The Levelized Cost of Energy (LCOE) is an industry-wide accepted measure but in the case of BESS, LCOE calculations are complex. As capital costs for all battery systems are presented for battery capital and management systems (expressed in terms of $/kWh), balance of plant (BOP) ($/kW), power conversion systems (PCS) ($/kW) to arrive at the capital cost of the BESS as a whole based on the kWh/kW rating of the system. However, some cost components are difficult to segregate on a kW and kWh basis such as construction and civil infrastructure cost. As it is difficult to segregate the overall cost of BESS on per kW and per kWh basis, thus, to be more precise and obtain accurate calculations of LCOE, it is prudent to treat each case as different and LCOE is calculated based on the total capital investments instead of estimating generic cost based on kW/kWh rating of the BESS. The approach for performing the analysis is presented in Figure 25 below, which is self-explanatory. The output energy required from BESS can simply be calculated by multiplying the energy required during peak hours (6:00 to 10:00 PM) and subtracting the solar generation during those hours.

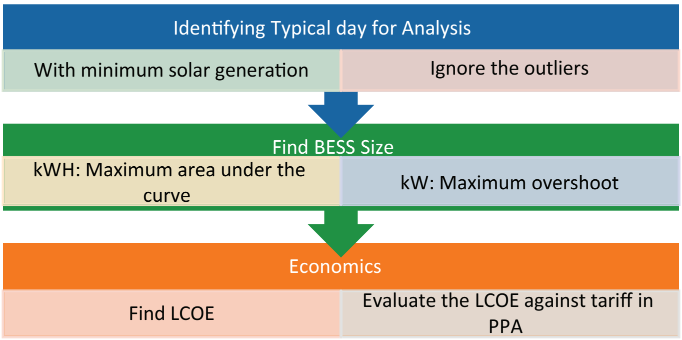


FIGURE 25: Preliminary Approach

This is coming out to be 997 MWh in the case study. The battery replacement cost has to be included in the cash flows. Replacement cost is a function of the total promised life cycles by the supplier, falling battery trajectory, and cycle per day. The other financial parameters are considered as per the latest CERC regulations.

Economic results: The Levelized cost of energy as per the assumptions (refer to Table 16) is computed to be INR 8–9 per kWh. At the same time-weighted average of revenue from electricity generation as per the revenue reckoned based on the peak and off-peak prices mentioned under PPA are comparatively less. This is INR 7 per unit during peak hours and INR 4 per kWh during off-peak hours. The cost of a solar PV plant and BESS along with capacity is depicted in figure 26.

Economics Overview

» Total investment: INR 876,808 lakh

» Capital structure: Debt to equity is 70:30

» Discount rate: 9.86%

» Total project life: 25 years

- BESS present cost: 500 $/kWh at MWh scale with an exchange rate of 78
- Battery replaced 2 times in tenure of 25 years with life a function of cycles per day
- Batteries replaced considering annual fall in the price of 5%
- Annual degradation of the system: 0.05%
- Tariff at peak hours as per PPA: 7 INR/kWh
- Tariff at non-peak hours as per PPA: 4 INR/kWh
- Other financial assumptions as per the tariff regulations 2020 of CERC

Financial Results

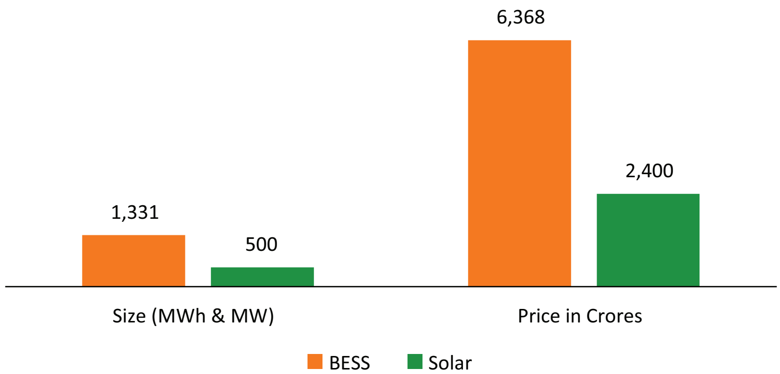


FIGURE 26: Solar and Battery Size and Price Proportions

TABLE 16: Financial Results of supplying firm power through RE coupled with storage

Levellised Benefits with AD	0.63 ₹/unit
Levalised Traiff	8.69
Levalised Traiff. A.D	8.06
Escalation in Levellised Tariff	0%
Escalation Period of Levellised Tariff	0
Project IRR	4.18%
Equity IRR	1.24%
Min DSCR	0.63
Average DSCR	0.81
NPV	(350,982) Lakhs

Conclusion and way forward: This is a prima facie analysis with the following conclusions:

- Economics cannot be positive till the weighted average of electricity tariffs received at peak and non-peak hours are higher than computed LCOE.
- Sensitivity can be performed over finding price signals that make economic sense.
- Sensitivity can be performed with falling battery prices, finding the year in which BESS projects start making more sense.

Prima facie project does not make economic sense. However, more deliberation on design aspects as per the local conditions, sharing of solar and BESS cost on actual, and point of connection will reveal a clearer picture.

Urban Microgrids

With the increasing share of RE in the power system, the resource adequacy planning exercise for DISCOMs is bound to change. The role of balancing fleets such as battery storage systems will gain prominence with falling batteries' prices and more opportunities in the power market. Flexibility and system reliability will be important attributes for distribution systems and thus microgrids will have a critical role to play in both urban and rural set-ups. In an urban setting, microgrids will not only help in synchronizing demand and supply but would also aid in improving the quality and reliability of the power supply. Such 'urban microgrids' have even got more relevance in congested cities such as Delhi, Kolkata, Mumbai where distribution equipment augmentation becomes a tedious task due to underground cabling and right of way challenges. A few recent examples of distribution grid failures in major metropolitan cities have established the need for black-start support at the distribution level. However, operational-use cases can be unique every time, depending on demand and supply patterns, power purchase portfolio, etc. One such case has been presented in this section which describes utilizing an urban microgrid to earn arbitrage benefits, providing black-start support, meeting RPO targets, and improving quality and reliability of power supply within the licensee area of BRPL, a distribution utility in Delhi.

The Delhi Government decided to use the campus of Radha Soami Satsang Beas in south Delhi's Chhattarpur to make the biggest COVID-19 temporary hospital in India with over 10,000 beds, roughly the size of 22 football fields, cooled by 18,000 tonnes of air conditioners to combat the rapidly rising cases of COVID-19 in the city. Consequently, the distribution infrastructure was set up in 15–20 days, which required a lot of network reconfiguration. Moreover, the load in a few days increased up to 100 times due to temporary health facilities that were set up at the site. The distribution equipment including three additional 11 kV feeders was put in place to supply the hospital. Once the situation normalizes, the electrical infrastructure set up to make temporary medical facility will become redundant. Additional three feeders were installed along with the feeder highlighted.

TERI, under facilitation support from BRPL, the distribution utility responsible for making such cumbersome arrangements in such a quick time, performed a broad-level analysis to assess the pre-feasibility of an urban microgrid. The basic reasons for selecting Radha Soami Satsang Beas are summarized here:

- Space availability of around 75,000 m^2 for solar PV installation
- Sufficient capacity of distribution network infrastructure to supply back to 11 kV bus
- Appropriate loading on distribution equipment to consume all solar generation and impact due to charging and discharging of BESS locally within 66/11 kV substation

The overload was not the case for this particular study as the maximum load on distribution equipment was found to be 40%–50% of the rated capacity. The minimal loading of the 11kV feeder provided an opportunity to supply power back to the 11kV bus and share the solar power generated amongst the 14 feeders emanating from the 11kV bus. The technical aspects were considered while appropriately sizing BESS to ensure that the charging and discharging operations of BESS did not result in supplying power back to the 66kV grid and the full potential of solar can be utilized. The generation of solar coupled with BESS is consumed locally in the 11kV distribution network. Accordingly, 4MWh of BESS was found to be optimum which will be a kind of AC-coupled system, integrated with the grid at the point of connection where power evacuation for solar PV is provided. The application of microgrids has been described in the previous section; therefore, it becomes imperative to design the appropriate control scheme for BESS operation, which is also the only controllable source within the microgrid architecture. In grid-connected mode, the discharge trigger will be given to the primary controller of BESS (that is, energy management system) when the variable cost of electricity is maximum in a day while the charging will take place when the cost of supply is minimal, thereby maximizing the benefit in terms of power purchase cost saving to utility. However, the charge and discharge duration alongside the rate of charge/ discharge will essentially be determined from the cost of supply in different time blocks which is generally being predicted on a day-ahead basis by the utility. Hence, the duration and rate at which charge/discharge operation is performed will be decided beforehand (one day before) in a practical scenario when BESS will be deployed at the site. Furthermore, the charge/discharge limitation will also be considered while designing the control topology as the life of the battery pack largely depends upon the rate at which charge/discharge is performed. To showcase the fundamental operation of BESS, the performance of the system has been shown monthly since the peak and off-peak time slots generally remain the same for a month. Thus, the threshold of charge/discharge operation has been maintained constant for one month. Moreover, the average monthly load curve (based on the average of each time slot of a day) was calculated as described in the preceding section, which is the representation of peak and off-peak time for each month of a year. Further, a fixed charge and discharge threshold has been evaluated for each month, and, consequently, the variable rate of discharge and charge has been proposed to ensure the optimal operation of BESS in such a way that the highest discharge rate is defined when the peak load is observed. Similarly, the charge rate will be higher when the system-level load is minimal. The control methodologies for BESS operation under different conditions are depicted in the form of a flow chart as shown in Figure 13.

» **Operating hours of BESS:** BESS control logic was designed to operate as per peak and off-peak hours of BRPL. Time-series loading data at the system level was assessed for the last five financial years. BESS was designed to charge during off-peak hours where there is a possibility to consume more from cheap power plants and discharge during peak durations whenever there is a possibility of curtailing power purchase from the expensive power plant to its technical minimum. The month-wise charging & discharging duration for BESS operation was defined based upon power purchase portfolio assessment for specific days and load curve analysis for the last five years. The charge & discharge operation is indicated in annexure-I. While discharging the BESS during peak hours, it becomes essential for utility/ system operators to ensure that the expensive power plants (gas and coal-based plants) are operated within their technical minimum, although the proposed size of BESS in this particular study is not so huge and it will have minimal impact on the existing operation of such plants.

» **Benefit assessment (stacking the different value streams):** As per the applications discussed in the previous section, the revenue streams were stacked together to calculate the true value of microgrids vis à vis a total cost of the system. The results are shown in Figures 27 and 28 for the Capex mode of financing.

Assuming a total investment cost of INR 44 crore, of which INR 32 crore for 8 MW of solar capacity and INR 12 crore for 4 MWh of BESS (LFP technology), the total undiscounted payback is between four and five years. Table 17 presents the non-discounted payback period with a change in the price of the battery.

TABLE 17: BESS cost versus payback period

BESS cost in $/kWh	450	400	350	300	250	200
Non-discounted PBP in years	4.96	4.79	4.63	4.47	4.3	4.14

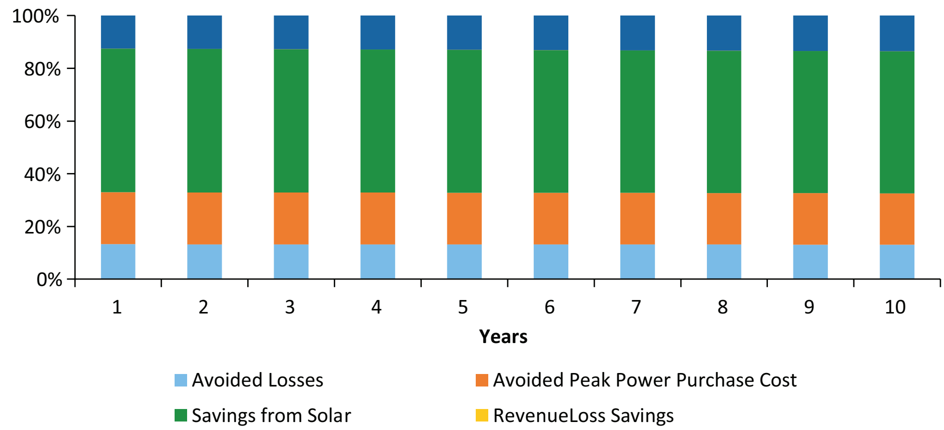


FIGURE 27: Proportion of benefits of a micro grid in an urban set-up

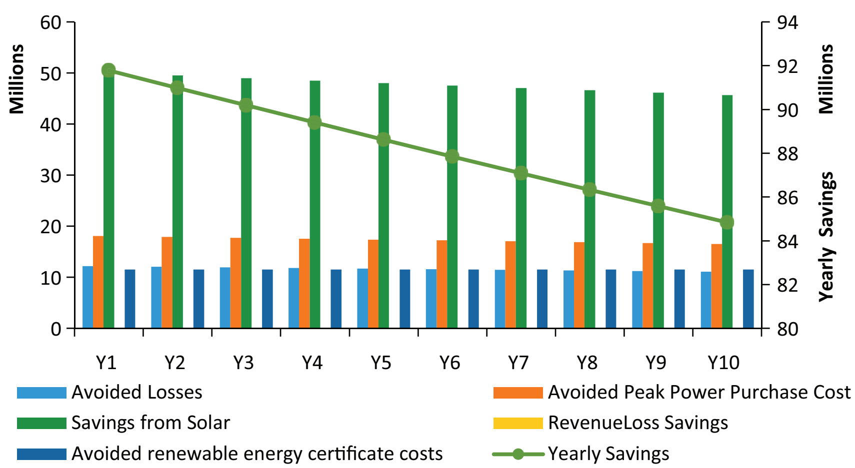


FIGURE 28: Benefits of a microgrid in an urban set-up

The other major assumptions are as follows:

» Cycle of BESS per day: 1 cycle

» Battery efficiency assumed: 90%

» Usable BESS capacity: 4000 kWh with efficiency losses

» Annual system degradation: 1%

» Annual hours of outage on the 11 kV feeder: 20 hours

» REC cost: INR 1000 per MWh

» Solar system cost: INR 4 crore per MW

The battery was sized to fully utilize the estimated solar potential to ensure no power is supplied above the 66 kV line, all solar generation is consumed locally within substation level. All generated electricity, at all instances, as an outcome of urban microgrid operations, was ensured to be consumed by the 14 feeders emanating from the 11 kV bus.

The other prospective applications are listed below:

Black start: Black start in power distribution system means restoring a generating unit with its auxiliaries present at distribution downstream which is supplied by DG set or energy storage and extending the power supply to loads after dead bus charging and energizing a distribution line to seek loads. This is the first step in system restoration post a partial or total blackout in any part of an electrical power grid. Because of the growing complexity in power systems with the addition of new RE generation, the need for a well-tested plan for system restoration has gained currency across system operators around the globe. Going forward, with a gradual development of a mature power market in India the black start facility of existing and upcoming generating stations can be commoditized and possibly traded as an ancillary service to the power system users for which each black start-capable generator would be required to get its black start-capability validated and certified regularly. In such a scenario, microgrids can provide ancillary services to support black start, if the network or customer grid goes down; energy storage can stand at the ready-to-start critical generators. Microgrid equipped with solar PV and BESS can provide black start support to the regional electricity grid by supplying active/reactive power to the network to maintain the voltage and frequency within the specified limit, which will essentially help to initiate the system restoration and load recovery from a partial blackout or total blackout situation. Critical challenges arising in system restoration using conventional blackout units (such as wind, hydro, and gas power stations) include reactive power balance, switching transient voltage, inrush current caused by no-load transformers, and generator self-excitation. Also, these units have low-regulating capacity due to the slow response while solar PV+BESS has a fast response time, in the range of milliseconds, and is capable of addressing the aforesaid issues.

Renewable energy-based electric vehicle charging: Since a sizeable amount of energy which is generated from solar PV plant will be supplied back to the main 11 kV common bus due to low demand at a particular 11 kV Radha Soami feeder (wherein microgrids interconnection is proposed), and sufficient space available for public EV chargers installation, the RE-based EV charging can also be seen as a plausible application. The charging of EVs during the daytime can be performed through solar PV-generated power while overnight charging can be done through BESS by utilizing two cycles of charge and discharge per day (one cycle for energy arbitrage and another for EV charging). The proposed approach of clean energy-based EV charging may also reduce the technical losses in the line especially when charging occurs through solar PV because the net amount of power flow in the 11 kV feeder will be reduced significantly in case multiple EV charging takes place at the same time. Despite these many merits, as PV is an intermittent source that lacks consistency in producing the output power, the charging during daytime can get hampered.

Therefore, a battery energy storage unit coupled with solar can optimize sources, when the EV charging is in operation. The appropriate control strategy and power flow management schemes for EV charging have not been elaborated in detail in this study.

The broad-level benefits of microgrids could be summarized as follows:

» RE integration

» Deferred network up-gradation

» Efficient demand-side management

» Savings under deviation settlement mechanism (DSM)

» Power backup during outages and black-start support

» Miscellaneous benefits: In addition to the above-mentioned benefits, these urban microgrids can have a more profound positive impact on DISCOM operations. First, the transmission and distribution losses would come down. Second, the availability of a firm RE capacity would reduce their generation capacity procurement under the power purchase agreements (PPAs), and in turn, the fixed charges.

Lastly, they could also cut the power procured from the contracted capacity to reduce the variable cost. Urban microgrids are an attractive value proposition to the consumers as well, as they can gain substantially from these systems in terms of reduced tariff and increased reliability of power supply.

Energy storage enables society to use more variable and uncertain renewable generation, such as wind and photovoltaic. By storing the renewable supply that exceeds the demand, rather than curtailing it, the RE can be shifted to times when it is needed. However, under some circumstances, curtailment of excess renewable generation may be more economical, less expensive than adding energy storage to the system.

2.3.2 Supplying Firm and Dispatchable Power

The feasibility study for the implementation of BESS has been carried out for a 26 MW hydro generating station, distributed in 3 segments of 8.825 MW each, erected in the Teesta canal of West Bengal. The generating station also has a 10-MW of solar PV plant which was commissioned in 2018 (refer to figure 29). At present, a dispatch from Teesta canal hydro is dependent on the irrigation schedule which is prepared by the irrigation department. Cleaning of garbage that accumulates over time, hindering the operation of the hydropower plant, also contributes to interrupted operations of the plant, thus resulting in an uncontrollable source of generation which eventually results in limited control in power scheduling. Besides, the solar PV plant is also a kind of non-dispatchable source of energy that is dependent on climatic conditions. It is therefore proposed to maximize the benefit to West Bengal State Electricity Distribution Company Limited (WBSEDCL) by using solar and other partial or non-dispatchable sources of generation herein canal hydropower plant and solar plant to supply firm/ dispatchable power, keeping in mind geographical constraints of PHS by utilizing the electrical energy storage capability of BESS. The proposed technological intervention will also have secondary benefits in terms of technical loss reduction as the net loading of power transformers will be reduced significantly, and line losses along the 133 kV line will also reduce up to some extent.

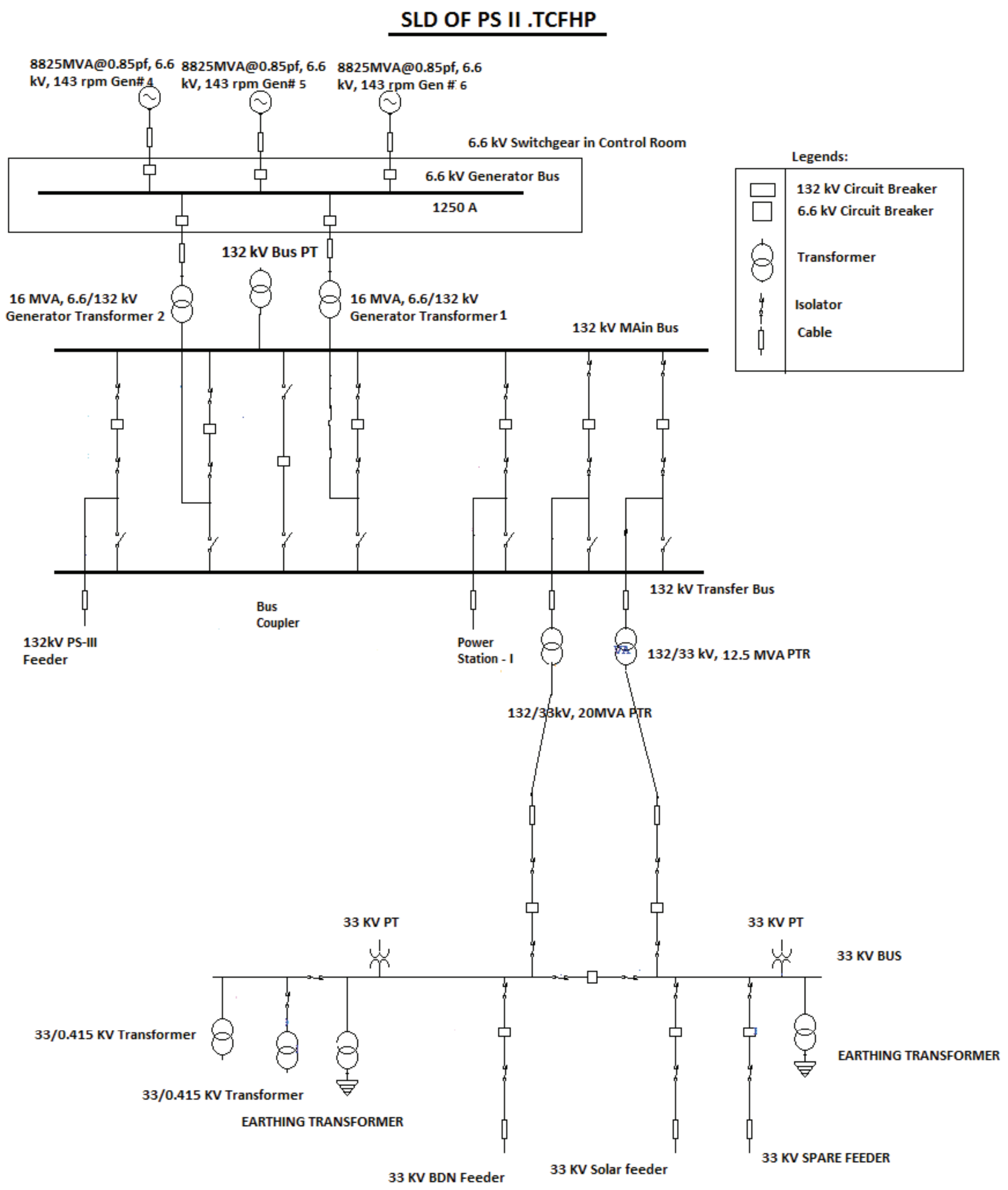


FIGURE29: SLD of Teesta canal

Outcomes of the Study

1. Analysis of cumulative power output from solar and Teesta power plants shows that the timing of cumulative generation output injection in the distribution grid is not in the best interest of the utility in terms of price of electricity to the WBSEDCL (refer to Figures 30, 31and 32).

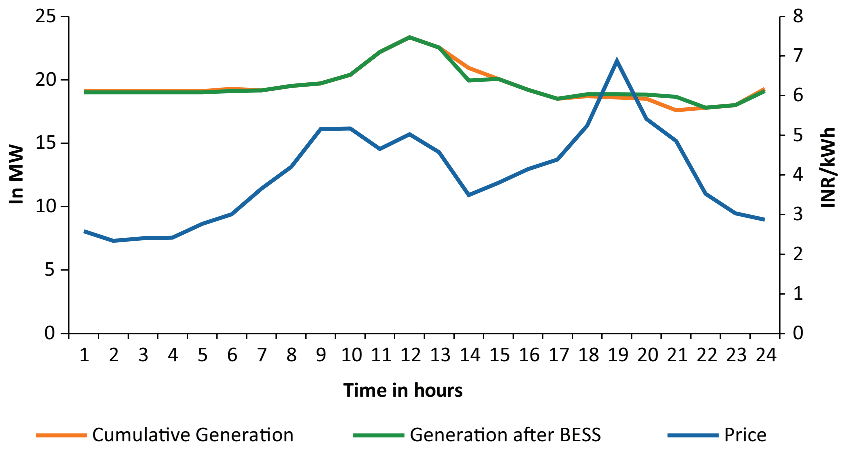


FIGURE 30: Variation in generation and price with time in December, 17

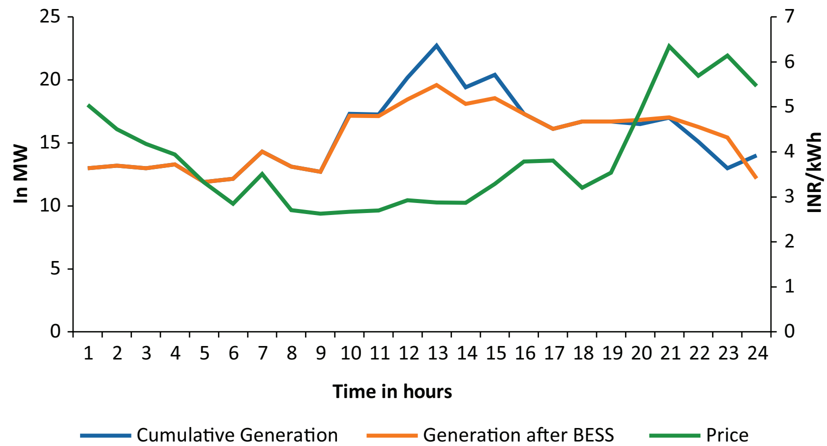


FIGURE 31: Variation in generation and price with time in June, 18

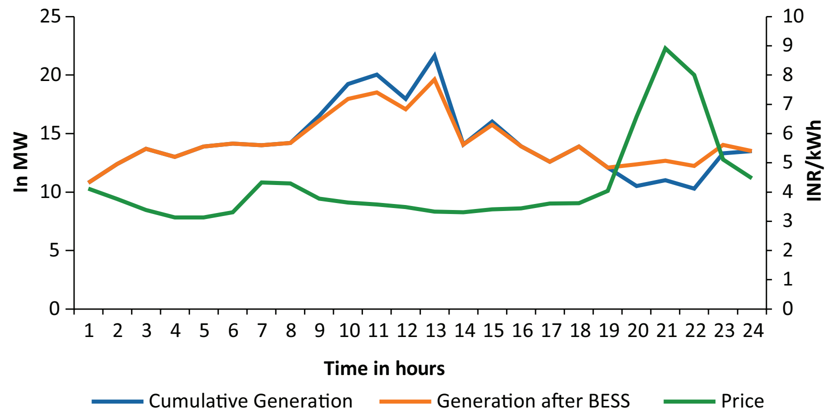


FIGURE 32: Variation in generation and price with time in August, 18

2. Impact on utility load curve considering 20 units of distributed solar and BESS (each unit having 10 MW of solar PV and 10 MWh of BESS):
    - The average peak demand reduction is 0.68%
    - Maximum peak demand reduction is 1.35% (73 MW)
3. Technical impacts on 12.5 MVA and 20 MVA power transformers (PTR) are evaluated in terms of loss-of-life (LoL) for a particular day of operation (that is, for 24 hours of operation), as indicated in Figures33 and 34. It can be seen from the results that LoL is reduced up to a certain extent.

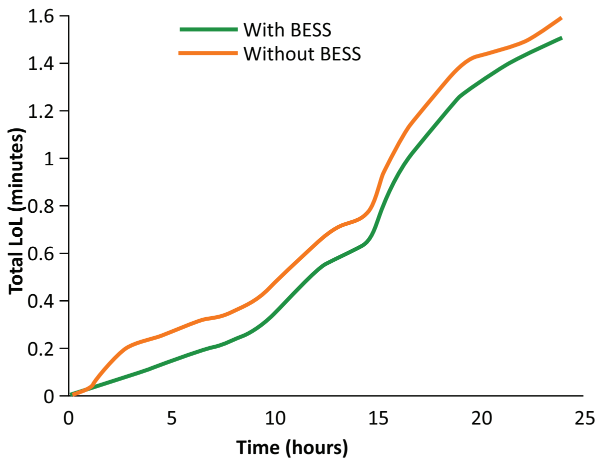


FIGURE 33: Impact onLoL of 12.5 MVA PTR

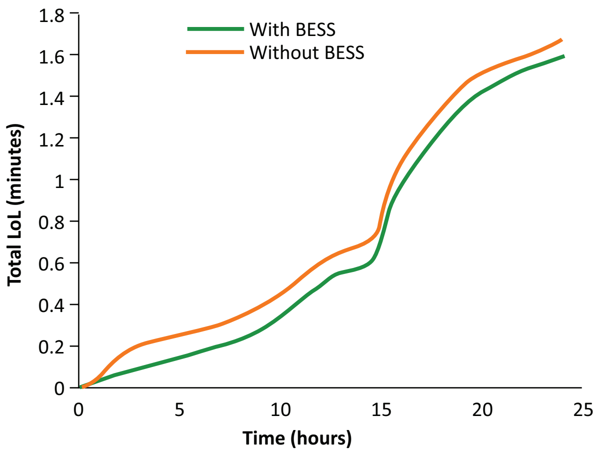


FIGURE 34: Impact on LoL of 20 MVA PTR

2.3.3 Frequency Regulation

Power system operation ensures the frequency to be maintained within the limit as defined under relevant grid code by dynamically matching the generation and demand for securing smooth network operation. Frequency regulation is a continuous adjustment of power flow through the electricity network to effectively manage the power dispatch schedule. The unexpected rise in demand causes a fall in supply frequency which may eventually lead to brownouts or blackouts in that particular region. Contrarily, lower demand for power than the generation will result in a frequency rise, thus possibly damaging all connected electrical assets. Also, frequency excursion causes load and generation tripping, which eventually led the system to collapse. Thus, the task of load balancing while maintaining the grid frequency is managed by system operators. In this regard, the Central Electricity Regulatory Commission has laid down the guidelines of deviation settlement mechanism (DSM), for adherence of schedules as given by system operators to generators and load-serving entities. CERC has constantly amended the regulation to bring frequencies close to 50 Hz. In this context, CERC had come up with Fifth Amendment in regulation on DSM and related matters which are now referred to as Central Electricity Regulatory Commission (DSM and related matters) (Fifth Amendment) Regulations, 2019. Some major changes in the Fifth Amendment include:

- The frequency band tightened to 49.85–50.05 Hz
- Deviation price vector linked to daily average area clearing price (ACP) in the day-ahead market of power exchange.
- DSM rate vector will have a dynamic slope determined by joining the identified price points at 50 Hz (daily avg. ACP), frequency below 49.85 (800 p/u), and 50.05 Hz (0 p/u) on daily basis.
- In the event of sustained deviation from schedule continues for 6th-time blocks, the regional entity (buyer), shall correct its position, by making the sign of its deviation from schedule changed or by remaining in the range of +/– 10 MW about its schedule, at least once, latest by 7th-time block.
- Additional charge @ 3%, 5%, and 10% of daily-based DSM for 1st to 5th, 6th to 10th, and 11th and above violations, respectively is proposed to be charged.

The distribution utilities now have to maintain more grid discipline and penalties could range in crores. Therefore, the role of energy storage, especially BESS in this regard becomes crucial since the BESS can provide regulating power with sub-second response time, and effectively managing the power flow in the line to reduce the quantum of the penalty and maintaining frequency within the specified range. The battery cells with high power density are preferable for frequency regulation. Real-time parameters, such as battery SoC (along with other critical parameters), power flow, and system frequency are communicated to the control station to perform charge/discharge control action. Moreover, with the advent of variable speed turbines and ternary systems, PHS plant operational flexibility has improved, which eventually allows systems to operate in frequency control mode by managing the supply and demand gap efficiently. A variable speed turbine, which is a replacement for traditional fixed-speed turbines brings operational flexibility to PHS plant and allows for power regulation during both pumping and generation mode. Contrary to this, the ternary systems, which comprises of motor-generator and a separate turbine and pump set allows the parallel operation of both pumping and generation mode at the same time. These innovative solutions have further improved the system's flexibility and response time.

As mentioned above, there are stern penalties imposed on violating the drawl limits beyond the frequency range of 49.85 Hz. Overdrawing beyond certain volume and also persistent nature of drawl. Here comes the role of BESS which can act to limit these sudden changes. In case of overdraw at a point, BESS can discharge the energy thus reducing DSM charges, this serves a two-way function of limiting overdrawl which is frequency linked, and also additional charges due to sign violation.

To understand the role of battery storage and its role in limiting DSM charges, this section presents a case study of a Kolkata-based DISCOM—CESC supplying electricity in the urban areas of Kolkata. The analysis was done for 30 days in March and April 2019. CESC had a peak load of X MW for the analysis period and the average load factor is. The bifurcated DSM account for the analysis period is shown in Figure35. As seen in the figure, the majority of the DSM penalty charges for the DISCOM include violation of overdraw limits linked to grid frequency followed by the violation in significant change for continuous six-time blocks (15 minutes each) and additional penalty due to over-drawl beyond frequency range.

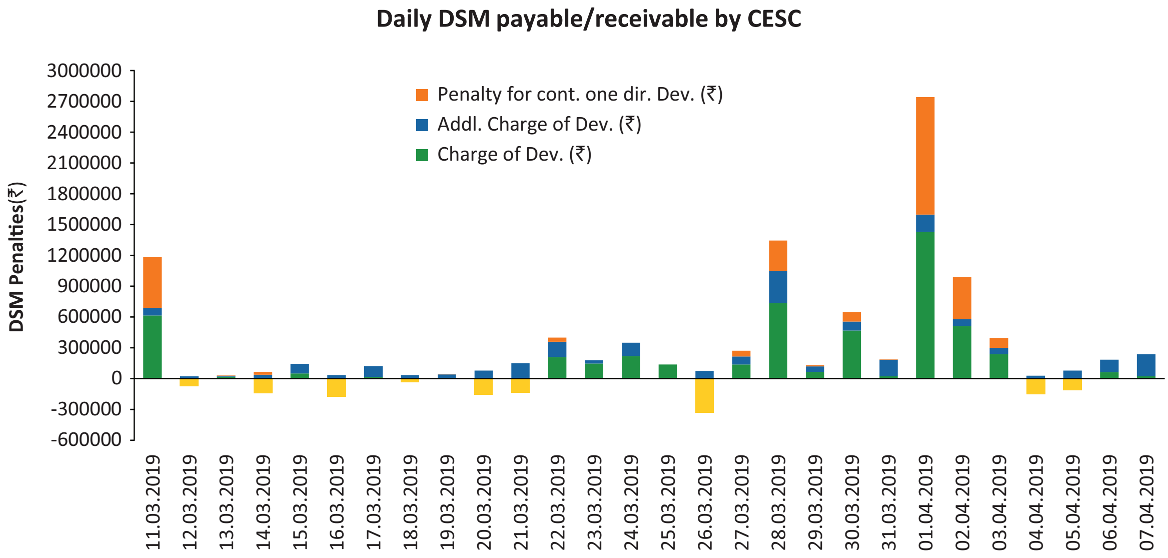


FIGURE 35: The bifurcated DSM account penalties

Control Logic for Operating Battery Energy Storage System to Reduce Deviation Settlement Mechanism Penalties

To analyse the BESS action on the impact on DSM penalties, a BESS was assumed to act in real-time block-wise. The constraints such as forecasted demand regulations as per CERC Fourth and Fifth amendments of DSM which mention frequency-related dynamic slope for the discovery of daily block-wise DSM penalty price are being considered while arriving at idle operations of BESS.

Overdrawl: As mentioned in Table 18, assumed mandatory discharging time blocks are the instances where the DSM penalties are higher either due to prevailing grid frequency (C1), due to the case of sign reversal (C9), or a violation occurring below 49.85 Hz frequency (C3). This ensures that most of the penalties are reduced in such periods. However, C9 and C3 are given much higher preference. C3 condition ensures partial discharging.

Underdrawl: In the case of underdrawl, CERC mentions a cap on rebate in the operating frequency range of 49.85–50 Hz at 12% of the scheduled demand for the time block. Hence C5 and C7 are those instances where no rebate is provided which are assumed for mandatory charging. C10 time block again follows continuous power under drawl which is given a higher preference, hence associated with a mandatory charging. Further C8 is associated with a high penalty for underdrawing above 50.05 Hz. Hence C8 & C10 get first preference in charging. C4 and C6 are associated with Idle SOC to avail rebate in operating range of 12% of the scheduled demand.

TABLE 18: Categorization of overdrawl and underdrawl conditions

Condition	Case	Frequency range	Penalty/rebate	Battery action
C1	Overdrawl	>49.85 Hz,< 50.00 Hz	High penalty	Discharge (compulsory)
C2		>50.00 Hz,< 50.05 Hz	Low penalty	Discharge (partially)
C3		<49.85 Hz	High penalty	Discharge (compulsory)
C4	Underdrawl	>49.85 Hz,< 50.00 Hz	High Rebate	Charge (idle)
C5		>49.85 Hz,< 50.00 Hz	No rebate	Charge (compulsory)
C6		>50.00 Hz ,< 50.05 Hz	Less rebate	Charge(idle)
C7		>50.00 Hz,< 50.05 Hz	No rebate	Charge (compulsory)
C8		>50.05 Hz	High penalty	Charge (compulsory)
C9	Sign reversal	Continuous 6 blocks (+ve)	High penalty	Discharge (compulsory)
C10		Continuous 6 blocks (-ve)	High penalty	Charge (compulsory)

Critical Period Analysis

As per Table 18, there is an optimistic opportunity for BESS to limit deviation charges w.r.t sign changes and exorbitant deviation charges crossing grid frequency levels mandated by CERC. Hence, in this section, we analyze such time blocks from the available data to demonstrate the capabilities of BESS in real-time. For the analysis purpose, battery roundtrip efficiency assumed of 90% and usable BESS capacity of 4500 kWh has been considered.

Here the critical period for analysis is 28 March 2019. As seen in Figure36, there is a continuous positive deviation in more than 12 blocks in a day which are not only incurring nominal deviation charge (DC) but also sign reversal penalties and additional deviation charges (ADC) due to violation of the 12% over drawl limit as can be visualized in Figure 37. One interesting thing to delve us in

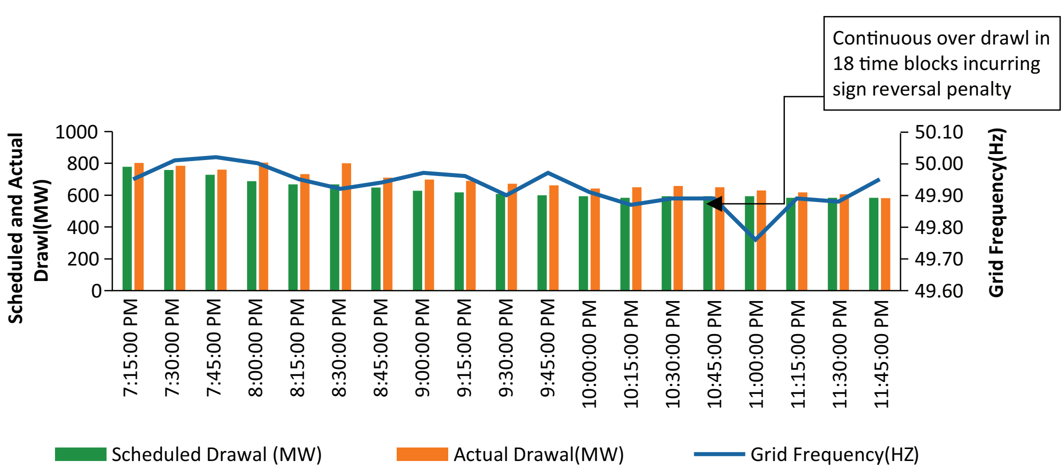


FIGURE 36: Critical Period Analysis of Drawl

this plot is that by reducing the sign reversal penalties, we are serving a dual purpose by avoiding sign reversal penalties and DC/ADC. One can see this in Figure 37 occurring in the time block 1,6,12. To capture such opportunities, we associate more priority to reducing sign reversal first and then reserve battery SOC for reducing nominal DC. Not limited to sign reversal penalty, it is also observed in Figure 34 that the fourth last time block has frequency going well below 49.85 Hz that being the case, ADC is double that of the DC for any time block. Hence, it should be noted that continuous monitoring of frequency is necessary to keep ADC in control.

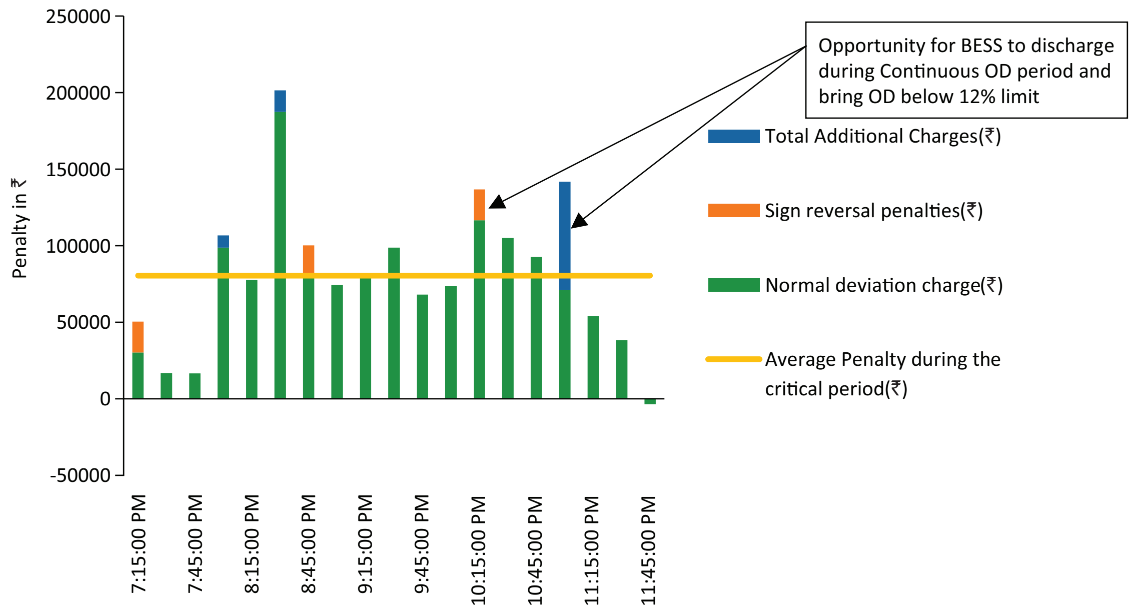


FIGURE 37: Type of Penalties during a critical period

Summary of Overall Reduce Deviation Settlement Mechanism Penalties

In this sub-section, we present the impact of using BESS in arresting different types of DSM penalties. Table 19 shows the type of penalty before and after using BESS. As can be seen in the table, there is a 48% overall reduction in DSM penalties. The majority penalty has been noted in reducing the ADC charges which are directly influencing the DC. Even though the sign reversal penalty has been given priority, the penalty reduction is mostly dependant on the available SOC of the battery. Partially availability of battery SOC in some instances has led to fragmented reduction of penalties only in some time blocks. This indicates monitoring of past trends of the system and intra-block forecasting to ensure sufficient SOC in the BESS.

TABLE 19: Monthly summary and distribution of DSM penalties

Category of penalty	Without BESS (In Rs)	Using BESS (In Rs)	Reduction (%)
Normal penalty (DC)	37,92,028	21,25,643	43.9
Additional penalty (ADC)	25,04,710	10,32,001	58.8
Sign reversal penalty	26,82,705	14,48,741	46.0
Total payable	89,79,443	46,06,385	48.7

To analyze the impact of DSM penalties pre and post-BESS action daily, Figure38shows daily variation in the penalties due to the charging and discharging cycle. It can be seen that the majority of the days have a significant reduction in penalties post-BESS action. This was following with adequate SOC available to charge/discharge at specific time blocks. However, on many days, there is a marginal increase in DSM penalties post BESS action due to the daily cycling behavior of BESS and unavailability of charging opportunities at favorable prices leading to the spike. Also, one can note that the battery is not completely utilized as seen in many days due to the non-requirement of DSM penalty reduction. This indicated towards idleness of BESS. Hence, one can avail the multiple revenue streams opportunity which can be tapped to benefit from price arbitrage, fast ancillary services which we expect will come in the future.

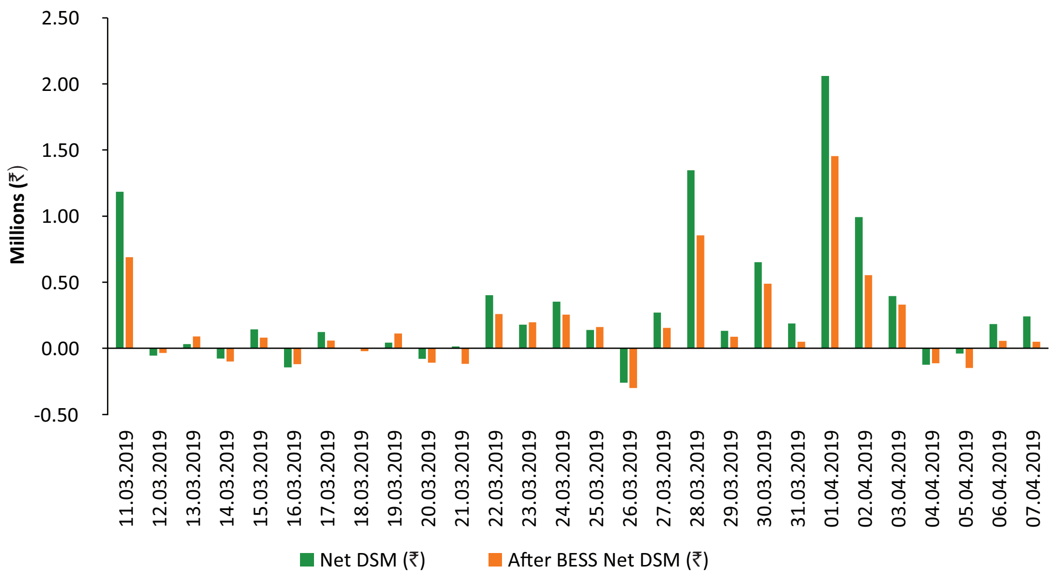


FIGURE 38: Aggregate DSM penalty for the analysis period

A few recommendations for using BESS to reduce DSM penalties of DISCOM and relative applications are listed here:

1. Being a fast response to the control, the use of BESS to mitigate DSM penalties can be done extensively to manage sign change violations and additional deviation penalties.
2. As already stated, the battery remains idle in many time blocks, it can be used to utilize price arbitrage benefits, and use BESS as a flexible ramping product thus opening up space for system operators to utilize BESS as a new ancillary services product. However, prioritizing applications and predicting the next violation and frequency is a tedious task. The requirement of manual judgment would be required.
3. Further, it was also noticed that at many time blocks, sufficient SOC availability in BESS remains a drawback, hence, accurate forecasting and scheduling needs to be done by DISCOMs to adhere to the scheduled demand and get the maximum benefit from the BESS operation by optimizing charging/discharging cycle.
4. Since forecasting and scheduling are the responsibility of DISCOM, recognizing energy storage as a grid asset in case of aforesaid application would be a challenge.

2.3.4 Peak-shaving or Overload Management of Distribution Transformers

The role of battery energy storage systems (BESS) thus becomes important for distribution network applications such as voltage regulation and peak shaving. With high summer peaks, distribution networks with high penetration of solar rooftop PV systems (SRPV) tend to have a low load factor. This has an impact on the rate of loss-of-life of equipment, especially distribution transformers (DTs) and thus for such feeders, the non-reduction in augmentation/replacement costs on these components offsets the benefits of load reduction through SRPV. Certain factors affect the health/life of DTs: (1) Overloading, (2) non-linear load operation, and (3) poor maintenance. Overloading is a major cause of DT failure (failure rate in India is around 12–15%), particularly, in urban areas where the population growth is high. The overloading of a DT can be prevented by the deployment of BESS at its secondary side, thus preventing DT augmentation. This section discusses the need for BESS at the distribution level to defer investments on DT augmentation and reduce DT failure while increasing the DT life. This application along with energy arbitrate could make BESS viable at the distribution level. A control logic developed for the battery monitoring system along with a detailed cost-benefit analysis under various scenarios has been reported in this section. The assessment of overloading depends on how DISCOM defines overloading and under what conditions DISCOM looks for alternatives. The distribution utility considers in this section identifies a transformer to be overloaded if its loading is greater than or equal to 120% of the rated capacity for consecutive two hours for any 7 days in a month. As a measure, the utility traditionally adopts the following steps to resolve the persistent overloading on any of the existing DTs:

» Load shifting through LT network: Shifting a certain amount of load to other existing DTs on the feeder.

» Capacity addition by installing new DT: If the load cannot be transferred to the nearby DTs due to LT network congestion, then a strategic location is identified to install a new DT near a common load center of the overloaded DT. The new transformer will not only relieve the concerned overloaded DT but will also provide better load management during an outage condition by supplying some parts of the area.

In case the above two options stand to be infeasible, the utility has to resort to the augmentation of the existing overloaded DT. This results in replacing the existing DT with another one of higher capacity.

The initial step was to identify a suitable DT which is overloaded to establish the feasibility of installing a BESS to manage the overloading. A site survey was conducted in the utility licensee area and a particular DT was shortlisted based on its overloading status.

Overloading of the DT was analyzed as per the criterion followed by the utility. However, a threshold of 80% of the rated capacity was taken as the change in demand pattern of DT in future years was not assessed under this study. The threshold of 80% of rated capacity was decided in consultation with the utility. The DT loading for any typical day has been shown in Figure 39.

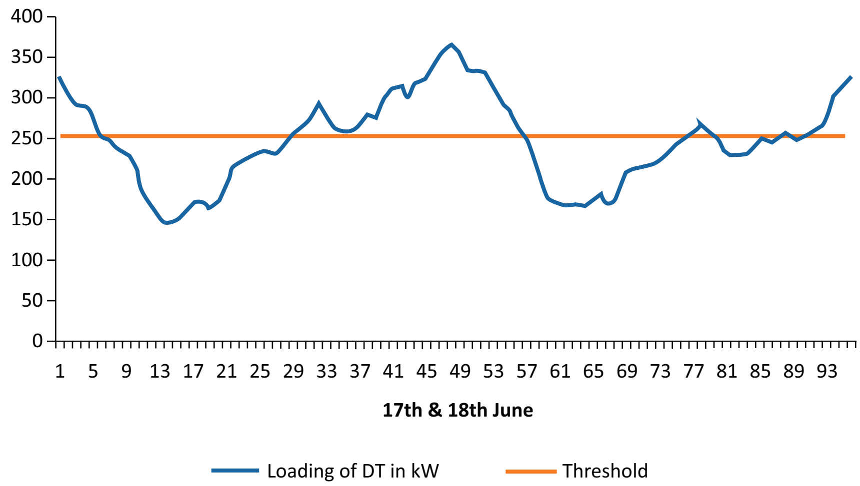


FIGURE 39: The DT loading

The load curve of the DT for a typical peak load day is shown in Figure 40. The figure also shows the utility load curve. It can be seen that the DT load curve follows the same pattern as the utility load curve. That means savings in peak power purchase can also be taken into account while calculating the true value of BESS.

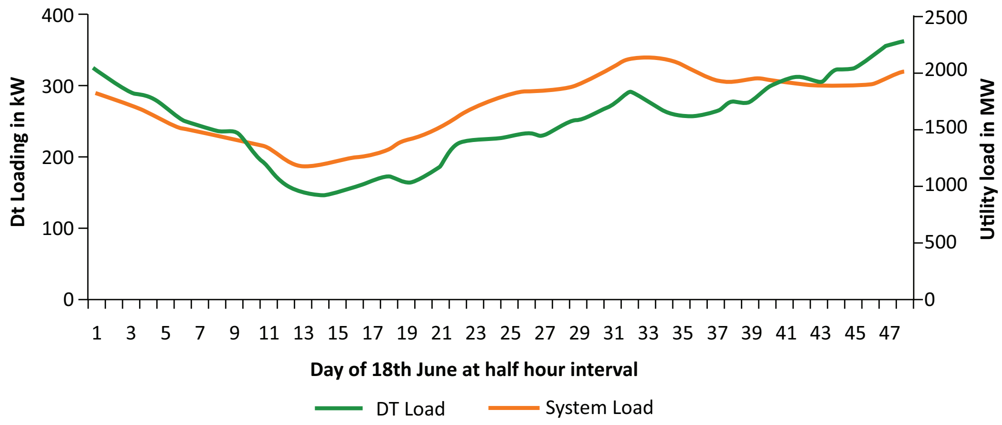


FIGURE 40: Load curve of the DT

The sizing of the BESS for the DT overload management application involved determining two quantities: (i) battery size in kWh and (ii) inverter/power converter unit rating in kVA. The sizing of these two invariably depends upon the level of peak-shaving required at the DT.

The sizing was done in the following two steps to arrive at the final rating of the BESS:

1. **Preliminary sizing:** Based on the total energy contained in the overload instances throughout the year to estimate the energy capacity as the rough size.
2. **Detailed sizing:** To rank all the overload instances according to their peak overshoots and identify whether the size obtained in step 1 is sufficient to completely meet all instances of overload, that is, sufficient charging time is available to bring the battery to a particular SoC level sufficient to meet the next duration of overload.

The control methodology aims to reduce the stress on the DT by the placement of BESS at the LT side. Charge/discharge rate limitations have also been proposed in this study for the safe operation of the battery pack as a high rate of charge or discharge may lead to a hazardous impact on the overall system as the battery state of health (SOH) depends on the rate of charge/discharge. It is therefore proposed to limit these values and if it exceeds the limiting value then the rate will be fixed at those limiting values (0.3 C in charging mode and 0.8 C during discharging as depicted in the flow diagram given in Figure 41).

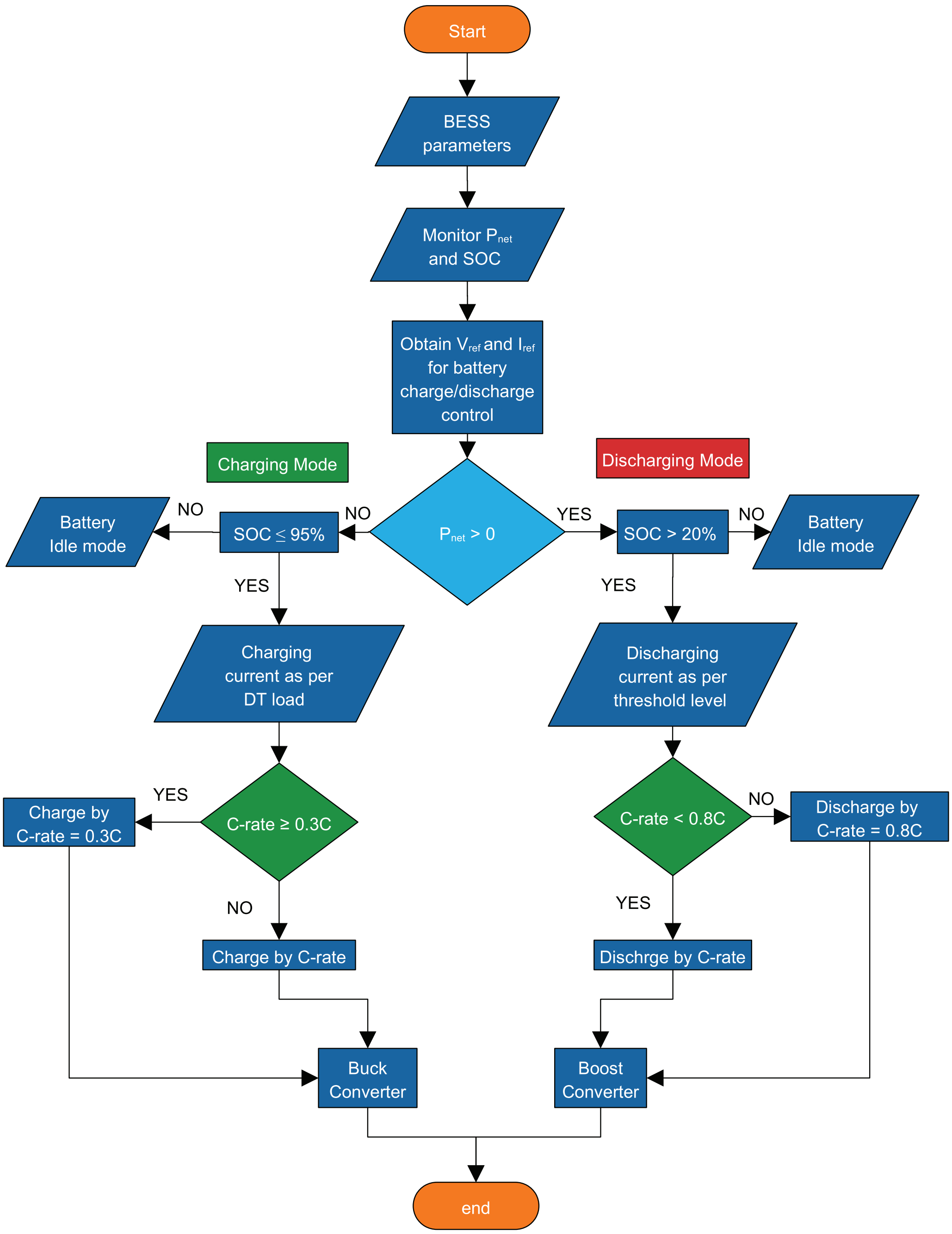


FIGURE 41: Flow chart for battery charge/discharge control methodology

The cost-benefit analysis of BESS depends on various factors such as BESS application, technology, government support towards technology implementation (through viability gap funding and associated funds), land availability (whether taken on leased or purchased), and other location-specific factors. Hence, a case-based approach should be adopted to perform (CBA) for more accurate results. Battery prices are continuously falling; therefore, it is essential to compute results under present and envisaged future costs after two to three years. Therefore, an appropriate time to invest in BESS should be selected.

So far, sections of this chapter have discussed how the size of the BESS for the present loading conditions is calculated, besides discussing associated benefits to cost weightage. However, taking into consideration the estimated number of cycles that a BESS will last for the presented application, it is important to project when the DT may get overloaded again, even after installation of a BESS, and what would be the number of years of deferring the DT's augmentation. Accordingly, the size required to manage the overload and the associated benefits (and costs) will change and must be projected for different compound annual growth rates (CAGR) of loading on the DT. This would depend on the CAGR in load and hence different scenarios of CAGR trajectory are important to study.

Figure42shows the CAGR-based loading analysis of the DT and what year will the threshold be crossed if different growth trajectories are followed. The number of instances shown on the Y-axis represents the number of days in a month when overloading is observed. This relates to the overloading criterion of the utility which says that any seven days of above 80% loading for two consecutive months qualify a DT to be overloaded. Accordingly, the threshold of seven days has been marked as a red-colored horizontal line on the curve. It can be seen that at a CGAR of 5%, the DT becomes overloaded in the seventh year and the number of such instances increases linearly.

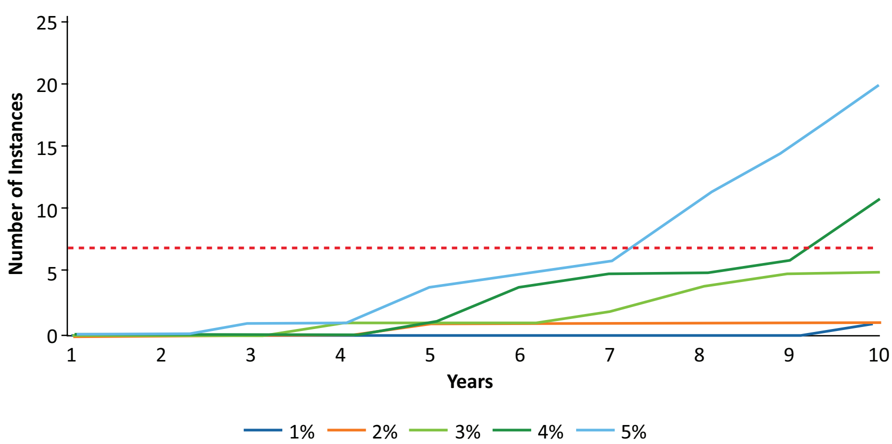


FIGURE 42: CAGR-based loading analysis of DT

Figure 43 shows the required BESS size for meeting the overload instances and the corresponding cost-benefit ratio and the project NPV to quantify the anticipated benefits for different scenarios of CAGR.

												@250 $/kWh	
CAGR/ Year	1	2	3	4	5	6	7	8	9	10	BESS Rating kWh*/kW*	NPV	Cost to Benefit Ratio
1%											231/71	(7,852,244)	0.57
2%											231/112	(9,821,100)	0.53
3%											231/157	(11,922,117)	0.49
4%											300/208	(15,383,420)	0.49
5%											860/262	(24,580,202)	0.57
estimated as per the present loading conditions i.e. 230 kWh/ 157 kW											*BESS Capacity required to suffice all overloading instances for 10 years		

FIGURE 43: BESS size for meeting overload instances corresponding to NPV and cost to benefit ratio

CAGR of DT load is observed to be a significant parameter to justify the investment in BESS at the LT side of DT. Installation of BESS is a justifiable solution in congested areas and preferably in areas of saturated load growth. Another important outcome is to go for phased installation instead of installing the whole capacity upfront to capture the benefits of falling prices of batteries.

2.3.5 Other Applications

Energy storage systems are considered enabling technologies for different smart grids' functionalities such as active management of network assets, network flexibility, improve power quality, self-healing, and resiliency. Many energy storage technologies are now available in the market with different capabilities and characteristics, which make them very useful in a wide range of applications. Also, energy storage systems can be designed in different sizes and capacities which can be placed at various locations throughout the grid, ranging from being distributed at consumers' levels, to being located at transmission-level as a utility-scale storage system. Two major factors characterize the type of application of an energy storage system: (i) the amount of stored energy and (ii) the rate of energy transferred. A list of some of these applications is given in Table 20.

TABLE 20: List of some key applications of energy storage systems

Grid application	Technical consideration
Arbitrage: Electric energy time-shift involves the storage of energy during periods of low prices or excess of RE, which then can be used or sold at a later time when the prices are high or at times of low renewable output.	Typical storage size: 1–500 MW Discharge duration:>1 h minimum Minimum cycles/year: + 250
Electric supply capacity: Utilizing energy storage to defer or reduce the need to buy new central station generation capacity or purchasing capacity in the wholesale electricity marketplace.	Typical storage size: 1–500 MW Discharge duration: 2–6 h Minimum cycles/year: 5–100
Regulation: It is a part of the ancillary services and involves managing interchange flows within the network and handles momentary variations in demand within the control area for maintaining system frequency.	Typical storage: 10–40 MW Discharge duration: 15 min to 1 h Minimum cycles/year: 250–10,000

TABLE 20: List of some key applications of energy storage systems

Grid application	Technical consideration
Voltage support: Provision of reactive power from energy storage rather than the power plants placed near large loads.	Typical storage size: 1–10 MVAr Discharge duration: not applicable Minimum cycles/year: not applicable
Load following/Ramping up of renewables: Characterized by power output that generally changes as often as every several minutes. The output changes in response to the changing balance between electric supply and load within a specific area.	Typical storage size: 1–100 MW Discharge duration: 15 min to 1 h Minimum cycles/year: not applicable
Transmission/distribution upgrade deferral: Delaying and in some cases avoiding utility investments in transmission/distribution system upgrades, by utilizing energy storage to relieve heavily loaded lines and reduces the need for upgrading distribution transformers to handle the increase in demand.	Transmission: Typical storage size: 10–100 MW Discharge duration: 2–8 h Minimum cycles/year: 10–50 Distribution: Typical storage size: 500 kW–10 MW Discharge duration: 1–4 h Minimum cycles/year: 50–100

2.4 Lessons Learned

As discussed in the previous sub-section, a few pilot installations have been done in India for demonstrating the various applications of energy storage in the power system. Some of these projects have been into a considerable duration of operation and some operational insights and experiences would be worth noting. Notably, the PGCIL pilot at Puducherry is the largest in terms of the storage size deployed. Testing for power system frequency-response was observed to be the widely used objectives of the pilots (including the TPDDL case) amongst a few other small applications, however, a lot of ground-based insights were obtained relating to the operations of such systems. Some of these learning are summarized as follows:

1. It has been found that BESS can be configured for various applications and it is possible by changing the operational logic of the EMS. However, any major changes in the control logic may also require hardware reconfigurations.
2. The DSM penalty-reduction application using BESS is not found to be encouraged enough by power utilities and there are mainly regulatory challenges in terms of recognizing energy storage as a grid asset and uncertainty associated with a change in regulations.
3. From field results, it has been found that the auxiliary consumption (specifically observed in the case of the Puducherry pilot) of the BESS is on a slightly higher side than anticipated and it also depends on the ambient conditions, therefore, sufficient consideration has to be given while sizing the system.

4. The BESS is a temporary solution for overload management specifically for the areas where the load is still expected to grow. At the same time, more benefits can be reaped if load growth downstream of distribution equipment has been saturated.

5. Looking at this from an economic perspective is very important as the cost of battery packs (usually mentioned in the literature) is only 30–50% of the total cost of the BESS, depending on the ticket size of the project and other local factors such as location. Thus, understanding the cost of other parts of a BESS is equally significant. The LCOE is an industry-wide accepted measure but in the case of BESS, LCOE calculations are a little tedious. As capital costs for all battery systems are presented for battery capital and management systems (expressed in terms of $/kWh), balance of plant (BOP) ($/kW), power conversion systems (PCS) ($/kW) to arrive at the capital cost of the BESS as a whole based on the kWh/kW rating of the system. But some cost components are difficult to segregate on a kW and kWh basis such as construction and civil infrastructure cost. Figure 44 details the percentage share of different components based on the ticket size. This is an indicative estimate as the costs of components are dependent on multiple factors.

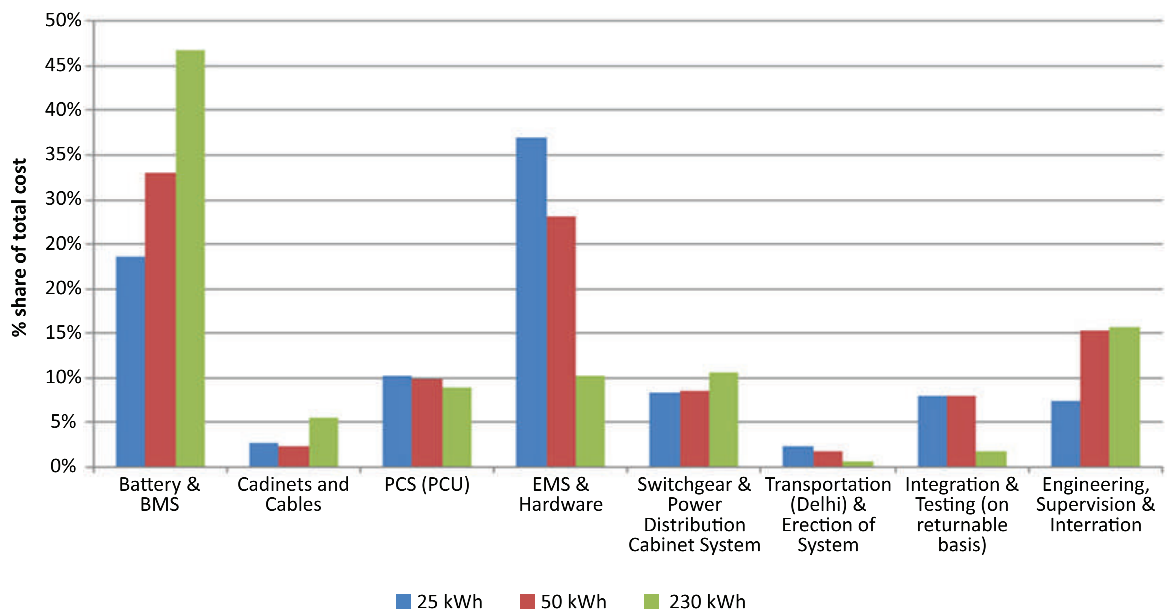


FIGURE 44: Cost of 25, 50, and 230 kWh Li-ion system

The percentage of components varies with ticket size, power rating, warranty terms and conditions, and other local conditions such as temperature, location. For a BESS of MWh scale, the cost of battery packs may fall in the range of 30–40% of the total cost. Another system with higher power requirements will have higher PCS cost, also, higher battery packs cost due to better performance, thus, expensive battery cells that can provide higher C-rates operations. The range of cost of different components of BESS for different technologies is presented in Figure 45. The PCS cost remains more or less the same for all the technologies but significant variation can be seen in the cost of battery packs and conversion cost. The length of the bars represents the possibilities of variation in cost due to local conditions, designing aspects, and other factors.

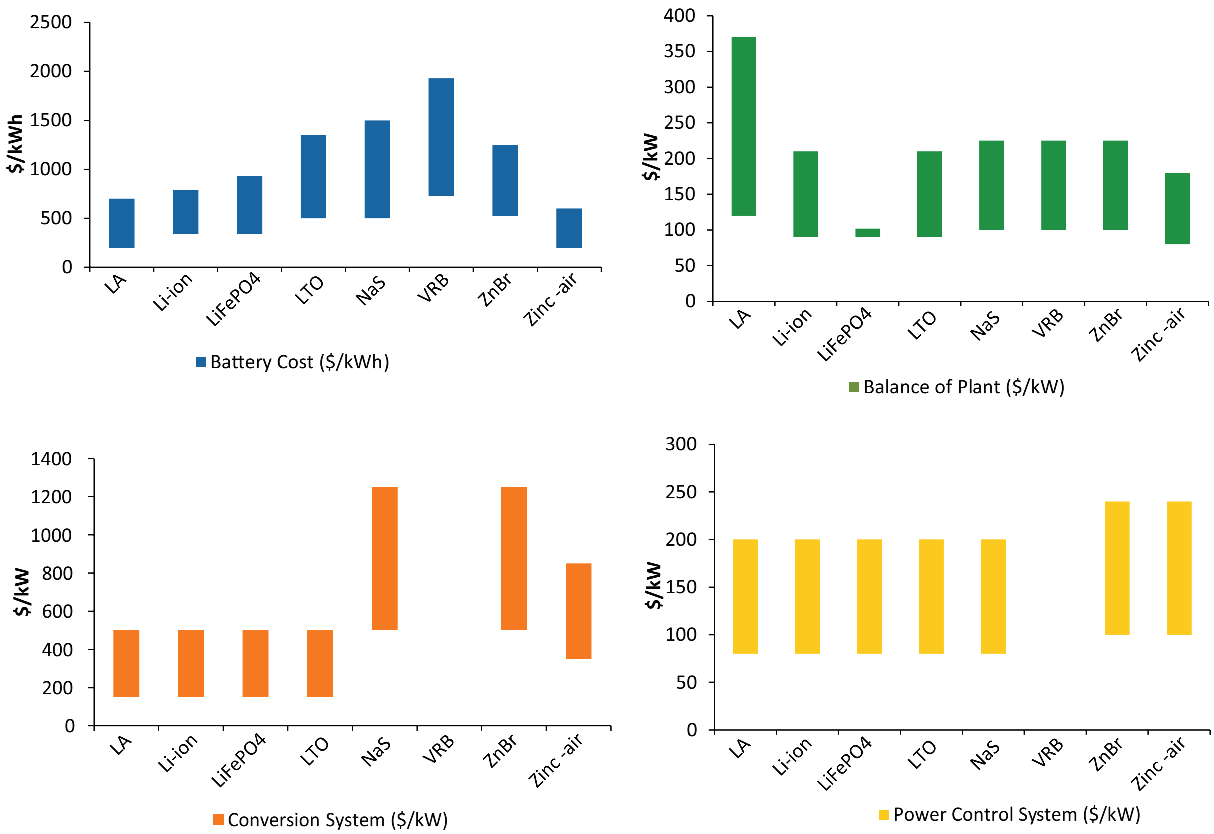


FIGURE 45: The range of cost of different components of BESS for different technologies

Source: TERI Analysis. Details available at<https://www.pnm.com/documents/396023/1506047/11-06-17+PNM+Energy+Storage+Report+-+Draft+-+RevC.pdf/04ca7143-1dbe-79e1-8549-294be656f4ca>

As mentioned, it is difficult to segregate total cost on per kW and per kWh basis, thus, to be more precise and obtain accurate calculations of LCOE, it is advised to treat each case as different and calculate LCOE based on the total capital investments instead of estimating generic cost estimates based on kW/kWh rating of the BESS.

LCOE has been used as an industry-wide accepted measure to examine the economic viability of flexibility sources, which is a little complex for a BESS. As such systems provide multiple benefits; there are multiple revenue streams to be taken into account. The stack of revenue streams has to be intelligently done considering the designing aspects of the system and evaluating the possibility of overlapping of applications. The cost-benefit assessment from the system also depends on business models and different ownership structures, which are discussed in the ensuing section. The main points of the discussion will be who owns the storage assets and whether the network and market values are captured. Battery cost, which is falling rapidly is still the most significant driver of project viability. Costs depend on the power-to-energy ratio of the battery. The terminal value at the end of the project's economic life also has a bearing, with a higher terminal value improving project economics.

Different business models and ownership structures

The predictable and unpredictable imbalance between demand and supply creates demand for storage solutions of different duration along the entire value chain of the energy system. Table 21 presents the potential ownership and financial mechanism for the battery energy storage system.

TABLE 21: Possible ownerships and financing mechanisms

Probable owners	Financing mechanism
Transmission utility-owned Distribution utility-owned	Capex
IPP-owned (including RE)	Battery as a service (BAAS)
Third-party service provider	
Load dispatch centres	
Shared ownership	

India has a decade-long experience in terms of operating models and financing mechanisms with the solar industry. The Indian power sector is well versed in the relevance of these models and financing mechanisms. Sufficient learning and experience are required for installing a system under RESCO. The possible ownership models and multiple applications add more dimensions to BESS in comparison to solar. BESS, being a balancing source, has got operational admissibility throughout the power evacuation chain. Energy storage systems can be owned by a wide range of owners: electricity generating companies, DISCOMs, transmission utilities, merchant power plants, bulk power consumers, and unrelated third parties. In this context, another challenge is the dependence of regulatory treatment on the ownership of energy storage assets which includes market entry fees, cost recovery structures/mechanisms (pricing), grid integration, use of licensee's assets, and revenue sharing.

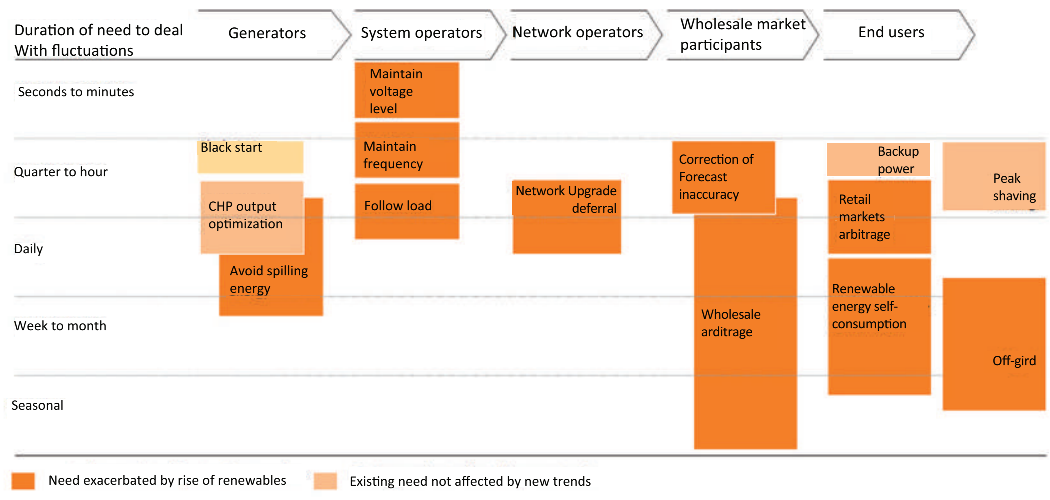


FIGURE 46: Energy storage needs along the value chain[27]

27 Berger, R. 2017 (May). Business Models in Energy Storage – energy storage can bring utilities back into the game. Roland Berger GmbH

The multiple applications across the value chain (indicated in figure 46)leave scope for shared ownership. For example, a BESS system used for overload management of distribution equipment renders it useless for approximately 8–10 months of a year as distribution equipment remains persistently overloaded only for 2–3 months a year. For the remaining time, BESS may be utilized by some other application or maybe by another stakeholder. Based on the ownership, application and recovery method, and contract type, ESS has been deployed broadly on three categories - i) generation coupled asset; ii) grid asset and iii) merchant asset.

Sonnen and Lichtblick are developing peer-to-peer networks where consumers can share their solar PV production and battery capacity. Sonnen is one of the leading energy storage system makers in Germany. The company experiments on a new concept called SonnenFlat in Australia, which allows owners of the battery system to participate in the market. Customers who also need to have a roof solar system installed can pay a small monthly fee in exchange for an annual consumption allowance. The small monthly fee replaces conventional usage charge (for example, $/kWh) and fixed supply charge (for example, $/day), which is much lower than purchasing power from the grid. In return, Sonnet can use the capacity of its batteries by offering frequency services to the grid operator. The company claimed that a similar project in Germany has created an economic value of $550 per customer. Trade-in power between consumers is feasible at lower than retail tariffs, but higher than the feed-in tariffs. Besides, the community of batteries can be used to provide ancillary services to the grid, tapping into additional revenue streams.

One of the operational use cases of Tesla's battery packs is the installation of 52 MWh (13MW) lithium-ion BESS in association with Kauai Island Utility Cooperative (KIUC).[28] The units are installed near a solar farm with an installed capacity of 13 MW. According to the agreement, KIUC agrees to buy power from the battery system for 20 years at the rate of 13.9 cents per unit which is economical than the tariff of existing diesel power plants during evening peaks. The BESS caters to multiple energy needs of the island, which are to maximize the solar output potential, reduce the reliance on fossil fuel plants (less favorable supply due to oil price fluctuation and higher emissions), and reduce the price of electricity during peak hours.

In 2017, Tesla also installed a 20-MW 4-hour lithium-ion battery system at Southern California Edison's Mira Loma substation in Ontario.[29] The BESS is charged during the daytime when solar production reaches its maximum and releases power during evening peaks. The project is part of an emergency response to the potential power shortage due to a huge leak from the Alison Canyon natural gas storage facility in 2015. The gas storage leakage has driven the growth of BESS in the last couple of years since utilities have to look for alternatives in a very short period to provide a secure supply during peak hours. Battery storage in the cases above is used to address specific needs in the energy system. First, there needs to be sufficient cheap energy production that can guarantee battery charging at minimum costs. This is usually the case when large-scale RE sources are available (such as in California and Hawaii). Second, the costs of using battery storage are cheaper for specific services (providing peaking services) than any existing technology. Third, there is an urgent need to replace the existing generators due to unexpected

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28 Wagman, D. 2017. Tesla Teams With Tiny Hawaiian Utility to Store Solar. *IEEE Spectrum*

29 Cardwell, D. 2017. Tesla Gives the California Power Grid A Battery Boost. *The New York Times*

closure (the Alison Canyon gas storage facility leakage reduced gas availability). Therefore, costs were not the primary concern compared to security. Nevertheless, these experiments gradually improve the applications of batteries at different scales in different locations, which in turn provide valuable insights into the growth of battery systems in electricity markets

In February 2020, In India, one of the significant turning points for the storage sector was seen, with the successful auction of SECI 1.2 GW of RE storage tender with guaranteed peak power supply. The renewable technology could be a solar system, a wind energy system, or a hybrid system, and storage could include BESS, pumped hydro storage, mechanical and chemical systems, or combinations thereof. Out of which 0.9 GW was won by Greenko and 0.3 GW by ReNew Power. Greenko opted for PHS while ReNew is planning BESS. ReNew offered a peak tariff of INR 6.85, a unit, and Levelized tariff of INR 3.60 which is even lower than the cost of new thermal power plants where the tariff is in the range of INR 4.5–6/ unit. The tariff rate, the need for round-the-clock supply, 80% annual CUF, and 100% power from renewable sources made this one of the most unique tenders of the Indian RE sector. As per the tender conditions, DISCOMS can ask for a peak power supply for 9 hours (morning peak 6.00–9.00 AM and evening peak from 6.00–12.00 PM) during the 24 hours of the day. The minimum energy storage system (ESS)-rated energy capacity installed shall be equal to "X/2" MWh, where X is the contracted capacity of the project as per PPA. Therefore, for ReNew, the BESS-rated capacity would be 150 MWh, while for GreenkoPHS capacity would be 450 MWh.

Likewise, larger systems of batteries are mainly used to provide grid-support functions and target a single revenue source. Application today is mainly in grids characterized by bottlenecks or those that are not well-connected to other regions. The revenues are highly dependent on rules and regulations, especially in the last couple of years, since utilities have to look for alternatives in a very short period to provide secure supply during peak hours. Battery storage in the cases discussed is used to address specific pain areas in the power system. First, there needs to be sufficient cheap energy production that can guarantee battery charging at minimum costs. This is usually the case when large-scale RE sources are available (such as in California and Hawaii). Second, the costs of using battery storage are cheaper for specific services (providing peaking services) than any existing technology. Third, there is an urgent need to replace the existing generators due to unexpected closure (the Alison Canyon gas storage facility leakage reduced gas availability). Therefore, costs are not the primary concern compared to security. Fourth, there is an important need for government bodies such as SECI in India to minimize the uptake risk and act as a demand aggregator. Nevertheless, these experiments gradually improve the applications of batteries at different scales in different locations, which in turn provide valuable insights into the growth of battery systems in electricity markets

Plausible revenue streams and stacking of revenues

Batteries mainly address a single purpose, but will increasingly be used for many different goals to optimize their value. The value of batteries can be better monetized when several revenue streams are targeted, especially when the various storage needs are not concurrent. However, regulation of ownership should enable this; it will also give rise to new business models on the ownership and management of batteries. Figure 47 shows applications of BESS at distribution downstream with associated plausible revenue streams. One application may have multiple revenue streams, depending on local conditions. Though, revenue streams may or may not add up, discussed next.

Applications and Revenue Streams

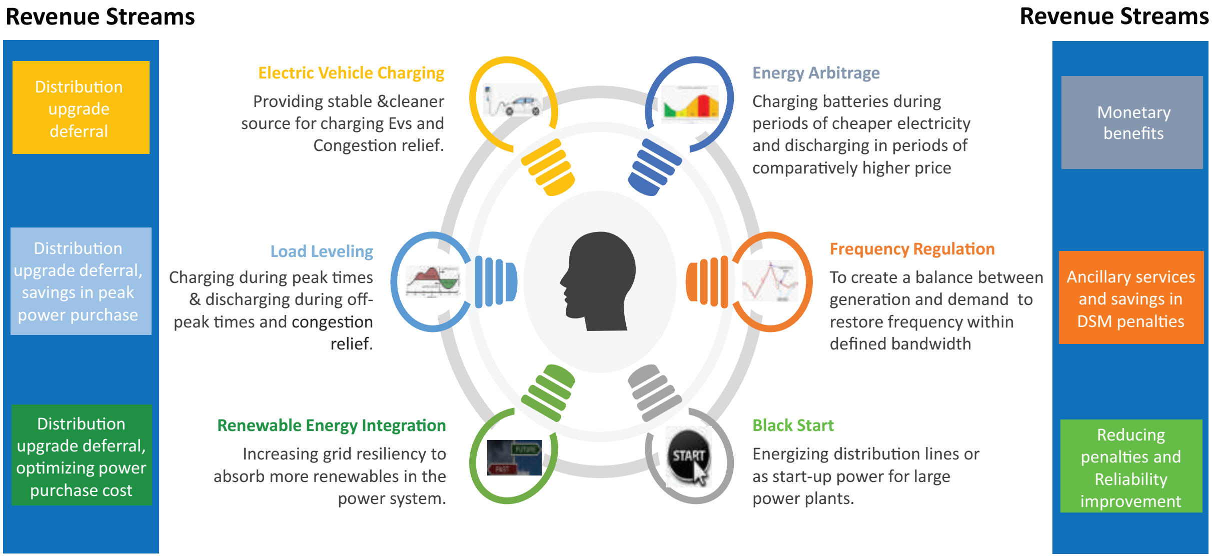

FIGURE 47: Plausible applications and corresponding revenue streams of energy storage systems

For example, in the case of overload management, we can count peak power purchase as one of the revenue streams if the loading of the distribution equipment is in symmetry with the system load of the distribution utility. In the case of urban microgrids, such systems are more beneficial for the distribution utilities which encounter afternoon system peaks by sizing urban microgrids with more solar capacity in proportion to energy storage. The stacking depends on multiple factors such as load patterns and their symmetry with system load, frequency of sustained loading of distribution equipment, local conditions, reliability and quality of current electricity supply, scale of installation, ownership, etc.

A grid-scale BESS is defined by various applications that it can serve to mitigate some of the broad challenges, as previously discussed. The technology, size, operational strategies, and various benefits that it can offer, are all dictated by the application(s) that a BESS can serve.

The marginal cost of power generation from renewables like solar and wind is zero. Hence, power from RE sources must be utilized as much as possible without any curtailments. However, forecasting these technologies is a difficult task that may involve inaccuracies up to 15%. These uncertainties may lead to high DSM penalties, load shedding, etc. Thus, a balancing source such as battery energy storage may be deployed to efficiently manage power scheduling and dispatch. The ultimate benefit of installing a grid-scale battery energy storage system is flattening of load curve, which may have indirect benefits such as:

» Better prediction of demand and thus optimization of the signing of power purchase agreements. This may reduce the total power purchase cost.

» Reduction in deviation settlement mechanism penalties due to better prediction of variable generation through RE sources.

- Reducing peak load requirement by providing ramping capacity. Hence, avoiding buying expensive power from peaking power plants.
- Better utilization of distribution system infrastructure by avoiding frequent upgrades required only for sporadic peaks. Thus, benefits in terms of investment deferral.
- Increasing the life of the distribution equipment due to sustained optimal loading and also reducing I^2R losses.

Though batteries are an expensive asset at this point, a study assessing the cumulative impact of batteries on aggregate revenue requirement (ARR) can be beneficial.

3. Policy and **Regulatory Scenario**

PHS is an established technology and sufficient clarity on regulatory aspects is available but at the same time, batteries for utility-scale applications are at nascent stages. This requires an enabling regulatory framework to provide initial support till battery energy storage becomes a self-sustainable technology. The absence of a regulatory framework for energy storage systems is one of the hindrances to its large-scale proliferation, as acknowledged by the Central Electricity Regulatory Commission (CERC) in 2018 in its staff paper on Introduction of Electricity Storage System in India (Figure 48). A decisive regulatory framework is essential for attracting investments in this sector.

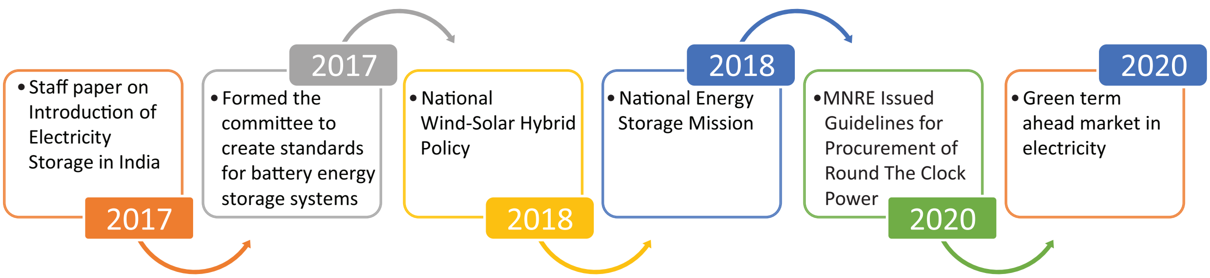

FIGURE 48: National Developments to promote energy storage

3.1 Key Policy Initiatives

From a regulatory perspective, there have been some developments in PHS. In 2017, the CERC released a staff paper on energy storage requirements for the Indian grid.[30] The staff paper initiated the discussions on energy storage in India around prima facie operational use cases, ownerships, prospective stakeholders, and prospective uncertainties in the energy storage ecosystem. The introduction of the staff paper was followed by the formation of the committee to create standards of BESS. The National Wind–Solar Hybrid Policy was introduced by the Ministry of New and Renewable Energy (MNRE) in 2018. This policy essentially aims at establishing a structure based on which large-scale wind-solar hybrid power projects can be promoted. MNRE has defined some purposes for which storage devices might be integrated with a hybrid power project which include:

» To improve the consistency with which the hybrid plant delivers output

» To enable the delivery of higher output than sanctioned load by increasing the capacity of the hybrid plant

» To ensure uninterrupted power supply

The benefits enjoyed by solar and wind power plants such as RPO eligibility apply to the project as a whole, thus, energy storage also receives similar benefits.

[30] Central Electricity Regulatory Commission. (CERC). 2017 (January). Staff Paper on Introduction of Electricity Storage System in India. Details available at http://www.cercind.gov.in/2017/draft_reg/SP.pdf

The proliferation of grid-level battery storage is majorly dependent on the slope of falling price trajectory which depends on the demand of batteries in a country, manufacturing capabilities and efficiencies, hold on supply chains, etc. The energy storage mission by Niti Aayog acknowledges the fact the electric vehicle (EV) adoption in India will be a significant factor to generate the demand for batteries in India, with possible opportunities for India under different scenarios.

Further, recently, MNRE issued guidelines for tariff-based competitive bidding process for procurement of round-the-clock (RTC) power from grid-connected RE power projects, complemented with power from coal-based thermal power projects under Section 63 of Electricity Act, 2003. Generators shall supply dispatchable RE power combined with thermal power, in an RTC manner, keeping a minimum of 85% annual availability and also at least 85% availability during peak hours. Peak hours were four hours out of 24 hours and must be specified by the procurer beforehand in the bidding documents. Generators got the leverage to combine energy storage systems for ensuring that it achieves the required minimum annual availability of 85%. However, annually a minimum of 51% of energy shall be supplied from RE sources. This 51% shall also include the output of electricity through the storage system, provided RE sources were used to store energy in the storage system. The bidder will also have the flexibility to choose the type of storage system to be installed like battery energy storage systems, pumped storage systems, mechanical and chemical systems. As an outcome, 400 MW RE projects with RTC supply conducted by SECI resulted in a first-year tariff of INR2.90/kWh. The first-year tariff shall be escalated @3% on an annual basis, up to the 15th year of the 25-year term of the PPA. As a result, the effective tariff for the said project amounts to INR3.59/kWh. However, there has been no declaration on energy storage capacity from winning parties. If, at all, energy storage will be the part of generation assets remains a question considering series of amendments by SECI, starting from 29 January 2020 (refer to table 22).

TABLE 22: Series of amendments by SECI

Request for selection: original terms	Request for selection: amended terms
Power generator to plan dispatch of electricity and inform the concerned state load dispatch center in advance	Deleted
Buying utilities to have the power to issue instructions to power generator to supply the electricity in a particular quantity and time	Deleted
It is mandated to make available the plant to the buying utility on an RTC basis	Deleted
The generated energy shall be dispatched through scheduling of power by the buying utility	Deleted
90% availability of the contracted supply for every year	80% capacity utilization factor cumulatively in a year; 70% in each month

TABLE 22: Series of amendments by SECI

Request for selection: original terms	Request for selection: amended terms
Availability of power to be defined in PPA with the distribution company	Deleted
The Lock-in period to own the project is 3 years	The project can be sold after one year
RPD to supply during supply hours on all days would be monitored every day	Deleted
RPD shall confirm power availability from the project 48 hours in advance	Deleted

Further, this compares well with another hybrid RE project which has been approved by the Maharashtra Electricity Regulatory Commission (MERC) in which Adani Electricity Mumbai Limited is contracting a 700-MW hybrid RE project with a CUF of 50% at a fixed tariff of INR 3.24/kWh for 25 years. This is being developed by Rosepetal Solar Energy Private Limited (a subsidiary of Adani Green Energy) and is expected to have an energy curtailment of 13%. It is likely to be fulfilled by a combination of 650 MW of wind and 650 MW of solar capacity. With the leverage to sell excess power in the markets and managing the cash flows, power markets offering better price signals would improve the economic viability of such projects.

After approving real-time market (RTM) trading in power exchanges, CERC approved green-term ahead market (GTAM) contracts on the Indian Energy Exchange (IEX) platform. Currently, IEX has been operating in the day-ahead market (DAM), term ahead market (TAM), renewable energy certificate (REC), and RTM. It offers an opportunity to corporates, generators, and other obligated entities better earnings prospects by using energy storage technologies and tapping energy arbitrage benefits. Further, the MNRE has a target to install 10,000 microgrids/500 MW of micro and mini-grids, which will offer an additional opportunity for energy storage.

3.2 Regulatory Interventions

Multiple areas require regulatory clarity in terms of:

» Application-wise tariff determination benchmarks, based on some predefined conditions as per Section 61 of Electricity Act, 2013

» Application-wise defined users for recovery of cost

» Cost recovery mechanism based on different ownership structures and the purpose for which storage assets are used

» Determination of the appropriate commission to have the jurisdiction

In the last decade, the RE tariffs have fallen reasonable to make such RE generation commercially viable. The history of RE sources induction in Indian power systems could be a solution to the swift integration of energy storage systems. The respective regulatory commissions can prescribe the appropriate share of storage in large-scale RE projects to SECI and at the distribution level and base level of distributed RE penetration. For example Haryana Electricity Regulatory Commission (Rooftop Solar Grid Interactive Systems Based on Net Metering) Regulations, 2019 has already stated that eligible consumer is mandated to install 25% battery storage for any incremental capacity of above 1 MW and up to 2 MW. This battery shall be able to store and deliver energy for two hours.

This could lead to appropriate price discovery, a competitive industry structure, and bring down the prices of storage systems. The idea is to start inducting small capacities of storage, so the consumer can absorb the marginal increase in the tariffs and until prices of energy storage technologies start making economic sense. Right decisions today could support the whole cause of arresting climatic change by not leading to more thermal power plants in the future with the increase in demand of India.

4. Stakeholder **Interaction**

This chapter briefly covers views and suggestions of stakeholders gathered during stakeholder interactions. These outcomes of discussion are broadly categorized under the scope of energy storage, regulatory and financial challenges in large-scale adoption. The key issues communicated by the stakeholders which include primarily, DISCOMs followed by system integrators, developers, and demand aggregators, in large-scale adoption of energy storage systems are brought out and explained under the aforementioned categories.

4.1 Scope of Energy Storage

Most of the stakeholders including DISCOMs are of opinion that energy storage is a new technology and is yet to find its niche in power systems. Though many large-scale pilot projects have been initiated globally, the operations of various stakeholders involved are still in the process of adopting energy storage technologies as an integral part of the electricity grid planning exercise. It is worth mentioning, SECI has a very important role to play in the large-scale adoption of energy storage, considering its present role in the development of large-scale solar installations, solar plants, and solar parks and to promote and commercialize the use of solar energy to reach the remotest corner of India. The main mandate of SECI is to promote renewable energy (RE), as 450 GW is targeted by 2030. Also, the changing load dynamics require adequate flexibility in the power system since an estimated load of 250 GW by 2030 would be present 5% of the time while the solar capacity itself would be 300 GW by 2030. However, since it is typical of solar to peak at noontime, there is a continued dependence on conventional sources of generation and these will have to ramp up from their technical minimum operational limit to the peak requirement during noon time if there is a sudden drop in solar generation. Hence the deficit can be supplied by BESS, however, on a larger note, BESS is required to absorb solar/wind generation in the system. Accordingly, SECI is studying three solutions and considering their feasibility after analyzing the typical grid pattern which shows a typical band of load for 12–16 hours between base and peak load. SECI has planned for specific PLF-targeted projects of solar + storage in Chhattisgarh and Leh where PLF of 37% and 55% have been targeted, respectively. This can meet the adequate requirement of an additional transmission network. Also, it is expected that 20% flexibility in the output of an RE generator can be expected after the addition of energy storage. On the contrary, developers are of the view that for the projects coupled with higher duration of storage leads to higher tariffs as LCOE increases due to high cost of batteries, and then DSICOMs may not prefer to buy electricity at such prices throughout the year. The DISCOMs prefer to buy from other generators and energy exchanges during peak times at more competent prices.

SECI mostly works on the generation side; however, in rooftop solar, it has shown willingness to work with DISCOMs to educate them about its benefits and to increase RE penetration through storage. SECI is involved in developing 10 distribution sub-stations integrating agro-photovoltaic and solar plus storage at the distribution network level in Tamil Nadu. There is planning for a tracker-type solar PV installation (regular and bi-facial type agro-PV system) and the objective of storage is generation flattening during the day. The energy storage unit will be of 1-hour duration to absorb the fluctuations of solar PV generation. SECI is investing in Tamil Nadu through a consortium mode and it may be operationalized through IPPs or RESCO mode through which different scales are possible. The state government will be giving the tariff initially which would be 30–40 P/unit more than the regular tariff.

DISCOMs believe that energy storage also seems to be one of the solutions to multiple operational issues faced by DISCOMs, specifically, BESS which can be integrated into local distribution networks to ease distribution grid operations. Every DISCOM is different from others; thus, operational challenges also differ from DISCOM to DISCOM. Here is the summarization of some operational challenges faced by the DISCOMs and corresponding redeemable revenue streams which can be partly or completely addressed by energy storage systems.

1. **Peak load management:** Economic development has contributed to increasing AC and heat loads. There has been a gradual change in the load pattern which depends on consumer mix and other local conditions such as temperature and geographical location. In the case of Madhya Pradesh, varied demand is in the range of 4–8 GW which poses challenges to distribution network management. The state has more agricultural demand and hence the power department of Madhya Pradesh has a banking facility with Punjab for purchasing the 1.9 GW power to manage the uneven demand. For a Delhi-based DISCOM, the ratio of peak and off-peak demand varies from 1.13 to 2.29, depending on the season to season. Also, distributed RE potential in terms of the solar rooftop is high in the case of cities with high-residential consumer density such as Delhi. There is a scope for further improving the load factor of the distribution grid.

2. **Managing agricultural load:** There are states with more proportion of agricultural consumers in comparison to other states such as Madhya Pradesh, Punjab, Haryana, and Karnataka. For example, Madhya Pradesh has more agricultural demand and hence the Power Department of Madhya Pradesh has a banking facility with Punjab for purchasing the 1900 MW power to manage the uneven demand. There have been Central-level schemes, emphasizing on separation of agricultural loads. States under the UDAY scheme of DISCOM debt restructuring are required to put up separate power feeders for agriculture load. Followed by guidelines issued by MNRE for the implementation of the INR 34,422 crore KUSUM scheme which makes DISCOM an obligated entity to purchase power from that commissioned solar power plants energizing electrical pumps. Karnataka is evaluating the implementation of 7 GW of solar coupled with 3 GWh of storage in Opex mode to cater to agricultural loads (pumps). This could help in shifting the consumption of agriculture pumping load to favorable times of peak system demand. Local solar power consumption shall not only help in reducing technical losses to supply end agricultural consumers but will also help in avoiding peak power purchases. However, the idea is still in the conceptualization stage. Such ideas stand valid for other agricultural-dominated states as well.

3. **Deferring distribution equipment upgrade in congested localities:** There exist some highly congested cities in India such as Mumbai, Delhi, Pune, and Kolkata where not only traffic congestion is a problem but upgrading power distribution equipment/network as and when required is a tedious task. There exist challenges in terms of the right of way issues, digging roads in case of underground cabling. The operation and maintenance investments to perform such upgrades could sometimes be hefty. The DISCOMs supplying electricity to such areas face these operational challenges.

   BESS has got relevance in the distribution grid of such DISCOMs in terms of peak load management without the requirement of any frequent distribution equipment upgrade and Right of way challenges.

4. **Improving power reliability:** Mumbai suffered the worst blackout in decades of over fifteen hours after a power outage. It took longer than expected for the power supply to resume because one of the two thermal power stations in the city and its vicinity, which have to act as a ready source as part of an islanding system to avert such situations, took longer to start generating power. The outage has established the need for black-start support at the distribution level as well.

   BESS has got relevance in such cities as well. A BESS can act as a source, energizing the local distribution grid in unforeseen situations such as distribution grid failure and supporting unplanned maintenance activities on the distribution network. However, operational use cases can be unique every time, depending on demand and supply patterns, power purchase portfolio, etc. For example, DISCOMs in Delhi have a mandate to supply uninterruptable power and are liable to pay penalties in cases of load shedding, such provisions do not exist for most of the distribution utilities in India. The avoided penalties add to the existing revenue streams in general such as fulfilling RPO targets, avoiding peak power purchase, better utilization of distribution grid infrastructure, etc.

5. **RE integration:** The increasing RE penetration at both supply and demand sides poses some operational and technical challenges, once RE penetration has increased beyond a certain benchmark. The solution lies in better prediction of variability on both supply and demand sides. Most of the DISCOMs feel that the current level of RE penetration is manageable and there is not much need for energy storage as such at this point in time to manage the current level of RE penetration. However, in near future, with further increasing penetration of RE and solar PV rooftop systems, the role of battery storage would become prominent as a local balancing fleet to sustain the agility of the distribution network.

6. **Arresting DSM penalties:** CERC has laid down the guidelines of deviation settlement mechanism (DSM), a set of guidelines determining the adherence of schedules as given by system operators to generators and load-serving entities. CERC had come up with the Fifth Amendment in regulation about DSM and related matters which is now referred to as Central Electricity Regulatory Commission (DSM and related matters) (Fifth Amendment) Regulations, 2019 with increased grid discipline in terms of narrowing frequency band and introduction of sign reversal penalties. The tightening of grid discipline with increasing RE penetration has resulted in hefty deviation settlement penalties to DISCOMs.

   But since forecasting and scheduling are the responsibility of a DISCOM, recognizing energy storage as a grid asset in case of aforesaid application would be a challenge in terms of regulatory approvals. Moreover, the unanticipated change in the regulations also adds to the existing uncertainty of regulatory recognition of energy storage as a grid asset to arrest DSM penalties.

7. **Energy arbitrage:** The increasing RE penetration has reduced the control of DISCOMs on the dispatchablity of power. Even, hydro-generation is sometimes dependent on other factors such as rainfall and demand of respective irrigation departments.

   The states such as West Bengal have a good potential for pumped hydro storage and they utilize hydro storage to supply during peak times while operating in pumping mode during off-peak times. A west Bengal-based DISCOM mentioned, though the gestation period is long and Capex requirements are high once commissioned remains intact up to 75–100 years with a change in machinery after 40 years. Another DISCOM mentioned that due to the high volume of power purchased from energy exchange and the good capacity of embedded generation, energy storage could act as an asset to monetize available energy arbitrage opportunities. This would result in a win-win situation for consumers, system operators, and DISCOMs.

8. **Renewable energy-based electric vehicle charging:** Renewable energy-based electric vehicle (EV) charging can also be seen as a plausible application. The charging of EVs during the daytime can be performed through solar PV-generated power while overnight charging can be done through BESS by utilizing additional energy stored. The proposed approach of clean energy-based EV charging may also reduce the technical losses in the line, especially when charging occurs through solar PV because the net amount of power flow in the local grid will be reduced significantly in case multiple EVs charging takes place at the same time.

   However, DISCOMs feel that given the current level of EV penetration, managing grid operations is not an issue. A Karnataka-based DISCOM mentions that existing EV charging stations in their licensee area had utilization of only 1%–2%. Thus, there was no immediate need for storage in the distribution grid. The distribution utility had identified highways to install EV charging infrastructure which could be electrified with solar coupled with storage systems with increasing adoption of EVs.

9. **Industrial applications:** The fast-responding batteries have also got relevance for behind-the-meter industrial applications as well where reliability is of utmost importance, considering complex manufacturing processes followed such as chemical factories where a minute duration of the outage may ruin the whole batch in process. The industries could also utilize the solar rooftop capacity better with a thoughtful capacity of battery storage. BESS can be used for energy arbitrage, charging batteries when the price of power is low, and sell in the grid when it is high. The time of day (ToD) tariff does not exist throughout the industrial segment and hence does not produce an economically feasible case. In the C&I segment, third-party (TP) ownership on the PPA / BOOT basis with industrial consumers can work well. However, the industry is not familiar with BESS and TP ownership will relieve them from taking a risk on technology, operation, and long-term maintenance

Overall, many DISCOMs and under apprehension about all features they require in the BESS to perform in the distribution network and build the business case accordingly. However, BESS can be equipped with many features but there is a cost to build the algorithms and hardware for it to perform in the distribution network. In case of the use changes, there is an additional cost to develop the software and add hardware if necessary.

4.2 Regulatory Challenges

The developers, system integrators, and demand aggregators are of the view that absorption of new technologies in the regulatory ecosystem is important from an investor's perspective. The same can be understood from the history of renewables when generation from solar PV was an expensive affair. The demand for solar PV from the countries such as Germany having high-paying consumers contributed to bringing prices of solar PV down. A similar pathway can be adopted; the pilot projects could be installed with some regulatory support. Such, pilot projects will help in better technological absorption and understanding the true value of energy storage with a marginal initial increase in tariff of the end consumer.

DISCOMs, in general, may not prefer power from RE generators which have been granted must-run status unless coupled with some energy storage technology. Energy storage technology may require an initial regulatory push in terms of directives from respective regulatory commissions to go for pilot projects and deliberation by Forum of Regulators to better manage induction of new storage technologies in the Indian power system. The enabling regulations will improve the prospects and better adoption of energy storage technologies in Indian power systems.

Many suggested that CEA could also update grid connectivity and safety regulations to accommodate stationary battery storage. The CERC could also specify the terms and conditions of tariff for battery energy storage technologies under Section 61 read with Section 178 of the EA Act for determination of tariff of the generating companies and transmission licensees who are covered under the jurisdiction of the Commission. The pollution control boards could also pitch in to ensure the safe disposal of batteries once the calendar life is over. The leading battery manufacturers said that they are committed to take back and safely dispose of this hardware at the end of their guaranteed life or during the middle of its useful life if they go bad. This service is usually priced in their offer. There seems no need for BESS owners to buy batteries from vendors who cannot dispose of them safely.

DISCOMs exemplified the FERC 2222 rule in the USA which broke new ground towards creating the grid of the future by knocking down barriers to entry for emerging technologies. The rule enabled distributed energy resource (DER) aggregators to compete in all regional organized wholesale electric markets. This bold action can empower new technologies to come online and participate on a level playing field, further enhancing competition, encouraging innovation, and driving down costs for consumers.

At the same time, DISCOMs are under apprehension about the space available to install storage systems at the distribution level, wherein unlike other cases of generation, space is arranged at the generator end. Though, battery storage has got advantages in terms of phased installation, high- energy density, and flexibility to install in rack systems. However, there is a need for ancillary markets to improve the economic aspects of the storage projects and gather participation from independent system operators. Recognizing energy storage technology as a grid asset would be an encouraging step towards a better uptake of such technologies.

The other stakeholders asserted that MoP was actively monitoring all the developments in the energy storage area and there would be regulatory interventions at the appropriate time in the form of an energy storage roadmap, including tariff-related guidelines from CERC. However, to uplift the entire ecosystem, the focus on battery manufacturing is important. The government could emphasize fixing the proportion of local content as did in the case of solar projects.

To summarize, institutional support includes (i) regulatory rate-based services from BESS to the DISCOMs' customers, (ii) accepting the investment as part of Capex of the DISCOMs, (iii), third-party investment in BESS based on long-term PPA with DISCOMs, iv) 6)There is a need of actionable and granular roadmap for adoption of energy storage for grid applications. We may not need storage till 2025 with the current level of RE penetration and after 2025, there could be more sensitivity to integrate battery storage technologies considering the actual need for storage and falling battery prices.

Energy storage has got relevance at multiple locations throughout the power evacuation chain. The ultimate beneficiary of such systems are DISCOMs and end consumers. Thus, it becomes imperative to have a clear and granular roadmap for energy storage adoption for grid-level technologies with proper timelines, considering falling battery prices and other alternatives, such as better forecasting and scheduling mechanisms.

4.3 Financial Challenges

All major stakeholders are of the consensus that the cost of battery storage technologies is a major challenge in large-scale adoption. But, an initial regulatory push can turn the opportunity to produce economies of scale. The different local conditions produce different operational use cases with different economics.

A Madhya Pradesh-based DISCOM stated that given the current operational challenges and business cases for utility and looking at current battery prices, the plausible application of BESS could be DSM, RE integration, and ramping requirement. However, the DISCOM is technology agnostic and whichever technology is suitable as per the requirement and cost constraint could be explored for demonstration purposes. The DISCOM further mentioned that utility ownership and battery as a service model could be viable financial models initially. However, regulatory pass-on through ARR is observed to be a challenge. The cost per unit of utility-scale battery is found to be more than INR 7/unit without considering the charging cost. Though, both Capex and Opex models have their merits and demerits in the Indian context. In the case of Capex, economic viability is an issue while in Opex mode; there are very few players in the market who are offering such solutions.

Multiple DISCOMs are interested in implementing stationary storage at the distribution level in the battery as a service model. A West Bengal-based DISCOM stated that they are overall positive about operational use cases of BESS at the distribution level and put their willingness to install BESS in MWh scale at one of the already identified sites. Preference for Opex mode was mentioned over making capital investments directly. The DISCOM further encouraged more studies at the distribution level to better appraise the true value of such systems, assess the impact on end-user tariffs, and evaluate different business models.

The BESS systems installed at the feeder level are relatively small (in the kWh range). Economies of scale effect would be delayed. Of course, the general declining trend of Battery prices will apply to small capacities as well, but the balance of system costs will not decline. The big challenge will be to operate decentralized systems installed in a distribution network in a manner that serve the objective(s) well. This will require cloud-based BESS management. Distribution companies are financially weak. The BESS asset requires regulatory approval and the services should be payable to the investor (DISCOMs or a third party). This implies that BESS capital expenditure (Capex) be treated like distribution services improvement investment and be made as a regulatory asset. At present, regulators are not able to agree to rate base the BESS, and DISCOMs are not interested to pay for Capex or Opex of the BESS.

Annexure 1: Month-wise charging & discharging duration of BESS

	00:15	00:30	00:45	02:00	02:15	02:30	02:45	03:00	03:15	03:30	03:45	04:00	04:15	04:30	04:45	05:00	05:15	07:00	07:15	07:30	07:45	08:00	08:15	08:30
Jan																								
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Mar																								
Apr																								
May																								
Jun																								
Jul																								
Aug																								
Sep																								
Oct																								
Nov																								
Dec																								

08:45	09:00	09:45	10:00	10:15	10:30	10:45	11:00	15:30	15:45	16:00	18:15	18:30	18:45	19:00	21:45	22:00	22:15	22:30	22:45	23:00	23:15	23:30	23:45	00:00

DUF Secretariat:
The Energy and Resources Institute,
6C, Darbari Seth Block, India Habitat Center Complex,
Lodhi Road, New Delhi, Delhi 110003
Email: DUF_Secretariat@teri.res.in
Phone: 91 11 41504900 Extn 2205

An initiative supported by:
Shakti Sustainable Energy Foundation,
4th floor, Capital Court, Munirka Phase III,
New Delhi 110067.
Phone: 91 11 474744000.
Email: powerteam@shaktifoundation.in