ESTIMATING ENERGY STORAGE REQUIREMENTS FOR RAJASTHAN GRID

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Abbreviation	Definition
ATC	Available Transfer Capability
AVVNL	Ajmer Vidyut Vitran Nigam Ltd
BASK	Bask Research Foundation
BESS	Battery Energy Storage System
BOOT	Build, Own, Operate, Transfer
CAGR	Compound annual growth rate
CEA	Central Electricity Authority
CERC	Central Electricity Regulatory Commission
CES	Customized Energy Solutions
CTPP	Chhabra Thermal Power Plant
CUF	Capacity Utilisation Factor
DISCOM	Electricity distribution company
EPS	Electric Power Survey
EU	European Utility Requirements
GST	Goods and Services Tax
GW	Giga Watt
IPP	Independent power producer
ISGS	Inter-state generating station
ISTS	Inter-state transmission system
JVVNL	Jaipur Vidyut Vitaran Nigam Ltd
LCOE	Levelized Cost of Energy
LFP	Lithium ferro-phosphate
MNRE	Ministry of New and Renewable Energy
MOP	Ministry of Power
MOU	Memorandum of understanding
MU	Million Units
MVA	Mega Volt Amperes
MW	Mega Watt
MYT	Multi-year tariff
NIWE	National Institute of Wind Energy

Abbreviation	Definition
NLDC	National Load Dispatch Center
NPCIL	Nuclear Power Corporation of India Ltd
NREL	National Renewable Energy Laboratory, USA
NRLDC	Northern Regional Load Despatch Centre
NSRDB	National Solar Radiation Database
PCS	Power conversion system
PHS	Pumped hydroelectricity storage
PLF	Plant Load Factor
POSOCO	Power System Operation Corporation
PPA	Power Purchase Agreement
PSA	Power Supply Agreement
PSP	Pumped Storage Plant
PV	Photovoltaic
RE	Renewable Energy
RERC	Rajasthan Electricity Regulatory Commission
REZ	Renewable energy zone
RJ	Rajasthan
RRECL	Rajasthan Renewable Energy Corporation Ltd
RTC	Round-the-clock
RUMSL	Rewa Ultra Mega Solar Ltd
RVPNL	Rajasthan Rajya Vidyut Prasaran Nigam Ltd
RVUN	Rajasthan Rajya Vidyut Utpadan Nigam Ltd
SECI	Solar Energy Corporation of India
SLDC	State Load Dispatch Centre
SOC	State of charge
STPS	Super Thermal Power Station
TNERC	Tamil Nadu Electricity Regulatory Commission
TPS	Thermal Power Station
TTC	Total Transfer Capability
WACC	Weighted average cost of capital
WRI	World Resources Institute

EXECUTIVE SUMMARY

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Rajasthan is the leading state in India for grid-scale renewable energy deployment, with 14 GW of solar PV generation capacity and 4.5 GW of wind generation capacity as of March 2022 (MNRE, 2022). By 2024-2025, the state plans to achieve 24 GW of grid scale solar, 3.5 GW of hybrid capacity and add 4 GW of wind capacity (Energy Department, Government of Rajasthan, 2019). This transition entails robust planning to enhance the overall grid stability with increased renewable integration by deploying flexible resources.

To support the government of Rajasthan along with the state regulator, state power utilities, and system operator in this transition, World Resources Institute India (WRII), CES and Bask Research undertook a long-term renewable capacity expansion planning study till 2030 which aims to help Rajasthan in its renewable energy integration plan with the support of BESS at grid level.

PyPSA (Python for Power System Analysis), an open-source toolbox, was used for simulating future generation and demand, and evaluating the energy storage requirements of Rajasthan in 2030. The findings presented in this study highlight that integrating BESS with a solar and wind energy-based power system is a feasible and economic pathway for Rajasthan's clean energy future. In any simulated Renewable Energy (RE) scenario, the addition of BESS lowers the Levelized Cost of Electricity (LCOE) of the system. Although the scale of the requirement is tied to RE penetration, its benefits in all the scenarios make it a universal solution.

There is a marginal benefit in LCOE (from INR 5.31/kWh to INR 5.30/kWh), when BESS is added in the low RE scenario. But, as the installed capacity increases and the system caters to increased peak export loads of 25 GW, 35 GW and 45 GW, the BESS benefits become more prominent. The addition of BESS brings down the LCOE from INR 6.32/ kWh to INR 6.20/ kWh in 25 GW export scenario, from INR 5.97/ kWh to INR 5.81/kWh in the 35 GW export scenario, and from INR 5.20/kWh to INR 5.15/kWh in the 45 GW export scenario.

In the simulated scenarios of this study, a storage asset is considered a standalone system, not coupled with a solar or wind asset. In view of the potential benefits of storage projects even in standalone form, a policy framework can be conceived for energy storage at a transmission level. So, in order to leverage the benefits of high renewable energy exports from Rajasthan, it is imperative that the transmission capacity expansion aligns with capacity addition in storage. The capacity planning of both assets can be complementary. In four simulated scenarios, this study evaluates the indicative annual capacity charges for transmission along with the respective storage sizing analysis.

The study also reveals that the introduction of long-duration pumped hydro storage lowers the total system cost in comparison to wind-solar-battery systems. The unit cost of electricity generation becomes lower with both PHS and BESS in the Rajasthan grid. In the 35 GW export scenario, the addition of BESS results in LCOE of INR 5.81/kWh, while inclusion of both BESS and PHS reduces the LCOE to INR 5.44/kWh. To ensure an economic discharge from PHS, a longer discharge duration becomes essential. As highlighted by the study results, BESS and PHS can fill complementary and unique roles, making both valuable to least-cost electricity systems.

Going forward, dedicated policy support mechanisms like capacity auctions for storage can help promote deployment by providing long-term revenue stability for a market player. Furthermore, a deep dive on the utility and economics of different storage technologies can be explored through ongoing research effort, to understand finer details of technology choices.

INTRODUCTION

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1. Rajasthan Power Generation Mix

Rajasthan is an Indian state in the country's northwestern region. Rajasthan leads the Indian states in solar PV generation capacity and wind generation capacity as of March 2022, with 14 GW and 4.5 GW, respectively (MNRE, 2022). According to the Solar Energy Policy 2019, the state has vast and largely untapped potential for intense solar irradiation, one of the highest numbers of annual sunny days and the availability of vast uncultivable & unutilised land (Energy Department, Government of Rajasthan, 2019). The state captures global horizontal irradiation of 4.8-5.8 kWh/m2 per day and direct normal irradiation of 4-5.5 kWh/ m2 per day with approximately 300 sunny days annually (Solargis for The World Bank, 2019).

Since 2020, the overall electricity landscape has been rapidly shifting towards renewable energy. As of July 2022, out of the total capacity installed within the state, renewable energy (wind & solar) constituted 54% of the installed capacity, followed by thermal power capacity at 39% (Central Electricity Authority, July 2022). The shift to renewable energy has also altered the market landscape , with IPPs owning nearly 64% of the total installed capacity within the state, as of July 2022 (compared to 51% as of July 2019) (Central of Electricity Authority, July 2019). However, in terms of electricity generation, thermal power continues to play a significant role in Rajasthan's portfolio. Herein, RVUN, a state entity, is the major player holding 60% of the thermal assets located within the state while the rest are either IPPs or Central Generating Stations. 91% of the total thermal installed capacity comes from coal, whereas the remaining 9% is contributed by gas (National Power Portal, 2022).

The generation capacity contribution of hydel sources is 5% (as of July 2022), while RERC provisioned for a 7% energy contribution through hydel sources in FY 2021-22 (Rajasthan Electricity Regulatory Commission, 2021). Hence, the grid's flexibility is somewhat constrained by a modest hydro energy generation catering to Rajasthan. Consequently, this limits the ramping capabilities of available generation assets, and adversely affects the grid balancing capabilities in high renewable generation scenarios. Further, Rajasthan doesn't have coal mines within the state except for a few lignite deposits and is dependent on coal mines across other states for fuel sourcing, which may exacerbate risks induced by externalities for Rajasthan's energy security.

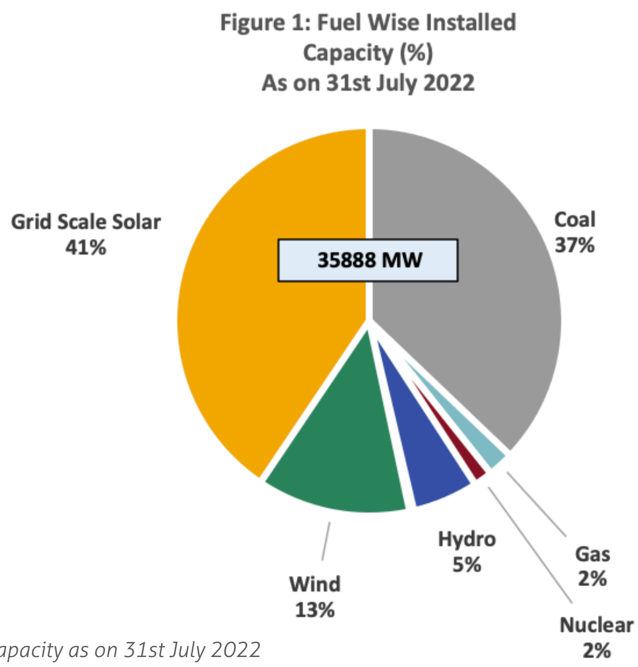


Figure 1: Fuel Wise Installed Capacity as on 31st July 2022

At the same time, the state has a potential of 142 GW for solar energy and large land tracts available for deployment (Energy Department, Government of Rajasthan, 2019). An ambitious state policy seeks to accelerate its deployment, shaping a spatial shift of local electricity generation from eastern Rajasthan to desert regions of western Rajasthan. By 2024-2025, the state plans to achieve 24 GW of grid scale solar, 3.5 GW of hybrid capacity and 4 GW of wind capacity (Energy Department, Government of Rajasthan 2019).

The state's average daily energy requirement of 245.76 MUs and a peak load of 15,752 MW as of 2022 (Northern Regional Load Despatch Centre, 2021-22) is far less than overall potential of 269 GW (solar and wind) and targeted deployment of 36 GW by 2025 (Energy Department, Government of Rajasthan, 2019). So, Rajasthan has limited capacity to consume its renewable energy potential within the state. This puts Rajasthan in a unique position, where it sees itself as a net exporter of renewable energy, especially to the neighbouring states of Punjab, Haryana and Gujarat.

But high RE penetration in the grid will create challenges for grid operators and power planners. While Rajasthan's transition to a RE-dominant grid is desirable, the following issues must be addressed:

Surplus RE Capacity:

The state aims for a cumulative solar capacity of 24 GW by 2025 (from the current 14 GW in 2022). And the state peak load demand will only increase to 21 GW by 2030 (from the current 16 GW). As solar generation exceeds increased demand, the issues of increasing intra-state consumption or creating avenues for exporting surplus solar generation become prominent. As a result, time shifting solar generation becomes a viable option that meets both needs.

Operational Limits of Coal Generation Assets:

For the grid to absorb increased RE generation, the coal plants in the state will need to operate flexibly (ramping at >1% per minute and lower technical minimum). Further, with the planned addition of new coal-based capacities, the technical limits of coal plant operation might be adversely pushed.

Transmission Capacity Expansion:

The expansion in export capacity of the transmission system also needs to be adequately planned (the current capacity is 5 GW) (Rajasthan SLDC, 2021). The transmission capacity expansion needs to be planned for optimum utilization and shall be key to higher RE integration.

In this study, deployment of energy storage at the grid level has been considered for mitigation of these challenges and to aid long term RE power planning in Rajasthan through BESS.

2. Scope and Objective of Analysis

World Resources Institute India (WRII), CES and Bask Research undertook this long-term renewable capacity expansion planning study, to support the government of Rajasthan, state regulatory commission, state power utilities, and the system operator in the journey towards the transition to high RE by 2030. The study aims to help Rajasthan in materialising its policy targets and RE integration plans till 2030 with the support of BESS at grid level. To determine the best possible energy mix in multiple scenarios, a production cost modelling framework was used to assess the overall generation system level cost.

PyPSA (Python for Power System Analysis), an open-source power system analysis package, was used for simulating supply and demand patterns while optimizing the electricity mix for the Rajasthan gridand evaluating the size and operation of energy storage for Rajasthan at grid level in 2030. The model considers multiple grid parameters on the demand side (current and forecasted demand - energy and capacity, power export etc), supply side (current and forecasted supply mix – energy and capacity, power import, long-term contracted capacities, plant-wise technical details, capacity of flexible assets, solar and wind availability profiles, RE expansion plans, etc.) and inter-state transmission capacities. The outputs of this model include a 2030 projection of generation mix (capacity and energy), power exports, generation fleet operations (daily generation), energy storage operational parameters (charging & discharging requirements) and generation cost.

This study looks beyond the near-term state targets (2024-25) to identify least-cost scenarios and opportunities by 2030 for the long-term development of Rajasthan's power system. The production cost model was run for multiple scenarios, considering different RE penetration levels and energy export cases. The scenarios were designed considering the current energy mix and the state's future plans.

3. Energy Storage – Applications, Benefits, and Trends

Energy storage finds application in various areas of electricity grid services – non-spinning reserve, energy arbitrage, frequency regulation, flexible ramping, black start support, voltage support and investment deferral for the T&D sector. Storage is especially useful in integrating more solar, wind, and distributed energy resources because it makes renewables much more reliable and firmer by reducing forced curtailments.

It aids in load shifting and peak generation, by smoothening the renewables supply curve while absorbing any excess generation during high resource periods and discharging the same during low resource periods. When the demand changes quickly, and flexibility is required, energy storage can inject or extract electricity to match the exact load – wherever, and whenever needed. In a nutshell, storage becomes an enabler in improving the grid balancing mechanism.

In this study, the analysis focuses on assessing the grid-scale storage system requirements for Rajasthan, including both battery storage and pumped hydro storage systems. Within battery storage, lithium-ion technology is discussed as it is more commercially viable. Figure 2 illustrates the various applications of BESS at grid-integration level.

Among the existing battery storage technologies under consideration, lithium-ion has been dominating the application spaces due to the exponential drop in costs and the ability to cater to varying application requirements up to 4 hours. Over the last one-decade (2011 – 2021), lithium-ion cells have seen a price drop of 86% (Figure 3). As of 2021, it stands at USD 132/kWh (Lazard, 2021). In 2022, even though supply chain constraints and inflation have driven up the average cell price to USD 150/kWh, the forecasted

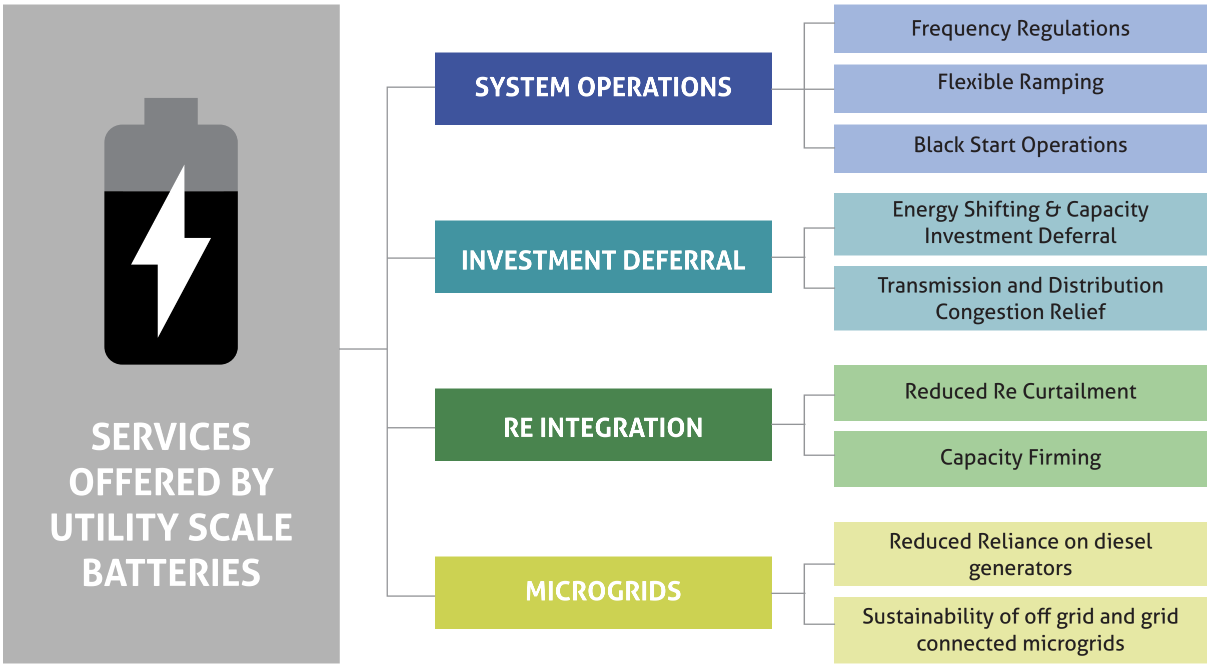


Figure 2: Applications of BESS at grid-integration level

price reduction trajectory (medium to long term) hasn't significantly altered. Although the price of a lithium-ion cell is still over USD 200/kWh for many applications, it is expected to fall to USD 127/kWh by 2023 and reach the USD 100/kWh benchmark by 2026 (BloombergNEF, 2022).

While evaluating the technology options for grid scale storage, pumped hydro storage was also reviewed. The Rajasthan government has undertaken an exercise to identify potential locations for pumped hydro storage and carry out a preliminary exploration study (Rajasthan Renewable Energy Corporation Ltd,

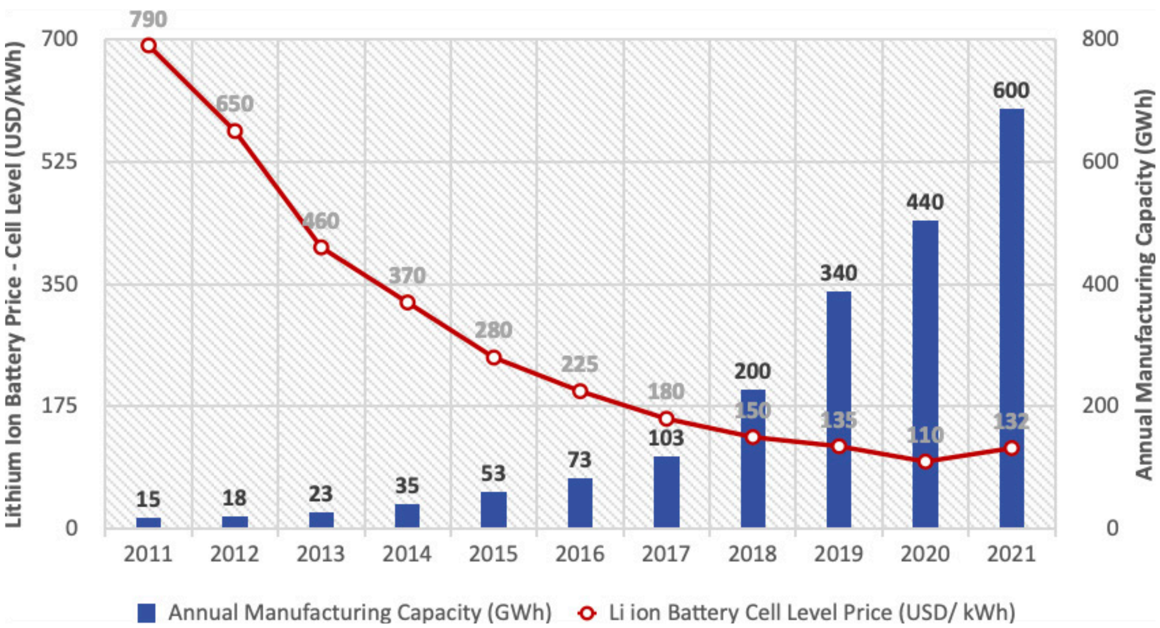


Figure 3: Lithium Cell Price vis-à-vis Global Lithium Battery Manufacturing Capacity

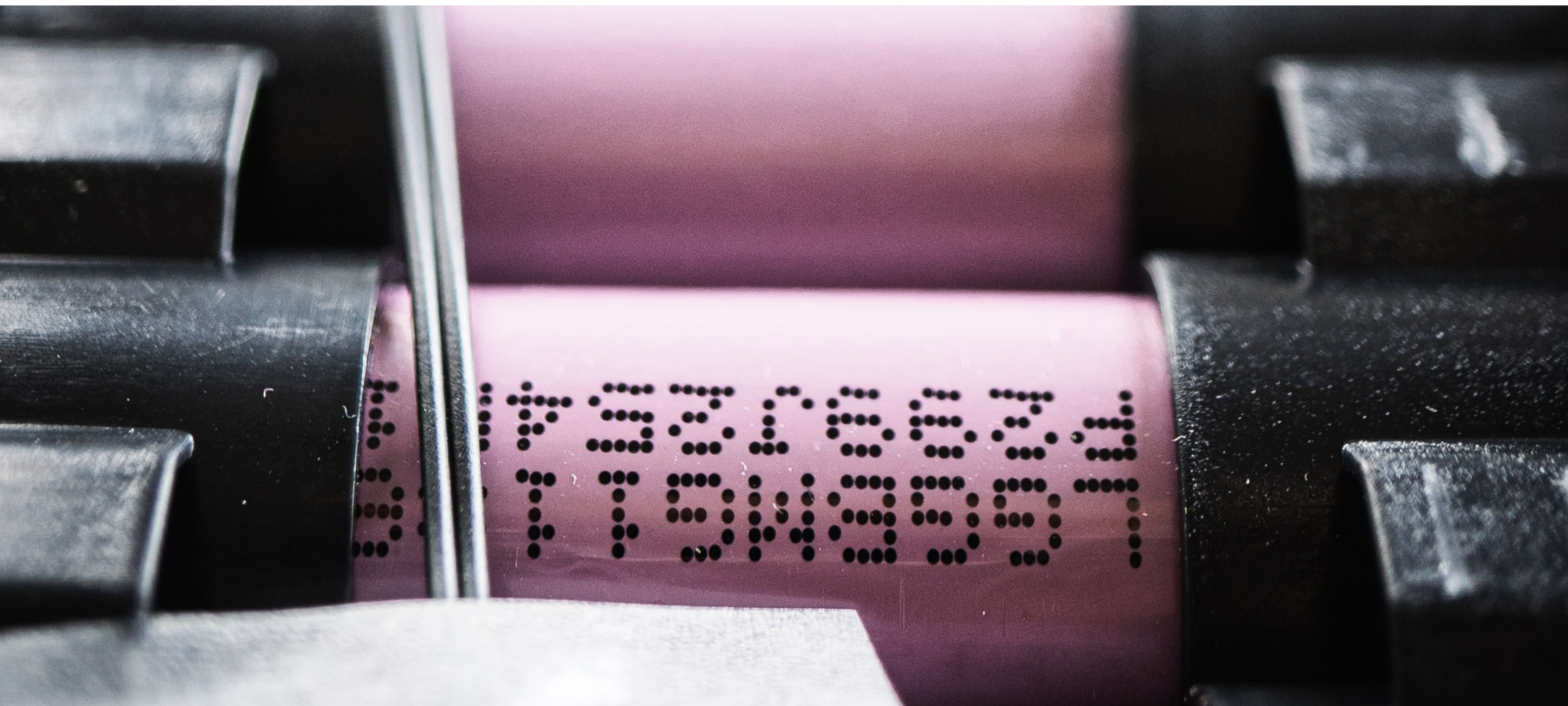
2022). While preliminary technical feasibility will be studied in this exercise, Greenko Group had previously identified three locations for pumped hydro storage projects in Rajasthan (Ministry of Environment, Forest and Climate Change - Forest Clearance, n.d.). The PHS projects are Shahpur (2520 MW), Sukhpura (2560 MW) and Teekhi Khera (2000 MW) (Greenko Compliance Report, 2021). Amongst these, the technical feasibility was evaluated for only Shahpur (2520 MW) (Greenko Energies Pvt Ltd, 2020). Shahpur is proposed not as a run-of-river project but as a standalone facility. Both the reservoirs of the facility will be located away from all existing river systems and have no or very small catchment area. Water will be lifted one time from the nearby Shahabad Kuno river to the PSP lower reservoir. As a closed cycle operation project, the water loss due to evaporation is expected to be minimal and will be replenished from the river. In view of the published feasibility study report, Greenko's 2520 MW Shahpur project is considered feasible by 2030.

Over time, the technological improvements seen in Lithium-ion energy storage along with the drop in battery cell prices, as shown in Figure 3, have made Lithium-ion energy storage competitive in comparison to other technologies (Lazard, 2021). As it stands, RE combined with battery storage is already more economical than newly built coal or peak load catering gas plants (Lazard, 2021).

Considering a few recent examples, the coal based thermal Power Purchase Agreement (PPA) signed between the Madhya Pradesh Power Management Company and Adani Power in May 2020, has a tariff of INR 4.79/kWh with escalation over the next 25 years (Financial Express, 2020). More recently, the 400 MW SECI RTC tender was won by Renew Power at a base year tariff of INR 2.9/kWh and an LCOE of INR 3.6/kWh (Renew Power, 2021).

Looking at global trends, the benchmark rates for utility-scale solar with storage in the US saw a 13% fall in LCOE from Q1 2020 to Q1 2021 (National Renewable Energy Laboratory, 2022). It is projected that the blended cost of renewables with storage (4 hours) will drop to around INR 4/kWh by 2027 (India Energy Storage Alliance, 2021). With more deployment of renewable projects coupled with storage, it is envisaged that the price of battery storage technologies, especially Li-ion will further drop considering technological improvements and scaling up of manufacturing facilities in India and across the globe. A 60-MW 4-hour utility scale BESS installation is projected to cost US$190/kWh or US$750/kW by 2030 (a reduction of 46% from 2020 costs) (National Renewable Energy Laboratory, 2022).

Considering all the advantages of BESS integration, a study has been conducted to assess storage sizes in an economic manner. The details of modelling process are described in the following sections.



SYSTEM ANALYSIS

3

Integration of variable and intermittent renewable resources into the grid demands that all factors affecting reliable operation be considered while planning the system. In this study, a production cost modelling-based approach is pursued to analyse Rajasthan's future electricity grid and solution for cost optimal expansion options of storage assets in the state. In this section the modelling approach is briefly discussed, along with the input data and key assumptions.

3.1 Introduction to Production Cost Model used

Production cost models are optimization models that try to minimize the overall cost incurred for electricity generation to reliably balance the load at high temporal and spatial resolution. The cost calculated in the model includes both fixed and variable costs. While balancing generation and load, production cost models also account for various operational constraints of the electricity system such as ramp rates, technical minimums, transmission thermal limits, generator ratings, renewable resource variability, etc. Thus, these models provide a means to create a simplified representation of the system and simulate its operation at the desired resolution. Application of this framework at high resolution allows evaluation of the impact of renewable resources. Using the model one can simulate power dispatch in different scenarios and thereby address questions related to system operation, capacity adequacy, flexibility requirements, generation curtailment, emissions etc.

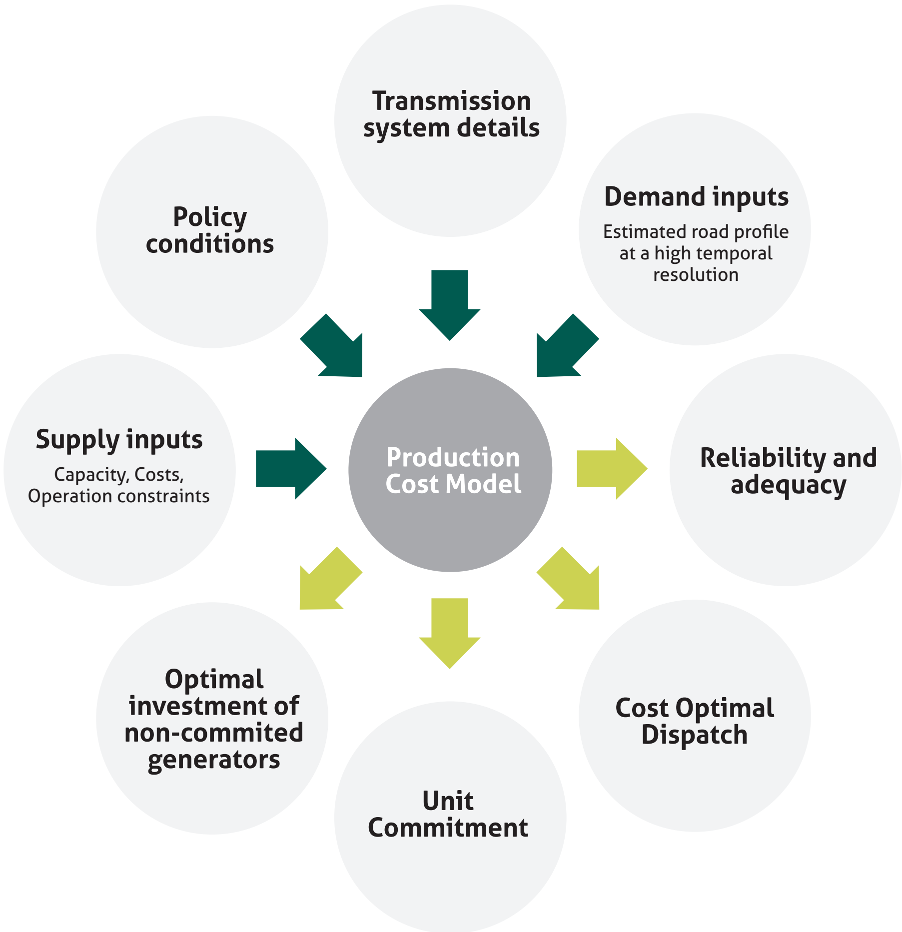


Figure 4: Input and Outputs of Production Cost Model

In this study, a representative model of the state grid of Rajasthan is constructed. It is a single node model that uses aggregate load from across the state as a time series. The generation capacity is considered at the unit level for conventional plants and the aggregated capacity for renewables. An open-source power system modeling framework called PyPSA (Python for Power System Analysis) is utilized to develop the model. The model has been augmented with additional constraints to suitably depict participation of seasonal resources (Figure 4). Furthermore, certain policy and regulation targets have been introduced as input constraints. The model developed using PyPSA minimizes the total system cost for the simulation period while considering all the system operating constraints. Also, since the model accounts for both fixed and variable costs, it can also evaluate investment options in power system. Therefore, while assessing the expansion of storage technologies, the model solves for the optimal system dispatch considering unit commitment of thermal plants.

With this model, scenario analysis has been done to gauge the requirement for energy storage technologies in the system. The specific inputs, scenarios and assumptions of the study are discussed in further sections. In each scenario, several metrics were calculated from the dispatch to understand the economics. The total system cost, total fixed cost, total variable cost, additional system level investments, total generation, total curtailment, utilization factors of all the generation sources, per unit levelized costs are calculated. A side by side comparison of a scenario with and without the expansion of storage shows the impact of addition of storage. A schematic of the system level analysis is shown below (Figure 5).

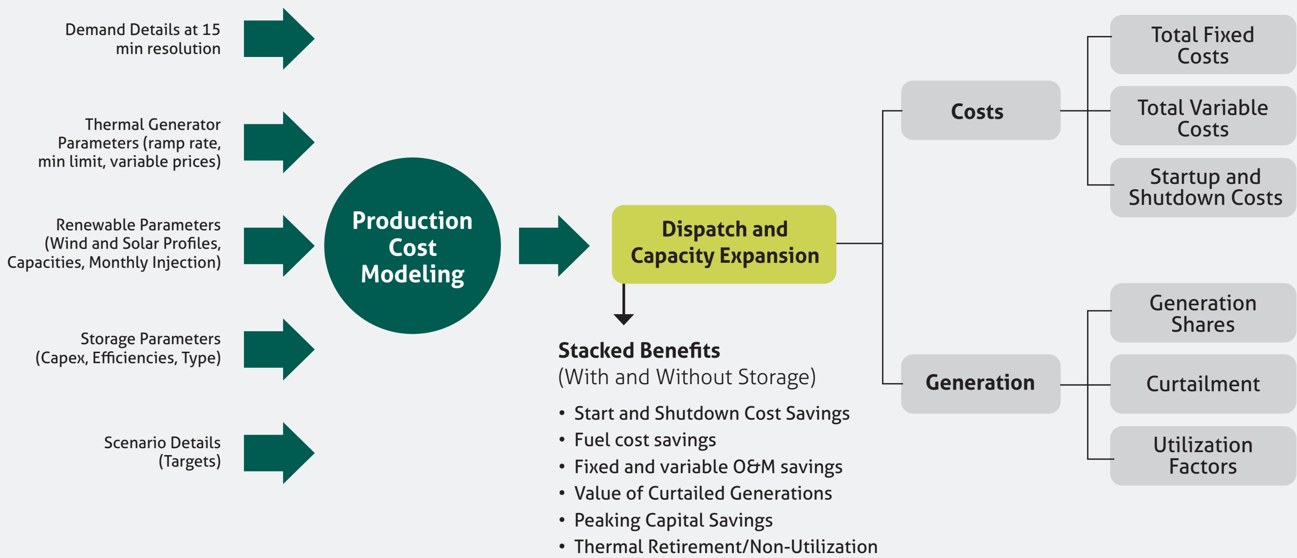


Figure 5: Process Flow - Modelling

3.2 Assumptions and Limitations

1. Projected Load Profile in 2030

As per the 19th Electric Power Survey published by the Central Electricity Authority, the demand projection for Rajasthan showed a CAGR between 5.47% – 5.97% in peak power demand. In total energy demand, the corresponding CAGR was 5.41% – 5.44% (Central Electricity Authority, 2019).

Rajasthan's 15-min block wise load profile in FY 2021-2022 is constructed based on analysis of the daily peak power demand & energy demand (Energy Analytics Lab - IIT Kanpur, 2022).

As per the projections for 2030, the peak annual load is projected at 21 GW, whereas the corresponding

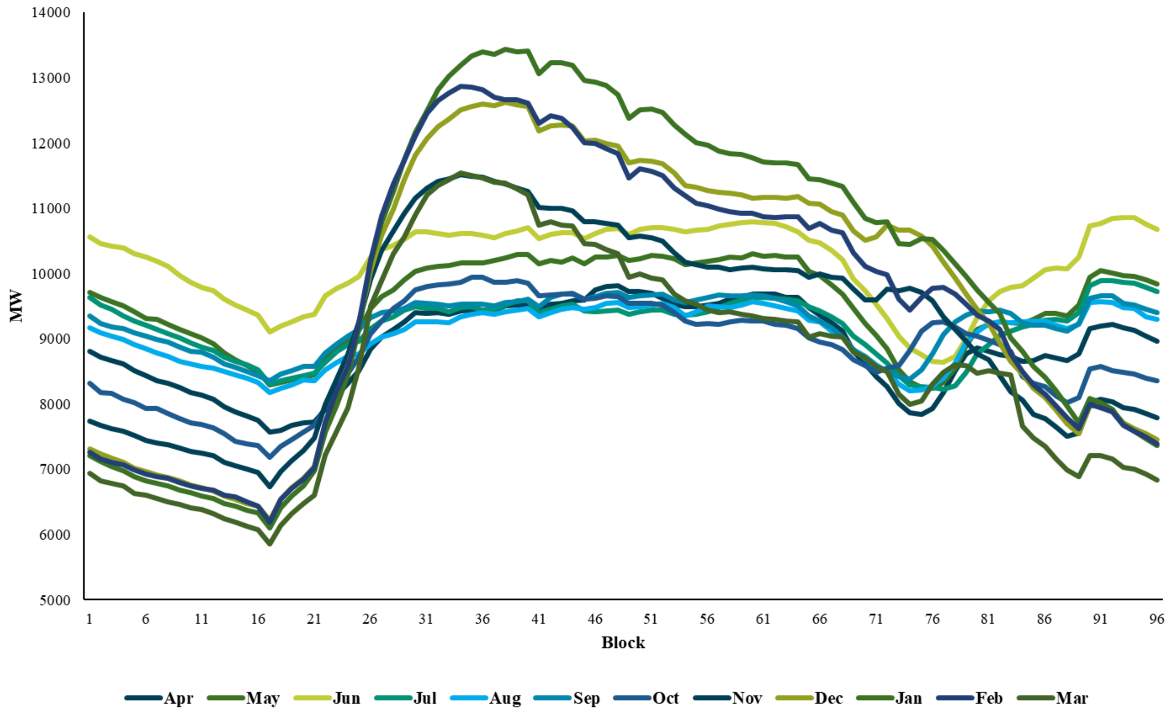


Figure 6: Average Load Profile 2021-22

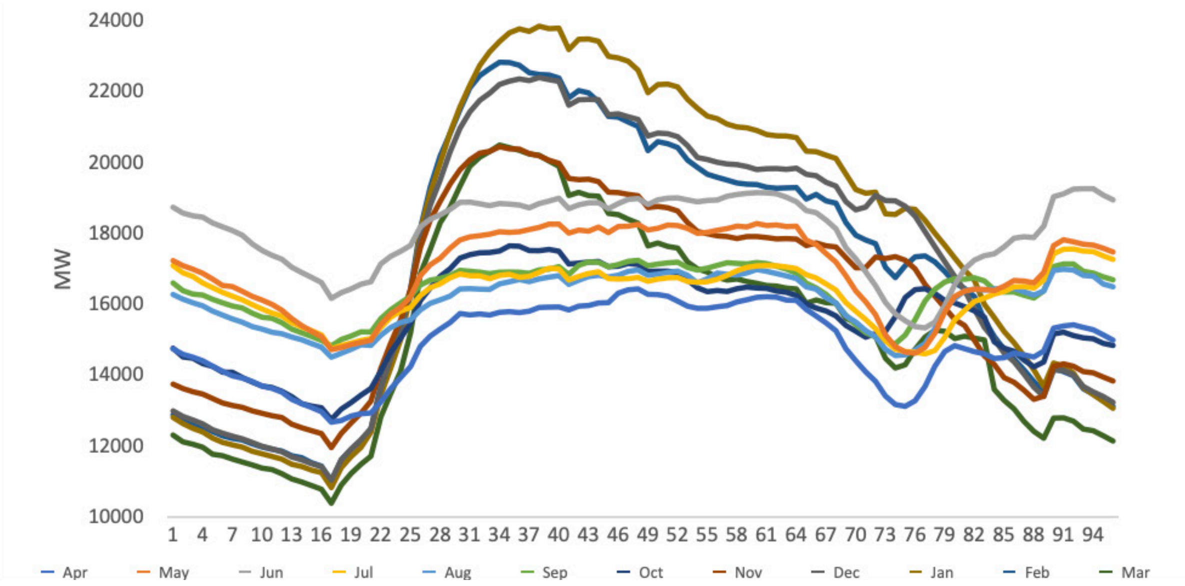


Figure 7: Average Load Profile 2029-30

peak in 2022 is 16 GW. The ratio of these two annual peak power demands is 1.31, which implies a CAGR of 3.4% between 2022 – 2030. Following a conservative estimate of 3.4% CAGR, a 15-min block wise load profile is constructed for 2030, assuming the hourly and seasonal pattern is similar to that in 2022.

2. Renewable Resource Availability

- Hourly solar and wind profiles were interpolated for 15-min time blocks from NREL database (NREL - National Solar Radiation Database, 2019) and NIWE database (National Institute of Wind Energy, n.d.). The annual average CUFs for solar and wind were assumed to be approx. 23.6% and 25.2%, respectively.
- Generation from hydro plants were considered to be similar to the previous years (2020, 2021), on a monthly level (RVPN, 2020, 2021).

3. Tariff and Tariff Escalation of Generation Assets

- RERC approved tariffs effective for FY 2021-22 were considered for the fixed & variable costs of coal, gas and hydro generation assets; and LCOE for nuclear, biomass, wind and solar generation assets (Rajasthan Electricity Regulatory Commission, 2021). The LCOE of nuclear plants was split into fixed & variable cost based on Lazard's analysis (Lazard, 2021). The LCOE of biomass plants was split into fixed & variable cost based on RERC's order on biomass energy tariff effective for FY 2021-22 (Rajasthan Electricity Regulatory Commission, 2021).
- For coal, gas and nuclear generation plants, 5.8% CAGR in annual fixed cost and 2.3% CAGR in variable cost is considered. The CAGR values were calculated based on the submitted tariff petitions of Jaipur Vidyut Vitran Nigam Limited from FY 2014-15 to FY 2019-20.
- For solar and wind generation plants, fixed tariffs were considered till 2030 (based on 2022 figures). This assumption aligns with the current regime of auction based fixed solar and wind tariff contracts in the country. In May 2022, in RUMSL's auction for the 300 MW floating solar park in Madhya Pradesh, the lowest bid winning tariff was INR 3.21/kWh, with no escalation (Powerline Magazine, 2022). Also in May 2022, SECI's auction for the 1.2 GW interstate transmission system-connected wind power projects (Tranche XII), saw the lowest winning tariff of INR 2.89/kWh, with no escalation (Powerline Magazine, 2022).
- No tariff escalation was considered for the hydro power stations and biomass plants.

4. Equivalent Annual Cost of BESS

- Capital Cost: As per the market estimates for 2030, the capital cost (pre-tax) of a lithium ferro-phosphate (LFP) battery pack and PCS is projected at US$180/kWh and US$70, respectively. For Vanadium redox flow batteries of 6-hour and 8-hour durations, the projected capital costs (pre-tax) are US$300/kWh and US$250/kWh, respectively. Based on prevailing taxes, a GST rate of 18% is assumed for battery packs and PCS.
- WACC: The International Energy Agency highlighted that the WACCs for new utility scale solar PV projects stood between 8.8-10.0% in India (in nominal terms after tax) (International Energy Agency, 2021). For the annual fixed cost assessment of a grid scale BESS project, WACC is assumed at 10%.
- Operating Parameters

Chemistry	Cycle Life	Storage duration hours	Total Project Cost ($/kWh)	Project capex (INR/MWh)	Equivalent Annual Cost per MWh	Fixed Cost (Rs/ MW)
LFP	6000	1	295	2,21,25,000	29,09,002	29,09,002
LFP	6000	2	254	1,90,27,500	25,01,742	50,03,484
LFP	6000	3	240	1,79,95,000	23,65,989	70,97,966
LFP	6000	4	233	1,74,78,750	22,98,112	91,92,448
Vanadium	15000	6	354	2,65,50,000	29,25,040	1,75,50,238
Vanadium	15000	8	295	2,21,25,000	24,37,533	1,95,00,264

LFP Chemistry Parameters (Yuliya Preger, 2020) (PowerTech Systems, n.d.)

Vanadium Chemistry Parameters (H.R. Jiang, 2020) (CIC EnergiGUNE, 2021)

Chemistry	Asset Life (Years)	Efficiency	SOC
LFP	8-10	85%	90%
Vanadium	25	70%	100%

Table 1: BESS Operating Parameters

5. Coal Capacity in 2030

Additions: As of March 2022, the contracted coal-based generation capacity of Rajasthan is 12691 MW. As per the Rajasthan government's Budget for 2022-23, the following additional capacities in coal are expected to be commissioned by 2030 (Finance Department, Rajasthan Govt, 2022) –

- Chhabra Super Critical thermal: 1320 MW
- Kalisindh Super Critical thermal: 800 MW
- Gurha Bikaner: 125 MW

Retirements: The Ministry of Power, Government of India vide its guidelines dated 22nd March 2021, has enabled the distribution companies to either continue with or exit from PPAs after completion of the term of the PPA i.e., beyond 25 years or the period specified in PPA. In view of the same, RERC vide order dated 28th October 2021, allowed the Rajasthan distribution companies to relinquish their allocation from the following coal generating station units w.e.f February 2022 (Rajasthan Electricity Regulatory Commission, 2021).

- Feroze Gandhi Unchahar Thermal Power Plant Unit I of 20 MW
- Farakka Super Thermal Power Plant Units 1, 2, 3, 4, 5 aggregating to 11 MW

Based on MOP and RERC's observations, it seems very likely that Kota TPS Units 1, 2, 3, 4, 5 aggregating to 850 MW will be decommissioned by 2030, as their operational life will be almost 40 years. The Rajasthan distribution companies are also likely to relinquish their allocation from all Singrauli STPS units aggregating to 300 MW, who have presently attained 35 years of operational life.

6. Gas Capacity in 2030

Additions: No new gas-based capacity is expected to be installed

Retirements: Based on the same Ministry of Power guidelines dated 22nd March 2021, and RERC order dated 28th October 2021, as mentioned previously, the Rajasthan distribution companies were allowed to relinquish their allocation from the following gas generating station units w.e.f February 2022 (Rajasthan Electricity Regulatory Commission, 2021).

- Anta Gas (all units) of 83 MW
- Auraiya Gas (all units) of 61 MW
- Dadri Gas (all units) of 77 MW

7. Nuclear Capacity in 2030

Additions: As per NPCIL's project assessment, Rajasthan Atomic Power Project Units 7 & 8 aggregating to 1400 MW, is expected to be commissioned before 2030 (Nuclear Power Corporation of India Limited, 2021).

Retirements: No decommissioning is assumed in this period.

8. Technical Minimum

Coal-based Thermal

A POSOCO study has shown the technical minimum limits of coal power plants in Rajasthan, based on operational data from 2011 to 2018 (POSOCO, 2020). The technical minimum limits of the power plants with more than 90% capacity allocation to Rajasthan are as follows: Chhabra CTPP units: 65-69%; Giral TPS: 73%; Kalisindh TPS units: 66-69%; Kota TPS units: 68-74%; Suratgarh TPS units: 65-74%; Adani Kawai units: 68-71%; RajWest Power: 46%; Barsingsar Lignite: 69%.

On the other hand, CERC has introduced 55% technical minimum for coal power plants, at central level (CERC Indian Electricity Grid Code, 2010). In view of the same, 55% is assumed in the model calibration for the present-day scenario. For the 2030 scenarios, 50% is assumed as the technical minimum (as the Regulations allow the reduction in technical minimum below 55%) (POSOCO Comments on Draft CERC Regulations, 2019).

Gas-based Thermal

Dholpur and Ramgarh are the only gas-based generation plants with entire capacity allocation to Rajasthan. There is no national or state level recommendation on the technical limits of gas power plants. Based on a case study which illustrates the operational results of a 110 MW combined-cycle power unit at minimum loads (George Marin, 2020), 35% is assumed to be the technical limit.

Nuclear Plant

According to the EUR, a nuclear plant unit is capable of continuous operation between 50% and 100% of its rated power (Sustainable Nuclear Energy Technology Platform, 2020). For the modelling, we have assumed 55% as the minimum operating capacity.

9. Ramp Rate

POSOCO guidelines based on CERC Tariff Regulations, 2019 state that in the case of coal power plants, the normative ramp rate is 1% per minute (POSOCO, 2020). The guidelines also note that combined cycle gas power stations can exhibit much higher ramp rates than 1% as per CEA standards. On average, the coal-based power plants across the world have ramp rates within 1% - 4% per minute, combined cycle gas turbines are between 2% - 4%, and open cycle gas turbines are within 8% - 12%. Hydro generators are able to provide ramp rates of the order of 10% - 30% per minute; however, the utilization is restricted at times due to various environmental constraints (National Renewable Energy Laboratory, 2020).

1% is assumed as the ramp rate for coal, and the same rate for nuclear plants, as the minimum ramp rate would lead to cost-effective operations. For gas and hydro plants, the ramp rate is considered at 3% per minute.

10. Pumped Hydro Storage Parameters in 2030

Parameters of Greenko Shahpur pumped hydro storage project are considered in the model. The data parameters from the Pre-feasibility report of the project (Greenko Energies Pvt Ltd, 2020) are furnished herein.

Greenko is planning to construct two artificial reservoirs (with no run-of-the-river system) to build a closed loop system.

Tariff

TNERC in Tariff Order for TANGEDCO, has approved a fixed cost of INR 221 Cr (in FY 2022-23) for Kadamparai pumped storage power plant, which has a capacity of 400 MW (Tamil Nadu Electricity Regulatory Commission, 2022). This translates to a fixed tariff of INR 60 Lakhs per MW, which is considered as reference for the current model.

Sl. No.	Parameter	Unit	Value
1	Energy Storage Capacity	MWh	17640
2	Power Rating	MW	2520
3	Expected Cycle Efficiency	%	80
4	Annual Availability	%	95
5	Generation Duration	Hours	7
6	Pumping Duration	Hours	9

Table 2: PHS Parameters

11. Power Export Capacity

The export capacity (export ATC) of Rajasthan was 5 GW for the period of June 2021 to August 2021 (Rajasthan SLDC, 2021). CEA, in October 2021 shared the 'Minutes of 4th meeting of Northern Regional Power Committee (Transmission Planning)', which includes the draft transmission plans as submitted by RVPNL. According to the network expansion plans, 16000 MVA additional pooling stations will be established for the evacuation of power from the upcoming 20 GW REZ in Rajasthan (Central Electricity Authority - Power System Planning Division, 2021). So, it is assumed that the export capacity will be 20 GW by 2030.

12. Annualized Fixed Charge for Transmission Augmentation

The required transmission network capacities for meeting the export load in multiple RE export scenarios, are also considered in the study. This analysis provides a reflection on the additional transmission expenditure, which will get added to the generation system cost and impact the end user tariffs.

For determining the annual transmission tariff, the Annual Transmission Charges approved by RERC for FY 2022-23 are considered (Rajasthan Electricity Regulatory Commission, 2022). The calculations are shown herein:

Particulars	Unit	Legend	Figures
Total Transmission Capacity	MW	A	15,845
Transmission Capacity for Long Term Open Access	MW	B	669
Transmission Capacity for DISCOMs	MW	C = A – B	15,176
Total Annual Transmission Charges (for 15845 MW)	INR Cr	D	2923
Transmission Charges from DISCOMs	INR Cr	E = D/A * C	2,799
Transmission Tariff (i.e. annualized fixed charge)	INR/ kW/ Month	F = E*1000/ C/ 12	154
Annualized fixed cost for 25GW capacity	INR Cr	G = F*12*25/ 10	4612
Annualized fixed cost for 35GW capacity	INR Cr	H = F*12*35/ 10	6458
Annualized fixed cost for 45GW capacity	INR Cr	I = F*12*45/ 10	8302

Table 3: Annual Fixed Charge of Transmission

13. Modelling Assumptions

- **Single Node Model:** The model is constructed on an aggregate basis, considering the entire state as a single entity having both demand and supply generation capacity. Congestion and other network related constraints were merely represented as efficiency parameters.
- The export load is modeled assuming the same profile as that of the solar generation, i.e., having a daily & seasonal demand profile similar to the grid-scale solar generation pattern. With the same pattern, the 15-minute block-wise export profile is constructed based on the ratio of annual peak export power and solar generation power.

3.3 Renewable Supply Scenarios

By March 2022, Rajasthan's installed capacities of grid-scale solar and wind assets were 14.0 GW and 4.5 GW respectively (MNRE, 2022). The cumulative installed capacities have seen a 51% CAGR in grid-scale solar and a 1% CAGR in wind in the last 5 years, i.e. since March 2017. In order to achieve the national target of 175 GW renewable capacity by 2022, MNRE envisaged Rajasthan's renewable power installation target as 5.7 GW of grid-scale solar and 8.6 GW of wind capacity (MNRE, 2017).

While the state has surpassed the MNRE target in grid-scale solar, it has been able to achieve around 50% of the MNRE target in wind.

The state solar and wind energy policy targets for 2024-25 are 24 GW grid-scale solar capacity, 3.5 GW hybrid capacity and addition of 4 GW of wind capacity (Energy Department, Government of Rajasthan, 2019). Project announcements in 2022 include THDCIL, NTPC, NHPC and SJVN signing MOUs with RRECL for developing solar capacity of a 40 GW (MOU signings with RRECL, 2022). So, the policy target in grid-scale solar capacity seems attainable. The policy goal in wind and subsequent project announcements suggest that a capacity addition of 2 GW will be achieved over March 2019 installed capacity of 3.2 GW.

According to Rajasthan's energy policies on solar and wind capacities, an installed grid-scale solar capacity of 24 GW and installed wind capacity of 5.2 GW by 2025, is considered for the study.

1. High RE Scenario

The modeled high RE scenario aligns with the state level RE policy targets through 2025. In this scenario, grid-scale solar and wind assets see a steady growth after meeting state policy 2025 targets. Grid-scale solar and wind assets are projected to grow at 20% and 5% CAGR , from 2022 to attain installed capacities of 58.5 GW and 6.7 GW by 2030, respectively.

Multiple cases are also modeled considering the export load profiles with varying annual peak loads. Hence, no export capacity constraints are considered in the high RE scenario.

Years	Wind Capacity (GW)	Solar Capacity (GW)	Peak Demand (GW)	RJ Annual Energy Demand (MU)	Annual Export Demand (MU)	% Annual Demand met by RE with storage
2022	4.5	14.0	15.7	91,953	8,320	35%
2030	6.7	58.5	20.7	118,914	58,254	58%

Table 4: Summary - High RE Scenario

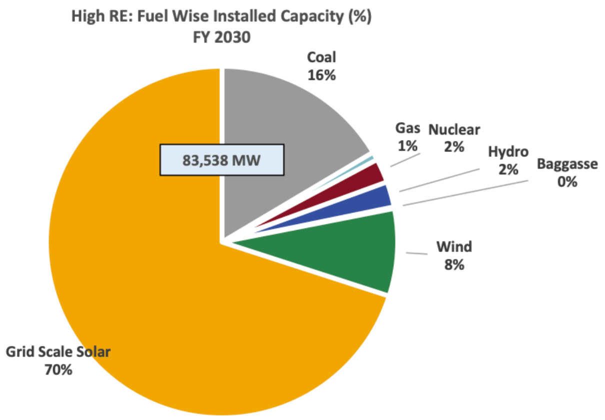


Figure 8: High RE - Fuel Wise Installed Capacity FY 2030

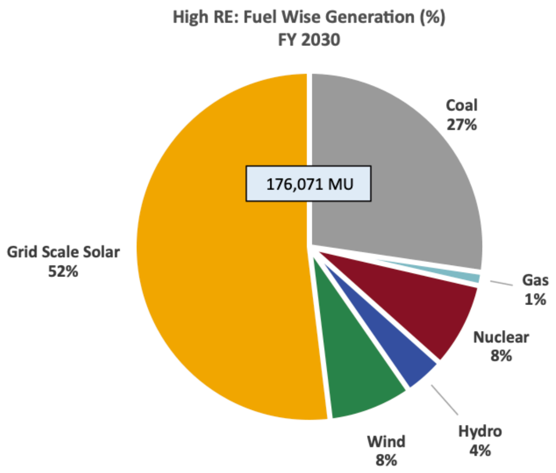


Figure 9: High RE - Fuel Wise Generation FY 2030

2. Low RE Scenario

A low RE scenario has been considered which assumes that the state RE policy targets will be delayed by 5 years, in the pessimistic case. Here, grid-scale solar and wind assets are projected to achieve installed capacities of 24.0 GW and 5.2 GW by 2030, instead of 2025.

The export load is modeled assuming an annual peak of 19 GW (since 20 GW is the export capacity constraint in 2030).

3. Optimal RE Scenario

The optimal RE scenario minimizes the overall generation cost, assuming minimum servable export power demand. The export load profile in this case is considered the same as that of the low RE scenario, i.e., with a 19 GW annual peak export load.

Years	Wind Capacity (GW)	Solar Capacity (GW)	Peak Demand (GW)	RJ Annual Energy Demand (MU)	Annual Export Demand (MU)	% Annual Demand met by RE with storage
2022	4.5	14.0	15.7	91,953	8,320	35%
2030	5.2	24.0	20.7	118,914	31,624	34%

Table 5: Summary - Low RE Scenario

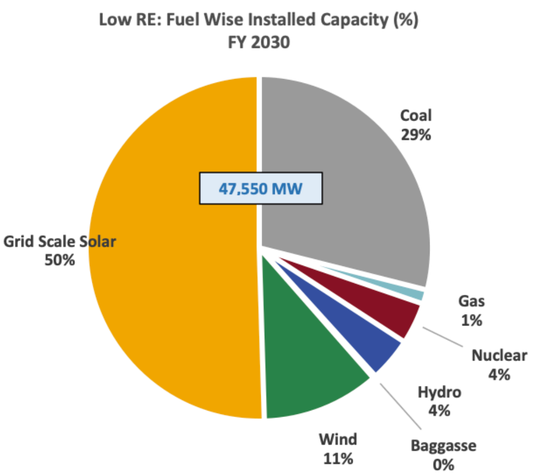


Figure 10: Low RE - Fuel Wise Installed Capacity FY 2030

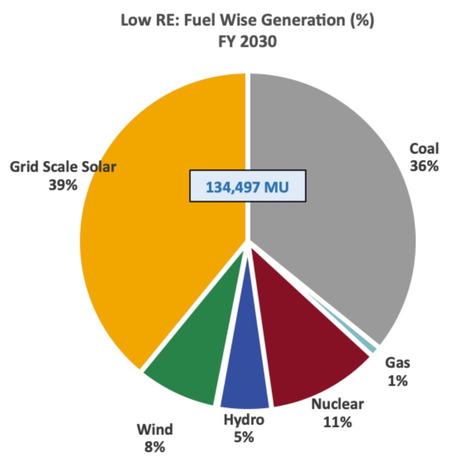


Figure 11: Low RE - Fuel Wise Generation FY 2030

OUTPUTS OF THE MODEL

4

1. Year 2030: Low RE Scenario

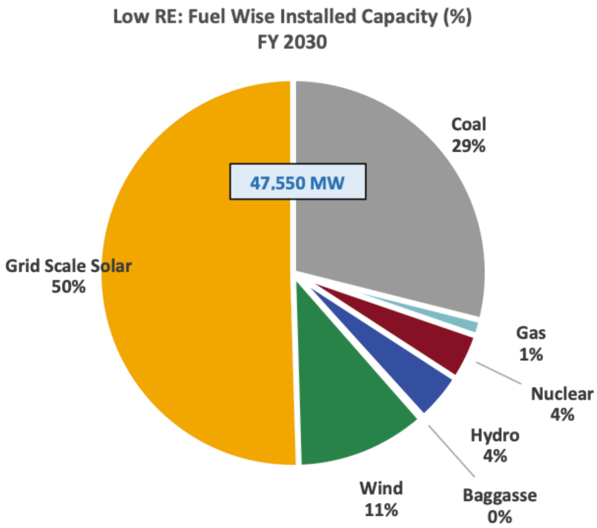


Figure 12: Low RE - Fuel Wise Installed Capacity FY 2030

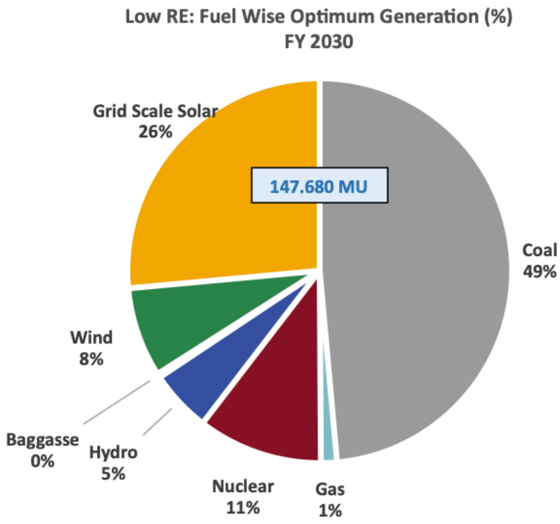


Figure 13: Low RE - Fuel Wise Optimum Generation FY 2030

Note: There is a mismatch (<1% of the total demand) in energy demand and generation due to modelling simplification

Capacity, Generation & Utilization

In the low RE case, the generation mix in terms of capacity remains the same in 'without' and 'with storage' cases, respectively. Coal continues to be the predominant source of generation. While RE sources constitute 51% of installed capacity, they contribute only 34% of generation. Even with the inclusion of storage, the model forecasts a BESS discharge share of only 0.4%, which results in coal thermal plants operating at the same PLF levels. The model output generation mix considers a peak power import capacity of 10 GW, to maintain grid reliability. It is observed that a total of 1036 MU is needed for the purpose.

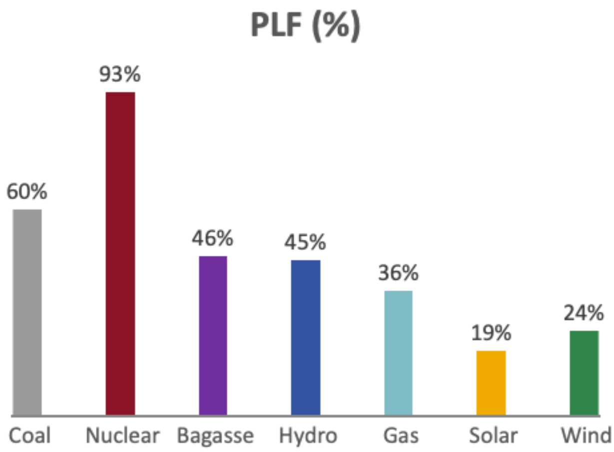


Figure 14: Low RE PLF

Storage Penetration

The model suggests an addition of 0.9 GWh of BESS. The duration of storage is 2 hours.

Energy Storage Details			
Duration	Optimal Installed Capacity (MW)	Discharge (MU)	Charge (MU)
2	458	833	-965

Table 6: Low RE Energy Storage Details

Renewable Curtailment

In this scenario, the spillage from solar decreases from 0.16% to 0.01% when storage is introduced. For wind, the spillage is 0.10%, which reduces to 0.05% with storage penetration in the grid. As the 'without storage' case doesn't mandate RE sources to operate as 'must run' plants, the curtailment reductions stand to be higher if 'must run' status of RE is strictly enforced. The RE curtailment figures are slightly higher for wind due to more instances of sharp variations seen in the wind generation profile.

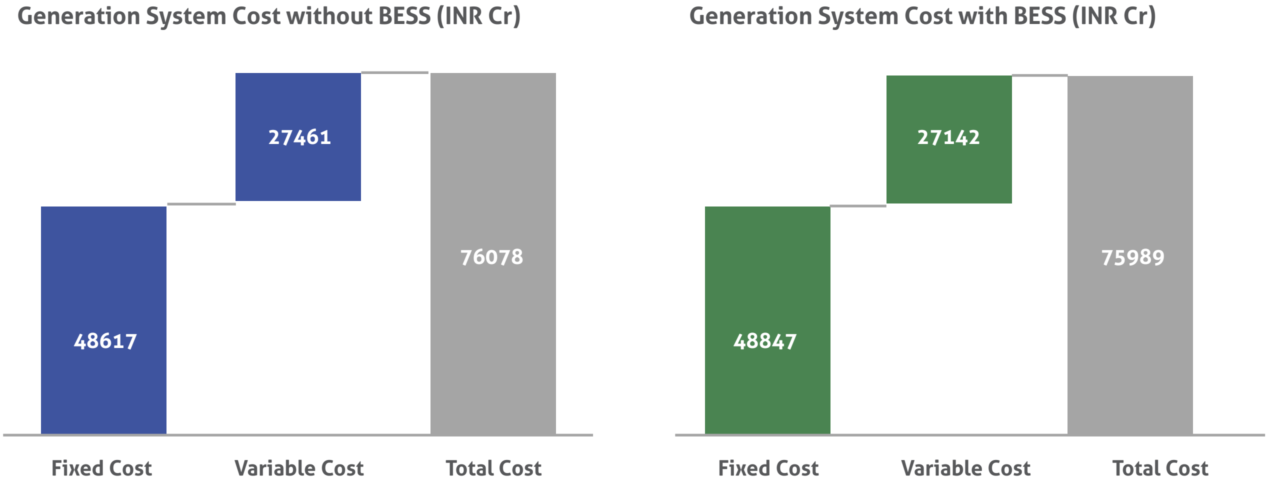


Figure 15: Low RE Generation System Cost without & with BESS

System Level Costs - Benefits

With storage addition, this scenario sees an annual saving on the system level cost of INR 89 Cr (from INR 76078 Cr to INR 75989 Cr) (Figure 15). Despite increase in fixed cost (from INR 48617 Cr to INR 48847 Cr), a net benefit in cost is seen due to the higher reduction in variable cost (from INR 27461 Cr to INR 27142 Cr).

Considering the additional transmission infrastructure required to cater to a 19 GW peak export load in this scenario, an additional fixed transmission cost of 3505 Cr (for additional transmission capital expenditure) is added to the system fixed cost. Hence the total system level cost (generation & transmission) is 79494 Cr (i.e., addition of 3505 Cr to 75989 Cr). With an energy demand of 150535 MUs including exported energy, the overall system level levelized cost of electricity becomes INR 5.30/kWh.

2. Year 2030: High RE Scenario

1. High RE Scenario with 25 GW Peak Export

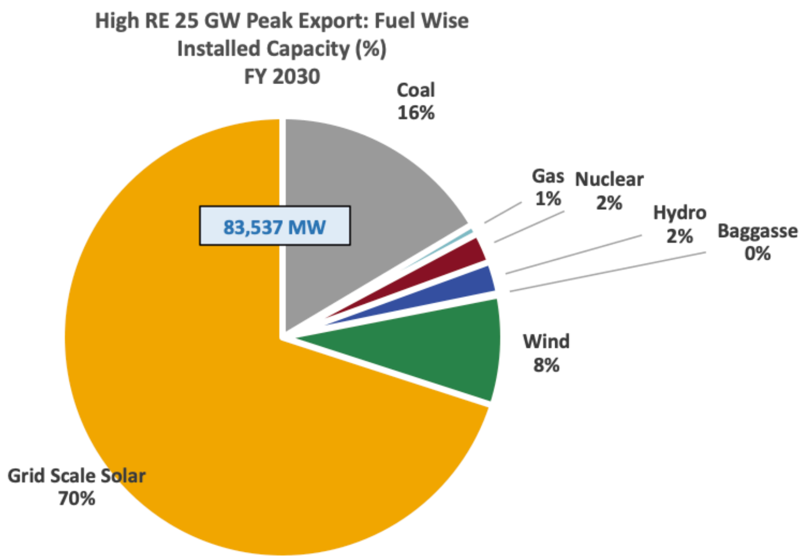


Figure 16: High RE 25 GW Peak Export - Fuel Wise Installed Capacity FY 2030

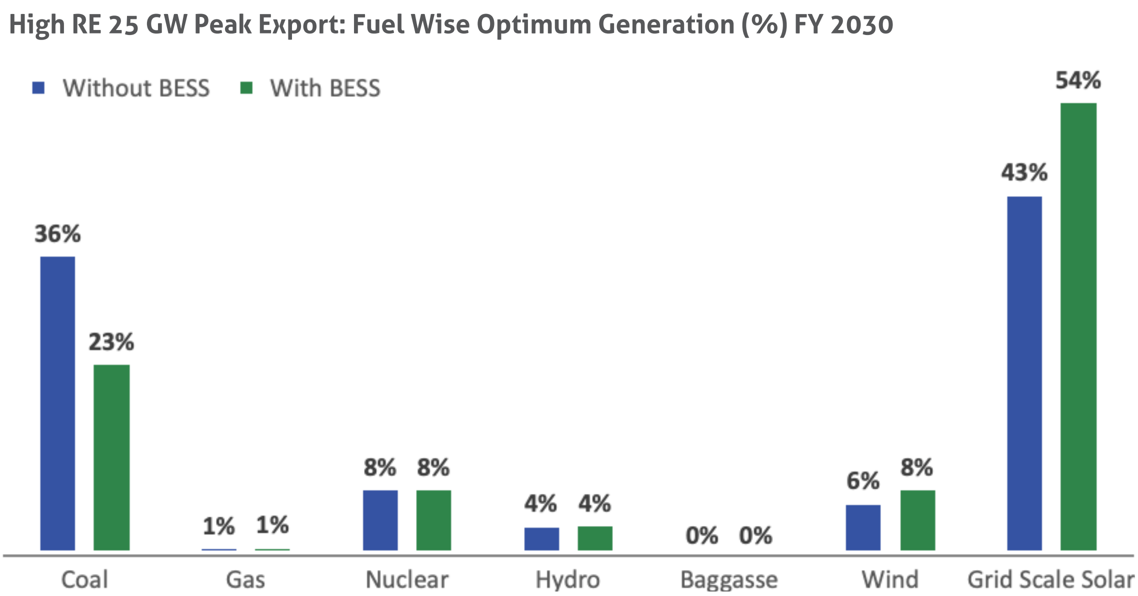


Figure 17: High RE 25 GW Peak Export - Fuel Wise Optimum Generation FY 2030

Note: There is a mismatch (<1% of the total demand) in energy demand and generation due to modelling simplification

Capacity, Generation & Utilization

In the high RE case with 25 GW peak export, the generation mix in terms of capacity remains the same in 'without' and 'with storage' cases, respectively.

But there is a significant shift in energy generation pattern – coal loses a share from 36% to 23% when BESS is introduced. This base load is being catered by additional RE generation, aided by BESS. The major contribution comes from solar, which increases from 43% to 54%, while the wind share increases from 6% to 8%.

RE sources constitute 69% of installed capacity, and 62% of generation, with storage. This gets reflected in a significant BESS discharge share of 9.1%, which also results in coal thermal plants operating at reduced PLF levels. The capacity of non-utilized coal thermal assets increases to 6.5 GW with BESS integration (from 1.9 GW without BESS).As a result, the model results indicate that an additional 4.6 GW of coal thermal assets are likely to be decommissioned or phased down in this case.

Finally, due to added flexibility of BESS in the grid, the increase in utilization levels are observed in hydro and gas assets as well (apart from the RE sources). The model output generation mix considers a peak power import capacity of 10 GW, to maintain grid reliability. With BESS, it is observed that a total of 2252 MU is needed for the purpose.

2030: Source-wise PLF

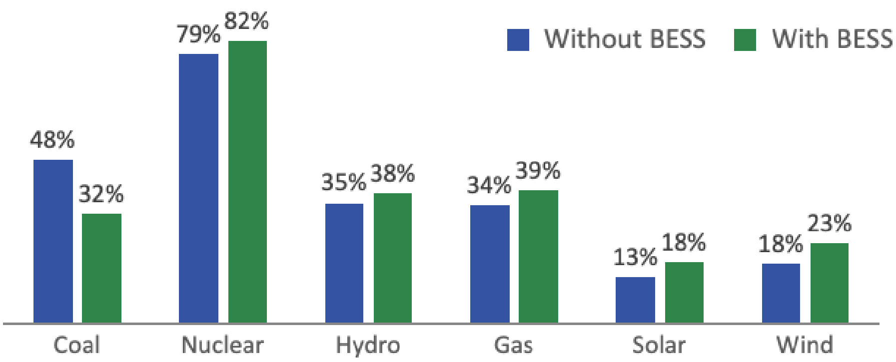


Figure 18: High RE 25 GW Export - PLF

Storage Penetration

The model suggests an addition of 34.5 GWh of BESS. The duration of storage is 1 hour (22.5 GW) and 2 hours (5.9 GW).

Energy Storage Details

Duration	Optimal Installed Capacity (MW)	Discharge (MU)	Charge (MU)
1	22578	13288	-24090
2	5980	6652	-10034

Table 7: High RE 25 GW Export - Energy Storage Details

Renewable Curtailment

In this scenario, the spillage from solar decreases from a high of 15.6% to 2.4% when storage is introduced. For wind, the spillage is a staggering 34% which reduces to 5.7% with storage penetration in the grid. As the 'without storage' case doesn't mandate RE sources to operate as 'must run' plants, the curtailment reductions stand to be higher if 'must run' status of RE is strictly enforced. The RE curtailment figures are slightly higher in wind due to more instances of sharp variations seen in the wind generation profile.

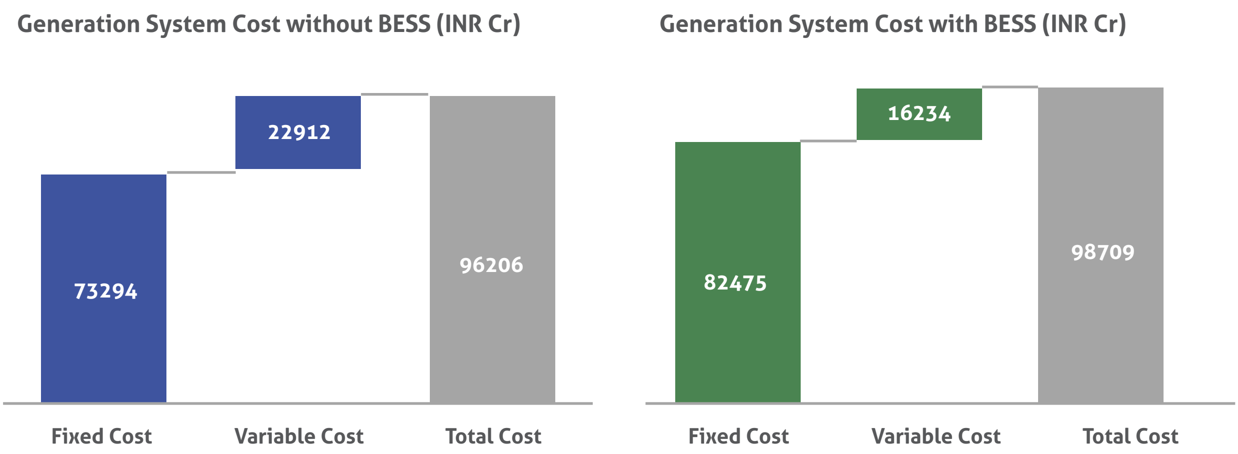


Figure 19: High RE 25 GW Export - Generation System Cost without & with BESS

System Level Costs - Benefits

With the addition of storage, the system level cost rises by INR 2503 Cr (from INR 96206 Cr to INR 98709 Cr) (Figure 19) (Figure 19). The increase in fixed cost (from INR 73294 Cr to INR 82475 Cr) outweighs the gain in variable cost (from INR 22912 Cr to INR 16234 Cr). But, with BESS penetration, the model projects a higher energy generation as compared to 'without BESS' situation. Consequently, the unit cost of generation becomes lower with BESS in the grid. (Refer 4.2.6 Overall System Level Cost Benefits)

Considering the additional transmission infrastructure required to cater to a 25 GW peak export load in this scenario, an additional fixed transmission cost of 4612 Cr (for additional transmission capital expenditure) is added to the system fixed cost. Hence the total system level cost (generation & transmission) is 103321 Cr (i.e., the addition of 4612 Cr to 98709 Cr). With an energy demand of 160521 MUs including exported energy, the overall system level levelized cost of electricity becomes INR 6.17/kWh.

2. High RE Scenario with 35 GW Peak Export

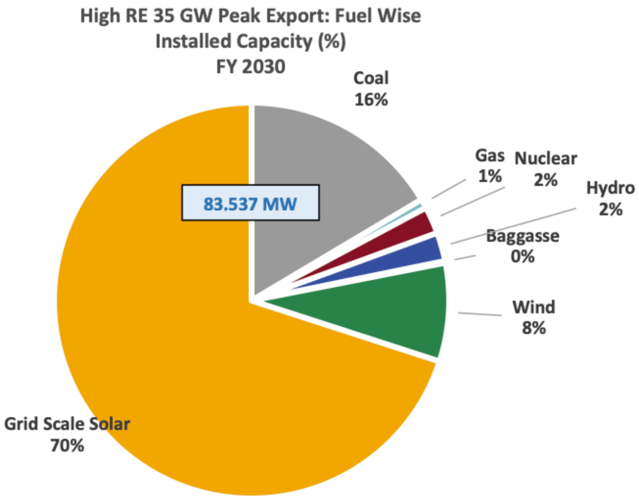


Figure 20: High RE 35 GW Peak Export - Fuel Wise Installed Capacity

Note: There is a mismatch (<1% of the total demand) in energy demand and generation due to modelling simplification

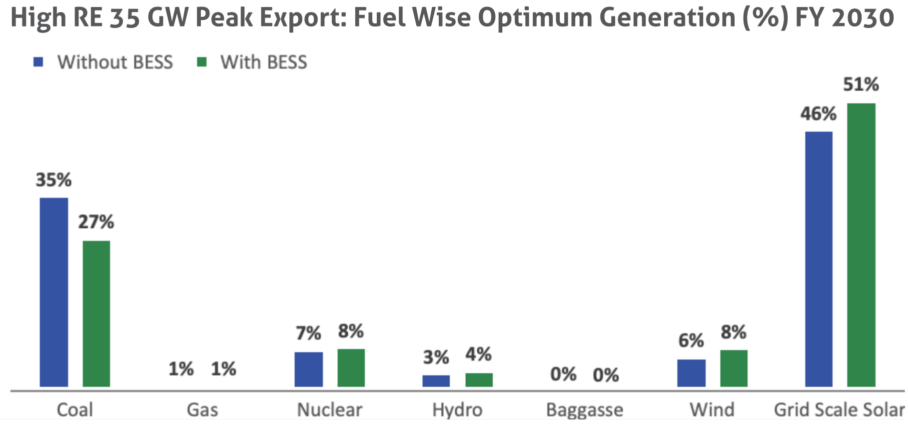


Figure 21: High RE 35 GW Peak Export - Fuel Wise Optimum Generation FY 2030

Capacity, Generation & Utilization

In the high RE case with 35 GW peak export, the generation mix in terms of capacity remains the same in 'without' and 'with storage' cases, respectively.

However there is a significant shift in energy generation patterns – coal loses its share from 35% to 27% when BESS is introduced. This base load is being catered by additional RE generation, aided by BESS. Solar contributes the most, increasing from 46% to 51%, while wind shares increase from 6% to 8%.

RE sources constitute 59% of installed capacity, and the same share of generation, with storage. This gets reflected in a fair BESS discharge share of 3.5%, which also results in coal thermal plants operating at reduced PLF levels. Also with BESS integration, the capacity of non-utilised coal thermal assets increases to 5.9 GW (from 0.8 GW without BESS). So, the model outcomes suggest a probable decommissioning or capacity deallocation of additional 5.2 GW coal thermal assets in this case.

Finally, due to the added flexibility of BESS in the grid, an increase in utilization levels is observed in hydro and gas assets as well (apart from the RE sources). The model output generation mix considers a peak power import capacity of 25 GW, to maintain grid reliability. With BESS, it is observed that a total of 2252 MU is needed for the purpose.

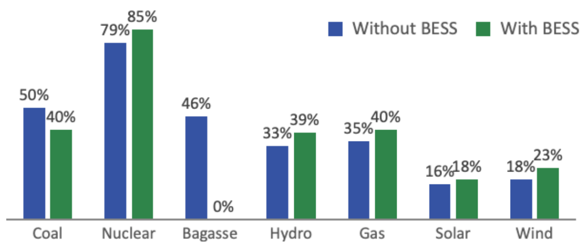


Figure 22: High RE 35 GW Export - PLF

Storage Penetration

The model suggests an addition of 19.9 GWh of BESS. The duration of storage is 2 hours (0.7 GW) and 4 hours (4.6 GW).

Energy Storage Details			
Duration	Optimal Installed Capacity (MW)	Discharge (MU)	Charge (MU)
2	690	759	-1128
4	4627	10602	-14651

Table 8: High RE 35 GW Export - Energy Storage Details

Renewable Curtailment

In this scenario, the spillage from solar decreases from a high of 9% to 2% when storage is introduced. Wind has a staggering 30% spillage which reduces to 5.4% with penetration of storage in the grid. As the 'without storage' case doesn't mandate RE sources to operate as 'must run' plants, the curtailment reductions stand to be higher if 'must run' status of RE is strictly enforced. The RE curtailment figures are slightly higher in wind due to more instances of sharp variations seen in the wind generation profile.

System Level Costs – Benefits

With storage addition, this scenario sees an annual saving on the system level cost of INR 1390 Cr (from 98535 Cr to 97145 Cr) (Figure 23). Despite the increase in fixed cost (from 73473 Cr to 77691 Cr), net benefit in cost is observed due to the higher reduction in variable cost (from 25062 Cr to 19454 Cr). And, with BESS penetration, the model also projects a higher energy generation as compared to 'without BESS'

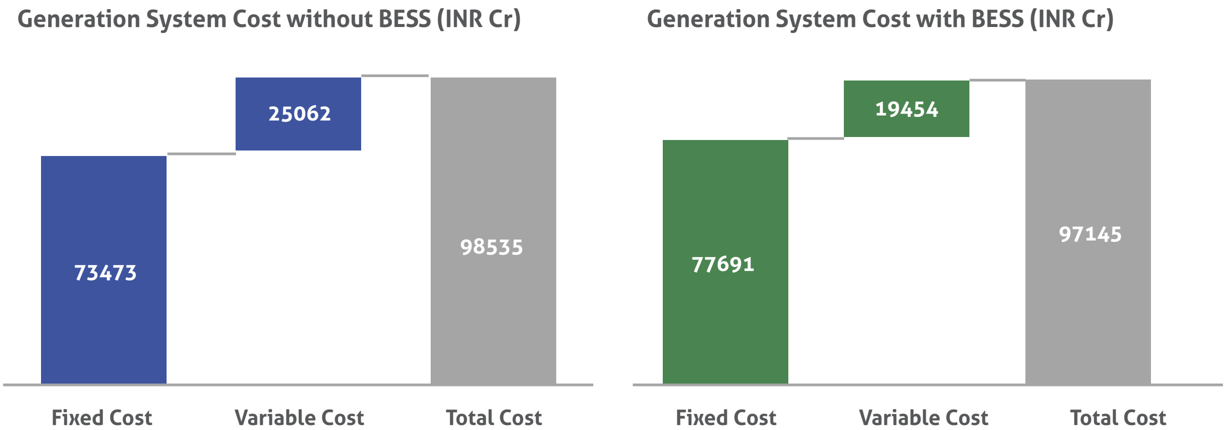


Figure 23: High RE 35 GW Export - Generation System Cost without & with BESS

situation. Consequently, the unit cost of generation becomes lower with BESS in the grid. (Refer 4.2.6 Overall System Level Cost Benefits)

Considering the additional transmission infrastructure required to cater to 35 GW peak export load in this scenario, an additional fixed transmission cost of 6458 Cr (for additional transmission capital expenditure) is added to the system fixed cost. As a result, the total system level cost (generation & transmission) is 103603 Cr (i.e., addition of 6458 Cr to 97145 Cr). With an energy demand of 177165 MUs including exported energy, the overall system level levelized cost of electricity becomes INR 5.81/kWh.

3. High RE Scenario with 45 GW Peak Export

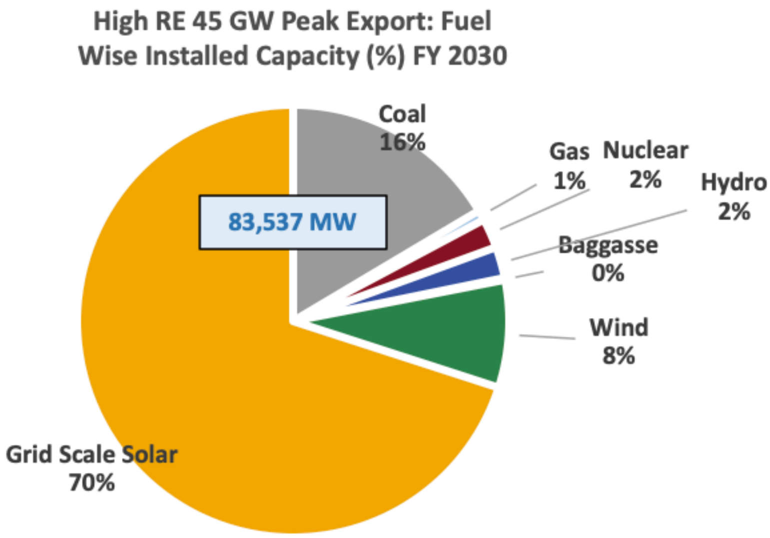


Figure 24: High RE 45 GW Peak Export - Fuel Wise Installed Capacity FY 20

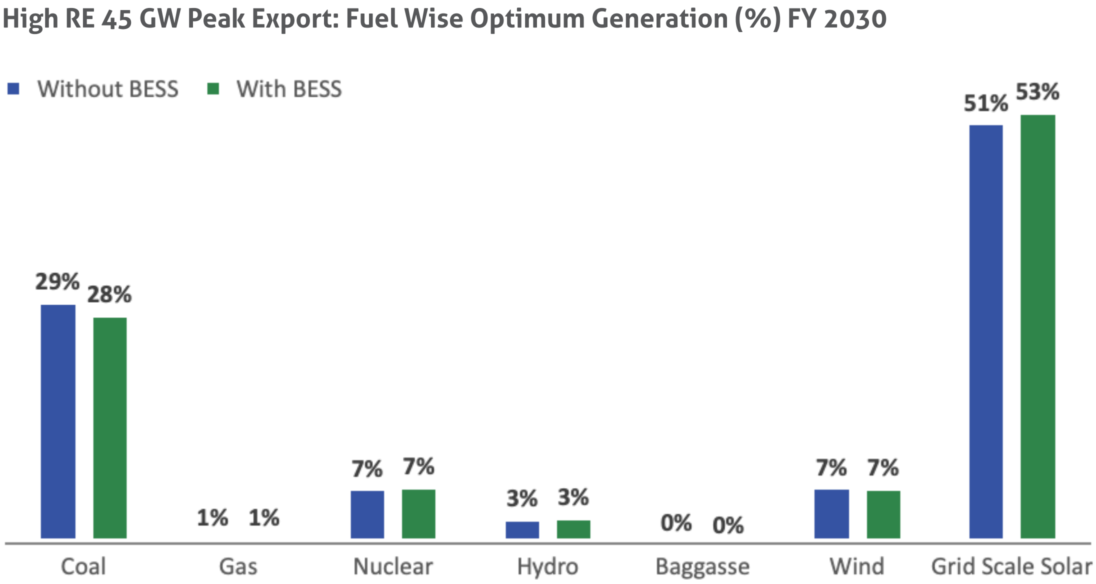


Figure 25: High RE 45 GW Peak Export - Fuel Wise Optimum Generation FY 2030

Note: There is a mismatch (<1% of the total demand) in energy demand and generation due to modelling simplification

Capacity, Generation & Utilization

In the high RE case with 45 GW peak export, the generation mix in terms of capacity remains the same in 'without' and 'with storage' cases, respectively.

Also, there is a marginal change in energy generation pattern of coal – it loses share from 29% to 28% when BESS is introduced. This base load is being catered by additional solar generation, aided by BESS. It increases from 51% to 53%. The wind share remains the same.

RE sources constitute 69% of installed capacity, and 60% of generation, with storage. This gets reflected in a modest BESS discharge share of 1.2%, which also results in coal thermal plants operating at slightly reduced PLF levels. Finally, due to the added flexibility of BESS in the grid, a slight increase in utilization levels is observed in hydro assets.

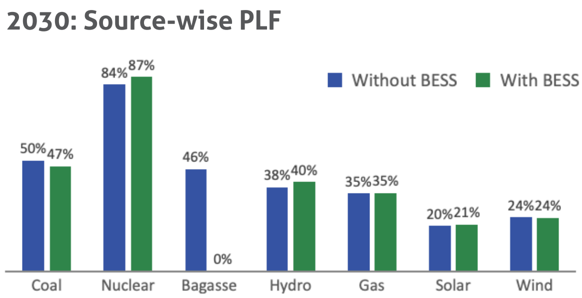


Figure 26: High RE 45 GW Export - PLF

Storage Penetration

The model suggests an addition of 5.3 GWh of BESS. The duration of storage is 2 hours (2.4 GW) and 4 hours (0.1 GW).

Energy Storage Details

Duration	Optimal Installed Capacity (MW)	Discharge (MU)	Charge (MU)
2	2354	3890	-4986
4	149	462	-562

Table 9: High RE 45 GW Export - Energy Storage Details

Renewable Curtailment

In this scenario, the spillage for solar decreases from 2.8% to 0.9% when storage is introduced. For wind, the spillage increases 0.8% and 1.8%, which is likely due to more instances of sharp variations seen in the wind generation profile.

System Level Costs - Benefits

With storage addition, this scenario sees an annual saving on the system level cost of INR 668 Cr (from INR 97050 Cr to INR 96382 Cr) (Figure 27). Despite the increase in fixed cost (from INR 73294 Cr to INR 74230 Cr), a net benefit in terms of cost is observed due to the higher reduction in variable cost (from INR 23756 Cr to INR 22152 Cr). And, with BESS penetration, the model also projects a higher energy

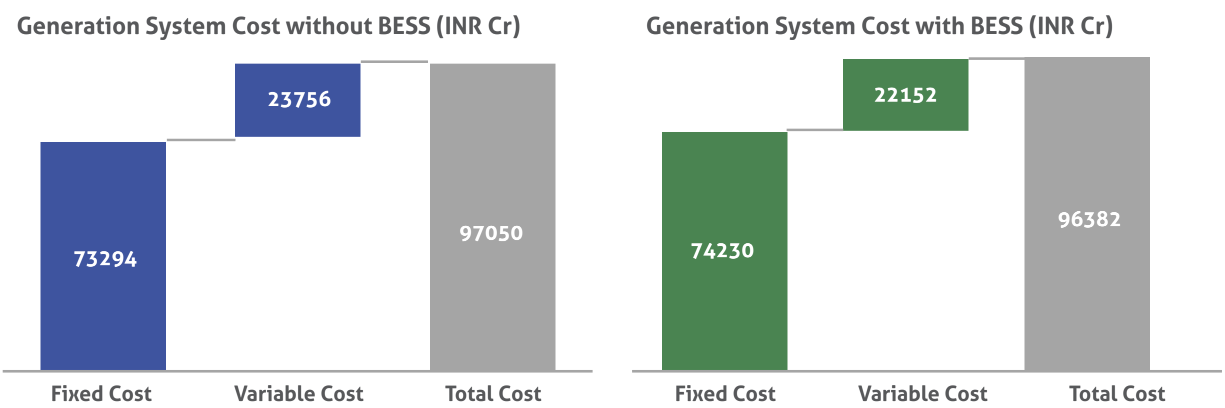


Figure 27: High RE 45 GW Export - Generation System Cost without & with BESS

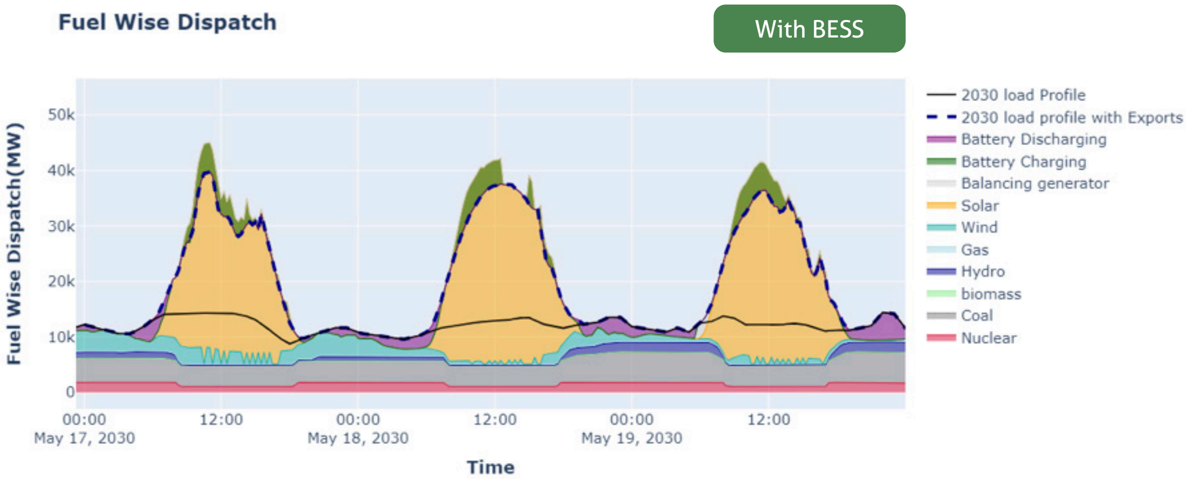
generation as compared to 'without BESS' situation. Consequently, the unit cost of generation becomes lower with BESS in the grid (Refer 4.2.6 Overall System Level Cost Benefits).

Considering the additional transmission infrastructure required to cater to a 45 GW peak export load in this scenario, an additional fixed transmission cost of 8302 Cr (for additional transmission capital expenditure) is added to the system fixed cost. Hence the total system level cost (generation & transmission) is 104684 Cr (i.e., the addition of 8302 Cr to 96382 Cr). With an energy demand of 193809 MUs including exported energy, the overall system level levelized cost of electricity becomes INR 5.15/kWh.

4. Overall Seasonal Dispatch Profile

The seasonal load profiles for high RE scenario (with 35 GW peak export) with storage are shown in Figure 28. To better understand the seasonal variation, profiles of February, May, and September were selected and studied. The month of September sees lower RE availability in the state, while February sees higher RE availability. Despite variation in solar availability profiles, it is observed that the role of BESS is more focused on providing a buffer against short term variations of solar and wind during the day and helping in managing evening peaks. Consequently, the BESS discharge duration is shorter (less than 4 hours). The profile also affirms that coal and nuclear helps in providing the base load. The ramp- up or ramp-down of coal is more prominent in high RE month, while the same generation profile is more uniform in low RE months.

Figure 28: High RE – Load Curve Trends (February 2030)



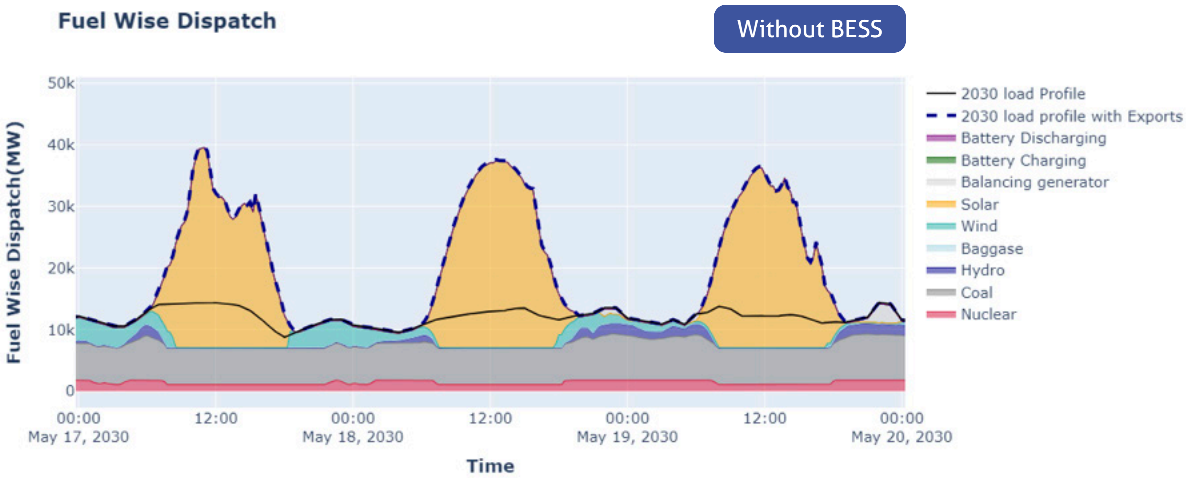
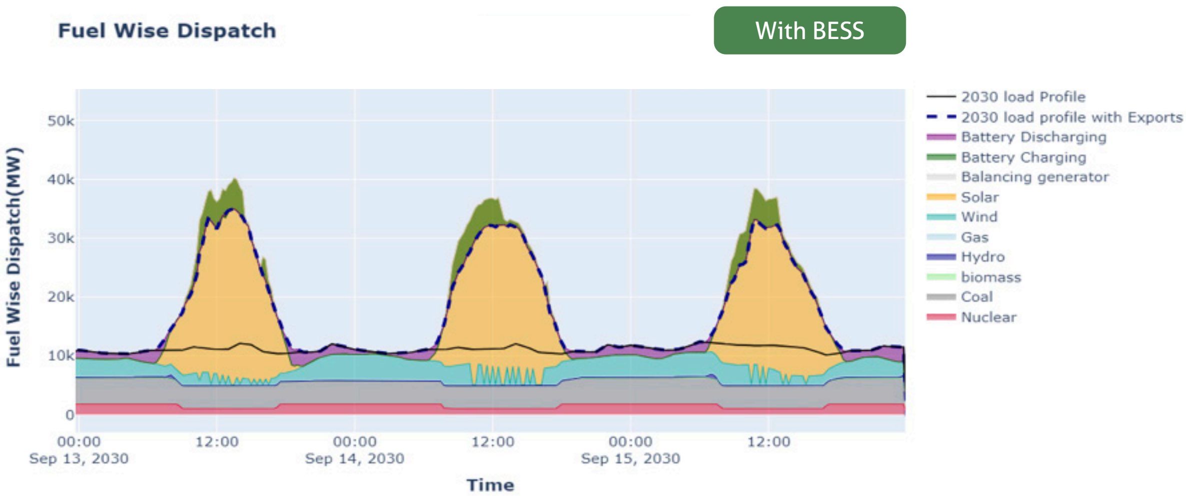


Figure 29: High RE – Load Curve Trends (May 2030)



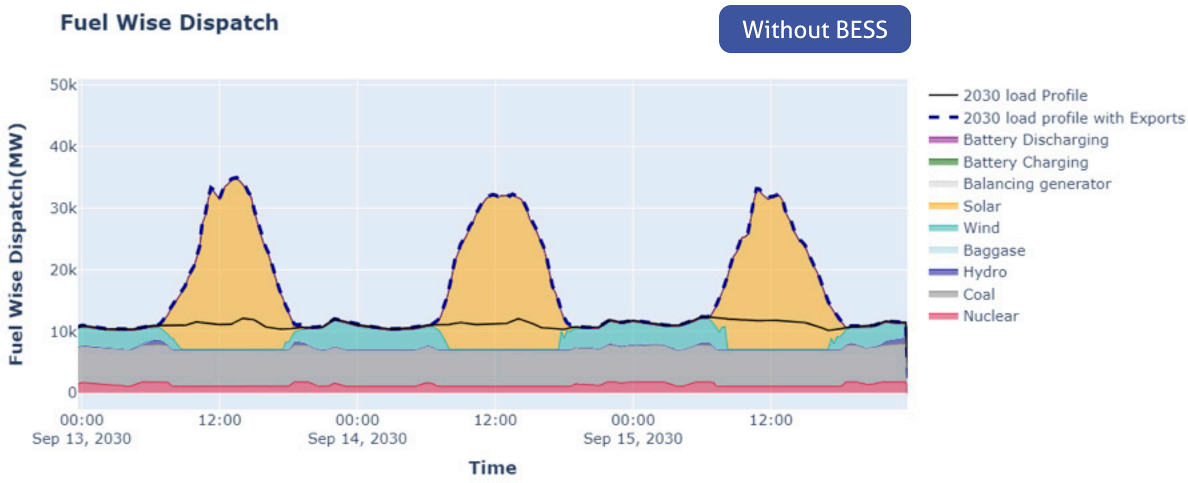


Figure 30: High RE – Load Curve Trends (September 2030)

5. BESS Penetration

Energy storage penetration in 2030 becomes more prominent in the grid in the lower export scenario (Figure 31). The GWh requirement is the highest in the lowest export scenario. The model outcome projects to inclusion of 2-hours and 4-hours storage in the highest export case and 1-hour to 4-hours for the lowest export case. For better distribution of storage types in lowest export scenario, the investment amongst different hour-wise capacities is exogenously optimized, while keeping the energy rating obtained from the model.

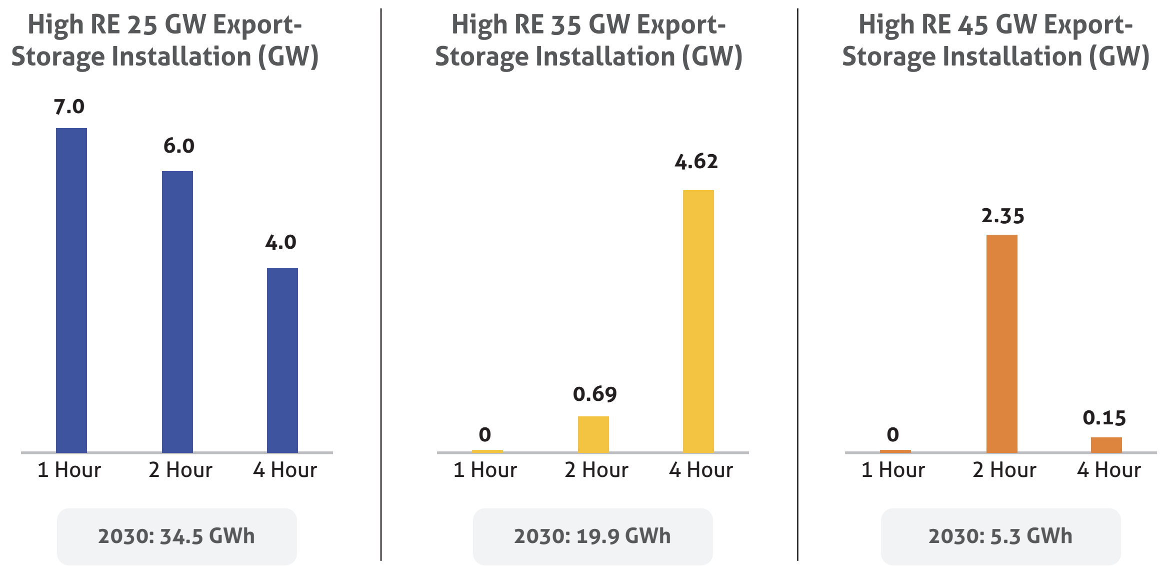


Figure 31: High RE Scenarios and Storage Capacities

In all the scenarios, the addition of BESS has resulted in lower solar and wind curtailments (Figure 32). The RE curtailments reduce gradually, as more RE generation continues to cater to increasing exports, i.e., increasing peak export loads from 25 GW to 45 GW. Interestingly, the PLFs of coal thermal plants rise as the peak exports go up. As exports from Rajasthan (in terms of power and energy) go up, and solar generation gets time-shifted due to addition of storage, this solar generation mainly caters to the export load. So, the intra-state energy demand is being met by increasing coal thermal generation.

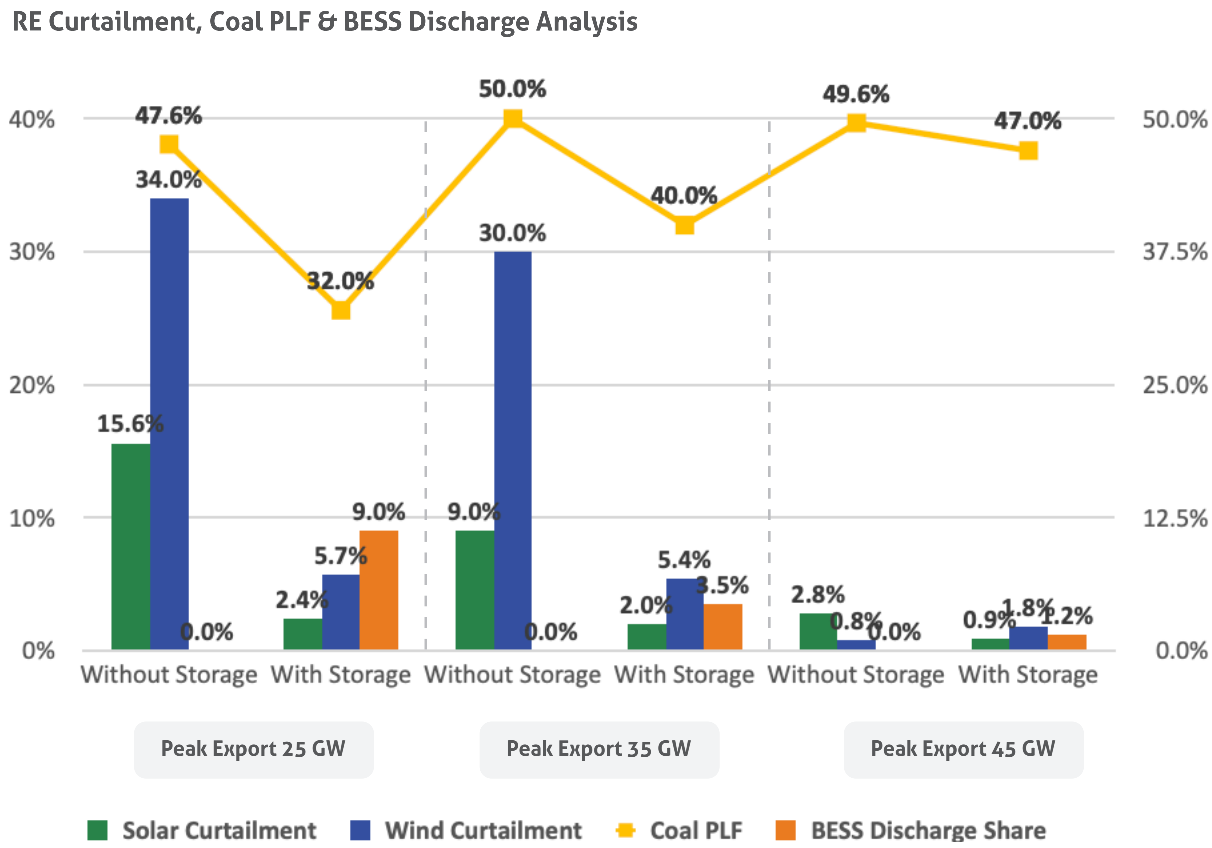


Figure 32: High RE - RE Curtailment, Coal PLF & BESS Discharge

6. Overall System Level Cost Benefits

With increasing peak export loads, the solar generation share in the system increases only when BESS is absent (Figure 33). As the peak export load increases, the solar generation sees lower curtailment, and is therefore able to contribute more energy in the generation mix. When BESS is introduced, the solar generation share in the system doesn't increase, instead, it moves within a band of 54.1% and 51.3%. As solar generation gets time-shifted due to storage, it helps cater to the state demand. When BESS is added, the generation system is able to respond to the load profile in more cost-effective manner, and hence the unit cost of energy sees a gradual decline.

With growing peak export loads, the generation system sees lower unit energy cost due to economies of scale (Figure 34). And with BESS integration, despite an increase in fixed cost of storage, a net benefit in cost is observed due to the combined effect of a reduction in variable cost and higher energy generation.

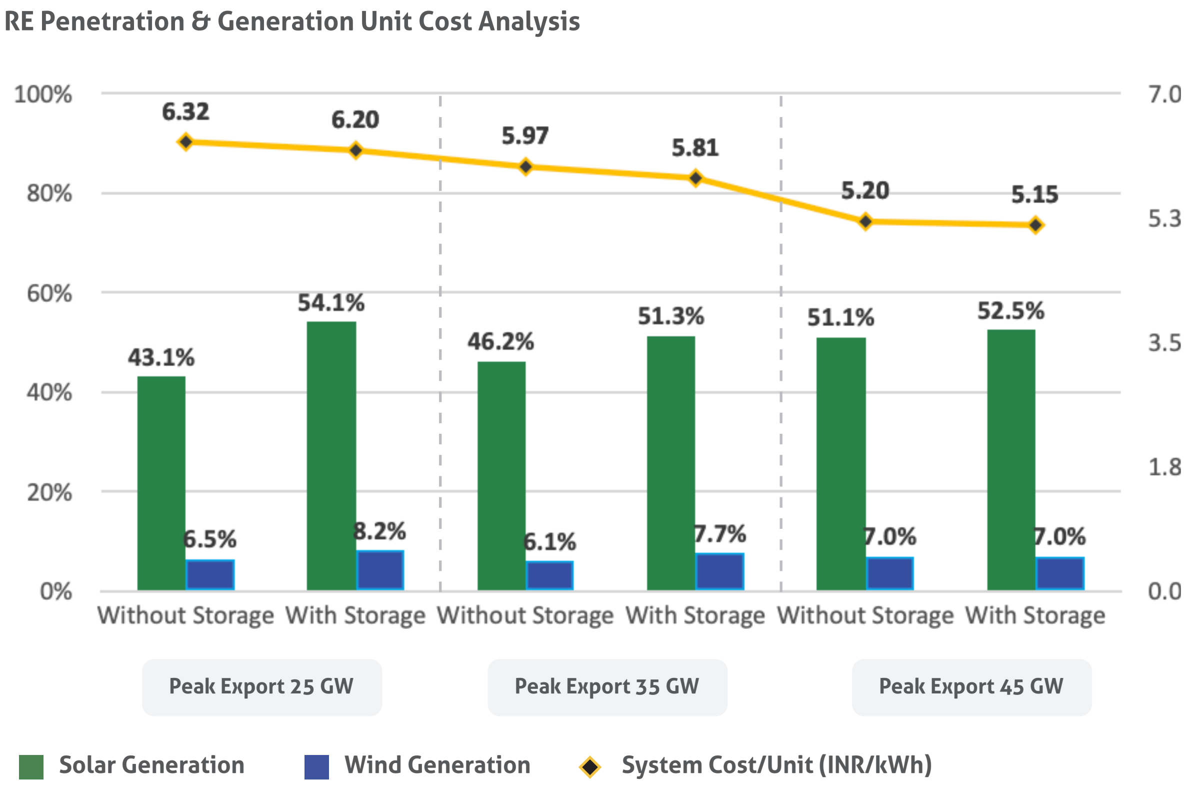


Figure 33: High RE - RE Penetration & Generation Unit Cost Analysis

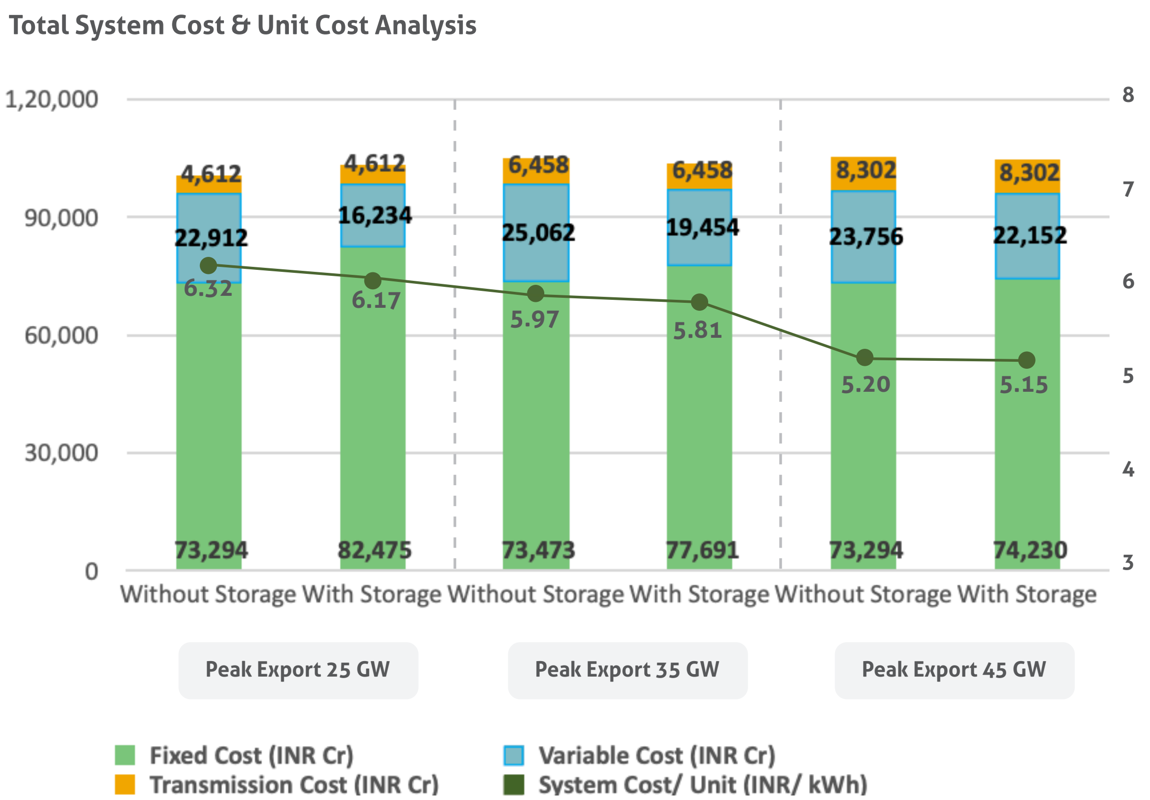


Figure 34: High RE - Total System Cost & Unit Cost Analysis

3. Year 2030: Optimal RE Scenario

Years	Wind Capacity (GW)	Solar Capacity (GW)	Peak Demand (GW)	RJ Annual Energy Demand (MU)	Annual Export Demand (MU)	% Annual Demand met by RE with storage
2022	4.5	14.0	15.7	91,953	8,320	35%
2030	4.5	21.6	20.7	118,914	31,624	30%

Table 10: Summary - Optimal RE Scenario

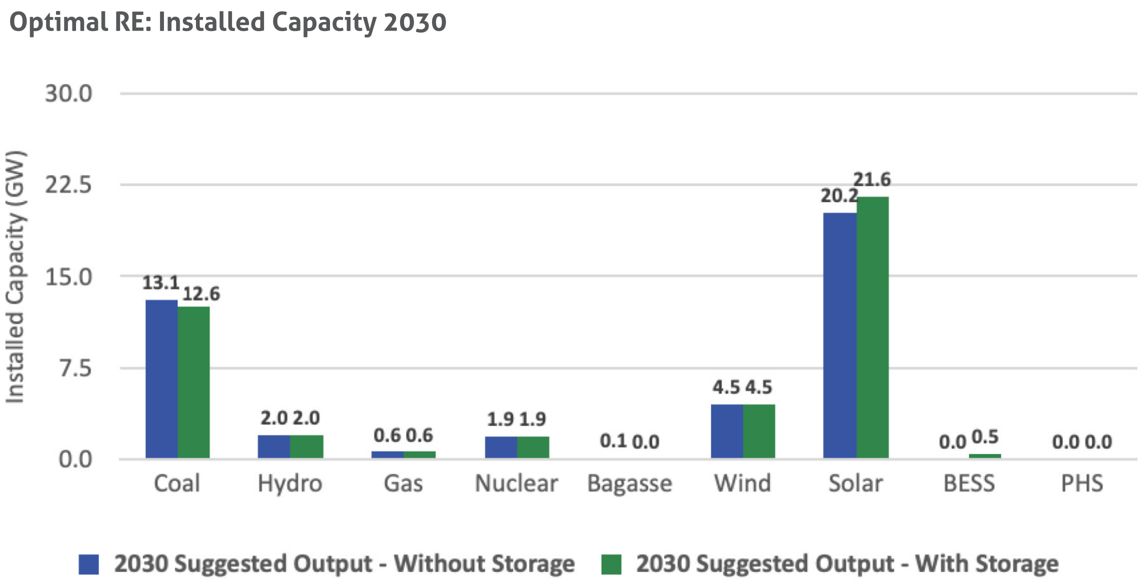


Figure 35: Optimal RE - Installed Capacity 2030 without & with BESS

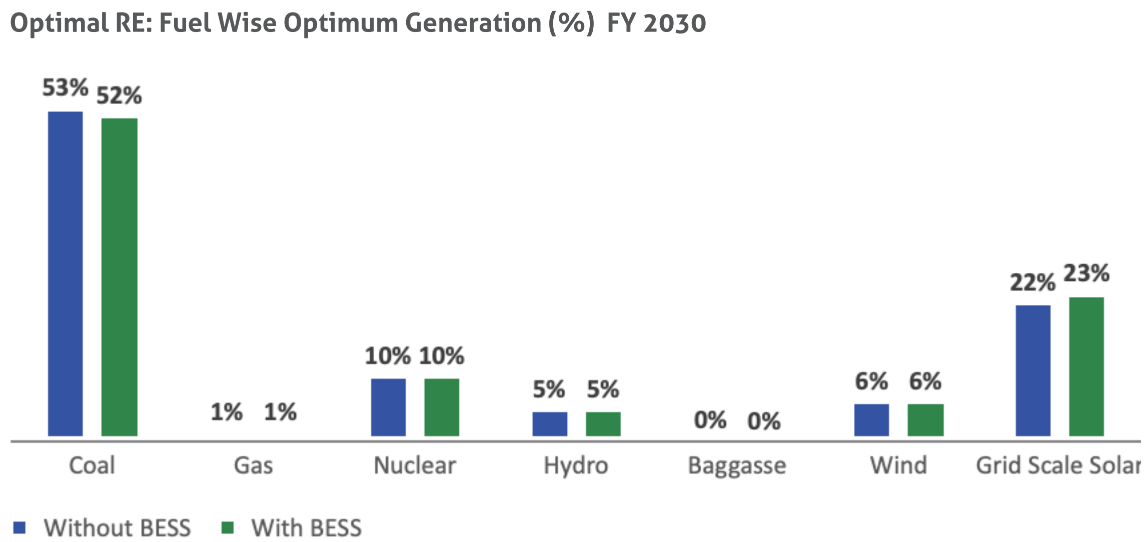


Figure 36: Optimal RE – Generation Share 2030 without & with BESS

Capacity, Generation & Utilization

In the optimal RE case with BESS, the model projects a net coal thermal capacity retirement of 100 MW from the existing capacity of 12.7 GW in 2022. Without grid storage penetration, a 400 MW addition to existing coal thermal capacity is proposed for 2022.. In gas, the model suggests a retirement of 200 MW of capacity (with or without BESS), due to higher variable cost of power generation. There is no further wind capacity addition from 2022 capacity. With the addition of BESS, the solar capacity addition is projected at 7.6 GW from the 2022 level.

The energy generation pattern is almost the same with or without BESS in the system. RE sources constitute 49% of installed capacity, and 30% of generation, with storage. Even with the inclusion of storage, the model forecasts a BESS discharge share of only 0.5%, which results in coal thermal plants operating at same PLF levels.

Renewables: As expected, there is no RE curtailment.

Optimal RE: Source-wise PLF

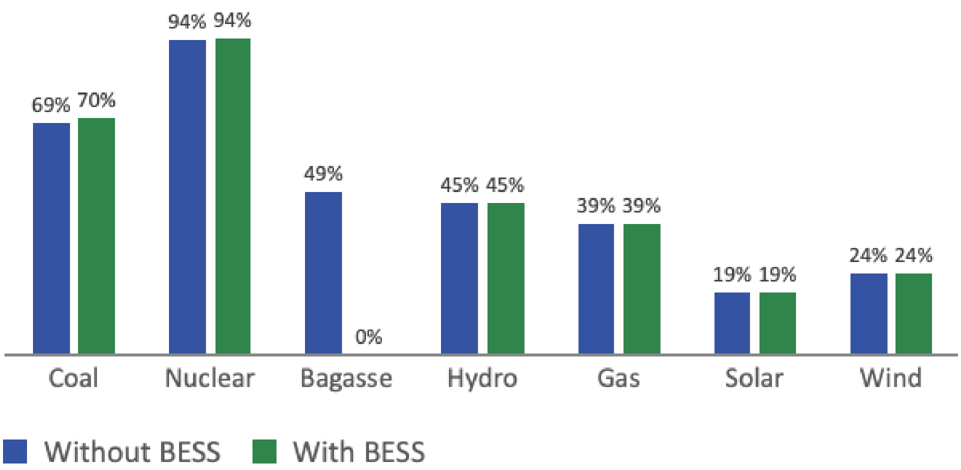


Figure 37: Optimal RE PLF without & with BESS

Storage Penetration

The model suggests an addition of 1.9 GWh of BESS. The duration of storage is 4 hours (0.5 GW).

Energy Storage Details			
Duration	**Optimal Installed Capacity (MW)**	**Discharge (MU)**	**Charge (MU)**
4	467	991	-1165

Table 11: Optimal RE - Energy Storage Details

Renewable Curtailment

In the optimised scenario, there is no RE curtailment, with or without BESS.

System Level Costs - Benefits

With storage addition, an annual saving on the system level cost of INR 720 Cr is observed. Despite the increase in fixed cost (211 Cr), net benefit of cost is observed due to the higher reduction in variable cost (INR 931 Cr). The unit cost of generation is also lower with BESS in the grid. (Refer to 4.2.6 Overall System Level Cost Benefits)

Considering the additional transmission infrastructure required to cater to a 19 GW peak export load in this scenario, an additional fixed transmission cost of 3505 Cr (for additional transmission capital expenditure) is added to the system fixed cost. Hence the total system level cost (generation & transmission) is 77564 Cr (i.e., addition of 3505 Cr to 74059 Cr). With an energy demand of 150535 MUs including exported energy, the overall system level levelized cost of electricity becomes INR 5.17/kWh.

Generation System Cost (INR Cr)

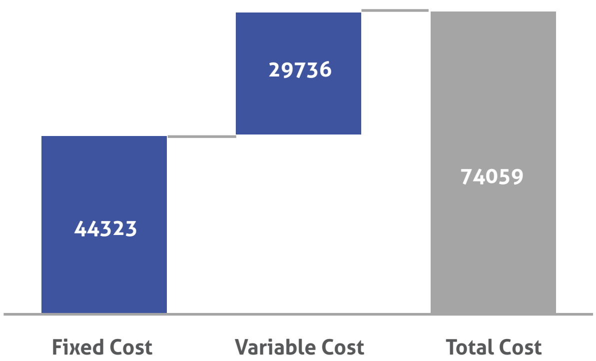


Figure 38: Optimal RE - Generation System Cost with BESS

4. Year 2030: High RE Scenario with Pumped Hydro Storage (PHS)

To evaluate the potential role of PHS in the system by 2030, this scenario with a 35 GW peak export load is modelled. In this case, both BESS and PHS are considered as storage options available for economic grid operations. The respective installed capacities of all the generation sources are assumed to be the same for both 'with PHS' and 'without PHS' cases. With the same installed capacities across all generation sources, the predicted generation pattern, PLFs, energy storage options, and system cost are examined below.

High RE 35 GW Peak Export: Generation Mix in 2030

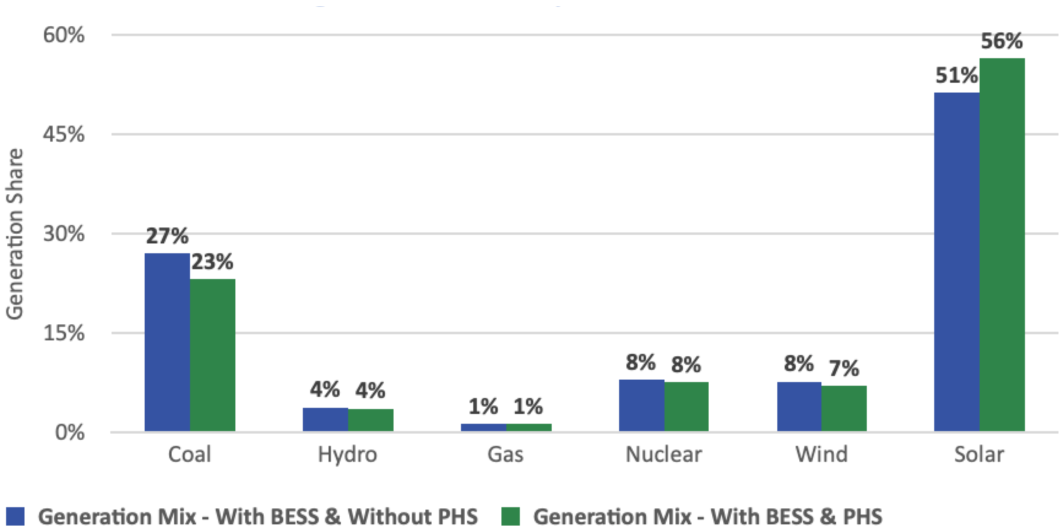


Figure 39: High RE 35 GW Peak Export - Generation share without and with PHS

When PHS is available, the higher solar generation share (from 51% to 56%) suggests that some part of this generation is getting time-shifted by the 7-hour storage offered by PHS. The generation share gain of solar mainly comes at the expense of reduced generation share of coal thermal (from 27% to 23%). This is also reflected in the PLFs of the generation assets, where the coal thermal PLF drops slightly along with a corresponding increase in the solar CUF. Coal thermal energy loses generation share on a merit-order basis.

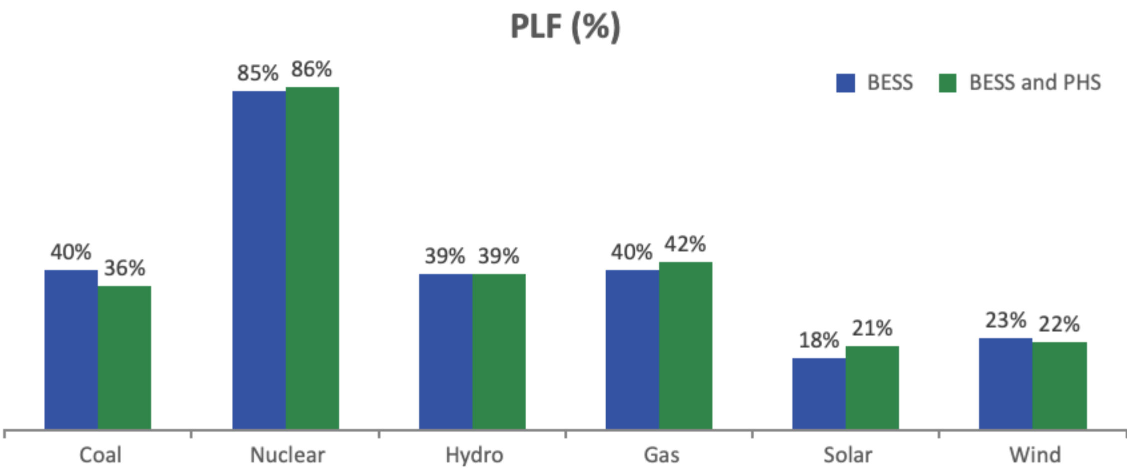


Figure 40: High RE 35 GW Peak Export - PLF without & with PHS

Storage Penetration

The model suggests an addition of 31.3 GWh of BESS. The duration of storage is 1 hour (9 GW), 2 hours (2.3 GW) and 7 hours (2.5 GW). With the addition of PHS to the system, BESS capacity for 1- and 2-hour durations increases. Also, the 4-hour storage is no longer required by the system. In lieu of the 4-hour storage, effectively, the shorter duration storage needs are fulfilled by BESS, and the longer duration storage service is provided by PHS.

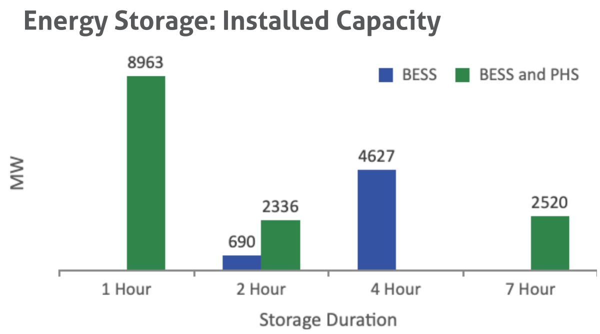


Figure 41: High RE 35 GW Peak Export – Energy Storage Capacity without & with PHS

System Level Costs - Benefits

With the addition of PHS, this scenario sees an annual savings on the system level cost of INR 702 Cr (from 97145 Cr to 96443 Cr) (Figure 42). Despite the increase in fixed cost (from 77691 Cr to 78583 Cr), net benefit of cost is observed due to the higher reduction in variable cost (from 19454 Cr to 17860 Cr). And, with the addition of PHS, the model also projects a higher energy generation as compared to 'with BESS and without PHS' scenario. Consequently, the unit generation cost decreases with PHS in the grid (from INR 5.81/kWh with BESS, to INR 5.44/kWh with BESS & PHS).

Considering the additional transmission infrastructure required to cater to a 35 GW peak export load in this scenario, an additional fixed transmission cost of 6458 Cr (for additional transmission capital expenditure) is added to the system fixed cost. Hence the total system level cost (generation & transmission) is 102901 Cr (i.e., the addition of 6458 Cr to 96443 Cr).

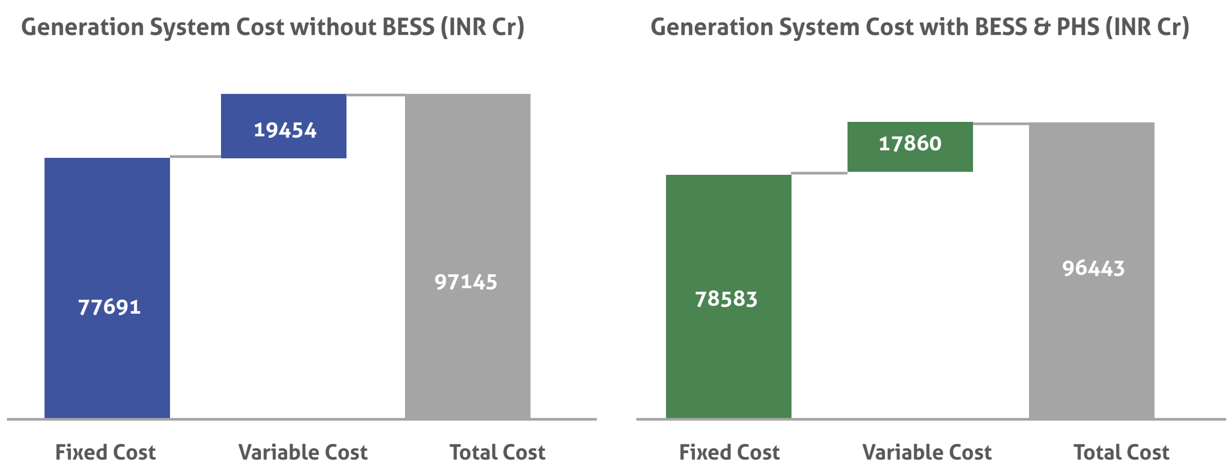


Figure 42: High RE 35 GW Export - Generation System Cost without & with PHS

5. Comparative Analysis: RE Supply Scenarios

The lower RE scenario sees significantly low RE curtailment when compared to the high RE scenario (Figure 43). Even though the peak export load goes up from 19 GW (low RE) to 25 GW (high RE), the high RE scenario sees much higher installed RE capacity (in solar 24 GW vs 58.5 GW, in wind 5.2 GW vs 6.7 GW). Hence, the generation from higher installed RE capacity in high RE scenario becomes surplus to the requirement of total system energy demand. On the other hand, the optimal generation mix suggests a RE generation share (29%) which is closer to the low RE scenario generation share (34%).

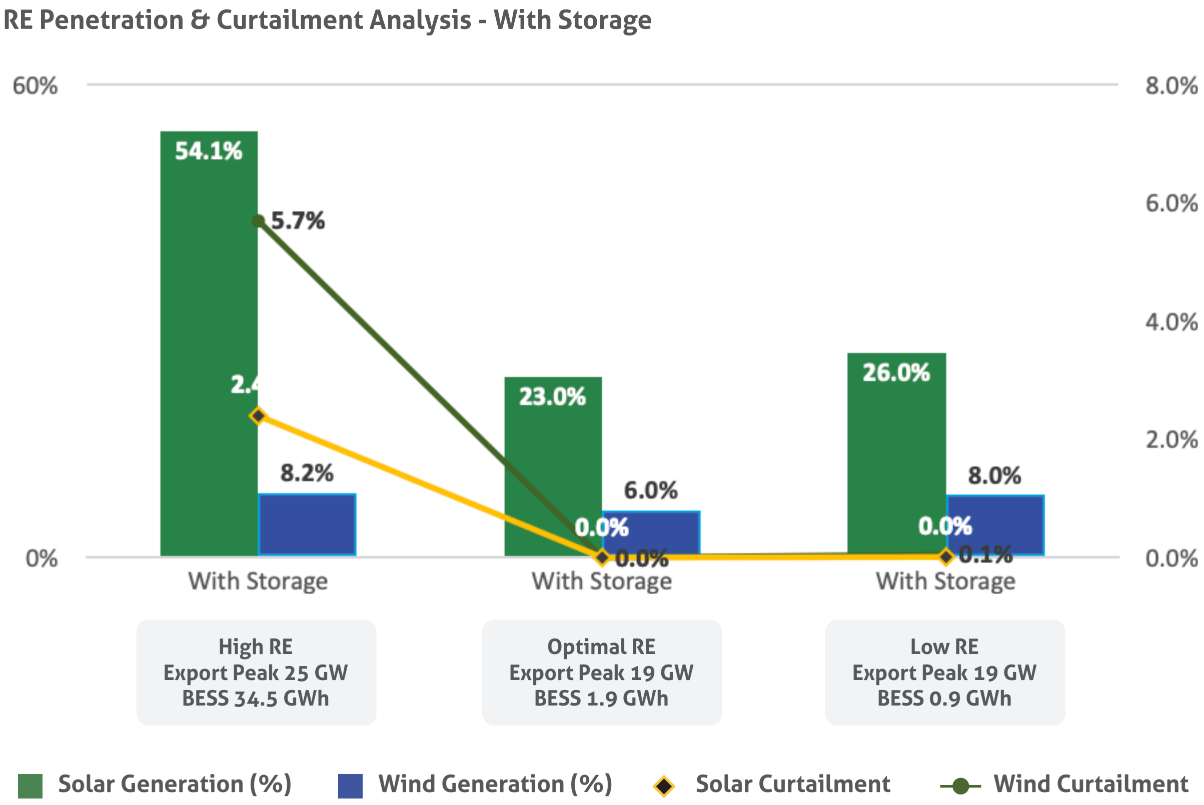


Figure 43: High, Low & Optimal RE - RE Penetration & Curtailment Analysis with Storage

The per unit system cost is lower in the low RE scenario (Figure 44). With lower RE installed capacity in the system and lower peak export load, the total system cost (generation and transmission) becomes lower. And, this lower system cost outweighs the impact of lower energy export, when the intra-state energy demand is the same. Hence, the per unit system cost is higher in the high RE scenario with 25 GW export. If the system caters to increased peak export loads like 35 GW and 45 GW, then a reduction in per unit system cost is observed (Figure 34).

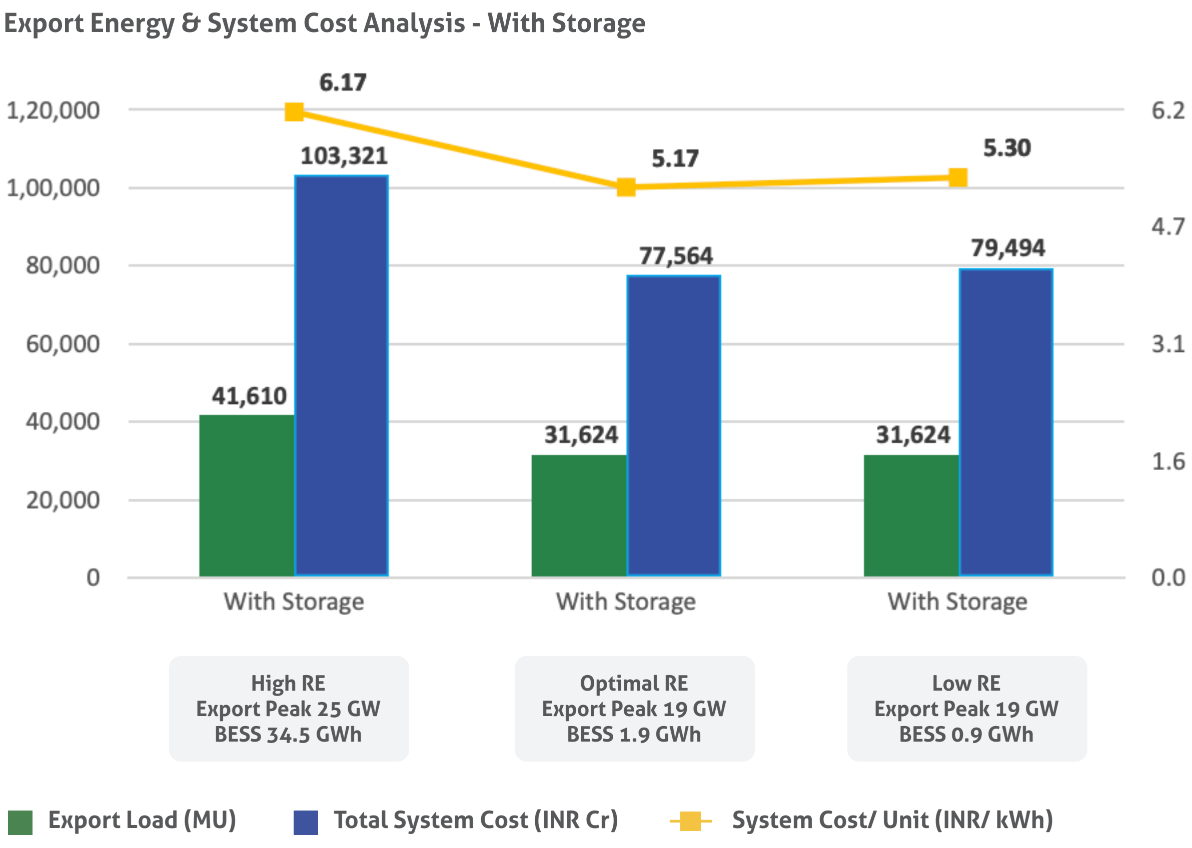


Figure 44: High, Low & Optimal RE - Export Energy & System Cost Analysis with Storage

CASE ANALYSIS:

SECI BESS 500 MW & GREENKO SHAHPUR PUMPED STORAGE 2520 MW

5

5.1 Scope and Objective of the Analysis

Till November 2022, the reverse auction of only one grid-scale BESS project has been conducted and the tender result was announced. The discovered tariff in the tender titled 'Selection of Battery Storage System Developers for Setting up of 1000 MWh (500 MW x 2 hours) Battery Energy Storage Systems' for 'on-demand usage' throws some interesting highlights on the economics of BESS in future. The 1000 MWh ISTS-connected pilot project would be set up on BOOT basis (Solar Energy Corporation of India Limited, 2021).

SECI issued this tender's final request-for-selection in April 2022; and this came in response to the considerable interest generated by prospective users/ consumers to use energy storage systems on-demand during peak and off-peak hours. Some other notable aspects of the tender were –

- Duration: Project term will be of 12 years
- Contractual Capacity: SECI's obligation will be for the offtake of 60% of the contracted capacity. Out of the 60% capacity contracted by SECI, 30% will be earmarked to be used by NLDC, POSOCO for grid ancillary services. The project developer will arrange for the utilization of the remaining 40% capacity.
- Technical Requirements: The developer is to make the BESS available for 2 operational cycles per day. The project has a mandated minimum availability of 95% annually and a minimum round-trip efficiency of 85% monthly.
- Tariff: BESS is treated as a subscription/ service. The tariff is to be paid in terms of fixed monthly payments for 12 years in return for using the system as 'on-demand' basis.
- The projects will be installed in the vicinity of the Fatehgarh-III Grid-Substation of the ISTS network, in the State of Rajasthan. They must be interconnected to the 400/220 kV Fatehgarh-III ISTS Substation.
- The Scheduled Commissioning Date for the full capacity of the project was set at 18 months

JSW Renew Energy emerged as the tender winner, with a bid of INR 1083500 per MW per month (equivalent to INR 130 Lakhs per MW annually) (Energy Storage News, 2022). The bid provides a reference to the expected levelized cost of electricity, which will be borne by SECI to improve grid stability.

Also, as discussed previously, standalone pumped storage projects are also being mooted as a viable solution to the needs of the state grid. And, Greenko Group, after evaluating suitable locations for hydro storage, has identified Shahpur, Baran District, Rajasthan for the proposed Shahpur standalone pumped storage project. In this context, the competitiveness of PSP vis-à-vis BESS is also analyzed in various storage requirement scenarios. A comparative analysis is done on the levelized cost of electricity for both technologies as per varying storage requirements.

5.2 Assumptions and Methodology

The key parameters that affect the LCOE of each technology, but are set by respective applications, are nominal power capacity, discharge duration, annual cycles and electricity tariff. While the first two affect capital investment and O&M cost, annual cycles affect project life and total discharged energy. The following assumptions form the basis of the comparative LCOE evaluation of PHS and BESS –

Parameter	Pumped Hydro Storage	Battery Storage
Power Capacity	2520 MW (Greenko project)	500 MW (SECI Tender)
Yearly Availability	95%	
Cycle Efficiency	80%	90%
Depth of Discharge	–	95%
Daily Cycle(s)	1	2, 3, 4
Operating Life	30 Years	12 Years
Discount Rate	10%	
Project Cost	INR 11737 Cr	INR 1794 Cr
Levelized Fixed Tariff as Revenue	INR 60 Lakhs/ MW/ Year	INR 130 Lakhs/ MW/ Year
Charging Cost	INR 3.5/ kWh	
Opex & Opex Escalation	8.5% of Levelized Fixed Tariff 4% yearly escalation	

Table 12: Parameters of PHS and BESS

The project cost of PHS is referred from Greenko's project estimate (Greenko Energies Pvt Ltd, 2020). The project cost of BESS assumes the same capital cost of battery pack and PCS, as explained in Section 3.2.3. The levelized fixed tariff of PHS maintains the same assumption as discussed in Section 3.2.9. For the concluded SECI BESS tender, the winning bid was equivalent to INR 130 Lakhs per MW annually. In combination with each technology's cycle efficiency, the electricity tariff affects the charging cost. Electricity prices during charging vary between user applications, regions and time horizons. This study assumes a generic value that is broadly representative of the wholesale price.

5.3 Economics of Battery Storage & Pumped Hydro Storage Projects

LCOE is employed as a metric for comparing the economics of the two aforesaid technologies. The LCOE value predominantly depends on the discharge duration of each storage technology. In this section, LCOEs for the two technologies are mapped for different storage durations, in Figure 45.

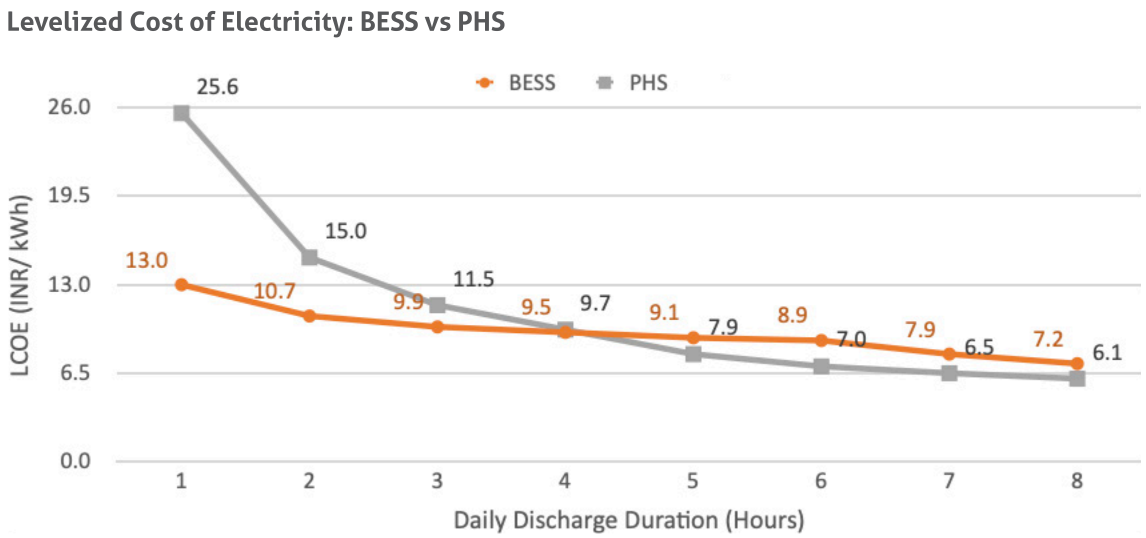


Figure 45: Levelized Cost of Electricity - BESS vs PHS

Grid applications with longer duration energy discharge requirements exhibit lower LCOE than applications with similar cycle and shorter discharge requirements. A few examples of such applications are T&D investment deferral or seasonal storage, as compared to applications with a lower discharge duration like black start, power quality and tertiary response.

From our indicative study for 2030, lithium-ion BESS appear to be most cost efficient (i.e., lower LCOE) for all discharge and cycle combinations below a 4-hour duration. Pumped hydro exhibits the lower LCOE beyond 4-hour discharge duration requirements. For those discharge durations (> 4-hour), the higher capital costs of PHS are outweighed by its longer lifetime, giving it a lower levelized cost. Also, due to the higher power-specific investment cost of PHS (which is INR 4.7 Cr/MW in PHS and INR 3.6 Cr/MW in BESS as per the study assumption), a higher cycle-wise energy discharge from the system consequently lowers the LCOE.

Hence, in order to leverage a higher energy discharge from PHS, a longer duration discharge is necessary, which is also exhibited by the analysis. While the option of customizing lithium-batteries of various kinds and sizes as per application needs, and their modular installation process are economically more beneficial, when compared to PHS.

In our view, ultimately, there is room for both lithium-ion batteries and pumped hydro storage, and they may even complement each other. Batteries are more cost-effective at delivering small amounts of energy over short time intervals at high power levels. Pumped storage is more cost-effective while releasing larger amounts of stored energy, thereby operating for longer hours. While projected capital cost reductions for battery technologies may limit the competitiveness of pumped hydro even for longer discharge periods, achieving the optimum storage solution will depend on finding the best fit as demanded by a particular application.

CONCLUSION & RECOMMENDA-TIONS

6

The indicative results from the simulation study highlight a key enabler to energy transition, i.e., energy storage. Storage integration is essential for making generation system more economical with ever increasing RE assets, apart from the other benefits highlighted in previous sections. In any simulated RE scenario, the addition of BESS lowers the LCOE of the system. Although the scale of the requirement is tied to RE penetration, its benefits in all the scenarios make it a universal solution.

There is a marginal benefit in LCOE (from INR 5.31/kWh to INR 5.30/kWh), when BESS is added in the low RE scenario. With lower RE installed capacity in the system and lower peak export load (19 GW), the RE energy in the system is the lowest amongst all simulated scenarios and so too are the potential benefits from BESS. But, as the installed capacity increases and the system caters to increased peak export loads of 25 GW, 35 GW and 45 GW, the BESS benefits become more prominent. In high RE scenario with 25 GW peak export load, the addition of BESS brings down the LCOE from INR 6.32/kWh to INR 6.20/kWh. With a 35 GW peak export load, the addition of BESS brings down the LCOE from INR 5.97/kWh to INR 5.81/kWh. And when the peak export is even higher at 45 GW, the BESS addition brings down the LCOE from INR 5.20/kWh to INR 5.15/kWh.

Interestingly, in the high RE with a 45 GW peak export scenario, the capacity of non-utilised coal thermal assets reduces to 1.9 GW with BESS integration as compared to 3.3 GW without BESS. As the share of export energy in the total system load is maximum in this scenario as compared to other scenarios, coal thermal assets don't see sharp fall in utilisation levels thereby benefitting from the integration of storage.

Although this study didn't include load-flow analysis, it is often observed that a rapid growth of renewable generation is leading to temporary congestion in the transmission infrastructure. The addition of transmission capacities doesn't help in the longer term, as the augmented capacities are often under-utilised throughout the year. A step towards mitigating this problem can be the exploration of non-transmission alternatives like energy storage technologies in the current transmission investment planning processes.

In the simulated scenarios of this study, a storage asset is considered a standalone system, not coupled with a solar or wind asset. In view of the potential benefits of storage projects even in standalone form, a policy framework can be conceived for energy storage at transmission level. In the current policy regime, transmission companies are tasked with making investment decisions on new transmission capacity. The transmission companies can't exercise control over any asset which can be considered generation or supply. Energy storage systems can be considered as generation when discharging and a load when charging. Thus, transmission companies cannot own or operate any energy storage system, while the planning and operation of energy storage systems is in the domain of other market players. Here, an enabling policy can help integrate energy storage into the transmission investment decision process.

In Western electricity markets, major revenue streams for energy storage assets are energy arbitrage at different time periods and payments for various regulation services such as frequency regulation. Congestion in a power system can open energy arbitrage opportunities and thereby increase the utilisation of energy storage. So, in order to leverage the benefits of high renewable energy exports from Rajasthan, it is imperative that the transmission capacity expansion aligns with capacity addition in storage. The capacity planning of both assets can be complementary.

Pumped hydro storage is the most widely deployed grid-scale storage technology today. The global installed capacity of PHS was around 160 GW in 2021. The energy storage capacity (global level) of PHS was around 8500 GWh in 2020, accounting for more than 90% of total electricity storage (IEA, 2022). Grid-scale batteries are expected to catch up in much faster manner, however. Although currently far smaller than pumped hydro storage capacity today, grid-scale batteries are projected to contribute to most of the storage growth in the next 10 years. Total worldwide installed grid-scale battery storage capacity stood at close to 16 GW in 2021. For the second year running, installations increased strongly in 2021, rising by 60% as compared with 2020 (IEA, 2022).

According to the results on this study, the unit cost of generation becomes lower with both PHS and BESS in the Rajasthan grid. Addition of BESS results in LCOE of INR 5.81/kWh, while inclusion of both BESS and PHS reduces the LCOE to INR 5.44/kWh. In order to leverage a higher energy discharge from PHS, a longer duration discharge becomes necessary. As highlighted by the study results, there is room for both battery storage and pumped hydro storage, and they may even complement each other.

In terms of grid-scale battery technology mix, lithium-ion battery storage continues to be the most widely used, making up the majority of all new capacities installed. Based on cost and energy density considerations, lithium iron phosphate batteries, a sub-category of lithium-ion batteries, are the preferred choice for grid-scale storage. More energy-dense chemistries for lithium-ion batteries, like nickel manganese cobalt (NMC) and nickel cobalt aluminium (NCA), are popular for other applications where space constraint is an issue.

Other than lithium-ion batteries, vanadium flow batteries were also considered in the production cost model in this study. Flow batteries could emerge as a breakthrough technology for stationary storage as they don’t suffer performance degradation for 25-30 years and can be sized according to energy storage needs. The technology is marked by long discharge duration, and long cycle life (~15000). While flow

batteries have higher upfront costs than lithium-ion, their longer cycle life can result in significantly lower lifetime costs. These batteries are in the initial stages of commercialization.

In a nutshell, it is desirable that pumped hydro storage and grid-scale batteries are considered integral parts of long-term strategic electricity plans, aligned with solar PV and wind capacity as well as grid capacity expansion plans. Dedicated support mechanisms like capacity auctions for storage, can help promote deployment by providing long-term revenue stability. To capture even more benefit, storage should be considered in the transmission and distribution planning process. While dealing with the key issue of ownership in storage, system operators can be allowed to procure storage services from third parties. Further, a deep dive on the utility and economics of different storage technologies can be explored through ongoing research effort, to understand finer details of technology choices.

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7

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