New PSH Capacity Can Be Cost-Effective in the Near Term

Cost scenarios show that in the near term, new PSH at 6.9 Crore ₹/MW (0.93 million $/MW) is cost-competitive with battery storage technologies. Further reductions in PSH costs result in more PSH capacity and delayed investments in BESS projects. PSH capacity reaches 52 GW with 630 GWh energy capacity by 2030 in the Low PSH Cost scenario (4.9 Crore ₹/MW in 2020). This buildout represents over half of the potential PSH capacity that has been identified by CEA (P. K. SHUKLA 2017). However, given rapidly declining costs for BESS, longer-term opportunities for economic PSH investments are limited. We see no new investments in PSH projects after 2030 across the capacity expansion scenarios evaluated for this study. However, upgrading existing reservoir storage with pumping capacity may be cost-effective, but is not considered in this study.

There Is a Strong Synergy Between Battery Storage and Solar Photovoltaic (PV) Deployment

We find significant reductions in solar PV deployment when battery storage costs are higher. In the High Battery Cost scenario, by 2030 there is 25 GW (110 GWh) less energy storage capacity and 19 GW less solar PV capacity, reductions of 30% and 7.6%, respectively, compared to the Reference Case. The same trend persists in the long term. By 2050, energy storage capacity is 20% lower and solar PV capacity is 19% lower in the High Battery Cost scenario compared to the Reference Case. We also explore the impacts of different assumptions for the future costs of solar PV technologies. The Low Solar PV Cost scenario has more investment in both solar PV and energy storage in the near- and long-term. There is 25% more energy storage capacity in the Low Solar PV Cost scenario by 2050 compared to the Reference Case. We also see a substantial reduction in wind capacity by 2050, declining by 30% in the Low Solar PV Cost scenario compared to the Reference Case. This result indicates that policies aimed at lowering the cost of solar PV may have important implications for the battery storage and wind power sectors as well.

Energy Storage Technologies Can Provide a Majority of Operating Reserve Requirements in 2030, if Allowed to Do so.

Operational modeling of the 2030 power system shows energy storage can play a major role in providing operating reserves in the future power system and there are significant system benefits to allowing these technologies to do so. Energy storage provides 80% of the annual operating reserves in 2030 in the Reference Case. We see a 3.3% increase in annual production cost in 2030 when storage is not allowed to provide operating reserves. This is because more thermal and gas machines are committed to provide reserves. Further, the average cost of providing reserves increases from around $7/MWh to $60/MWh. Allowing energy storage to provide operating reserves also reduces the need for fossil-fuel based plants to remain committed. On average, 7% more gas-fired units and 4% more coal-fired units are scheduled to run throughout the year when energy storage is not allowed to provide operating reserves.

Energy Storage Provides System Balancing, Ramping, and RE Integration Services

Storage can support the system by providing balancing services and help integrate more RE. Results show that by 2030, India's maximum hourly net load ramp could reach 60 GW. Energy storage can meet the majority of these needs by storing excess generation during high-RE periods and discharging to meet evening ramp needs (see Figure ES-5). The role of storage to integrate RE becomes increasingly important by 2050, when coal, gas and hydro contribute only

20% toward the country's generation mix. The results also show that energy storage is primarily charged during the daytime, enabling higher penetration of solar. Further, on some days, storage reduces its generation during the evening when wind generation picks up, helping to absorb higher levels of wind in the grid.

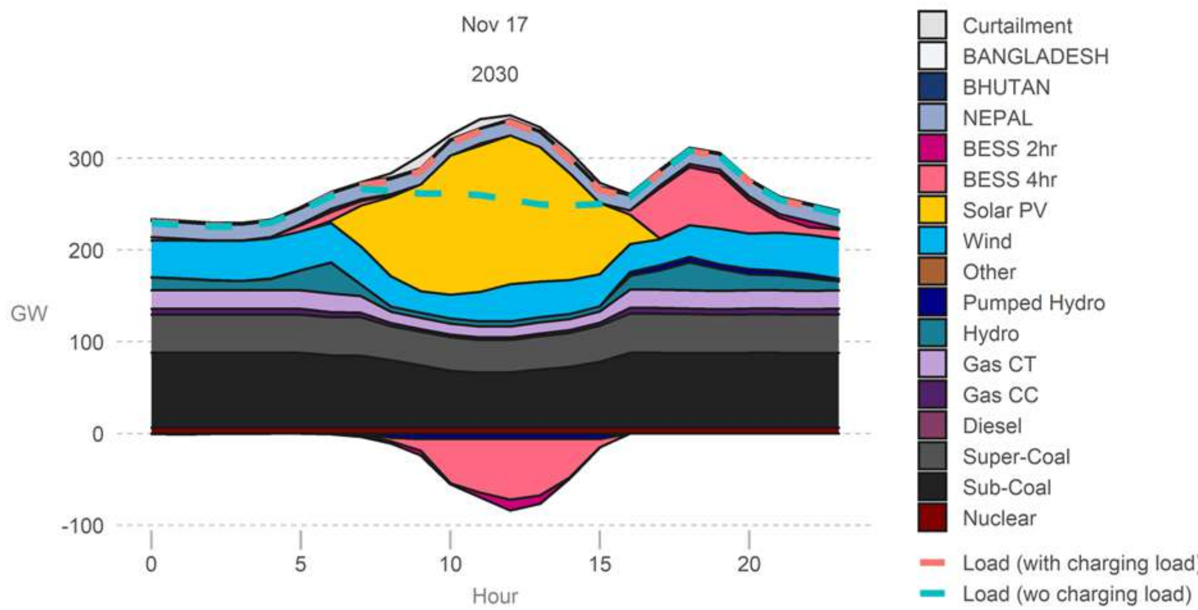

Figure ES-5. Dispatch stack for one day with the highest net load ramp in 2030

Energy Storage and RE Capacity Grows More Slowly in the Long Term When New Investments in Gas-Fired Capacity Are Restricted

In the No New Gas scenario, where investments in new gas-fired capacity are not allowed, long-term energy storage capacity grows slower and ends 38% lower in 2050 compared to the Reference Case. This result is somewhat unexpected, given that energy storage can serve similar peaking capacity functions as gas-fired power plants. Instead, we see that gas-fired capacity from the Reference Case is replaced primarily by super-critical coal capacity in the No New Gas scenario. With more coal in the capacity mix, the energy time-shifting value for energy storage decreases due to a lower electricity price differential between the low-value and high-value periods. By 2050, the average energy time-shifting value of energy storage is 28% lower compared to the Reference Case. With reduced time-shifting value, less energy storage is cost-effective. And with less cost-effective energy storage, there is less opportunity for cost-effective solar PV deployment in the No New Gas scenario compared to the Reference Case.

The Results Point to Several Trends That Can Inform Regulations, Policies, and Market Rules for Energy Storage in South Asia

- Establishing a level playing field for energy storage to compete with conventional technologies can lead to increased RE integration and reduced air emissions from the power sector. Modeling results show that when energy storage can compete directly with conventional resources to provide various system services, more energy storage becomes cost-effective, which results in increased solar PV deployment and reduced generation from fossil-fueled resources. Leveling the playing field can include new ways to value the performance of generating resources to meet system needs, such as ramp rates, response time, and minimum generation level.

- Energy storage systems can achieve their full economic potential if they are able to provide and monetize multiple system services. In the South Asia context, this means that new regulatory proceedings at the national and state levels may be needed to enable energy storage projects to participate as a source of both load and generation, and to provide multiple grid services. For utility-owned energy storage devices, where costs are recovered under a cost-of-service regulation, utilities and regulators can establish agreed-upon methods to quantify and compensate the full system value that energy storage provides to the power system.
- Access to cost-reflective energy markets, with daily price fluctuations, is a key revenue stream that can enable energy storage to be cost-competitive with conventional resources. Regulators can consider allowing energy storage to participate in the wholesale and real-time energy market. In the absence of markets, tariffs structures that reflect system value, such as rewarding energy storage for discharging during high-value periods, can help storage devices monetize the energy time-shifting value they provide to the system.
- Energy storage can be a significant source of reliable capacity for India's power system. Valuing the capacity contribution of energy storage, through tariff design or other mechanisms such as capacity auctions or capacity payments, can enable cost-effective energy storage to compete with fossil-fueled capacity resources. Regulators can begin by establishing clear and agreed-upon methods to quantify and compensate all resources (including energy storage devices) for contribution to reliable capacity.
- Energy storage can help meet operating reserve requirements and therefore reduce commitments of thermal generators. However, providing operating reserves is a relatively small portion of the full value of energy storage for the power system. Regulators can help ensure that market rules governing operating reserves and other ancillary services enable energy storage to provide multiple grid services from the same device. In India, for example, the Central Electricity Regulatory Commission (CERC) has issued draft regulations explicitly allows energy storage to participate in the proposed ancillary services markets (CERC 2021).
- There is a strong synergy between energy storage and solar PV deployment. Policymakers can include energy storage in national energy policies and master plans and acknowledge the complementarity between solar PV targets and increasing opportunities for energy storage technologies.

Table of Contents

List of Figures

List of Tables

1 Introduction

During the last decade, the cost of energy storage technologies, primarily lithium-ion battery energy storage systems (BESS), has declined rapidly and is projected to decline another 50% over the next decade. Several landmark utility-scale projects around the globe, such as the 150-MW/194-MWh Hornsdale Power Reserve in South Australia and the 250-MW/250-MWh Gateway Energy Storage project in California, have demonstrated that energy storage can provide a cost-effective source of flexibility and reliability services for the electric grid (LS Power 2020; AEMO 2018). At the same time, questions remain about the opportunities for energy storage in India and other South Asia countries. India, one of the world's largest synchronized power systems serving over one billion people, plans to increase the deployment of variable renewable energy (RE) resources to 175 GW in 2022 and further to 450 GW by 2030. To cost-effectively integrate increasing levels of RE, India's power system could require substantially more supply and demand-side flexibility. The International Energy Agency (IEA) in its India Energy Outlook 2021 noted that "India has a higher requirement for flexibility in its power system operation than almost any other country in the world" (IEA 2021). While energy storage has garnered increased interest from policymakers as a potential source of flexibility, uncertainty remains about the technology costs, as well as rules governing energy storage operations, ownership, and compensation mechanisms.

This study provides a first-of-its-kind assessment of cost-effective opportunities for grid-scale energy storage deployment in South Asia both in the near term and the long term, including a detailed analysis of energy storage value streams, potential barriers, and the role of energy storage in system operations. We conducted scenarios-based capacity expansion modeling to assess when, where, and how much energy storage can be cost-effectively deployed in India through 2050. The analysis relies on state-of-the-art modeling approaches to uncover and compare the value streams of 2-hour, 4-hour, 6-hour, 8-hour, and 10-hour battery storage, as well as pumped storage hydropower (PSH). We also run hourly simulations of system operations in 2030 and 2050 to understand how energy storage will be utilized by system operators to help integrate RE and reduce operating costs. For Bangladesh, Nepal, and Bhutan, we use operational simulations to explore how increasing deployment of energy storage can help optimize the use of domestic resources and cross-border electricity trade (CBET).

This study is conducted under a broader program focused on identifying opportunities and barriers for energy storage in South Asia. Other publications in this series include:

- *A Framework for Readiness Assessments of Utility-Scale Energy Storage* (Rose, Koebrich, et al. 2020)
- *Policy and Regulatory Environment for Utility-Scale Energy Storage: India* (Rose, Wayner, et al. 2020)
- *Policy and Regulatory Environment for Utility-Scale Energy Storage: Bangladesh* (forthcoming)
- *Policy and Regulatory Environment for Utility-Scale Energy Storage: Nepal* (forthcoming).

2 Modeling Approach

The modeling approach for this study relied on several interlinked modeling tools and multiple scenarios to assess different aspects of energy storage opportunities in India, Bangladesh, Bhutan, and Nepal.

2.1 Modeling Tools

Figure 1 illustrates how different modeling tools were linked to analyze the opportunities for energy storage in South Asia.

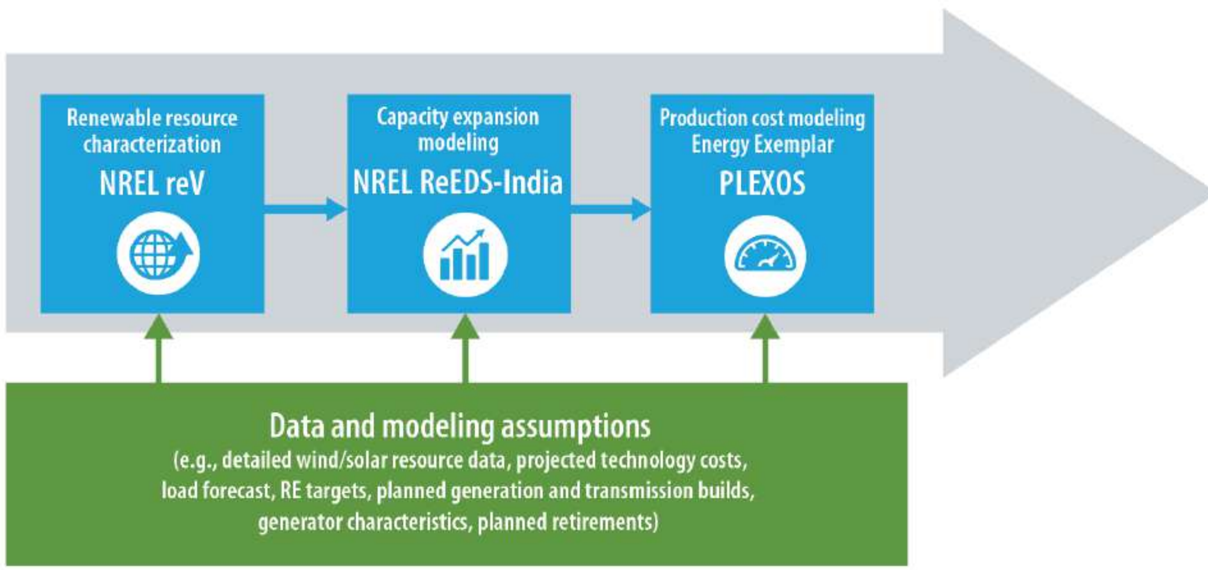

Figure 1. Modeling tools used in this study

The Renewable Energy Potential (reV) tool is a detailed spatio-temporal modeling tool that is used to assess renewable resource potential, technical potential, generation, and cost based on geospatial intersection with grid infrastructure and land-use characteristics. Coupled with NREL's System Advisor Model, the reV model's generation module estimates system performance based on technology parameters, including solar panel tilt angle, azimuth, inverter load ratio, efficiency, and others. Wind systems are defined based on their hub height, rotor diameter, power curve, and other wind-specific configurations. The resource potential identified in reV is input into the Regional Energy Deployment System India (ReEDS-India) capacity expansion model (CEM) to identify the least-cost mix of generation, storage, and transmission infrastructure required to meet system needs, including needs for energy and reserves.

The ReEDS-India model is the cornerstone of the modeling framework for this study, informing where, when, what types and how much energy storage is cost-effective for deployment in each year between 2020 and 2050. The model includes three levels of spatial resolution: regions, balancing areas, and resource regions. Regions include the five operating regions that make up the all-India interconnection, namely the Northern region, Northeastern region, Eastern region, Southern region, and Western region. Bangladesh, Bhutan, and Nepal are represented as single nodes that trade power with respective transmission-connected states in India. We considered 34 total balancing areas in India. Each balancing area represents a state or union territory with aggregated electricity demand, conventional generation capacity, and transmission. We assumed there are no hurdles to electricity trade among balancing areas. Finally, within each balancing area, there are multiple resource regions designed to capture differences in RE resources at a higher level of granularity. There is a total of 146 resource regions.

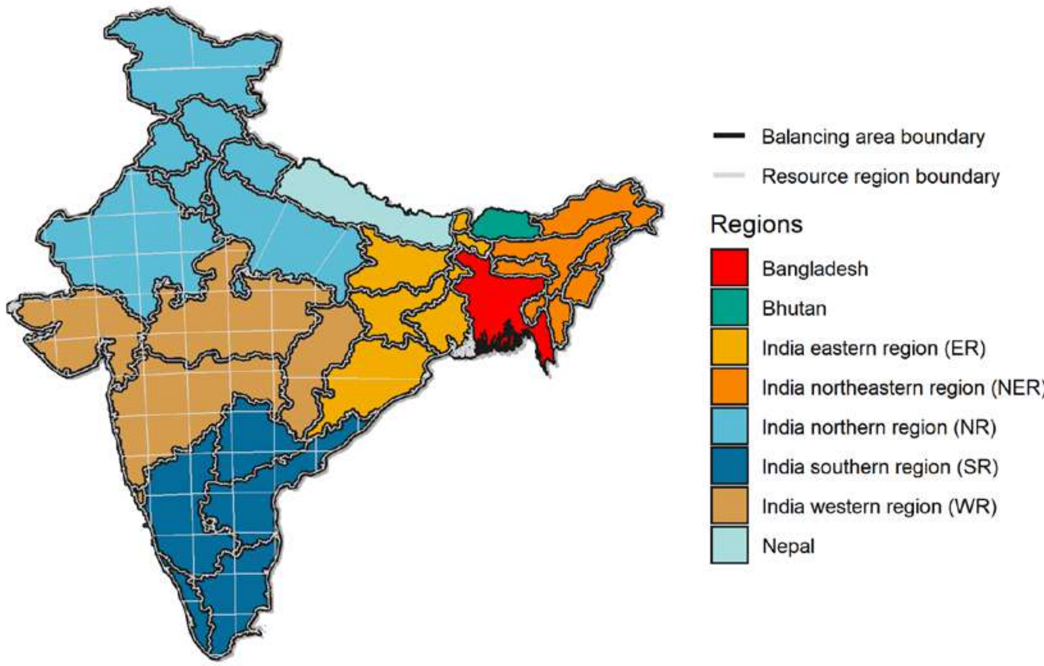

Figure 2. Balancing areas and RE resource regions

State-wise electricity demand is represented using 35 representative periods or "time slices" per year. The time slices capture changes in seasonal and daily demand patterns, as well as variability in renewable generation. The transmission network is represented as the aggregate transfer capacity between balancing areas. Energy flows on the transmission network are represented as pipe-flow energy transfers in each time slice. There are 77 transmission corridors represented in the model. Operational reserves are modeled as 5% of load. See Appendix A for more details about the modeling approach and inputs.

The model includes several updates and new features for representing energy storage since the initial ReEDS-India release, as described in (Rose, Chernyakhovskiy, et al. 2020). First, we expanded the set of options for energy storage investments. The model selected among six different configurations of stand-alone BESS between 1 and 10 hours of duration, as well as PSH with 12 hours of duration. For each energy storage technology, we calculated the capacity credit, or the contribution that different energy storage durations can provide to meeting capacity adequacy requirements. The methods used to calculate energy storage capacity credit are described in Frazier et al. (2020). Further, we added a dispatch simulation to calculate the potential revenue that different energy storage technologies can receive for shifting energy to different periods of the day. Storage time-shifting revenue includes the value to the system of shifting the time of supply from low-value to high-value periods. In India, this can mean shifting energy from the middle of the day when there is abundant solar energy to high-demand periods in the early morning and/or late evening. At the same time, storage time-shifting helps to avoid startup costs for conventional generators and to reduce RE curtailment. See Frazier et al. (2021) for further details on the method used to calculate time-shifting revenues in this study.