Opportunities for Renewable Energy, Storage, Vehicle Electrification, and Demand Response in Rajasthan's Power Sector

Ilya Chernyakhovskiy, Mohit Joshi, Sika Gadzanku,
Sarah Inskeep, and Amy Rose

National Renewable Laboratory

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Technical Report
NREL/TP-6A40-83240
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Reviews are provided in a personal capacity and do not indicate a formal endorsement from affiliated organizations.

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List of Acronyms

ATB	Annual Technology Baseline
BA	balancing area
BESS	battery energy storage systems
CAGR	compound annual growth rate
CT	combustion turbine
DISCOM	distribution company
EV	electric vehicle
FAME	Faster Adoption and Manufacturing of Electric Vehicles
NREL	National Renewable Energy Laboratory
PV	photovoltaic
ReEDS	Regional Energy Deployment System
VRE	variable renewable energy

Executive Summary

Rajasthan is the leading state in India for utility-scale renewable energy deployment, with 14 GW of solar generation capacity and 4.5 GW of wind generation capacity as of May 2022 (MNRE 2022). The state government has plans to achieve 30 GW solar and 7.5 GW wind and hybrid capacity by 2024–2025 (Energy Department, Government of Rajasthan 2019).[1] This transition will require robust planning to meet policy targets while ensuring cost-effective and reliable power system operations. To support the government of Rajasthan in this transition and inform state policymakers, regulators, planners, and system operators, the National Renewable Energy Laboratory (NREL) undertook a long-term capacity expansion planning study. We used NREL's flagship capacity expansion planning tool for the power sector called the Regional Energy Deployment System India (ReEDS-India) to understand the generation, transmission, and energy storage needs of Rajasthan through 2050. The findings presented in this study show that a renewable energy-based power system is a feasible and least-cost pathway for Rajasthan's energy future.

Rajasthan is likely to see unprecedented growth in cost-effective variable renewable energy (VRE) capacity over the next decade. NREL's modeling shows that by 2030, total VRE capacity in the state could reach over 60 GW, with 30 GW of solar photovoltaics (PV) and 30 GW of wind in our Reference scenario.[2] The contribution of VRE in Rajasthan's capacity mix would grow from 44% in 2021 to over 80% by 2030. By 2050, Rajasthan could deploy between 240 GW and 450 GW of cost-effective VRE capacity and supply between 550 TWh and 860 TWh of zero-carbon electricity.[3]

In the long term, it may be cost-effective to build new transmission corridors connecting high-renewable energy resource regions in Rajasthan with load centers in Haryana, Delhi, Uttar Pradesh, and Madhya Pradesh. By 2050, modeling results show that a mix of expanded alternating current (AC) connections and long-distance, high-voltage direct current (DC) transmission can enable electricity exports from Rajasthan's renewable resource-rich districts in the western part of the state. Figure ES-1 shows the areas with cost-effective VRE resources, expanded AC connections, and new DC links that were found to be cost-effective by 2050.

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[1] Hybrids are renewable energy plants with co-located solar PV and wind capacity with a solar PV percentage between 20% and 80%, as per the criterion from the Ministry of New and Renewable Energy (MNRE 2018).

[2] For all results presented in this study, we assume no constraints on supply chains for VRE technologies and/or workforce availability for project construction and commissioning. Supply chain and workforce constraints are outside the scope of this study and can be explored in future work.

[3] Zero-carbon electricity generation technologies include wind, solar PV, hydropower, and nuclear.

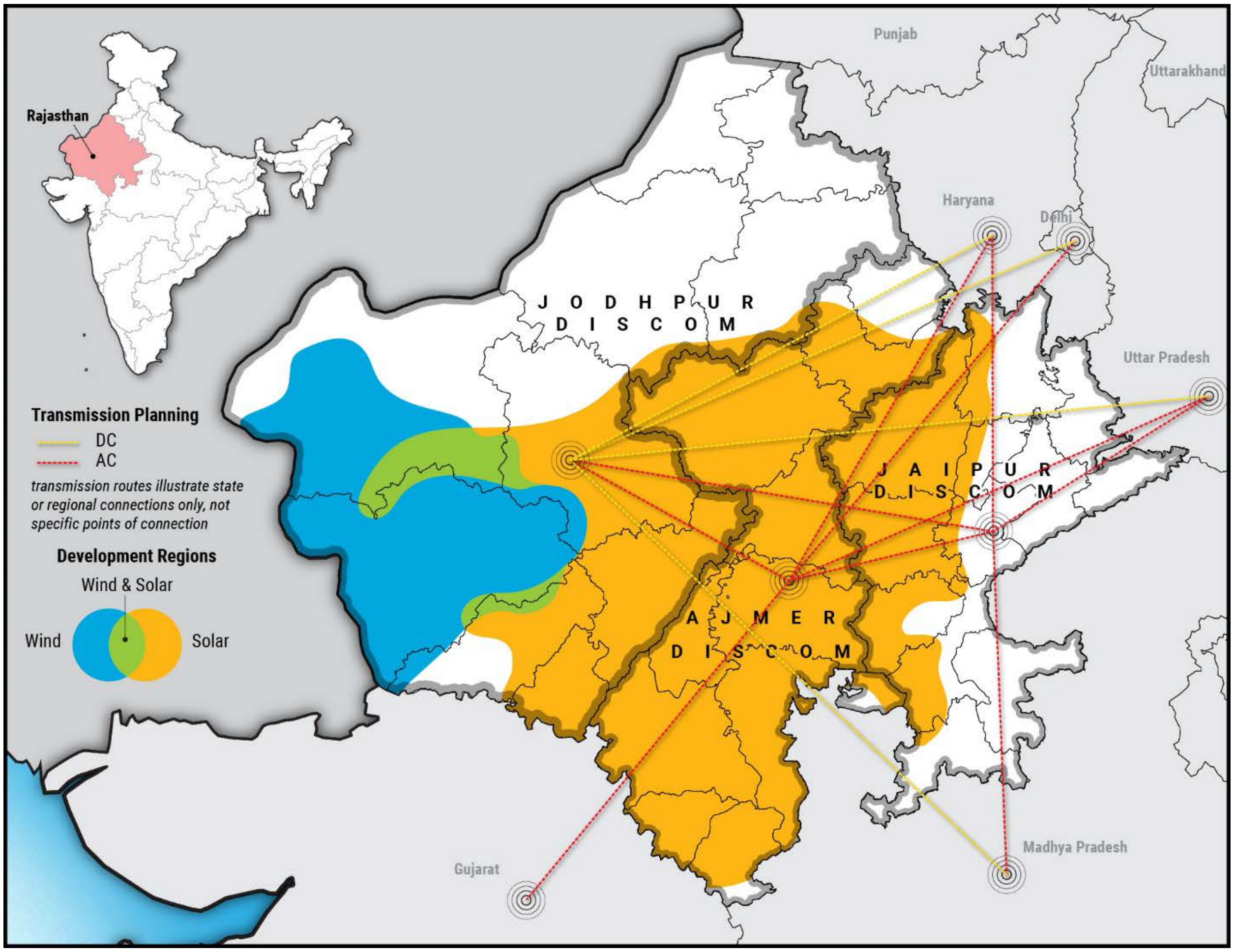

Figure ES-1. Rajasthan has the potential to fully meet domestic electricity needs with in-state clean energy resources and supply electricity exports for neighboring states.

Note: Figure shows renewable energy development regions and transmission routes that are cost-effective by the year 2050 under the reference scenario. Illustration by Billy Roberts, NREL.

Rajasthan can rely on local resources to meet the bulk of local electricity demand while providing electricity exports to neighboring states. Across all modeled scenarios, between 72% and 81% of generation in the state comes from VRE by 2030. Between 25% and 40% of electricity generated within the state is exported to neighboring states in our modeled scenarios.

Rajasthan can integrate 30 GW of solar PV and 30 GW of wind capacity by 2030 **while keeping state-wide curtailment below 1% annually.** A combination of battery energy storage, coal plant flexibility, and electricity trade with neighboring states can provide sufficient daily balancing and seasonal flexibility to integrate over 60 GW of VRE by 2030.[4]

System operations in Rajasthan is likely to change substantially by 2030. **Avoiding large renewable energy curtailments may require significant flexibility from the coal fleet.** Modeling results show that coal plants could be required to operate at minimum generation

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[4] VRE curtailment values presented in this study are based on results from the ReEDS-India capacity expansion model. Detailed operational analyses, including unit commitment and dispatch modeling, power flow modeling, and dynamic stability modeling, are outside the scope of this study.

levels and/or shut down for long periods at a time to accommodate increased renewable energy generation.

The transmission system will play a major role in providing power system flexibility. Rajasthan will increasingly rely on intra- and inter-state transmission networks for supply-demand balancing. By 2030, results show that Rajasthan would export electricity to neighboring states in most times of the year. During peak demand periods in certain seasons, Rajasthan would switch from exporting to importing power to meet local demand. Beyond 2030, Rajasthan is expected to be a net electricity exporter across all times of day and seasons of the year.

Shifting agricultural demand to daytime hours can provide significant cost savings for the power sector. If agricultural demand in Rajasthan, which makes up nearly 50% of overall state electricity demand, is shifted to daytime hours, modeling results show that overall costs for the power sector are 18% lower in Rajasthan and 1.5% lower across India by 2050. Lower costs are driven by a reduced need for capacity to meet afternoon and evening demand, as well as reduced energy storage capacity used to shift excess solar generation to evening hours. In the long term, shifting agricultural demand from evening to daytime hours also reduces the amount of solar capacity needed to charge energy storage during daytime hours.

Adding electric vehicle (EV) load to the system can reduce dependence on grid-scale batteries for diurnal flexibility. In the event of accelerated EV deployment compared to zero EV adoption, overall Rajasthan capacity increases in the short term to meet the increase in load. However, as EV load becomes more flexible in the long term due to availability of charging infrastructure and willingness of drivers to delay and shift charging times, we see an overall decrease in installed capacity (largely due to reduced battery deployment). Deploying EVs also shifts the generation mix across balancing areas, with Ajmer region deploying substantial wind to meet the increased demand at night and during peak demand hours. The increase in load from EVs also marginally reduces exports to neighboring states.

Power sector emissions of $PM_{2.5}$, SO_2, and NO_x in Rajasthan will continue to increase through 2025 under Reference scenario assumptions. Though emissions begin to decrease in the summer and rainy seasons in 2030, total annual emissions will not return to the estimated 2020 baseline until 2035. This is mostly due to increase in coal generation to meet growing demand in the near-term, which toward 2035 is replaced by generation from renewables. Lower costs for wind, solar, and battery storage could accelerate emissions reductions after 2025.

Preface

This report—Least-Cost Pathways for Rajasthan's Power System Transformation—is part of a broader program focused on supporting Indian states with long-term power system planning. More information about this program can be found at https://www.nrel.gov/international/india-renewable-energy-integration.html.

Other publications in this series include:

- *Pathways for Tamil Nadu's Electric Power Sector: 2020–2040* (Rose et al. 2021)
- *Opportunities for Hybrid Wind and Solar PV Plants in India* (Schwarz et al. 2022)
- *How to Conduct a Long-Term Planning Study: Guidelines for Power System Planners* (NREL 2021)
- *Power System Planning: Advancements in Capacity Expansion Modeling* (NREL 2021b)
- *Road Map for Advanced Power System Planning in Indian States with High Re*newable Energy (NREL 2021c)
- *Role of Renewable Energy, Storage, and Demand Response in Karnataka's Power Sector Future* (Joshi, Rose, and Chernyakhovskiy 2022).

Together, this work helps identify the necessary investment and operational strategies to achieve India's clean energy goals and equips key institutions and decision makers with the tools, data, and resources to inform and implement these strategies.

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1. Introduction

Rajasthan is a state in the northern region of India. As of May 2022, Rajasthan is leading among Indian states, with 14 GW of solar generation capacity and 4.5 GW of wind generation capacity (MNRE 2022). Rajasthan has plans to achieve 30 GW solar and 7.5 GW wind and hybrid capacity by 2024–2025 (Energy Department, Government of Rajasthan 2019). This study looks beyond the near-term targets to identify least-cost options and opportunities for the long-term development of Rajasthan's power system. We used detailed modeling tools and scenario analysis to help inform state-level planning efforts. Because wind and solar generation are subject to variable weather conditions, robust planning of generation and transmission investments can help ensure sufficient resources will be available to balance supply and demand across daily, seasonal, and yearly timescales. The scope of power system planning can also be expanded to consider the role of energy storage and demand response for transmission congestion management, reserves, capacity adequacy, and system flexibility services.

To support the government of Rajasthan in this transition and inform state policymakers, regulators, planners, and system operators, the National Renewable Energy Laboratory (NREL) undertook a long-term capacity expansion planning study. We used NREL's flagship capacity expansion planning tool for the power sector called the Regional Energy Deployment System India (ReEDS-India) to understand the generation and transmission needs of Rajasthan through 2050.[5] This model uses load forecasts, policy targets, generation and transmission infrastructure costs, fuel costs, and operating parameters, along with details of the existing and planned power system to optimize generation and transmission investments. Importantly, NREL's modeling framework includes co-optimized decisions about generation, energy storage, transmission, and reserves investments needed to meet future demand while maintaining reliable electricity supply. We conducted a scenario analysis to assess a range of potential future scenarios, providing insight for planning agencies, utilities, and local stakeholders about key power system trends. The outputs of this model include a projection across many years of generation capacity additions, generation retirements, and additional transmission capacity on different corridors, as well as generation fleet operations, transmission flows, and reserves requirements.

The next section provides a brief overview of the modeling approach, data inputs, and key assumptions for this study. Section 3 provides the results and insights from the Reference scenario. Sections 4, 5, and 6 focus on scenarios related to transmission, technology costs, and demand, respectively. Section 7 focuses on the direct air emissions and air quality impacts of Rajasthan's power sector development. Section 8 suggests potential future work, and Section 9 concludes the report.

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[5] For details about the ReEDS-India model, see Rose et al. (2020).

2. Modeling Framework and Key Assumptions

Detailed information about ReEDS can be found in Ho et al. (2021), and details on the application to India can be found in Rose et al. (2020). The model is implemented in the General Algebraic Modeling System (GAMS) programming language. A publicly available version of the ReEDS model developed for national-level planning in India can be accessed from https://www.nrel.gov/analysis/reeds/.

The national ReEDS-India model represents each Indian state and union territory, which are represented within India's transmission network as one balancing area (BA) each. However, as we are focusing on Rajasthan in this study, each distribution company (DISCOM) of Rajasthan, namely Jaipur Vidyut Vitran Nigam Ltd. (JVVNL), Ajmer Vidyut Vitran Nigam Ltd. (AVVNL) and Jodhpur Vidyut Vitran Nigam Ltd. (JdVVNL), is modeled in detail and assumed to operate as a separate BA (see Figure 1). Electricity demand, transmission lines, and non-variable renewable energy (VRE) generators are aggregated for each BA. For the purposes of this study, we do not make distinctions between the ownership of assets within BAs. All private, state, and central government owned power system assets, including transmission lines, substations, and generators, are aggregated based on their geographic location within the boundaries of each BA. Within BAs, each district of Rajasthan is modeled as a separate renewable energy resource region to capture differences in renewable resources at a higher granularity. Details on transmission assumptions for intra-state and inter-state transmission corridors are provided in Annex A.

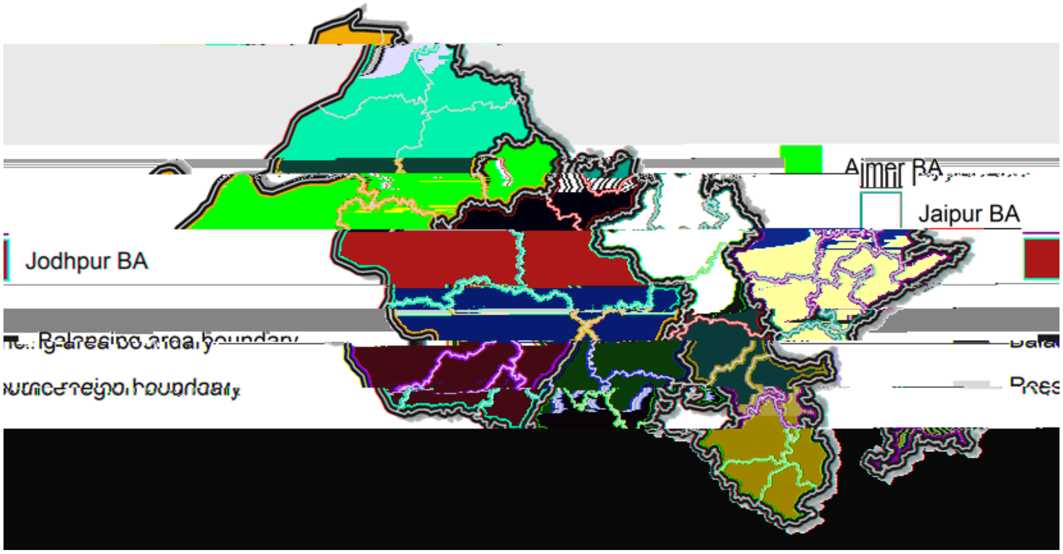

Figure 1. Rajasthan balancing areas and resource regions

2.1 Demand Projections

The demand projection for Rajasthan is based on the nineteenth electric power survey published by the Central Electricity Authority (CEA 2018) and adjusted to reflect changes to demand due to the COVID-19 pandemic (CEA 2018).[6] Total demand of Rajasthan was apportioned to each DISCOM based on actual energy consumption from 2019 to 2021. Figure 2 shows the annual energy, peak demand, and average hourly demand profile for each DISCOM through 2050. Table 1 shows the projected energy and peak demand in 2020, 2030, 2040 and 2050. Total annual demand in the state is projected to grow at a compound annual growth rate (CAGR) of 4.5% from 2020 to 2050. Peak annual demand is projected to grow at a higher rate, with a 5% CAGR over the same period. The higher growth of peak demand relative to total demand results in changes to the hourly demand profile as show in Panel C of Figure 2. Overall, the hourly demand profile has a decreasing load factor over time.[7]

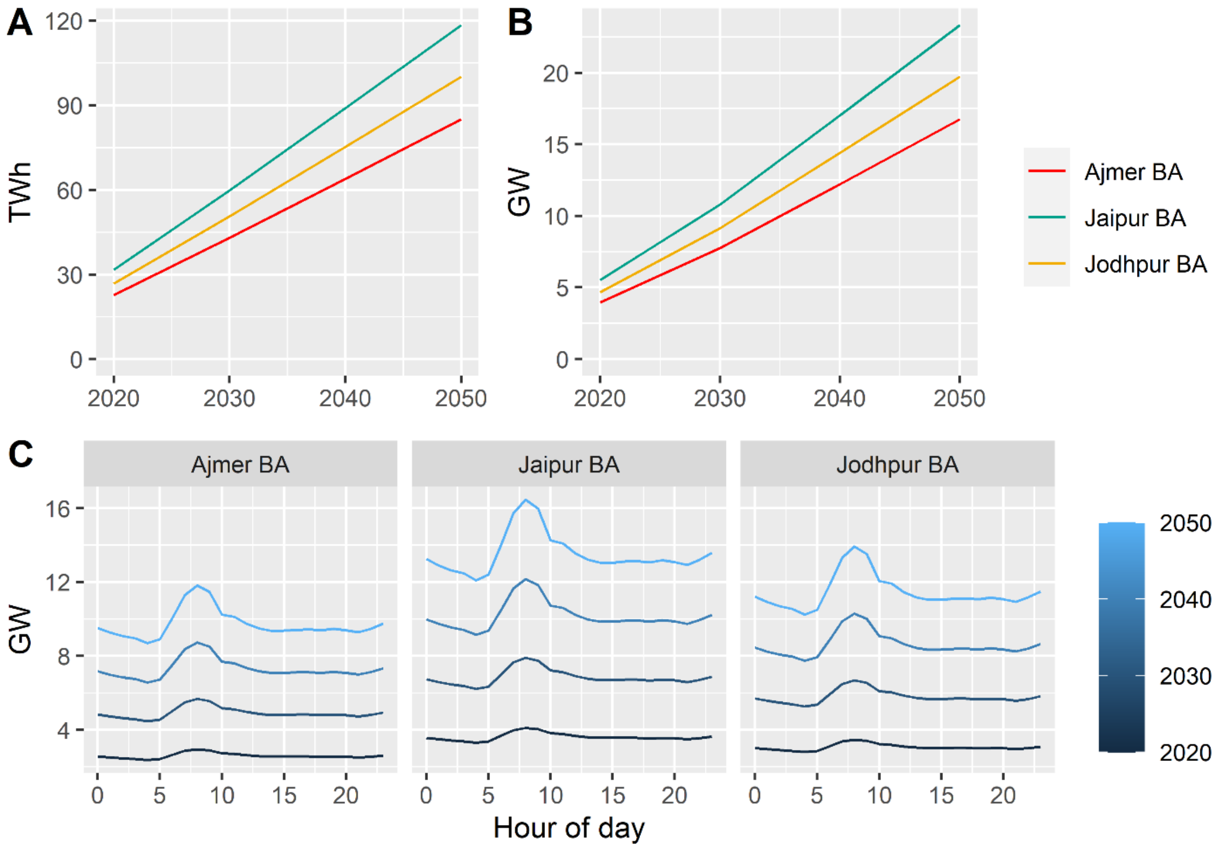

Figure 2. Annual energy (A), peak annual demand (B), and average hourly demand profile (C) by BA

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[6] We used the same approach described in Chernyakhovskiy et al. 2021 to forecast peak load and total energy demand through 2050 for each BA represented in the model.

[7] The load factor is the ratio of average demand to peak demand.

Table 1. Projected energy demand and peak demand

	Energy demand (TWh)				Peak demand (GW)			
Year	**2020**	**2030**	**2040**	**2050**	**2020**	**2030**	**2040**	**2050**
Ajmer BA	23	43	64	85	4	7.8	12	17
Jaipur BA	32	60	89	120	5.5	11	17	23
Jodhpur BA	27	51	75	100	4.7	9.1	14	20
Rajasthan total	81	154	228	304	14	28	44	60

Seasonal and diurnal changes in demand are represented in the model using time slices. We use 35 representative time slices per year. Each time slice provides a representation of the typical electricity demand that occurs within the respective period (e.g., the “evening” time slice for April–June represents mean electricity demand between 6 p.m. and 10 p.m. from April through June). More information about how the time slices are developed is provided in Rose et al. (2020).

2.2 Technology Costs

Initial capital and operational costs for generation technologies are based on NREL’s 2021 Annual Technology Baseline (ATB) (NREL 2021). We applied a 19% discount on all costs obtained from the ATB to reflect lower India labor costs. Learning rates (i.e., cost declines over time) for each technology follow the learning rates from NREL’s 2021 ATB (NREL 2021a). The methodology used to project costs for energy storage technologies is the same as presented by Chernyakhovskiy et al. (2021), with initial values and learning rates updated to reflect estimates in NREL’s 2021 ATB. Figure 3 shows the capital expenditure cost assumptions used for key technologies in this study. For consistency, we chose to use a single source, NREL’s 2021 ATB, for all technology costs in this study. Notably, the capital expenditure for supercritical coal is significantly higher compared to numbers used in previous ReEDS-India studies as well as numbers published in the Central Electricity Authority’s India Technology Catalogue (Rose et al. 2020; 2021; CEA 2022). However, comparisons of technology costs across different sources are outside the scope of this study.

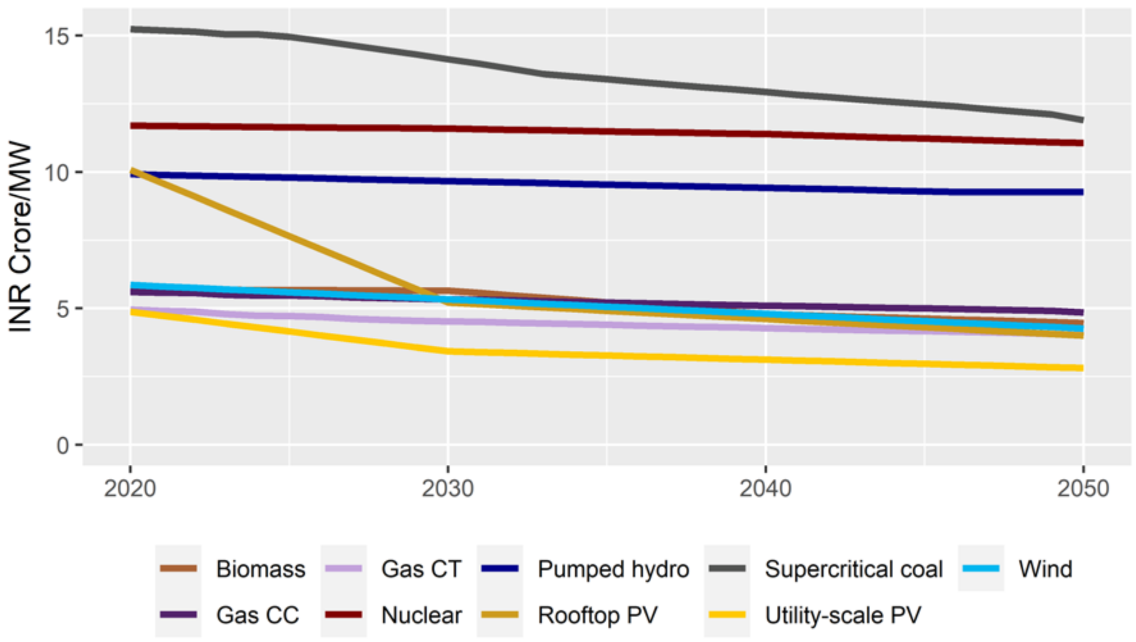

Figure 3. Technology capital expenditure cost assumptions

Detailed inputs and assumptions about technology performance characteristics, including operational and maintenance costs, fuel prices, operating constraints, as well as renewable energy resource availability and renewable energy supply curves, are available in Rose et al. (2020).

3. Reference Scenario Results

In the near term, to meet Rajasthan's state target of 30 GW solar photovoltaics (PV) by 2025, solar PV deployment will need to achieve a 32% CAGR from the end of calendar year 2021 when Rajasthan had about 10 GW installed solar PV. Wind capacity is not expected to grow in the near term, remaining stable at 5 GW. Some of this wind is expected to be co-located with solar PV (i.e., hybrid projects). A more detailed assessment of opportunities for hybrids is provided by Schwarz et al. 2022. Battery energy storage systems (BESS) can also play a role in helping Rajasthan to achieve renewable energy targets. The Reference scenario shows that 4.4 GW of 2-hour BESS would be cost-effective by the end of 2025 (see Figure 4).

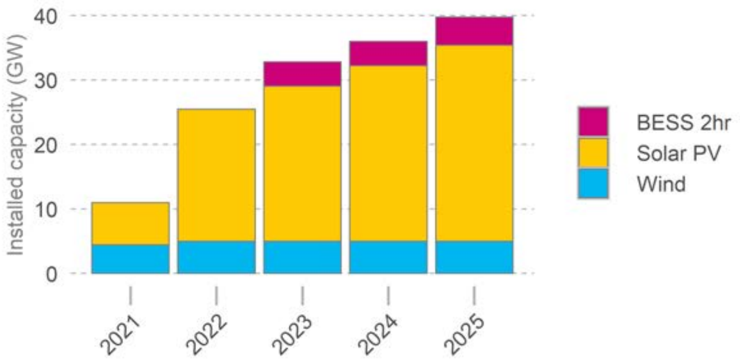

Figure 4. Solar PV, wind, and energy storage capacity in Rajasthan from 2022 to 2025, Reference scenario

3.1 Generation Capacity Until 2030

In the medium term until 2030, Rajasthan is likely to increasingly rely on VRE, energy storage, and electricity trade with neighboring states to meet supply-demand balancing needs. By 2030, the contribution of VRE in the generation mix grows to 73% annually in the Reference scenario, compared to 33% today. After 2022, only wind, solar PV, and BESS capacity is built in Rajasthan, with no new investments in conventional capacity. Installed capacity of solar PV and wind reaches 30.4 and 30.3 GW, respectively. Utility-scale BESS reaches 8,400 MW or 10% of total installed capacity and provide 25,000 MWh of diurnal energy storage capacity for supply-demand balancing. Figure 3 shows the evolution of installed capacity in Rajasthan from 2020 to 2030.

Figure 5. Installed capacity in Rajasthan from 2020 to 2030, Reference scenario

Wind and solar PV capacity are concentrated in Jodhpur BA. Figure 6 shows the district-wise capacity of wind and utility-scale solar PV by 2030. By 2030, Jodhpur BA has a total of 50 GW of solar PV and wind, or about 60% of the state-wide total renewable energy capacity.

Figure 6. District-wise wind (A) and solar PV (B) capacity in 2030, Reference scenario

Ajmer BA also sees significant investment in utility-scale solar PV. High solar resource areas in Naguar, Ajmer, Bhilware, and Rajsamand districts each have over 1 GW of solar PV capacity by 2030. This result may be somewhat counterintuitive, given that most solar deployment to date was concentrated in Jodhpur BA. However, the results show that Ajmer BA has a distinct advantage of direct AC connections with load centers in Delhi and Haryana, which enable electricity exports. In Jodhpur BA, wind and solar resources must compete for limited export capacity of AC transmission corridors and may be curtailed when transmission is congested. This trade-off between generation and transmission is explored further in the Copperplate scenario (Section 4).

3.2 Electricity Trade and System Operations Until 2030

Electricity trade with neighboring states, diurnal energy storage, and thermal plant flexibility emerge as crucial tools for balancing supply and demand in Rajasthan. Figure 7 shows the dispatch of generation resources in Rajasthan in different times of day and through the seasons in 2030. By 2030, Rajasthan exports 22% of in-state generation to neighboring states on an annual basis. Imports are used to meet demand only during peak hours in seasons when renewable energy resources are relatively low, compared to other times of year. For example, during peak demand periods in April–June, total generation, including energy storage discharge in Rajasthan, is 16 GW, while total demand is 19 GW (seen in Figure 7), with the remaining 3 GW supplied by imports from neighboring states. In energy terms, this represents 630 GWh of local generation and 130 GWh of out-of-state imports used to supply 760 GWh during 40 hours of peak demand periods in April–June. Annual imported energy in 2030 is 400 GWh in the Reference scenario, while annual energy exports total 61,000 GWh. The large volume of electricity exports to demand centers in neighboring states is enabled by planned investments in Rajasthan's transmission system. During peak renewable hours, energy flows from Jodhpur BA to Ajmer and Jaipur BAs, supplying local demand, while excess electricity is wheeled to Delhi, Haryana, and Uttar Pradesh.

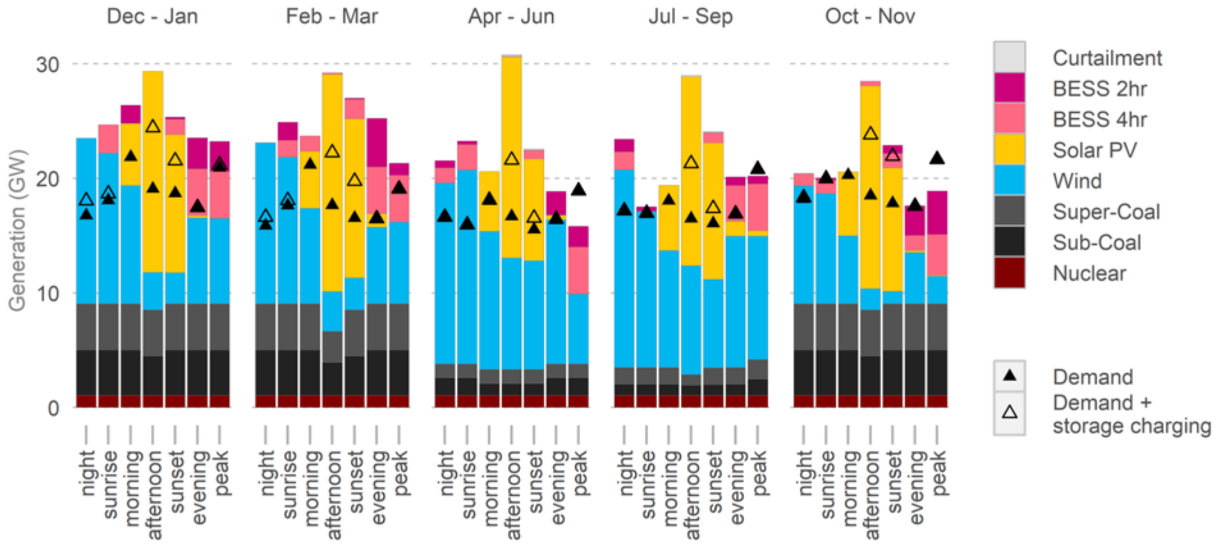

Figure 7. Generation dispatch, storage operations, and demand in 2030, Reference scenario

Note: The peak time slices represent demand within Rajasthan during the national peak demand period, which typically occurs in the late evening.

As seen in Figure 7, seasonal balancing is provided by flexibility in Rajasthan's coal fleet. During the high wind months between April and September, coal plants across the state are turned down to their minimum generation levels, and units in Jaipur BA are shut down for several months at a time. This flexibility enables the full utilization of Rajasthan's abundant wind and solar resources, while keeping state-wide curtailment below 1% annually in 2030. During lower-wind months from October to March, coal plants primarily operate at maximum capacity, turning down only during peak solar hours. The bulk of diurnal flexibility is provided by BESS. Both 2-hour- and 4-hour-duration BESS primarily charge during peak solar hours in the afternoon and discharge their stored energy during morning and evening peak periods.

3.3 Long-Term Results

In the long term, the Reference scenario points to a complete transformation of Rajasthan's electricity generation mix and increased transmission interconnections with load centers in neighboring states. Figure 8 provides a high-level view of renewable energy development regions and transmission connections that are found to be cost-effective by 2050 in the Reference scenario.

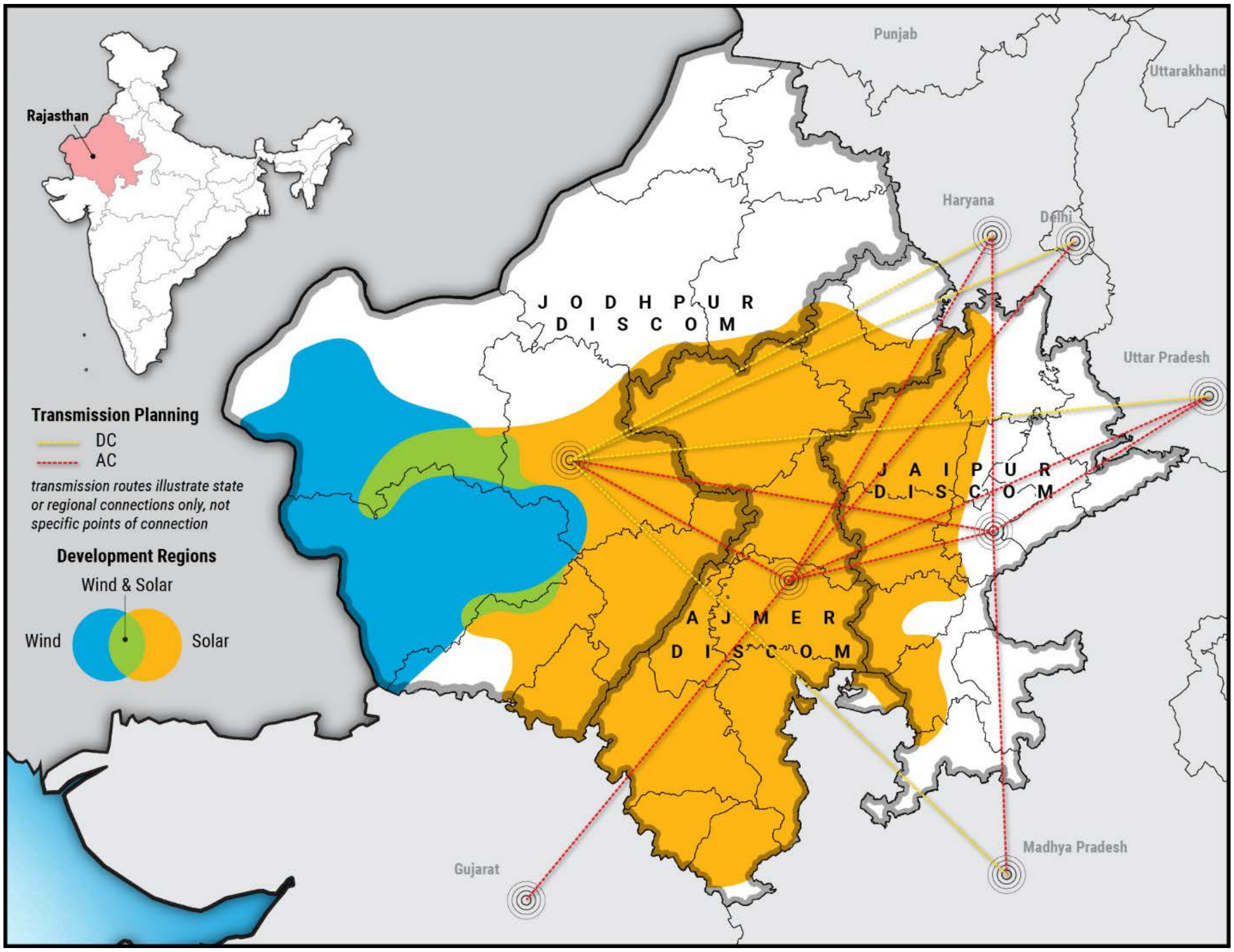

Figure 8. Cost-effective regions for renewable energy development and transmission connections by 2050, Reference scenario. Illustration by Billy Roberts, NREL.

By 2040, fossil fuels supply just 5% of annual generation, and by 2045 their contribution falls to 0%. By 2050, results from the Reference scenario show that Rajasthan's total generation capacity reaches 330 GW, the majority of which comes from utility-scale wind and solar PV. This represents an eightfold increase in installed capacity compared to 2022. Notably, wind capacity grows to over 110 GW, primarily concentrated in Jodhpur BA (Figure 9). The western districts of Jodhpur BA have some of the best wind resources in India, with annual average capacity factors exceeding 30% in many locations. New solar PV capacity is concentrated in Ajmer BA. Given the trade-off between generation investments and transmission expansion needed to evacuate excess renewable energy generation, the results demonstrate that wind can outcompete solar in certain locations due to higher resource quality and transmission availability.

This is particularly true in western Rajasthan.

Figure 9. Installed capacity by BA from 2030 to 2050, Reference scenario

3.3.1 Long-Term Reliability

We include a planning reserve margin (PRM) constraint for long-term reliability. The PRM requires that generation capacity exceeds peak demand by 15% in each season within each of India's operating regions (e.g., Northern Region). This is otherwise known as a "firm capacity" requirement. The amount of capacity considered "firm" depends on the technology type. Coal, gas, nuclear, and biomass technologies contribute their full installed capacity to the PRM with no seasonal variation. The firm capacity of dispatchable hydro technologies (i.e., storage and pondage hydro) is based on historic seasonal average capacity factors. The firm capacity of solar PV and wind technologies is based on simulations of hourly resource availability during peak net demand in each region and each season. Energy storage firm capacity is based on the duration of peak net demand in each region and each season.[8]

Historically, coal plants provided most of the firm capacity in Rajasthan. However, coal plants across the state are fully phased out by 2050 due to age-based retirements. With coal plants

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[8] See Box 2 in (Chernyakhovskiy et al. 2021) for details about the calculation of firm capacity of energy storage resources in ReEDS-India.

retired and new wind and solar resources making up most new generating capacity, Rajasthan will require new sources of capacity to maintain long-term reliability. A combination of wind, 4-hour storage, and gas combustion turbine (CT) power plants are used to meet the PRM in the Reference scenario. Solar PV does not provide firm capacity because it is unavailable during peak demand periods under Reference scenario assumptions. Wind contributes significantly to the PRM, although the contribution is highly seasonal. With total wind capacity of 110 GW in Rajasthan by 2050, the PRM contribution ranges from 8 GW during February–March to 36 GW during the windy season in October–November. BESS contribution to resource adequacy is also highly seasonal. Out of the total BESS capacity of 85 GW in 2050, the capacity contribution ranges from 12 GW during February–March to 37 GW during October–November. However, despite the significant capacity contributions from wind and BESS, additional renewable energy and storage would contribute less to resource adequacy as more of these resources are built.[9]

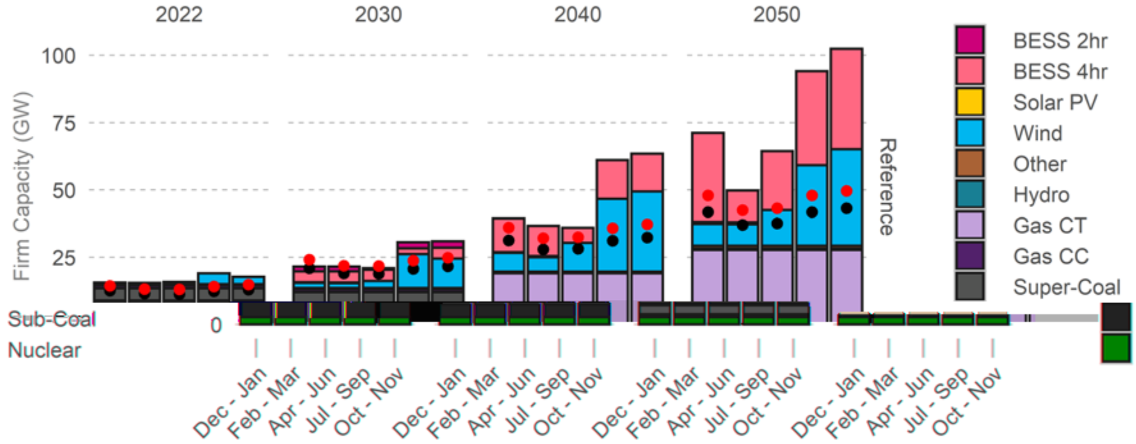

Figure 10. Peak demand, reserve margin, and capacity adequacy contribution of different technologies over time

Note: The black dot represents seasonal peak demand. The red dot is the seasonal planning reserve margin requirement.

Additional firm capacity is provided by existing nuclear and hydro plants, as well as new investments in gas CT "peaker" plants. The total capacity of gas CT peakers reaches 24 GW in 2050. These plants are built exclusively for resource adequacy purposes and do not provide energy on a regular basis. By 2050, gas CT plants are available for resource adequacy but are not dispatched for energy at any time of the year. Between 2030 and 2050, the total generation from gas CT plants built in this period is about 4,000 GWh, which translates to an average annual capacity factor of just 0.4%. While these plants do not provide much energy, their contribution to resource adequacy helps ensure the power system would remain reliable during contingency events such as adverse weather, transmission line outages, and generation outages.

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[9] The declining capacity contribution of RE and storage resources is well documented in Denholm et al. 2019, Zhou, Cole, and Frew 2018, and related literature.

Why Does the Model Build Gas-Fired Power Plants?

Gas CT plants are built to meet the **planning reserve margin** requirement. The planning reserve margin measures the amount of capacity that exceeds peak demand, which is an established method to ensure **resource adequacy** of the power system. For the ReEDS-India model, we assume that a planning reserve margin of at least 15% is required to ensure resource adequacy. Gas CT plants provide a relatively low-cost source of capacity that can reliably contribute to the planning reserve margin. Gas CT plants are relatively inexpensive to build from a capital-expenditure point of view, compared to other conventional technologies like coal and nuclear power plants. However, in a highly decarbonized future, it may be desirable to seek alternative sources of firm capacity that do not rely on fossil fuels. While “peaker” gas plants would not burn much fuel and would typically run during 1% or fewer hours of the year, they rely on natural gas mining, processing, and transportation infrastructure, which has additional environmental impacts and may not serve broader decarbonization policies of Rajasthan or the whole country. Emerging alternatives to gas CT “peaker” plants that could serve a similar resource adequacy role for the power system include low-carbon hydrogen technologies such as fuel cells and hydrogen combustion turbines, as well as long-duration storage technologies like compressed air energy storage and flow batteries, among others. Exploring these options is outside the scope of this study. Nevertheless, the results from the Reference scenario for Rajasthan highlight the need for a source of reliable capacity that can contribute to the long-term resource adequacy of the power system.

4. Copperplate Scenario

The Copperplate scenario demonstrates how generation resources would be allocated within Rajasthan in the absence of transmission considerations. In other words, results from the Copperplate scenario can highlight the limitations of considering generation in a separate planning model and process from transmission. We model the Copperplate scenario by allowing unlimited flows across transmission corridors, both between the Rajasthan BAs and with neighboring states. Compared to the Reference scenario, renewable energy investments in the Copperplate scenario are much more geographically concentrated. By 2050, Jodhpur BA has about 250 GW of wind and solar PV capacity, compared to 66 GW in Ajmer BA and 0 GW in Jaipur BA (Figure 11).

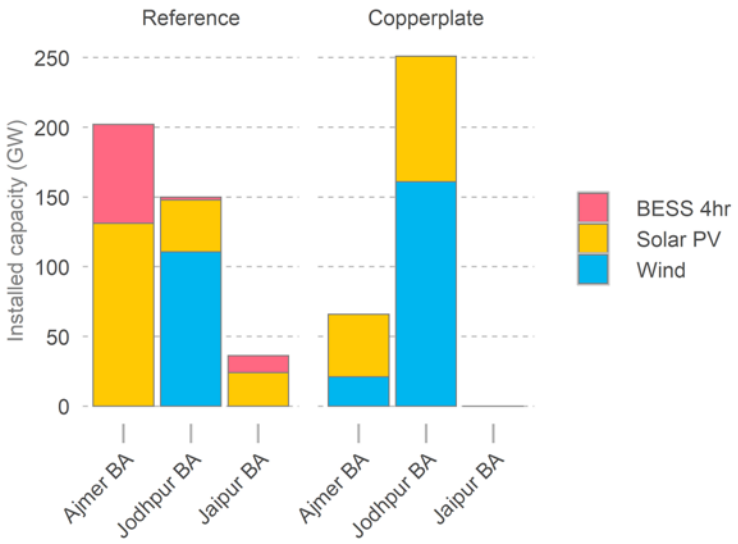

Figure 11. Solar PV, wind, and storage capacity by BA in 2050 in the Reference and Copperplate scenarios

The geographic concentration of renewable energy would require significant transmission capacity to export excess renewable energy generation from Jodhpur BA to demand centers. By 2050, maximum transmission flows out of Jodhpur BA would exceed 80 GW during some periods in the Copperplate scenario. This would be about five times the local peak demand within Jodhpur BA and over 30% greater than maximum transmission flows in the Reference scenario. Developing sufficient transmission capacity to enable such energy flows would be costly, and in the absence of sufficient transmission, the excess renewable energy in Jodhpur BA would be curtailed. Additionally, there are no energy storage investments in Rajasthan in the Copperplate scenario. Because the Copperplate scenario ignores transmission, there are no opportunities for energy storage to provide energy shifting (i.e., charging during periods of congestion and discharging when transmission is available). This result further highlights the importance of coordination between state-level generation and storage planning with transmission capacity that is planned by national entities such as Power Grid Corporation of India Limited.

5. Technology Cost Scenarios

We explored a range of technology cost scenarios to assess the impact of technology cost assumptions on investment outcomes. The choice of scenarios was driven by consultations with stakeholders and observations of cost trends. In general, past cost projections have tended to overestimate the future costs of solar PV and wind technologies. Therefore, we focus on lower-cost scenarios for solar PV and wind to assess the impact of further cost declines. Battery storage costs are more uncertain compared to wind and solar PV due to a relative lack of experience, especially in India, and relatively limited number of large-scale projects that can be used to verify cost estimates. We evaluated a high-cost BESS scenario in this study to capture potential impacts of higher-than-expected costs for raw materials as well as added costs due to supply chain disruptions. We also included a combined low-cost wind, solar, BESS scenario. Table 2 provides descriptions of each cost scenario in relation to the Reference case. Cost curves are based on NREL's 2021 ATB with adjustments for India labor costs. We used ATB Moderate costs for the Reference case, ATB Advanced costs for the low-cost scenarios, and ATB Conservative costs for the High-Cost BESS scenario.

Table 2. Description of Cost Scenarios Modeled in This Study

Scenario	Description
Low-Cost Solar	Solar PV costs are **18% lower by 2030** and **25% lower by 2050** compared to the Reference case.
Low-Cost Wind	Wind technology costs are **26% lower by 2030** and **31% lower by 2050** compared to the Reference case.
Low-Cost BESS	Averaged across all durations modeled, BESS technology costs are **27% lower by 2030** and **40% lower by 2050** compared to the Reference case.
High-Cost BESS	Averaged across all durations modeled, BESS technology costs are **26% higher by 2030** and **70% higher by 2050** compared to the Reference case.
Low-Cost Wind+Solar+BESS	Combination of Low-Cost Solar, Low-Cost Wind, and Low-Cost BESS scenarios

Total solar PV and wind capacity in Rajasthan ranges between 61–86 GW in 2030 and between 240–450 GW in 2050 across all cost scenarios modeled for this study (Figure 12). The Low-Cost Wind+Solar+BESS scenario has the highest wind and solar PV capacity, both in 2030 and by 2050. The Reference scenario is lowest by 2030 (61 GW), whereas the High-Cost BESS scenario has the lowest wind and solar PV capacity (240 GW) in 2050.

In general, the results indicate that near-term renewable energy deployment until 2025 is largely driven by policy targets. Cost scenarios do not impact total renewable energy deployment by 2025, when Rajasthan plans to achieve a 30 GW solar PV and 7.5 GW wind+hybrids target. Beyond 2025, uncertainty in renewable energy and BESS costs influences the cost-optimal buildout, which will also impact the amount of annual energy imports and exports that Rajasthan can expect in the future. Across the cost scenarios, Rajasthan has net energy exports between 30 to 90 GWh by 2030 and between 270 to 350 GWh by 2050.

Figure 12. Total solar PV and wind capacity in Rajasthan under various cost scenarios, (A) 2022 to 2030 and (B) 2030 to 2050. The Reference scenario is highlighted in red.

Notably, significant amounts of battery storage remain cost-effective in the near term under the High-Cost BESS scenario, although investments shift from 4-hour to 2-hour duration storage (Table 2). The near-term cost-effectiveness of BESS, despite uncertainty in the technology's costs in India, can be associated with flexibility needs that arise from Rajasthan's renewable energy targets for 2025 and 2030.

Table 3. Clean Energy Capacity in Rajasthan Under Cost Scenarios Modeled in This Study

	Installed capacity by 2030/2050 in GW				
Scenario	**Wind**	**Solar PV**	**BESS 2 hr**	**BESS 4 hr**	**Pumped Hydro**
Reference	30/110	30/190	4.4/0	4.1/85	0/0
Low-Cost Solar	40/76	30/340	6.9/0	1.6/160	0/0
Low-Cost Wind	45/210	30/75	4.9/4.4	8.1/16	0/0
Low-Cost BESS	42/97	30/240	10/3.3	8/190	0/0
High-Cost BESS	53/130	30/110	7.2/17	4.5/22	0/3.8
Low-Cost Wind+Solar+BESS	55/110	30/350	7.5/5.4	9.8/320	0/0

6. Demand Scenarios

We considered two factors that are likely to change the diurnal profile of electricity load in Rajasthan: (1) responsive agricultural demand, and (2) EV adoption. We defined agricultural demand shifting and EV demand as responsive loads that could be shifted in time as a response to utility control, time-varying electricity pricing, or other incentives. Table 4 summarizes key modeling assumptions for the demand scenarios. In modeling responsive agricultural demand in ReEDS-India, we assumed that shifting load does not change overall energy demand and the modeling does not account for the potential indirect effects of load rescheduling. Additionally, we do not assume any direct costs to infrastructure or utility costs to realize this load shifting, which may be required if meters or software is required. In modeling potential EV adoption, we assumed adoption will add to the overall electricity demand as the Electric Power Survey, which is the basis for our reference demand projections, does not cover EV adoption in the total energy projection.

Table 4. Summary of Demand Scenarios

Demand Scenario	**Description**	**Demand Response Potential**	**Demand Response Timing**	**Demand Response Direction**	**Demand Response Duration**
Responsive Agricultural Demand “Agshift”	Considers how shifting agricultural load (which is largely irrigation pumping) to peak solar hours could impact capacity expansion	70% for metered agricultural load 100% for free/fully subsidized agricultural load	Peak solar hours	Preponement from evening (7 p.m.–11 p.m.) to afternoon (1 p.m.–5 p.m.)	5 hours[10]
EV Adoption “LowEV” and “AccEV”	Considers how low and accelerated adoption of two-, three-, and four-wheel EVs could impact the shape and magnitude of the load profile and capacity expansion decisions	75%	Day and Night	Postponement (shift day charging to peak solar output hours and spread out both day and night charging)	All day

The average diurnal profile of demand in each BA is shown in Figure 13. In developing these scenarios, we considered the potential to shift demand from national peak demand hours to (1) non-peak demand periods, and/or (2) peak solar production hours.

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[10] Based on a report noting that the Government of Rajasthan tries to provide at least 6 hours of power for irrigation, but due to various challenges, it often ends being much less; however, there are ongoing efforts to improve power supply (Shripad Dharmadhikary, Ashwini Dabadge, and Sreekumar N 2019; Gulati, Priya, and Bresnyan 2020).

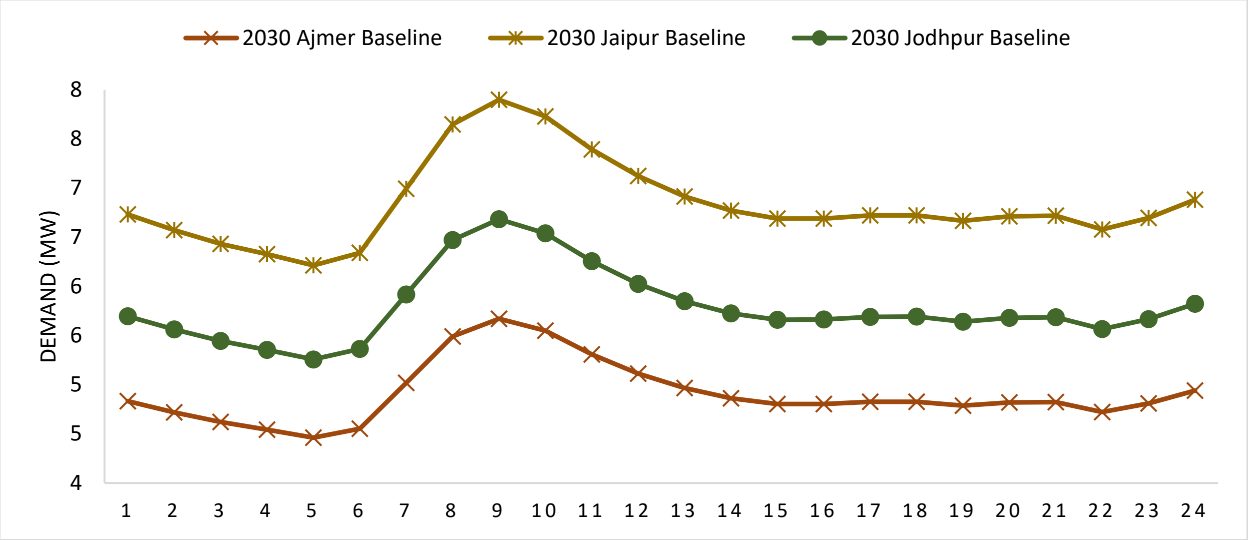

Figure 13. Average 2030 diurnal demand profile of Rajasthan BAs

6.1 Responsive Agricultural Demand "Agshift" Scenario

Rajasthan is an agriculture-centric state, with agricultural load accounting for 47% of overall electricity demand in 2018 and 2019. In developing the Agshift scenario, we reviewed the current state of agricultural demand in Rajasthan, specifically policy discussions around aligning agricultural load and solar production. Power supply interruptions in recent years in Rajasthan have meant that many farmers receive a few hours of power, compared to the 7 hours of electricity per day needed to fully irrigate various farms (Dharmadhikary, Dabadge, and Sreekumar 2019; Gulati, Priya, and Bresnyan 2020). Additionally, electricity has typically been provided during nighttime hours, but there have been long-standing requests for power to be provided during the day to take advantage of solar resources and also reduce the likelihood of injuries that happen during nighttime irrigation (Gulati, Priya, and Bresnyan 2020).

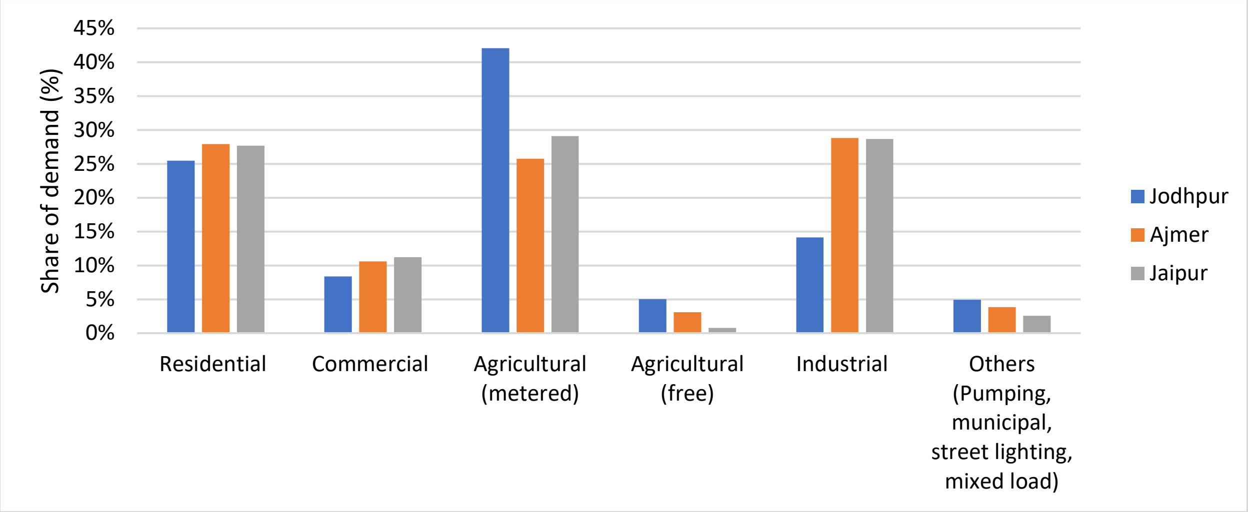

Figure 14. Breakdown of load by sub-sector in Rajasthan balancing area

To help determine how this context could inform modeling the Agshift scenario in ReEDS-India, we assessed the share of overall 2019 load by sector in each BA. As shown in Figure 14, a plurality of demand in Jodhpur BA (over 45% in this year) is agricultural demand, with Ajmer BA and Jaipur BA having overall higher demand from the industrial and commercial sectors. Jodhpur BA also has slightly higher demand from "other" uses, such as pumping/irrigation and municipal street lighting. Informed by the average diurnal profile and the share of agricultural demand in the overall load profile, the Agshift scenario considered the potential impact of shifting Rajasthan's agricultural demand (assumed to currently occur in the evening) to peak solar hours in the afternoon.[11] The government of Rajasthan has a stated goal of providing 6 hours of power; however, we assumed a slightly lower provision of 5 hours of uninterrupted supply with 70% of metered agricultural load that could be shifted (as this is the surveyed percentage of the share of electric irrigation pumps) along with 100% of the fully subsidized agricultural demand.[12]

In the Agshift scenario, we saw a significant change in the afternoon and evening time slice load (Figure 15). This is due to the shifting of a portion of evening load (21% in Ajmer, 21% in Jaipur, and 34% in Jodhpur) to the afternoon time slice. This shift changes the magnitude and timing of peak load, with the peak load now occurring during the afternoon time slice instead of the morning time slice in the Reference case. In terms of magnitude, the 2030 peak load increases from ~20 GW in the Reference case to ~23 GW and by 2050, the peak load is ~45 GW in the Agshift scenario compared to ~42 GW in the Reference case. The evening load is also significantly lower (as expected), due to the shift of part of the evening time slice load to peak solar hours earlier in the day.

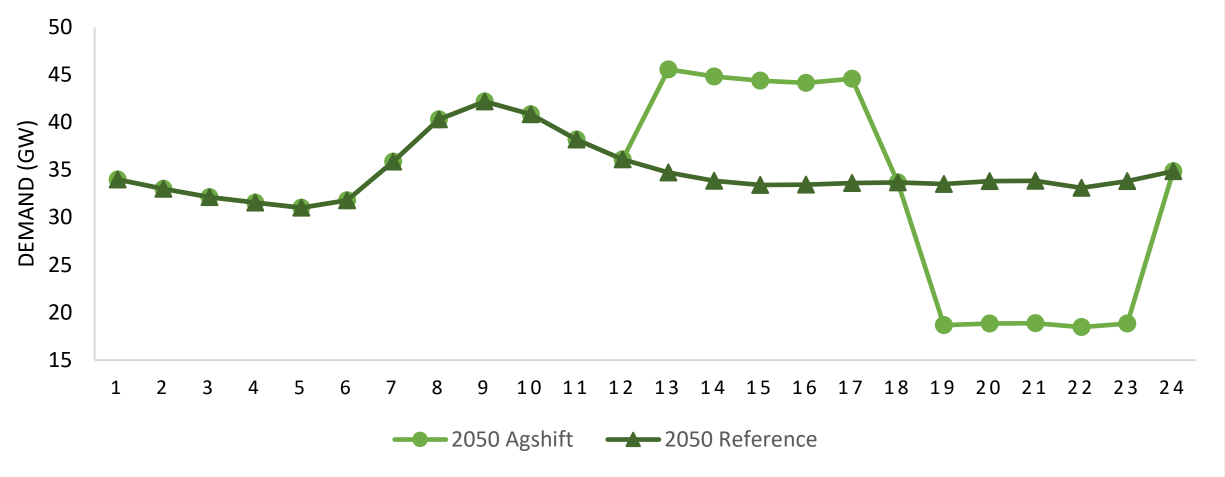

Figure 15. Average 2050 diurnal demand profile of Agshift scenario compared to Reference scenario

In general, the results indicate that compared to the Reference scenario, the Agshift scenario results in an overall net decrease in installed capacity, specifically wind, a shift from longer-duration to shorter-duration batteries, and an increase in electricity trade with neighboring states.

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[11] The peak hours in the overall national energy demand are used to set the peak demand periods. These may not match with the peak demand periods for individual states.

[12] Based on sampling of agricultural load in Rajasthan published by the Rockefeller Foundation (2019).

This is due to the change in the overall shape of the load profile. Shifting agricultural load (which is modeled as 20%–30% of overall evening load across the Rajasthan BAs) leads to peak demand occurring during the afternoon time slice across all seasons.

By 2030, total Rajasthan installed capacity is 81 GW, 2% lower than the Reference scenario, with marginal differences in wind and battery storage capacities compared to the Reference scenario. By 2050, total Rajasthan installed capacity is 319 GW, 24% lower than the Reference scenario. Here, the Agshift scenario has overall less solar capacity, less 4-hour BESS capacity, and less gas CT peaking capacity compared to the Reference scenario. Table 5 compares the installed capacity in Rajasthan between the Reference and Agshift scenarios.

Table 5. Generation Capacity in Rajasthan Under the Reference and Agshift Demand Scenarios

	Installed Capacity by 2030/2050 in GW								
Scenario	**Wind**	**Solar PV**	**BESS 2 hr**	**BESS 4 hr**	**BESS 6 hr**	**BESS 8 hr**	**BESS 10 hr**	**Natural Gas Combined Cycle**	**Natural Gas CT**
Reference	30/110	30/190	4.4/0.0	4.1/85	0/0	0/0	0/0	1.0/0.6	0/24
Agshift	29/110	30/140	4.9/0.1	3.7/43	0/0	0/0	0/0	1.0/0.6	0/22

Notably, the Agshift scenario has overall lower costs for Rajasthan's power system due to lower investment in generation capacity. By 2050, overall costs are 18% lower compared to the Reference scenario in Rajasthan and 1.5% lower across all India (see Figure 16). This result shows the importance of the shape of a BA's demand curve on the investments needed to maintain reliable electricity supply. When demand is shifted to solar hours, less energy storage capacity and less thermal capacity is needed to provide energy during evening hours. Unexpectedly, compared to the Reference scenario, there is also less solar capacity built in the long term. This is because excess solar energy is used to charge storage in the Reference scenario. When evening demand is shifted, less energy is needed to charge storage, and thus less overall solar capacity is needed to serve demand.

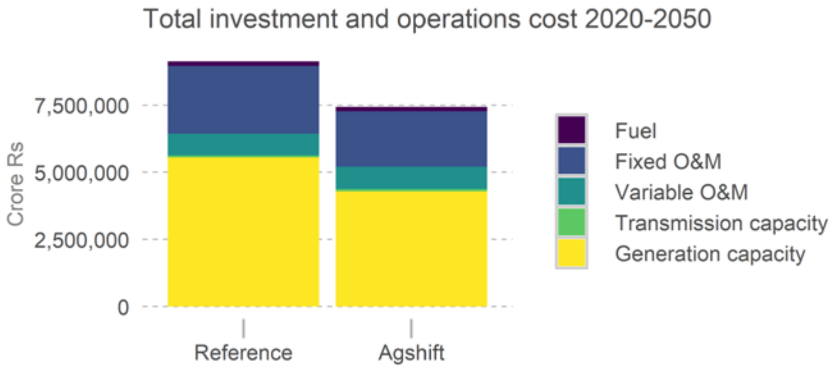

Figure 16. Total investment and operating costs for Rajasthan's power system, 2020–2050

6.2 EV Demand Scenarios

To develop the EV adoption scenarios, we reviewed the current state of EV adoption in Rajasthan, the existing policy environment for EVs and EV infrastructure, and potential short- and long-term trends in the sector. India signed on to the EV30@30 campaign, which has a goal of EVs forming 30% of all car sales by 2030 (IEA 2022). Toward this goal, India has introduced several policy instruments including the Faster Adoption and Manufacturing of Electric Vehicles (FAME) I and II schemes, in addition to incentives to spur local EV manufacturing and workforce development (Singh et al. 2019; Ministry of Heavy Industries 2021). In response to this national target, various states have developed policies to enable EV deployment, with a large emphasis on local job creation, development of a local EV manufacturing sector, and installation of accessible EV charging infrastructure (Pathak and Patel 2021).

Theoretically, EVs offer a great opportunity for demand response. When home charging and workplace charging is available, a 3–4-hour charge can happen over a 10–12-hour window, offering an opportunity to shift load. To model potential impacts of EV adoption on the shape and magnitude of load, we considered two EV adoption scenarios—low and accelerated deployment. The low deployment scenario assumes a negligible increase by 2030 in the share of the EVs in the overall vehicle stock but higher than the Reference scenario. The accelerated deployment assumes India (and by extension Rajasthan) would meet its 30% EV share by 2030 target. First, we collected data on historical EV sales in Rajasthan (and by district in Rajasthan, where available), as well as data on the current vehicle stock in the state. Data collected and literature reviewed indicates that two- and three-wheelers currently form an overwhelming majority of EV adoption in Rajasthan and India more broadly. This is due to various factors, including affordability, mobility needs in various urban areas, and existing charging infrastructure (TERI 2019).

EV load profiles were then modeled using the NREL EVI-Pro Lite tool, which provides a high-level estimate of potential charging load magnitude and profile for a given set of EV assumptions and charging scenarios. The EVI-Pro Lit models EV charging patterns based on assumptions about:

- access to home charging,
- use of slow versus fast chargers,
- preference for home charging as opposed to public and workplace charging, and
- assumptions around home charging and workplace charging strategies.

In general, we assumed that in the low EV deployment scenario, potential EV adopters are less flexible on when and where they charge their vehicles. In the accelerated EV deployment scenario, compared to the low EV case, we assumed that EV adopters have more flexible charging options including greater access to home charging and other charging options such as public and workplace charging, increased availability of fast charges, and increased opportunity to spread out home charging and optimize workplace charging to coincide with work hours.

By default, EVI-Pro Lite is based on U.S. driving and EV adoption assumptions. We adjusted the U.S.-based inputs (including the size of the EV fleet and ambient temperatures) to be reflective of major cities in Rajasthan. This adjustment does not account for driving patterns, which could be explored in future work. Most importantly, the load profile was adjusted to reflect our assumption that the majority of EV adoption in the foreseeable future would be two-wheelers.

Specifically, EV load was derated by 79%, and then this load profile (which was modeled for two years, 2025 and 2030) was allocated to each BA based on historical shares of two-wheelers ownerships across Ajmer, Jaipur, and Jodhpur. Future EV load projections (i.e., 2031–2050) were based on the calculated CAGR of overall vehicle stock in Rajasthan from 2015–2020, which was ~9%. These load profiles were then added to the baseline load profile in all the BAs across all seasons of the year.

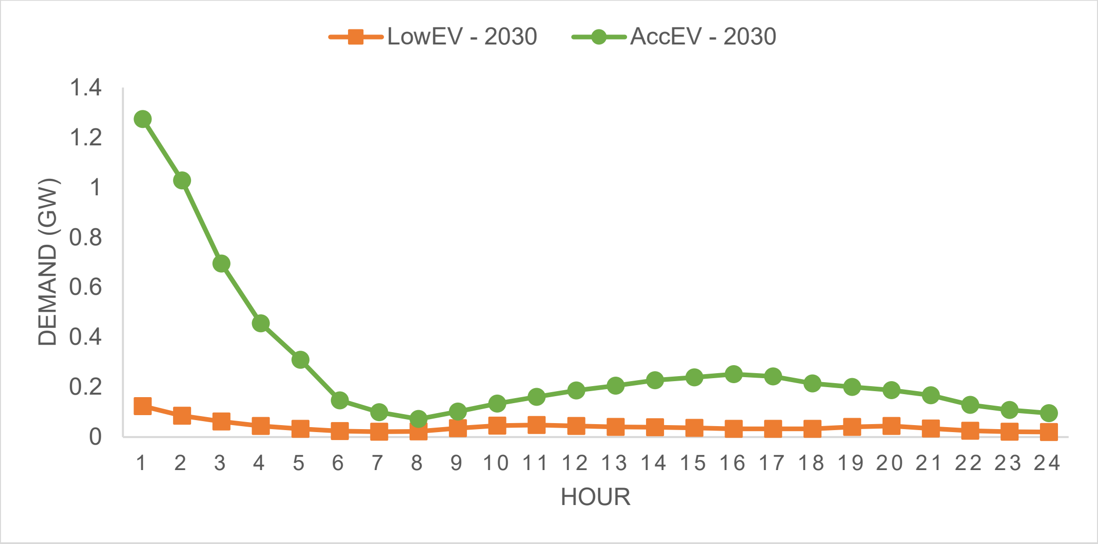

Figure 17. Average Daily Electric Vehicle (EV) Load for Low EV Deployment and Accelerated EV Deployment Scenarios

The modeled EV load was added to the baseline load starting in 2025. The EV adoption scenarios led to relatively small changes in the shape of the final load profile and small to substantial changes in the magnitude of overall annual load. Figure 18 shows the average 2050 diurnal load profile for the Reference and accelerated EV ("AccEV") adoption scenarios with the magnitude and impact of the modeled EV charging load varying with the scale of EV deployment. State-wide, the maximum additional hourly load in the low EV deployment scenario is ~0.12 GW, compared to over 1.2 GW in the AccEV scenario. In 2030, compared to the Reference scenario, this translates to a 5% increase in annual load in the LowEV scenario and a 28% increase in annual load in the AccEV scenario.

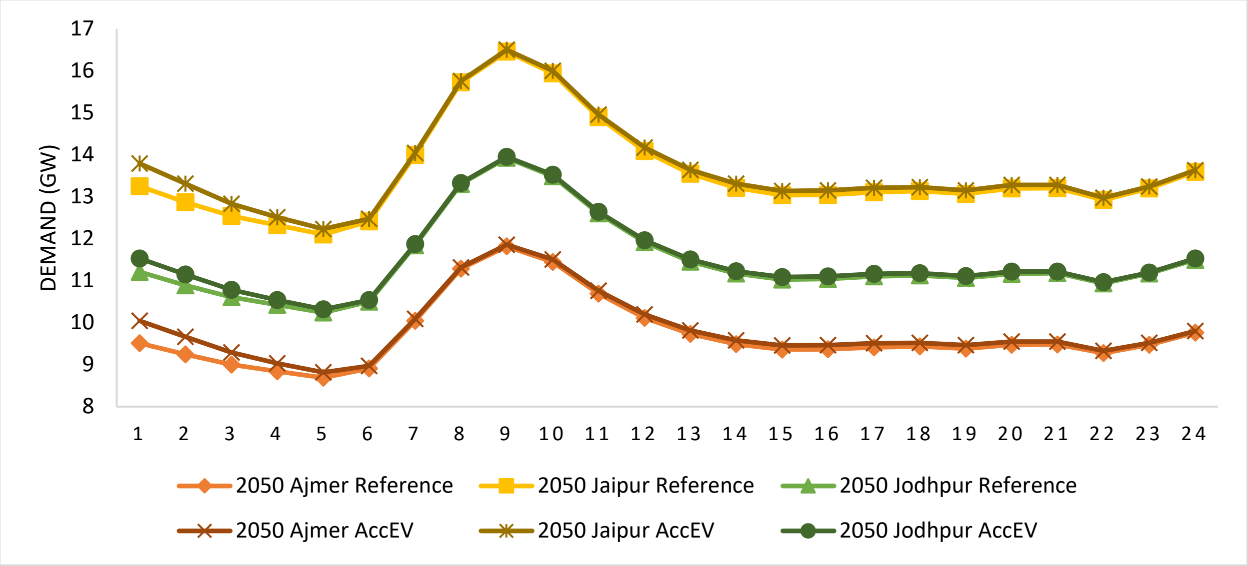

Figure 18. Average 2050 diurnal demand profile by BA, AccEV scenario compared to Reference scenario

Note: LowEV scenario is omitted from this figure.

These changes in the load profiles were incorporated into ReEDS-India and results analyzed to explore potential impacts on power sector investment decisions. As seen in Table 6, by 2030, EV charging leads to a 24% and 27% increase in overall capacity in Rajasthan in the LowEV and AccEV scenarios, respectively, compared to the Reference scenario (83 GW in the Reference scenario compared to 103 GW and 105 GW, respectively). This increase is largely due to increased deployment of wind and 2-hour BESS in Ajmer. However, the difference at the national level is small (1% and 1.3% increase in wind capacity in LowEV and AccEV scenarios, respectively, compared to the Reference scenario), suggesting that in the short term, EV adoption in Rajasthan shifts wind buildout from other Indian states to Rajasthan. There is also no substantial change in wind generation on a national scale.

By 2050, compared to a total installed capacity of 417 GW in the Reference scenario, the LowEV and AccEV scenarios have 340 GW and 345 GW, respectively, within Rajasthan. This decrease is largely due to lower deployment of solar PV and 4-hour BESS in the state. However, at the national level, solar PV and BESS capacity are relatively unchanged. In general, the results indicate that EV adoption can impact decisions about wind and solar PV siting, with evening and nighttime EV charging driving wind deployment closer to centers of EV demand, and solar PV deployment favoring areas with relatively higher daytime load.

The sensitivity of RE deployment in Rajasthan to relatively modest changes in the demand profile demonstrates the importance of more detailed efforts to understand RE siting decisions and the potential value of demand response and other demand shifting policies and incentives. It should also be noted that EV adoption in other Indian states and union territories would impact wind and solar PV deployment in Rajasthan. However, modeling EV adoption outside Rajasthan is outside the scope of this study and can be explored in future analysis efforts.

Table 6. Renewable Energy, Storage, and Gas Capacity in Rajasthan Under EV Adoption Demand Scenarios

	Installed capacity by 2030/2050 in GW					
Scenario	**Wind**	**Solar PV**	**BESS 2 hr**	**BESS 4 hr**	**Natural Gas Combined Cycle**	**Natural Gas CT**
Reference	30/110	30/190	4.4/0.0	4.1/85	1.0/0.6	0/24
Low EV Adoption (LowEV)	51/115	30/150	6.1/0.1	1.5/50	1.0/0.6	0/22
Accelerated EV Adoption (AccEV)	52/123	30/140	7.3/0.15	1.7/50	0.1/0.6	0/26

In general, the increased buildout of wind in Ajmer is used to meet the additional EV load occurring during the evening, afternoon, and peak time slices in both the LowEV and AccEV scenarios. In 2030, we see significantly higher wind generation (largely from Ajmer) during peak demand hours. This also leads to an increase in electricity exports from Ajmer BA during national peak demand hours. Additionally, due to the higher overall installed wind capacity, more exports to neighboring states are possible. We also see slightly higher use of 2-hour BESS during peak demand hours. Outside of these changes, we see a similar trend in how batteries are used to provide diurnal flexibility (charging during peak solar hours and discharging during other periods of the day) and in how coal is used for seasonal balancing (i.e., coal plants at minimum generation levels during high wind months of April to September and operating at maximum capacity during low wind months of October to March). Additionally, gas CT plants are similarly used to provide peaking capacity, as described in Textbox 1.

By 2050, a slightly different picture emerges. In both LowEV and AccEV scenarios, as mentioned above, there is significantly lower overall solar PV capacity. This translates to slightly less electricity exports to neighboring states (total 2040–2050 transmission investments are 21 GW and 23 GW in the LowEV and AccEV scenarios, respectively, compared to 24 GW in the Reference scenario). Finally, there are slight differences in battery charging. Almost all batteries deployed in 2050 are 4-hour BESS. However, as shown in Figure 19, even though charging still happens during peak solar hours, less battery storage charging is happening (due to reduced battery capacity within Rajasthan).

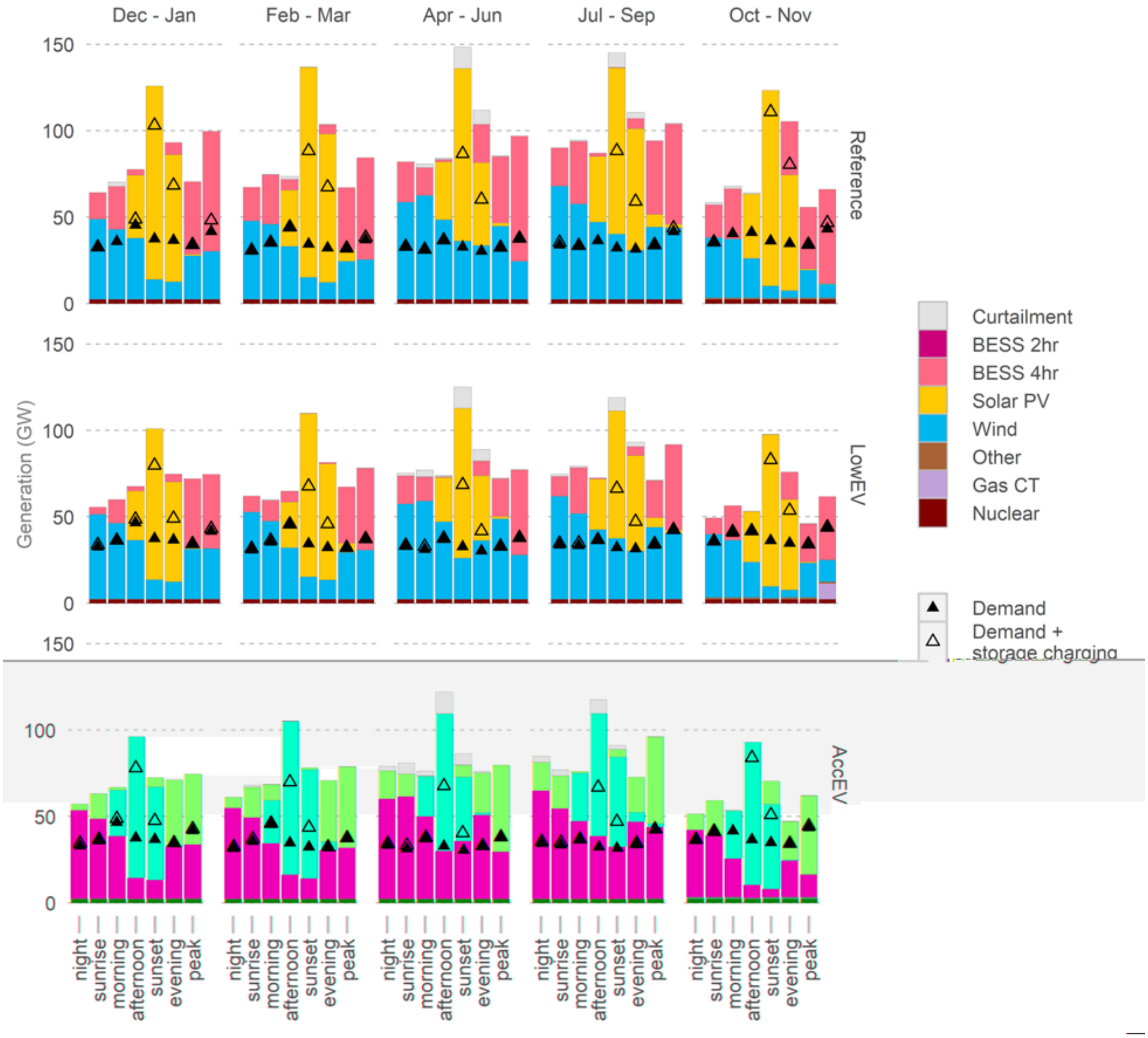

Figure 19. Generation dispatch, storage operations, and demand in 2050, Reference, LowEV, and AccEV scenarios

7. Power Sector Air Pollution Emissions

The connection between health and air pollution is well-established. Exposure to high concentrations of $PM_{2.5}$, SO_2, and NO_x over time has been associated with impaired prenatal development and can lead to an increased risk of health impacts such as heart and lung disease (TERI 2021; NIH 2022). Newer research, however, examines policies regulating air pollution and better quantifies these impacts in ways that could significantly inform renewable energy deployment strategies through 2050. For example, a 2021 study gives an overview of the effectiveness of existing policies related to air pollution in South Asian countries and provides suggestions for improvement (Ness 2021). Another study from the same year in Lancet Planet Health shows that even with existing policies in India in 2019, 1.7 million deaths were attributable to air pollution—this accounts for 18% of deaths in India that year. Of those, 0.98 million were from ambient particulate matter pollution. Rajasthan is included as one of the states with the highest economic loss as a proportion of state GDP ($\geq$1.5%) due to air pollution-related premature deaths and morbidity (India State-Level Disease Burden Initiative 2021).

Furthermore, the connection between air pollution and solar power generation potential is less well studied, but a recent paper from IIT Delhi focuses on this topic. The results indicate that 29% of utilizable global horizontal irradiance was lost between 2001 and 2018 due to air pollution, which is equivalent to 245–835 million USD annually. Mitigation of emissions to meet WHO Air Quality Guidelines could allow India to generate a surplus of 10–28 TWh per year from the solar power capacity existing in 2018 (Ghosh 2022).

These impacts in mind, for the Reference scenario and for each of the cost scenarios described above, we estimated the resulting emissions of $PM_{2.5}$, SO_2, and NO_x from coal and natural gas in Rajasthan. Figure 20 shows national emissions of these three pollutants by sector, in gigagrams (Gg). Note that the residential and industrial sectors are the main sources of primary $PM_{2.5}$. However, we have included $PM_{2.5}$ in our analysis of the power sector here due to its impact on human health.

The power sector is a primary source of SO_2 and NO_x in India (TERI 2021). In addition to causing health damage individually, SO_2 and NO_x in the air can form secondary $PM_{2.5}$. Secondary $PM_{2.5}$ has the same detrimental health effects as primary $PM_{2.5}$, but it is generally dispersed over a larger area as it forms in the air, whereas primary $PM_{2.5}$ is usually concentrated around the source of pollution (EPA 2021).

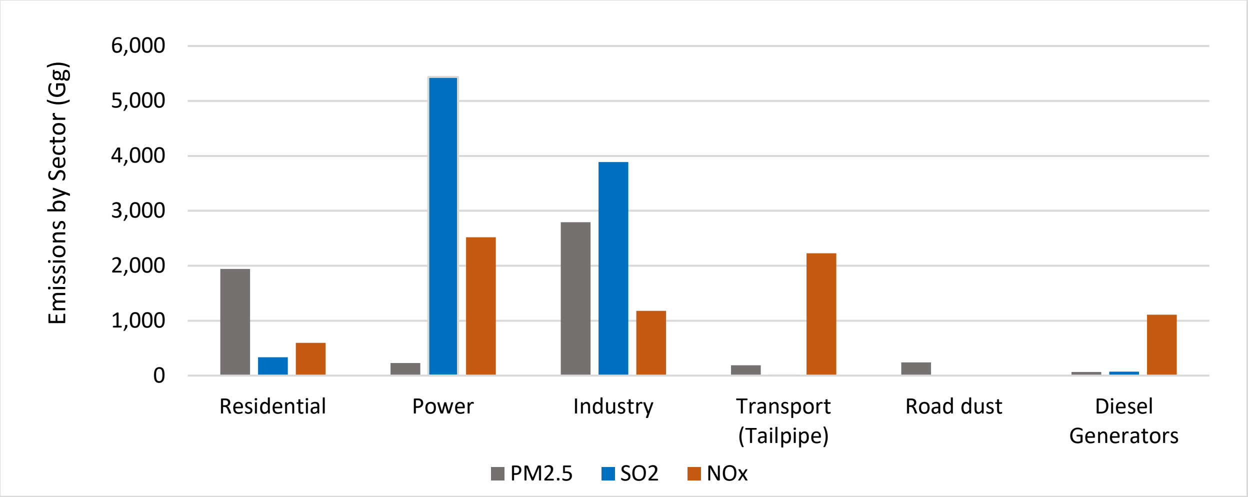

Figure 20. National $PM_{2.5}$, SO_2, and NO_x emissions by sector (TERI 2021)

7.1 Emissions Estimation Methods

To estimate emissions, we used the equations described in TERI 2021. The equation describing emissions of gaseous pollutants (SO_2 and NO_x) from coal and natural gas and for $PM_{2.5}$ from natural gas is:

$$[E_p]_f = P_f \times [EF_p]_f \times (1 - [RE_p]_f)$$

where $[E_p]_f$ is the emissions of pollutant p from fuel source f, P_f is the amount of fuel f consumed, $[EF_p]_f$ is the emissions factor for pollutant p from fuel source f, and $[RE_p]_f$ is the removal efficiency of any installed emissions reduction technology for pollutant p from fuel f.

The equation describing emissions of $PM_{2.5}$ from coal plants is:

$$[E_p]_c = P_c \times A_c \times (1 - fb_r) \times M \times (1 - [RE_p]_c)$$

where $[E_p]_c$ is the emissions of pollutant p from coal in kg, P_c is the amount of coal consumed, A_c is the ash content of the coal, fb_r is the ratio of bottom ash to total ash, M is the particulate mass fraction, and $[RE_p]_c$ is the removal efficiency of any installed emissions reduction technology for pollutant p from coal.[13]

Specific data sources for each input variable are noted in Table 7.

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[13] [M] = particulate mass fraction (0.4 for $PM_{2.5}$ to PM_{10}, 0.75 for PM_{10}).

Table 7. Data Sources for Each Input Variable Used To Calculate Emissions Estimates of $PM_{2.5}$, SO_2, and NO_x From Coal and Natural Gas Plants

Input	Source
Heat rates	ReEDS-India inputs
Energy content of coal	India Ministry of Coal
Energy content of natural gas	India Ministry of Petroleum and Natural Gas
Generation amounts from each fuel type	ReEDS-India results
Emission factors (SO_2 and NO_x, $PM_{2.5}$ from natural gas)	TERI 2021
Emission factors ($PM_{2.5}$ from coal)	Sharma and Kumar 2016
Ratio of bottom ash to top ash (20%)	TERI 2021
Particulate mass fraction	TERI 2021
Current emissions reduction technologies	TERI 2021

Using this method, we first calculated national estimates for power system emissions from national ReEDS-India outputs, which were validated against Sharma and Kumar's 2016 business-as-usual emissions scenario. Next, BA-level estimates were calculated for Rajasthan, based on generation data from the ReEDS-India model for each of Rajasthan's three BAs. Note that BA-level outputs are the closest spatial resolution possible in the ReEDS-India model.

Our results for $PM_{2.5}$ aligned well with previous studies at the national level, though there remain several key areas of uncertainty. The most significant uncertainties are due to $PM_{2.5}$ emissions estimates being based on:

- An unchanging emission factor over time
- An unchanging ratio of bottom ash content in coal-fired plants (20%)
- The use of current emissions reduction technologies technology and policies, operating effectively—according to TERI's report, all coal plants have $PM_{2.5}$ reduction technology (electrostatic precipitators or ESPs) operating at 99.98% removal efficiency
- Projected BA-level generation totals, without knowledge of which plants are responsible for the greatest outputs (this is most significant in Jodhpur, where both coal and lignite plants are present).

Our estimates for SO_2 and NO_x were generally lower than previous studies at the national level. Key uncertainties for SO_2 and NO_x emissions estimates are related to:

- Unchanging emission factors over time
- The use of current emissions reduction technologies and policies, operating effectively—according to TERI's report, all natural gas plants have NO_x reduction technology (selective catalytic reduction) operating at 85% removal efficiency.

7.2 Emissions Results

Figure 21 and Figure 22 show projected emissions from coal and natural gas power plants through 2045, respectively. Note the difference in scale of the y-axis between Figure 20 and Figure 21. While emissions from natural gas are still significant for NO_x, they account for only 0.01% of total emissions from coal and natural gas combined. Thus, here we will focus on trends in emissions from coal; additional results examining trends for natural gas can be found in Appendix C.

While coal and natural gas capacity are highest in the southern districts of Jaipur BA, there are coal plants present in Jodhpur and Ajmer BAs as well. The ReEDS model used here does not identify which specific plants provide designated capacity, but the proximity of plants to areas of high population density (or to areas with utility PV installations) is a key consideration when thinking about the impact of emissions.

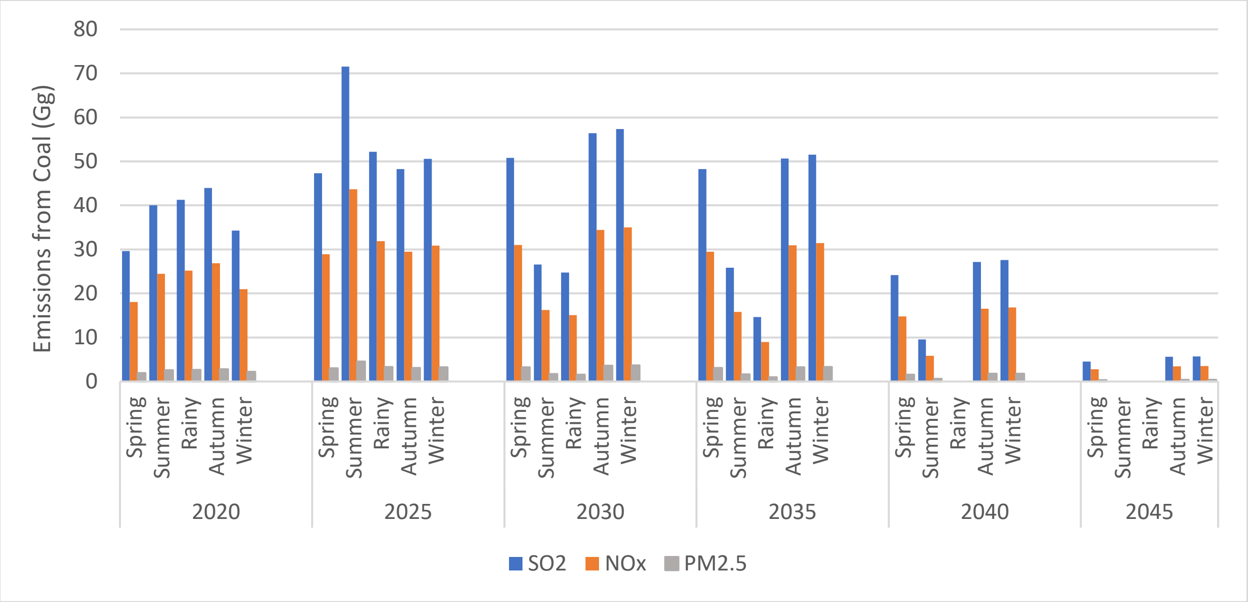

Figure 21. Projected $PM_{2.5}$, SO_2, and NO_x emissions from coal based on generation outputs of the Reference case

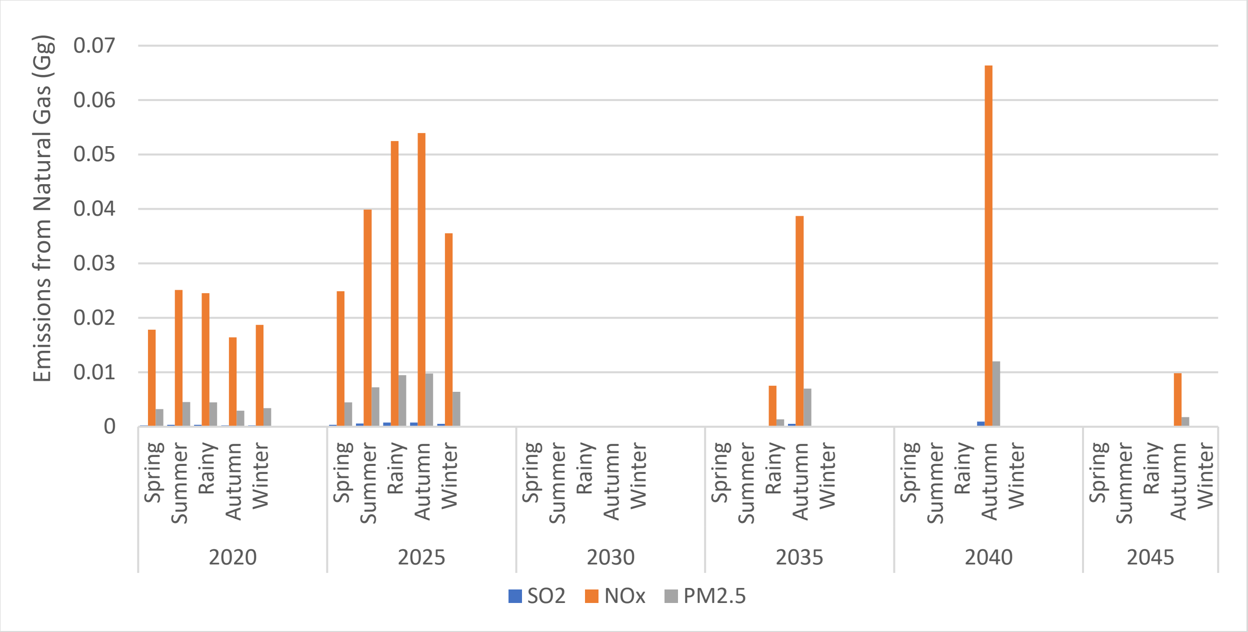

Figure 22. Projected $PM_{2.5}$, SO_2, and NO_x emissions from natural gas based on generation outputs of the Reference case

Examining projected emissions from coal for the Reference case, the High-Cost BESS scenario, and the Low-Cost Wind+Solar+BESS scenario leads to several key insights, drawn from Figure 23 and Figure 24:

- Even with current renewable energy deployment rates, power sector emissions of SO_2 and NO_x will increase through 2025 and will not be lower than present levels until 2030–2040, depending on the season.
- Compared to the Reference scenario, the Low-Cost Wind+Solar+BESS scenario (Figure 22) sees a 10% decrease in emissions from coal during the spring and summer by 2025. After 2030, emissions during all seasons are equivalent to or lower than the Reference case, with the greatest changes during the summer and rainy seasons. Rainy season emissions are lower by 40% in 2030 and by nearly 100% in 2035, while summer emissions are lower by 32% in 2030 and 60% in 2035.
- Compared to the Reference case, the High-Cost BESS scenario (Figure 23) sees a short-term increase of 5 to 10 Gg SO_2 and NO_x during the rainy, autumn, and winter seasons. This scenario results in buildout of pumped hydro beginning in 2030, and, as a result, overall emissions from coal decrease after 2035.

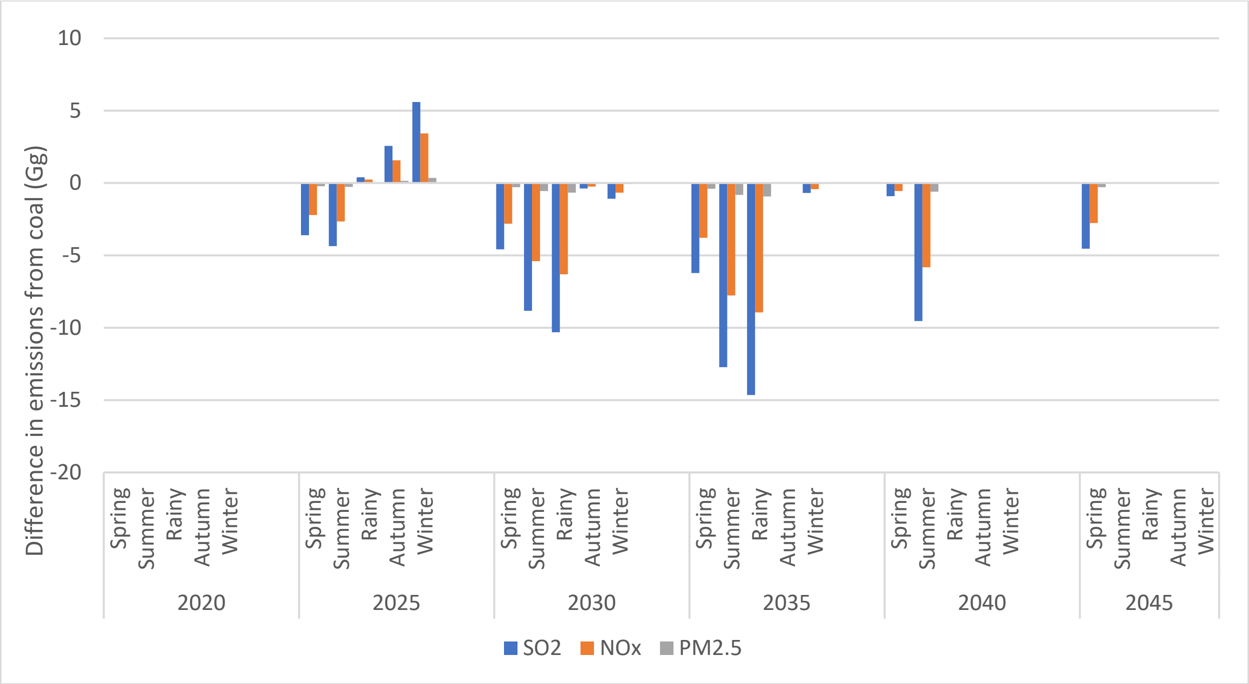

Figure 23. Projected PM$_{2.5}$, SO$_2$, and NO$_x$ emissions from coal in the Low-Cost Wind+Solar+BESS scenario, difference from Reference scenario

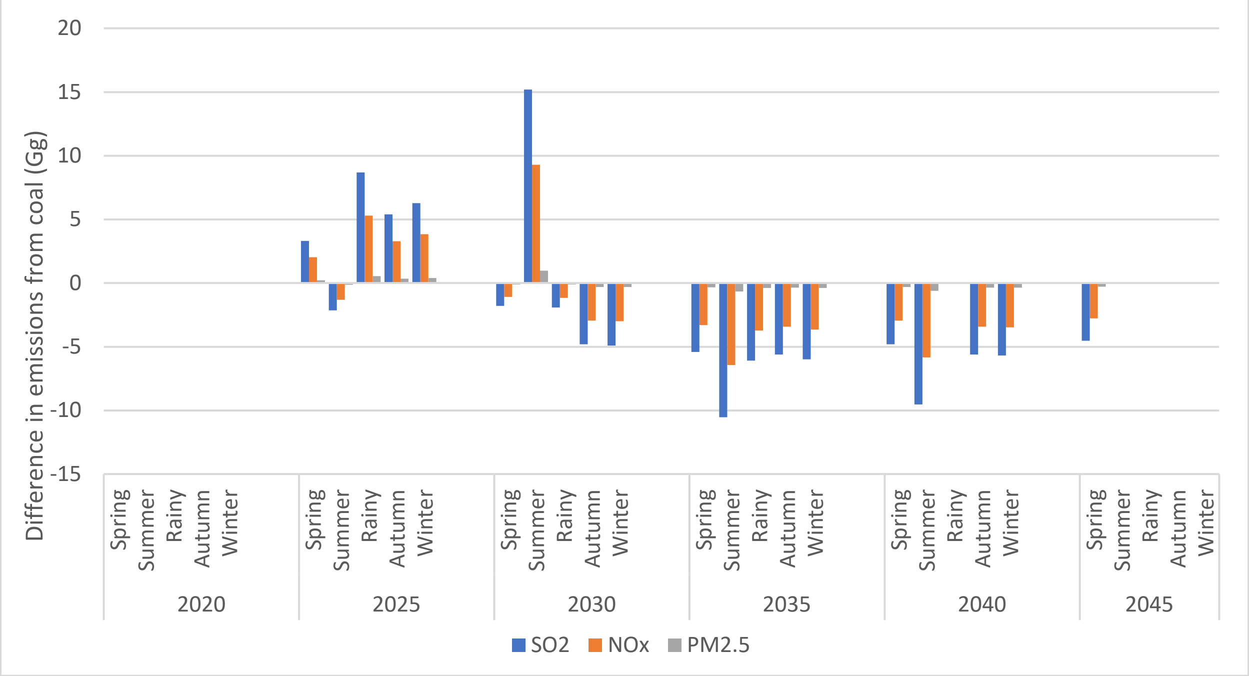

Figure 24. Projected PM$_{2.5}$, SO$_2$, and NO$_x$ emissions from coal in the High-Cost BESS scenario, difference from Reference Case

8. Future Work

This analysis represents a snapshot of potential pathways for power sector deployment in Rajasthan. Future work can expand on the modeling and analysis conducted in the following ways:

- This study did not assess power system operations on hourly or sub-hourly timescales. Future studies can conduct unit commitment and dispatch modeling to identify constraints and potential strategies for generation, transmission, energy storage, and demand response resources to balance supply and demand at more granular time scales than were evaluated in this study.
- Probabilistic resource adequacy analysis can provide more detailed insights into the critical contingencies (i.e., generation and transmission resource outages) and the resources needed to maintain reliable electricity supply under a changing generation mix in Rajasthan.
- More robust EV modeling and analysis can be conducted to assess potential state- and national-scale impacts. Future work can also improve the underlying EV load profiles used in this analysis by developing a load profile that accounts for mobility characteristics unique to India, such as differences in driving patterns across rural and urban geographies and charging infrastructure.
- This report did not attempt to translate emissions projections into health impacts. However, this could be done using a tool like Global InMAP. Global InMAP is a high-resolution air quality model that can be used to estimate the number of premature deaths and the approximate health-related costs accrued from different scenarios of $PM_{2.5}$ concentrations. Additional air quality analysis can also assess the health impacts of NO_x emissions from transportation and industrial sectors.

9. Conclusion

Rajasthan is poised to become a major supplier of cost-effective renewable energy for India. Short-term targets for solar PV deployment, combined with medium-term trends in wind energy and battery storage costs, are expected to transform Rajasthan's energy mix by 2030. Under the least-cost planning scenarios evaluated in this study, we find that between 60 GW and 85 GW of combined solar PV and wind capacity would be cost-effective in Rajasthan by 2030. This is more than double the current policy target for 2025. Policymakers, energy sector regulators, power system planners, and engineers can use these findings to anticipate and respond to potential changes in the power system. Additional key insights for Rajasthan from this study include:

- In the long term over the next 30 years, a combination of solar PV, wind, and battery storage can provide the majority of new generation capacity needed to reliably meet growing demand.
- Wind energy is highly cost-effective in western parts of Rajasthan. Policymakers can consider including wind energy in future state-wide clean energy targets.
- Rajasthan can be mostly self-sufficient in electricity supply with in-state resources by 2030. Electricity imports would be limited to periods of peak net demand. Beyond 2030, Rajasthan can be expected to export electricity to neighboring demand centers.
- Ongoing transmission expansions under India's Green Energy Corridors would be sufficient to support clean energy exports in the medium-term. We find no need for additional transmission expansion beyond current plans by 2030. In the long term, new high-voltage DC connections between high-renewable energy regions in Jodhpur BA and demand centers in neighboring states, including Madhya Pradesh, Uttar Pradesh, Haryana, and Delhi, would be cost-effective to support increased electricity exports from Rajasthan.
- New coal plant investments beyond what is currently planned are not cost-effective in any of the scenarios evaluated in this study. Instead, we find a consistent trend of coal being phased out of Rajasthan's energy mix by the mid-2040s due to age-based retirements.
- Short-duration battery storage is expected to be cost-effective in the near term if storage projects are allowed to provide multiple grid services and receive revenue from multiple value streams.
- Expected acceleration of EV deployment may increase the cost-effectiveness of wind capacity in the short term, but further analysis is needed to consider how different charging options will impact the overall grid.
- Shifting agricultural load may allow an opportunity to provide more reliable electricity supply while maximizing the use of the abundant in-state solar resources.

These insights provide a snapshot of the long-term planning trends that can be gleaned at the time of this publication. As the landscape of policies, power system regulations, and technology cost and performance evolve over time, the specific results and trends may change as well. Therefore, it would be prudent to periodically revisit the underlying assumptions and set of questions that motivate our findings. The data, methods, tools, and analyses described in this study provide a framework for future planning studies for Rajasthan as well as other Indian states and union territories.

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Appendix A. Modeling Transmission in ReEDS and Transmission Planning in Rajasthan

ReEDS uses a pipe flow model to approximate power flows between BAs with transmission expansion modeled as additional MW of capacity to be added between BAs. This model does not model any AC or DC flow, but rather represents the operational limit on transfer capacity between BAs. The total cost of transmission expansion depends on distance and amount of MW of capacity to be added between the BAs. Rajasthan has some of the highest renewable energy potential in India, especially in the largest desert area in Jodhpur, which is in the southwest part of the state.

Given its abundant solar and wind resources, and ambitious 2025 and 2030 renewable energy deployment targets, Rajasthan is set to become a net electricity importer to neighboring states. Specifically, by 2025, the state has goals to install 30 GW of solar PV, 2 GW of wind and some capacity of hybrid generation. Toward achieving these ambitious goals, India's Central Electricity Authority granted regulatory approval to PFGIL, the state grid operator, to set up specific solar energy zones for Rajasthan. These zones will involve two phases of transmission expansion, Phase 1 consisting of 8.9 GW of transmission capacity, and Phase 2 consisting of 11.1 GW.

To develop the transmission inputs for this state analysis, transmission capacity and potential buildout were considered for each BA in the state (Ajmer, Jodhpur, and Jaipur). We reviewed reported data on the state's existing transmission network, specifically outlining existing and planned interconnection lines and substations at three voltages: 220 kV, 400 kV, and 765 kV. Each line is then classified by town, district, and BA.

Table A-1. Rajasthan District-Balancing Area Classification

Balancing Area	District
Jodhpur BA	Barmer, Bikaner, Churu, Ganganagar, Hanumangarh, Jaisalmer, Jalore, Jodhpur, Pali, Sirohi
Ajmer BA	Ajmer, Banswara, Bhilware, Chittorgarh, Dungarpur, Jhunjhunu, Nagaur, Rajsamand, Sikar, Udaipur
Jaipur BA	Alwar, Baran, Bharatpur, Bundi, Dausa, Dhaulpur, Jaipur, Jhalawar, Karauli, Kota, Sawai Madhupur, Tonk

The data collected for existing lines were validated using the previously validated transmission data used in previous India-wide ReEDS analyses. For planned projects, we reviewed monthly and annual Central Electricity Authority reports on the status of planned projects. For the lines without planned completion dates, we assumed the project would take at least 3 years to complete, with the transmission capacity available for use at the beginning of the calendar year following the reported project commission date and our assumed project completion date. For example, projects completed in October 2021 were assumed to be available in 2022. This data collection was also conducted for interstate transmission projects, which would be critical to evacuating excess solar and wind power generation.

The final planned transmission input data is summarized in Table A-2. Overall, 46 GW of intra-state transmission is planned by 2025, with the majority of this buildout to evacuate solar build out in Jodhpur and Ajmer. Jodhpur has abundant solar resources, and Ajmer has abundant solar resources and lower overall electricity demand. Additionally, 10 GW of inter-state transmission is planned, with lines from Ajmer to major load centers in Delhi, Uttar Pradesh, and Haryana.

Table A-2. Summary of Planned Intra- and Inter-State Rajasthan Transmission Buildout

From (BA)	To (BA)	Year of Capacity Addition	Transmission Type	Capacity (MW)
Planned Intra-State Transmission				
Ajmer	Jodhpur	2022	AC	2,200
Ajmer	Jodhpur	2023	AC	1,100
Ajmer	Jodhpur	2024	AC	650
Ajmer	Jodhpur	2025	AC	15,660
Jodhpur	Jaipur	2025	AC	22,000
Jaipur	Ajmer	2022	AC	2,200
Jaipur	Ajmer	2025	AC	2,200
Planned Inter-State Transmission				
Ajmer	Delhi	2022	AC	4,400
Ajmer	Uttar Pradesh	2025	DC	4,400
Ajmer	Haryana	2025	AC	1,100

Appendix B. Background That Informed EV Adoption Scenarios

EV charging infrastructure is key to EV deployment, as the availability of charging infrastructure impacts when and how EV adopters can charge their vehicles for short- and long-duration trips. As such, there has been an emphasis on developing charging infrastructure across India. As of June 2020, there is no public EV charging infrastructure in Rajasthan (Central Electricity Authority, Government of India 2020). However, as of January 2020, 205 charging stations have been allotted charging infrastructure incentives under the national EV policy program, FAME II (RMI India 2020).[14] Additionally, the Rajasthan government in its 2019 solar policy outlined plans and incentives to promote renewable energy-based EV charging infrastructure (Energy Department, Government of Rajasthan 2019). However, the announced rollout order for EV public charging infrastructure may involve a highway running through Rajasthan (i.e., the Delhi-Jaipur corridor).[15]

To develop this scenario, we referenced two prior analyses/frameworks on potential load curves in a system with varying EV penetration levels. First, we considered a framework developed by NREL in collaboration with BSES Rajdhani Power Limited. Researchers developed a framework for analyzing the economic and technical benefits/challenges of EV and BESS integration, to help optimize grid infrastructure decisions (Ghosh et al. 2019; Nagarajan et al. 2020).[16] For EVs, the framework considered potential value streams (or grid services) of peak shaving and energy arbitrage assuming how various charging scenarios (residential, public, and workplace) and EV penetration levels could impact load curves. Additionally, we considered the load curves developed by Rocky Mountain Institute in its guide on EV readiness for DISCOMs in India. Their analysis indicated that for public AC charging, as utilization increases, the daily load profile typically flattens as more users charge early in the morning and late evening (RMI India 2020). In areas with high retail activity, peaks tend to occur in late afternoon and evening. For Public DC charging, these stations can serve a higher number of customers and so overall peak demand needs are higher.

RMI also considered various load flexibility considerations for different vehicle types. From Table 4, we see that private two and four-wheeler vehicles are probably the most flexible EV

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[14] The states with the most infrastructure (in descending order) were Andhra Pradesh, Telangana, Karnataka, Delhi, Maharashtra, Jharkhand, Himachal Pradesh, West Bengal, Gujarat, Uttarakhand, Madhya Pradesh, Kerala, and Assam.

[15] There are two phases under the Ministry of Power EV Public Charging Rollout. Phase 1 (1-3 years): all cities with population of more than 4 million people as at the 2011 census and expressways connected to these cities; and Phase 2 (3-5 years): big cities like state capitals and UT headquarters. There are no cities in Rajasthan that would fall under Phase 1. However, there is one Rajasthan-related corridor that would be prioritized in Phase 1 (i.e., the Delhi-Jaipur corridor).

[16] See (Nagarajan et al. 2020) for background on the analytical framework. The analytical framework involved modeling EV integration using an "object-oriented approach of individual EV, charging statin and charger treated as separate objectives with corresponding static properties." Three key variables informed the framework: number of EVs (by type and level of penetration), charging scenarios (residential dominant, public station dominant, or commercial/workplace dominant), and length of simulation. The case study focused on Delhi feeders and leveraged previous work on estimating overall charging demand for various EV penetration levels, with charging scenarios also informed by the types of AC and DC chargers used in some Delhi EV charging locations.

loads with typical charging happening during the day and/or evening depending on the available charging and tariffs.

Appendix C. Additional Air Emissions Results

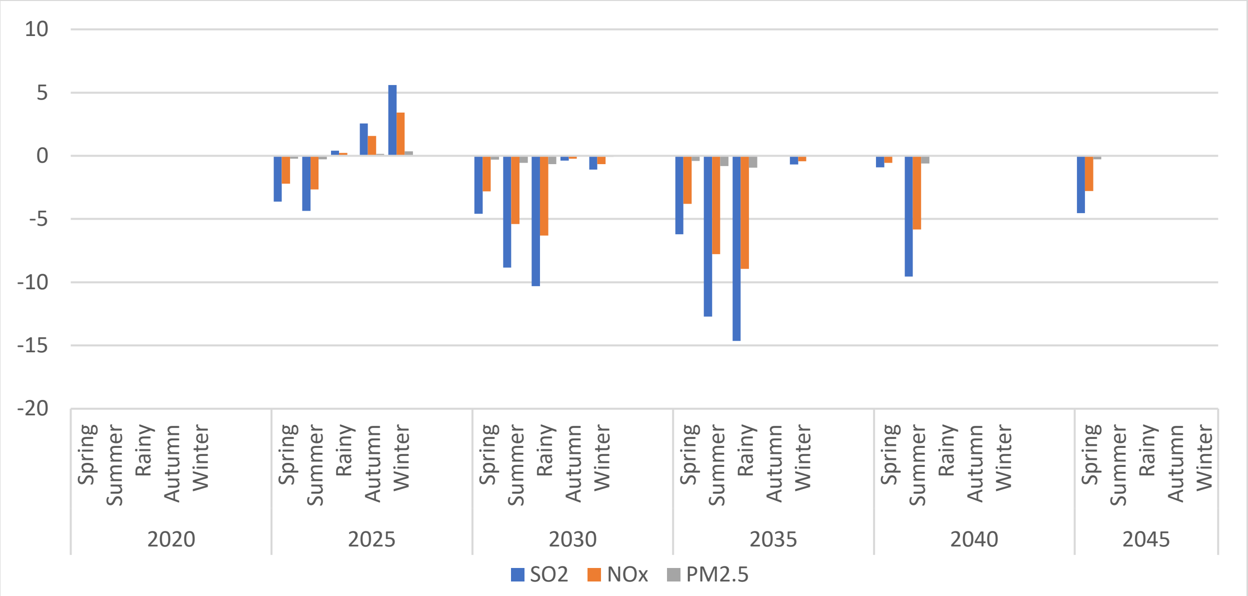

Figure C-1. Difference from Reference case projected $PM_{2.5}$, SO_2, and NO_x emissions from coal in the Low-Cost Wind+Solar+BESS scenario

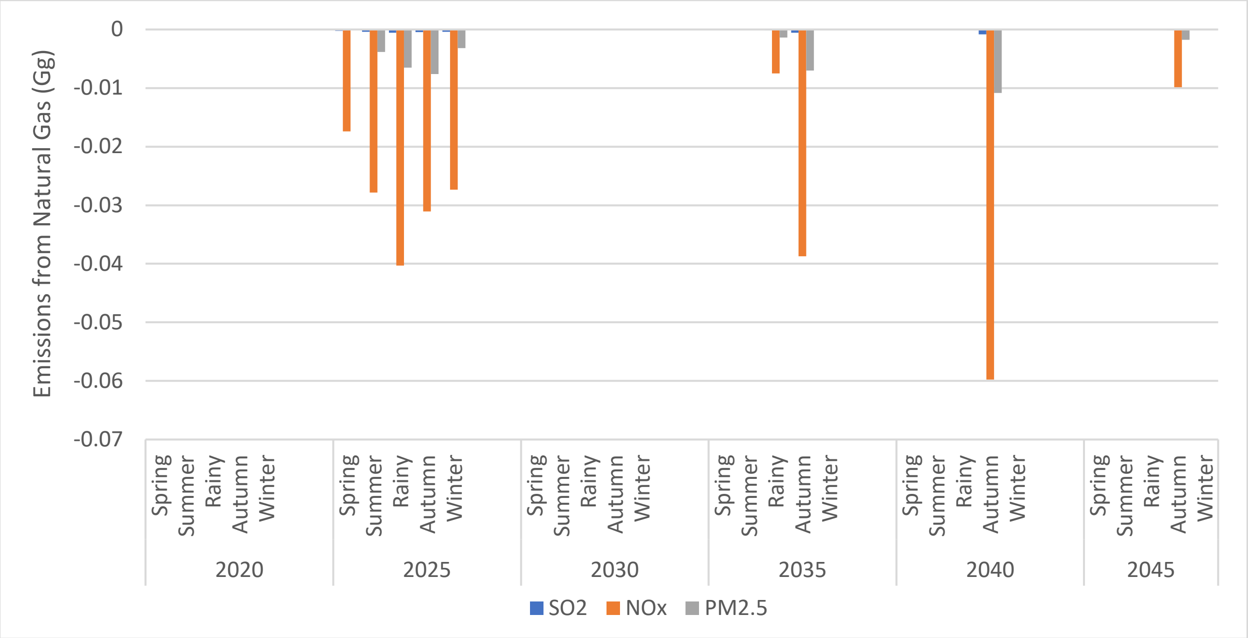

Figure C-2. Difference from Reference case projected $PM_{2.5}$, SO_2, and NO_x emissions from natural gas in the Low-Cost Wind+Solar+BESS scenario

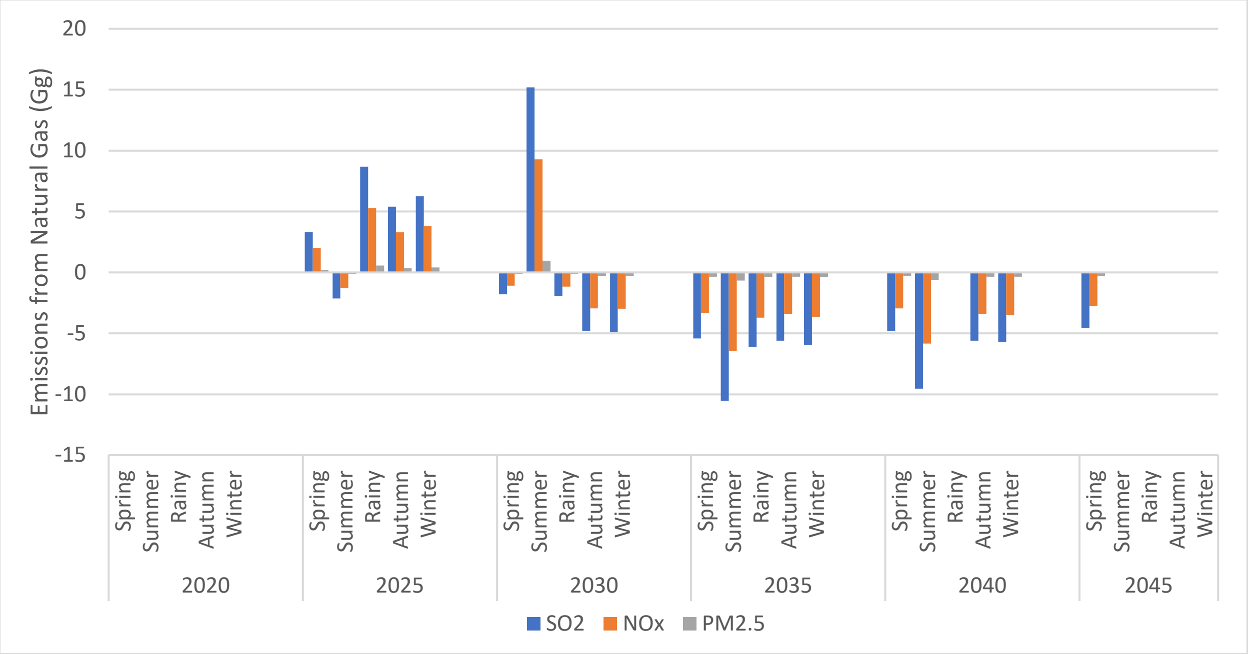

Figure C-3. Difference from Reference case projected $PM_{2.5}$, SO_2, and NO_x emissions from coal in the High-Cost BESS scenario

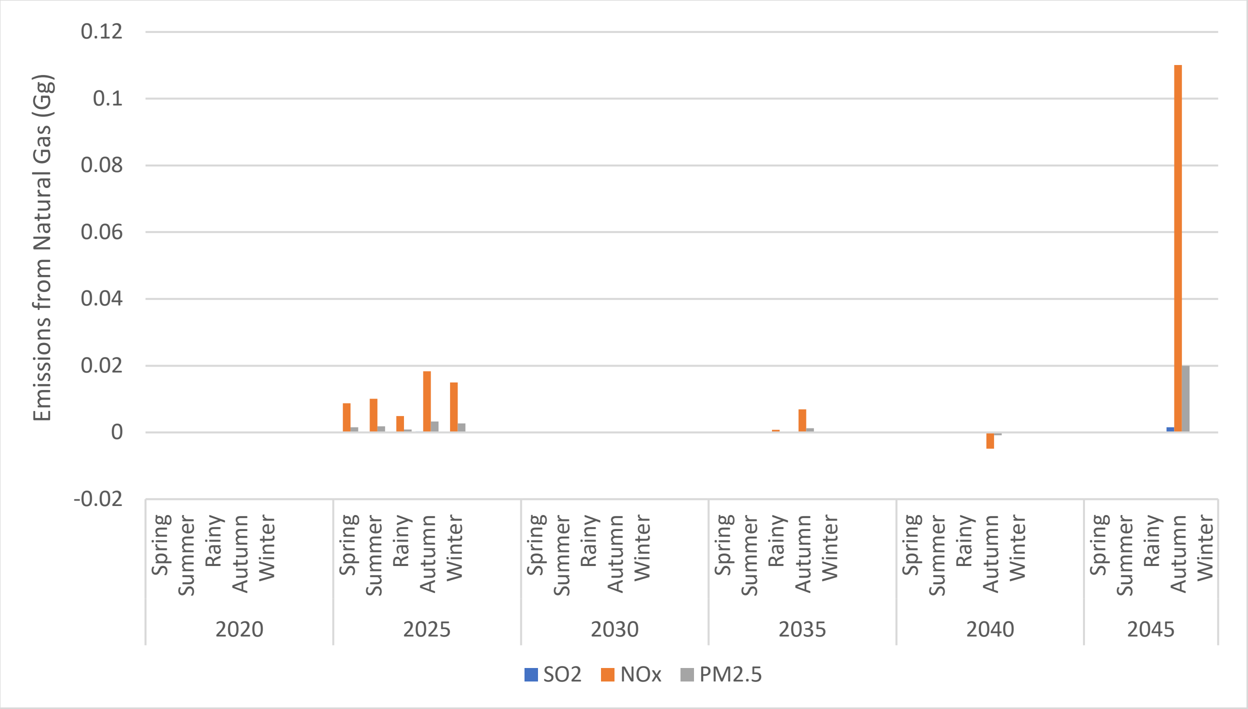

Figure C-4. Difference from Reference case projected $PM_{2.5}$, SO_2, and NO_x emissions from natural gas in the High-Cost BESS scenarios

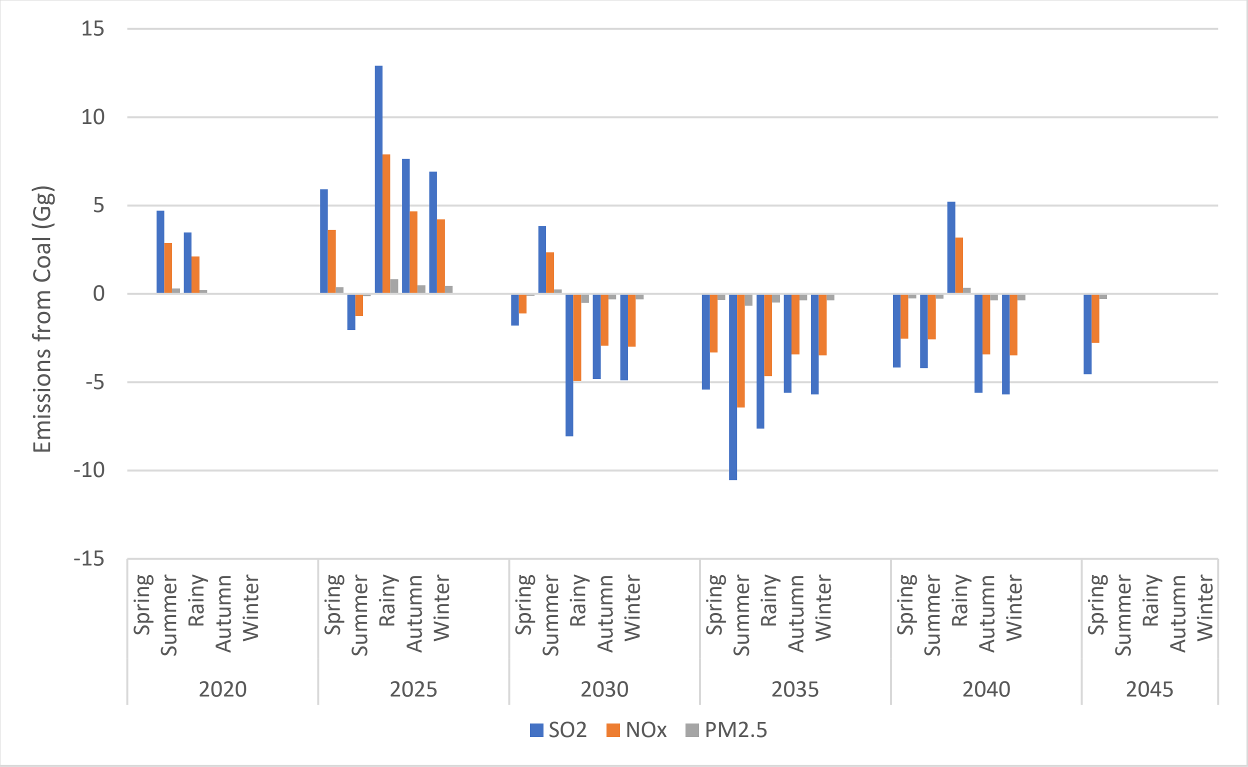

Figure C-5. Difference from Reference case projected $PM_{2.5}$, SO_2, and NO_x emissions from coal in the Agshift scenario

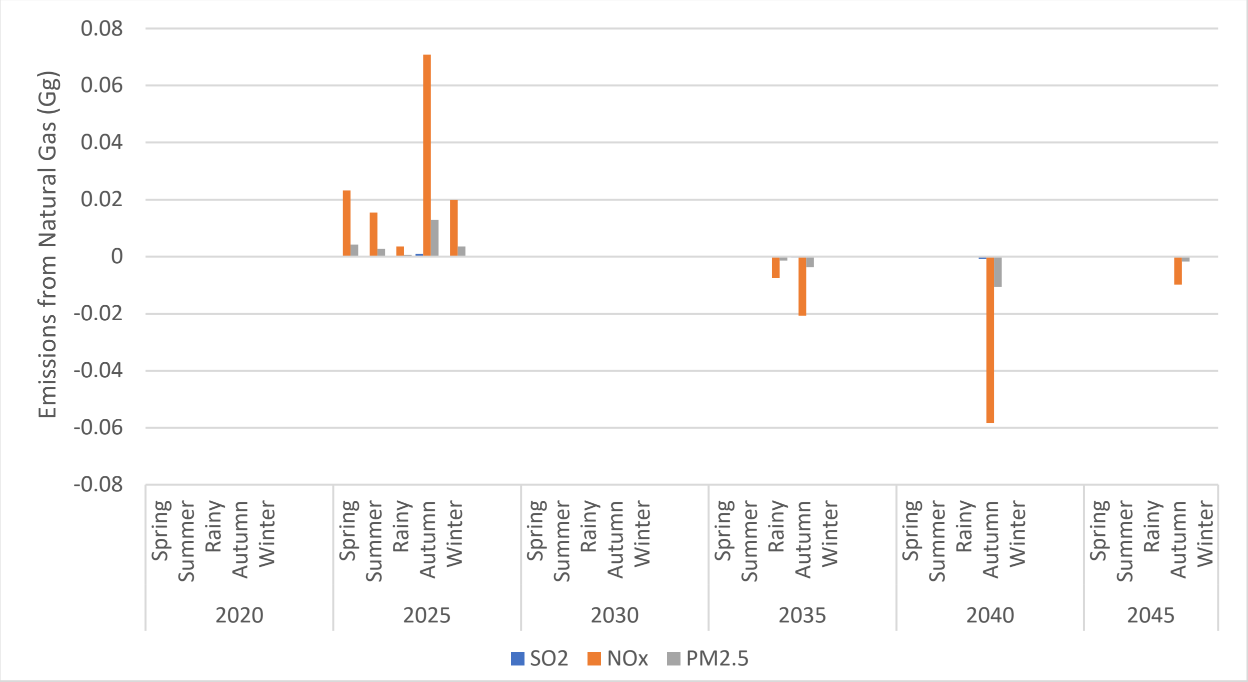

Figure C-6. Difference from Reference case projected $PM_{2.5}$, SO_2, and NO_x emissions from natural gas in the Agshift scenario