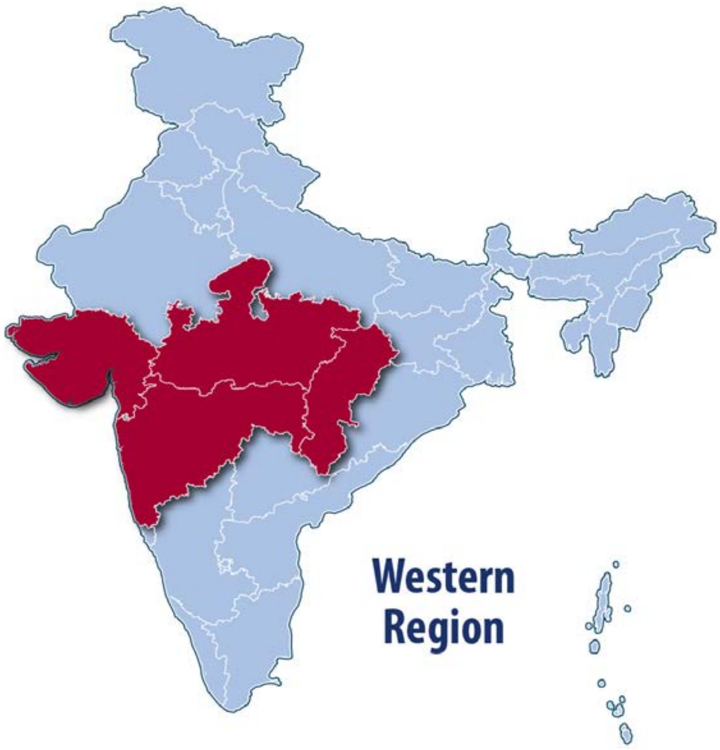
GREENING THE GRID:

Integrating 175 Gigawatts of Renewable Energy into India's Electric Grid—A Detailed Look at the Western Region

About the Study



"Greening the Grid: Pathways to Integrate 175 Gigawatts of Renewable Energy into India's Electric Grid" uses advanced weather and power system modeling to explore the operational impacts of meeting India's 2022 renewable energy (RE) targets, including 100 gigawatts (GW) of solar and 60 GW of wind, and identify actions that may be favorable for grid integration.

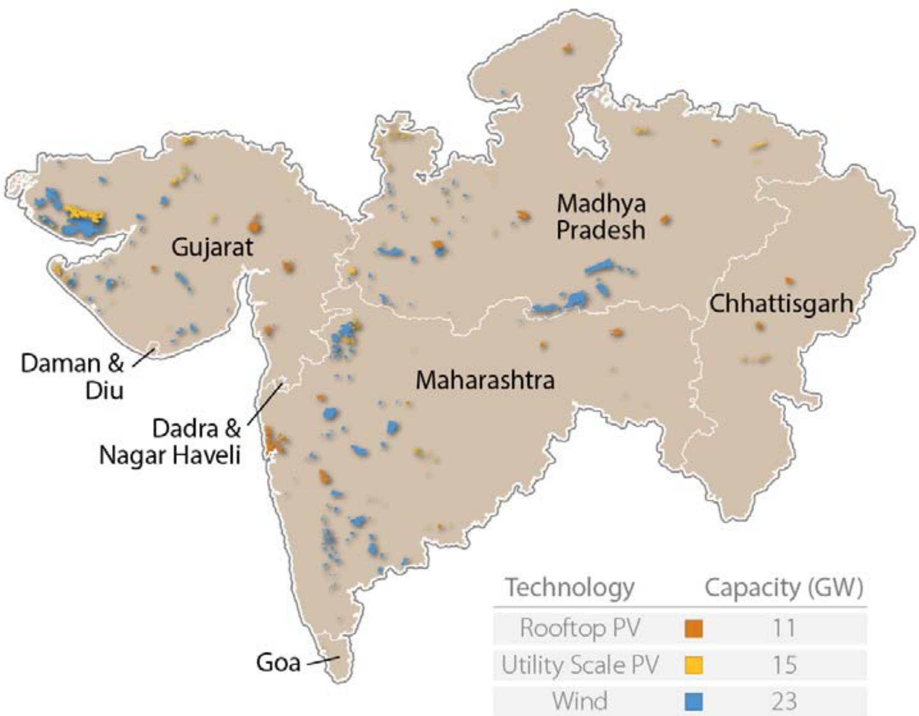
The study team's primary tool was a detailed production cost model, which simulates optimal scheduling and dispatch of available power generation in a future year (2022) by minimizing total production costs subject to physical, operational, and market constraints. They used this model to identify how the Indian power system is balanced every 15 minutes, the same time frame used by power system operators.

The multi-institutional study team used two different modeling approaches—national and regional—to answer a range of questions in appropriate levels of detail. The national model (focus of Volume I) runs relatively quickly, which enabled the team to explore more questions and spot major trends in power system operations from a national perspective, such as major energy flows across the country and roles for coal plants to facilitate system balancing.

To investigate system operations in each of the states with the potential for significant growth in RE capacity, the study team also used a higher-resolution model that includes intrastate transmission details. This regional model—and the focus of Volume II and this Western region summary—builds upon the same inputs in the national model but includes all transmission lines and substations within each of the states in the Southern and Western regions plus Rajasthan. Therefore, the regional model provides more robust views of localized operations and can offer more relevant insights to support state-level planning. The regional model provides a rigorous framework for future work and can be updated with the characteristics of new capacity as more information on the future power system is known.

Results Overview

Volume II—the Regional Study—shows that in the context of meeting India's RE goals of 160 GW of solar and wind, the Western region can integrate 49 GW of RE at 15-minute timescales. Because of its advantages, including strong interconnectedness with other regions and intraregional coal flexibility, the Western region is able to effectively smooth swings in net load and limit RE curtailment. Coal-dominant states such as Chhattisgarh, Maharashtra, and Madhya Pradesh serve as critical sources of flexibility for high-RE states like Gujarat. The value of these coal resources in supporting RE integration is further enhanced with regional coordination and minimum generation levels lowered to 40% of rated capacity, whereas a less flexible system, with 70% minimum generation levels, experiences significantly increased RE curtailment.

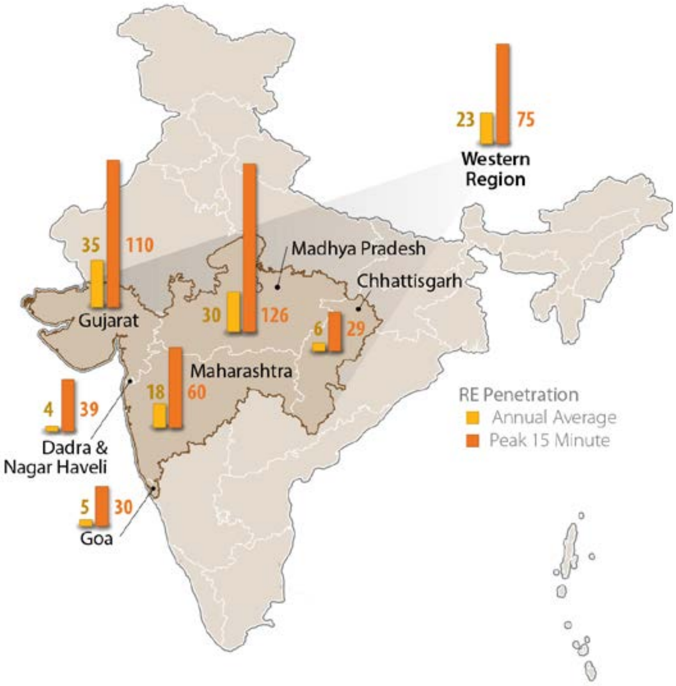


Locations for installed solar and wind capacity in the Western region, 100 GW solar and 60 GW wind scenario (100S-60W)

KEY FINDINGS:
How the Western Region Power System Could Operate in the 100S–60W Scenario

The Western region generates 108 terawatt-hours (TWh) of RE, which is equivalent to 23% of total load.

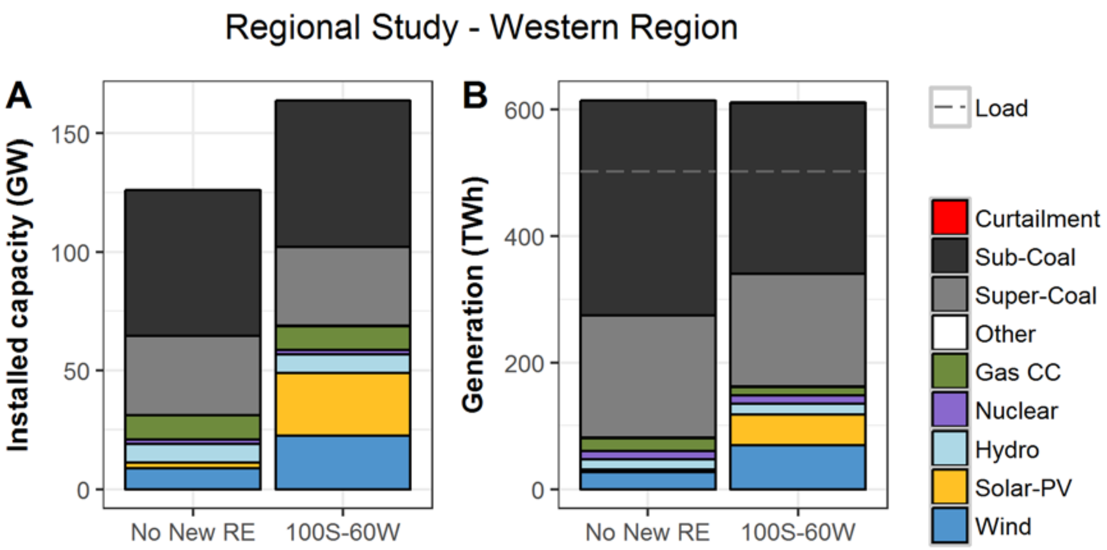
Forty-nine GW of wind and solar capacity in the Western region in the 100S-60W scenario displace 16% of coal and 31% of gas compared to the No New RE scenario. Two states, Gujarat and Madhya Pradesh, meet the equivalent of 30% or more of their annual load with RE while reaching instantaneous RE penetrations of greater than 100%.



Annual and 15-minute peak instantaneous penetration of RE generation as a percent of load, 100S-60W, Western region

The Western region's maximum 1-hour net-load ramp falls from 9.3 GW to 7.9 GW in the 100S-60W scenario because solar generation during daylight hours mitigates steep morning load up-ramps.

The Western region often experiences peak demand midday and therefore has some of its most severe up-ramps during the morning rather than the evening. This allows solar generation to help meet some of the region's most extreme ramps and reduce the stress placed on the thermal and hydro fleet. Overall, this trend is more evident in the nonmonsoon season as solar accounts for a greater percentage of RE and net load has a more dramatic diurnal pattern. During the monsoon, wind contributes substantially more to the decrease in net load, although solar still has a large effect on the decreased up-ramping required of the thermal and hydro fleets during these lower net load periods.

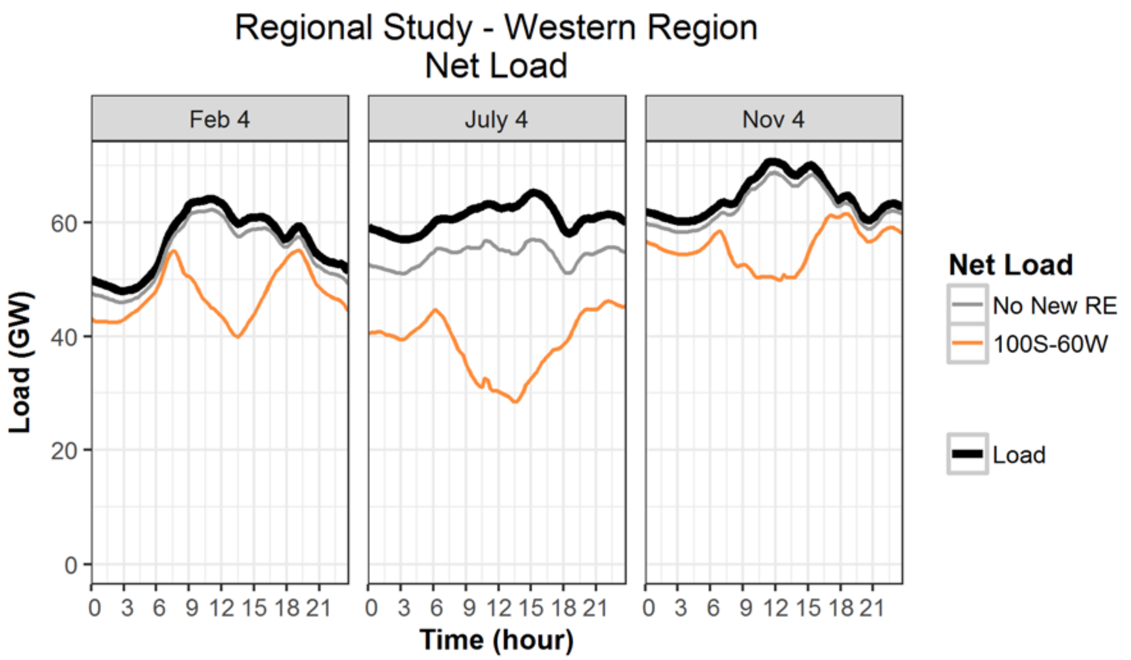


Installed capacity (A) and annual generation (B), No New RE and 100S-60W, Western region

The change in net load shape requires changes to operations of hydro and thermal plants to keep the system balanced. In the 100S-60W scenario, hydro generation turns down during the day—when solar generation is high—and instead contributes more to ramping and energy needs during the morning and evening net load peaks.

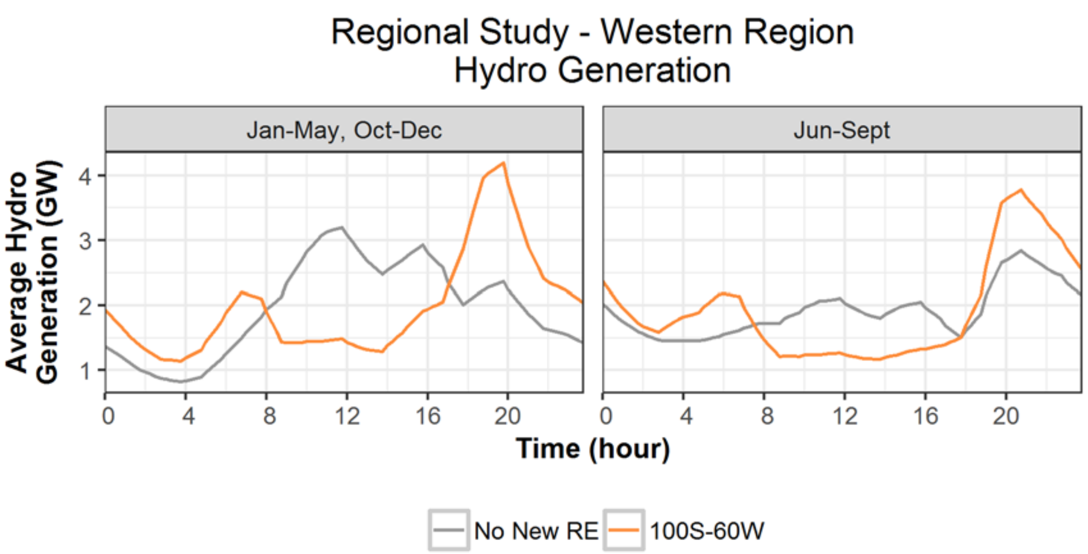
Increased RE in the 100S-60W scenario significantly changes the magnitude of peak flows on a number of state-to-state corridors in the Western region, especially connections with the coal-dominant states of Madhya Pradesh, Maharashtra, and Chhattisgarh.

The transmission flows on state-to-state corridors in the Western region change in response to more RE on the system in the 100S-60W scenario compared



Comparison of net load by season, No New RE and 100S-60W, Western region

Note: Net load is load minus wind and solar generation postcurtailment.



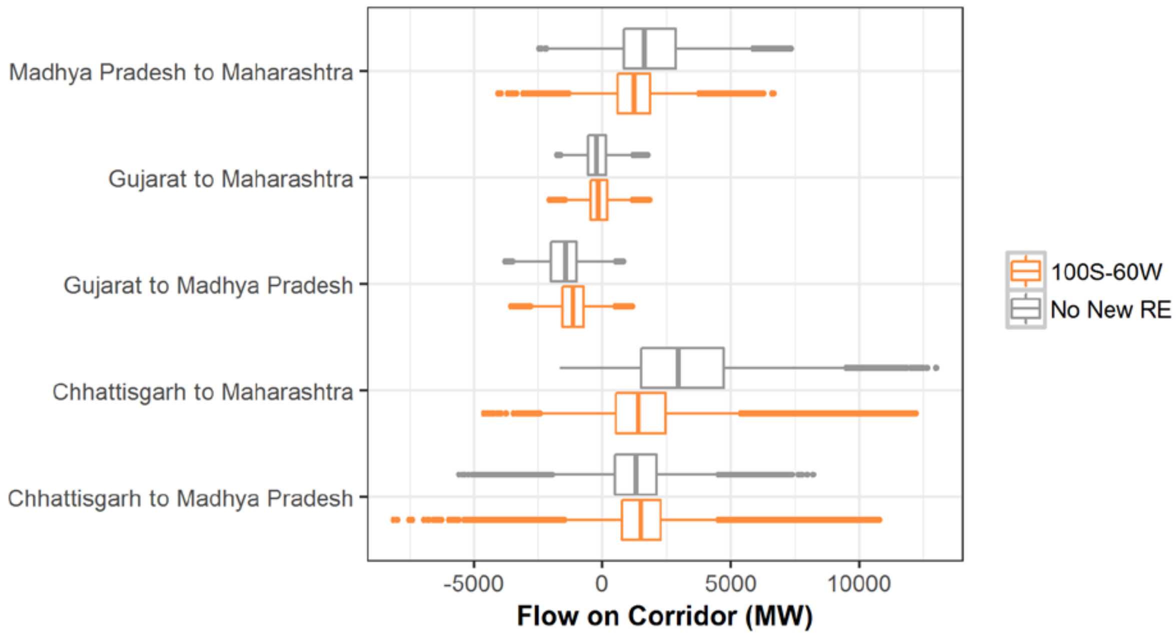
Comparison of average day of hydro operations by season, No New RE and 100S-60W, Western region

to No New RE. The most significant changes take place on corridors connecting coal-dominant states of Madhya Pradesh, Maharashtra, and Chhattisgarh. The Chhattisgarh-Madhya Pradesh corridor has a peak flow that is 45% higher in the 100S-60W scenario, while the Madhya Pradesh-Maharashtra corridor has a peak flow that is 65% higher in the 100S-60W scenario. Increases along these borders indicate that the transmission system connecting coal-dominant regions of the country is playing a critical role in system balancing by enabling access to coal flexibility. Another factor affecting the flows in this part of the country is decreased exports to the Southern region, which is now able to serve more of its demand with zero-operating-cost RE.

KEY FINDINGS: Impacts of Integration Strategies—Lowering Coal Minimum Generation Levels, Regional Coordination

Lowering minimum generation levels from 70% to 55% and 40% reduces RE curtailment from 3.4% to 1.6% and 0.9%, respectively, in the Western region.

Lowering minimum generation levels of coal has a significant impact on RE integration in the Western region. The impact of not requiring coal plants to reduce minimum generation levels to 55% (from 70%) could result in a 2.2% increase in RE curtailment.[1] This may be especially acute for Gujarat, which sees the largest



Distribution of flows across state-to-state corridors within the Western region, No New RE and 100S-60W

Note: Boxes represent divisions into 25th percent quantiles. The middle line is the median. Positive flow indicates direction as indicated in legend, and negative flows the opposite direction.

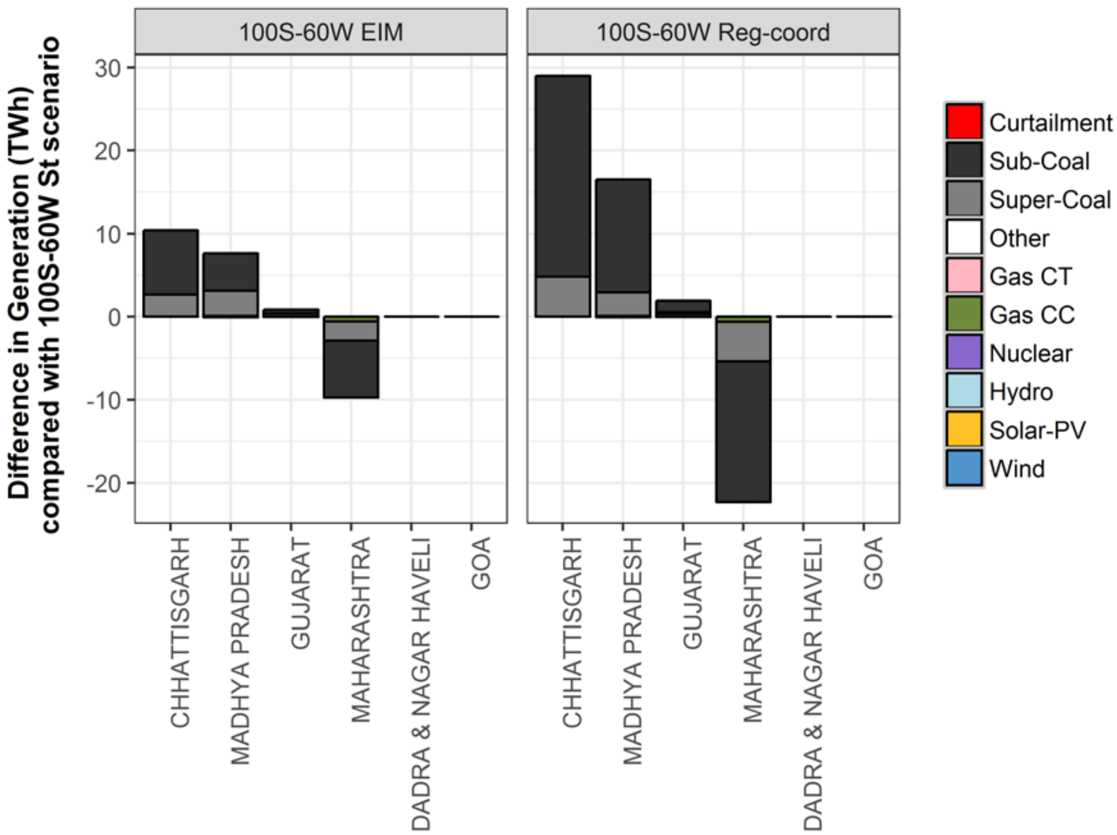
[1] Curtailment figures are based on assumptions made for this study about locations of RE and available intrastate transmission, and include the addition of nine intra-regional and three interregional transmission lines to supplement Central Electricity Authority's 2021–2022 plans.

reduction in curtailment, from 5.3% to 2.4% of its available RE capacity, when moving to 55% minimum coal generation levels. A large part of the increased curtailment in Gujarat is the result of intrastate congestion causing a lack of access to flexibility elsewhere in the region. An additional reduction to 40% minimum generation reduces the Western region's curtailment to 0.9%.

Full regional coordination reduces the Western region's average variable costs by 0.9% while simultaneously boosting its exports, made possible by more efficient operation of its thermal fleet.

We evaluated two aspects of coordination at the regional level—dispatch only and combined scheduling (unit commitment) and dispatch. With coordinated dispatch, or energy imbalance market (EIM), states make unit commitment decisions separately but can coordinate dispatch in real time via a centralized market or system operator. Full regional coordination enables states to collectively optimize day-ahead unit commitment, as well as real-time dispatch, turning the Western region into a single balancing area.

The Western region interacts more efficiently with its neighbors with regional coordination, increasing exports to displace its neighbors' more expensive marginal units. Exports to the Southern region rise by 27% with coordinated dispatch and 160% with full regional coordination. Despite its increased generation, which entails rising marginal costs, the Western region reduces average generation costs by 1.1% with coordinated dispatch and 0.9% with full regional coordination. Maharashtra, which has relatively expensive thermal generation, generates over 20 TWh less energy from coal plants with full regional coordination and benefits from increased imports, while Chhattisgarh and Madhya Pradesh increase output. The Western region's RE curtailment does not change significantly with improved dispatch coordination.



Difference in annual generation of regional coordination compared to state dispatch with EIM (left) and unit commitment and dispatch (right), in the Western region by state

Summary

The Western region is able to integrate a substantial amount of RE with minimal curtailment because of a number of advantages, such as strong interconnections to multiple other regions and the strong interstate connections within the region that allow for effective balancing of large changes to net load. However, coordinating commitment and dispatch allows for the Western region to increase its value to neighboring regions and increase exports by providing access to inexpensive generation around the region. Meeting the 55% minimum generation limit Central Electricity Regulatory Commission (CERC) regulation also has profound effects on the ability to utilize RE in the Western region.

The callout box consolidates key findings specific to the Western region in the context of meeting India's 160-GW wind and solar goals nationwide.

While transmission does not present significant constraints to RE integration overall, specific corridors do adversely affect system flexibility. Also, these results are contingent on the 12 intra- and interregional lines added to Western region in the model to serve new RE installations in the region, which supplement the Central Electricity Authority's 2021–2022 plans. Without these added lines, annual RE curtailment is very high in certain locations. Although transmission planning is outside the scope of this study, this model can be used to help identify the value and operational impacts of new transmission. Because of the sensitivity of RE curtailment to intrastate transmission capacity, this study does reinforce the value of planning that optimizes both transmission and generation capacity using high-resolution RE resource data.

Key Findings for the Western Region Power System in the 100S–60W Scenario

RE generation in the Western region:

- 49 GW of wind and solar power in the Western region, as part of the 160-GW national goal, generates 120 TWh annually (70 TWh wind, 48 TWh solar), which is 19% of all generation in the Western region.
- Wind and solar generation result in an average annual RE penetration of 23% of load.
- In June and July, the months with the highest RE generation, RE meets more than 35% of the Western region's load, with an instantaneous peak of 75% in July.

Impacts on thermal units and plant operations in the Western region compared to the No New RE scenario:

- Peak 1-hour net load up-ramp is 7.9 GW, down from 9.3 GW.
- Maximum net load valley-to-peak ramp is 24 GW on 29 December, up from a peak of 23 GW on the same day in the No New RE scenario.
- Coal and natural gas generation decrease 85 TWh and 6.3 TWh, respectively, a drop of 16% and 31%.
- Plant load factors (PLFs) of coal drop from 64% to 54%; PLFs of state and private plants fall from 59% to 48%.
- 720 MW of coal capacity never starts, compared to 600 MW in the No New RE scenario.
- Coal units with the highest variable costs are impacted most by increased RE availability, with the PLFs of the top third most expensive units dropping to an average of 37% from 51%.

Impacts on imports and exports and transmission flows compared to the No New RE scenario:

- Annual generation across all generation types in the Western region decreases by 1% to 610 TWh due to the net effect of increased RE generation, decreased thermal generation, and decreased net exports of 5%.
- Peak transmission flows on the Chhattisgarh-Madhya Pradesh corridor increase by 45% and on the Madhya Pradesh-Maharashtra corridor by 65% in the 100S-60W scenario compared to No New RE. Transmission allows for the coal-dominant region of the country to play a significant role in system balancing.

Implications for Policy

In addition to the policy implications detailed in the **National Study**, specific policy implications can be customized for the Western region:

- State regulatory standards for coal flexibility in low-RE, coal-dominant states can play an important role in facilitating RE integration elsewhere in the region. With 55% minimum generation standards, coal plants in Chhattisgarh and Madhya Pradesh, which are relatively low-variable-cost producers and have sufficient capacity to export, are able to back down and reduce exports midday, which contributes to overall low RE curtailment in the region. Thus, there is value to considering state standards for coal flexibility, even in non-RE-rich states.
- The challenge will be in designing policies that sufficiently incentivize the provision and performance of this flexibility, and providing technical assistance to operators of older coal plants to implement required modifications. Experience with older coal plants elsewhere has demonstrated that cycling-related costs can be minimized with changes to operating practices (e.g., controlling temperature ramp rates, implementing rigorous training and inspection programs), even if physical modifications are cost-prohibitive.[2] One pilot being considered under the U.S. Agency for International Development (USAID)-Ministry of Power Greening the Grid program includes a partnership with Gujarat State Electricity Corporation Limited (GSECL) to demonstrate technical and economic feasibility of coal flexibility, including a cost-benefit analysis. Under the pilot, the Greening the Grid program will also help develop a road map to guide GSECL on improving coal flexibility, including investment requirements and regulatory support.
- Regional or even national coordination—particularly at both unit commitment and dispatch timescales—improves efficient operations of plants and export opportunities. The relatively small change in operating costs within the region—INR 1400/MWh from 1410/MWh—that results from improved coordination masks several significant changes to trade flows and dispatch patterns. For example, exports to the Southern region increase 130% when commitment and dispatch are coordinated. Within the region, commitment patterns change—coal generation in Maharashtra falls 17%, while it increases 19% across Chhattisgarh and Madhya Pradesh.

Sponsors and Contributors

This work is conducted under a broader program, Greening the Grid, which is an initiative co-led by India's Ministry of Power and USAID, and includes collaboration with the World Bank Energy Sector Management Assistance Program and the 21st Century Power Partnership. The modeling team comprised a core group from the Power System Operation Corporation, Ltd. (POSOCO), which is the national grid operator (with representation from the National, Southern, and Western Regional Load Dispatch Centers), the National Renewable Energy Laboratory, and Lawrence Berkeley National Laboratory, and a broader modeling team drawn from Central Electricity Authority, POWERGRID (the central transmission utility), and State Load Dispatch Centers in Maharashtra, Gujarat, Rajasthan, Tamil Nadu, Karnataka, and Andhra Pradesh.

Technical stakeholder review and guidance was provided by more than 150 technical experts from central agencies, state institutions (grid operators, power system planners, RE nodal agencies, distribution utilities), and the private sector (RE developers, thermal plant operators, utilities, research institutions, market operators, other industry representatives).

Learn more: www.nrel.gov/india-grid-integration/

[2] Cochran, Jaquelin, Debra Lew, and Nikhil Kumar. 2013. *Flexible Coal: Evolution from Baseload to Peaking Plant*. BR-6A20-60575. Golden, CO: 21st Century Power Partnership. ***http://www.nrel.gov/docs/fy14osti/60575.pdf***.

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NREL/BR-6A20-70354 • October 2017
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