GREENING THE GRID:

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

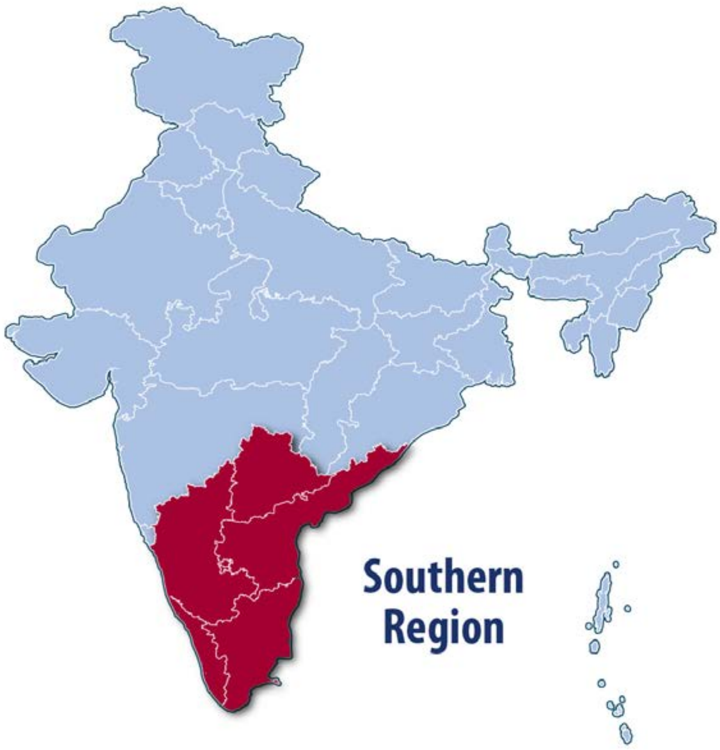
About the Study

"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.

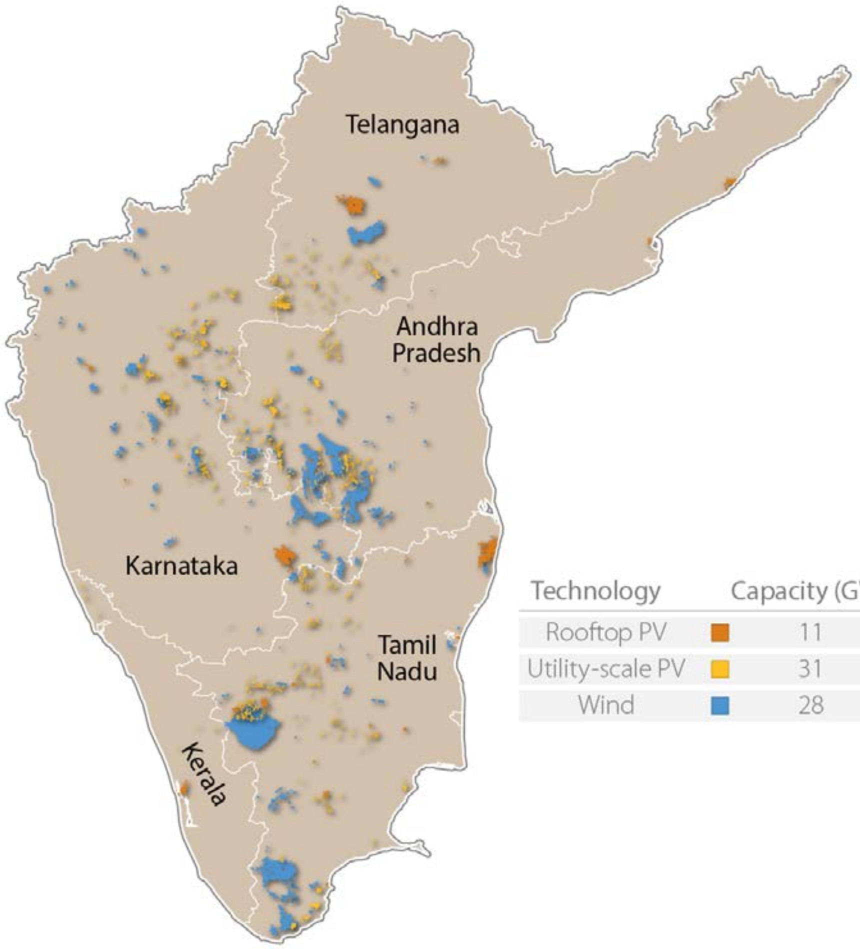
The multi-institutional study team used two different modeling approaches—national and regional—to answer a range of questions in appropriate levels of detail. The national model (focus of Volume I) runs relatively quickly, which enabled the team to explore more questions and spot major trends in power 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 Southern 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 Southern region can integrate 70 GW of RE at 15-minute timescales. However, because of constraints related to interconnectedness with other regions, gas storage, and potentially high RE penetrations relative to load, the Southern region may experience relatively high levels of RE curtailment compared to other regions. But these constraints are surmountable; both regionally coordinated scheduling and dispatch and improved coal flexibility offer large improvements to power system operations and costs.



Technology		Capacity (GW)
Rooftop PV	■	11
Utility-scale PV	■	31
Wind	■	28

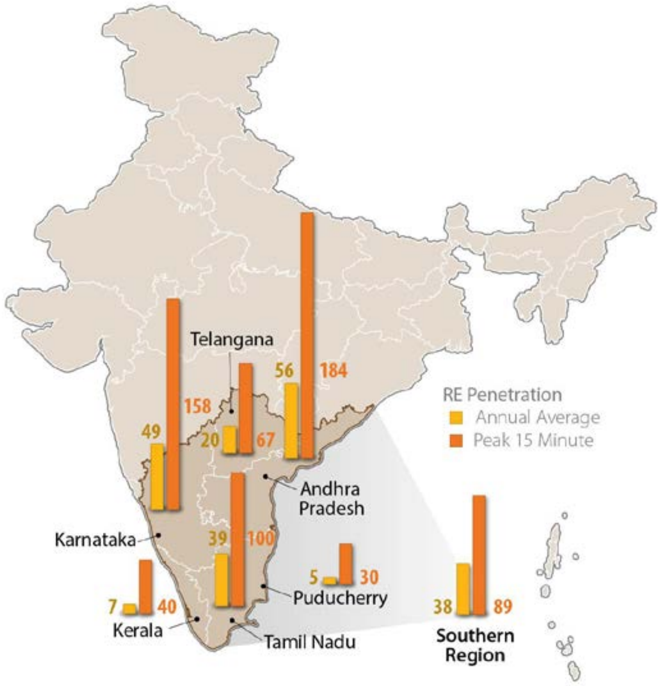
Locations for installed solar and wind capacity in the Southern region, 100 GW solar and 60 GW wind scenario (100S-60W)

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

The Southern region generates 160 terawatt-hours (TWh) of RE, which is equivalent to 38% of total load.

Seventy GW of wind and solar capacity in the Southern region in the 100S-60W scenario displace 33% of coal and 48% of gas, and also reduce the need for annual energy imports compared to the No New RE scenario.

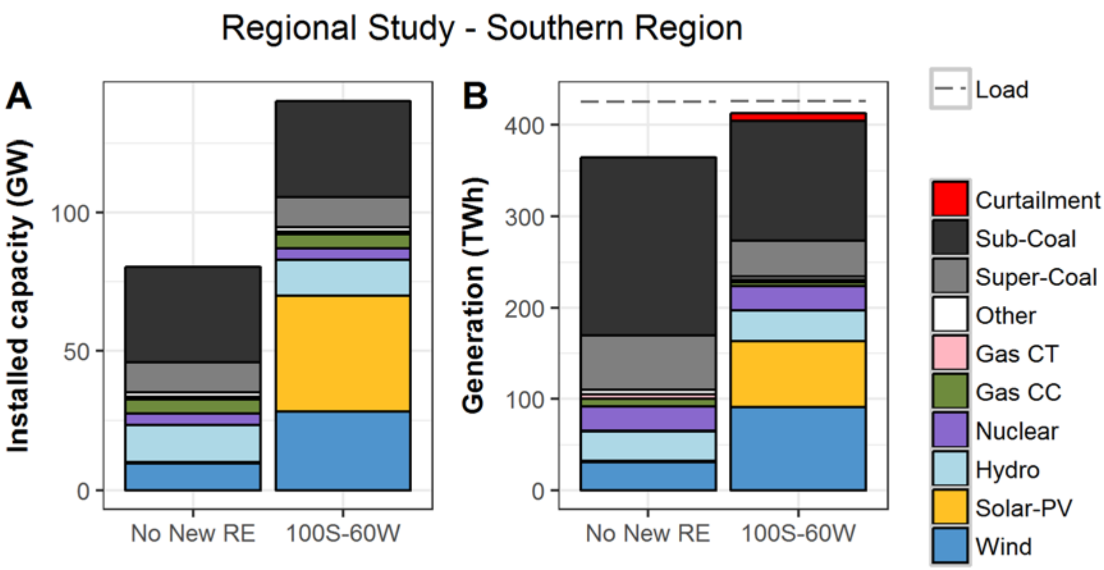
Two states, Andhra Pradesh and Karnataka, meet the equivalent of more than 40% of their annual load with RE while reaching instantaneous RE penetrations of greater than 100%.



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

The Southern region experiences little to no RE curtailment for the majority of the year; however, significant changes to net load during the monsoon (midday) do increase the need for system flexibility.

Increased wind generation in the monsoon season combined with year-round midday solar generation creates conditions in which the Southern region's thermal fleet, hydro fleet, and transmission network can no longer provide sufficient flexibility to avoid RE curtailment. The majority of RE curtailment occurs in daylight hours during the monsoon season when net load is especially low because of increased wind generation.

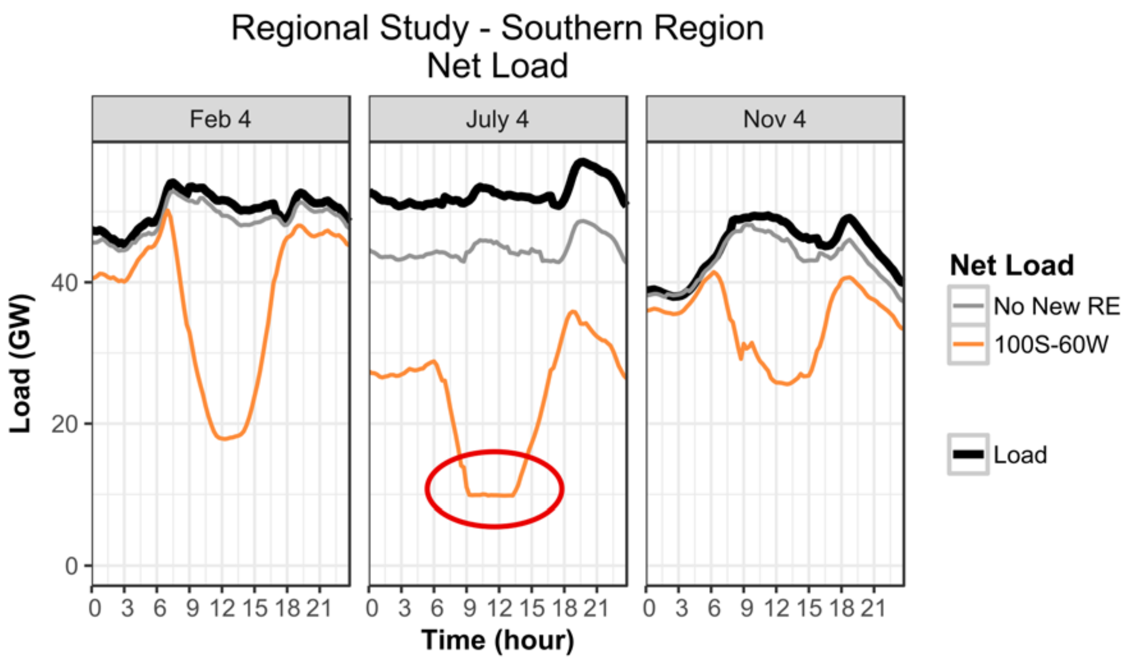


Installed capacity (A) and annual generation (B), No New RE and 100S-60W, Southern region

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 lower 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.

Inexpensive, centrally owned coal plants are dispatched more frequently and therefore cycle more than expensive state-owned plants.

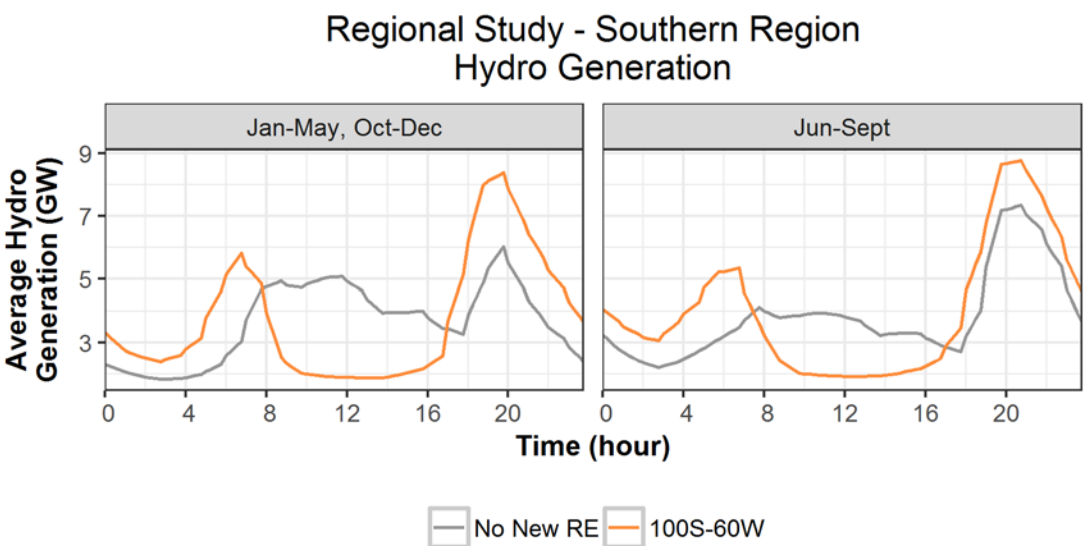
The Southern region's coal generation falls by 33% in the 100S-60W scenario, and average coal plant load factors (PLFs) drop from 64% to 43% compared to the No New RE scenario. PLFs of expensive state and private coal plants fall the most because of more shutdowns. Less expensive, more efficient coal plants



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

On 4 July, system constraints prevent further reductions to midday net load, and excess RE generation is curtailed (red circle).

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, Southern region

are dispatched but are subjected to more cycling to provide most of the increased flexibility necessary to balance the more variable net load. The least-cost plants (i.e., below the 33rd percentile of variable cost) experience an increase in total starts of 64% in the 100S-60W scenario. Centrally owned units, many of which have low variable costs, experience an increase in total starts of 72%.

Peak flow increases on almost all state-to-state corridors in the Southern region in the 100S-60W scenario, indicating the importance of transmission in accessing least-cost system balancing in the higher RE scenario. However, total annual state-to-state imports and exports of energy decrease in the 100S-60W scenario compared to No New RE because of the increase in local RE generation, which can help serve load and reduce imports.

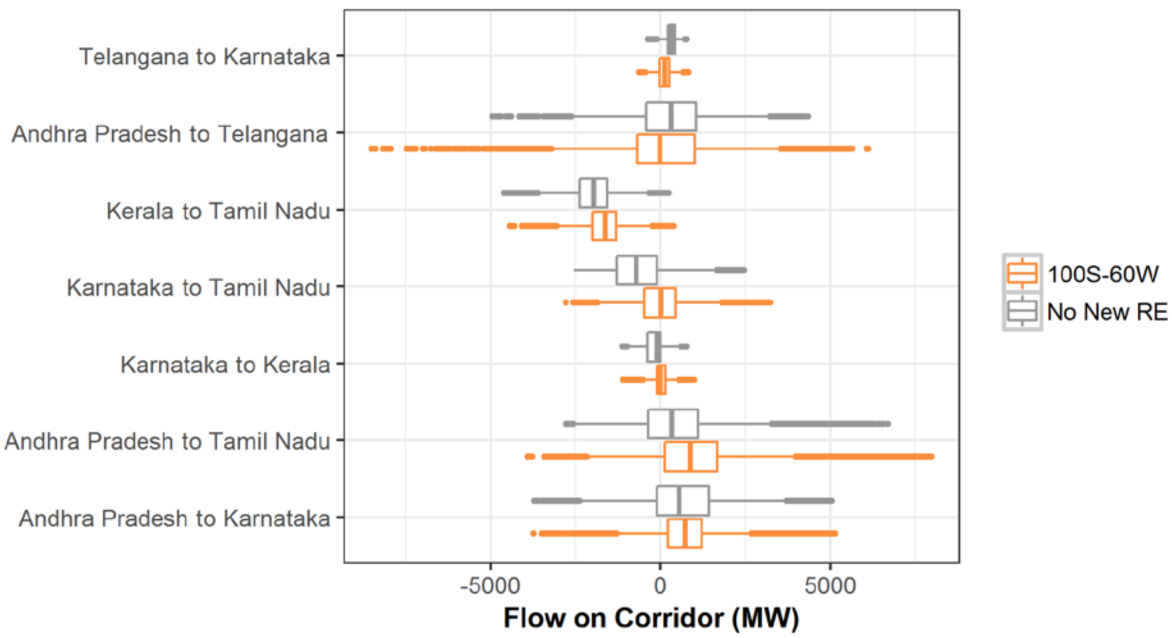
The transmission flows between states in the Southern region change in response to more RE on the system, both in terms of peak and total usage. This change leads to some periods when there is a greater reliance on transmission for balancing. Although many corridors have very similar distributions of flow magnitude between the scenarios, a few corridors experience much greater changes. For example, the flows from Andhra Pradesh to Telangana experience a peak flow that is 72% higher in the 100S-60W scenario.

While peak flows generally increase, annual interstate energy exchanges and interstate congestion inside the Southern region fall 8% and 17%, respectively, in the 100S-60W scenario, as all states use RE generation to serve load. For example, annually Karnataka shifts from a net importer to a net exporter, while Tamil Nadu decreases exchanges with other states by 22%. Across the region, annual generation increases 11% to 405 TWh, enabling the region to reduce its net imports by 64%.

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

Lowering minimum generation levels from 70% to 40% reduces RE curtailment from 8.4% to 3.0%. Andhra Pradesh experiences the largest reduction, from 10.4% to 2.8%.

Coal flexibility affects RE curtailment significantly. Minimum generation levels of 70%, 55%, and 40% have RE curtailment of 8.4%, 4.9%, and 3.0%, respectively.



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

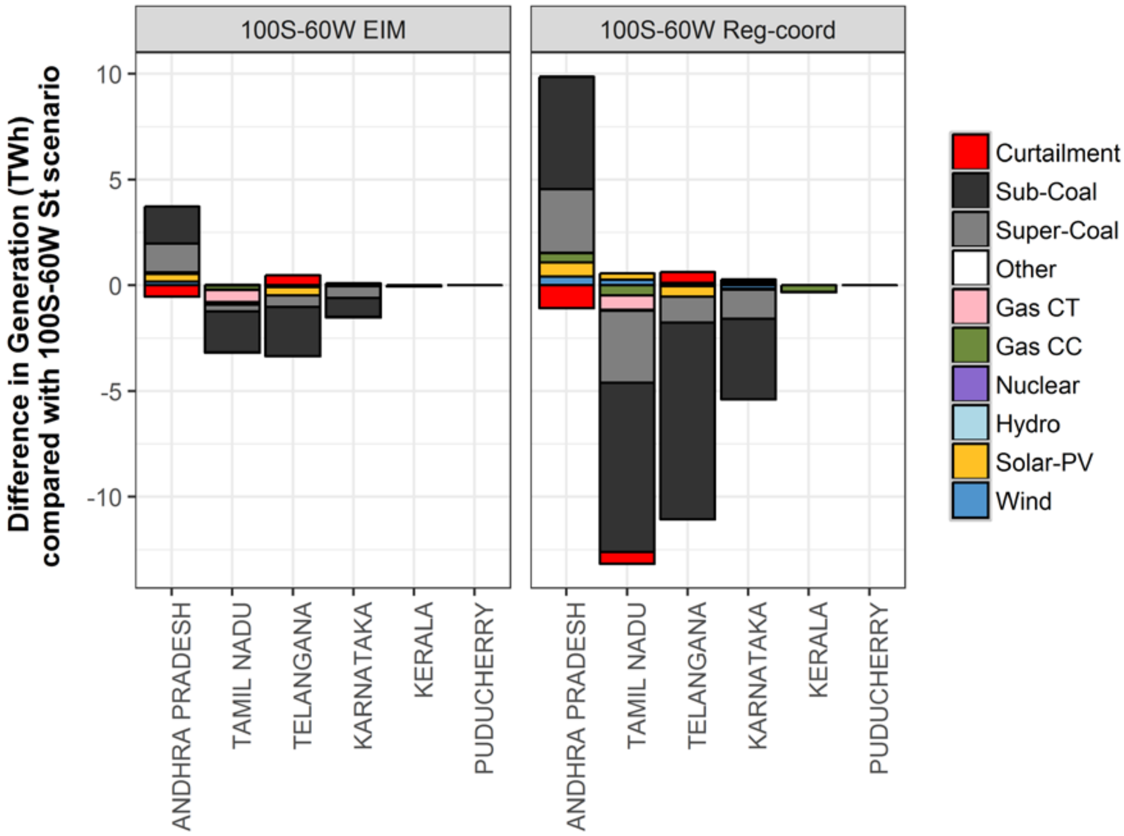
Note: Boxes represent divisions into 25th percent quantiles. The middle line is the median. Positive flow indicates direction as indicated in the legend, and negative flows the opposite direction.

Although all states show reduced curtailment from the increased flexibility, Andhra Pradesh (10.4% to 2.8%) and Karnataka (11.1% to 5.1%) experience the largest gains in terms of using available RE.[1] Reduced curtailment translates into production cost savings of 2.3% with 55% minimum generation levels, and an additional 1.3% (total 3.6%) with 40% minimum generation levels. Most of the production cost savings associated with increased coal flexibility come from reductions to RE curtailment, with RE displacing thermal generation.

Full regional coordination reduces average variable costs by 5.4% in the Southern region, made possible by increased lower-cost imports, more efficient operation of the region's thermal fleet, and reduced RE curtailment.

We evaluated two aspects of coordination at the regional level—dispatch only and combined scheduling (unit commitment) and dispatch. With coordinated dispatch (sometimes called an energy imbalance market [EIM] or energy imbalance service), 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 Southern region into a single balancing area. With full coordination, the Southern region's average cost of generation falls by 5.4%, driven by increased lower-cost imports from the Western and Eastern regions, more efficient thermal operations, and reduced RE curtailment.

Because the Southern region can interact with its neighbors as a single balancing area, it schedules interregional flows more efficiently. Imports, which rise by 19% with EIM and 85% with full regional coordination, allow the Southern region to displace generation from some of its most expensive units. Low-cost thermal generators in Andhra Pradesh increase output by 10 TWh with full regional coordination, displacing more expensive generation in Tamil Nadu and Telangana. Regionwide RE curtailment also falls from 4.9% with state dispatch to 4.3% with full regional coordination, replacing even more thermal generation with zero-marginal-cost wind and solar energy.



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

1. Curtailment figures are based on assumptions made for this study about locations of RE and available intrastate transmission, and include the addition of one inter-regional and six intraregional transmission lines to supplement Central Electricity Authority's 2021–2022 plans.

Summary

As a result of a comparatively constrained system and high levels of RE relative to load, RE integration strategies have a larger impact and value in the Southern region compared to other parts of India. Nevertheless, both regionally coordinated scheduling and dispatch and improved coal flexibility offer larger improvements to production costs and RE curtailment compared to the rest of the country.

The callout box consolidates key findings specific to the Southern region in the context of meeting India's 160-GW wind and solar goals nationwide. Also, these results are contingent on the seven intra- and interregional transmission lines added to Southern region in the model to serve new RE installations in the region, which supplement the Central Electricity Authority's 2021–2022 plans.

Due to the higher levels of RE curtailment in the Southern region relative to other parts of the country, policymakers may want to consider multiple strategies to reduce these levels, including strategies outside the scope of this study, such as alternative locations of RE generation or new transmission connections. Because in the Southern region, in particular, strategies such as coordinated operations and coal flexibility impact flows and congestion, implementing such integration strategies would benefit from transmission planning (both inter- and intrastate) conducted in tandem. 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 Southern Region Power System in the 100S–60W Scenario

RE generation in the Southern region:

- 70 GW of wind and solar power (as part of the 160-GW national goal) generates 160 TWh annually (91 TWh wind, 72 TWh solar), which is 40% of all generation in the Southern region.
- Wind and solar generation result in an annual RE penetration of 38% of load.
- In July, the month with the highest RE generation, average RE penetration is 63%, with an instantaneous peak of 89% of total load.

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

- Peak 1-hour net load up-ramp is 22 GW, up from 9.9 GW.
- Maximum net load valley-to-peak ramp is 34 GW on 24 March, up from a peak of 15 GW on 30 August in the No New RE scenario.
- Coal and natural gas generation decrease 85 TWh and 6.3 TWh, respectively, a drop of 33% and 48%.
- Plant load factors of coal drop from 64% to 43%; PLFs of state and private plants fall from 61% to 38%.
- 830 MW of coal capacity never starts compared to 0 MW in No New RE.
- Coal units with the highest variable costs are impacted most by increased RE availability, with PLFs of the top third most expensive units dropping to an average PLF of 15% from 42%.

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

- Peak flow increases on almost all state-to-state corridors in the Southern region, including a 72% increase in the peak transmission flow from Andhra Pradesh to Telangana.
- Interstate energy exchanges inside the Southern region fall 8% between No New RE and 100S-60W as all states decrease their reliance on imports to serve load.
- With new RE, total annual generation in the region across all generation types increases 11% to 405 TWh, enabling the region to reduce its net imports by 64%.
- Karnataka shifts from net importer to net exporter, while Tamil Nadu decreases exchanges with other states by 22%.
- Tamil Nadu experiences a 56% increase in periods when intrastate congestion affects dispatch as a net result of increased use of intrastate transmission to transfer RE and decreased exchanges with neighbors. Karnataka, on the other hand, experiences a 16% decrease in intrastate congestion.

Implications for Policy

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

- State regulatory standards for coal flexibility that meet or exceed CERC standards may offer substantial benefits to RE integration. With 55% minimum generation standards, coal plants in Andhra Pradesh, Karnataka, and Tamil Nadu are able to back down and significantly reduce curtailment regionwide. 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 enables the Southern region to access less expensive coal generation in Andhra Pradesh in response to changing net load regionwide. Average costs for the region decrease substantially if states are able to collectively commit generation based on forecasts. Another benefit of coordinated scheduling is the ability to increase imports to the region by 85% and commit less generation overall, especially in Tamil Nadu and Telangana, in response. An important aspect of this policy is in increasing access not only to inexpensive generation within the region, but also to inexpensive imports from other regions, such as the Western region, into Tamil Nadu and enabling regionwide access to this flexibility.

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.

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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15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

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Contacts

S R Narasimhan
Additional General Manager, System Operations
POSOCO
srnarasimhan@posoco.in

Monali Zeya Hazra
Regional Energy Manager and Clean Energy Specialist, Clean Energy and Environment Office
USAID/India
mhazra@usaid.gov

Jaquelin Cochran
Senior Energy Analyst
National Renewable Energy Laboratory
jaquelin.cochran@nrel.gov

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