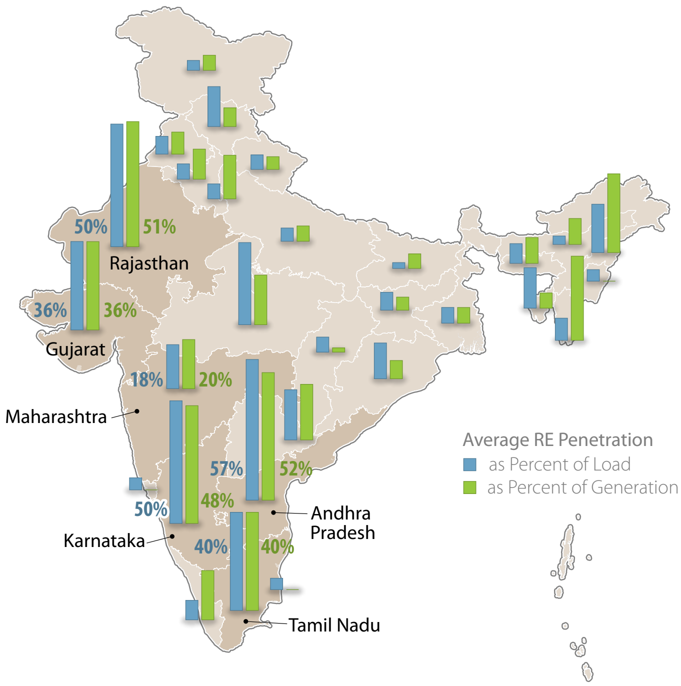
GREENING THE GRID:
Pathways to Integrate 175 Gigawatts of Renewable Energy into India's Electric Grid

About the Study

The use of renewable energy (RE) sources, primarily wind and solar generation, is poised to grow significantly within the Indian power system. The Government of India has established a target of 175 gigawatts (GW) of installed RE capacity by 2022, including 60 GW of wind and 100 GW of solar, up from 29 GW wind and 9 GW solar at the beginning of 2017. Thanks to advanced weather and power system modeling made for this project, the study team is able to explore operational impacts of meeting India's RE targets and identify actions that may be favorable for integration.

Our primary tool is a detailed production cost model, which simulates optimal scheduling and dispatch of available generation in a future year (2022) by minimizing total production costs subject to physical, operational, and market constraints. We use this model to identify how the India power system is balanced every 15 minutes, the same dispatch interval used by power system operators. The results can be used to inform policy and regulatory decisions that support system flexibility and RE investment.



Annual RE penetration exceeds 50% of load in 3 states

KEY FINDINGS:
How India's Power System Could Operate with 100 GW Solar and 60 GW Wind

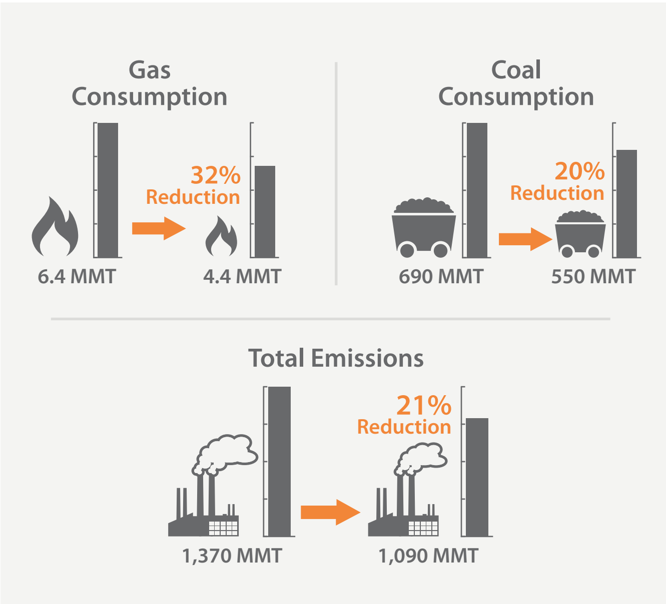
Power system balancing with 100 GW of solar and 60 GW of wind is achievable at 15-minute operational timescales with minimal RE curtailment. This RE capacity generates 370 terawatt hours (TWh) annually, a 22% share of total electricity consumption in India, reaching a nationwide instantaneous peak of 54%. Annual RE curtailment (assuming sufficient in-state transmission) is 1.4%, consistent with experiences in other countries with this level of RE penetration.

Fuel requirements for coal and gas fall 20% and 32%, respectively, and CO_2 emissions fall 21% (280 million tonnes) in 100S-60W compared to a No New RE scenario. As a result, plant load factors for coal drop from 63% to 50% with nearly 20 GW that is never economical to start.

Changes to operational practice can reduce the cost of operating the power system and reduce RE curtailment, but are not essential for 160 GW RE integration. Scheduling and dispatch that is optimized at the regional, rather than state level can support more efficient operations of thermal plants and reduce annual operating costs by 2.8%, or INR 6300 crore[1] (approximately USD 980 million).[2] In addition to improving access to least-cost generation, coordination between states helps reduce the number of coal plants at part load, providing

1.Crore, a widely used term in India, equals 10 million.
2.Exchange rate in late June 2017 was INR 64.5 to USD 1.

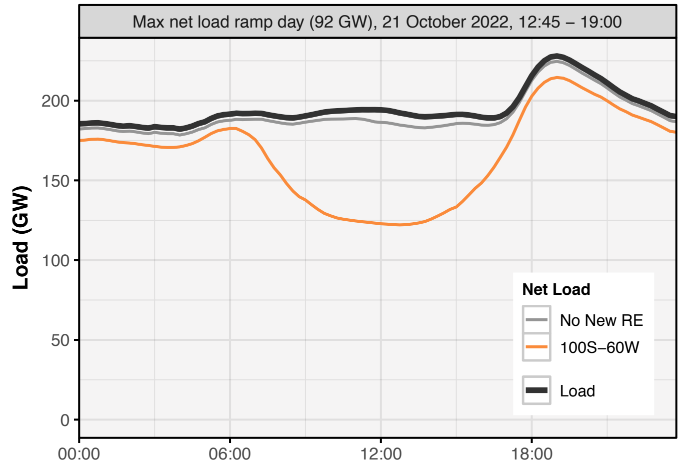
greater operational range to the remaining committed coal plants to lower generation output when RE generation is high. National coordination provides even further cost savings (3.5% savings) and reduced RE curtailment (to 0.9%).



Fuel consumption reduction of 20% coal, 32% gas compared to the No New RE scenario. Total CO_2 emissions reduction of 21%

Reducing minimum generation levels of large thermal plants is the biggest driver to reducing RE curtailment. Changing minimum generation levels of all coal plants, from 70% today to 55% of rated capacity (consistent with the CERC regulations) reduces RE curtailment from 3.5% to 1.4% and annual operating cost by 0.9%, or INR 2000 crore. Reducing minimum generation levels further, to 40%, reduces RE curtailment to 0.76%, with negligible decreases to annual operating costs.[3] If only centrally owned plants achieve 55% minimum generation levels but state-controlled plants maintain minimum generation levels of 70%, RE curtailment is 2.4%.

The peak systemwide 1-hour up-ramp increases 27% compared to a system with no new renewables, to almost 32 GW up from 25 GW. This ramp rate can be met if all generating stations exploit their inherent ramping capability. Aggregated nationally, for 56 hours of the year, system-wide up-ramps exceed 25 GW/hour, greater than any ramp requirement in the No New RE scenario, and peak at almost 32 GW/hour. The current generation fleet is shown to successfully respond to these ramp events within our operating assumptions. We found no significant change in either production cost or RE curtailment when coal generation ramp rates were made less flexible in the simulations, although



Load and net load on the day with the maximum net load ramp (92 GW over 6 hours)

this study assumes a similar load shape for 2022 as prevailing today. A significant change in load shape could affect the net load ramp rate. Five-minute scheduling and dispatch has been demonstrated elsewhere to better handle ramping, if required at a later stage.

A copper plate sensitivity delivers 4.7% savings and 0.13% RE curtailment. Our "copper plate" represents a transmission system with no constraints and operations with no barriers to scheduling. Though not a physically plausible scenario, this scenario provides insights into the maximum achievable savings if all transmission and market constraints could be relaxed. Such a scenario reduces RE curtailment to 0.13% and production costs by 4.7%. In comparison, scheduling and dispatch optimized at the regional level and with transmission constraints delivers over half of these savings. Nationally coordinated dispatch combined with an additional 25% interregional transmission capacity delivers 84% of the savings compared to the idealized copper plate.

Batteries insignificantly impact emissions and total cost of generation. Batteries do reduce curtailment (from 1.4% to 1.1%); however, the value of this curtailment is offset by the batteries' efficiency losses during operation. In the 100S-60W scenario, 2.5 GW of batteries (75% efficient) reduce RE curtailment by 1.2 TWh annually but lose 2.0 TWh annually due to inefficiencies. Also, there is insignificant impact on the total cost of generation because the overall generation mix changes little. Batteries could be economically desirable for RE integration for grid services that are outside the scope of the study (e.g., frequency regulation, capacity value, local transmission congestion).

3. In this report, changes to production costs that are less than 0.5% are considered negligible.

Retiring 46 GW of coal (20% of installed coal capacity) does not adversely affect system flexibility, assuming adequate in-state transmission. Retiring coal plants that operate less than 15% of their capacity annually (205 generation units, totaling 46 GW in capacity) has almost no effect on system operations.

Summary: Power system balancing with 100 GW of solar and 60 GW of wind is achievable with minimal integration challenges, bringing benefits of reduced fuel consumption and emissions. Meeting existing regulatory targets for coal flexibility, enlarging geographic and electrical balancing areas, expanding transmission in strategic locations, and planning for future flexibility can enable efficient and reliable operation of the power system now and in the future.

KEY FINDINGS: Different Pathways to Meeting RE Targets; Looking Beyond 2022

A wind-dominated system achieves higher RE penetration rates and requires less thermal fleet flexibility. Compared to the official RE targets, a scenario with more wind (100 GW wind, 60 GW solar), helps achieve a higher annual RE penetration rate (26% compared to 22%, due to wind's higher capacity factors), reduces CO_2 emissions an additional 6.1%, and has less RE curtailment, 1.0% compared to 1.4%. Because of its relatively less variable net load profile, the higher wind scenario creates fewer conditions requiring thermal plant flexibility.

A 250 GW RE system could achieve India's Nationally Determined Contribution targets, but 16% annual RE curtailment in the Southern region would likely signal the need for modified strategies. To identify a more viable pathway toward 250 GW, additional studies can evaluate the trade-off among increasing system flexibility versus locating more of the RE capacity in other regions.

Potential Planning and Policy Actions that Can Support RE Integration

1. Coordinate RE generation and transmission at the state level to ensure sufficient in-state transmission.

2. Create regulatory or policy guidelines to support institutionalization of cost-optimized capacity expansion planning. Create and maintain a nationwide model that helps optimize generation and transmission buildouts, which can then be used to inform investment decisions and RE policies.

3. Evaluate options for enhanced coordination of scheduling and dispatch between states and regions.

RE INTEGRATION STRATEGIES

100 GW SOLAR 60 GW WIND

NORMAL OPERATIONS	COORDINATED SCHEDULING AND DISPATCH		COAL PLANT FLEXIBILITY		
STATE-LEVEL DISPATCH, 55% MINIMUM GENERATION	REGIONAL	NATIONAL	LOWER MINIMUM PLANT GENERATION (40% of capacity)	HIGHER MINIMUM PLANT GENERATION (70% of capacity)	LOWER MINIMUM PLANT GENERATION (40% of capacity) WITH REGIONAL BALANCING AREA COORDINATION
230,000 INR Crore Annual Production Cost	2.8% Savings annually	3.5% Savings annually	Negligible Savings annually	0.90% Increased cost annually	3.3% Savings annually
1.4% Renewable energy curtailment	1.3% Renewable energy curtailment	0.89% Renewable energy curtailment	0.76% Renewable energy curtailment	3.5% Renewable energy curtailment	0.73% Renewable energy curtailment

Impact of RE integration strategies on production costs and RE curtailment

4. Establish at central and state levels comprehensive regulations regarding flexibility of conventional generators, including minimum generation levels, ramp rates, and minimum up and down times.

5. Develop a new tariff structure that moves away from focusing on energy delivery. Agreements can specify various performance criteria, such as ramping, specified start-up or shut-down times, minimum generation levels, along with notification times and performance objectives that achieve flexibility goals.

6. Revise policy/regulatory-level guidelines to utilize the full capability of hydro and pumped hydro stations. Suitable incentive mechanisms can encourage operation of hydro and pumped hydro depending upon system requirements.

7. Use the regulatory platform to require merit order dispatch based on production costs; supplementary software may be required to identify economic scheduling and dispatch that considers the combined effects of conventional and renewable variable costs, transmission congestion and losses, among other factors.

8. Create model PPAs for RE that move away from must-run status and employ alternative approaches to limit financial risks, such as annual caps on curtailed hours.

9. Achieving more ambitious RE levels will benefit from detailed, model-based planning, including both capacity expansion and production cost modeling. Regulatory guidelines may be issued to make it mandatory for stakeholders to provide data required to perform such studies.

10. Equip all states with latest and state-of-the-art load forecasting facilities. In addition, equip RE-rich states with state-of-the-art RE forecasting tools. Further, build capacity of all system operators in this regard so that in-house capability is developed to create and customize such tools in the future.

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 the U.S. Agency for International Development (USAID), and includes collaboration with World Bank (ESMAP) 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), National Renewable Energy Laboratory, and Lawrence Berkeley National Laboratory, and a broader modeling team drawn from Central Electricity Authority, POWERGRID (the national 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:

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