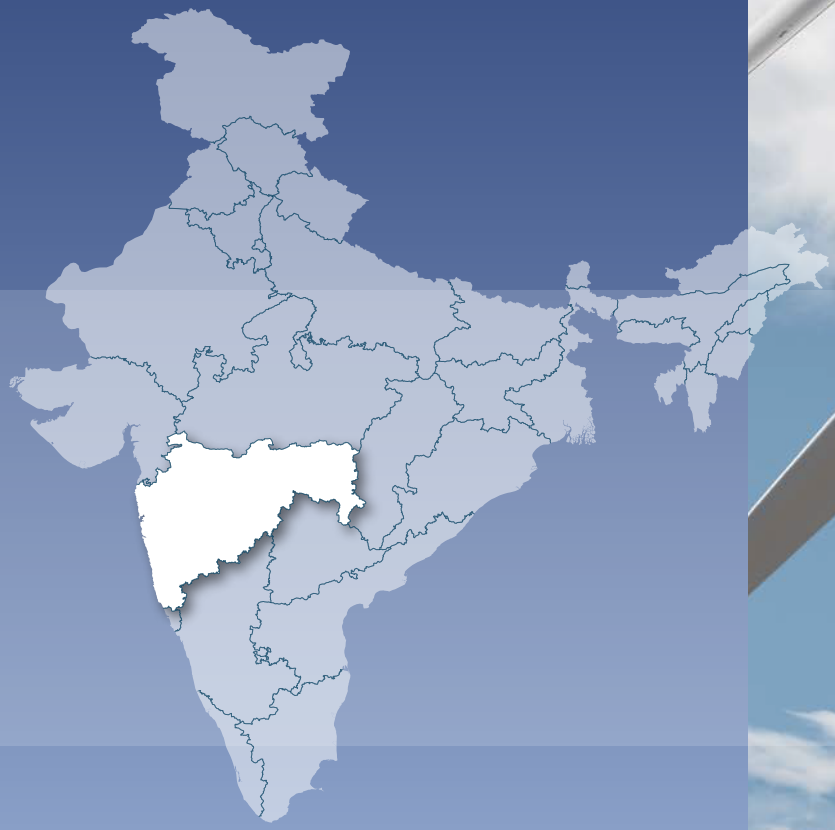
Greening the Grid



Maharashtra

Pathways to Integrate 175 Gigawatts of Renewable Energy into India's Electric Grid

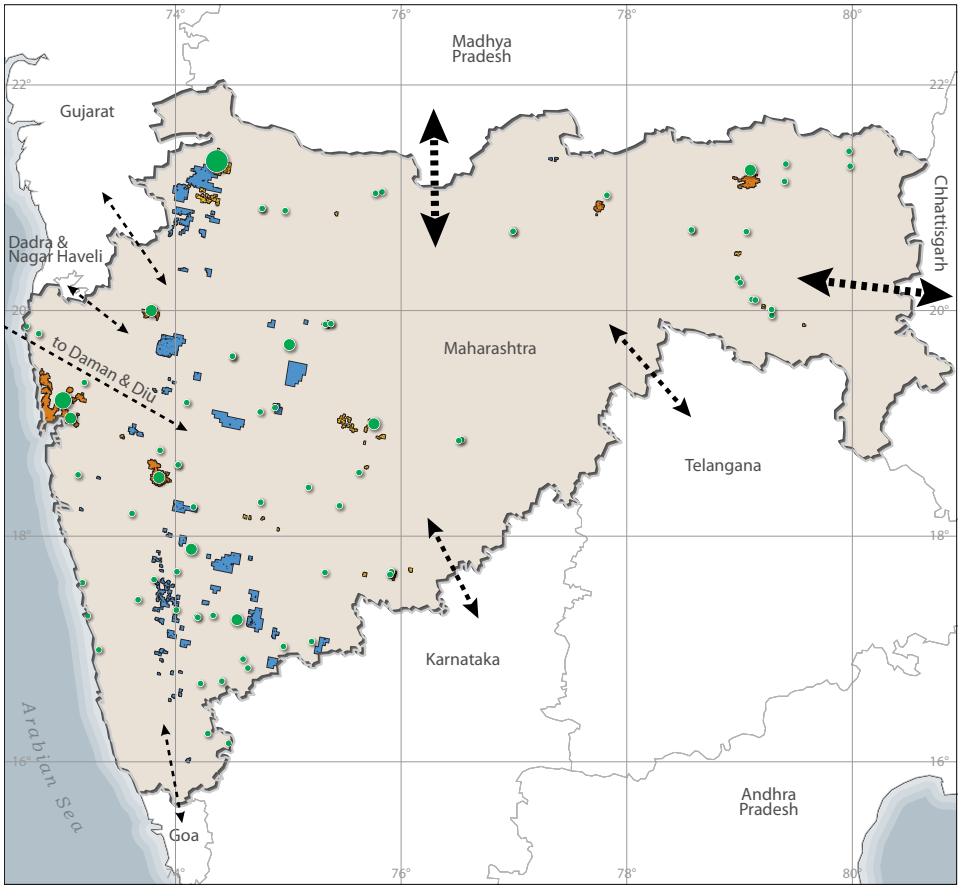
State-specific results from Volume II, which includes all of India. The full reports include detailed explanations of modeling assumptions, results, and policy conclusions.

www.nrel.gov/india-grid-integration/

NREL/TP-6A20-70951

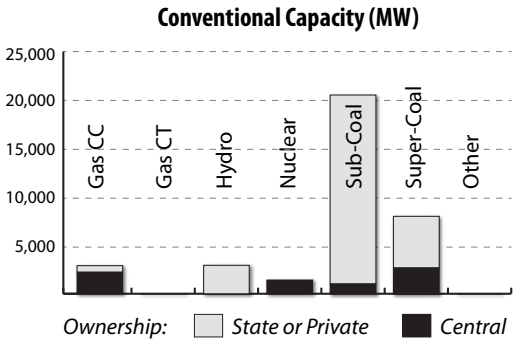
Assumptions About Infrastructure, Demand, and Resource Availability in 2022

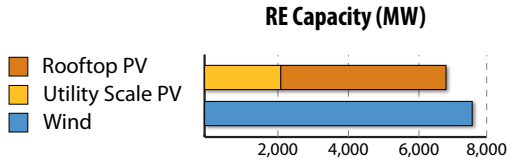
Assumptions about RE and conventional generation and transmission in Maharashtra in 2022

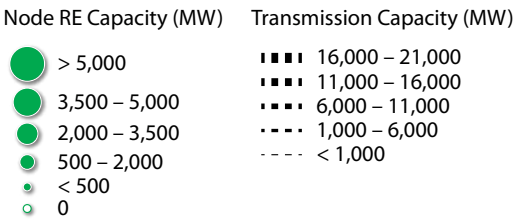


NREL and LBNL selected RE sites based on the methodology explained in Volume 1 of this report, which is available at www.nrel.gov/docs/fy17osti/68530.pdf.

Rooftop PV has been clubbed to the nearest transmission node.





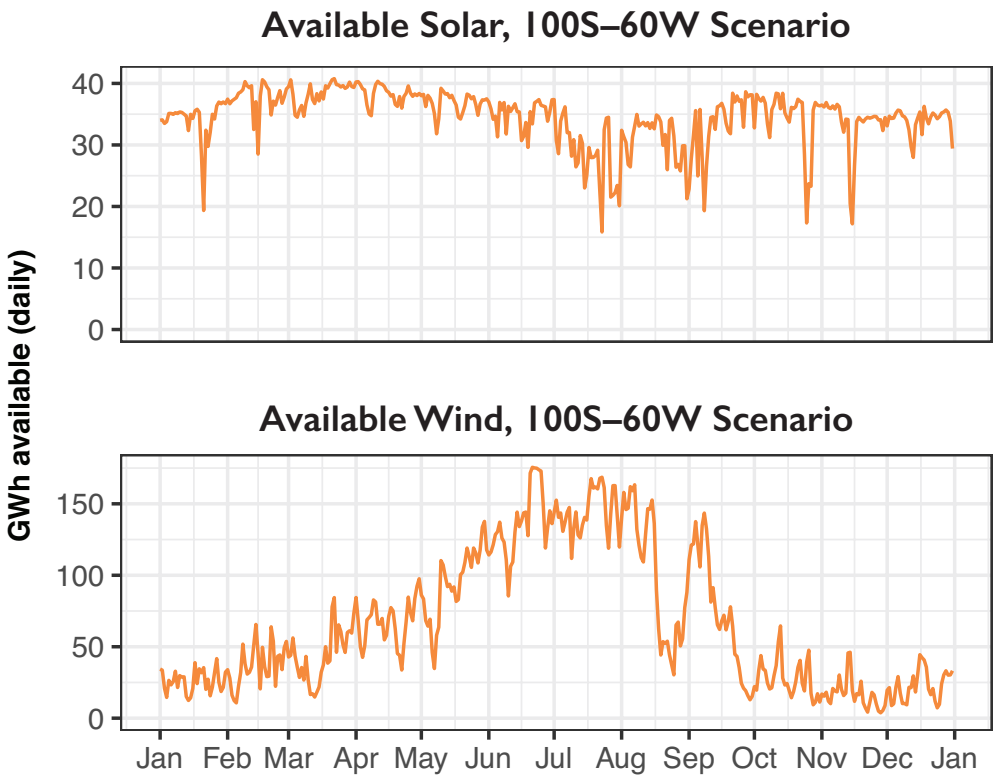


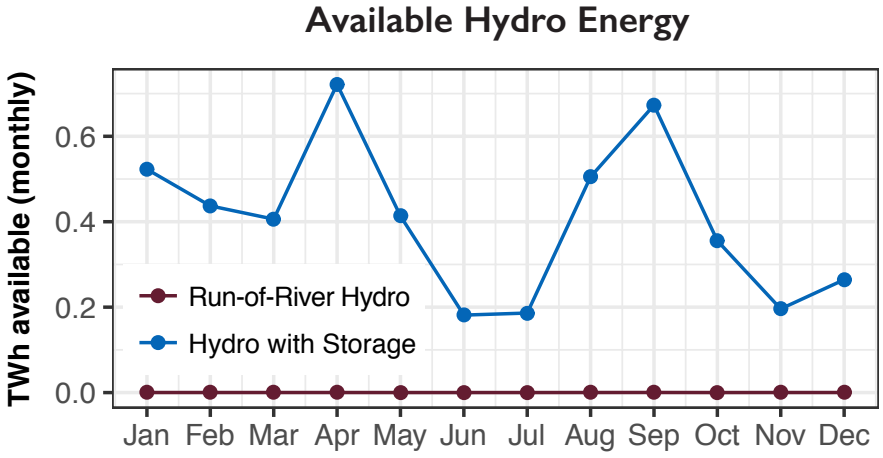
Peak load (GW)	34
Total annual load (TWh)	420
Installed non-RE capacity (GW)	35
Installed RE capacity (GW)	14
Total import/export capacity (GW)	61

Maharastrha has 41 tie-lines connecting it to other states in this model.

Maharashtra Resource Availability in 2022

Available wind, solar, and hydro energy throughout the year in Maharashtra





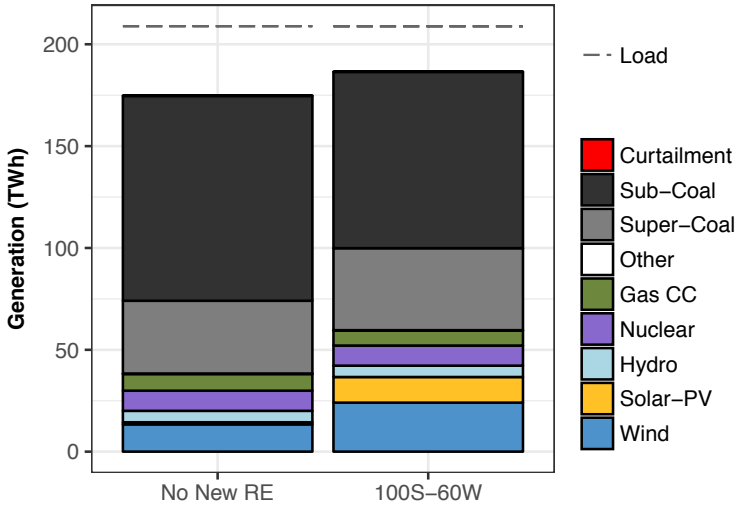
Note: Y-axis is different for each resource

Daily solar energy is relatively consistent throughout the year, while wind energy varies seasonally.

Operation in Maharashtra with Higher Levels of RE: RE Penetration in 2022

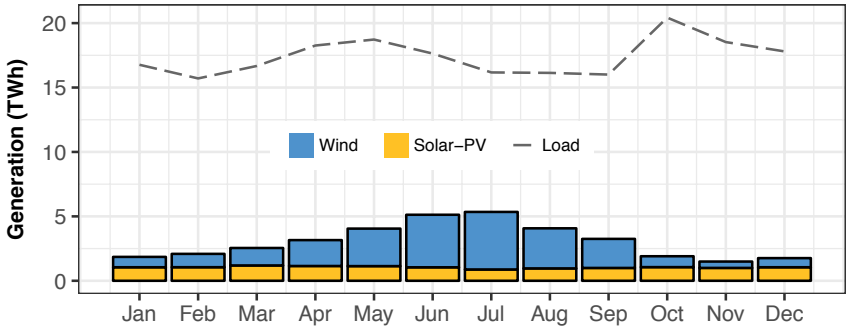
Increased amounts of RE available in Maharashtra change Maharashtra's generation mix and therefore the operation of the entire fleet.

Annual energy generation in Maharashtra



14 GW of wind and solar power generates 37 TWh annually.

Monthly RE generation and load in Maharashtra in the 100S-60W scenario



Wind and solar produce 20% of total generation in Maharashtra and meet 17% of load.

RE penetration by load and generation

	100S-60W
Percent time RE is over 50% of load	0.80
Peak RE as a % of load	60
Percent time RE is over 50% of generation	1.7
Peak RE as a % of generation	61

Coal generation falls by 6.9% and gas by 10% between No New RE and 100S-60W.

Operation in Maharashtra with Higher Levels of RE: Imports and Exports

Increased RE generation inside and outside of Maharashtra affects flows with surrounding states.

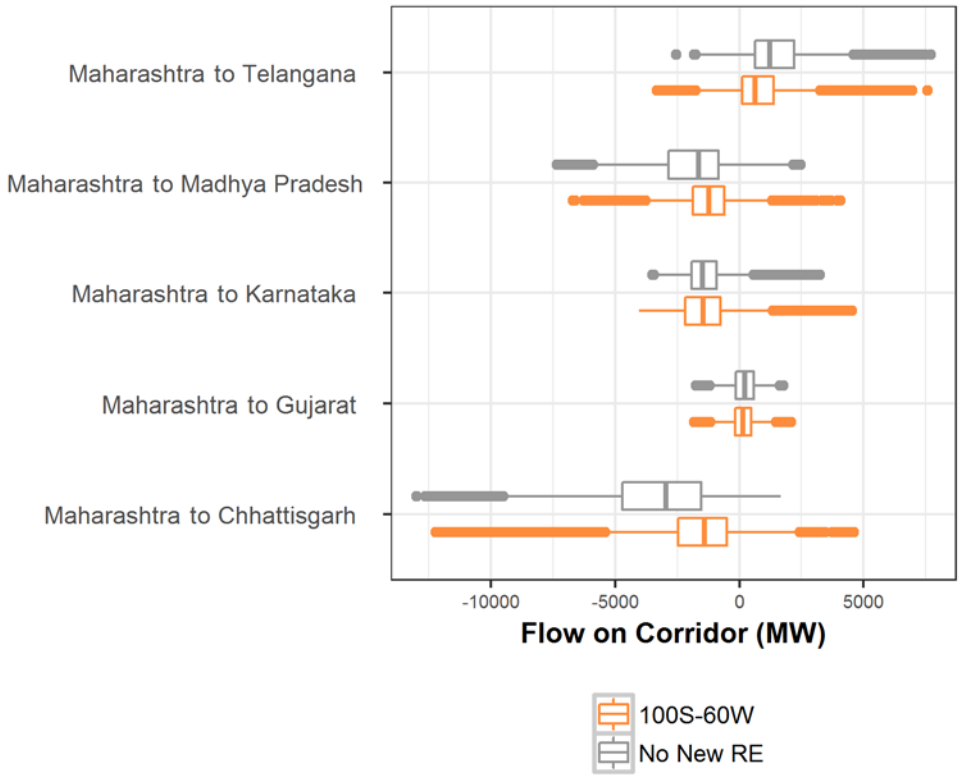
Maharashtra's imports and exports both fall in the 100S-60W scenario because all states with RE rely more on local generation to serve load. Maharashtra imports less thermal generation from Chhattisgarh and Madhya Pradesh and reduces its exports to Telangana.

Imports fall by **27%** annually

Exports fall by **19%** annually

SCENARIO	NET EXPORTS (TWh)	
No New RE	-33	net importer
100S-60W	-22	net importer

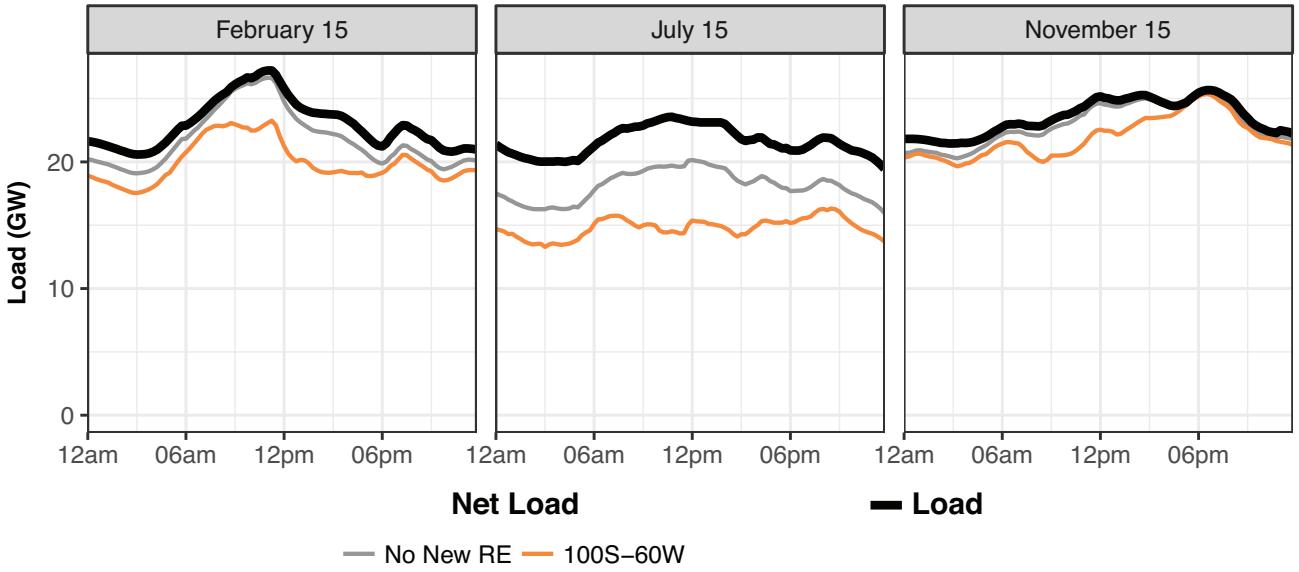
Distribution of flows across state-to-state corridors



Operation in Maharashtra with Higher Levels of RE: Rest of the Fleet

The addition of RE in Maharashtra changes net load, which is the load that is not met by RE and therefore must be met by conventional generation. Due to changes in net load, hydro and thermal plants operate differently in higher RE scenarios.

Example days of load and net load in Maharashtra

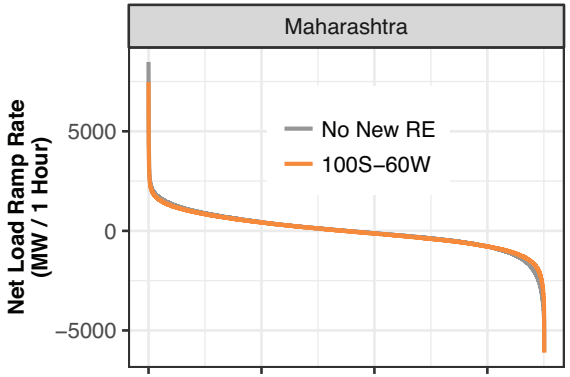


Because of its large size and high wind capacity relative to solar in the 100S-60W scenario, Maharashtra experiences less severe daytime net load ramps than other high-RE states. Its load often peaks midday, as on 15 February and 15 July, during which solar generation smooths the net load profile.

Peak 1-hour net load up-ramp in the **100S-60W scenario is 7.5 GW**, down from **8.5 GW in the No New RE scenario.**

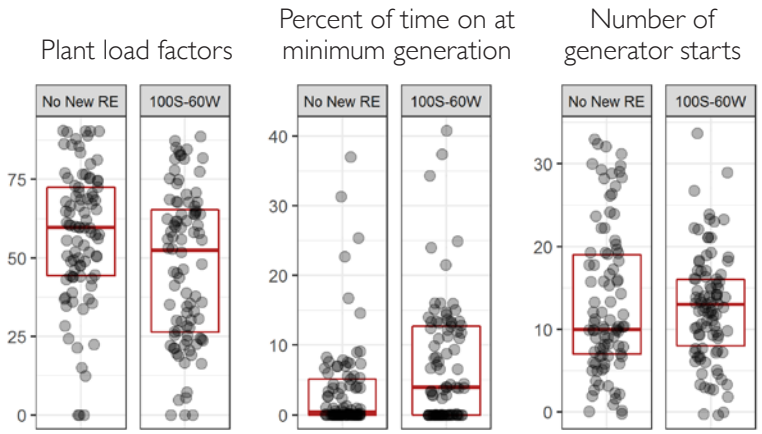
Maximum net load valley-to-peak ramp is **11 GW in the 100S-60W scenario**, down from **12 GW in the No New RE scenario.**

Hourly net load ramps for all periods of the year, ordered by magnitude



Changes to Maharashtra's Coal Fleet Operations

Operational impacts to coal



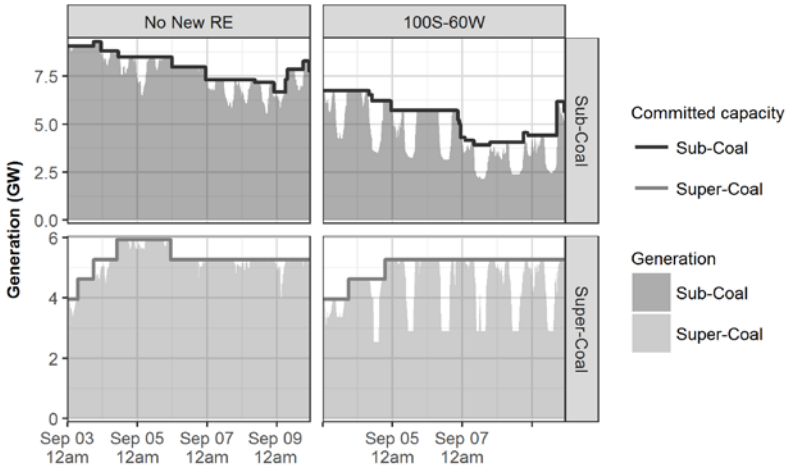
Coal plant load factors (PLFs) are lower in the 100S-60W scenario due to more frequent cycling and operation at minimum generation levels.

While coal PLFs are lower fleetwide in 100S-60W, the most expensive generators experience the greatest drop in PLF.

Average PLF of coal generators in Maharashtra, disaggregated by variable cost

RELATIVE VARIABLE COST	NO NEW RE	100S-60W
Lower 1/3	63	68
Mid 1/3	44	33
Higher 1/3	55	30
Fleetwide	56	52

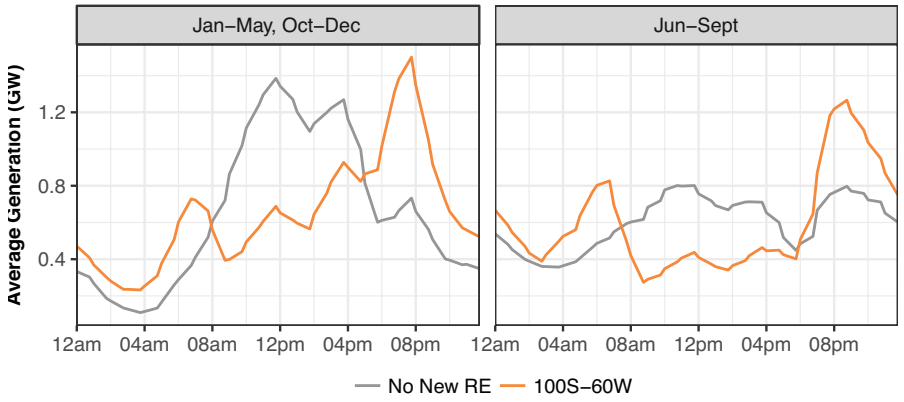
One week of coal operation in Maharashtra



The coal fleet is turned off more and its output varies daily due to midday availability of solar power in the 100S-60W scenario.

Changes to Maharashtra's Hydro Fleet Operations

Average day of hydro in Maharashtra by season



Minimum generation levels during the monsoon season hinder the ability of hydro to shift generation to net load peaks as it does more fully in the months outside of the monsoon.

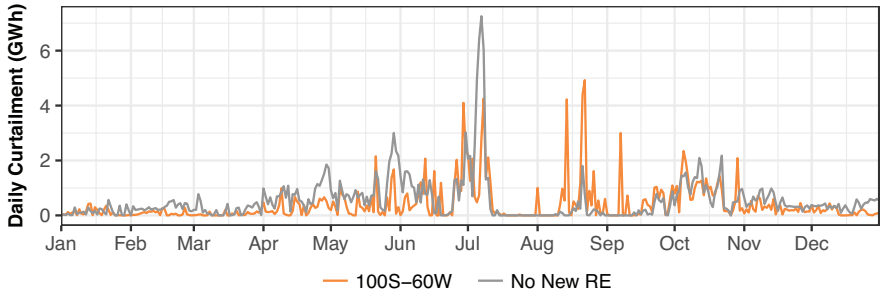
Hydro plants follow a more pronounced two-peak generation profile due to availability of solar power during the middle of the day.

How Well Is RE Integrated?
Curtailment and Operational Snapshots

Curtailment levels indicate how efficiently RE is integrated. Large amounts of curtailment signal inflexibility in the system, preventing grid operators from being able to take full advantage of the available renewable resources.

0.4% of wind and solar is curtailed annually.

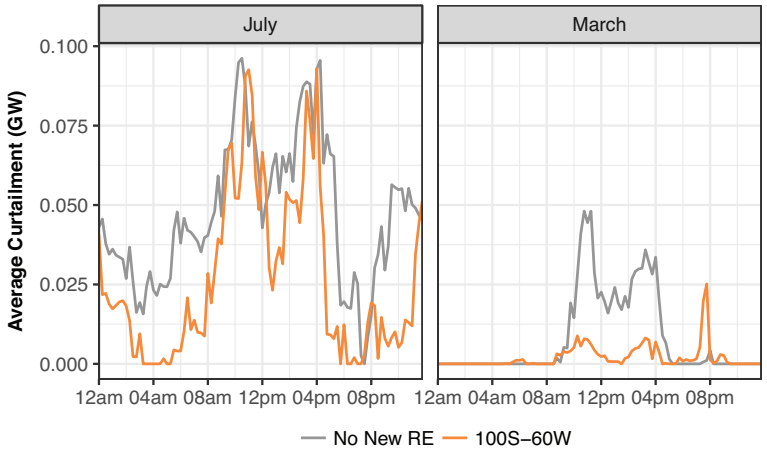
Total daily curtailment throughout the year in Maharashtra



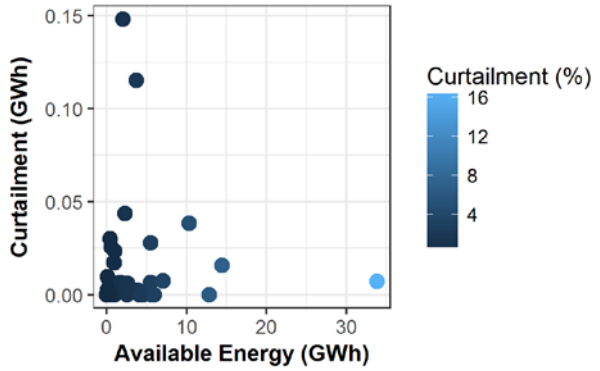
Maharashtra experiences the lowest RE curtailment of any state with significant RE capacity. Its thermal fleet is fully constrained only 0.2% of the year in the 100S-60W scenario, indicating that the RE curtailment that does happen is caused primarily by transmission congestion and trade barriers.

Almost all of RE curtailment occurs in 9.9% of periods of the year.

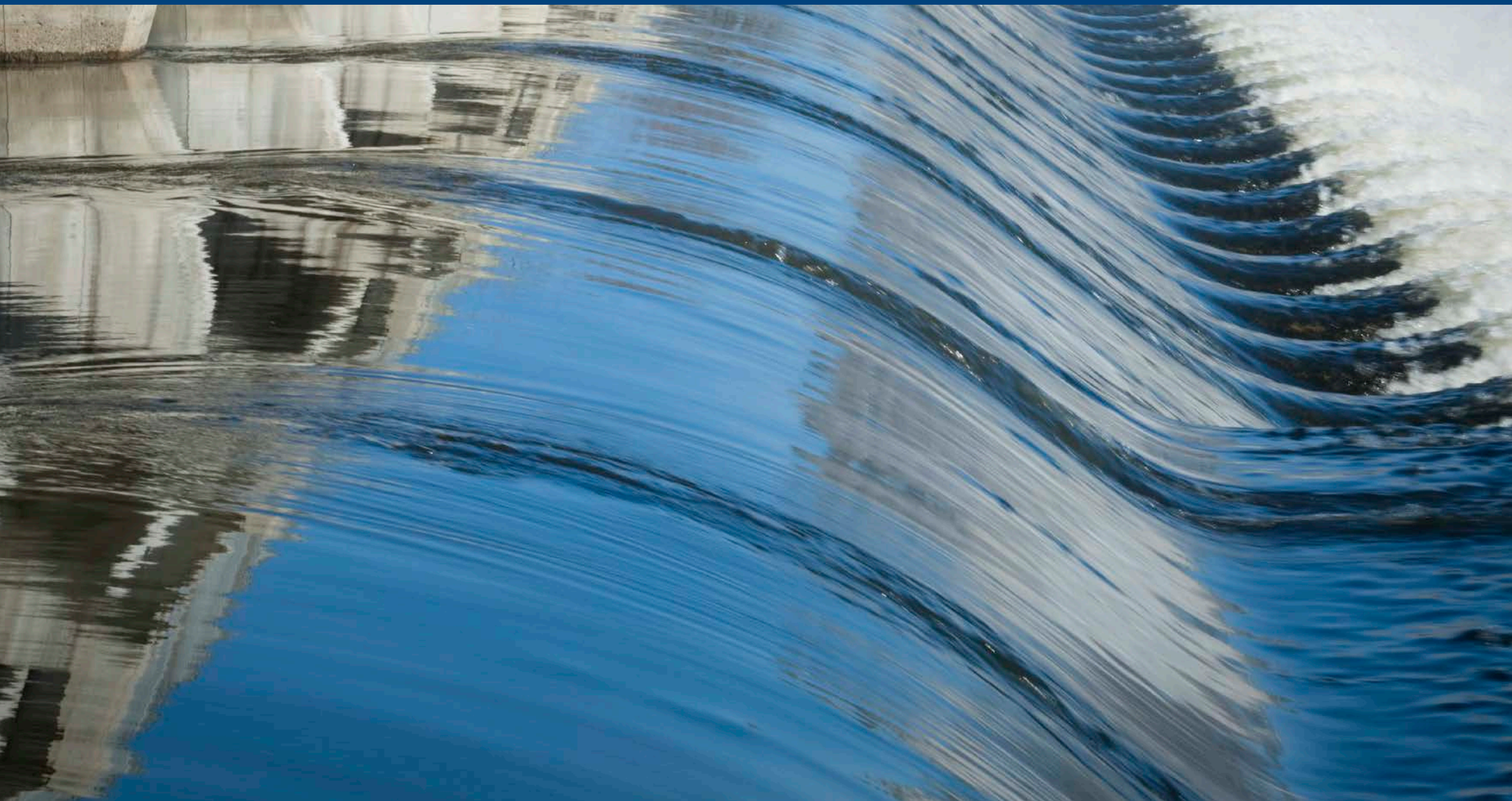
Average daily curtailment in March and July in Maharashtra



RE curtailment as a percent of available energy by substation (each dot represents a substation)



Examples of Dispatch During Interesting Periods in Maharashtra

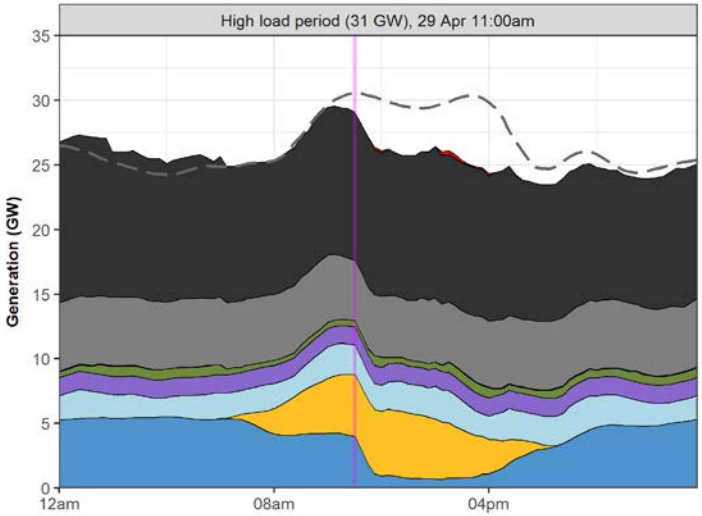


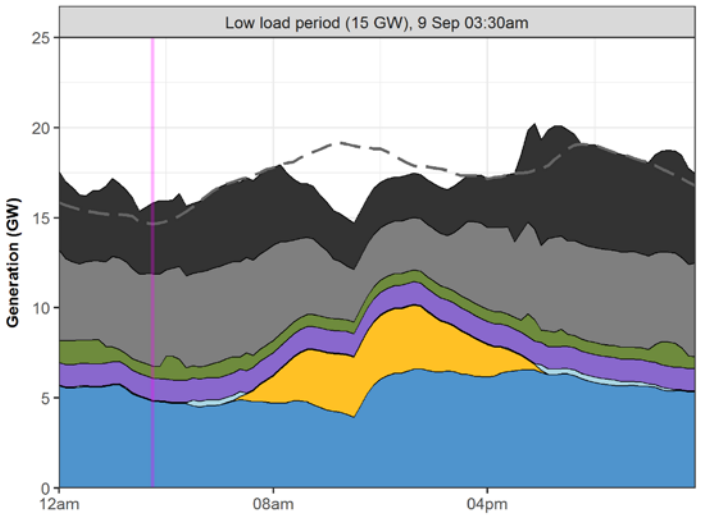
The following pages show dispatch in Maharashtra during several interesting periods throughout 2022. The vertical magenta line highlights the dispatch interval associated with the figure title.

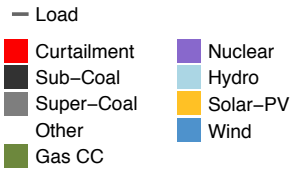
High load period: Generation, load, and interchange (values in GW unless otherwise specified)

29 April 11:00 am

LOAD	CURTAILMENT	HYDRO	NUCLEAR	OTHER	COAL	GAS	RE	NET IMPORTS	RE PENETRATION (%)
30.6	0	2.3	1.4	0	16.1	0.5	8.8	1.5	29







Low load period: Generation, load, and interchange (values in GW unless otherwise specified)

9 September 3:30 am

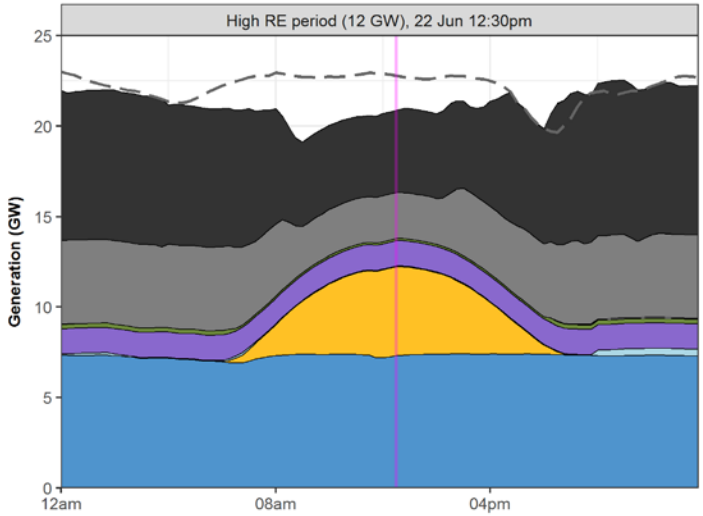
LOAD	CURTAILMENT	HYDRO	NUCLEAR	OTHER	COAL	GAS	RE	NET EXPORTS	RE PENETRATION (%)
14.6	0	0	1.2	0	9.1	0.7	4.8	1.2	33

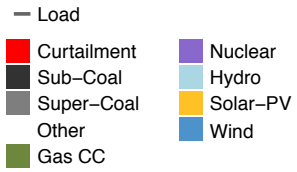
Example Dispatch Days

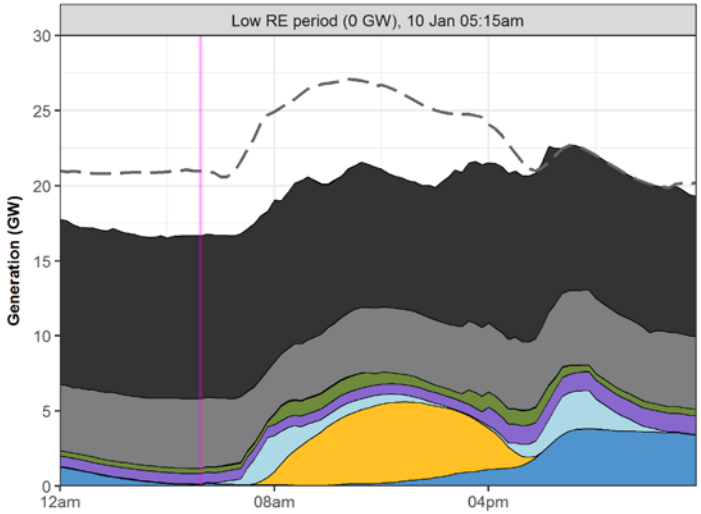
High RE period: Generation, load, and interchange (values in GW unless otherwise specified)

22 June 12:30 pm

LOAD	CURTAILMENT	HYDRO	NUCLEAR	OTHER	COAL	GAS	RE	NET IMPORTS	RE PENETRATION (%)
22.8	0	0	1.4	0	7.1	0.1	12.2	1.9	54







Low RE period: Generation, load, and interchange (values in GW unless otherwise specified)

10 January 5:15 am

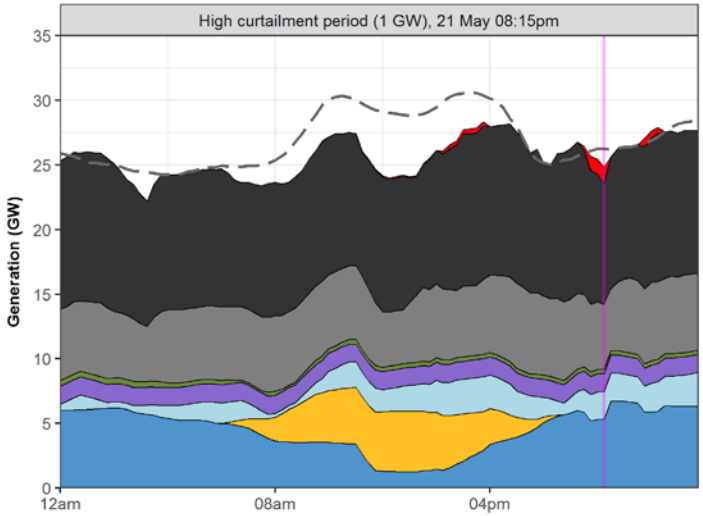
LOAD	CURTAILMENT	HYDRO	NUCLEAR	OTHER	COAL	GAS	RE	NET IMPORTS	RE PENETRATION (%)
21	0	0	0.7	0	15.5	0.3	0.1	4.3	0.4

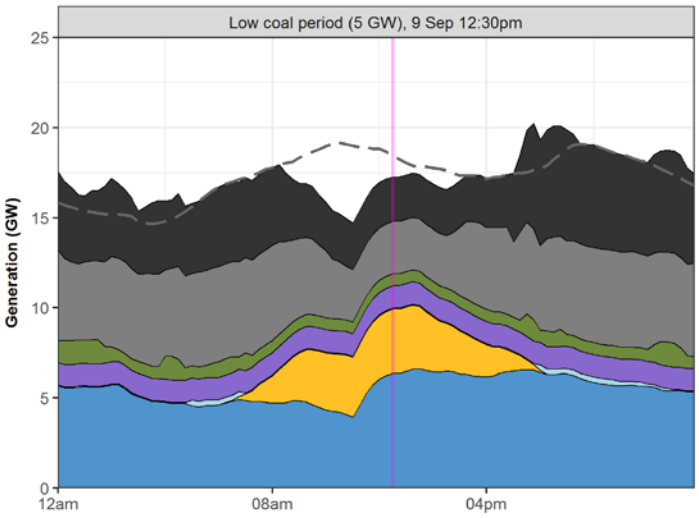
Example Dispatch Days

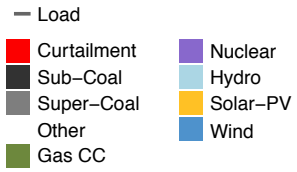
High curtailment period: Generation, load, and interchange (values in GW unless otherwise specified)

21 May 8:15 pm

LOAD	CURTAILMENT	HYDRO	NUCLEAR	OTHER	COAL	GAS	RE	NET IMPORTS	RE PENETRATION (%)
26.2	1.3	2.1	1.4	0	14.4	0.3	5.3	2.7	20







Low coal period: Generation, load, and interchange (values in GW unless otherwise specified)

9 September 12:30 pm

LOAD	CURTAILMENT	HYDRO	NUCLEAR	OTHER	COAL	GAS	RE	NET IMPORTS	RE PENETRATION (%)
18.5	0	0	1.2	0	5.4	0.7	9.9	1.2	54

Conclusions

Based on this study's assumptions about demand and installed generation and transmission capacity in Maharashtra and nationwide, Maharashtra can integrate the equivalent of 20% of its total generation in 2022 with 0.4% annual wind and solar curtailment. The RE changes the way Maharashtra's grid must operate. Compared to a 2022 system with no new RE, net exports rise by 33% annually, and the PLF of the coal fleet falls from 56% to 52%.

Maharashtra often has sufficient flexible thermal capacity online to facilitate RE generation with minimal RE curtailment. However, strategies for coordination with neighboring states may benefit Maharashtra, as thermal flexibility is needed to balance changes to net load regionwide.

What can the state do to prepare for higher RE futures?

- Establish process for optimizing locations and capacities for RE and transmission; inadequate transmission has a large effect on RE curtailment in the model. This requires good information on possible areas for RE locations.
- Match or exceed CERC guidelines for coal flexibility. Reducing minimum operating levels for coal plants has the largest impact to RE curtailment among all integration strategies evaluated.
- Consider mechanisms to better coordinate scheduling and dispatch with neighbors, which can reduce production costs and allow each state to better access least-cost generation, smooth variability and uncertainty, and better access sources of system flexibility.
- Create a new tariff structure for coal that specifies performance criteria (e.g., ramping), and that addresses the value of coal as PLFs decline.
- Create model PPAs for RE that move away from must-run status and employ alternative approaches to limit financial risks.
- Use PPAs to require RE generators to provide grid services such as automatic generation control and operational data.
- Create policy and regulatory incentives to access the full capabilities of existing coal, hydro, and pumped storage.
- Require merit order dispatch based on system-wide production costs; supplementary software may be required.
- Improve the production cost model built for this study to address state-specific questions.
- Institute organization and staff time to maintain the model over time.
- Update power flow files to include more information related to high RE futures; conduct dynamic stability studies.
- Adopt state-of-the-art load and RE forecasting systems.
- Address integration issues at the distribution grid, including rooftop PV and utility-scale wind and solar that is connected to low voltage lines.

For a broader set of policy actions, see the executive summary for the National Study at www.nrel.gov/docs/fy17osti/68720.pdf.

Ways to use the model for state planning

You can use this model for operational and planning questions such as:

What is the effect on operations of different reserve levels?

How will changes to operations or new infrastructure affect coal cycling?

What is the impact on dispatch of changes to market designs or PPA requirements?

How will different RE growth scenarios affect fuel requirements and emissions targets?

How does a new transmission line affect scheduling and costs?

What are plant-specific impacts (PLFs, curtailment) based on different scenarios?

What are critical periods for follow-up with a power flow analysis, and what is the generation status of each plant during these periods?

What flexibility is required of the system under different future scenarios?

What technologies or systematic changes could benefit the system most?

The production cost model built for this study is ready for you to use!

Next Steps to Improve the Model for State Planning

The production cost model used in this study has been built to assess region- and nationwide trends, and lacks some of the plant-specific detail that will be more important if the model is used for planning at the state level. Further improvements are suggested for use at the state level:

Input load specific to each substation level

Current model allocates a statewide load to each substation proportionate to peak

Modify load shapes to reflect expected changes to appliance ownership and other usage patterns

Current model uses 2014 load shape, scaled up to 2022 peak demand

Revise RE locations and transmission plans as investments evolve

Current model uses best RE locations within the state based on suitable land availability; transmission plans are based on CEA's 2021–2022 PSS/E model and do not reflect anticipated changes to in-state transmission to meet new RE

Improve generator-specific parameters (e.g., variable costs, minimum up/down time, hub heights, must run status)

Current model uses generator-specific information when available, but also relies on averages (e.g., all utility PV employs fixed tracking)

Create plant-specific allocations of central generations

Current model allocates all central plant generating capacity to the host state

Allocate balancing responsibility for new RE plants to host state versus offtaker state or central entity

Current model allocates responsibility for balancing to host state

Create an equivalent but computationally simpler representation of transmission in states or regions where operations do not affect focus area

Current model includes level of detail for the country that may be unnecessary for a specific state, creating computational challenges

Appendix

Supplemental information on study assumptions

Total generation capacity in Maharashtra (GW) in the 100S-60W scenario		
	OWNERSHIP	**TOTAL CAPACITY (GW)**
Gas CC	State/Private	0.7
Gas CC	Central	2.2
Hydro	State/Private	2.9
Nuclear	Central	1.4
Other	State/Private	0.1
Sub-Coal	State/Private	19.0
Sub-Coal	Central	1.0
Super-Coal	Central	2.6
Super-Coal	State/Private	5.3
Total non-RE		35.2
Solar-PV	State/Private	6.8
Wind	State/Private	7.6
Total RE		14.4
Total capacity		**49.6**

Total capacity (surge impedance limit [SIL]) of transmission lines connecting Maharashtra to other states

**To evacuate new RE capacity, transmission was added in this study to supplement CEA plans for 2022.*

CONNECTING	VOLTAGE (kV)	NO. LINES
Maharashtra to Chhattisgarh	220	1
Maharashtra to Chhattisgarh	400	9
Maharashtra to Chhattisgarh	765	6
Maharashtra to Dadra & Nagar Haveli	400	2
Maharashtra to Daman & Diu	400	2
Maharashtra to Goa	220	2
Maharashtra to Goa	400	4
Maharashtra to Gujarat	220	4
Maharashtra to Gujarat	400	5
Maharashtra to Gujarat	765	1
Maharashtra to Karnataka	220	2
Maharashtra to Karnataka	765	4
Maharashtra to Karnataka*	400	3
Maharashtra to Madhya Pradesh	132	2
Maharashtra to Madhya Pradesh	220	1
Maharashtra to Madhya Pradesh	400	5
Maharashtra to Madhya Pradesh	765	8
Maharashtra to Telangana	400	2
Maharashtra to Telangana	765	6
Total import/export capacity		**69**

Total capacity (SIL) of transmission lines within Maharashtra

**To evacuate new RE capacity, transmission was added in this study to supplement CEA plans for 2022.*

CONNECTING	VOLTAGE (kV)	NO. LINES
Intrastate	100	54
Intrastate	132	385
Intrastate	220	436
Intrastate	765	27
Intrastate*	400	173
Total intrastate capacity		**1,075**

RE capacity by substation and type

SUBSTATION (NUMBER_NAME_VOLTAGE)	SOLAR-PV (MW)	WIND (MW)
372004_KARAD2_220	0	96
372039_AHMED2_220	0	437
372055_MIRAJ2_220	0	20
372065_ALEPHAT_220	0	303
372076_MALHRPTH_220	0	444
372077_WANKUSWD_220	1,248	1,830
372078_MUMEWADI_220	0	15
372084_BEED2_220	523	0
372110_VITA2_220	0	568
372126_BHIGWAN_220	97	15
372142_GHATNDAR_220	30	0
372160_WATHAR_220	0	761
372180_GANGAPUR_220	0	627
372181_SATARA_220	0	17
372301_ALKUD_220	0	203
372402_JATH_220	0	190
372403_KHANDAKE_220	0	247
372407_KADEGAON_220	0	138
374001_KALWA4_400	1,740	0
374002_KHARGAR_400	634	0
374006_CHNDR4_400	30	0
374008_DHULE4_400	0	76

RE capacity by substation and type

SUBSTATION (NUMBER_NAME_VOLTAGE)	SOLAR-PV (MW)	WIND (MW)
374009_KORADI-I_400	579	0
374010_BHUSAWAL-I_400	28	0
374012_PADGH4_400	145	0
374013_KOLHAPUR_400	0	71
374014_AURANGBD-I_400	37	0
374015_JEJ4_400	0	273
374016_SHOL4_400	141	0
374018_BOIS4_400	3	0
374025_NKOY4_400	0	11
374026_KOY4-4_400	0	181
374028_NGTHANE_400	0	14
374029_CHAKAN_400	78	122
374035_IEPL_400	63	0
374036_AMRAVATIIBL_400	189	15
374037_CHANDRPR-II_400	16	0
374040_SHOLAPUR-PG_400	80	0
374042_PUNE-PG-AIS_400	756	0
374045_PUNE-PG-GIS_400	40	0
374047_AURANGABD-II_400	38	19
374055_SINNARTPP_400	313	896
374090_SOLAPURSTPP_400	39	0
Total RE capacity	**6,847**	**7,589**

Annual energy generation fuel type, No New RE and 100S-60W		
	100S-60W (TWh)	**NO NEW RE (TWh)**
Gas CC	7	8
Hydro	6	6
Nuclear	10	10
Other	0	0
Solar-PV: rooftop	9	0
Solar-PV: utility scale	4	1
Sub-Coal	87	101
Super-Coal	40	36
Wind	24	13
Total Generation	186	175
Imports	55	73
Exports	33	39
RE Curtailment	0	0