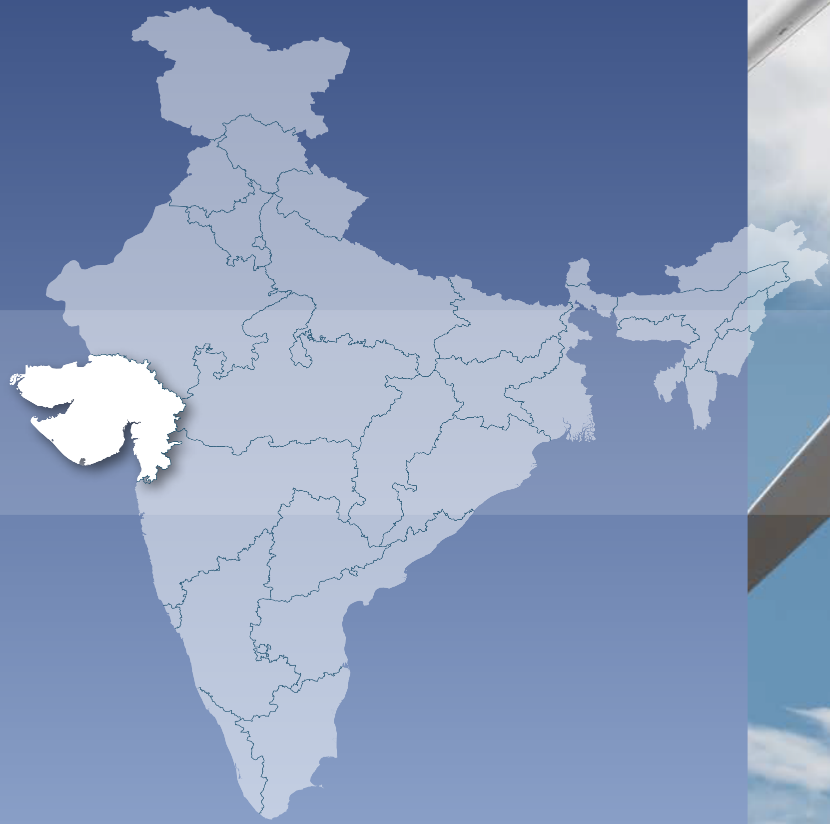
Greening the Grid

Gujarat



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

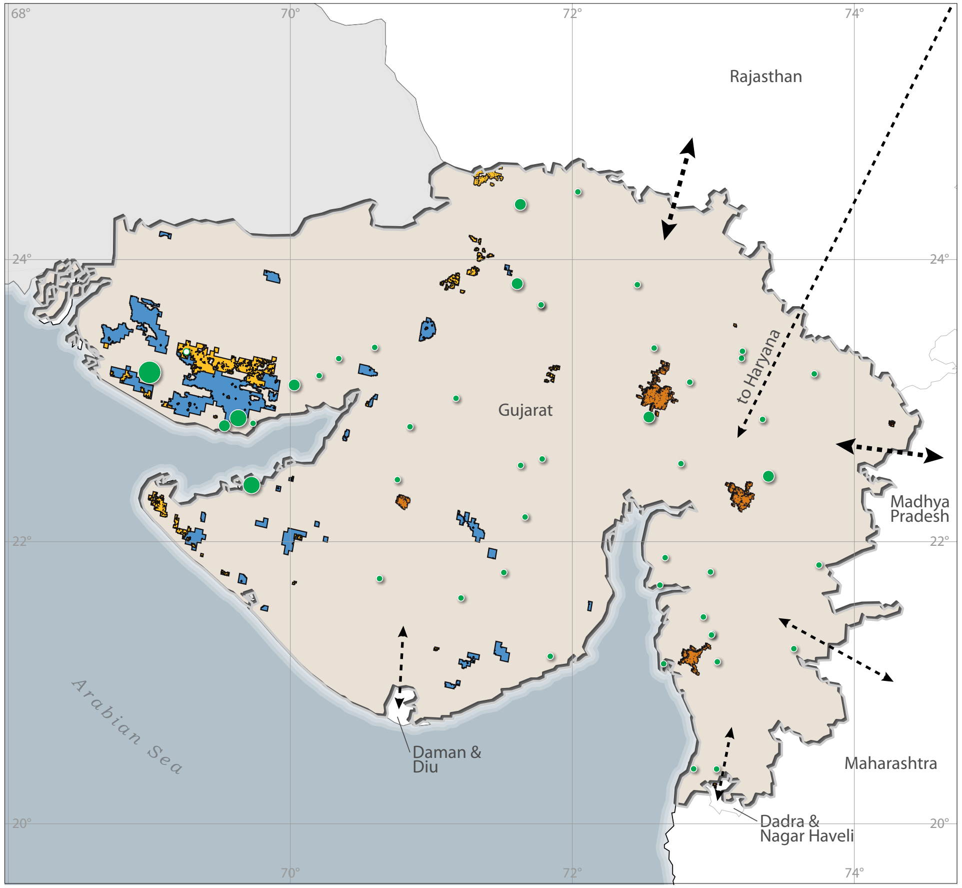
State-specific results from Volume II, which includes all of India. The full reports include detailed explanations of modeling assumptions, results, and policy conclusions.

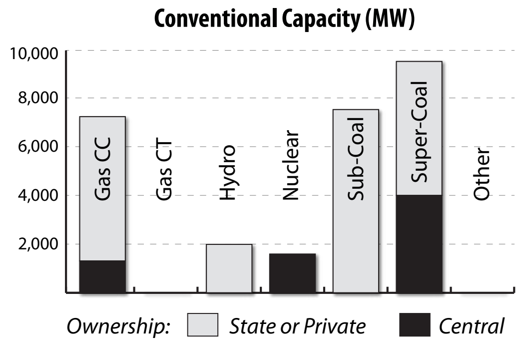
www.nrel.gov/india-grid-integration/

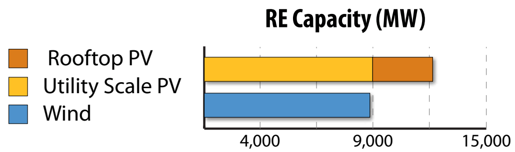
NREL/TP-6A20-70949

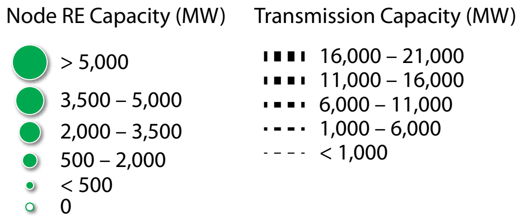
Assumptions About Infrastructure, Demand, and Resource Availability in 2022

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









Peak load (GW)	23
Annual load (TWh)	287
Installed non-RE capacity (GW)	27
Installed RE capacity (GW)	21
Total import/export capacity (GW)	25

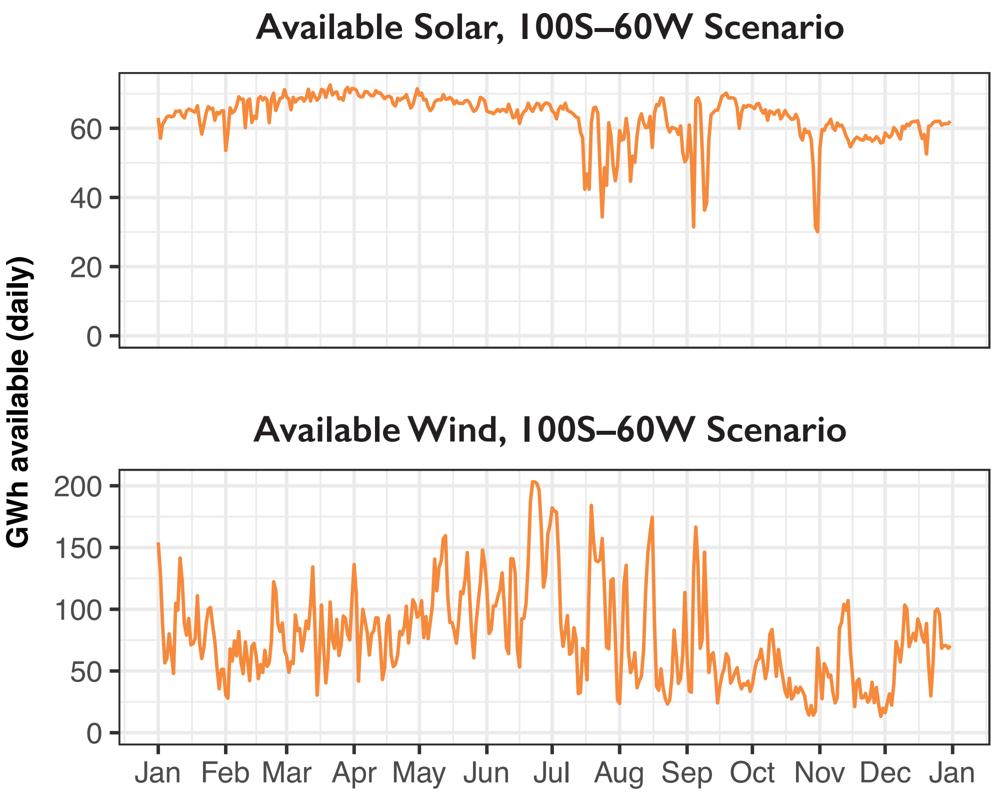
Gujarat has 28 tie-lines connecting it to other states in this model.

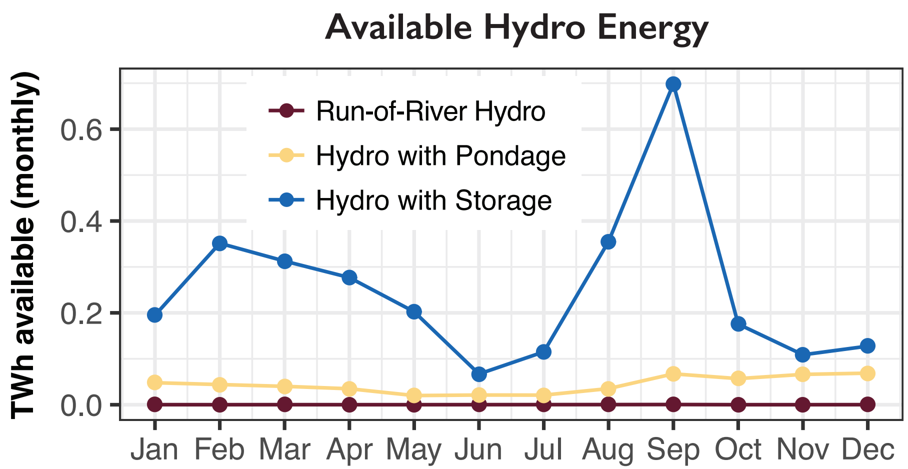
NREL and LBNL selected RE sites based on the methodology explained in Volume I of this report, which is available at www.nrel.gov/docs/fy17osti/68530.pdf.

Rooftop PV has been clubbed to the nearest transmission node.

Gujarat Resource Availability in 2022

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





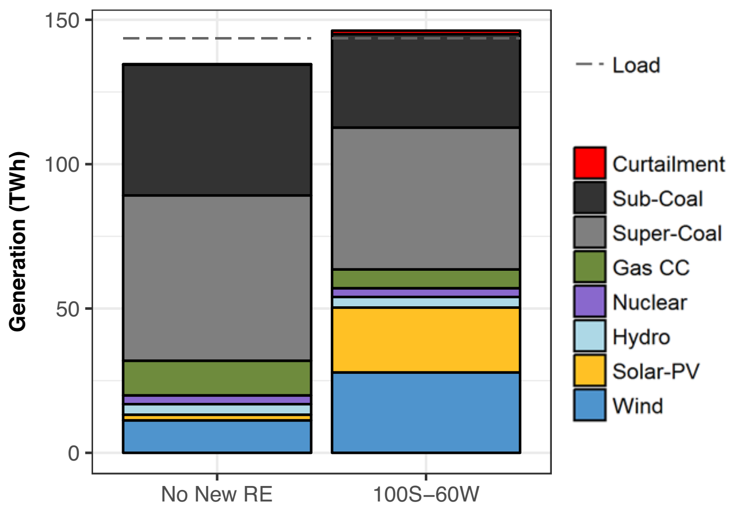
Daily solar energy is relatively consistent throughout the year while wind energy varies seasonally.

Note: Y-axis is different for each resource

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

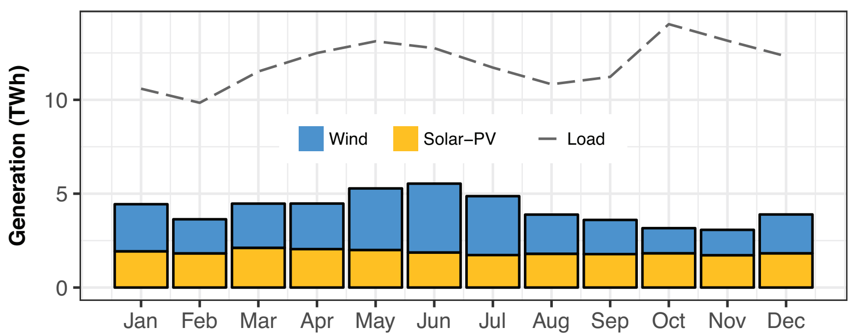
Increased amounts of RE available in Gujarat change Gujarat's generation mix and therefore the operation of the entire fleet.

Annual energy generation in Gujarat



21 GW of wind and solar power generates 50 TWh annually.

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



Wind and solar produce 35% of total generation in Gujarat and meet 35% of load.

RE penetration by load and generation

	100S-60W
Percent time RE is over 50% of load	23
Peak RE as a % of load	110
Percent time RE is over 50% of generation	19
Peak RE as a % of generation	81

Coal generation falls by 21% and gas by 46% between No New RE and 100S-60W.

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

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

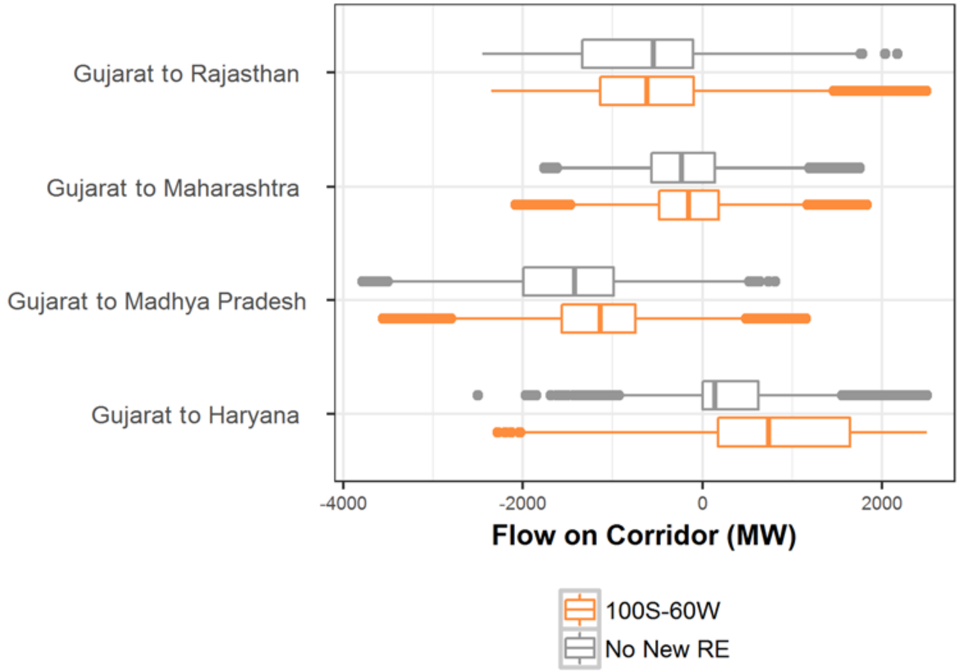
Gujarat transitions from a net importer in the No New RE scenario to net exporter in 100S-60W. This is largely driven by increased exports to Haryana, which is also associated with frequent congestion along that corridor.

Imports fall by **11%** annually

Exports rise by **44%** annually

SCENARIO	NET EXPORTS (TWh)	
No New RE	-9.1	net importer
100S-60W	1.5	net exporter

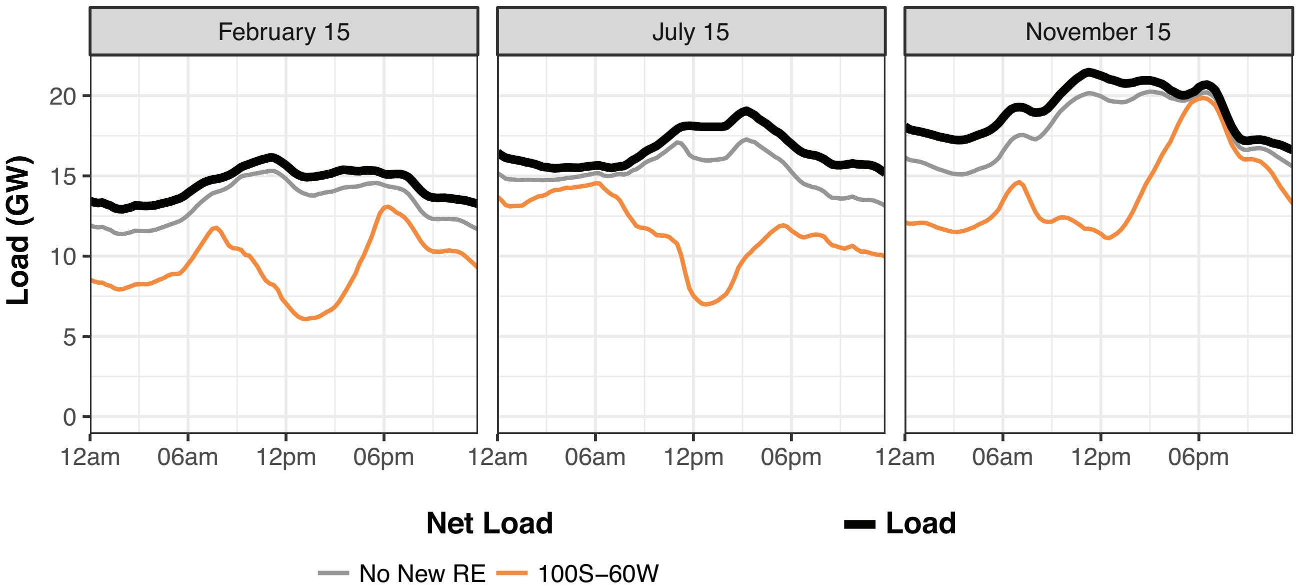
Distribution of flows across state-to-state corridors



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

The addition of RE in Gujarat 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 Gujarat

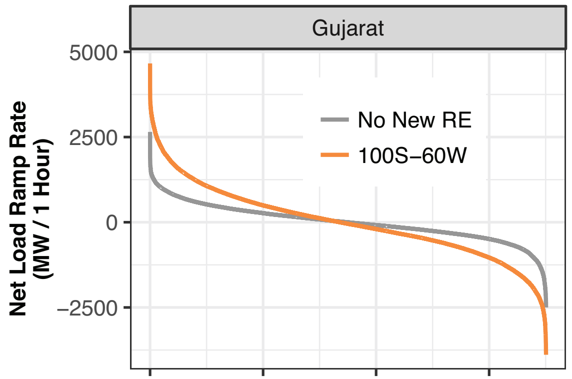


Increased daytime solar generation causes a dip in net load, which requires Gujarat to either increase net exports, turn down its thermal generators, or curtail RE.

Peak 1-hour net load up-ramp in the **100S-60W scenario is 4.7 GW**, up from **2.7 GW in the No New RE scenario.**

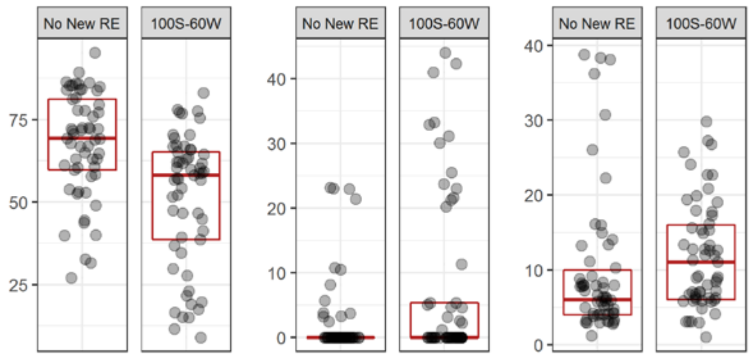
Maximum net load valley-to-peak ramp is **12 GW in the 100S-60W scenario**, up from **6.9 GW in the No New RE scenario.**

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



Changes to Gujarat's Coal Fleet Operations

Operational impacts to coal



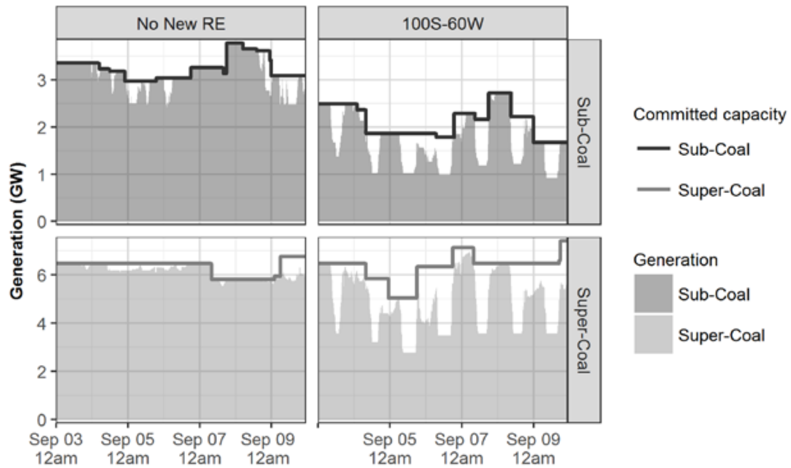
Coal plant load factors (PLFs) are lower in the 100S-60W scenario due to more frequent cycling and operation at minimum generation levels.

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 Gujarat, disaggregated by variable cost

RELATIVE VARIABLE COST	NO NEW RE	100S-60W
Lowest 1/3	67	58
Mid 1/3	76	65
Highest 1/3	59	29
Fleetwide	69	55

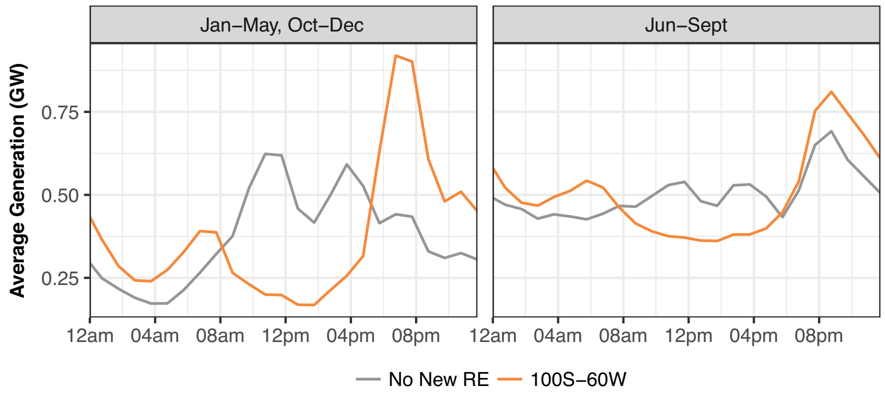
One week of coal operation in Gujarat



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 Gujarat's Hydro Fleet Operations

Average day of hydro in Gujarat by season



Minimum generating limits 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.

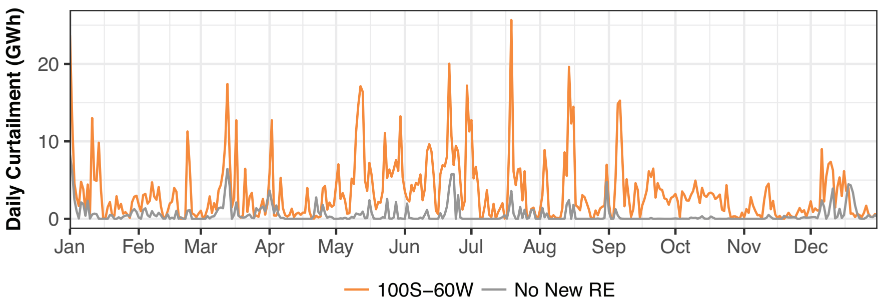
Hydro plants follow a more pronounced two-peak generation profile due to availability of solar power during the middle of the day.

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.

2.4% of wind and solar is curtailed annually.

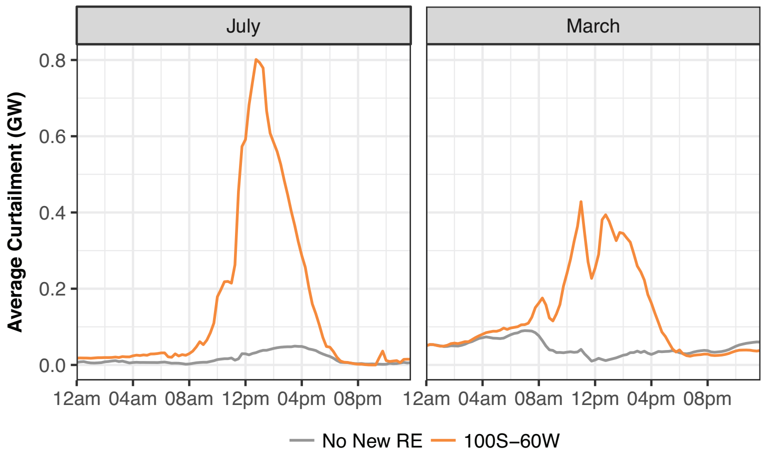
Total daily curtailment throughout the year in Gujarat



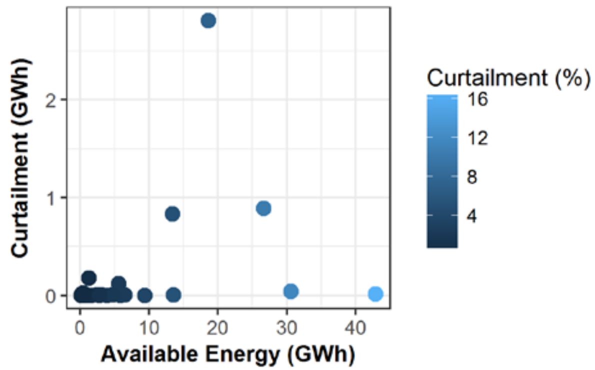
Gujarat's RE curtailment in 100S-60W primarily occurs in only three substations. RE curtailment also occurs in the No New RE scenario when the Western region has flexible thermal capacity available, implying that a portion of Gujarat's RE curtailment is caused by transmission congestion.

Almost all of RE curtailment occurs in 19% of periods in the year.

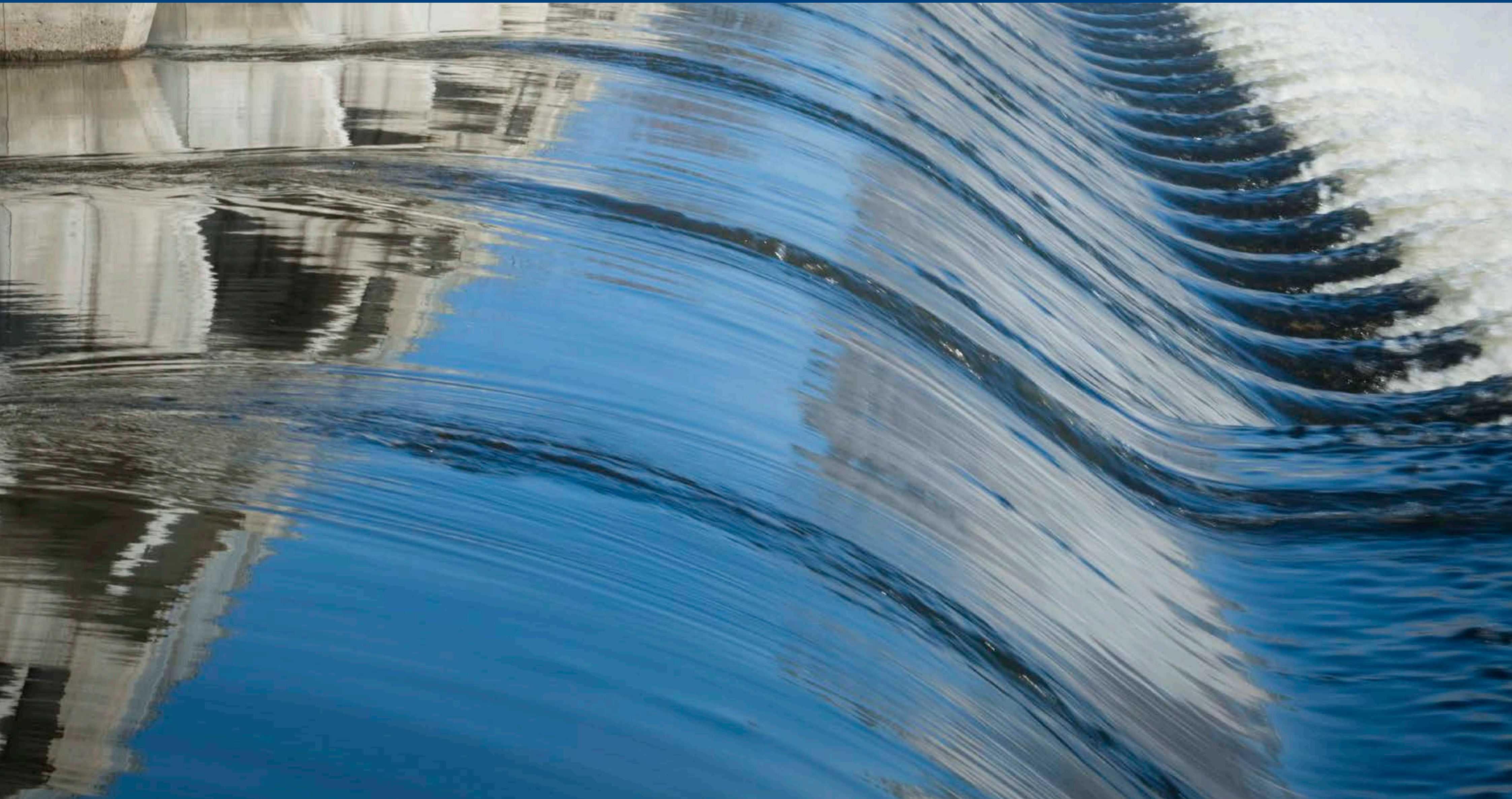
Average daily curtailment in March and July in Gujarat



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



Examples of Dispatch During Interesting Periods in Gujarat

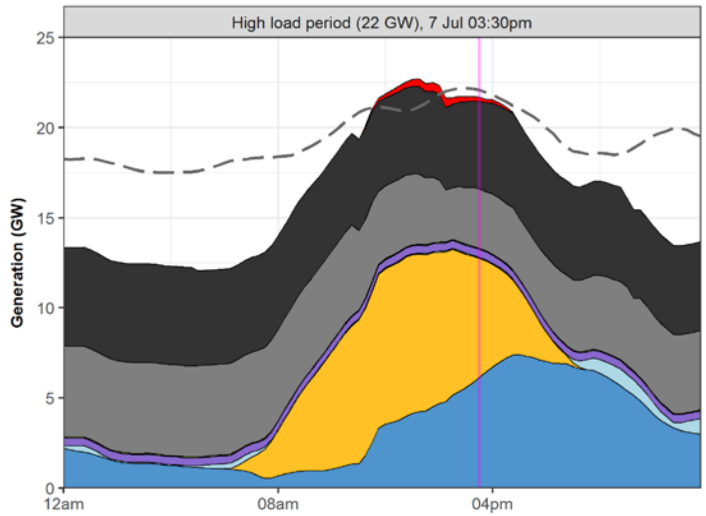


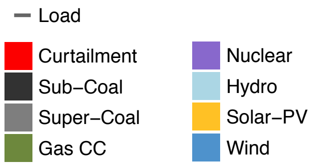
The following pages show dispatch in Gujarat during several interesting periods throughout 2022. The vertical magenta line highlights the dispatch interval associated with the figure title.

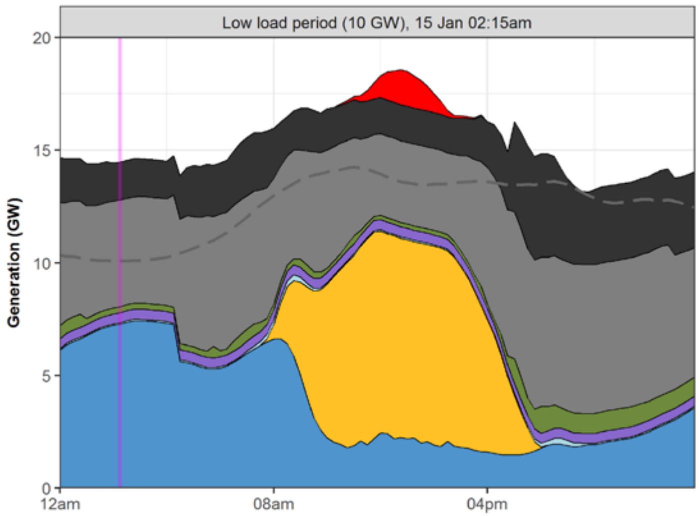
High load period: Generation, load, and interchange (values in GW unless otherwise specified)

7 July 3:30 pm

LOAD	CURTAILMENT	HYDRO	NUCLEAR	COAL	GAS	RE	NET IMPORTS	RE PENETRATION (%)
22.1	0.2	0.1	0.4	8.1	0.1	12.7	0.6	58







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

15 January 2:15 am

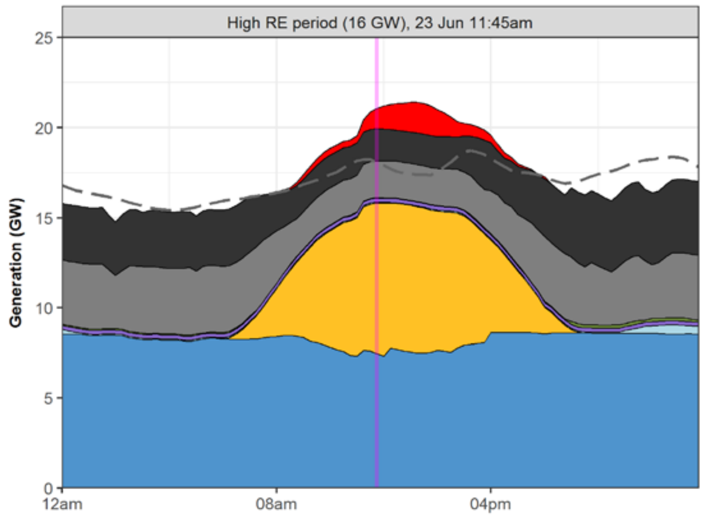
LOAD	CURTAILMENT	HYDRO	NUCLEAR	COAL	GAS	RE	NET EXPORTS	RE PENETRATION (%)
10.1	0	0.1	0.4	6.4	0.3	7.3	4.4	72

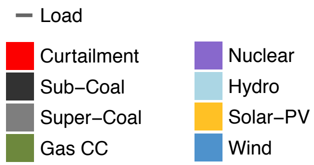
Example Dispatch Days

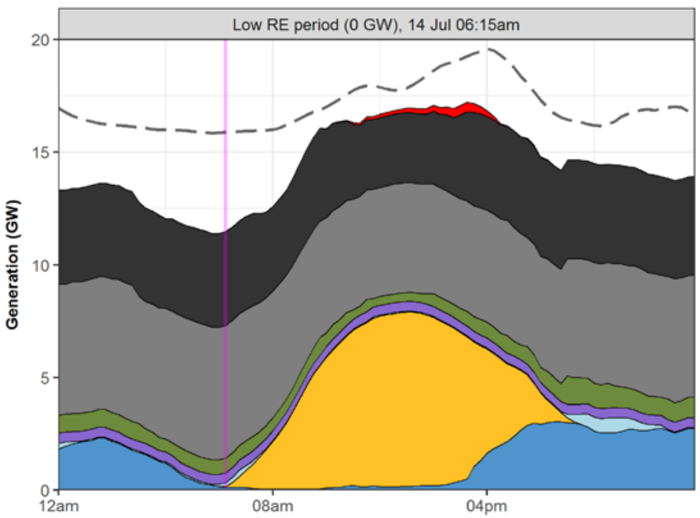
High RE period: Generation, load, and interchange (values in GW unless otherwise specified)

23 June 11:45 am

LOAD	CURTAILMENT	HYDRO	NUCLEAR	COAL	GAS	RE	NET EXPORTS	RE PENETRATION (%)
18.1	1.1	0.1	0.2	3.8	0	15.8	1.9	87





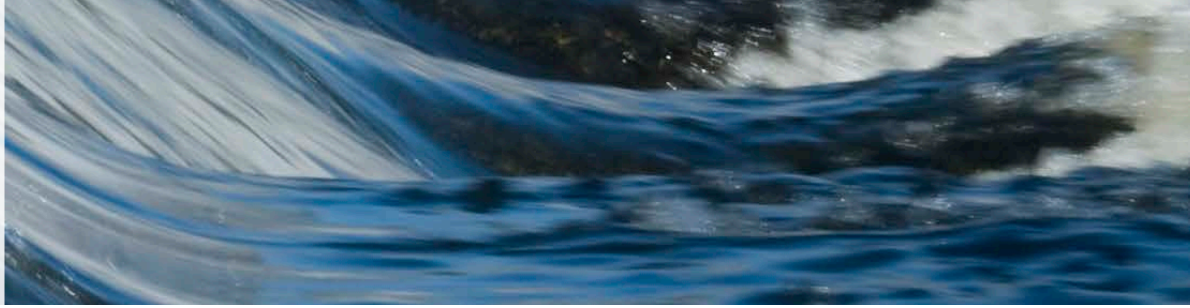


Low RE period: Generation, load, and interchange (values in GW unless otherwise specified)

14 July 6:15 am

LOAD	CURTAILMENT	HYDRO	NUCLEAR	COAL	GAS	RE	NET IMPORTS	RE PENETRATION (%)
15.9	0	0.2	0.4	10.1	0.6	0.2	4.4	1

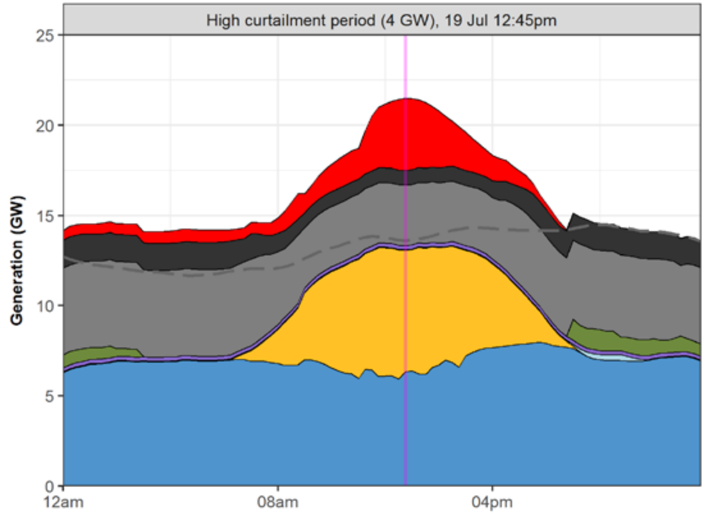
Example Dispatch Days

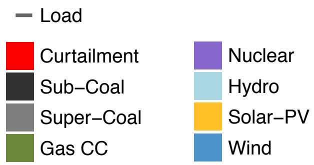


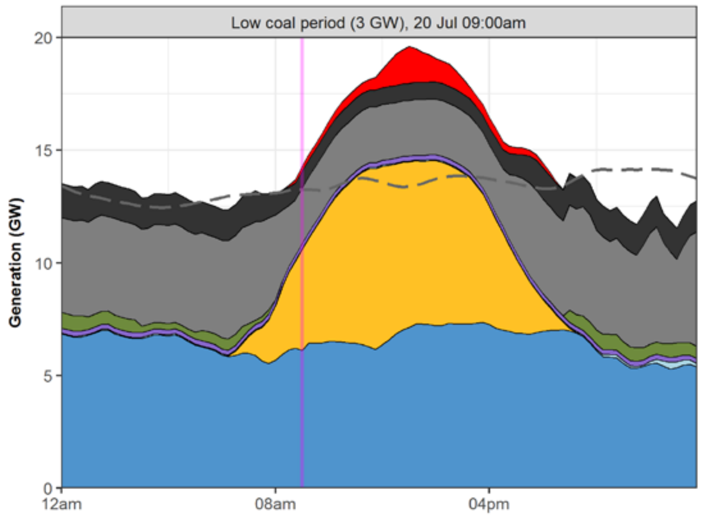
High curtailment period: Generation, load, and interchange (values in GW unless otherwise specified)

19 July 12:45 pm

LOAD	CURTAILMENT	HYDRO	NUCLEAR	COAL	GAS	RE	NET EXPORTS	RE PENETRATION (%)
13.6	4	0	0.2	4.2	0	13.1	3.9	96







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

20 July 9:00 am

LOAD	CURTAILMENT	HYDRO	NUCLEAR	COAL	GAS	RE	NET EXPORTS	RE PENETRATION (%)
13.3	0.2	0	0.2	3.2	0	10.6	0.8	80

Conclusions

Based on this study's assumptions about demand and installed generation and transmission capacity in Gujarat and nationwide, Gujarat can integrate the equivalent of 35% of its total generation in 2022 with 2.4% annual wind and solar curtailment. The RE changes the way Gujarat's grid must operate. Compared to a 2022 system with no new RE, net exports rise by 117% annually, and the PLF of the coal fleet falls from 69% to 55%.

Coordinated planning between intrastate transmission and locations of new RE can alleviate the risk of RE curtailment. As the highest RE state in the Western region, sufficient transmission will be necessary to not only evacuate RE, but also enable the full use of flexible resources such as coal or hydro.

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 Gujarat in the 100S-60W scenario		
	OWNERSHIP	TOTAL CAPACITY (GW)
Gas CC	Central	1.3
Gas CC	State/Private	5.9
Hydro	State/Private	2.0
Nuclear	Central	0.4
Sub-Coal	State/Private	7.5
Super-Coal	State/Private	5.5
Super-Coal	Central	4.0
Total non-RE		26.6
Solar-PV	State/Private	12.0
Wind	State/Private	8.8
Total RE		20.8
Total capacity		**47.4**

Total capacity (surge impedance limit [SIL]) of transmission lines connecting Gujarat 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
Gujarat to Dadra & Nagar Haveli	66	5
Gujarat to Dadra & Nagar Haveli	220	5
Gujarat to Dadra & Nagar Haveli	400	2
Gujarat to Daman & Diu	66	3
Gujarat to Daman & Diu	220	2
Gujarat to Daman & Diu	400	2
Gujarat to Haryana	400	2
Gujarat to Madhya Pradesh	400	8
Gujarat to Madhya Pradesh	765	2
Gujarat to Maharashtra	220	4
Gujarat to Maharashtra	400	5
Gujarat to Maharashtra	765	1
Gujarat to Rajasthan	765	2
Gujarat to Rajasthan*	400	4
Total import/export capacity		**47**

Total capacity (SIL) of transmission lines within Gujarat
**To evacuate new RE capacity, transmission was added in this study to supplement CEA plans for 2022.*

CONNECTING	VOLTAGE (kV)	NO. LINES
Intrastate	132	130
Intrastate	220	326
Intrastate	765	2
Intrastate*	400	122
Total intrastate capacity		**580**

RE capacity by substation and type

SUBSTATION (NUMBER_NAME_VOLTAGE)	SOLAR-PV (MW)	WIND (MW)
352016_ANJAR2_220	926	468
352028_RAJKOT2_220	267	36
352054_DHANS2_220	15	0
352062_THARAD_220	811	0
352069_NAKH2_220	3,170	1,397
352086_MORBI_220	26	17
352104_RADHANPR_220	804	50
352109_SHIVLAKH_220	0	424
352113_DHASA_220	0	310
352114_BOTAD_220	0	35
352117_OTHA_220	0	213
352124_SUTHARI_220	29	0
352135_BHUJPOOL_220	1,123	1,353
352201_BHACHUNDA_220	493	2,073
354001_ASOJ4_400	790	0

RE capacity by substation and type

SUBSTATION (NUMBER_NAME_VOLTAGE)	SOLAR-PV (MW)	WIND (MW)
354003_DEHGM4_400	101	0
354005_SOJA4_400	141	0
354008_JET4_400	16	20
354012_SUGEN4_400	209	0
354014_PIRANA_P_400	1,266	0
354015_MUNDRA4_400	153	329
354016_SAMI4_400	172	0
354020_AMRELI4_400	28	211
354022_HAZIRA4_400	214	0
354023_CGPL_400	435	777
354024_BACHAU_400	0	15
354025_VERSANA_400	0	38
354026_VADINAR_400	779	1,021
354034_NAVSARI_400	179	0
354036_HALVADNEW_400	0	21
Total RE capacity	**12,147**	**8,808**

Annual energy generation fuel type, No New RE and 100S-60W		
	NO NEW RE (TWh)	100S-60W (TWh)
Gas CC	12	7
Hydro	4	4
Nuclear	3	3
Solar-PV: rooftop	0	6
Solar-PV: utility scale	2	17
Sub-Coal	45	32
Super-Coal	57	49
Wind	11	28
Total Generation	134	145
Imports	27	24
Exports	18	26
RE Curtailment	0	1