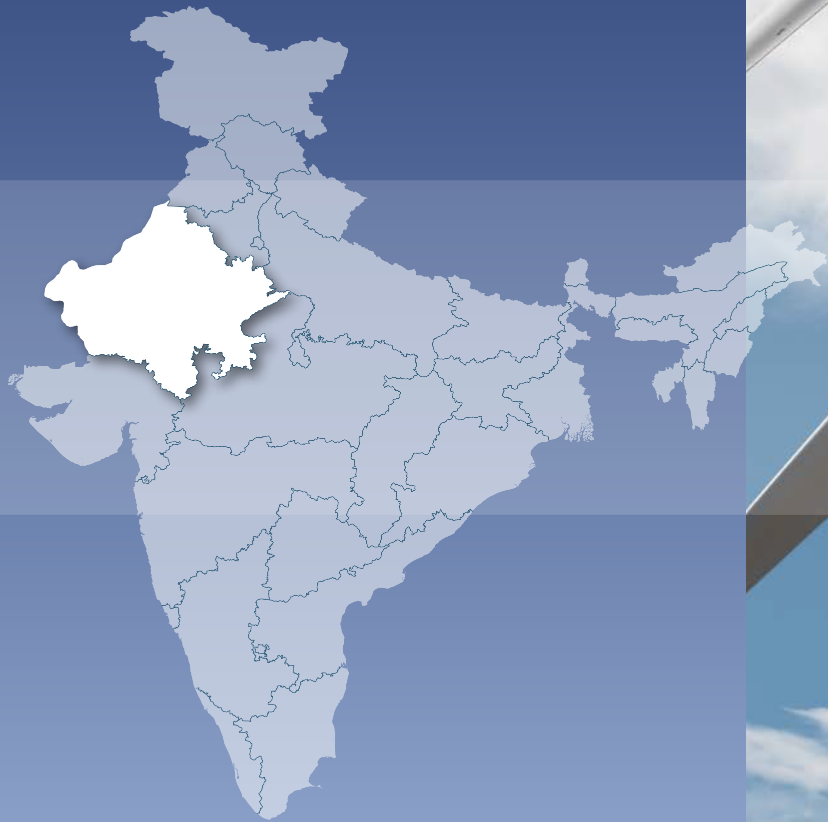
Greening the Grid



Rajasthan

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

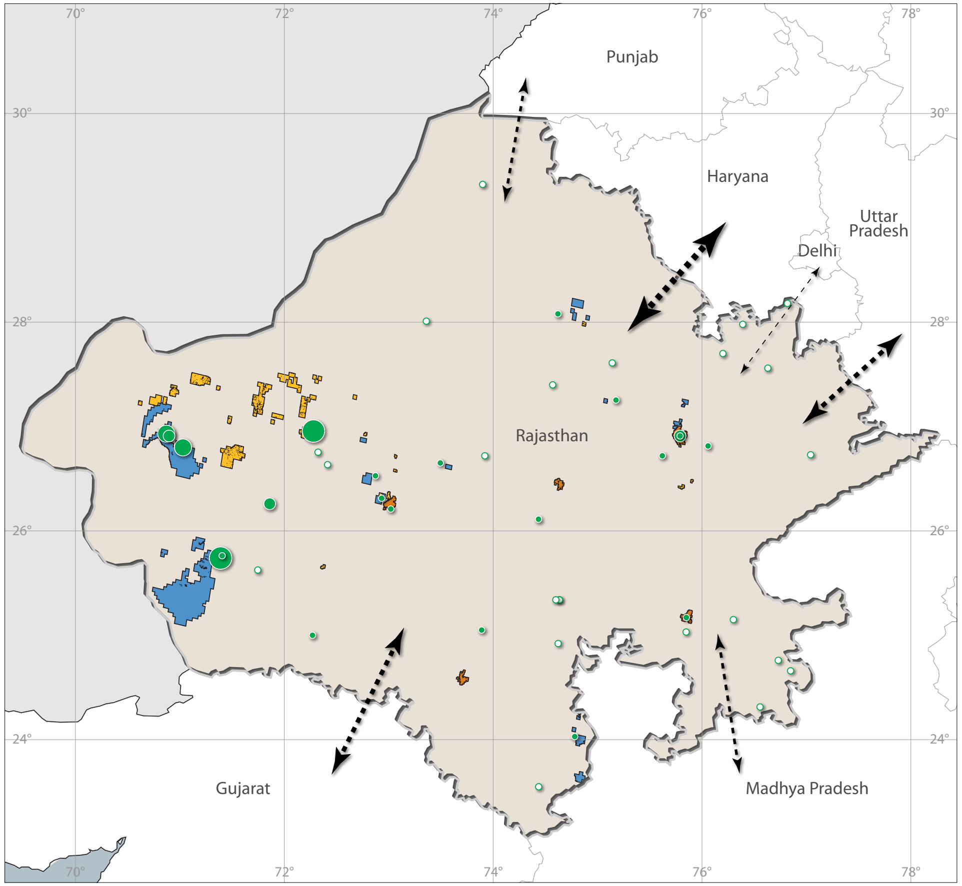
State-specific results from Volume II, which includes all of India. The full reports include detailed explanations of modeling assumptions, results, and policy conclusions.

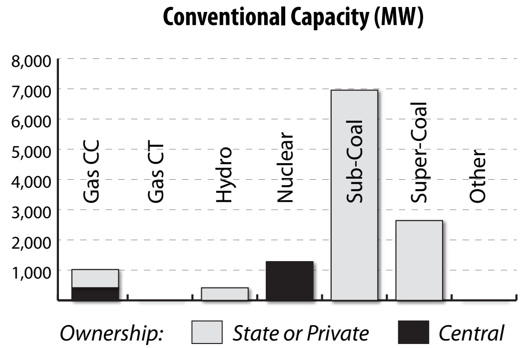
www.nrel.gov/india-grid-integration/

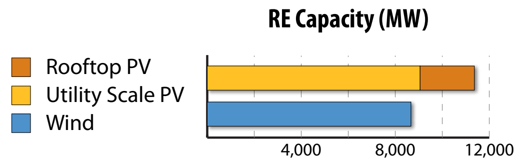
NREL/TP-6A20-70952

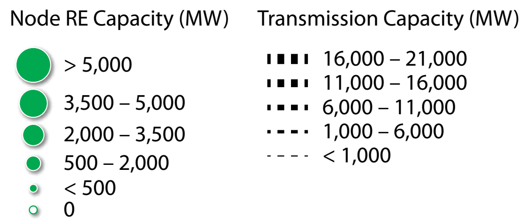
Assumptions About Infrastructure, Demand, and Resource Availability in 2022

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









Peak load (GW)	17
Total annual load (TWh)	191
Installed non-RE capacity (GW)	12
Installed RE capacity (GW)	20
Total import/export capacity (GW)	36

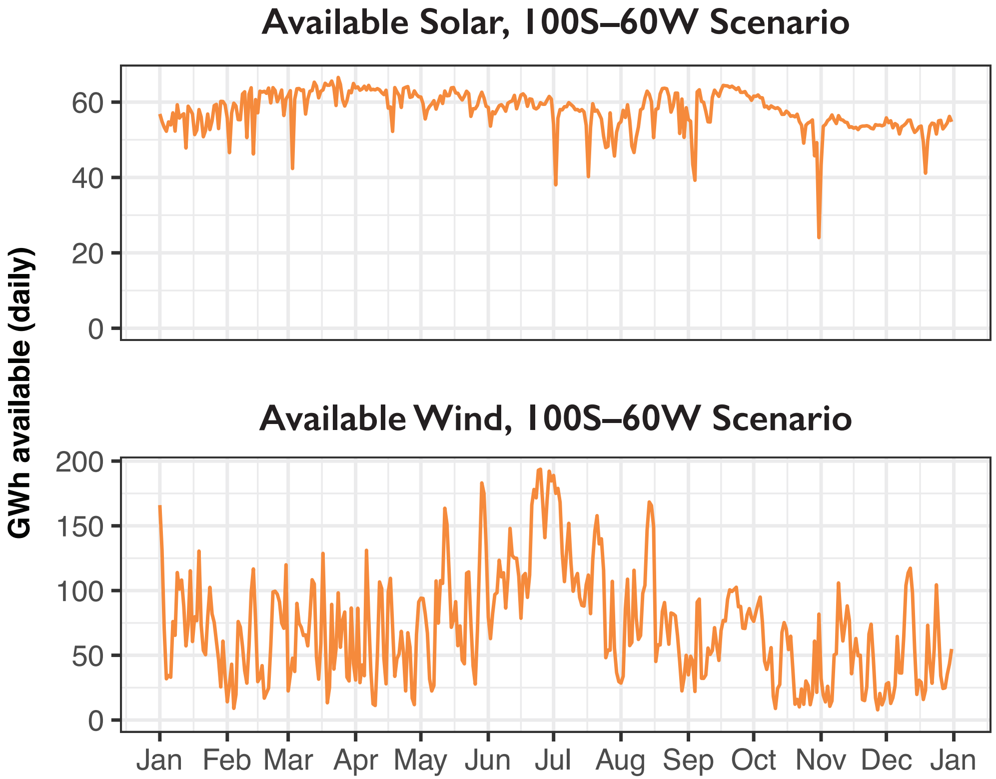
Rajasthan has 30 tie-lines connecting it to other states in this model.

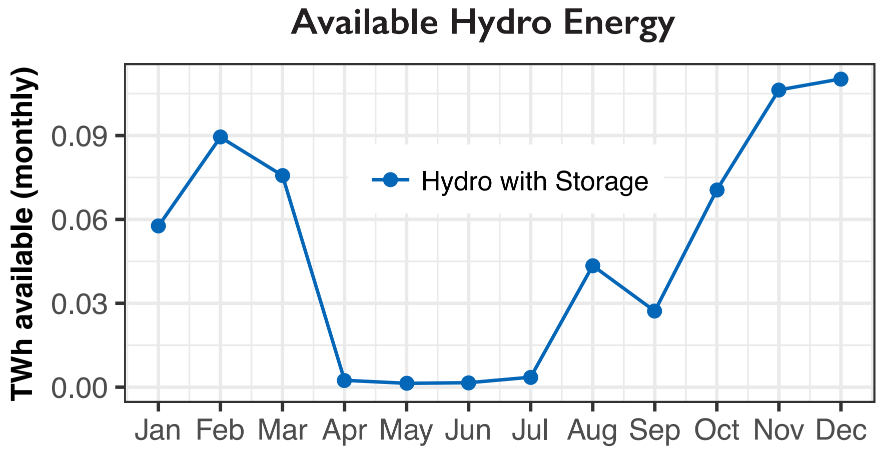
NREL and LBNL selected RE sites based on the methodology explained in Volume 1 of this report, which is available at www.nrel.gov/docs/fy17osti/68530.pdf.

Rooftop PV has been clubbed to the nearest transmission node.

Rajasthan Resource Availability in 2022

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





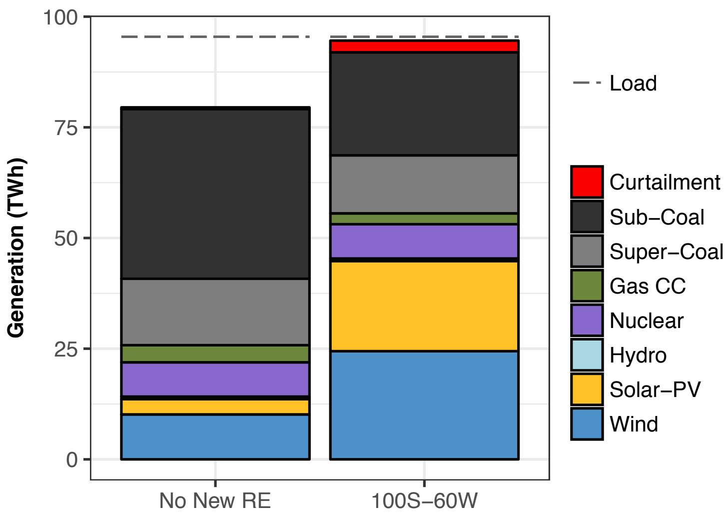
Daily solar energy is relatively consistent throughout the year while wind energy varies seasonally.

Note: Y-axis is different for each resource

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

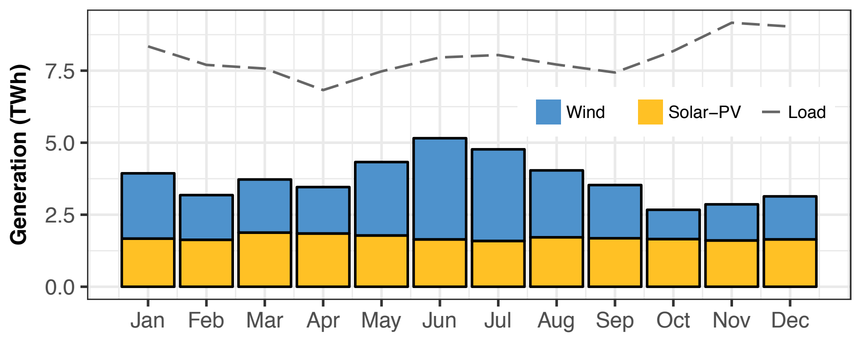
Increased amounts of RE available in Rajasthan change Rajasthan's generation mix and therefore the operation of the entire fleet.

Annual energy generation in Rajasthan



20 GW of wind and solar power generates 45 TWh annually.

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



Wind and solar produce 49% of total generation in Rajasthan and meet 47% of load.

RE penetration by load and generation

	100S-60W
Percent time over 50% of load	50
Peak RE % of load	134
Percent time over 50% of generation	50
Peak RE % of generation	83

Coal generation falls by 32% and gas by 37% between No New RE and 100S-60W.

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

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

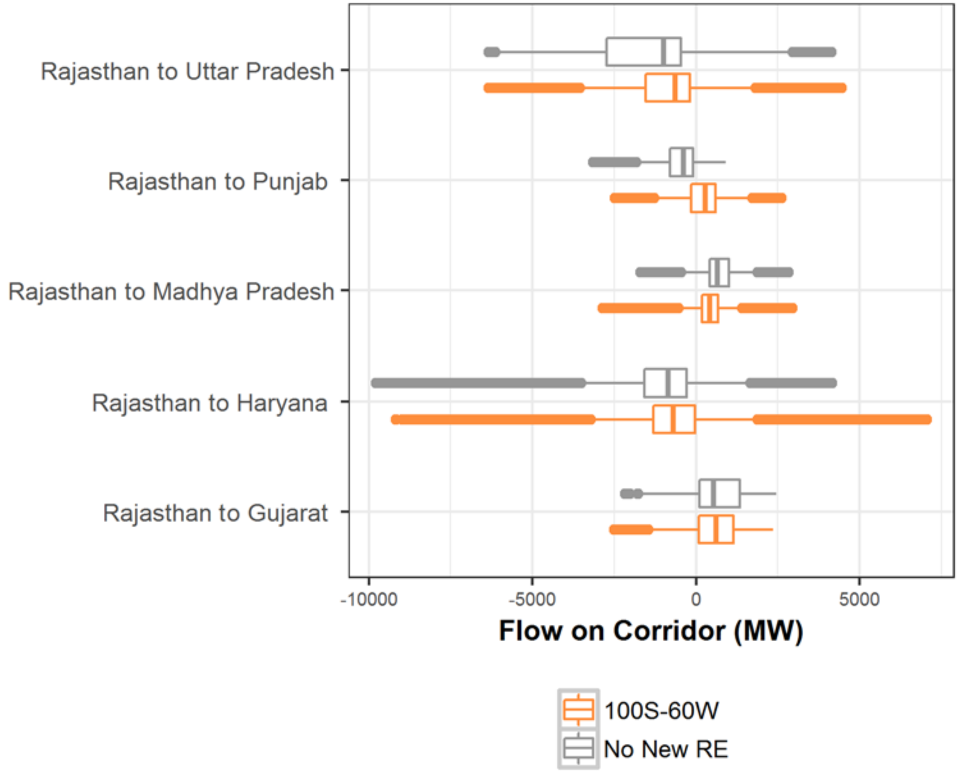
Rajasthan's increased RE generation in the 100S-60W scenario allows it to rely less on imports from the rest of the Northern region, particularly Punjab, Haryana, and Uttar Pradesh.

Imports fall by **22%** annually

Exports rise by **11%** annually

SCENARIO	NET EXPORTS (TWh)	
No New RE	-16	net importer
100S-60W	-3.5	net importer

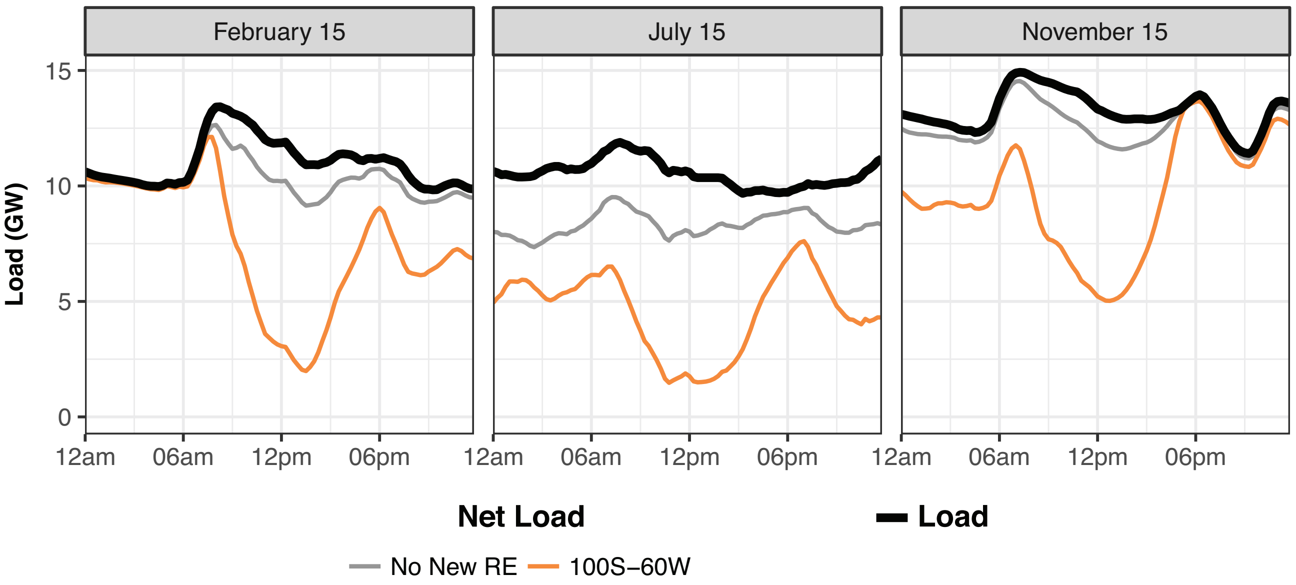
Distribution of flows across state-to-state corridors



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

The addition of RE in Rajasthan 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 Rajasthan

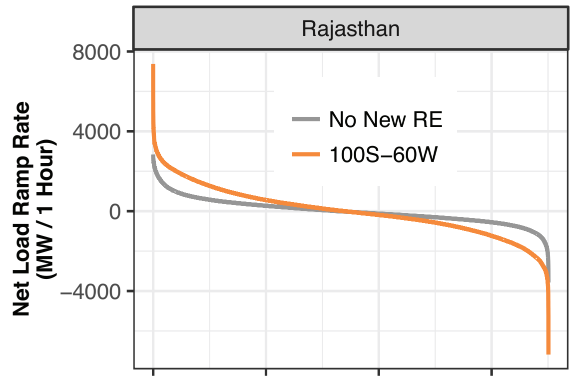


Increased daytime solar generation causes a dip in net load, which requires Rajasthan to either increase net exports, turn down its thermal generators, or curtail RE. On 15 July, increased monsoon season wind generation shifts Rajasthan's net load curve downward during all hours of the day.

Peak 1-hour net load up-ramp in the **100S-60W scenario is 7.4 GW**, up from **2.8 GW in the No New RE scenario.**

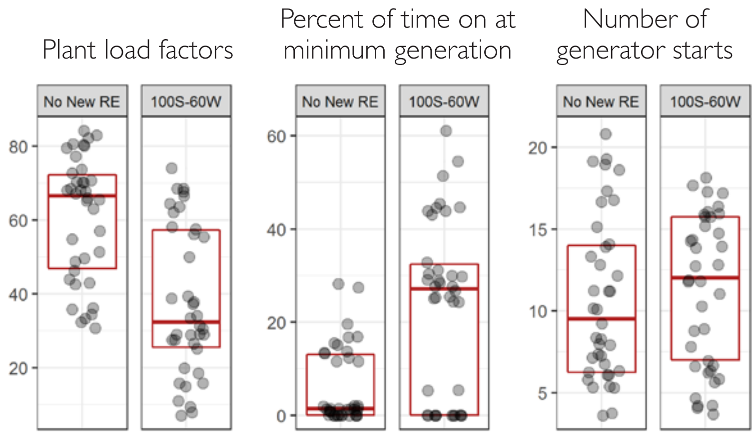
Maximum net load valley-to-peak ramp is **13 GW in the 100S-60W scenario**, up from **8.0 GW in the No New RE scenario.**

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



Changes to Rajasthan's Coal Fleet Operations

Operational impacts to coal



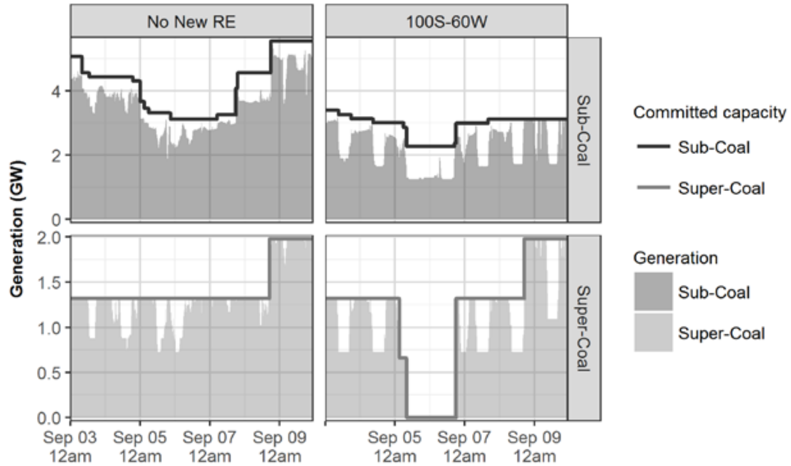
Coal plant load factors (PLFs) are lower in the 100S-60W scenario due to more frequent cycling and operation at minimum generation levels.

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 Rajasthan, disaggregated by variable cost

RELATIVE VARIABLE COST	NO NEW RE	100S-60W
Lower 1/3	58	51
Mid 1/3	60	50
Higher 1/3	54	14
Fleetwide	63	43

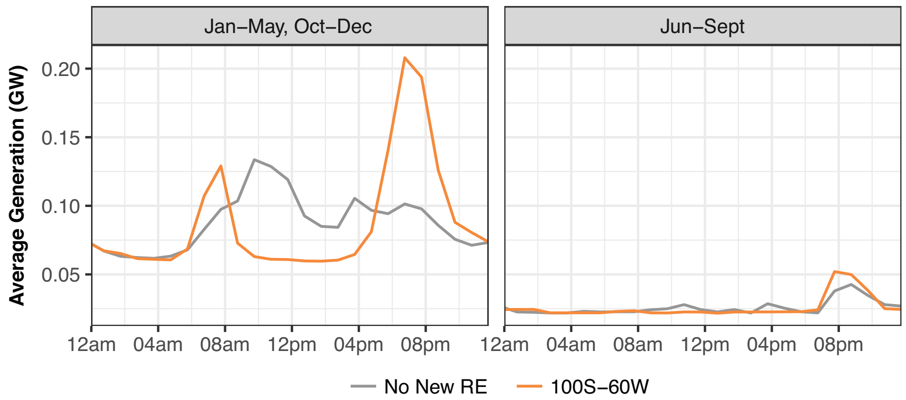
One week of coal operation in Rajasthan



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 Rajasthan's Hydro Fleet Operations

Average day of hydro in Rajasthan by season



Low hydro availability in Rajasthan limits its effectiveness in helping to balance changes to net load.

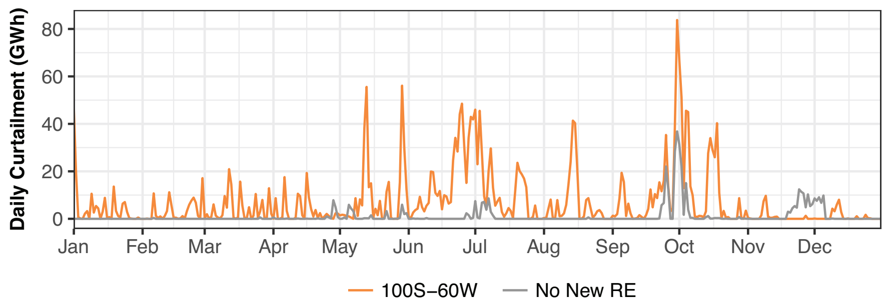
Hydro plants follow a more pronounced two-peak generation profile due to availability of solar power during the middle of the day.

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.

5.6% of wind and solar is curtailed annually.

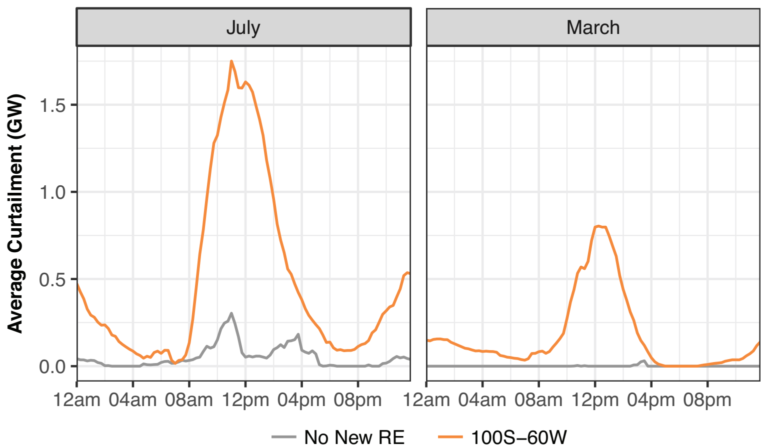
Total daily curtailment throughout the year in Rajasthan



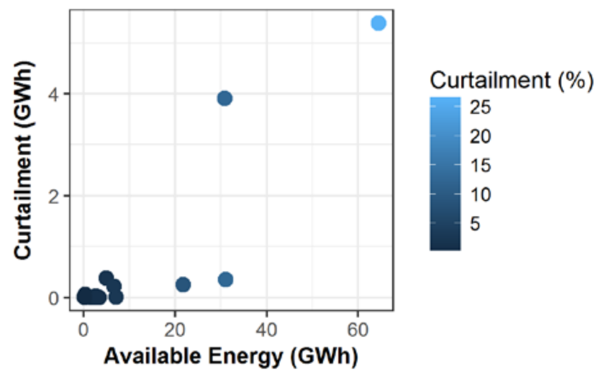
Two substations contribute the majority of Rajasthan's RE curtailment, despite the addition to this model of nine in-state lines to reduce curtailment. This suggests that thorough in-state transmission planning will be necessary for Rajasthan to effectively consume and export RE generation.

Almost all of RE curtailment occurs in 15% of periods in the year.

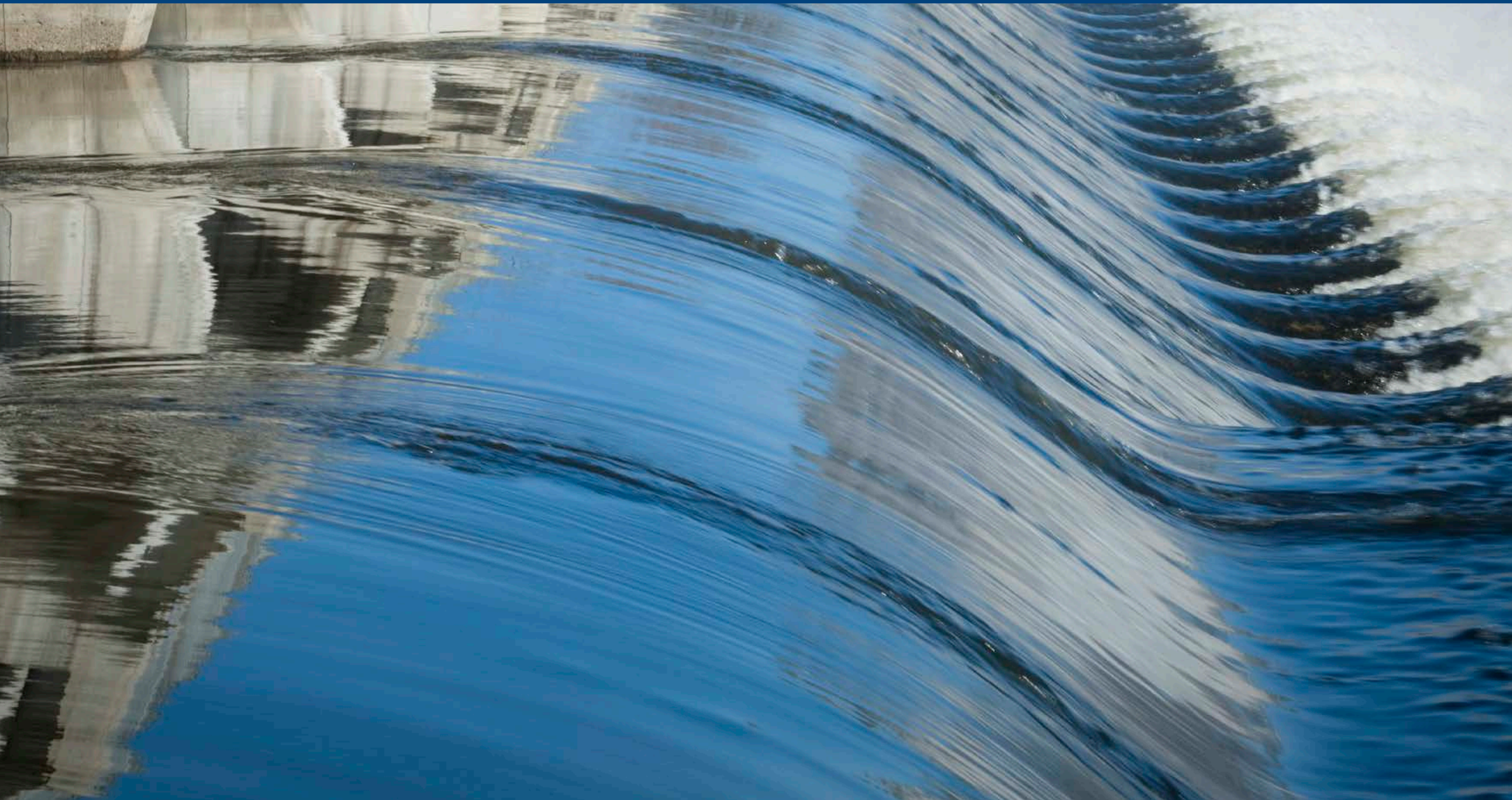
Average daily curtailment in March and July in Rajasthan



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



Examples of Dispatch During Interesting Periods in Rajasthan

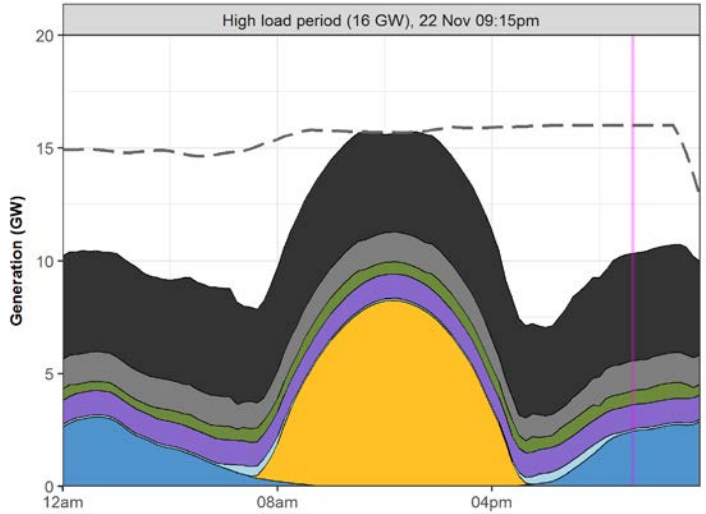


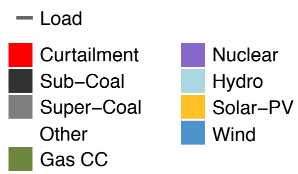
The following pages show dispatch in Rajasthan during several interesting periods throughout 2022. The vertical magenta line highlights the dispatch interval associated with the figure title.

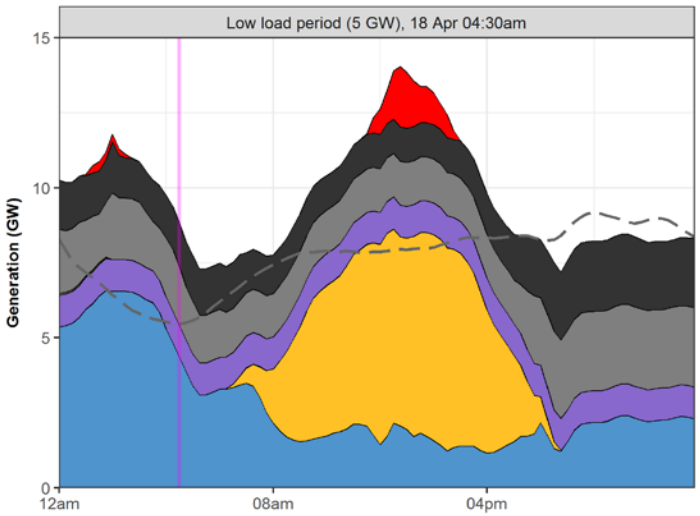
High load period: Generation, load, and interchange (values in GW unless otherwise specified)

22 November 9:15 pm

LOAD	CURTAILMENT	HYDRO	NUCLEAR	COAL	GAS	RE	NET IMPORTS	RE PENETRATION (%)
16	0	0.1	1.1	6.1	0.6	2.5	5.7	15







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

18 April 4:30 am

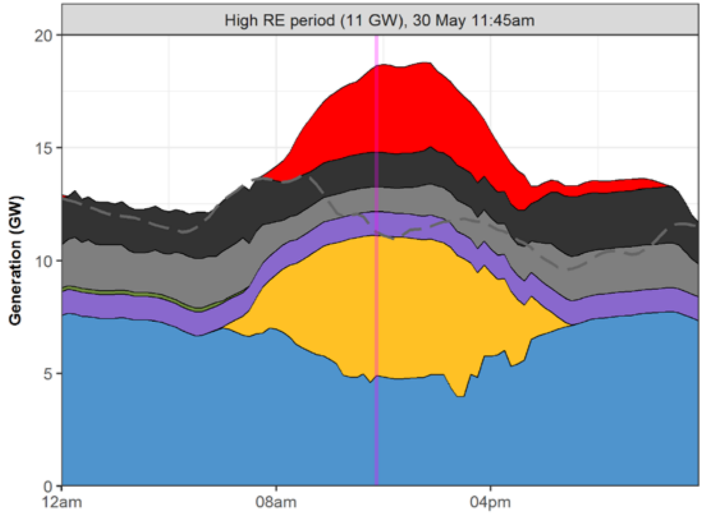
LOAD	CURTAILMENT	HYDRO	NUCLEAR	COAL	GAS	RE	NET EXPORTS	RE PENETRATION (%)
5.5	0	0	1.1	3.4	0	4.4	3.4	80

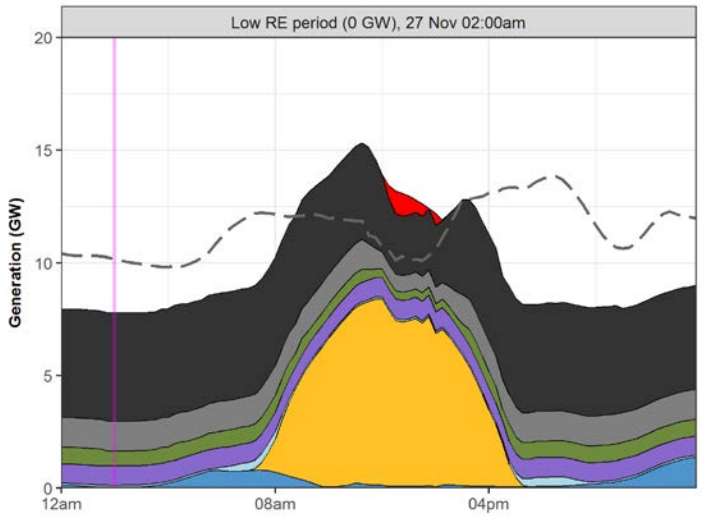
Example Dispatch Days

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

30 May 11:45 am

LOAD	CURTAILMENT	HYDRO	NUCLEAR	COAL	GAS	RE	NET EXPORTS	RE PENETRATION (%)
11.3	3.8	0	1.1	2.6	0	11.1	3.6	99

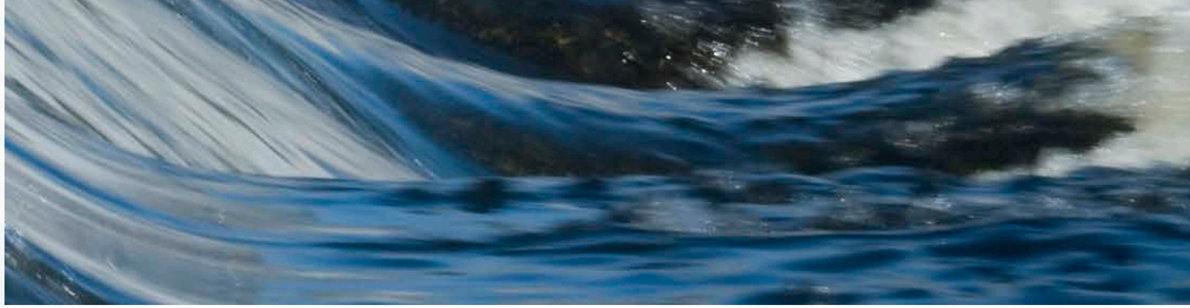




Low RE period: Generation, load, and interchange (values in GW unless otherwise specified)

27 November 2:00 am

LOAD	CURTAILMENT	HYDRO	NUCLEAR	COAL	GAS	RE	NET IMPORTS	RE PENETRATION (%)
10.2	0	0.1	0.9	6.1	0.7	0	2.4	0.4

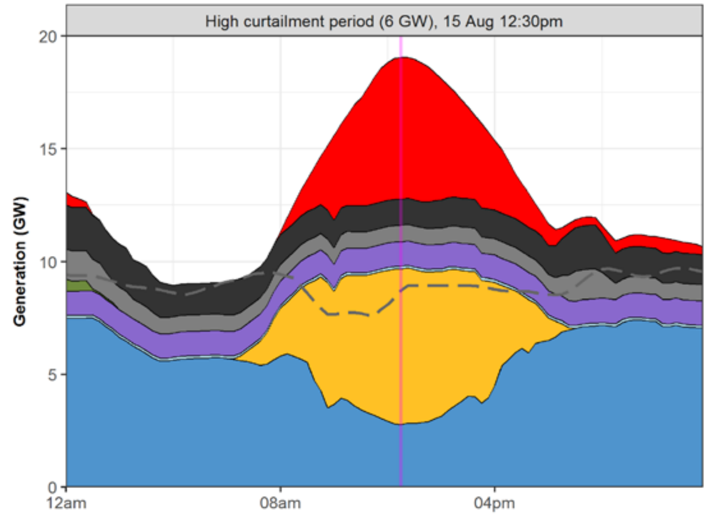


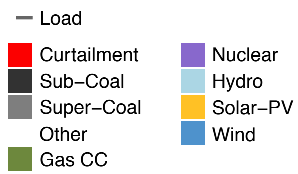
Example Dispatch Days

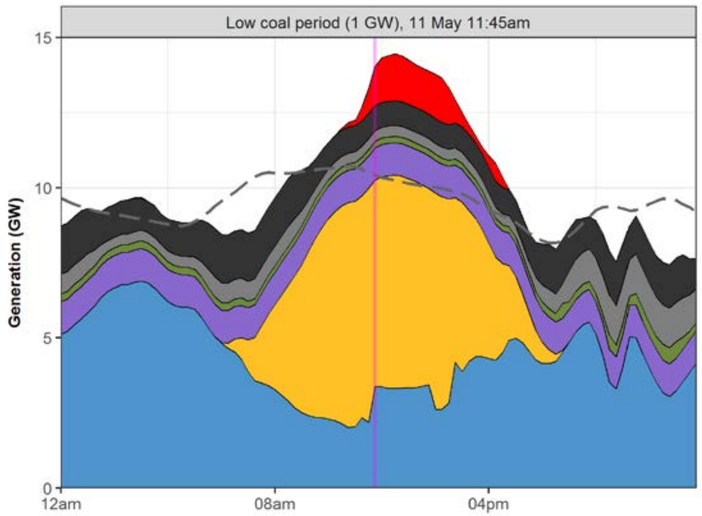
High curtailment period: Generation, load, and interchange (values in GW unless otherwise specified)

15 August 12:30 pm

LOAD	CURTAILMENT	HYDRO	NUCLEAR	COAL	GAS	RE	NET EXPORTS	RE PENETRATION (%)
8.7	6.3	0.1	1.1	1.9	0	9.7	4	111







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

11 May 11:45 am

LOAD	CURTAILMENT	HYDRO	NUCLEAR	COAL	GAS	RE	NET EXPORTS	RE PENETRATION (%)
10.4	1.3	0	1.1	1.2	0.2	10.3	2.3	98

Conclusions

Based on this study's assumptions about demand and installed generation and transmission capacity in Rajasthan and nationwide, Rajasthan can integrate the equivalent of 49% of its total generation in 2022 with 5.6% annual wind and solar curtailment. This changes the way Rajasthan's grid must operate. Compared to a 2022 system with no new RE, net exports rise by 79% annually and the PLF of the coal fleet falls from 63% to 43%.

Rajasthan has the largest percentage of RE capacity outside the Southern region. Coordinated planning between intrastate transmission and locations of new RE can alleviate the risk of RE curtailment. 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 Rajasthan (GW) in the 100S-60W scenario		
	OWNERSHIP	**TOTAL CAPACITY (GW)**
Gas CC	State/Private	0.6
Gas CC	Central	0.4
Hydro	State/Private	0.4
Nuclear	Central	1.3
Sub-Coal	State/Private	7.0
Super-Coal	State/Private	2.6
Total non-RE		12.3
Solar-PV	State/Private	11.0
Wind	State/Private	8.6
Total RE		19.6
Total capacity		**31.9**

Total capacity (surge impedance limit [SIL]) of transmission lines connecting Rajasthan 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
Rajasthan to Delhi	220	1
Rajasthan to Gujarat	765	2
Rajasthan to Gujarat*	400	4
Rajasthan to Haryana	132	3
Rajasthan to Haryana	220	5
Rajasthan to Haryana	400	12
Rajasthan to Haryana	765	2
Rajasthan to Madhya Pradesh	220	2
Rajasthan to Madhya Pradesh	400	2
Rajasthan to Madhya Pradesh	765	4
Rajasthan to Punjab	765	2
Rajasthan to Uttar Pradesh	220	1
Rajasthan to Uttar Pradesh	400	9
Total import/export capacity		**49**

Total capacity (SIL) of transmission lines within Rajasthan

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

CONNECTING	VOLTAGE (kV)	NO. LINES
Intrastate	132	601
Intrastate	220	296
Intrastate	765	10
Intrastate*	400	113
Total intrastate capacity		**1,020**

RE capacity by substation and type

SUBSTATION (NUMBER_NAME_VOLTAGE)	SOLAR-PV (MW)	WIND (MW)
162216_BARMER_220	0	15
162237_AMARSAGAR-W_220	1,552	935
162238_TINWARI-WS_220	67	202
162240_BHOPALGA_220	0	40
162284_BARLI_2_220	158	113
162395_SANWREEJ-WS_220	4,151	0
162760_PRATAPGARH-W_220	0	312
164110_JAISALMER_400	573	192
164401_AKAL-4_400	1,700	1,511
164402_BARMER-4_400	0	4,912
164403_RAMGARH_400	0	19
164406_HERAPU-4_400	46	0

RE capacity by substation and type

SUBSTATION (NUMBER_NAME_VOLTAGE)	SOLAR-PV (MW)	WIND (MW)
164408_RATANGAR_400	41	242
164413_RAJWEST_400	658	0
164433_JODHPU-4_400	456	0
164451_JAIPUR_RS_400	836	107
184403_BHINMAL_400	43	0
184404_KANKROLI_400	309	0
184407_KOTA_400	382	0
184430_BASSI_400	16	0
184458_SHRECEM_400	233	0
184473_JAIPUR_PG_400	56	0
Total RE capacity	**11,277**	**8,600**

Annual energy generation fuel type, No New RE and 100S-60W		
	100S-60W (TWh)	NO NEW RE (TWh)
Gas CC	2	4
Hydro	1	1
Nuclear	8	8
Solar-PV: rooftop	4	0
Solar-PV: utility scale	16	3
Sub-Coal	23	38
Super-Coal	13	15
Wind	24	10
Total Generation	92	79
Imports	34	44
Exports	31	28
RE Curtailment	3	0