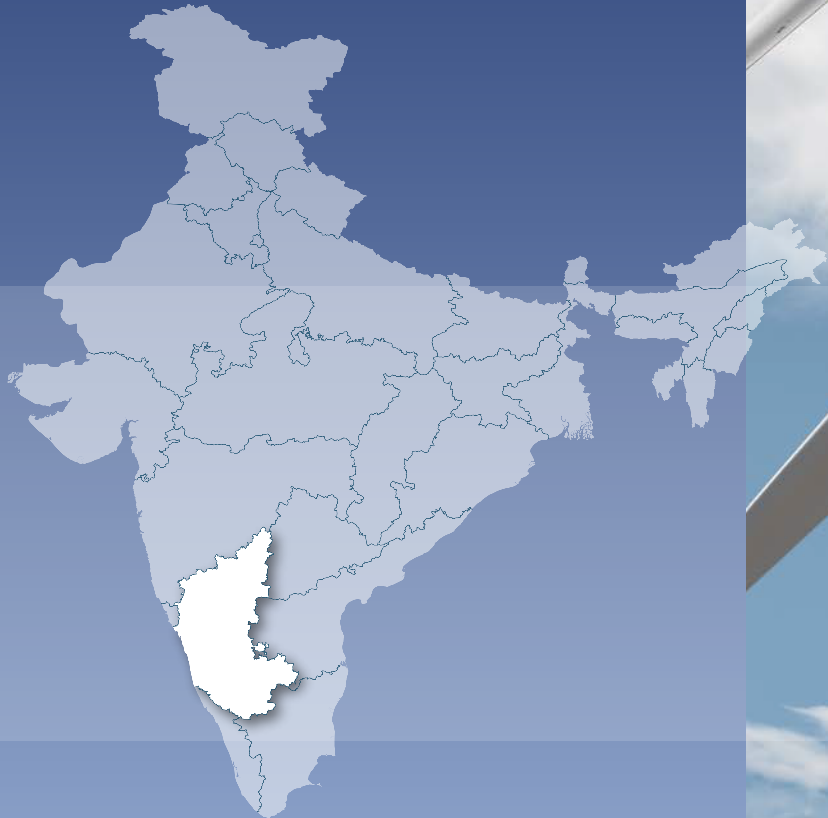
Greening the Grid



Karnataka

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

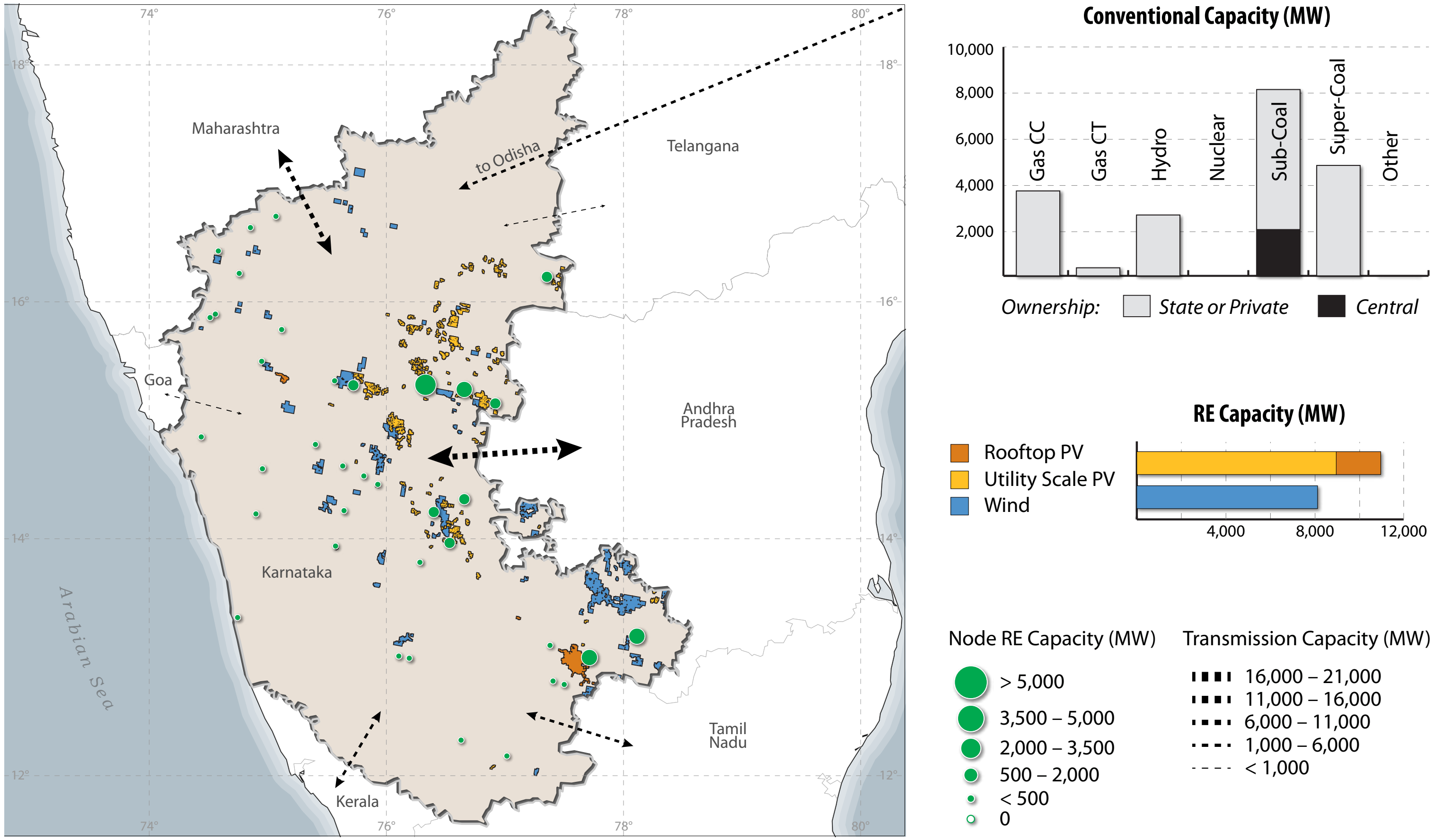
State-specific results from Volume II, which includes all of India. The full reports include detailed explanations of modeling assumptions, results, and policy conclusions.

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

NREL/TP-6A20-70950

Assumptions About Infrastructure, Demand, and Resource Availability in 2022

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



Peak load (GW)	14
Total annual load (TWh)	150
Installed non-RE capacity (GW)	14
Installed RE capacity (GW)	17
Total import/export capacity (GW)	27

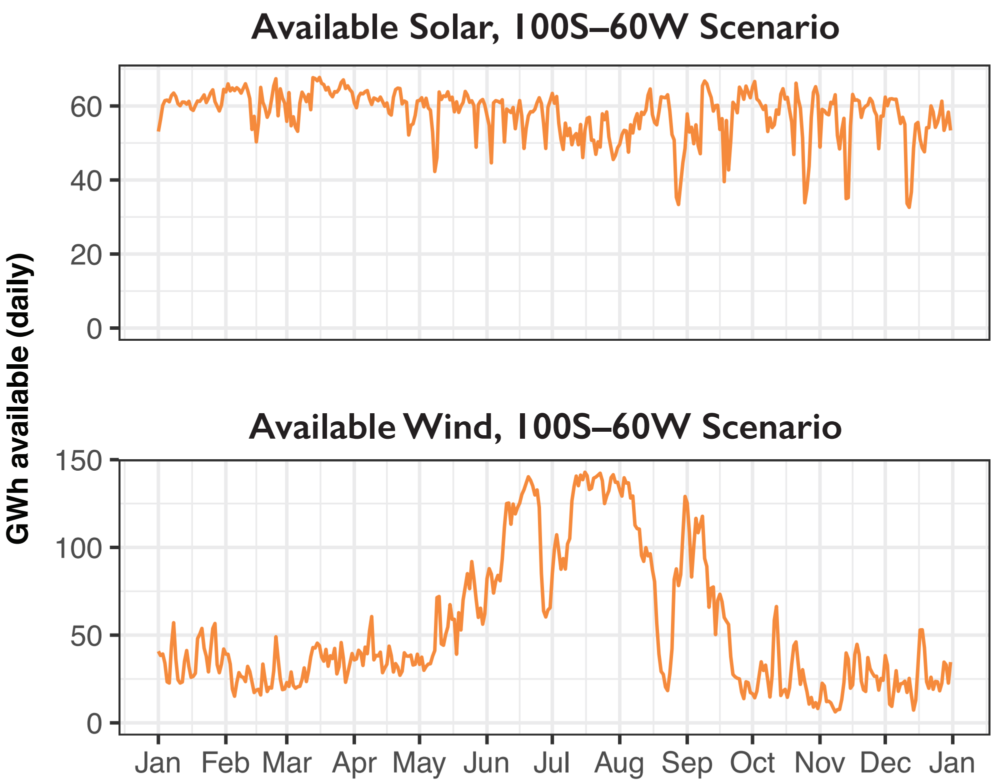
Karnataka has 35 tie-lines connecting it to other states in this model.

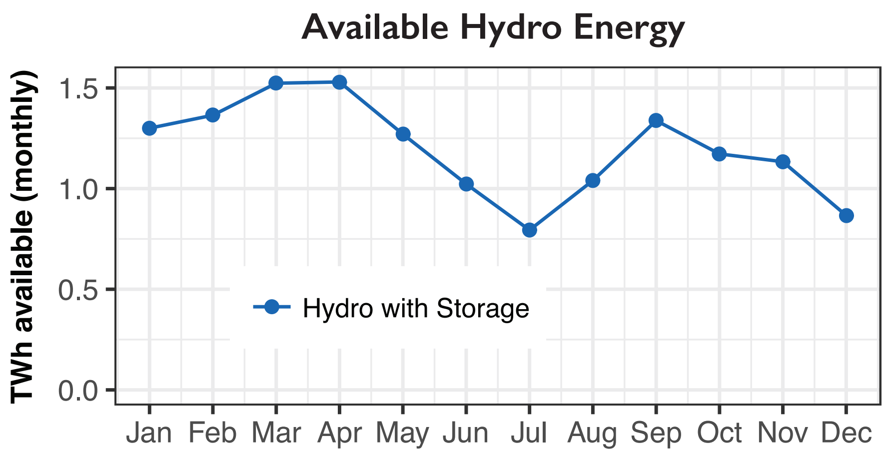
NREL and LBNL selected RE sites based on the methodology explained in Volume 1 of this report, which is available at www.nrel.gov/docs/fy17osti/68530.pdf.

Rooftop PV has been clubbed to the nearest transmission node.

Karnataka Resource Availability in 2022

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





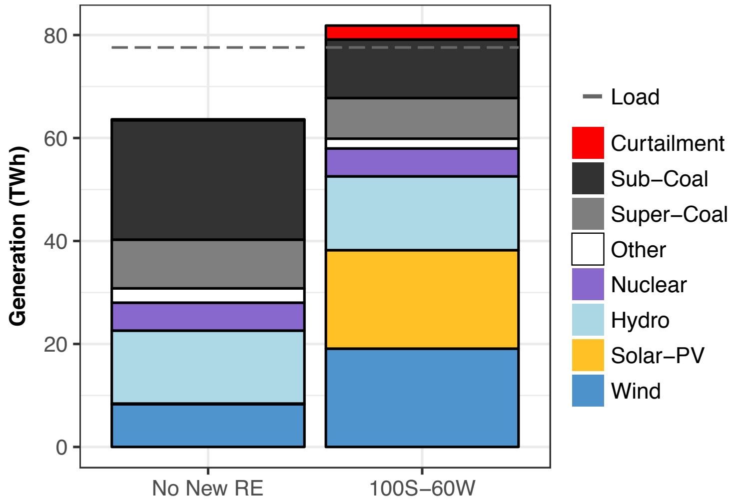
Daily solar energy is relatively consistent throughout the year, while wind energy varies seasonally.

Note: Y-axis is different for each resource

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

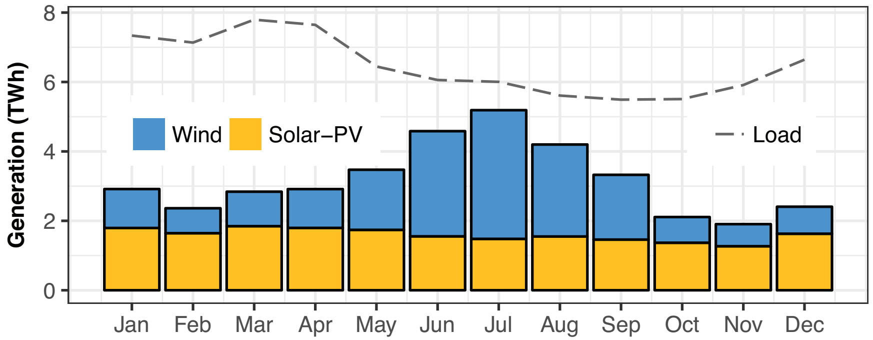
Increased amounts of RE available in Karnataka change Karnataka's generation mix and therefore the operation of the entire fleet.

Annual energy generation in Karnataka



17 GW of wind and solar power generates 38 TWh annually.

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



Wind and solar produce 48% of total generation in Karnataka and meet 49% of load.

RE penetration by load and generation

	100S-60W
Percent time RE is over 50% of load	47
Peak RE as a % of load	160
Percent time RE is over 50% of generation	45
Peak RE as a % of generation	93

Coal generation falls by 41% between No New RE and 100S-60W.

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

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

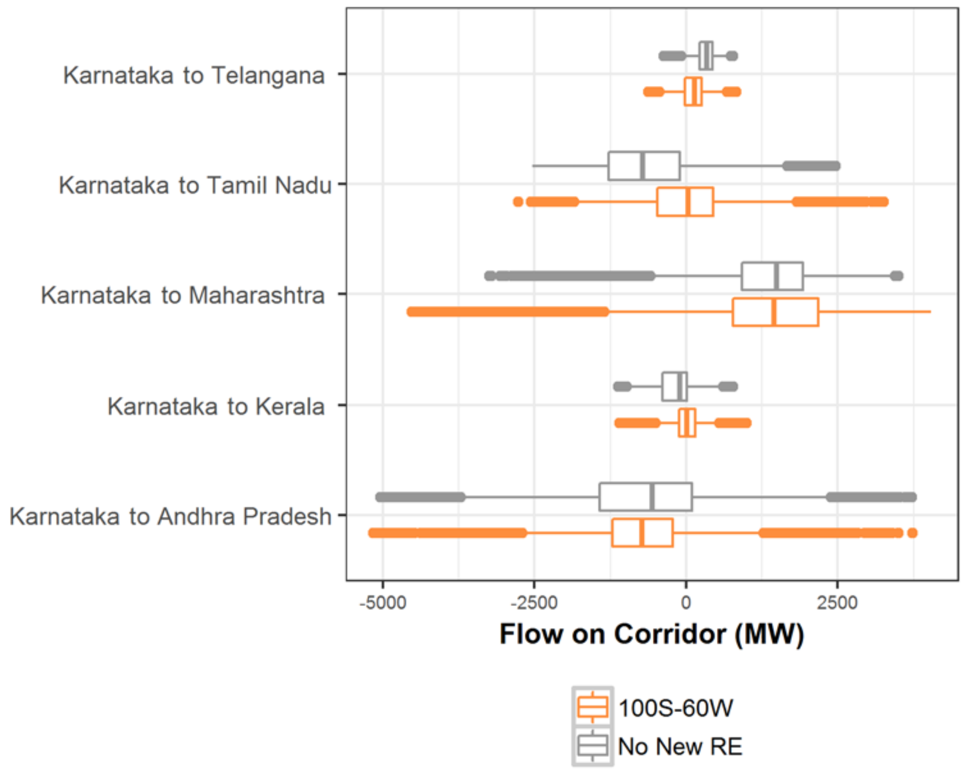
Karnataka is responsible for a large portion of the Southern region's exports to the Western region. It changes from a net importer in the No New RE scenario to a net exporter in the 100S-60W scenario, driven primarily by accepting fewer imports from Tamil Nadu, which in turn imports less from Chhattisgarh.

Imports fall by **36%** annually

Exports rise by **1.9%** annually

SCENARIO	NET EXPORTS (TWh)	
No New RE	-14	net importer
100S-60W	1.6	net exporter

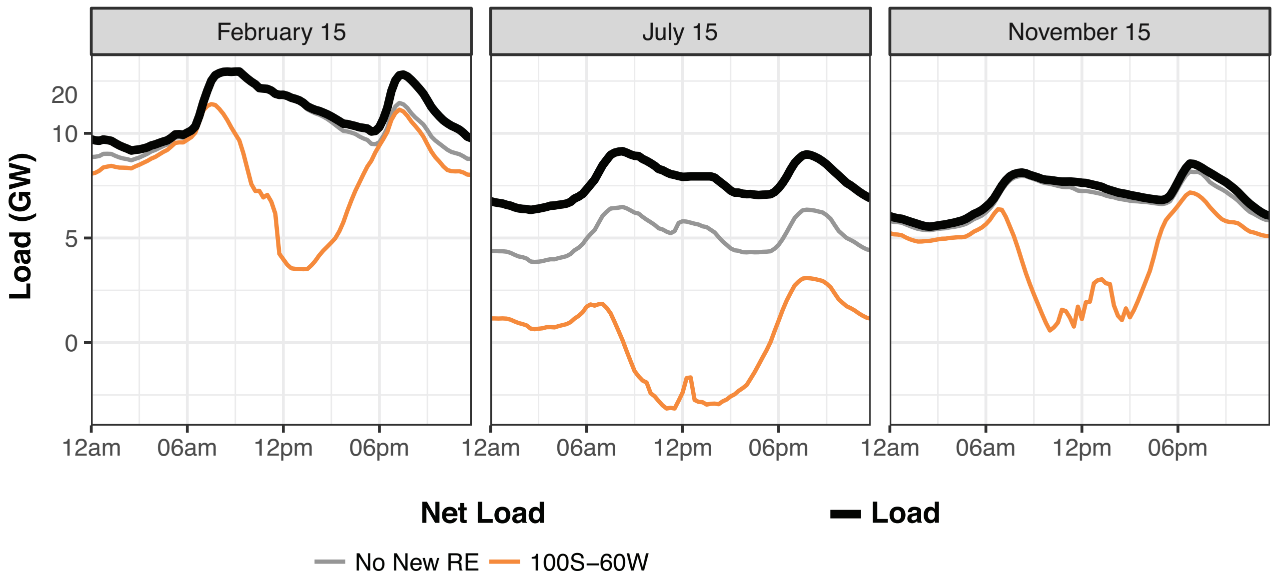
Distribution of flows across state-to-state corridors



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

The addition of RE in Karnataka 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 Karnataka

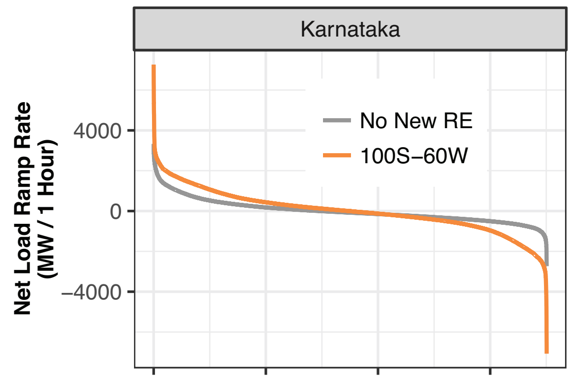


Increased daytime solar generation causes a dip in net load, which requires Karnataka to either increase net exports, turn down its thermal generators, or curtail RE. On 15 July, increased monsoon season wind generation drives Karnataka's daytime net load below zero (>100% RE penetration) for several hours. However, despite its lower RE penetration, 15 November has the larger nationwide valley-to-peak net load ramp, and RE curtailment on that day is higher.

Peak 1-hour net load up-ramp in the **100S-60W scenario is 7.3 GW,** up from **3.3 GW in the No New RE scenario.**

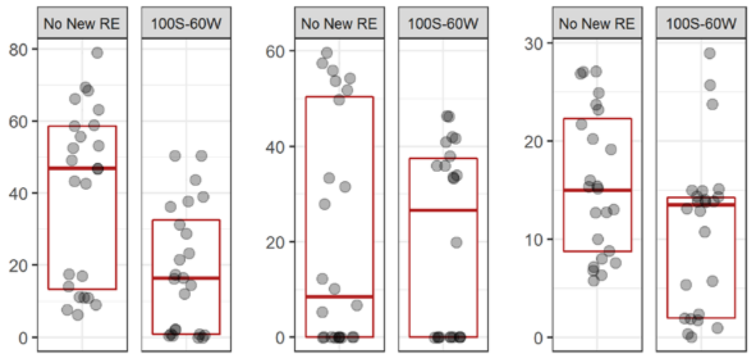
Maximum net load valley-to-peak ramp is **10 GW in the 100S-60W scenario,** up from **6.2 GW in the No New RE scenario.**

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



Changes to Karnataka's Coal Fleet Operations

Operational impacts to coal



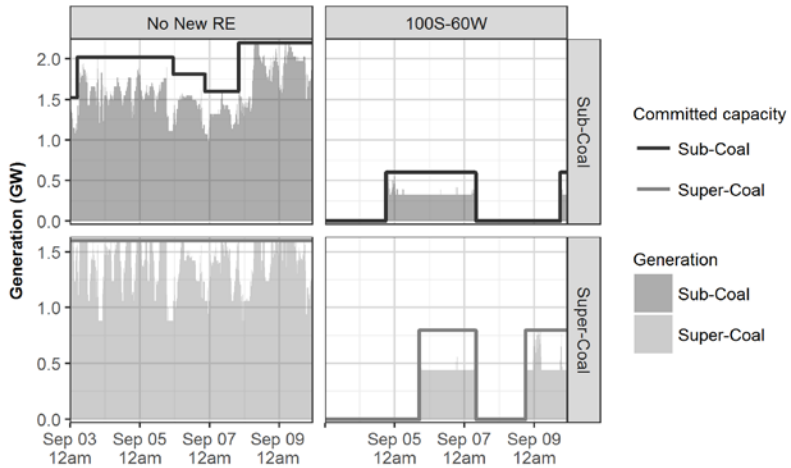
Coal plant load factors (PLFs) are lower in the 100S-60W scenario due to more frequent cycling and operation at minimum generation levels.

While coal PLFs are lower fleetwide in 100S-60W, generators with higher variable costs are impacted more.

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

RELATIVE VARIABLE COST	NO NEW RE	100S-60W
Lower 1/3	56	41
Mid 1/3	53	18
Higher 1/3	9.0	0.30
Fleetwide	47	28

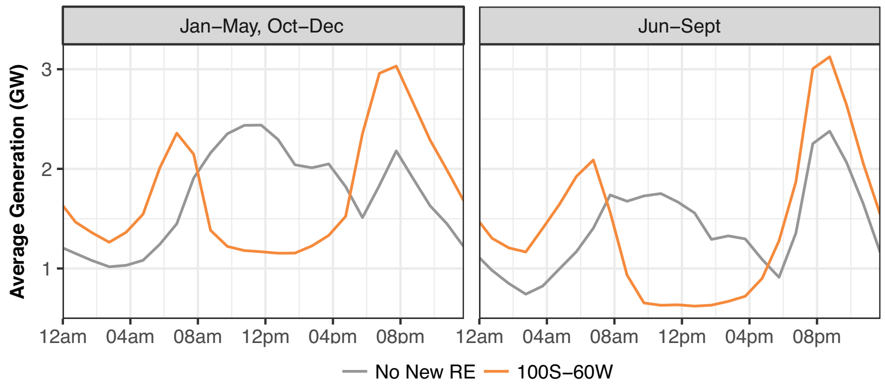
One week of coal operation in Karnataka



The coal fleet is committed much less and operates at or near minimum generation more in the 100S-60W scenario.

Changes to Karnataka's Hydro Fleet Operations

Average day of hydro in Karnataka by season



Minimum generation limits and higher hydro energy availability during the nonmonsoon season hinder the ability of hydro to shift generation to net load peaks as it does more fully in June through September.

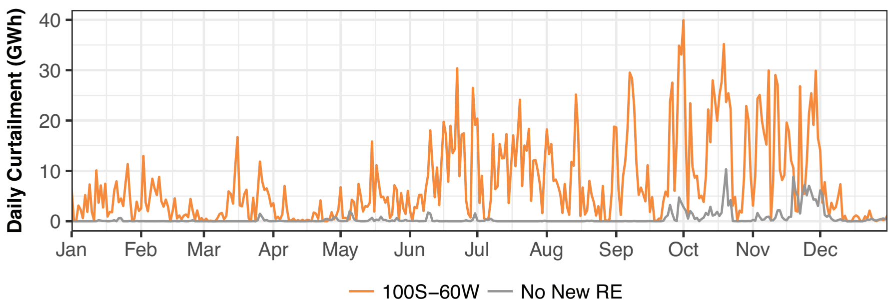
Hydro plants follow a more pronounced two-peak generation profile due to availability of solar power during the middle of the day.

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.

6.6% of wind and solar is curtailed annually.

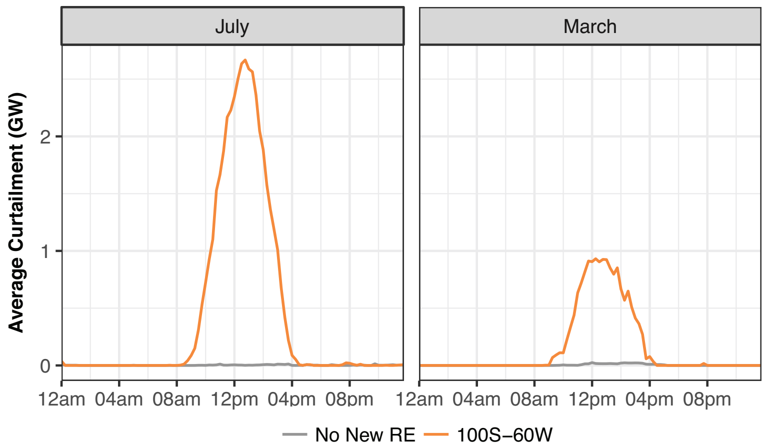
Total daily curtailment throughout the year in Karnataka



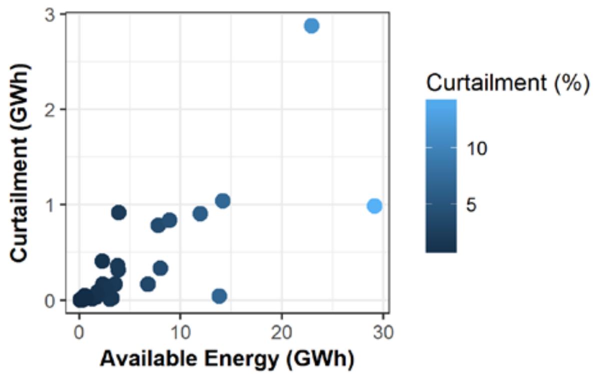
Karnataka experiences the highest RE curtailment as a percent of available capacity in the Southern region, particularly in October and November when curtailment exceeds 18%. It has the lowest ratio of thermal to RE capacity in the region, making curtailment sensitive to minimum coal generation levels, transmission constraints, and trade barriers.

Almost all of RE curtailment occurs in 11% of periods in the year.

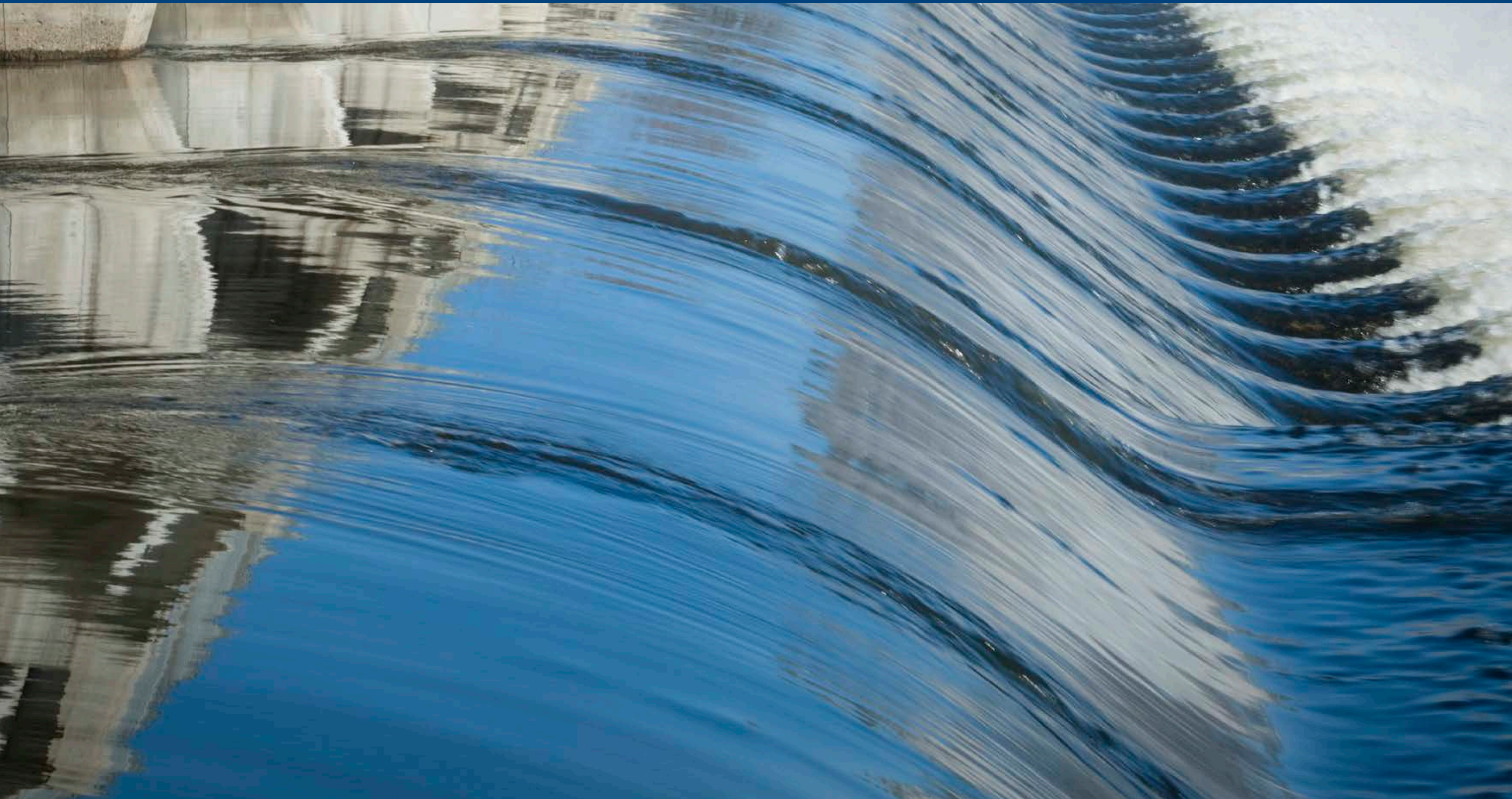
Average daily curtailment in March and July in Karnataka



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



Examples of Dispatch During Interesting Periods in Karnataka

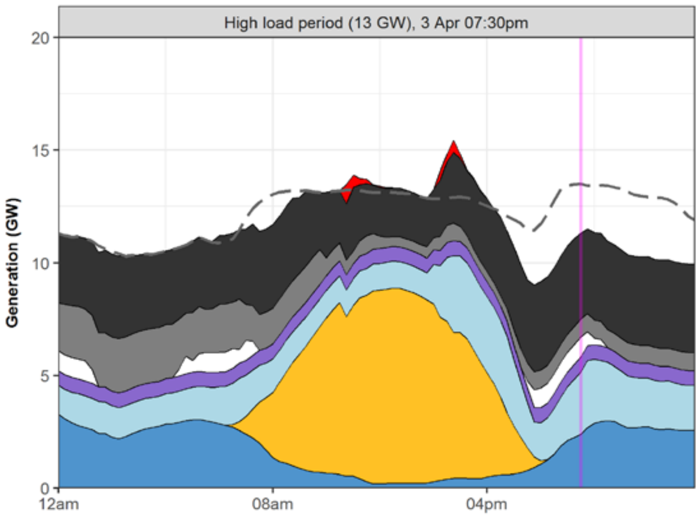


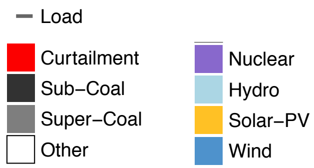
The following pages show dispatch in Karnataka during several interesting periods throughout 2022. The vertical magenta line highlights the dispatch interval associated with the figure title.

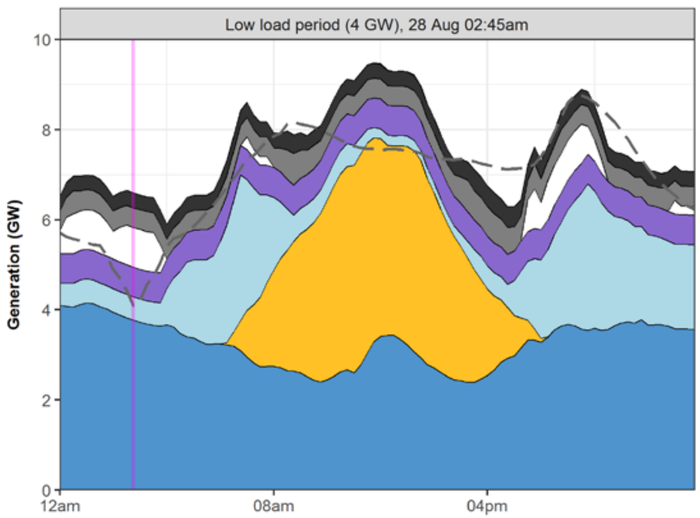
High load period: Generation, load, and interchange (values in GW unless otherwise specified)

3 April 7:30 pm

LOAD	CURTAILMENT	HYDRO	NUCLEAR	OTHER	COAL	RE	NET IMPORTS	RE PENETRATION (%)
13.5	0	2.8	0.7	0.9	4.6	2.4	2.2	18







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

28 August 2:45 am

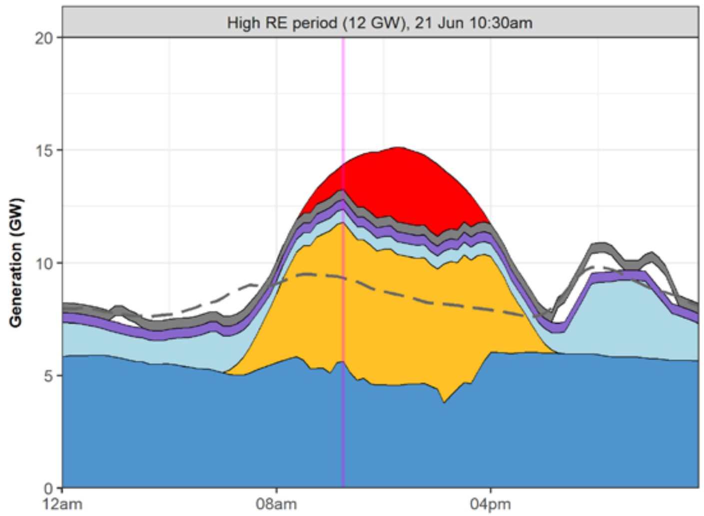
LOAD	CURTAILMENT	HYDRO	NUCLEAR	OTHER	COAL	RE	NET EXPORTS	RE PENETRATION (%)
4.1	0	0.5	0.7	0.9	0.8	3.8	2.5	92

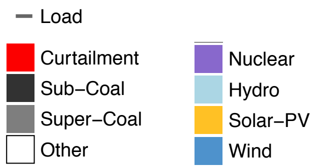
Example Dispatch Days

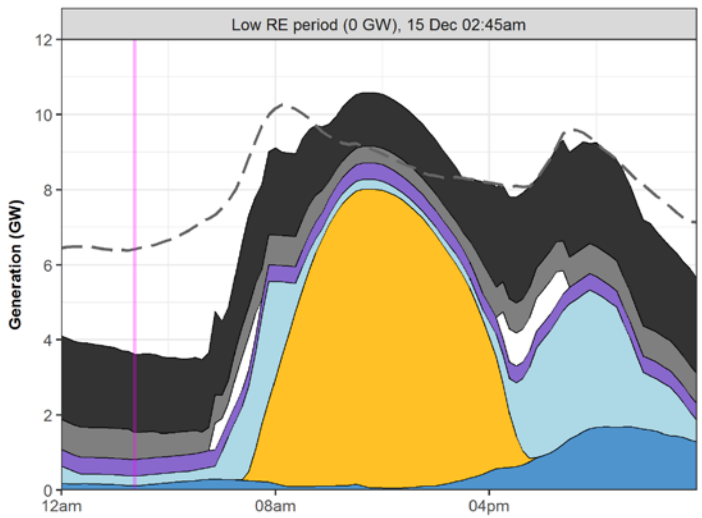
High RE period: Generation, load, and interchange (values in GW unless otherwise specified)

21 June 10:30 am

LOAD	CURTAILMENT	HYDRO	NUCLEAR	OTHER	COAL	RE	NET EXPORTS	RE PENETRATION (%)
9.3	1.1	0.6	0.4	0	0.4	11.8	3.9	126







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

15 December 2:45 am

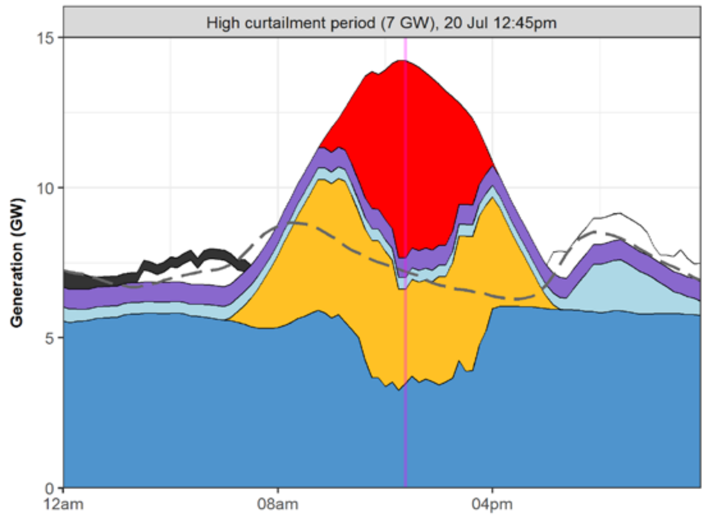
LOAD	CURTAILMENT	HYDRO	NUCLEAR	OTHER	COAL	RE	NET IMPORTS	RE PENETRATION (%)
6.4	0	0.3	0.4	0	2.8	0.1	2.8	1.9

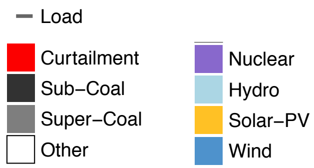
Example Dispatch Days

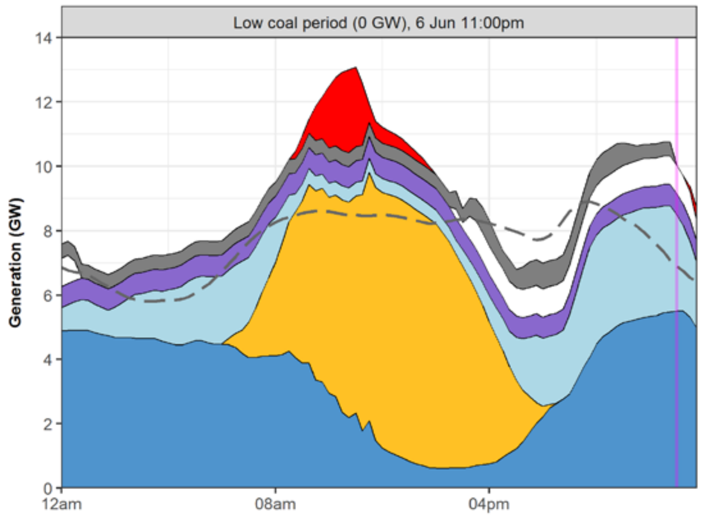
High curtailment period: Generation, load, and interchange (values in GW unless otherwise specified)

20 July 12:45 pm

LOAD	CURTAILMENT	HYDRO	NUCLEAR	OTHER	COAL	RE	NET EXPORTS	RE PENETRATION (%)
7.2	6.6	0.4	0.7	0	0	6.6	0.4	92





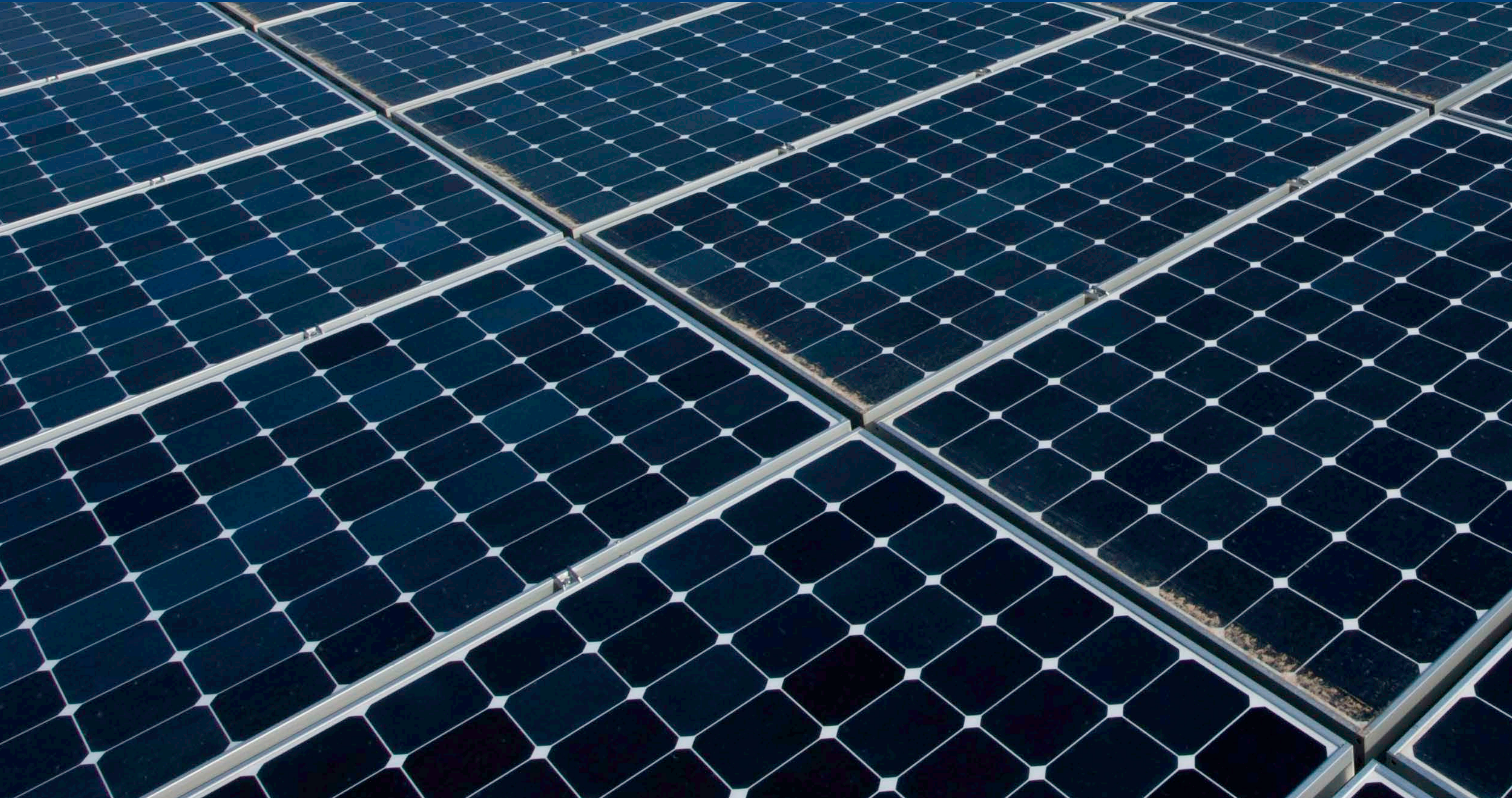


Low coal period: Generation, load, and interchange (values in GW unless otherwise specified)

6 June 11:00 pm

LOAD	CURTAILMENT	HYDRO	NUCLEAR	OTHER	COAL	RE	NET EXPORTS	RE PENETRATION (%)
6.9	0	3	0.7	0.9	0	5.5	3.1	80

Conclusions



Based on this study's assumptions about demand and installed generation and transmission capacity in Karnataka and nationwide, Karnataka can integrate the equivalent of 48% of its total generation in 2022 with 6.6% annual wind and solar curtailment. The RE changes the way Karnataka's grid must operate. Compared to a 2022 system with no new RE, net exports rise by 111% annually, and the PLF of the coal fleet falls from 47% to 28%.

Lowering coal minimum generation levels from 70% to 55% in all states particularly helps Karnataka in reducing the risk of RE curtailment. Karnataka also benefits from added transmission capacity (beyond Central Electricity Authority 2021–2022 plans) to Maharashtra, which typically has flexible thermal capacity available.

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 Karnataka in the 100S-60W scenario

	OWNERSHIP	TOTAL CAPACITY (GW)
Hydro	State/Private	3.7
Nuclear	Central	0.9
Other	State/Private	0.9
Sub-Coal	State/Private	5.6
Super-Coal	Central	2.4
Total non-RE		13.5
Solar-PV	State/Private	11.0
Wind	State/Private	6.2
Total RE		17.2
Total capacity		**30.7**

Total capacity (surge impedance limit [SIL]) of transmission lines connecting Karnataka 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
Karnataka to Andhra Pradesh	220	2
Karnataka to Andhra Pradesh	400	16
Karnataka to Andhra Pradesh	765	2
Karnataka to Goa	220	2
Karnataka to Kerala	220	1
Karnataka to Kerala	400	7
Karnataka to Maharashtra	220	2
Karnataka to Maharashtra	765	4
Karnataka to Maharashtra*	400	3
Karnataka to Odisha	400	2
Karnataka to Tamil Nadu	230	1
Karnataka to Tamil Nadu	400	10
Karnataka to Telangana	220	2
Total import/export capacity		**55**

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

CONNECTING	VOLTAGE (kV)	NO. LINES
Intrastate	220	430
Intrastate*	400	120
Total intrastate capacity		**550**

RE capacity by substation and type		
SUBSTATION (NUMBER_NAME_VOLTAGE)	**SOLAR-PV (MW)**	**WIND (MW)**
522023_KUDUCHI_220	0	56
522024_ATHANI_220	0	294
522025_SOUNDATI_220	0	53
522026_CHIKKODI_220	0	72
522027_GHATPRBH_220	0	20
522033_BELG_220	0	11
522036_DAVA_220	272	164
522041_HAVR_220	0	223
522058_MLNG_220	28	28
522068_SHIM_220	44	0
522072_TALLAK_220	239	366
522104_CHITRDRG_220	391	379
522113_RANIBNNR_220	16	34
522115_HONNALI_220	0	161
522136_DHONI_220	913	414
522137_HARTI2_220	24	131
522143_KANABRGI_220	0	47

RE capacity by substation and type		
SUBSTATION (NUMBER_NAME_VOLTAGE)	**SOLAR-PV (MW)**	**WIND (MW)**
522154_HASSAN-KAR_220	0	110
522203_HOSUDURGA_220	15	118
524001_SMNH_400	171	142
524002_MNRB_400	2,806	132
524003_RAIC_400	525	0
524004_DAVAN4_400	30	333
524005_HOODI4_400	1,598	134
524007_NELMANG4_400	309	50
524009_HASSAN4_400	0	15
524011_KOLAR_400	209	2,058
524013_RAIC-NEW_400	304	0
524044_HIRY_400	738	177
524047_NAREND-4_400	156	106
524076_TORNGL4_400	1,451	263
524077_BIDADI_400	15	0
524082_BELLARY_400	992	108
Total RE capacity	**11,246**	**6,199**

Annual energy generation fuel type, No New RE and 100S-60W		
	NO NEW RE (TWh)	100S-60W (TWh)
Hydro	14	14
Nuclear	5	5
Other	2	3
Solar-PV: rooftop	4	0
Solar-PV: utility scale	15	0
Sub-Coal	11	23
Super-Coal	8	9
Wind	19	8
Total Generation	79	63
Imports	27	42
Exports	28	28
RE Curtailment	3	0