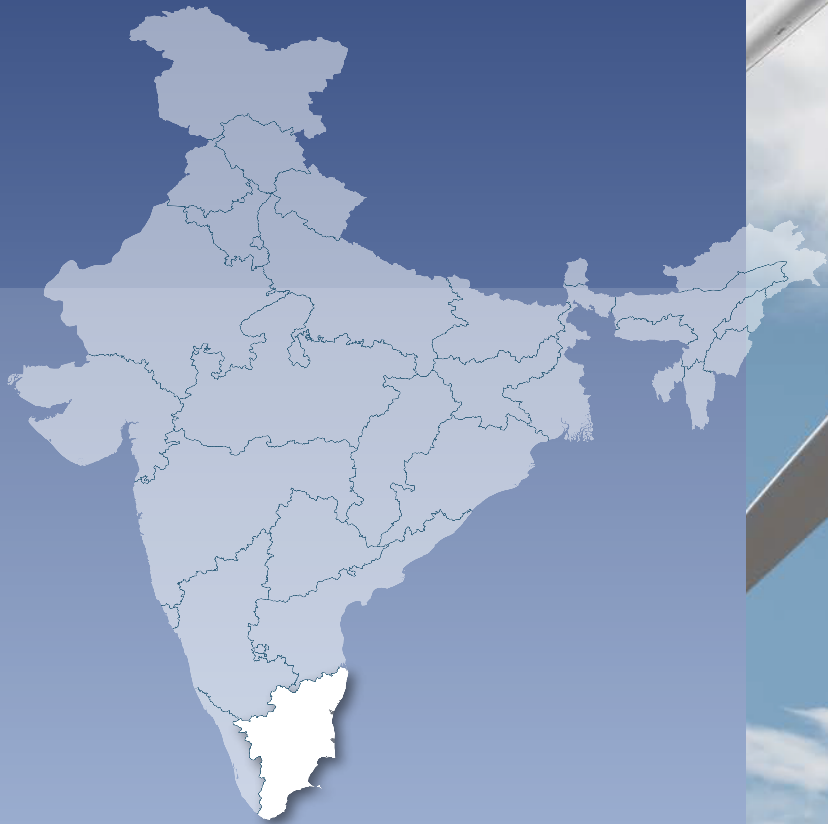
Greening the Grid



Tamil Nadu

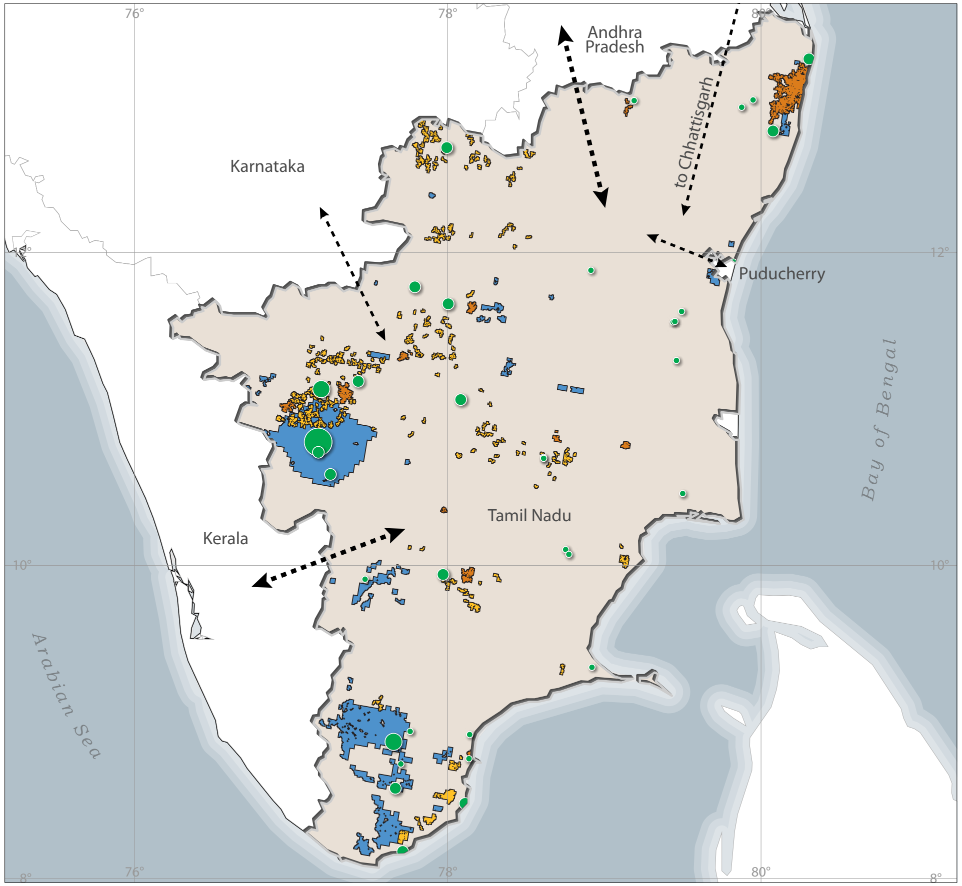
Pathways to Integrate 175 Gigawatts of Renewable Energy into India's Electric Grid

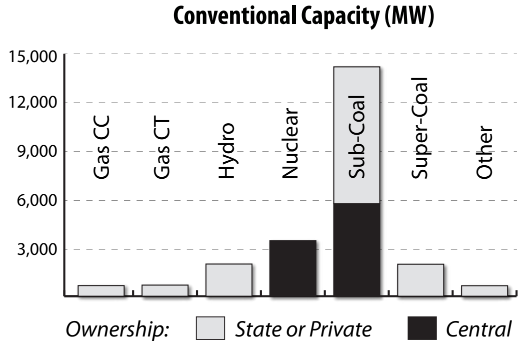
State-specific results from Volume II, which includes all of India. The full reports include detailed explanations of modeling assumptions, results, and policy conclusions.

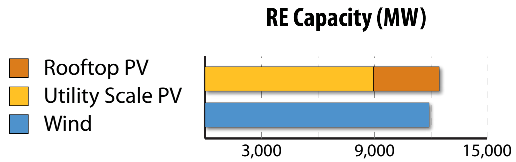
www.nrel.gov/india-grid-integration/

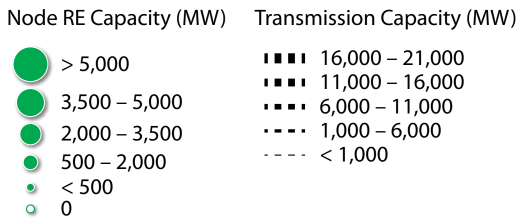
Assumptions About Infrastructure, Demand, and Resource Availability in 2022

Assumptions about RE and conventional generation and transmission in Tamil Nadu in 2022









Peak load (GW)	25
Total annual load (TWh)	316
Installed non-RE capacity (GW)	24
Installed RE capacity (GW)	24
Total import/export capacity (GW)	29

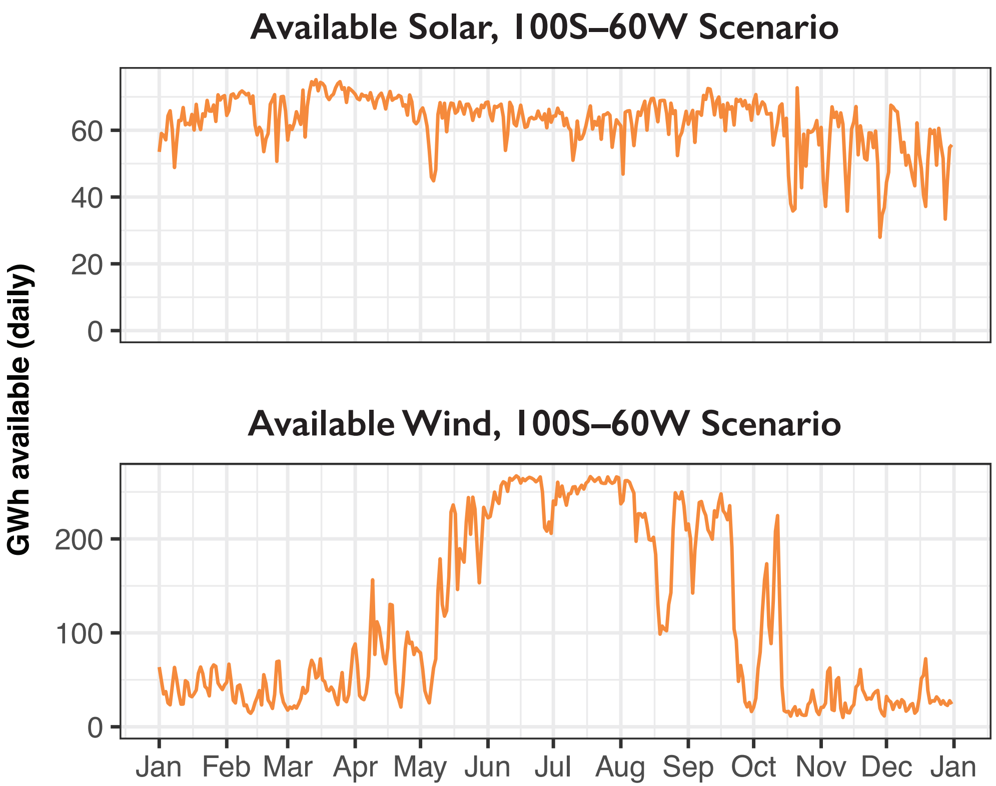
Tamil Nadu has 35 tie-lines connecting it to other states in this model.

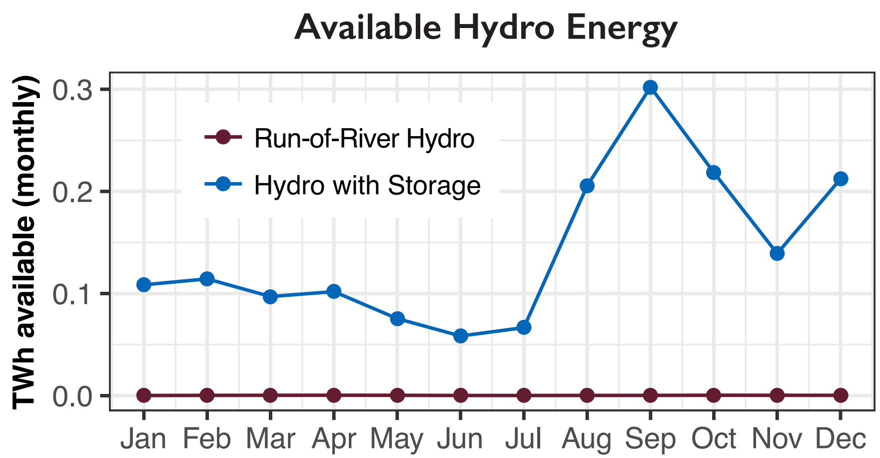
NREL and LBNL selected RE sites based on the methodology explained in Volume I of this report, which is available at www.nrel.gov/docs/fy17osti/68530.pdf.

Rooftop PV has been clubbed to the nearest transmission node.

Tamil Nadu Resource Availability in 2022

Available wind, solar, and hydro energy throughout the year in Tamil Nadu





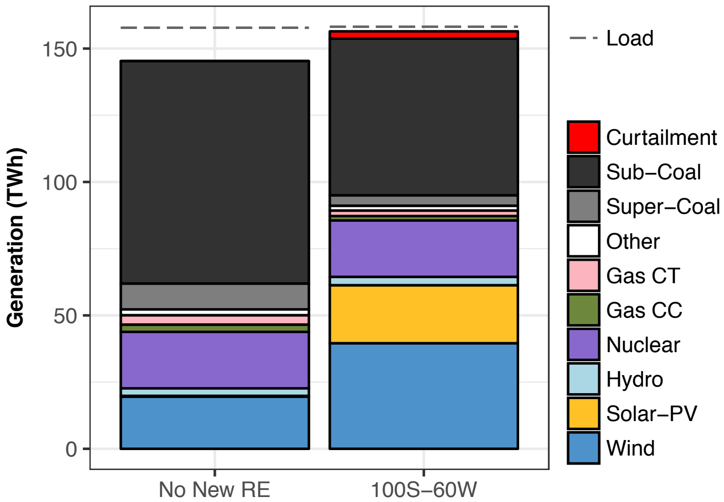
Daily solar energy is relatively consistent throughout the year while wind energy varies seasonally.

Note: Y-axis is different for each resource

Operation in Tamil Nadu with Higher Levels of RE: RE Penetration in 2022

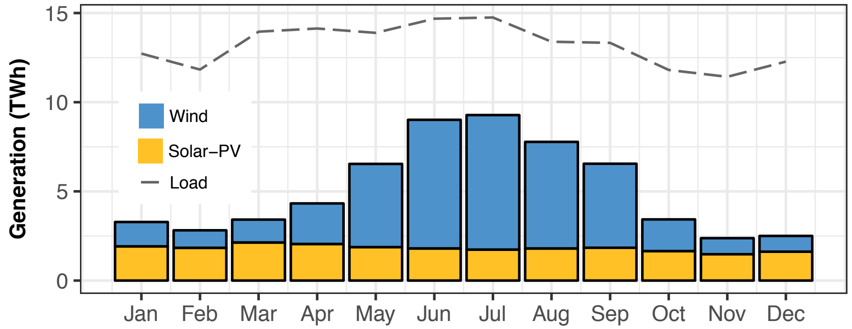
Increased amounts of RE available in Tamil Nadu change Tamil Nadu's generation mix and therefore the operation of the entire fleet.

Annual energy generation in Tamil Nadu



24 GW of wind and solar power generates 61 TWh annually.

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



Wind and solar produce 40% of total generation in Tamil Nadu and meet 39% of load.

RE penetration by load and generation

	100S-60W
Percent time over 50% of load	33
Peak RE % of load	100
Percent time over 50% of generation	37
Peak RE % of generation	82

Coal generation falls by 33% and gas by 41% between No New RE and 100S-60W.

Operation in Tamil Nadu with Higher Levels of RE: Imports and Exports

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

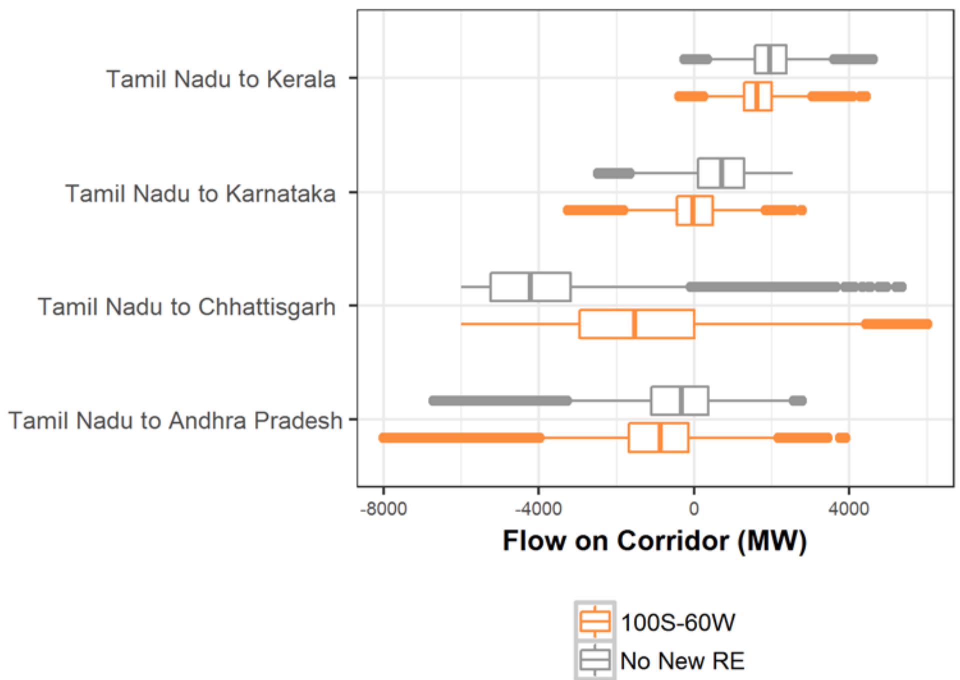
Tamil Nadu's increased RE generation allows it to reduce imports from Chhattisgarh. The state also reduces its net exports to Karnataka, Kerala, and Andhra Pradesh, which likewise are relying more on their local RE generation. The shift in flows away from traditional corridors contributes to a 56% increase in periods when in-state congestion affects dispatch.

Imports fall by **11%** annually

Exports fall by **16%** annually

SCENARIO	NET EXPORTS (TWH)	
No New RE	-12	net importer
100S-60W	-4.4	net importer

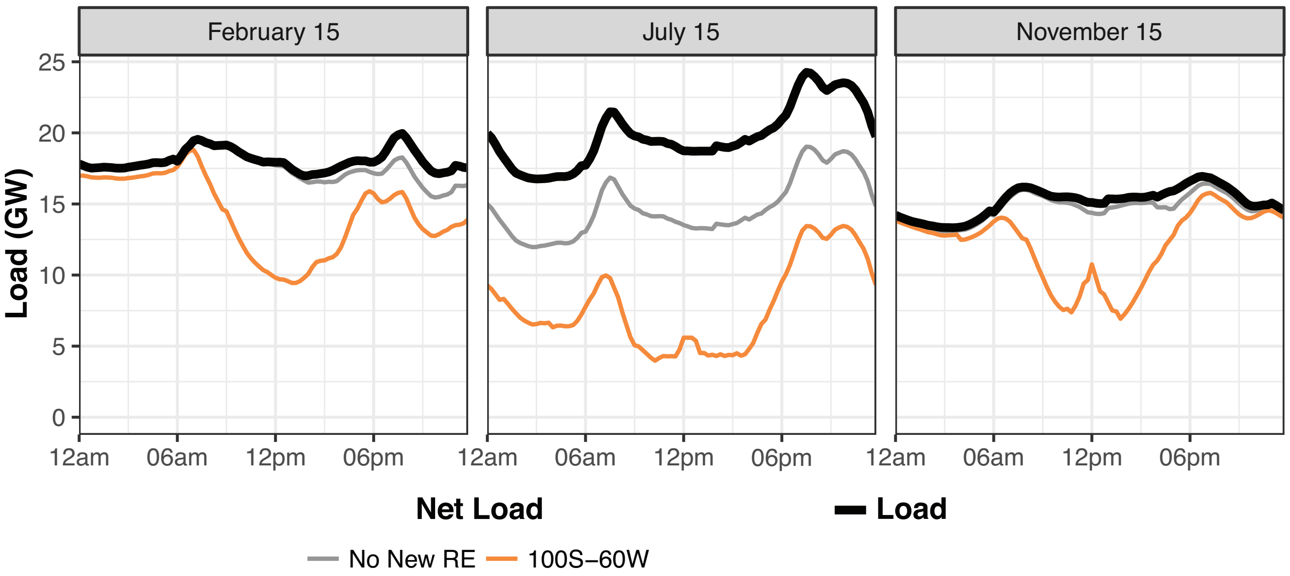
Distribution of flows across state-to-state corridors



Operation in Tamil Nadu with Higher Levels of RE: Rest of the Fleet

The addition of RE in Tamil Nadu 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 Tamil Nadu

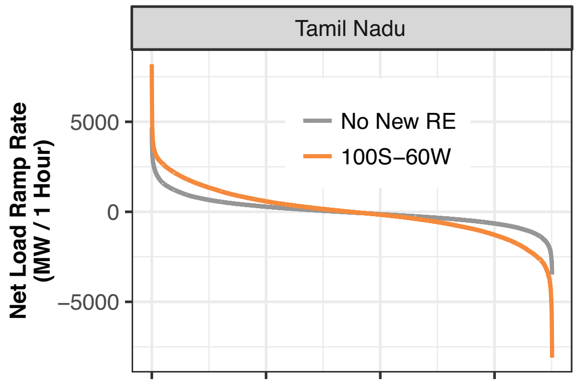


Increased daytime solar generation causes a dip in net load, which requires Tamil Nadu to either increase net exports, turn down its thermal generators, or curtail RE. On 15 July, increased monsoon season wind generation reduces Tamil Nadu's net load throughout the day.

Peak 1-hour net load up-ramp in the **100S-60W scenario is 8.2 GW**, up from **4.7 GW in the No New RE scenario.**

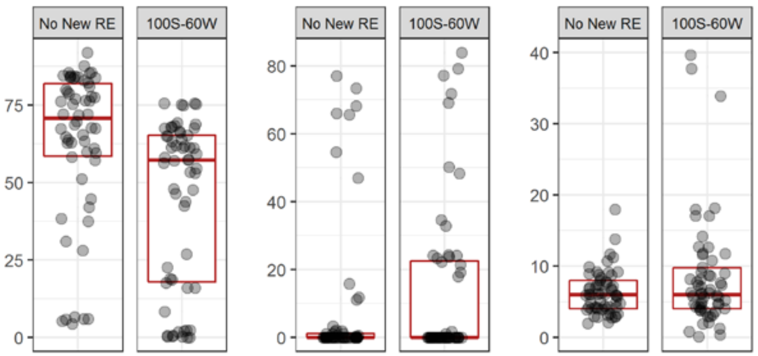
Maximum net load valley-to-peak ramp is **14 GW in the 100S-60W scenario**, up from **8.6 GW in the No New RE scenario.**

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



Changes to Tamil Nadu's Coal Fleet Operations

Operational impacts to coal



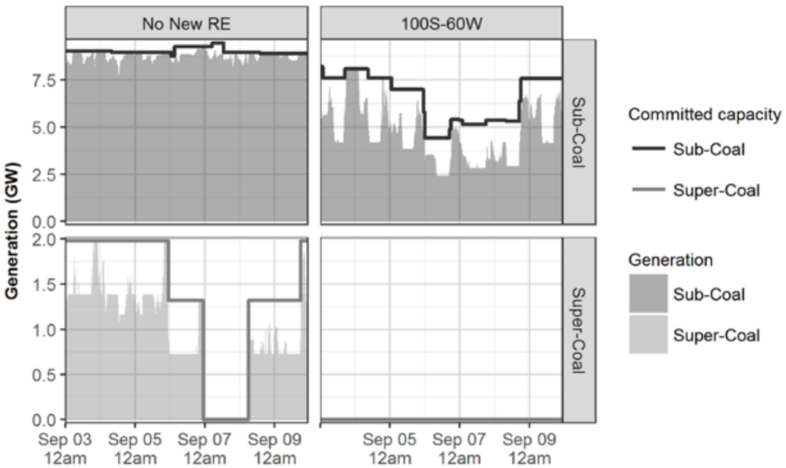
Coal plant load factors (PLFs) are lower in the 100S-60W scenario due to more frequent cycling and operation at minimum generation levels.

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 Tamil Nadu, disaggregated by variable cost

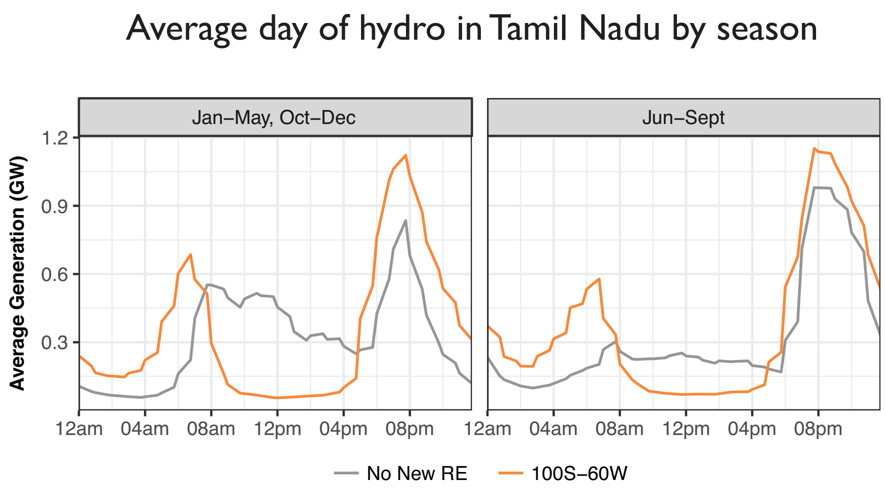
RELATIVE VARIABLE COST	NO NEW RE	100S-60W
Lower 1/3	76	66
Mid 1/3	79	58
Higher 1/3	43	12
Fleetwide	66	44

One week of coal operation in Tamil Nadu



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 Tamil Nadu's Hydro Fleet Operations



Tamil Nadu is able to utilize most of the flexibility available in hydro in both nonmonsoon and monsoon seasons. This is partially aided by the flexibility supplied from pumped hydro.

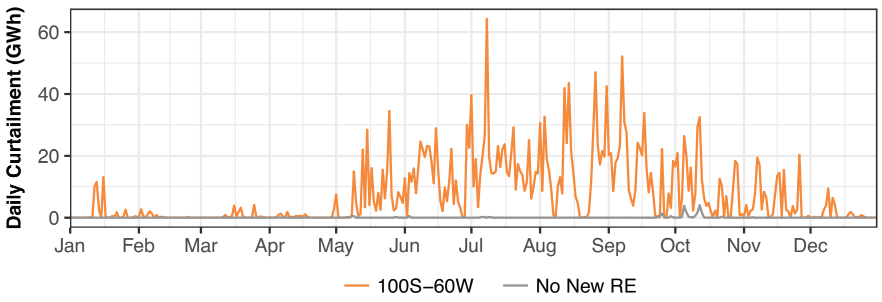
Hydro plants follow a more pronounced two-peak generation profile due to availability of solar power during the middle of the day.

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.

4.3% of wind and solar is curtailed annually.

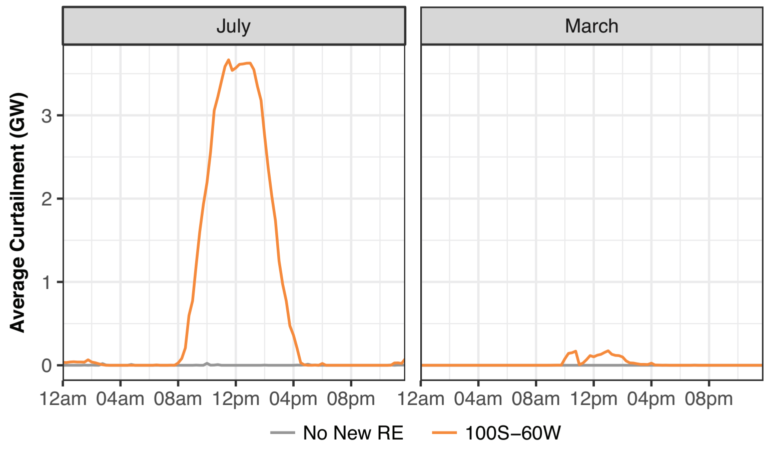
Total daily curtailment throughout the year in Tamil Nadu



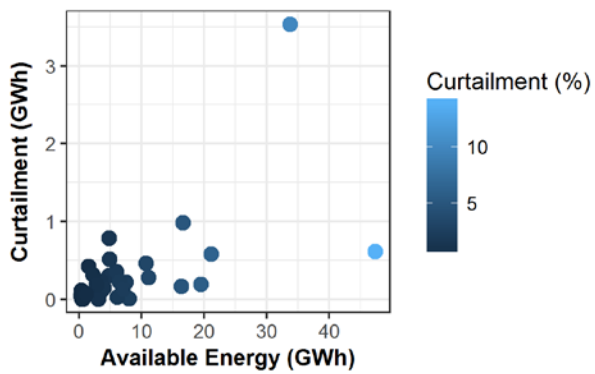
Tamil Nadu's RE curtailment is relatively low from January through April but rises during the monsoon season, and this persists through November. In-state congestion affects its dispatch for 56% of the year, and for 13% of the year its thermal fleet is fully inflexible. Both of these factors contribute to RE curtailment. Tamil Nadu's geographic location can restrict access to external markets, making adequate local thermal and transmission flexibility especially important.

Almost all of RE curtailment occurs in 8.4% of periods in the year.

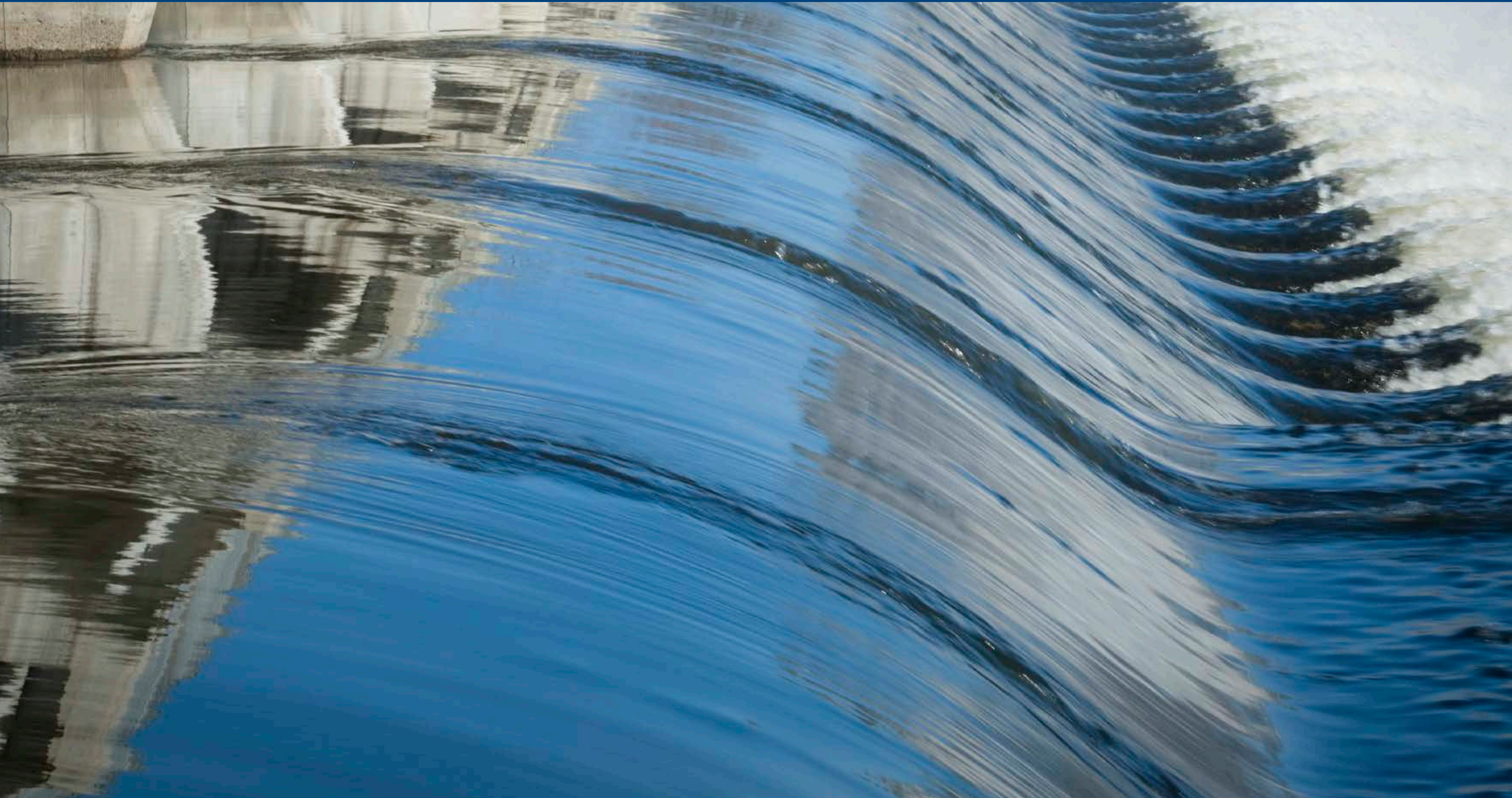
Average daily curtailment in March and July in Tamil Nadu



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



Examples of Dispatch During Interesting Periods in Tamil Nadu

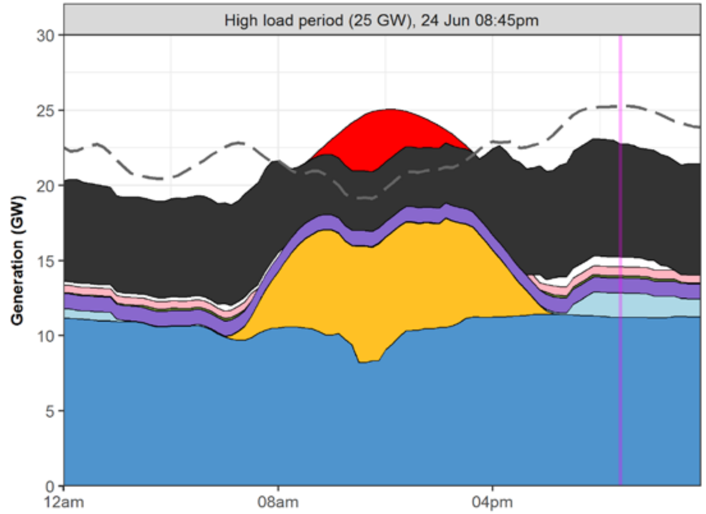


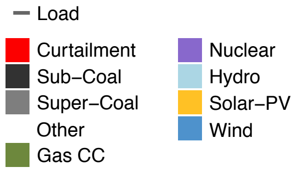
The following pages show dispatch in Tamil Nadu during several interesting periods throughout 2022. The vertical magenta line highlights the dispatch interval associated with the figure title.

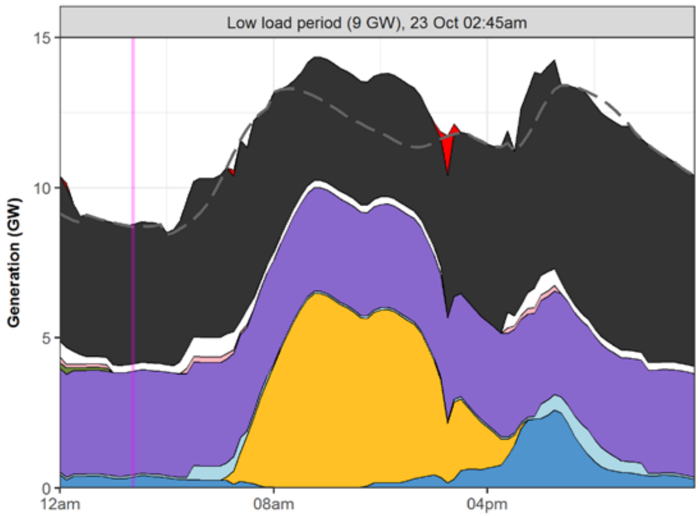
High load period: Generation, load, and interchange (values in GW unless otherwise specified)

24 June 8:45 pm

LOAD	CURTAILMENT	HYDRO	NUCLEAR	OTHER	COAL	GAS	RE	NET IMPORTS	RE PENETRATION (%)
25.3	0	1.6	1	0.6	7.5	0.7	11.2	2.5	44







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

23 October 2:45 am

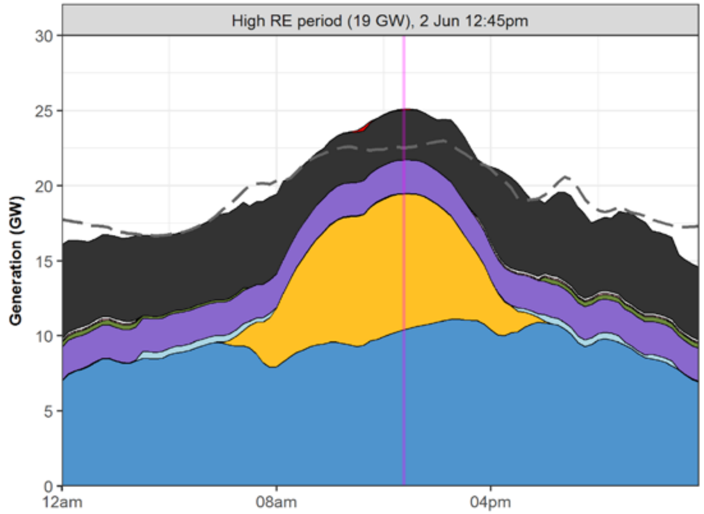
LOAD	CURTAILMENT	HYDRO	NUCLEAR	OTHER	COAL	GAS	RE	NET EXPORTS	RE PENETRATION (%)
8.7	0	0.1	3.4	0.2	4.6	0	0.4	0.1	4.2

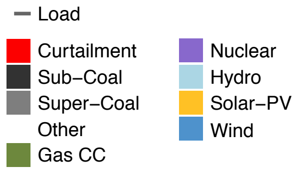
Example Dispatch Days

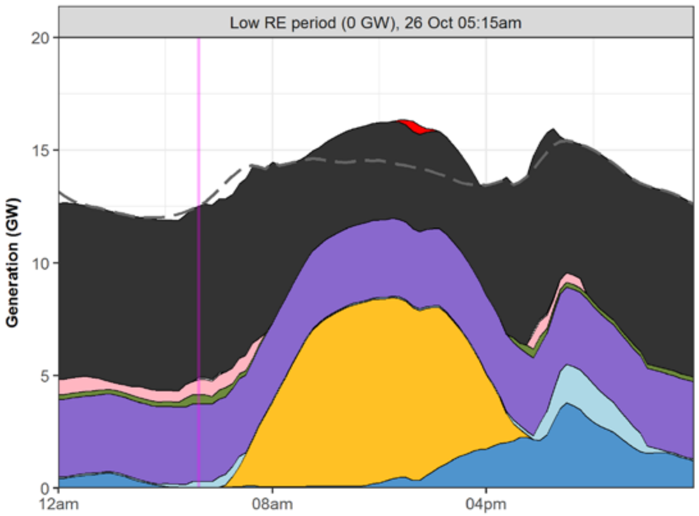
High RE period: Generation, load, and interchange (values in GW unless otherwise specified)

2 June 12:45 pm

LOAD	CURTAILMENT	HYDRO	NUCLEAR	OTHER	COAL	GAS	RE	NET EXPORTS	RE PENETRATION (%)
22.5	0.1	0	2.2	0	3.3	0	19.4	2.5	86







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

26 October 5:15 am

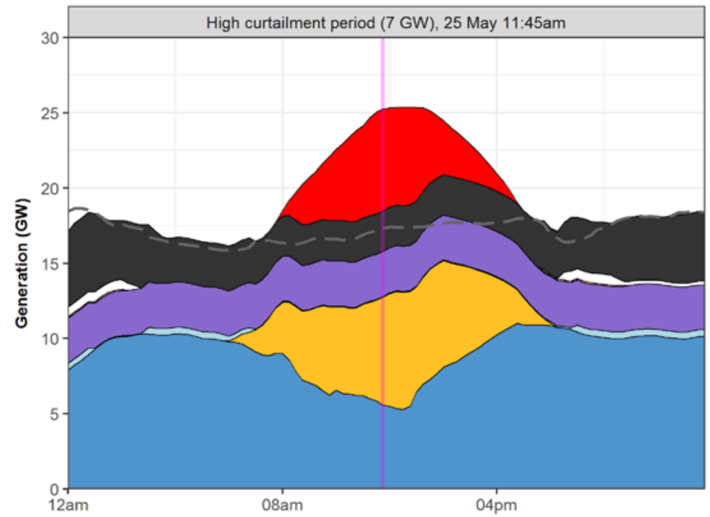
LOAD	CURTAILMENT	HYDRO	NUCLEAR	OTHER	COAL	GAS	RE	NET EXPORTS	RE PENETRATION (%)
12.5	0	0.3	3.4	0.1	7.6	1.1	0	0	0.2

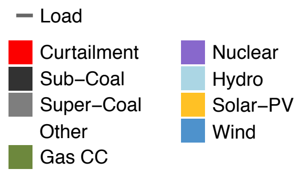
Example Dispatch Days

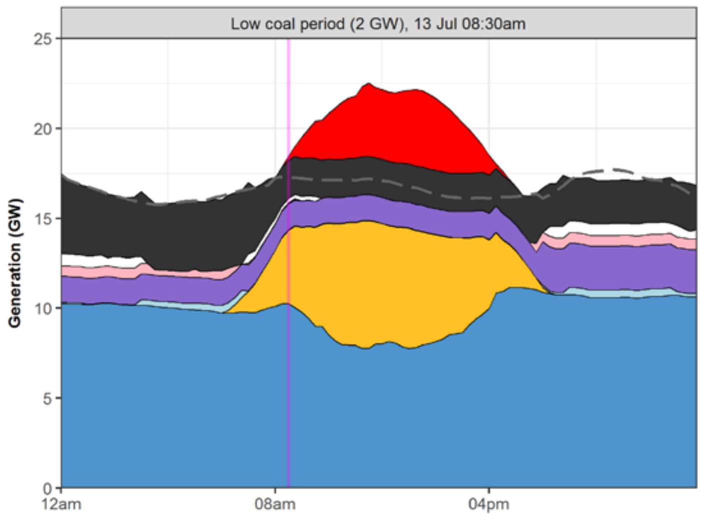
High curtailment period: Generation, load, and interchange (values in GW unless otherwise specified)

25 May 11:45 am

LOAD	CURTAILMENT	HYDRO	NUCLEAR	OTHER	COAL	GAS	RE	NET EXPORTS	RE PENETRATION (%)
17.3	6.8	0	3	0	2.7	0	12.7	1.2	74





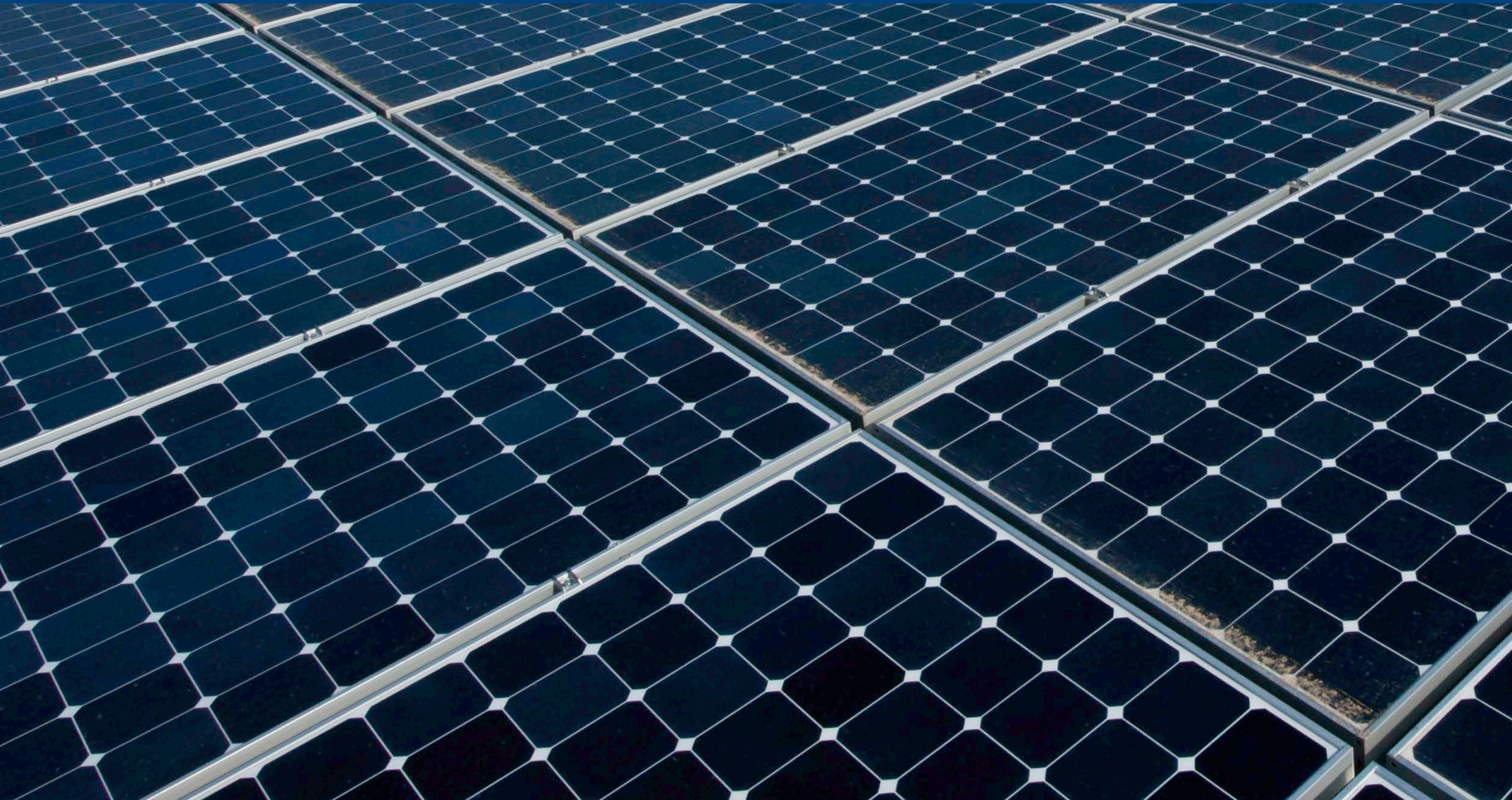


Low coal period: Generation, load, and interchange (values in GW unless otherwise specified)

13 July 8:30 am

LOAD	CURTAILMENT	HYDRO	NUCLEAR	OTHER	COAL	GAS	RE	NET EXPORTS	RE PENETRATION (%)
17.3	0.2	0	1.4	0.2	2.1	0.1	14.4	0.9	83

Conclusions



Based on this study's assumptions about demand and installed generation and transmission capacity in Tamil Nadu and nationwide, Tamil Nadu can integrate the equivalent of 40% of its total generation in 2022 with 4.3% annual wind and solar curtailment. This changes the way Tamil Nadu's grid must operate. Compared to a 2022 system with no new RE, net exports rise by 36% annually, and the PLF of the coal fleet falls from 66% to 44%.

Because Tamil Nadu borders the ocean with limited interstate transmission capacity, it is especially affected by constraints in Andhra Pradesh, in Karnataka, and on the Southern-to-Western-region interface. Regionwide solutions will be especially impactful to Tamil Nadu because of these factors.

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 Tamil Nadu (GW) in the 100S-60W scenario

	OWNERSHIP	TOTAL CAPACITY (GW)
Gas CC	State/Private	0.7
Gas CT	State/Private	0.7
Hydro	State/Private	2.0
Nuclear	Central	3.4
Other	State/Private	0.6
Sub-Coal	Central	5.7
Sub-Coal	State/Private	8.5
Super-Coal	State/Private	2.0
Total non-RE		23.6
Solar-PV	State/Private	12.0
Wind	State/Private	12.0
Total RE		24.0
Total capacity		**47.6**

Total capacity (surge impedance limit [SIL]) of transmission lines connecting Tamil Nadu 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
Tamil Nadu to Andhra Pradesh	230	2
Tamil Nadu to Andhra Pradesh	400	9
Tamil Nadu to Andhra Pradesh	765	6
Tamil Nadu to Chhattisgarh	400	2
Tamil Nadu to Karnataka	230	1
Tamil Nadu to Karnataka	400	10
Tamil Nadu to Kerala	230	5
Tamil Nadu to Kerala*	400	19
Tamil Nadu to Puducherry	230	6
Tamil Nadu to Puducherry	400	2
Total import/export capacity		**62**

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

CONNECTING	VOLTAGE (kV)	NO. LINES
Intrastate	110	87
Intrastate	230	423
Intrastate*	400	194
Intrastate*	765	25
Total intrastate capacity		**729**

RE capacity by substation and type

SUBSTATION (NUMBER_NAME_VOLTAGE)	SOLAR-PV (MW)	WIND (MW)
542014_ARASUR2_230	808	2,881
542015_JAMBNNPRM2_230	303	94
542064_THENI2_230	0	487
542105_KNARPT-W_230	91	2,369
542112_VALUTHUR2_230	58	0
542114_ANIKDV-W_230	0	1,119
542118_SADAYMPLYM-W_230	1,131	238
542170_SANKARPURI_230	24	10
544003_SALE_400	773	156
544004_TRIC_400	301	0
544005_MADURAI4_400	793	15
544006_UDMP_400	0	1,344
544007_HOSUR4_400	1,417	17
544010_NEYEXTN4_400	0	120
544012_NAGAPTNM4_400	86	0

RE capacity by substation and type

SUBSTATION (NUMBER_NAME_VOLTAGE)	SOLAR-PV (MW)	WIND (MW)
544013_PUGALUR4_400	549	68
544014_ARSUR4_400	1,740	596
544017_KARAIK_400	206	0
544018_TIRUNEL4_400	0	232
544021_KUDAN4_400	416	877
544025_TIRUNVLPOOL_400	0	642
544027_KAYATHAR4_400	16	351
544041_METTUR4_400	536	5
544071_TUTICORN_400	600	37
544086_MALEKTT_400	707	107
544087_TIRUVLM_400	63	0
544088_VALLURTPS_400	1,091	10
544095_TUTI-POOL_400	284	116
544133_GUINDY4_400	434	0
Total RE capacity	**12,427**	**11,891**

Annual energy generation fuel type, No New RE and 100S-60W		
	100S-60W (TWh)	NO NEW RE (TWh)
Gas CC	2	3
Gas CT	2	4
Hydro	3	3
Nuclear	21	21
Other	2	2
Solar-PV: rooftop	6	0
Solar-PV: utility scale	15	0
Sub-Coal	59	83
Super-Coal	4	10
Wind	40	20
Total Generation	154	145
Imports	37	52
Exports	33	39
RE Curtailment	3	0