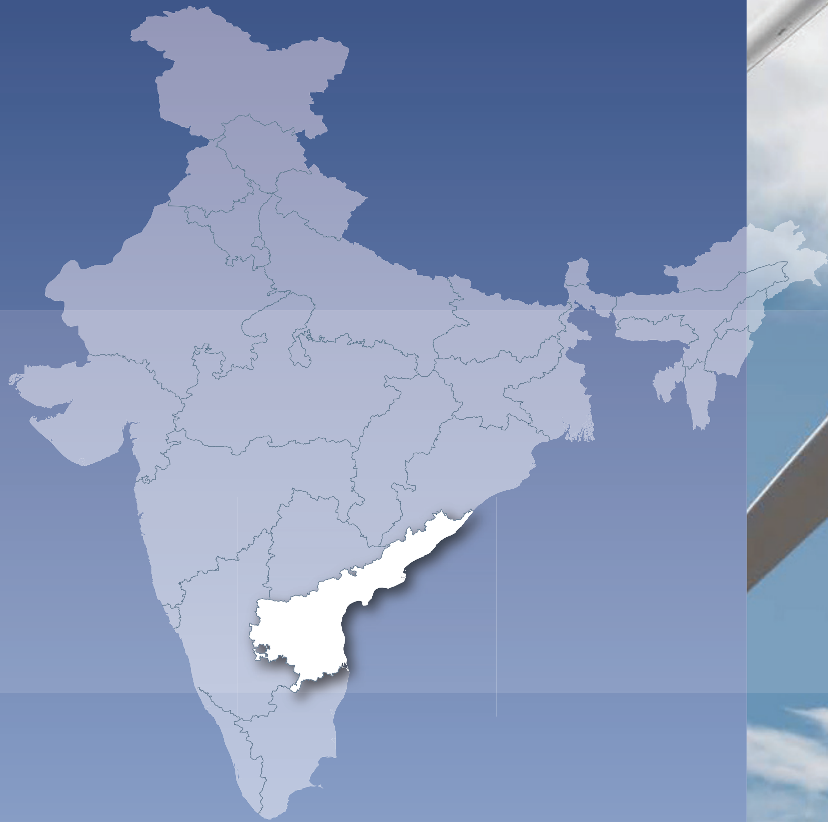
# Greening the Grid

# Andhra Pradesh



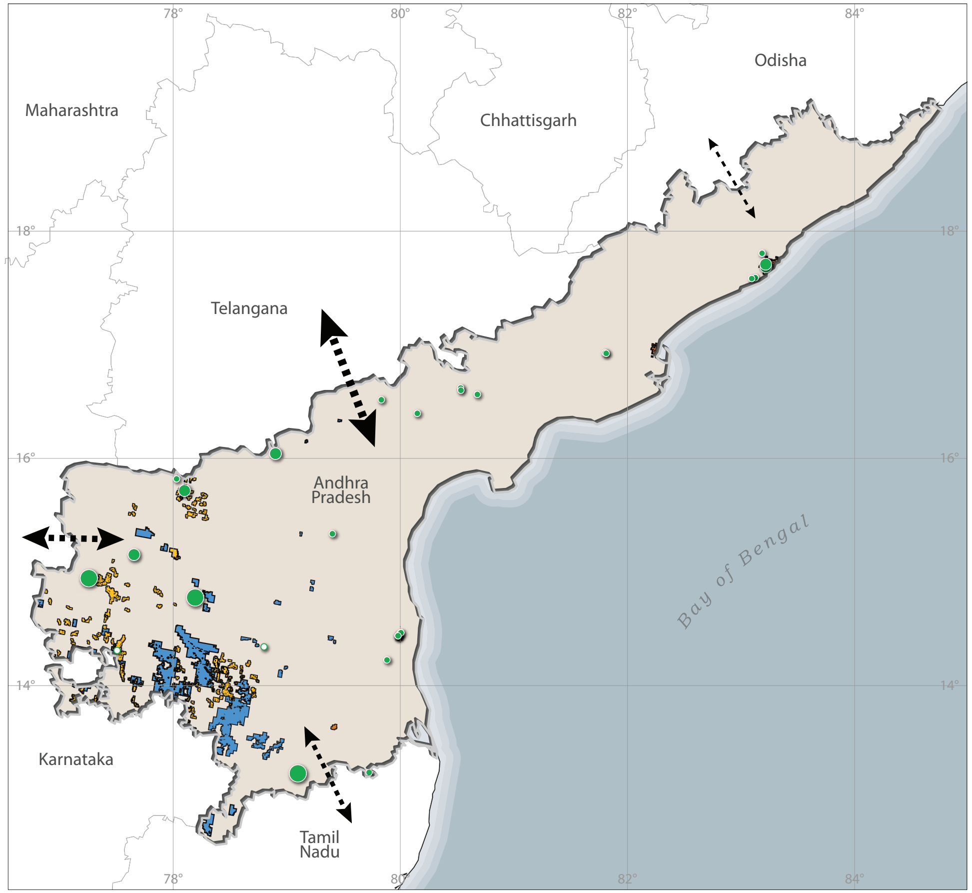
*Pathways to Integrate 175 Gigawatts of Renewable Energy into India's Electric Grid*

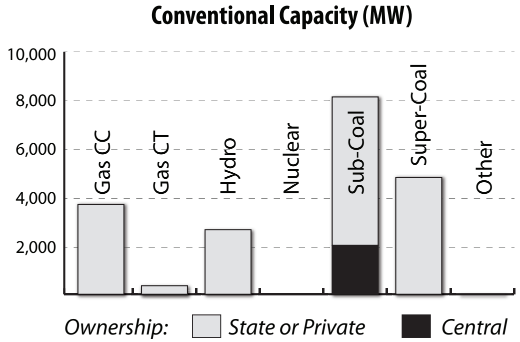
State-specific results from Volume II, which includes all of India. The full reports include detailed explanations of modeling assumptions, results, and policy conclusions.

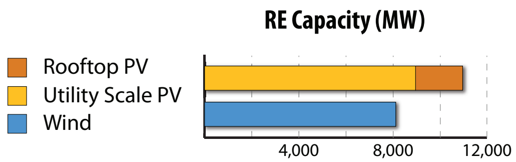
www.nrel.gov/india-grid-integration/

# Assumptions About Infrastructure, Demand, and Resource Availability in 2022

# Assumptions about RE and conventional generation and transmission in Andhra Pradesh in 2022




**Node RE Capacity (MW)**

- > 5,000
- 3,500 – 5,000
- 2,000 – 3,500
- 500 – 2,000
- < 500
- 0

**Transmission Capacity (MW)**

- 16,000 – 21,000
- 11,000 – 16,000
- 6,000 – 11,000
- 1,000 – 6,000
- < 1,000

| | |
|---|---|
| Peak load (GW) | 12 |
| Total annual load (TWh) | 160 |
| Installed non-RE capacity (GW) | 20 |
| Installed RE capacity (GW) | 19 |
| Total import/export capacity (GW) | 47 |

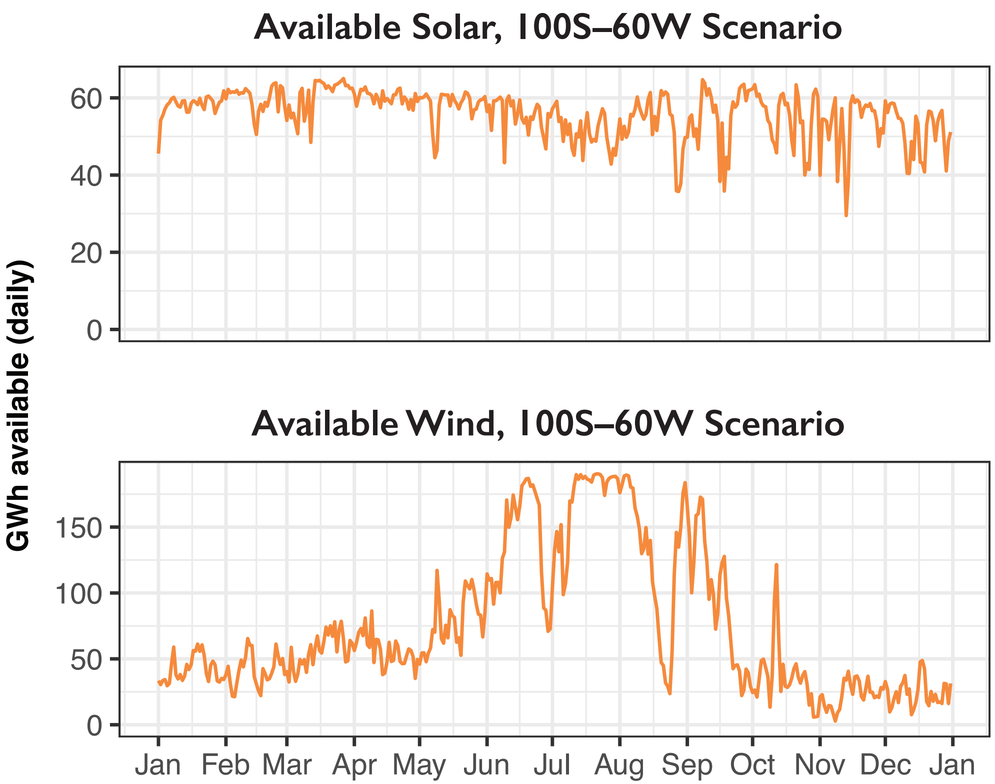
Andhra Pradesh has 50 tie-lines connecting it to other states in this model.

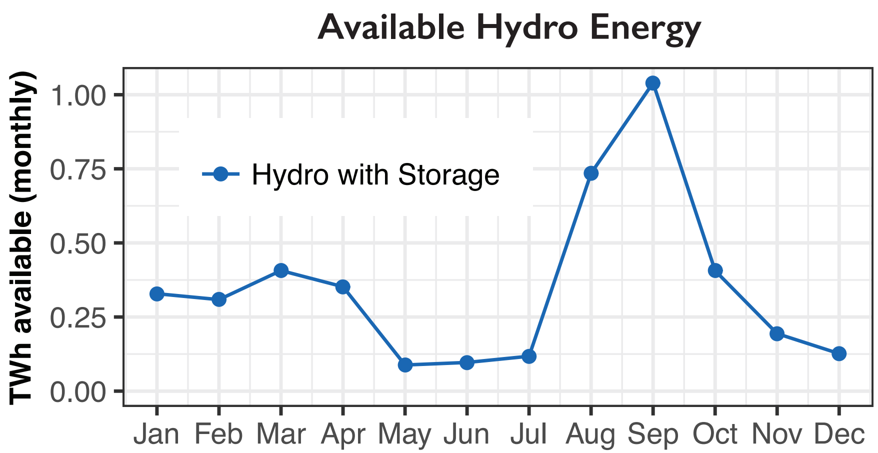
NREL and LBNL selected RE sites based on the methodology explained in Volume 1 of this report, which is available at www.nrel.gov/docs/fy17osti/68530.pdf.

Rooftop PV has been clubbed to the nearest transmission node.

# Andhra Pradesh Resource Availability in 2022

Available wind, solar, and hydro energy throughout the year in Andhra Pradesh



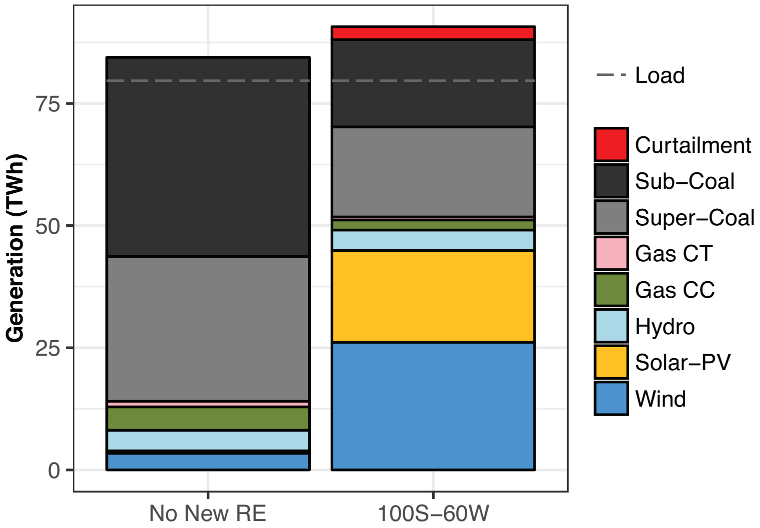

Daily solar energy is relatively consistent throughout the year, while wind energy varies seasonally.

Note: Y-axis is different for each resource

# Operation in Andhra Pradesh with Higher Levels of RE: RE Penetration in 2022

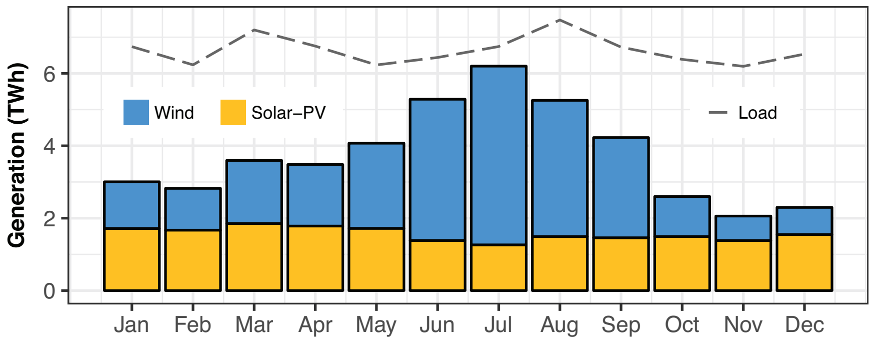
# Increased amounts of RE available in Andhra Pradesh change Andhra Pradesh's generation mix and therefore the operation of the entire fleet.

Annual energy generation in Andhra Pradesh




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

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

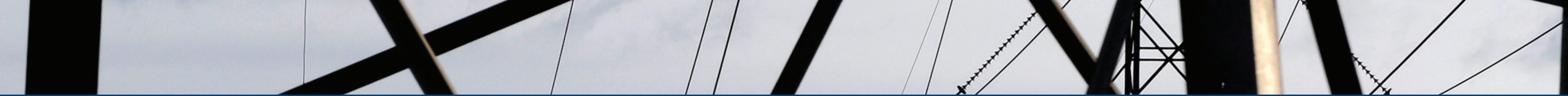



Wind and solar produce 51% of total generation in Andhra Pradesh and meet 56% of load.

RE penetration by load and generation

| | 100S-60W |
|---|---|
| Percent time RE is over 50% of load | 54 |
| Peak RE as a % of load | 180 |
| Percent time RE is over 50% of generation | 51 |
| Peak RE as a % of generation | 98 |

Coal generation falls by 48% and gas by 55% between No New RE and 100S-60W.



# Operation in Andhra Pradesh with Higher Levels of RE: Imports and Exports

# Increased RE generation inside and outside of Andhra Pradesh affects flows with surrounding states.

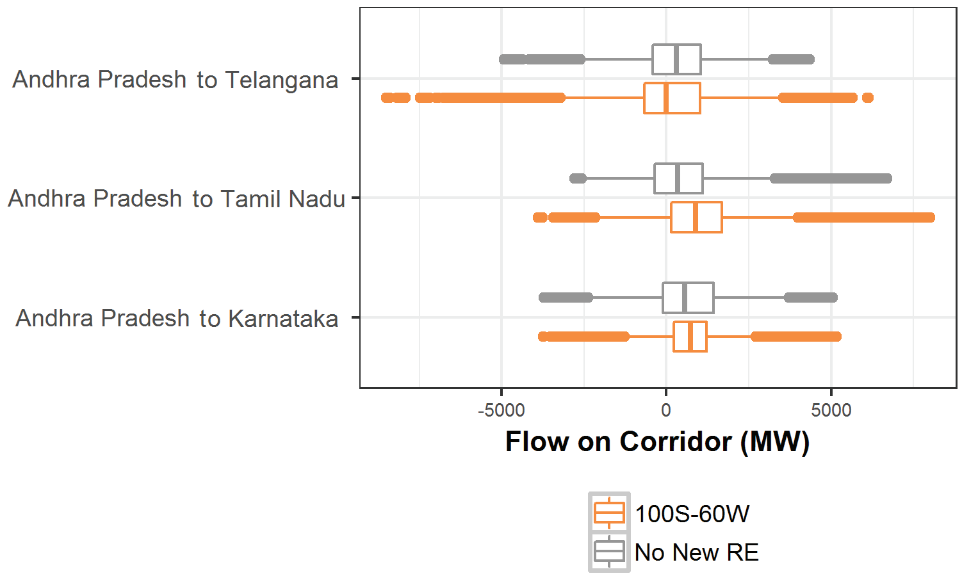
Andhra Pradesh's net exports are nearly double in the 100S-60W scenario compared to No New RE. A large portion of the increase in exports is to Tamil Nadu, which is able to decrease its imports from Chhattisgarh as a result.

**Imports** fall by **6.6%** annually

**Exports** rise by **5.0%** annually

| SCENARIO | NET EXPORTS (TWh) | |
|---|---|---|
| No New RE | 4.8 | net exporter |
| 100S-60W | 8.4 | net exporter |

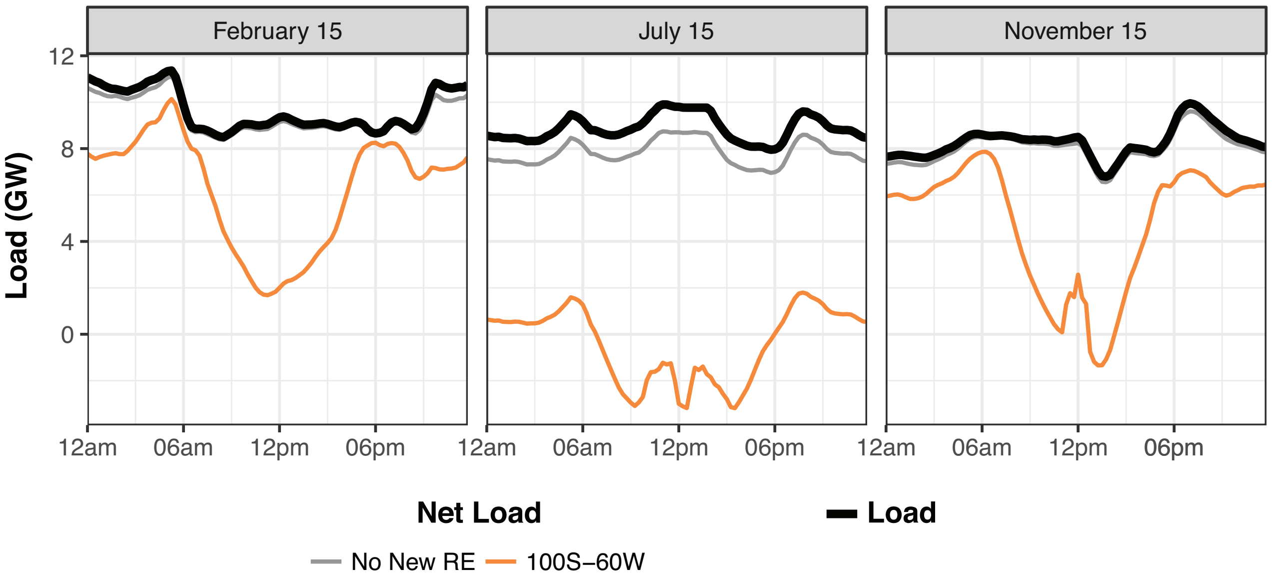
Distribution of flows across state-to-state corridors



# Operation in Andhra Pradesh with Higher Levels of RE: Rest of the Fleet

# The addition of RE in Andhra Pradesh 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 Andhra Pradesh




Increased daytime solar generation causes a dip in net load, which requires Andhra Pradesh to increase net exports, turn down its thermal generators, or curtail RE. For much of the day on 15 July, increased wind generation drives Andhra Pradesh's daytime net load below zero (>100% RE penetration).

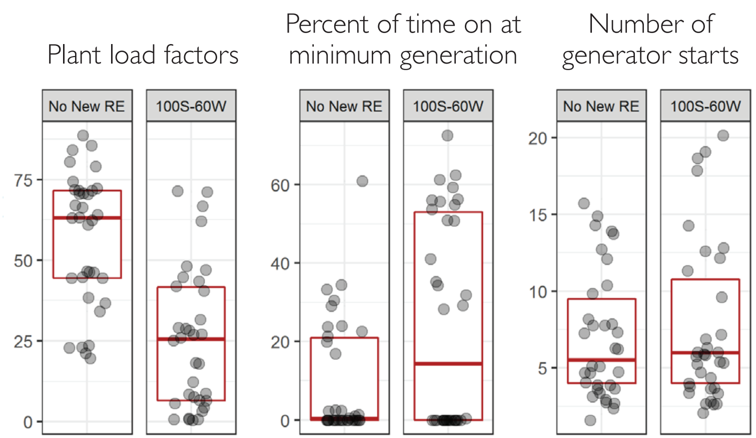
Hourly net load ramps for all periods of the year, ordered by magnitude


Peak 1-hour net load up-ramp in the **100S-60W scenario is 9.1 GW**, up from **2.1 GW in the No New RE scenario.**

Maximum net load valley-to-peak ramp is **13 GW in the 100S-60W scenario**, up from **4.0 GW in the No New RE scenario.**

# Changes to Andhra Pradesh's Coal Fleet Operations

## Operational impacts to coal



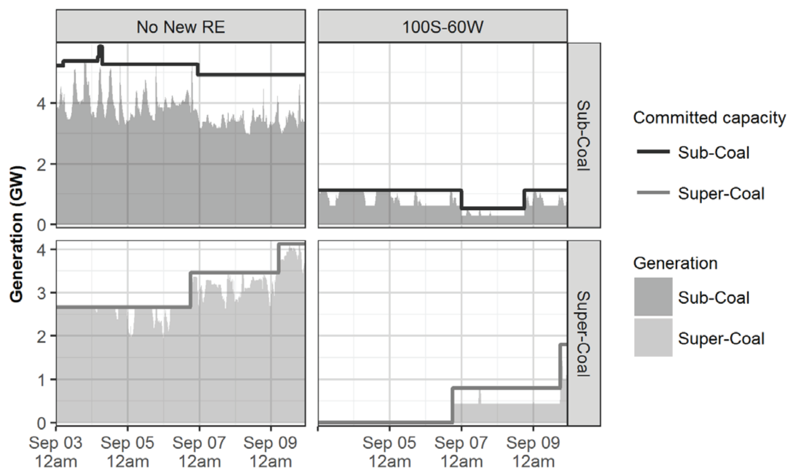

Coal plant load factors (PLFs) are lower in the 100S-60W scenario due to more frequent cycling and operation at minimum generation levels.

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

## Average PLF of coal generators in Andhra Pradesh, disaggregated by variable cost

| RELATIVE VARIABLE COST | NO NEW RE | 100S-60W |
|---|---|---|
| Lowest 1/3 | 73 | 46 |
| Mid 1/3 | 55 | 16 |
| Highest 1/3 | 27 | 1.6 |
| Fleetwide | 63 | 32 |

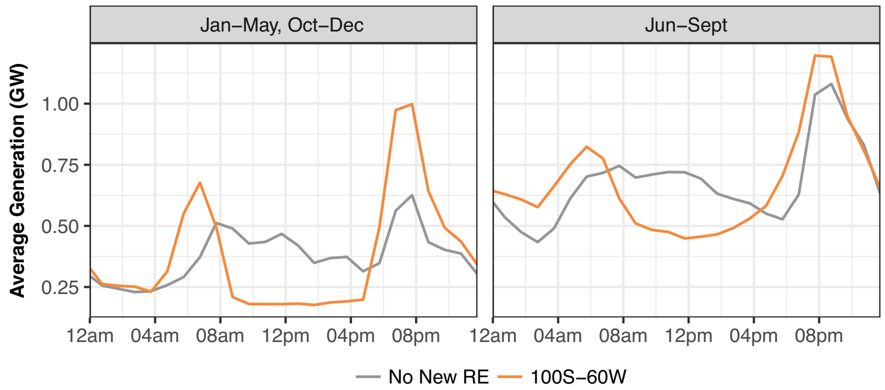
## One week of coal operation in Andhra Pradesh




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

# Changes to Andhra Pradesh's Hydro Fleet Operations

Average day of hydro in Andhra Pradesh 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.

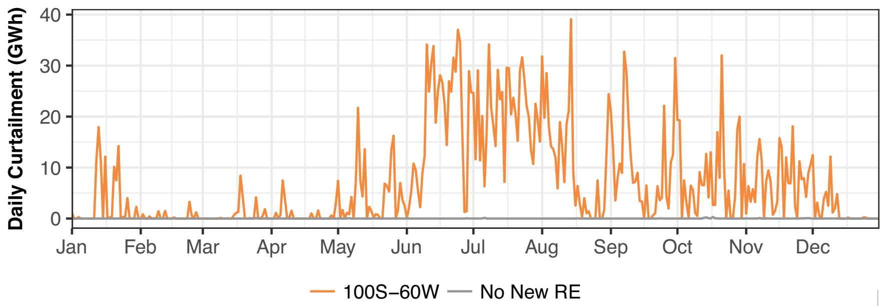
Hydro plants follow a more pronounced two-peak generation profile due to availability of solar power during the middle of the day.

# 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.

5.6% of wind and solar is curtailed annually.

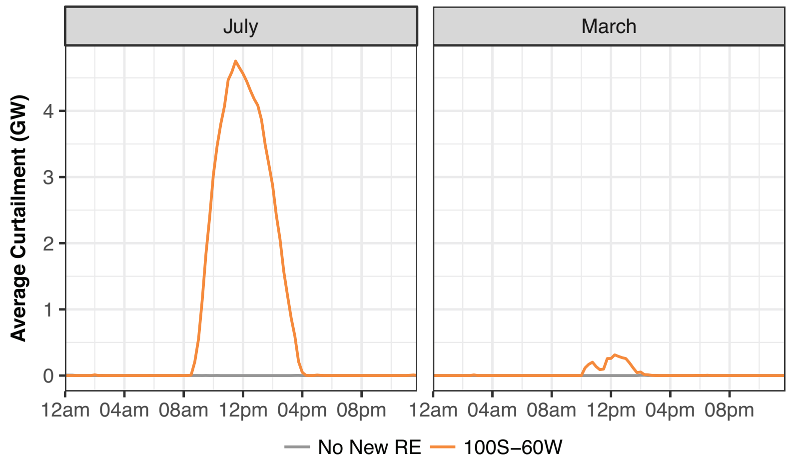
Total daily curtailment throughout the year in Andhra Pradesh



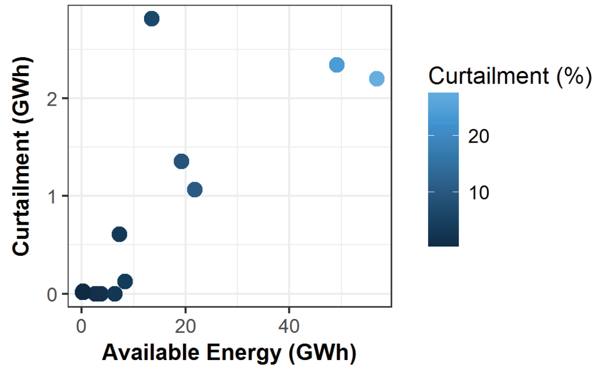

Curtailment is highest in June and July when wind energy is highest. Monthly curtailment is higher than 6% June through November.

Almost all RE curtailment occurs in 7.1% of periods in the year.

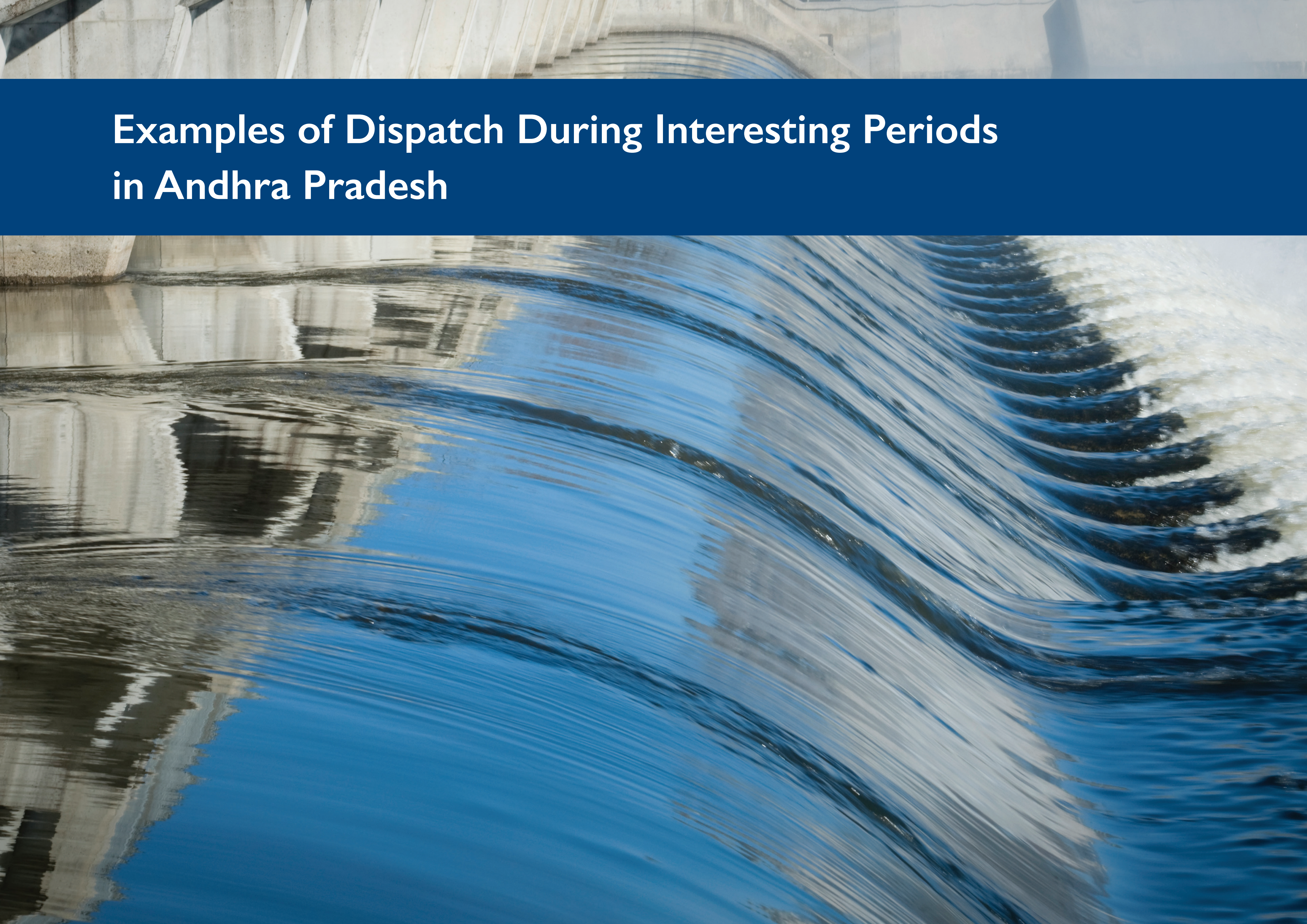
Average daily curtailment in March and July in Andhra Pradesh




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



# Examples of Dispatch During Interesting Periods in Andhra Pradesh

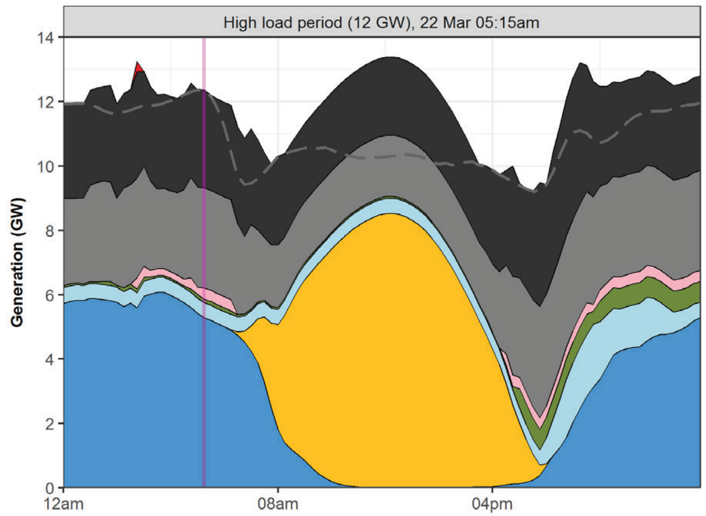


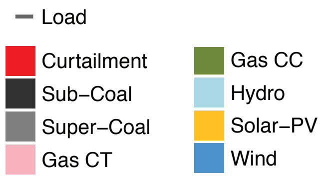
## The following pages show dispatch in Andhra Pradesh during several interesting periods throughout 2022. The vertical magenta line highlights the dispatch interval associated with the figure title.

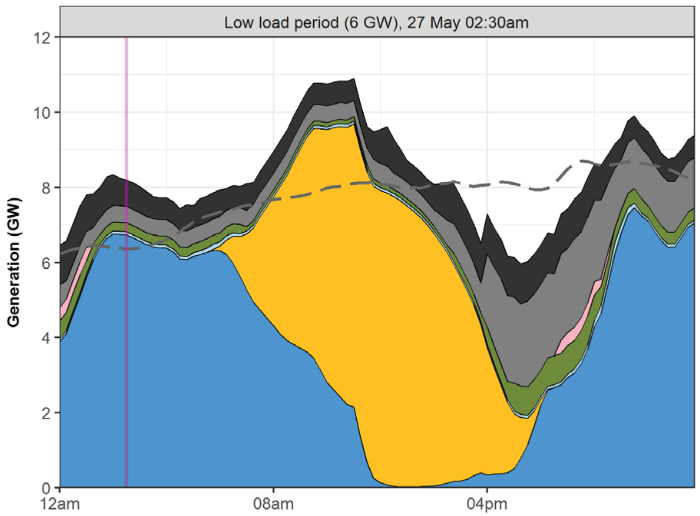
### High load period: Generation, load, and interchange (values in GW unless otherwise specified)

22 March 5:15 am

| LOAD | CURTAILMENT | HYDRO | COAL | GAS | RE | NET EXPORTS | RE PENETRATION (%) |
|---|---|---|---|---|---|---|---|
| 12.4 | 0 | 0.5 | 6.1 | 0.5 | 5.3 | 0 | 43 |




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

27 May 2:30 am

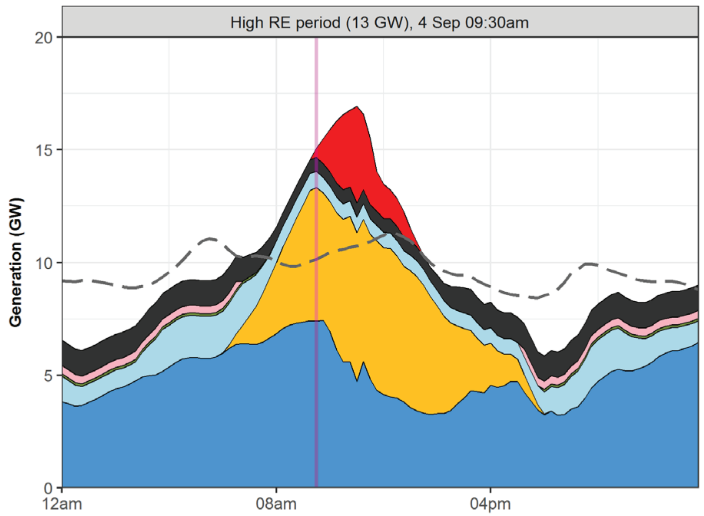
| LOAD | CURTAILMENT | HYDRO | COAL | GAS | RE | NET EXPORTS | RE PENETRATION (%) |
|---|---|---|---|---|---|---|---|
| 6.4 | 0 | 0.1 | 1.1 | 0.2 | 6.7 | 1.8 | 106 |

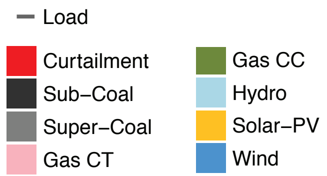
# Example Dispatch Days

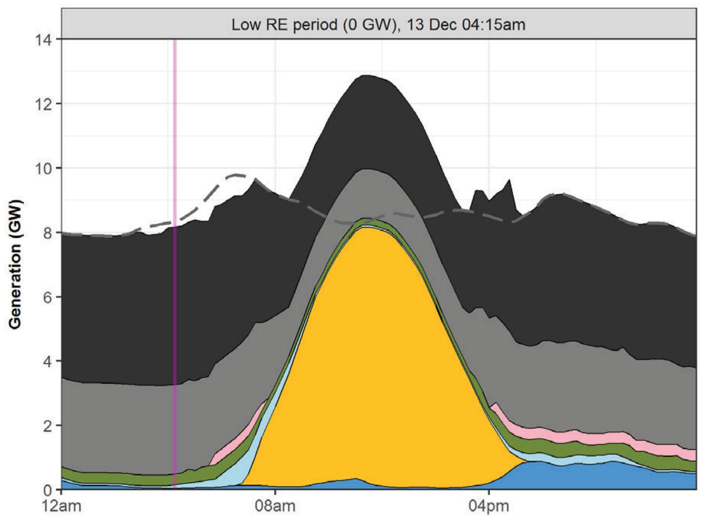
### High RE period: Generation, load, and interchange (values in GW unless otherwise specified)

4 September 9:30 am

| LOAD | CURTAILMENT | HYDRO | COAL | GAS | RE | NET EXPORTS | RE PENETRATION (%) |
|---|---|---|---|---|---|---|---|
| 10.1 | 0.4 | 0.7 | 0.6 | 0 | 13.3 | 4.5 | 131 |




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

13 December 4:15 am

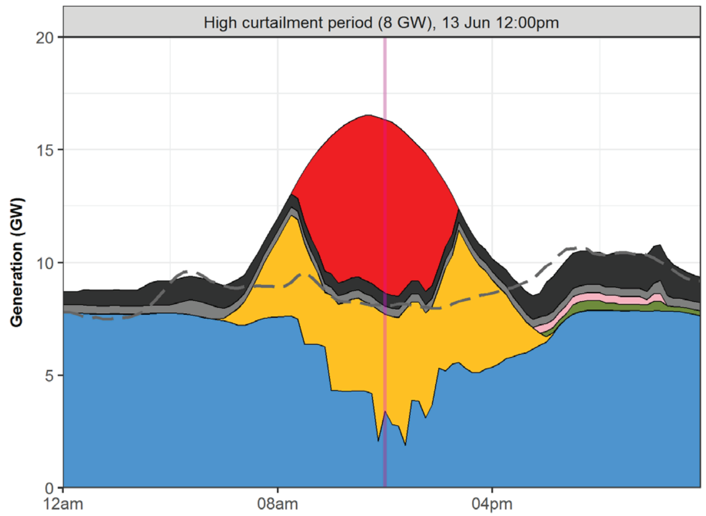
| LOAD | CURTAILMENT | HYDRO | COAL | GAS | RE | NET IMPORTS | RE PENETRATION (%) |
|---|---|---|---|---|---|---|---|
| 8.3 | 0 | 0.1 | 7.7 | 0.3 | 0 | 0.2 | 0.5 |

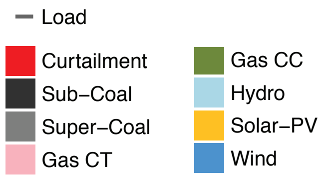
# Example Dispatch Days

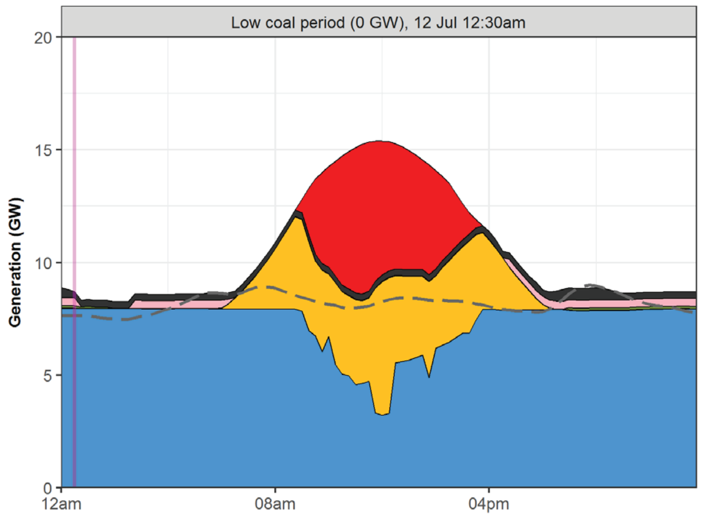
**High curtailment period: Generation, load, and interchange (values in GW unless otherwise specified)**

13 June 12:00 pm

| LOAD | CURTAILMENT | HYDRO | COAL | GAS | RE | NET EXPORTS | RE PENETRATION (%) |
|---|---|---|---|---|---|---|---|
| 8.1 | 7.7 | 0 | 0.9 | 0 | 7.7 | 0.5 | 95 |



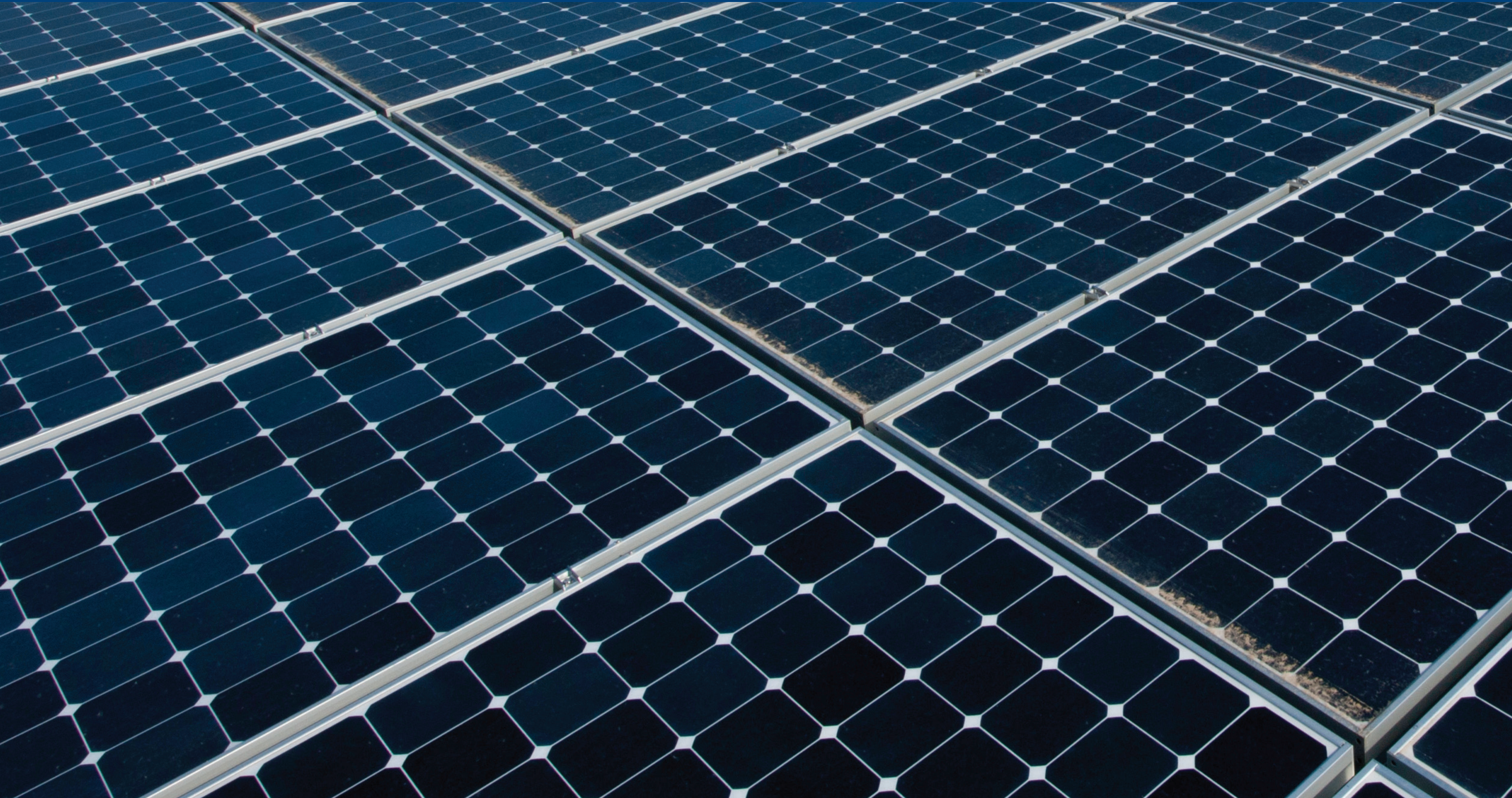




**Low coal period: Generation, load, and interchange (values in GW unless otherwise specified)**

12 July 12:30 am

| LOAD | CURTAILMENT | HYDRO | COAL | GAS | RE | NET EXPORTS | RE PENETRATION (%) |
|---|---|---|---|---|---|---|---|
| 7.6 | 0 | 0 | 0.3 | 0.5 | 7.9 | 1.1 | 104 |

# Conclusions



Based on this study's assumptions about demand and installed generation and transmission capacity in Andhra Pradesh and nationwide, Andhra Pradesh can integrate the equivalent of 51% of its total generation in 2022, with 5.6% annual wind and solar curtailment. The RE changes the way Andhra Pradesh's grid must operate. Compared to a 2022 system with no new RE, net exports rise by 75% annually and the PLF of the coal fleet falls from 63% to 32%.

Andhra Pradesh has the highest RE penetration of any state and relatively high RE curtailment. As a result of large amounts of low-cost RE, energy exports to interconnected states increase dramatically in the 100S-60W scenario.

## 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 Andhra Pradesh (GW) in the 100S-60W scenario | | |
|---|---|---|
| | OWNERSHIP | TOTAL CAPACITY (GW) |
| Gas CC | State/Private | 3.7 |
| Gas CT | State/Private | 0.3 |
| Hydro | State/Private | 2.6 |
| Sub-Coal | State/Private | 6.1 |
| Sub-Coal | Central | 2.0 |
| Super-Coal | State/Private | 4.8 |
| Total non-RE | | 19.5 |
| Solar-PV | State/Private | 11.0 |
| Wind | State/Private | 8.1 |
| Total RE | | 19.1 |
| **Total capacity** | | **38.6** |

**Total capacity (surge impedance limit [SIL]) of transmission lines connecting Andhra Pradesh 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 |
|---|---|---|
| Andhra Pradesh to Karnataka | 220 | 2 |
| Andhra Pradesh to Karnataka | 400 | 16 |
| Andhra Pradesh to Karnataka | 765 | 2 |
| Andhra Pradesh to Odisha | 400 | 4 |
| Andhra Pradesh to Odisha | 765 | 2 |
| Andhra Pradesh to Tamil Nadu | 230 | 2 |
| Andhra Pradesh to Tamil Nadu | 400 | 9 |
| Andhra Pradesh to Tamil Nadu | 765 | 6 |
| Andhra Pradesh to Telangana | 132 | 5 |
| Andhra Pradesh to Telangana | 220 | 11 |
| Andhra Pradesh to Telangana | 765 | 8 |
| Andhra Pradesh to Telangana* | 400 | 17 |
| **Total import/export capacity** | | **84** |

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

| CONNECTING | VOLTAGE (kV) | NO. LINES |
|---|---|---|
| Intrastate | 220 | 139 |
| Intrastate | 400 | 117 |
| Intrastate | 765 | 16 |
| **Total intrastate capacity** | | **271** |

## RE capacity by substation and type

| SUBSTATION (NUMBER_NAME_VOLTAGE) | SOLAR-PV (MW) | WIND (MW) |
|---|---|---|
| 512019_NELL_220 | 0 | 27 |
| 512109_RAMAGIRI_220 | 2,967 | 2,550 |
| 512132_KONDPRM-W_220 | 285 | 1,441 |
| 512133_URVKND_220 | 1,612 | 100 |
| 512136_MOGULV2_220 | 0 | 34 |
| 512137_BRMPLI_220 | 0 | 12 |
| 514006_GAZW_400 | 891 | 0 |
| 514007_CUDP_400 | 2,464 | 2,307 |
| 514008_GOOT_400 | 615 | 281 |
| 514013_KURNOOL4_400 | 975 | 0 |
| 514024_CHITOR_400 | 212 | 1,359 |
| 514028_KURL-NEW_400 | 32 | 0 |
| 514096_GMR-OA_400 | 376 | 0 |
| 514098_HINDJ-OA_400 | 519 | 0 |
| **Total RE capacity** | **10,948** | **8,111** |

| Annual energy generation fuel type, No New RE and 100S–60W | | |
|---|---|---|
| | NO NEW RE (TWh) | 100S–60W (TWh) |
| Gas CC | 2 | 5 |
| Gas CT | 1 | 1 |
| Hydro | 4 | 4 |
| Solar-PV: rooftop | 4 | 0 |
| Solar-PV: utility scale | 15 | 1 |
| Sub-Coal | 18 | 41 |
| Super-Coal | 18 | 30 |
| Wind | 26 | 3 |
| Total Generation | 88 | 84 |
| Imports | 27 | 29 |
| Exports | 36 | 34 |
| RE Curtailment | 3 | 0 |