Appendix A. CEM Inputs

Model Regions

The model included three levels of spatial resolution: regions, balancing areas, and resource regions. Regions included the five operating regions of India, namely the Northern region, Northeastern region, Eastern region, Southern region, and Western region. Each region is composed of balancing areas representing states and union territories connected by the transmission network. We considered 34 total balancing areas. Finally, within each balancing area, there were multiple resource regions designed to capture differences in RE resources at a higher level of granularity. There were a total of 146 resource regions.

Electricity Demand Representation

Electricity demand in ReEDS is represented by a set of time slices that capture changes in seasonal and daily demand patterns, as well as interactions between demand and renewable generation.

The ReEDS-India model represents annual demand with 35 time slices. The time slices include five seasons (Winter, Spring, Summer, Rainy, and Autumn) with seven times of day per season (Night, Sunrise, Morning, Afternoon, Sunset, Evening, Peak). Figure A- 1 shows how the demand in each hour is allocated to a particular time slice.

	January	February, March	April, May, June	July, August, September	October, November	December
	Winter	**Spring**	**Summer**	**Rainy**	**Autumn**	**Winter**
1	Night	Night	Night	Night	Night	Night
2	Night	Night	Night	Night	Night	Night
3	Night	Night	Night	Night	Night	Night
4	Night	Night	Sunrise	Night	Night	Night
5	Night	Sunrise	Sunrise	Sunrise	Sunrise	Night
6	Sunrise	Sunrise	Sunrise	Sunrise	Sunrise	Sunrise
7	Sunrise	Sunrise	Morning	Sunrise	Sunrise	Sunrise
8	Sunrise	Morning	Morning	Morning	Morning	Sunrise
9	Morning	Morning	Morning	Morning	Morning	Morning
10	Morning	Morning	Morning	Morning	Morning	Morning
11	Morning	Morning	Morning	Morning	Morning	Morning
12	Afternoon	Afternoon	Afternoon	Afternoon	Afternoon	Afternoon
13	Afternoon	Afternoon	Afternoon	Afternoon	Afternoon	Afternoon
14	Afternoon	Afternoon	Afternoon	Afternoon	Afternoon	Afternoon
15	Afternoon	Afternoon	Afternoon	Afternoon	Afternoon	Afternoon
16	Sunset	Sunset	Afternoon	Sunset	Sunset	Sunset
17	Sunset	Sunset	Sunset	Sunset	Sunset	Sunset
18	Sunset	Sunset	Sunset	Sunset	Sunset	Sunset
19	Evening	Evening	Sunset	Evening	Evening	Evening
20	Evening	Evening	Evening	Evening	Evening	Evening
21	Evening	Evening	Evening	Evening	Evening	Evening
22	Evening	Evening	Evening	Evening	Evening	Evening
23	Night	Night	Night	Night	Night	Night
24	Night	Night	Night	Night	Night	Night

Figure A- 1.Time Slices in the ReEDS-India Capacity Expansion Model

Sunrise and sunset periods were determined based on 2022 solar generation profiles developed by NREL. They represent the first and last 3 hours of the day when solar generation is available, respectively. Peak period time slices are not depicted in Figure A- 1 because the peak hours vary by state. Seasonal peak load in each state was based on the highest 40 demand hours.

After every hour of the year was allocated to one of the 35 time slices, the demand was calculated as the mean load from all hours assigned to that time slice. We used hourly state-wise load data from 2014 as the baseline for all demand calculations to align with the available weather data for 2014.

Generation Technologies

The generation fleet is represented by a number of different technology types, each with their own techno-economic parameters. Table A- 1 contains the generation technologies considered in the model.

Table A- 1. Generation Technologies Considered in the Model

Conventional	Renewable
Combined Cycle Gas Turbine	Distributed PV
Combustion Turbine Gas	Hydro pondage
Cogeneration Bagasse	Hydro ROR
Diesel	Hydro storage (reservoir)
Nuclear	Onshore wind
Subcritical Coal	Utility PV
Subcritical Lignite	
Subcritical Oil	
Supercritical Coal	
Waste Heat Recovery	

Input data for exogenously defined capacity include existing capacity, planned capacity additions, and planned retirements. These were sourced from the Greening the Grid database, CEA's National Electricity Plan, and consultations with CEA.

Operating Parameters

The operational inputs and assumptions were designed to capture the cost and performance characteristics of each technology type used to generate electricity. In some cases, these were assumed to remain constant across all balancing areas and model years while others were disaggregated based on location, technology type, or year. Unless otherwise stated, all inputs were taken from the Greening the Grid database.

Table A- 2 contains the input parameters assumed to remain constant for all model years and balancing areas.

Table A- 2. Input Parameters that Remain Constant Across Model Years and Balancing Areas

Technology	Ramping Limits (%/min)	Minimum Loading Fraction	Planned/ Unplanned Outage (%)	Co2 Emissions (ton/GJ)[19]
Combined Cycle Gas Turbine-Gas	3%	0.5	2.4/8.5	0.0486
Combined Cycle Gas Turbine Liquified Natural Gas	3%	0.5	2.4/8.5	0.065
Combined Cycle Gas Turbine-Naptha	3%	0.5	2.4/8.5	0.065
Cogeneration Bagasse	1%	0.5	2.4/8.5	-
Combustion Turbine-Gas	5%	0	4.1/4.3	0.0486
Diesel	2%	0.5	4.1/4.3	0.068
Distributed PV	NA	0	0/0	-
Hydro Pondage	10%	0	0/0	-
Hydro Pumped	10%	0.2	0/0	-
Hydro ROR	10%	0	0/0	-
Hydro Storage	10%	0	0/0.71	-
Nuclear	0.5%	1	2.3/8.3	-
Subcritical-Coal	1%	0.55	5.1/10	0.0892
Subcritical-Lignite	1%	0.55	5.1/10	0.0989
Subcritical-Oil	1%	0.55	5.1/24.7	0.0708
Supercritical-Coal	1%	0.55	5.1/8	0.0892
Utility PV	NA	0	0/0	-
Waste Heat Recovery	1%	0	5/8.5	-
Wind	NA	0	0/0	-
BESS	100%	0	0/0	-

Variable Costs (VCs)

The total VCs for generators in ReEDs are represented by the following equation:

[19] Based on fuel emissions factors in table in Appendix B pg. 31 of “CO2 Baseline Database for the Indian Power Sector --- User Guide” from CEA (http://cea.nic.in/reports/others/thermal/tpece/cdm_co2/user_guide_ver10.pdf).

$$VC = Heat\ rate \times Fuel\ cost + VOM$$

VOM is the variable O&M costs that do not include fuel costs, such as labor. The source for this data was the publicly available variable tariffs for central and state-owned generators as of early 2016, which was collected for the Greening the Grid study. The plants that did not have variable charges publicly available were assigned the average for the technology and state, or region if a state does not already have a certain plant type. Disaggregating the VC into the components of the equation above is required to be able to design scenarios with different fuel costs while maintaining plant-specific characteristics. The following sections focus on the source for these VC components and how plant-wise variability is maintained within these assumptions.

VC Representation

Maintaining a tractable optimization problem requires that individual plants be simplified into representative parameters. To achieve this, each balancing area, technology type, and year was assigned a specific VC based on the existing capacity. The VC parameter was defined separately for two types of capacity: (1) existing or planned capacity exogenously prescribed in the model, and (2) newly built capacity endogenously built by ReEDS. These costs were derived from the total VC as explained above.

For exogenously prescribed capacity, that which already exists or is known to be added based on the National Electricity Plan or Greening the Grid database, the model managed the number of variables and overall size of the model by clustering units in each balancing area into "performance bins" based on their VC. We stipulated that each bin must have at least 5 units and the minimum deviation in average VC between bins must exceed 200 ₹/MWh.

For new capacity endogenously built in ReEDS, VC varied by state based on capacity-weighted average costs. In cases where state-level data were not available (e.g., no plants of a certain type exist), VCs were based on regional or national averages. Table A- 3 contains the average VC assumed for each technology.

Table A- 3. Average Variable Cost by Technology

	Combined Cycle Gas Turbine-Gas	Combined Cycle Gas Turbine-Liquified Natural Gas	Cogeneration-Bagasse	Combustion Turbine-Gas	Nuclear	Supercritical-Coal	WHR
Average VC for new builds (₹/MWh)	3,932	6,065	4,869	8,020	2,498	2,473	3,770

Distributed PV, hydropower plants, utility PV, and wind plants were assumed to have no VCs. All VCs were assumed to remain constant over the model period.

Heat Rate

Plant heat rates are distinguished based on the type of technology and include some assumed efficiency improvements over time. Table A- 4 contains the heat rate and assumed efficiency improvements over time for all technologies.

Table A- 4. Heat Rate and Efficiency Improvement Over Time by Technology

Technology	2022 Heat Rate (GJ/MWh)[20]	Efficiency Improvement[21]
Combined Cycle Gas Turbine-Gas	7.22	0.2% annual improvement until 2030
Combined Cycle Gas Turbine-Liquified Natural Gas	7.22	0.2% annual improvement until 2030
Combined Cycle Gas Turbine-Naptha	7.22	0.2% annual improvement until 2030
Cogeneration Bagasse	12.3	None
Combustion Turbine-Gas	10.94	0.6% annual improvement until 2030
Diesel	11.48	None
Subcritical-Coal	11.12	None
Subcritical-Lignite	12.3	None
Subcritical-Oil	11.12	None
Supercritical-Coal	11.08	0.05% annual improvement until 2030

Fuel Cost

Fuel costs were broken into a variable component and a static component to allow for flexibility in modeling. The static component was determined by the fuel cost assumptions in the following table, which was roughly the cost of fuel in 2016.[22] The variable component captured the cost differences between plants by representing the total landed cost of fuel at a plant, which included costs for transportation, long-term contracts, quality of the fuel, and plant efficiency.

All fuel costs other than coal were assumed to remain constant over the model period.[23] Coal fuel cost has an additional annual escalation rate of 2%, in addition to the annual inflation rate. Note that nuclear plants were not assigned a fuel cost. All nuclear fuel cost is represented with its single variable tariff, as their operation is largely dictated outside of economic dispatch decisions.

[20] Value assumed for all plants commissioned in or before 2017. Source: CERC norms.
[21] Based on NREL 2018 ATB (https://atb.nrel.gov).
[22] Exact estimates of fuel costs are not required with this method if VCs at the plant level are captured.
[23] All calculations of future cost include a uniform inflation rate.

Table A- 5. Fuel Prices

Fuel	Price (₹/GJ)
Gas	200
Coal	50 (increasing 2% annually)
Oil	20
Diesel	400
Lignite	50
Naphtha	200
Bagasse	205[24]

Fuel Supply Limits

Fuel supply limits were imposed on gas technologies based on historic domestic and imported gas supplies. For 2017 and 2018, gas supplies were assumed to reflect current gas supply condition. For 2019–2024, the gas supply situation was assumed to gradually improve. The maximum available gas supply is reached in the year 2024, after which the gas fuel limit remains constant through 2047.

Table A- 6. Gas Fuel Supply Limits

Year	Gas Limit (MMSCMD)[25]	Gas Limit (GJ/yr)
2020	68.27	927,959,975
2021	86.32	1,173,304,600
2022	104.37	1,418,649,225
2023	122.42	1,663,993,850
2024	140.472	1,910,000,000
2025–2050	140.472	1,910,000,000

Capital Costs

Capital costs included all overnight costs to build a new power plant, excluding construction period financing. Unless otherwise stated, all capital costs assumptions were taken from CEA National Electricity Plan 2018 table “Assumptions for Estimating Capital Costs of Power Projects” (pg. 11.4).

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[24] See CERC RE Tariff Order 2017-18 (http://www.cercind.gov.in/2017/orders/05.pdf). Estimate for bagasse costs in “all other states” is given as 1964.71 ₹/ton. A conversion factor of 9.6 GJ/ton is used to calculate a fuel cost of 204.647 ₹/GJ.

[25] MMSCMD = million metric standard cubic meters per day. Conversion for GJ/yr: MMSCMD * (365 days/yr) * (10^6 m^3/million m^3) * (1/26.853 GJ/m^3) = GJ/yr.

Table A- 7. Capital Costs

Technology	2020 capital cost (crore/MW)	Notes
Combustion Turbine-Gas	4	CEA (2016)[26]
Combined Cycle Gas Turbine-Gas	4.68	Use NREL ATB[27] assumption that CC units are 17% more expensive that CT units
Combined Cycle Gas Turbine-LNG	4.68	Assume same as Combined Cycle Gas Turbine-Gas
Combined Cycle Gas Turbine-Naphtha	4.68	Assume same as Combined Cycle Gas Turbine-Gas
Cogeneration-Bagasse	5.7	
Concentrated Solar Power	6.08	Based on CERC benchmark capital cost[28]
Diesel	4	NREL 2018 ATB value for CT-Gas
Distributed PV (rooftop)	11	Bloomberg New Energy Finance (2017)[29] value for commercial rooftop PV
Hydro - Pondage	10	
Hydro - Pumped	10	
Hydro - ROR	6.5	
Hydro – Storage	10	
Nuclear	10.2	
Subcritical Coal	6.5	
Subcritical Lignite	6.5	
Subcritical Oil	6.4	Assume same as Diesel
Supercritical Coal	7.9	
Solar PV (Utility)	5.5	
Waste Heat Recovery	5.7	Assume same as cogeneration-bagasse
Onshore Wind	6	NREL 2020 ATB.
BESS 2-hour	4.9	NREL 2020 ATB.
BESS 4-hour	8.5	NREL 2020 ATB.
BESS 6-hour	11.9	NREL 2020 ATB.
BESS 8-hour	15.4	NREL 2020 ATB.
BESS 10-hour	18.8	NREL 2020 ATB.

26 CEA. Draft National Electricity Plan (Volume 1) Generation. December 2016. http://www.cea.nic.in/reports/committee/nep/nep_dec.pdf.

27 NREL (National Renewable Energy Laboratory). 2018. 2018 Annual Technology Baseline. Golden, CO: National Renewable Energy Laboratory. http://www.nrel.gov/analysis/data_tech_baseline.html.

28 Central Electricity Regulatory Commission (CERC). Petition No. 17/SM/2015: Determination of Benchmark Capital Cost Norm for Solar PV power projects and Solar Thermal power projects applicable during FY 2016-17. March 23, 2016.

29 Bloomberg New Energy Finance (BNEF). "Accelerating India's Clean Energy Transition: The future of rooftop PV and other distributed energy systems in India." November 2017.

Changes in Capital Costs Over Time

For all technologies, both mature and emerging, there is a learning rate that results in changes in capital costs over time. We adopted the same learning rates used in NREL's 2020 ATB. Table A-8 presents the assumed cost reductions and underlying data sources used to derive these values. These changes in capital costs are separate from anticipated changes in labor and material costs, which are anticipated to increase in India over the planning period. This increase is captured by the inflation rate included in ReEDS financial assumptions.

Table A- 8. Change in Capital Cost Over Time

Technology	Annual Reduction in Capital Cost (%)	Source
Combustion Turbine-Gas	0.39	U. S. Energy Information Administration (EIA). 2018. Annual Energy Outlook 2018 with Projections to 2050. Washington, D.C: U.S. Department of Energy. February 6, 2018.
Combined Cycle Gas Turbine-Gas	0.37	Same source as Combustion Turbine-Gas
Combined Cycle Gas Turbine-Liquified Natural Gas	0.37	Assumed same as Combustion Turbine-Gas
Combined Cycle Gas Turbine-Naphtha	0.37	Assumed same as Combustion Turbine-Gas
Cogeneration-Bagasse	0.24	Same source as Combustion Turbine-Gas
Concentrated Solar Power	1.5	Feldman, David, Jack Hoskins, and Robert Margolis. 2017. Q2/Q3 2017 Solar Industry Update. U.S. Department of Energy. NREL/PR-6A42-70406. November 13, 2017. https://www.nrel.gov/docs/fy18osti/70406.pdf.
Diesel	0.39	Assumed same as Combustion Turbine-Gas
Distributed PV (rooftop)	4.0: 2017-2030 1.0: 2031-2040 0.5: 2041-2050	Same source as Concentrated Solar Power
Hydro - Pondage	0	DOE (U.S. Department of Energy). 2016. Hydropower Vision: A New Chapter for America's Renewable Electricity Source. Washington, D.C.: U.S. Department of Energy. DOE/GO-102016-4869. July 2016. https://energy.gov/sites/prod/files/2016/10/f33/Hydropower-Vision-10262016_0.pdf.
Hydro - Pumped	0.26	Same source as Hydro - Pondage
Hydro - ROR	0	Same source as Hydro - Pondage
Hydro – Storage	0.26	Same source as Hydro - Pondage
Nuclear	0.46	Same source as Combustion Turbine-Gas
Subcritical Coal	0.26	Same source as Combustion Turbine-Gas
Subcritical Lignite	0.26	Same source as Combustion Turbine-Gas
Subcritical Oil	0.39	Assumed same as Diesel
Supercritical Coal	0.26	Same source as Combustion Turbine-Gas
Solar PV (Utility)	6.8: 2017-2021 1.1: 2022 – 2050	Multiple sources. See NREL 2020 ATB.
Waste Heat Recovery	0.24	Assumed same as Cogeneration-Bagasse
Onshore Wind	0.82 in 2017 declining linearly to 0 in 2050	Wiser, Ryan, Karen Jenni, Joachim Seel, Erin Baker, Maureen Hand, Eric Lantz, and Aaron Smith. 2016. Forecasting Wind Energy Costs and Cost Drivers: The Views of the World's Leading Experts. Berkeley, CA: Lawrence Berkeley National Laboratory. LBNL-1005717. June 2016. https://emp.lbl.gov/publications/forecasting-wind-energy-costs-and.
BESS	Cost reductions based on NREL 2020 ATB.	See NREL 2020 ATB.

Plant Lifetime

The plant lifetime is the maximum age of the plant. When a plant reaches the maximum age, it must be either retired or refurbished.

Table A- 9. Plant Lifetime

Technology	Plant Lifetime
Combustion Turbine-Gas	55
Combined Cycle Gas Turbine-Gas	55
Combined Cycle Gas Turbine-Liquified Natural Gas	55
Combined Cycle Gas Turbine-Naphtha	55
Cogeneration-Bagasse	45
Concentrated Solar Power	30
Diesel	55
Distributed PV (rooftop)	30
Hydro - Pondage	100
Hydro - Pumped	100
Hydro - ROR	100
Hydro – Storage	100
Nuclear	70
Subcritical Coal	25
Subcritical Lignite	25
Subcritical Oil	25
Supercritical Coal	25
Solar PV (Utility)	30
Waste Heat Recovery	45
Onshore Wind	24
BESS	15

First Year for Economic Builds

The first year for economic builds is the initial year when new capacity can be built based on economic criteria. Prior to the first year, only prescribed additions can be built by the model. All technologies begin economic builds in 2023.

Absolute Growth Limit

An absolute growth limit in MW is imposed on hydro, biomass, and waste heat recovery technologies. The state-wise limits were based on CEA National Electricity Plan 2018 Annexure-6.1 “State-Wise Details of Estimated Potential for Renewable Power in India” (pg. 6.24-6.25).

Weather Data

To estimate electricity output, we used spatio-temporal weather data to calculate electricity output of various PV and wind turbine systems across multiple years, if available. For this study, we used the National Solar Radiation Database (NSRDB) and India WIND Toolkit (WTK). The characteristics of these data sets are below:

Table A- 10. Characteristics of Weather Data

Data Set	Spatial Resolution	Temporal Resolution	Observation Period
NSRDB	10 km	Hourly	2000–2014
WTK	3 km	Hourly	2014

RE Generator System Configurations

PV System Configuration

There are two types of possible PV systems that have separate supply curves in ReEDs: utility-scale or distributed systems. Specific locations were assigned the appropriate supply curves based on geographic information (i.e., rural versus urban; see *Land Exclusions* below). The following table gives the configuration parameters for utility-scale PV.

Table A- 11. Solar PV System Configuration

Parameter	Value
System Capacity	1,100 kWdc
DC to AC Ratio	1.1
Losses	14 %
Inverter Efficiency	96 %
Array Type	Fixed open rack
Tilt	Tilt = latitude
Azimuth	180 degrees (South facing)
Model Type	Standard
Ground Cover Ratio	0.40

PV systems were assigned generation profiles based on the quality of the resource at a specific location. Each 10-km^2 grid cell is assigned a resource class based on the annual average irradiance for that location based off hourly 8,760 profiles from the NSRDB database.

Wind System Configuration

Wind turbine classes are designated for each location based on the annual average wind speed in the following table:

Table A- 12. Wind System Configurations

IEC Class	Annual or Multiyear Mean Wind Speed
Class I	> 9 m/s
Class II	> 8 m/s & <= 9 m/s
Class III	<= 8 m/s

Below are the system configurations for each class of turbine.