Flexible Resources Initiative of the

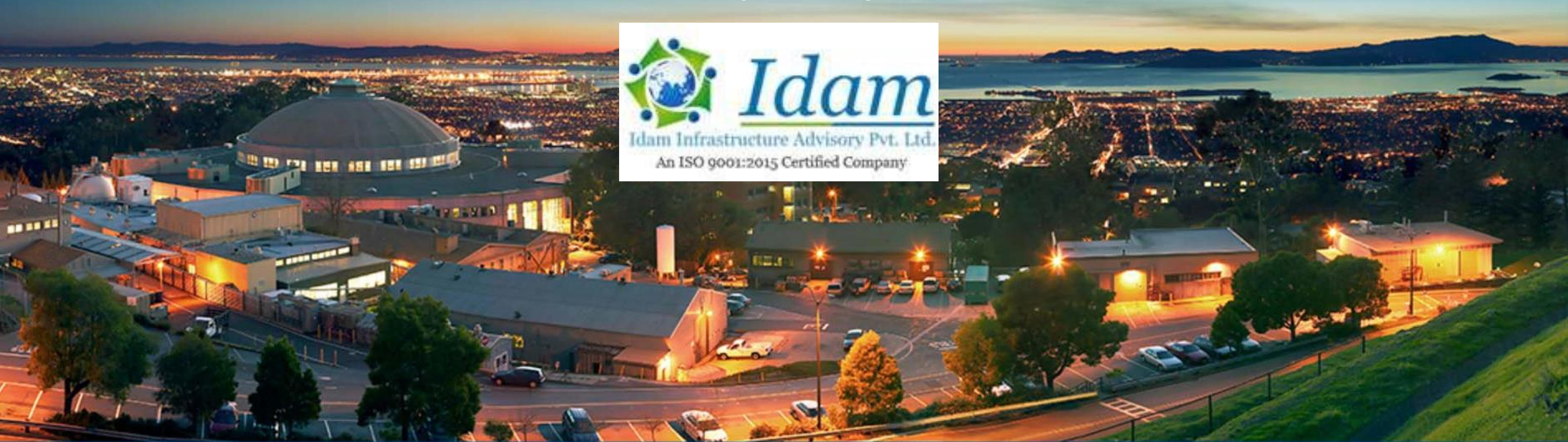
U.S.-India Clean Energy Finance Task Force

Least Cost Pathway for Power Sector Investments in Rajasthan through 2030

Submitted to

Lawrence Berkley National Laboratory

Prepared by



February 2023

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Abbreviations

AVVNL	:	Ajmer Vidyut Vitran Nigam Limited
CAGR	:	Compound Annual Growth Rate
CEA	:	Central Electricity Authority
CERC	:	Electricity Regulatory Commission
DR	:	Demand Response
EPS	:	Electrical Power Survey
InSGS	:	Intra-State Generating Stations
IPP	:	Independent Power Producer
ISGS	:	Inter-State Generating Stations
JdVVN	:	Jodhpur Vidyut Vitran Nigam Limited
JVVNL	:	Jaipur Vidyut Vitran Nigam Limited
LGB	:	Load Generation Balance
LT	:	Long Term
MNRE	:	Ministry of New and Renewable Energy
O & M	:	Operations & Maintenance
RE	:	Renewable Energy
RERC	:	Rajasthan Electricity Regulation Commission
RoR	:	Run-of-river
RVUNL	:	Rajasthan Rajya Vidyut Utpadan Nigam Ltd
SLDC	:	State Load Dispatch Centre
ST	:	Short Term
VC	:	Variable Cost
vRE	:	Variable Renewable Energy
yr	:	Year

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Executive Summary

Rajasthan has a peak load of 14.4 GW and annual electricity consumption of 85.2 TWh in 2021, which is expected to increase by 103 % by 2030. Rajasthan is also a renewable energy (RE) rich state with solar and wind potential of 142 GW and 18.8 GW respectively. RE installed capacity in Rajasthan is 14.5 GW solar and 4.5 GW wind as on March 2022, with RE contributing to 28.2% in total electricity generation in financial year 2021-22 (CEA 2021-22). As share of RE increases, the system would need more flexible resources to address increased variability and intermittency. The objective of this study is to find the least-cost and operationally feasible resource mix for Rajasthan to meet its load reliably through 2030, in sync with the national grid, and by considering key flexible resources such as energy storage and demand response solutions including agricultural load shift as well as flexibility provided by thermal generators and hydro resources. The study uses the latest RE and battery cost data, an industry-standard power system modelling platform (PLEXOS), and exhaustive analytical methods (optimal capacity expansion and power plant-level hourly grid dispatch simulations).

Key Study Findings:

1. **Rajasthan's electricity demand by 2030 will largely be met by a generation mix consisting of large amounts of RE and battery storage as well as existing thermal, nuclear, and hydro assets.**

   - **Using the CEA EPS load projections for 2030** (peak load of 36.2 GW and energy consumption of 173 TWh/yr by 2030) and limiting the RE capacity addition to 4.5 GW/yr (seven times the historical levels), the **Primary Least Cost (PLC) investment pathway for Rajasthan** consists of a combination of 45.2 GW of RE comprising of 39 GW_{DC} solar and 6.2 GW wind, 10.5 GW coal (including central sector allocation), 0.5 GW of nuclear, 1.9 GW of hydro, 12.4 GW of energy storage in the state is found to be economical.

   - **Using load forecast by the state utilities / regulator** (peak load of 31.4 GW and energy consumption of 150 TWh/yr by 2030), **Primary Least Cost investment** consists of a combination of 65.9 GW of RE comprising of 59.1 GW_{DC} solar and 6.8 GW wind, 10.5 GW coal, 0.5 GW of nuclear, 1.9 GW of hydro. Higher limits on RE capacity addition, 9.5 GW/yr results in increase in RE installation by 2030.

   - **If RE installation continues at the historical rate of 3.3 GW/yr (current policy scenario) and using the 2019 CEA EPS load forecast,** a combination of 38.6 GW of RE**,** comprising of 32.5 GW_{DC} of solar and 6.1 GW of wind, 10.5 GW coal, 0.5 GW of nuclear, 1.9 GW of hydro and 9.6 GW of 4-hrs battery storage is found to be economical.

   - **If RE installation increases on higher rate of 9.5 GW/yr and using CEA EPS load projections for 2030,** a combination of 69.5 GW of RE comprising of 62.2 GW_{DC} solar and 7.3 GW wind, 10.5 GW coal, 0.5 GW of nuclear, 1.9 GW of hydro and 22.2 GW of 4-hrs battery storage is found to be economical.

   - **Considering load shift of 3 GW by 2030 and using CEA EPS load projections for 2030,** a combination of 69.5 GW of RE comprising of 62.2 GW_{DC} solar and 7.3 GW wind, 10.5 GW coal, 0.5 GW of nuclear, 1.9 GW of hydro and 22.2 GW of 4-hrs battery storage is found to be economical.

   - The average generation cost in 2030 in the Primary Least Cost Case (EPS) is 13 % lower than in 2020 owing to the inflation-proof, low-cost RE and improved coal capacity factors for existing units.

Table 1: Installed Capacities by 2030 for Various Scenarios (2020-2030)

S. No	Technology	Actual (2020)	Primary Least Cost (State load)	Primary Least Cost (EPS load)	Current Policies Scenario	High RE Installation	State Sensitivity
1	Coal (including central sector allocation)	10.5	10.5	10.5	10.5	10.5	10.5
2	Nuclear	0.8	0.8	0.8	0.8	0.8	0.8
3	Hydro	0.5	0.5	0.5	0.5	0.5	0.5
4	Hydro PSH	1.9	1.9	1.9	1.9	1.9	1.9
5	Solar	10.1	59.1	39.0	32.5	62.2	33.3
6	Wind	5.0	6.8	6.20	6.1	7.3	9.0
7	Biomass	0.03	0.03	0.03	0.03	0.03	0.03
8	Small Hydro	0.0	20.8	12.4	9.6	22.2	10.0
9	Battery	10.5	10.5	10.5	10.5	10.5	10.5

- Inflation-proof and low-cost RE and energy storage are the primary drivers of these results. Battery storage obviates the need for building thermal capacity to meet the morning and evening peak load, while agricultural and industrial load shifting from night to solar hours significantly reduces the night-time load and, in turn, the requirement for new base load coal-fired capacity.

2. No new thermal power plant is found to be economical in the state by 2030

- In the Primary Least Cost cases and also in the current policy case, we do not find any new thermal power plant addition in the state to be cost-effective despite near doubling of electricity demand between 2020 and 2030. This is primarily because the load growth is balanced by solar and wind generation. In addition to this, energy storage is also supporting to meet the demand in non-solar hours.
- By 2030, average utilisation of coal plants drops to 41% from 45% in 2020. Average utilization for coal power plants with VC > 4 Rs/kWh would be less than 10% and that for power plants with VC > Rs 3/kWh would be less than 30 %.

3. Rajasthan's electric grid will be dependable even without any new thermal capacity additions

- Existing thermal plants, nuclear, hydro, and RE and battery capacity along with import from other states will suffice the load growth of Rajasthan by 2030.
- Deployment of flexible resources with new interstate transmission capacity built can avoid new thermal power built, while maintaining reliability of the grid.
- Imports from bilateral contracts or wholesale electricity markets and variable monthly PLF of thermal plants can provide seasonal balancing.
- Flexible resources like battery storage provide diurnal balancing of the grid.

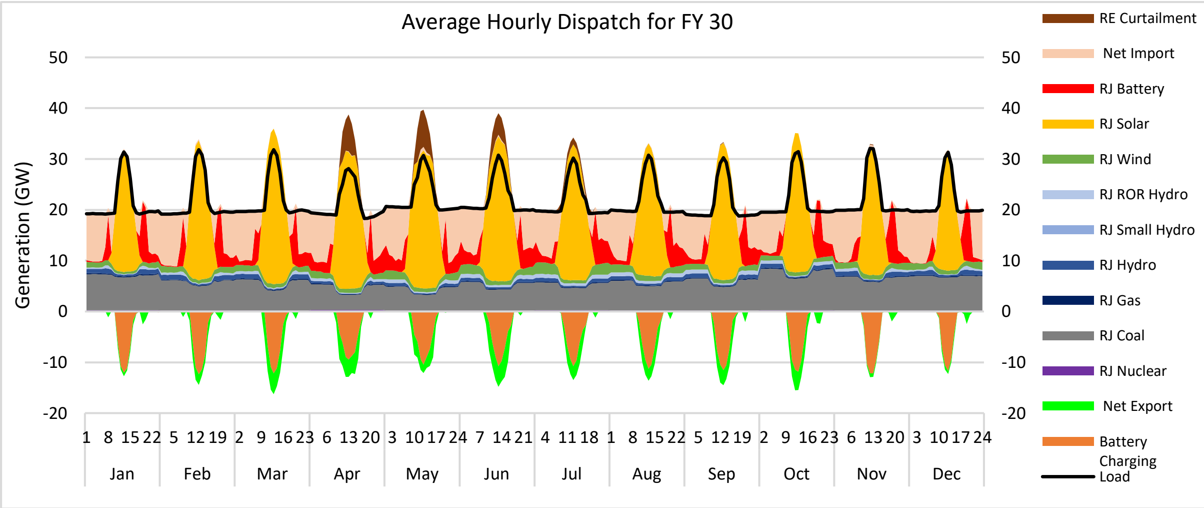

Figure 1: Dispatch in 2030

4. Rajasthan is a net importer of energy by 2030

- Though cheaper vRE power generation increases within the State, Rajasthan will remain net importer till 2030 (PLC – EPS projections).
- The state would import 53 TWh out of 173 TWh load (30.6%) EPS projection scenario and export 8 TWh out of 150 TWh load (5.3%) in State projections scenario as shown in figures below.
- Imports from bilateral contracts or wholesale electricity market, variable operation of thermal plants provides seasonal balancing.
- As cheaper power is available in neighbouring states such as Chhattisgarh, the state imports high energy to meet its energy needs. Moreover, most of the central sector generation plants have a lower VC than state generation plants, so they are dispatched first on merit.
- Import is going to be higher in the EPS projections due to different load profiles and imported power would be high on the merit order

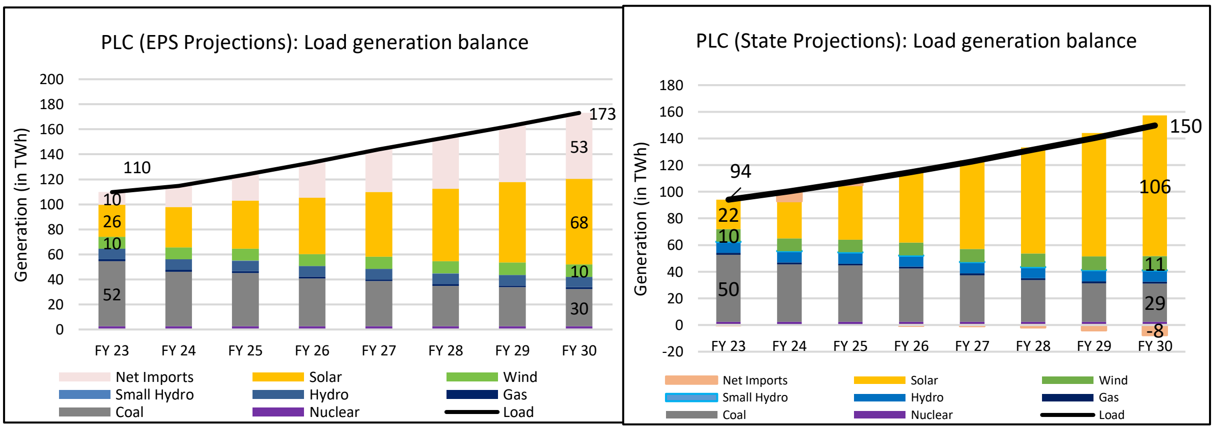

Figure 2: Annual Generation and Load by Resource Type in Primary Least Cost (PLC) (EPS Projections) (left) and Primary Least Cost (PLC)(State Projections) (right) FY 2023-30

5. State Level Challenges

- In order to deploy renewable energy at this scale and maintain grid reliability, important new policy and regulatory frameworks would need to be put in place, including resource adequacy, capacity markets, long-term planning, broader and deeper energy markets.
- Results show that Rajasthan would suffer high RE curtailment during high solar season, partly because of limited demand management tools like agricultural shift. This could be avoided by adopting demand management approaches like shifting night-time load to solar hours.

1 Introduction

1.1 Background and Objectives

India has set an ambitious clean energy target for the power sector, namely 175 GW of renewable energy (RE) installed capacity by 2022. In 2021, Prime Minister Modi increased this ambition by announcing a target of 500 GW of installed non-fossil capacity by 2030. India has made rapid progress towards achieving these goals. Between 2015 and 2021, India's renewable energy capacity more than doubled from 40 GW to 100 GW, supplying nearly 10% of the total electricity generated in the fiscal year 2021 (CEA, 2021). Over the last decade, India has been successful in achieving some of the lowest RE costs in the world. Between 2010 and 2020, it saw the largest reduction of 85% in country-level solar levelized cost of energy (LCOE), while the average solar tariff in 2020 was 34% lower than the global weighted average. India also had the lowest country-level installed cost for solar and wind in 2020 (BNEF, 2020a) (Figure 3).

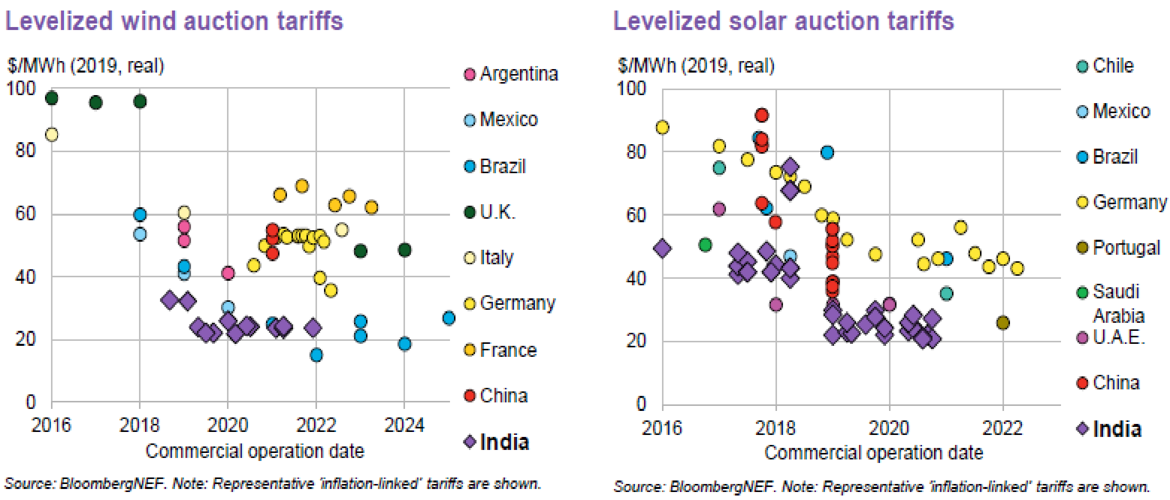

Figure 3: Solar and Wind Energy Prices in Key Countries, including India[1]

Source: BNEF (2020a)

It is well accepted that renewable electricity costs have dropped below coal costs on a levelized basis. Nonetheless, many countries around the world, including India, continue to invest in new coal power plants primarily because: (a) RE generation is intermittent and may need significant system flexibility for grid integration, (b) RE generation does not coincide with peak electricity demand periods which is in the evening for India, and (c) legacy planning and regulatory frameworks may not fully capture the value and capabilities of RE and energy storage technologies. In this context, the dramatic decline in battery storage costs — 90% cost reduction at the battery pack level since 2010 —could serve as a turning point, because it enables the cost-effective supply of low-cost renewable electricity during peak times (Figure 4). Notably, several large utility-scale RE + storage projects are underway globally and, in several cases, offer electricity generation prices well below that from fossil power plants. For example, a recent solar + storage auction by Los Angeles Department of Water and Power (LADWP) resulted in a combined PPA price of \$39/MWh (Rs 3/kWh) for storing over 50% of the solar energy in batteries in 2020.

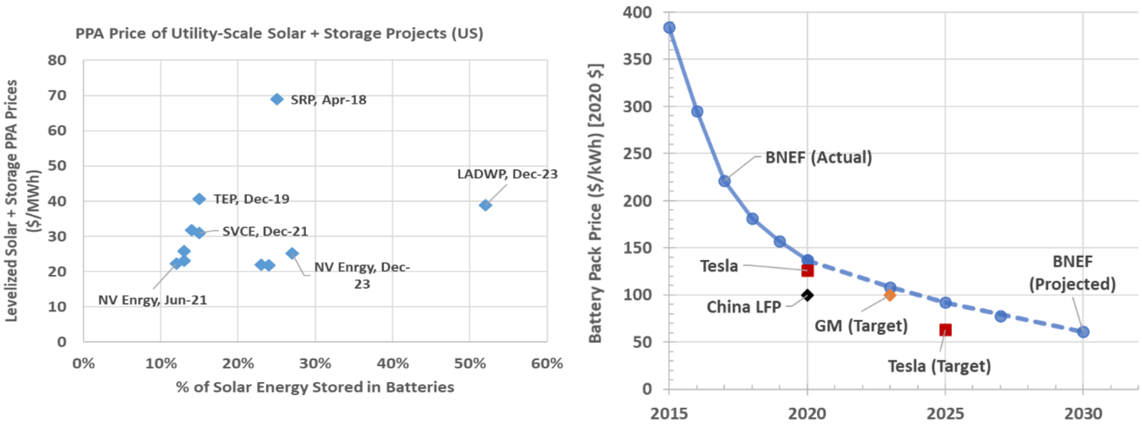

Figure 4: Global Average Battery Pack Price (Left) and Solar + Battery Storage PPA Prices in the United States (Right)[2]

Source: BNEF (2020b) and Deorah, et al (2020)

Indian utilities are also using several other flexible resources such as demand response for integrating renewable energy. Several states (e.g., Karnataka, Maharashtra, and Gujarat) have already shifted a major part of their agricultural load from nighttime to solar hours (over 6 GW total in 2020). Electricity market reforms in India, falling global natural gas prices, and demand response also offer some important flexibility options to the grid.

Given that a large part of India's electricity grid infrastructure is yet to be built, such cost reductions offer India a unique opportunity to leapfrog to a more flexible, robust, and sustainable power system. Several recent studies have assessed a similar question (e.g., CEA (2020), NREL (2020 & 2021b), TERI (2020), BNEF (2020a), and IEA (2021)).

Objective of the Study:

The objective of the study is to assess the least-cost resource mix for Rajasthan by 2030, as it is one of the RE-rich states with solar and wind potential of 142GW and 18.8 GW respectively (MNRE Statewise Potential) and with installed capacity of 14.5 GW solar and 4.5 GW wind as of July 2022. It is one of the leading states in terms of high RE installation. The study majorly focusses on identifying the gaps in present studies and addressing them by:

- Developing a spatially and temporally resolved capacity expansion and economic dispatch model using an industry standard platform, PLEXOS, that assesses the least cost resource mix at the state level, interstate transmission requirement, and power plant level hourly economic dispatch
- Using the latest renewable energy and storage cost estimates and trends, informed by prices observed in the market, and
- Including demand side resources, in particular, shifting of the agricultural and heavy industry load from night-time to solar hours.

1.1 State Background

Rajasthan has three distribution companies, viz. Jodhpur Vidyut Vitran Nigam Limited (JdVVNL), Ajmer Vidyut Vitran Nigam Limited (AVVNL), and Jaipur Vidyut Vitran Nigam Limited (JVVNL).

Rajasthan has been able to keep deficit in peak demand nearly zero from FY16 to FY22, and has a slight increase deficit in the energy supply from 0.31% in FY16 to approx. 0.46% in FY 21[3] as shown in figures below:

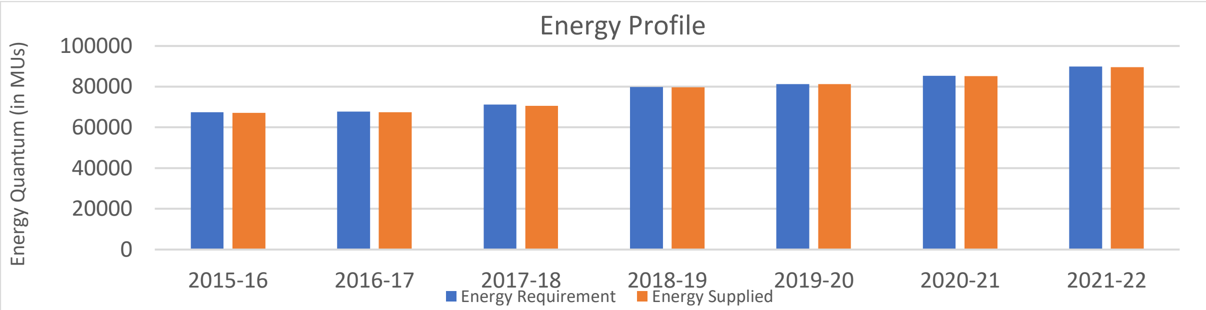

Figure 5: Rajasthan Historical Energy Trends

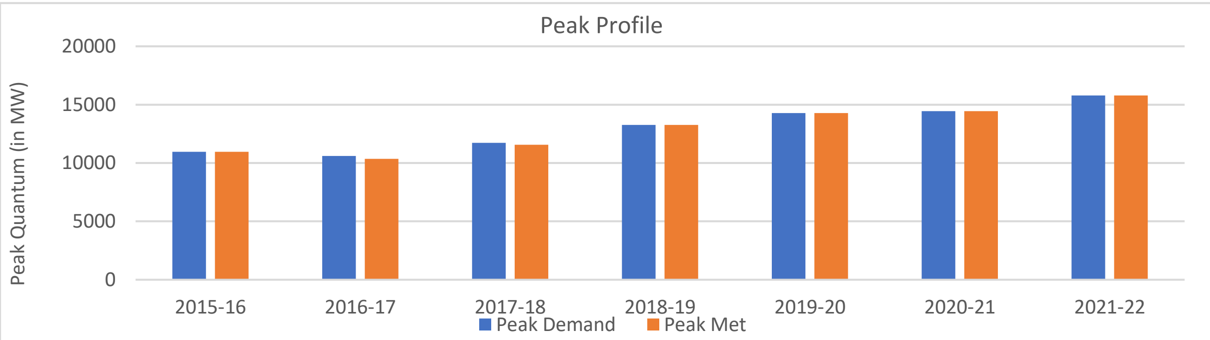

Figure 6: Rajasthan Historical Peak Demand Trends

The installed capacity in Rajasthan is 36609 MW as on September 2022.

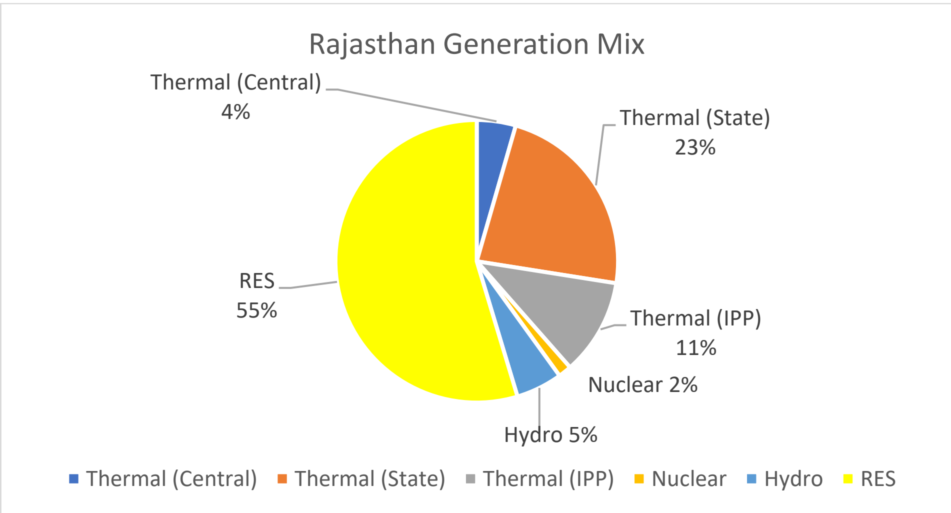

Figure 7: Rajasthan State Generation Mix (Sep-2022)

[3] (CEA LGBR FY16, FY17, FY18, FY19, FY20, FY21)

2 Methods, Data, and Assumptions

2.1 Modelling Philosophy

A capacity expansion model minimizes the total system cost to meet system load considering technical limits of generation, and a production cost model solves the optimal power flow formulation by taking into consideration generation limits and operational constraints such as ramp rates and transmission limits.

PLEXOS is an industry standard tool used in various applications such as Long-Term Capacity Expansion Planning, Production Cost Modelling, Transmission Planning Analysis, Demand Modelling, System Security and Adequacy, Ancillary Services and Energy Co-Optimisation, Optimally Times Maintenance etc.

The capacity expansion model for Rajasthan is built on PLEXOS to understand the optimal way to include more RE in Rajasthan's system, followed by analysing the production cost for the year 2030 as shown below in Figure 8.

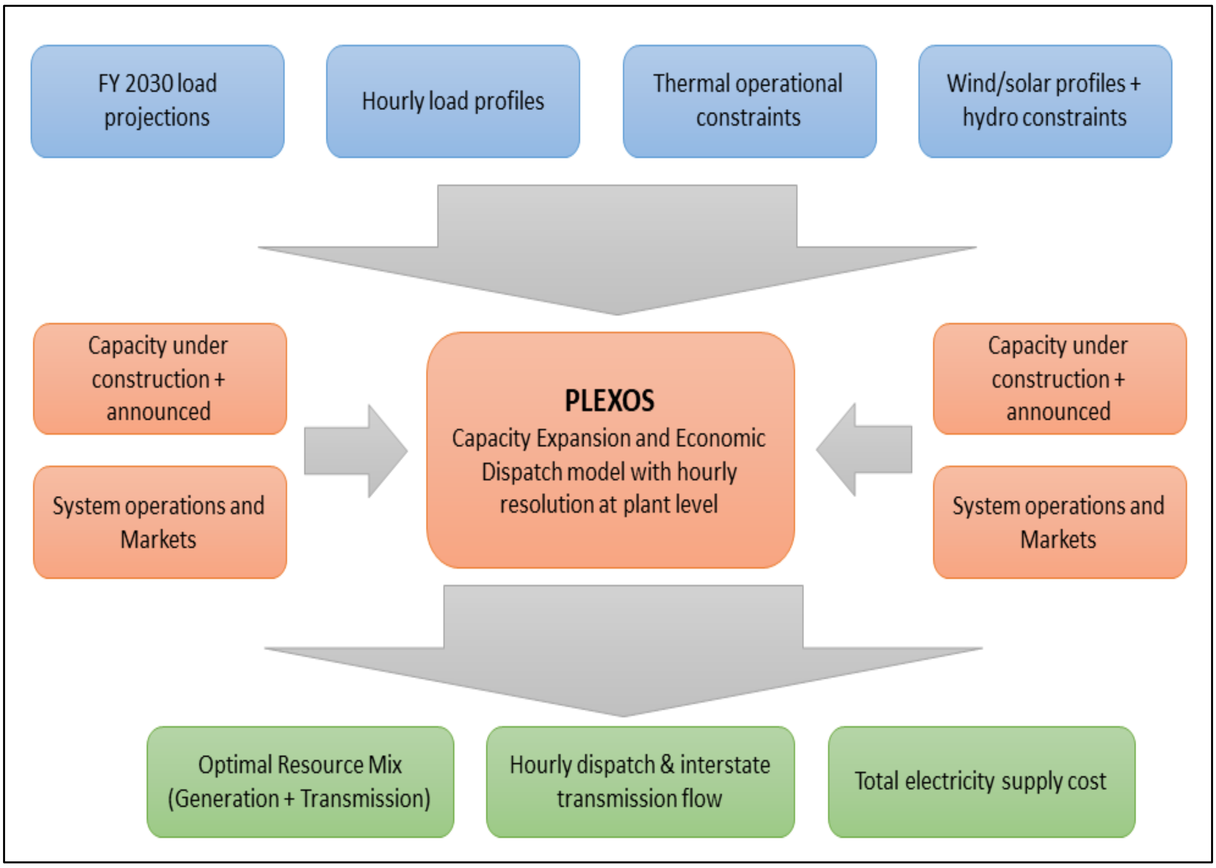

Figure 8: Modelling Philosophy

2.2 Capacity Expansion Model

The capacity expansion model optimizes capital and generation costs and consists of the following stages as shown below in Figure 9:

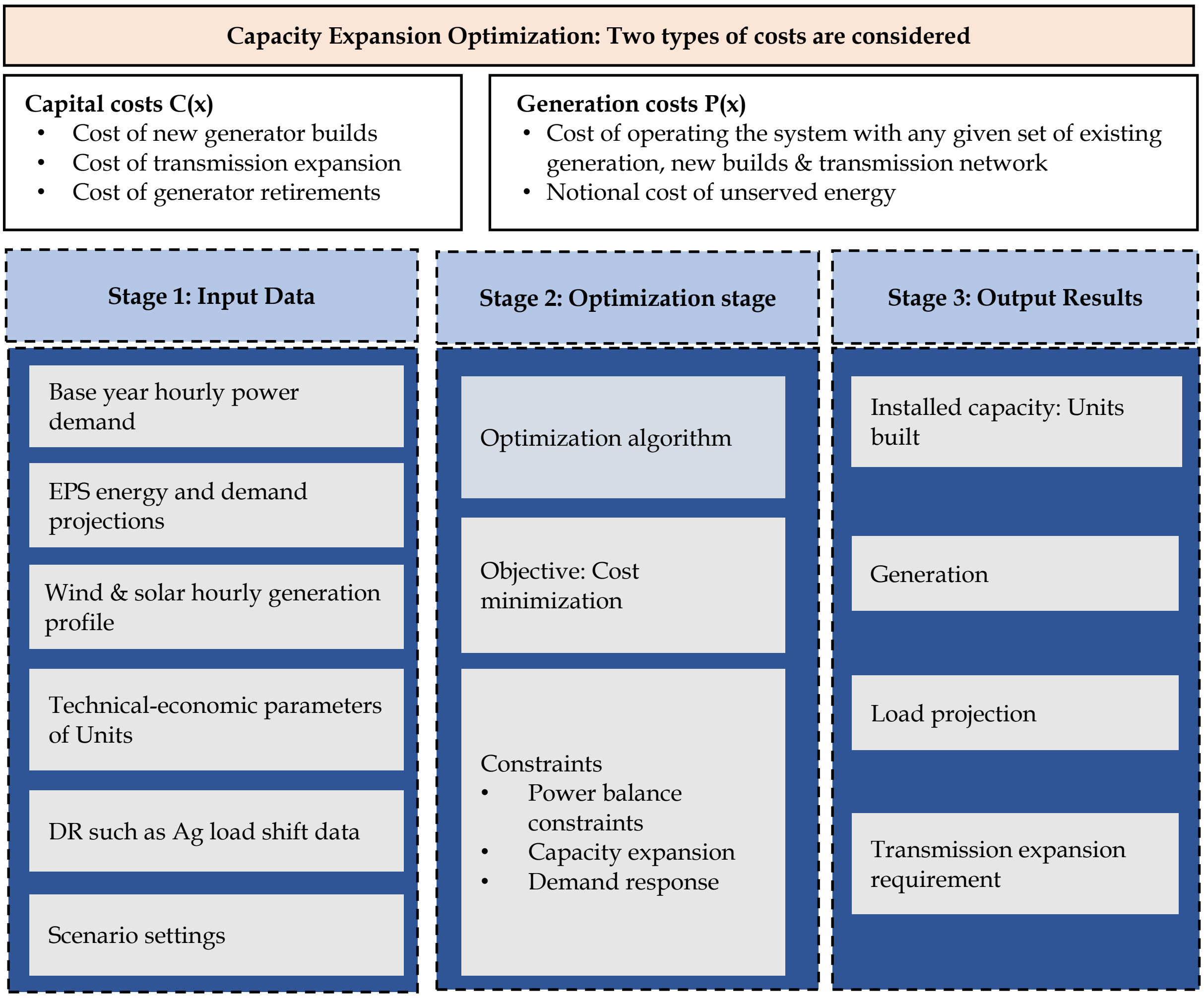

Figure 9: Overview of LT Expansion Modelling

2.3 Production Cost Modelling

Production cost modelling intends to assess the generator-wise dispatch with the objective of minimizing the total production cost. In other words, it is the process of allocating the required load demand between the available generation units such that the cost of operation is minimized. Production cost modelling captures all the costs of operating a fleet of generators and is developed into an hourly, chronological, and security-constrained unit commitment and economic dispatch simulation which minimizes costs while simultaneously adhering to a wide variety of operating constraints. It helps the utilities to manage fuel inventories and budget for required operations.

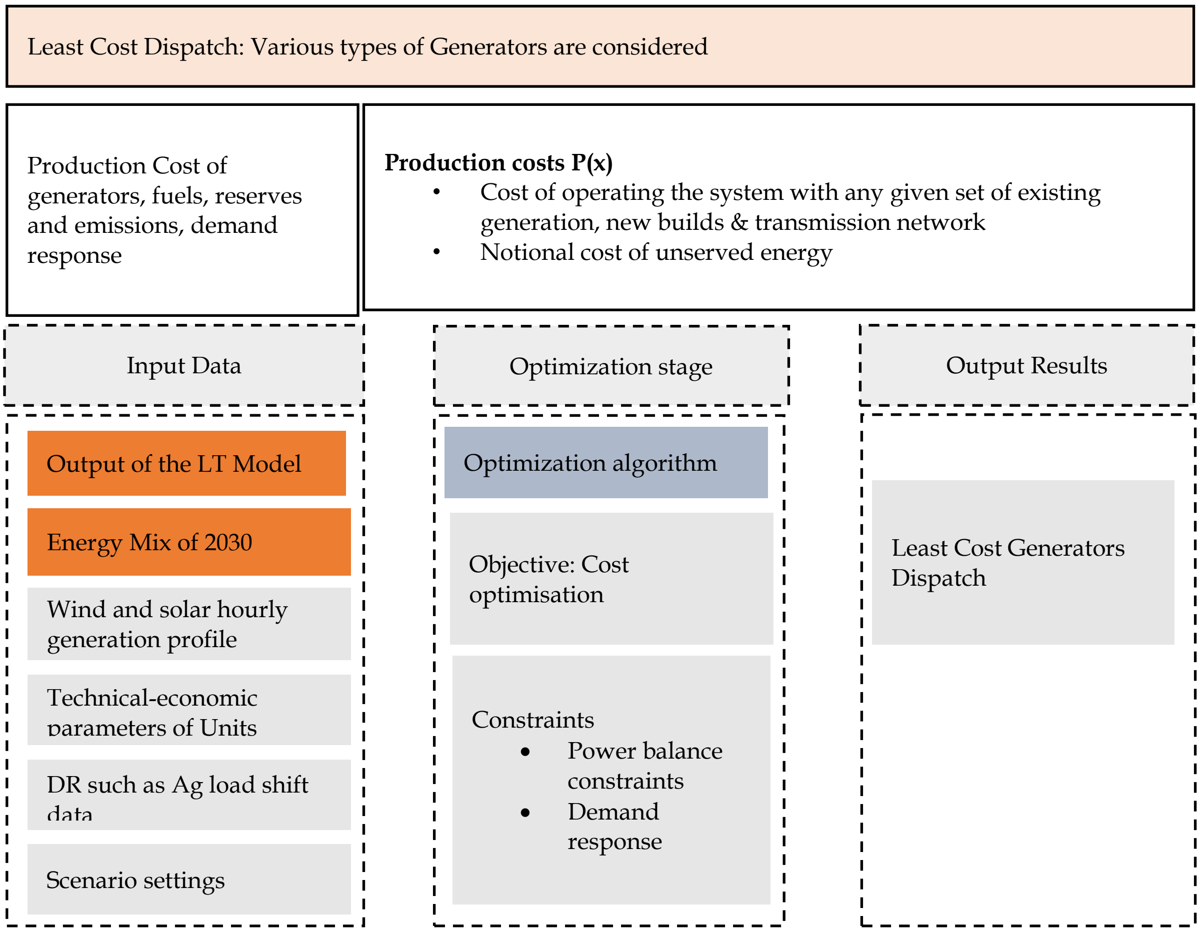

Figure 10: Overview of Production Cost Modelling

The production cost has been analysed for the scenario considering moderate cost of vRE and battery with state power projections as in figure below:

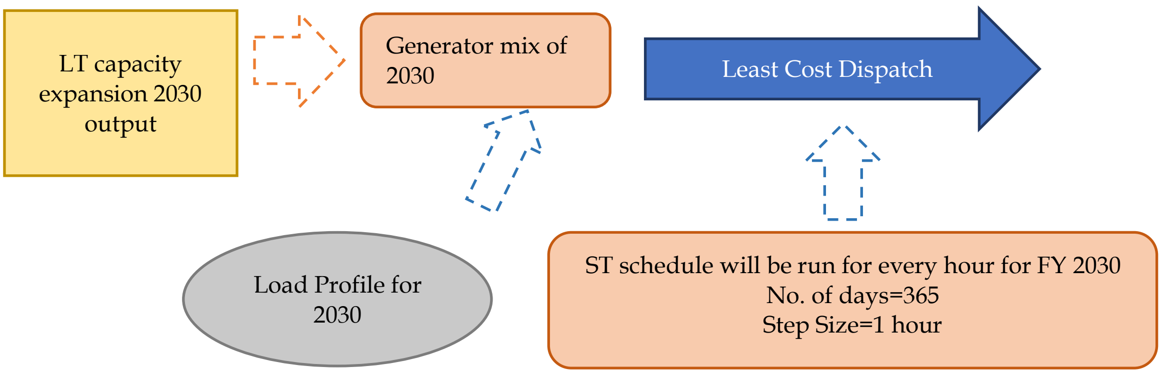

Figure 11:Least Cost Dispatch Modelling Approach

2.4 Scenarios Considered

Based on the cost of vRE and demand projections (lower and higher), following scenarios are developed to understand impact of cost and load projections. In all the scenarios, it is considered that agricultural load will be shifted from night to solar hours.

Table 2: Scenarios Considered for Capacity Expansion

	Criteria	**Current Policy Scenario**	**Primary Least Cost Case**	**Primary Least Cost Case**	**High RE Installation Case**	**Sensitivity Case**
Capacity Expansion	Load	EPS projections	State projections	EPS projections	EPS projections	EPS projections
	Capital Cost of solar (Rs Cr/MW)	4.20 in 2020 to **2.94** by2030	4.20 in 2020 to **2.94** by 2030	4.20 in 2020 to **2.94** by 2030	4.20 in 2020 to **2.94** by2030	4.20 in 2020 to **2.94** by 2030
	Capital Cost of wind (Rs Cr/MW)	6.62 in 2020 to 5.96 by 2030	6.62 in 2020 to 5.96 by 2030	6.62 in 2020 to 5.96 by 2030	6.62 in 2020 to 5.96 by 2030	6.62 in 2020 to 5.96 by 2030
	Capital Cost of battery (Rs Cr/MW)	6.30 in 2020 to **3.77** by 2030	6.30 in 2020 to **3.77** by 2030	6.30 in 2020 to **3.77** by 2030	6.30 in 2020 to **3.77** by 2030	6.30 in 2020 to **3.77** by 2030
	Yearly PLF (Thermal Plants)	55% PLF for minimum dispatch (25% minimum yearly PLF) for plants starting 2023	55% PLF for minimum dispatch (25% minimum yearly PLF) for plants starting 2023	55% PLF for minimum dispatch (25% minimum yearly PLF) for plants starting 2023	55% PLF for minimum dispatch (25% minimum yearly PLF) for plants starting 2023	55% PLF for minimum dispatch (25% minimum yearly PLF) for plants starting 2023

The hourly dispatch model is built on 2030 result of the primary least cost case (EPS Projections).

2.5 Rajasthan State Model

Rajasthan is modelled as a part of Indian grid in the model as in figure below with further details of Rajasthan power system. While the generation of all other states excluding Rajasthan has been considered lumped, generators of Rajasthan has been modelled.

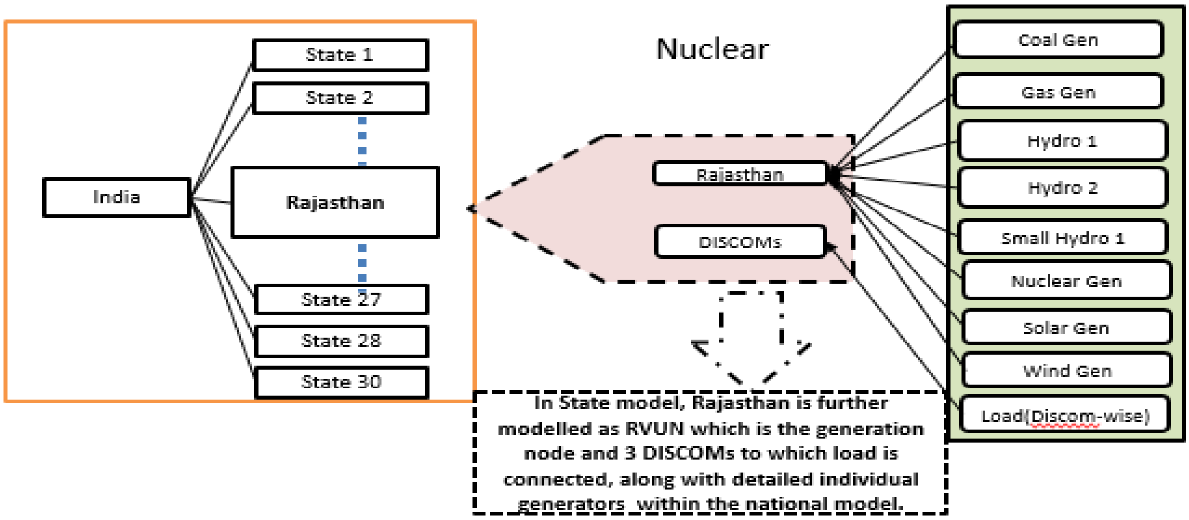

Figure 12:Rajasthan as a part of the whole Indian grid

2.6 Generators

Different approaches have been considered to model different technologies as detailed below.

2.6.1 Thermal Generators

Thermal InSGS, ISGS, and IPPs are modelled station-wise as shown in the figure below:

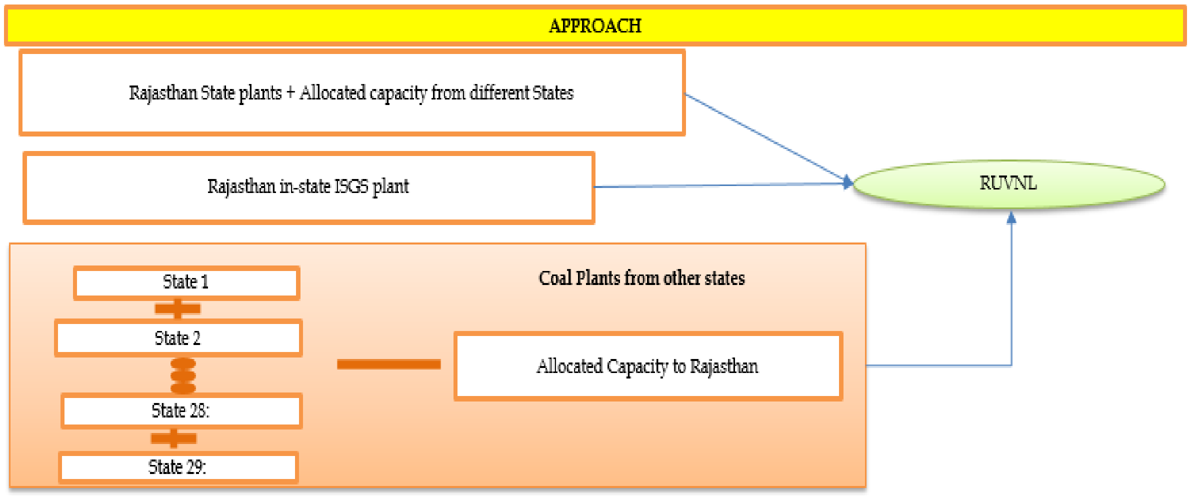

Figure 13: Thermal Generator Modelling Approach

2.6.2 Hydro Generators

Hydro generators were classified as RoR, reservoir based, PSH, or as small-hydro and are modelled with constraint on the max energy that can be produced by a hydro plant in a month as available in CEA's monthly hydro generation status. Further as small hydro generators are mostly connected to distribution network, they are connected at DISCOMs level.

2.6.3 Nuclear Generators

Nuclear generators are modelled similar to thermal generators. Basic properties such as ramp rates, fuel price etc. (decrement or increment in fuel price is not considered) are given as input to the system.

2.6.4 RE Generators

Historical installed capacity of solar and wind generators as received from state was used to model generators of vRE in the state.

2.6.5 Battery

As Rajasthan has multiple DISCOMs with different load profile, the need of battery would be different. Thus, to have a better understanding of battery needs of each DISCOM, the need of batteries was modelled for each DISCOM.

2.6.6 Agricultural Shift

Ag shift has been modelled as a virtual pumped storage which reduces the load during night and increases the demand during the day for specific hours. As Ag load varies seasonally, the quantum of 3000 MW of Ag shift is specifically considered for sensitivity case.

3 Key Findings

3.1 Incremental Demand Met Through Increase in Generation from Renewable Sources

Incremental demand through 2030 could be met by investments in RE and storage resources. No new thermal plant is optimal, and the grid is dependable with existing thermal resources and new RE and storage resources. The primary least cost mix (state projections) in 2030 includes ~7 GW of wind and ~59 GW of solar respectively with additional ~21 GW of energy storage requirements and primary least cost mix (EPS projections) in 2030 includes ~6 GW of wind and ~39 GW of solar respectively with additional ~12 GW of energy storage requirements.

Despite increasing demand, Rajasthan will be able to meet its incremental load with additional solar, wind, and flexible resources only. No new thermal is cost effective and required in any of the cases considered. Table 4 shows installed capacity mix by 2030 for all scenarios considered.

Table 3: Technology wise Installed Capacity in the Optimal Generation Mix 2030

	Installed capacity (GW)		
Technology	**Current Policies Scenario**	**Primary least cost of scenario (State Projections)**	**Primary least cost of scenario (EPS Projections)**
Coal (GW)	10.5	10.5	10.5
Gas (GW)	0.8	0.8	0.8
Nuclear (GW)	0.5	0.5	0.5
Hydro (GW)	1.9	1.9	1.9
Solar (GW)	32.5	59.1	39.0
Wind (GW)	6.1	6.8	6.20
Small Hydro (GW)	0.03	0.03	0.03
Battery (GW)	9.6	20.8	12.4
Total	**61.9**	**100.4**	**71.3**

With this mix, the share of non-fossil resources in total installed capacity is 39 GW in current policy scenario and is 66 GW and 45 GW in the Primary Least Cost scenario (state projections and EPS projections respectively).

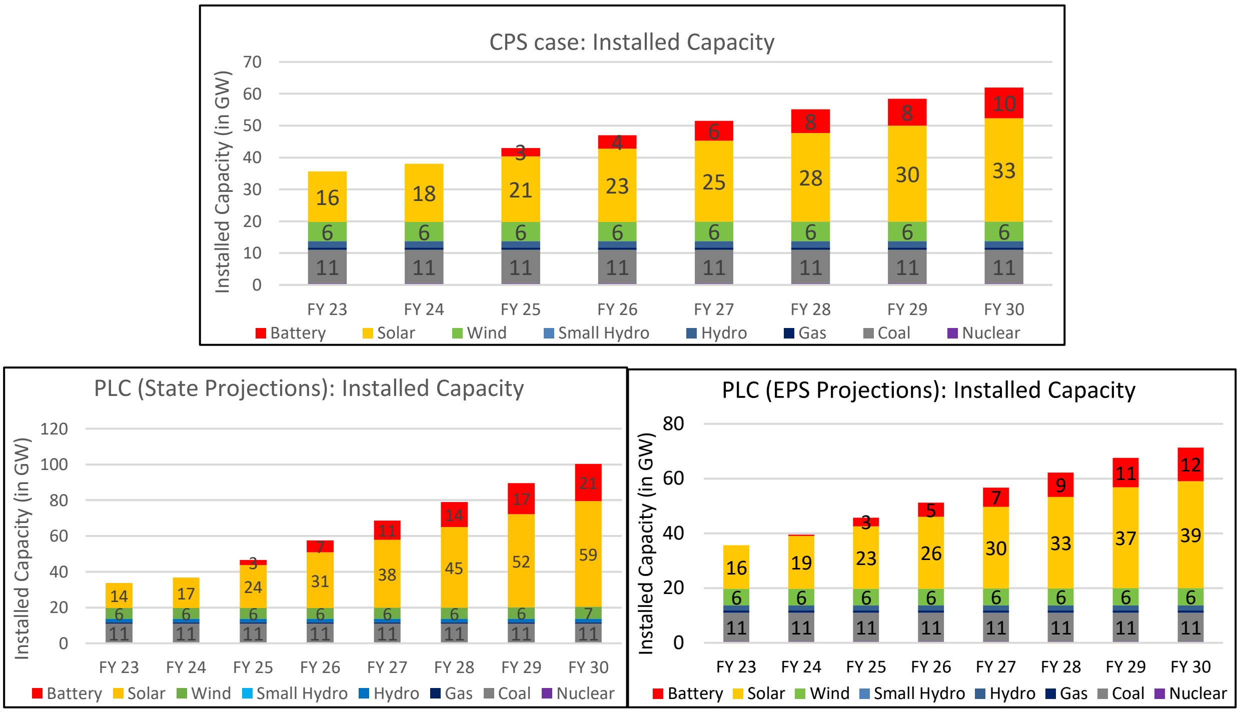

Figure 14: Installed Capacity by Resource type in CPS (Top), PLC (State-Projections)(Bottom - Left) and PLC (EPS Projections) (Bottom-Right) FY 23-30

a. Non-fossil generation constitutes more than half of total generation

With increase in RE and storage capacity, generation from thermal decreases from 52 TWh to 30 TWh in the CPS Projections, 50 TWh to 29 TWh in the primary least cost case (state projections) and 52 TWh to 30 TWh in the primary least cost case (EPS projections). This decrease is aided by increase in generation from RE sources with increasing contribution of storage generations which enhances the value of solar energy in the grid. Table below shows generation from different sources in all different cases considered.

Table 4: Yearly Generation from Different Technologies in 2030

	Generation in TWh		
Technology wise generation	**Current Policies Scenario**	**Primary least cost of scenario (State Projections)**	**Primary least cost of scenario (EPS Projections)**
Coal	29.8	28.6	29.7
Gas	1.4	1.4	1.4
Nuclear	2.5	2.5	2.5
Hydro	8.3	8.3	8.3
Solar	56.4	105.6	68.4
Wind	9.7	10.8	9.9
Small Hydro	0.1	0.1	0.1

Technology wise generation	Current Policies Scenario	Primary least cost of scenario (State Projections)	Primary least cost of scenario (EPS Projections)
	Generation in TWh		
Net Import	64.5	-7.5	52.6
Total	**172.7**	**149.7**	**173.1**

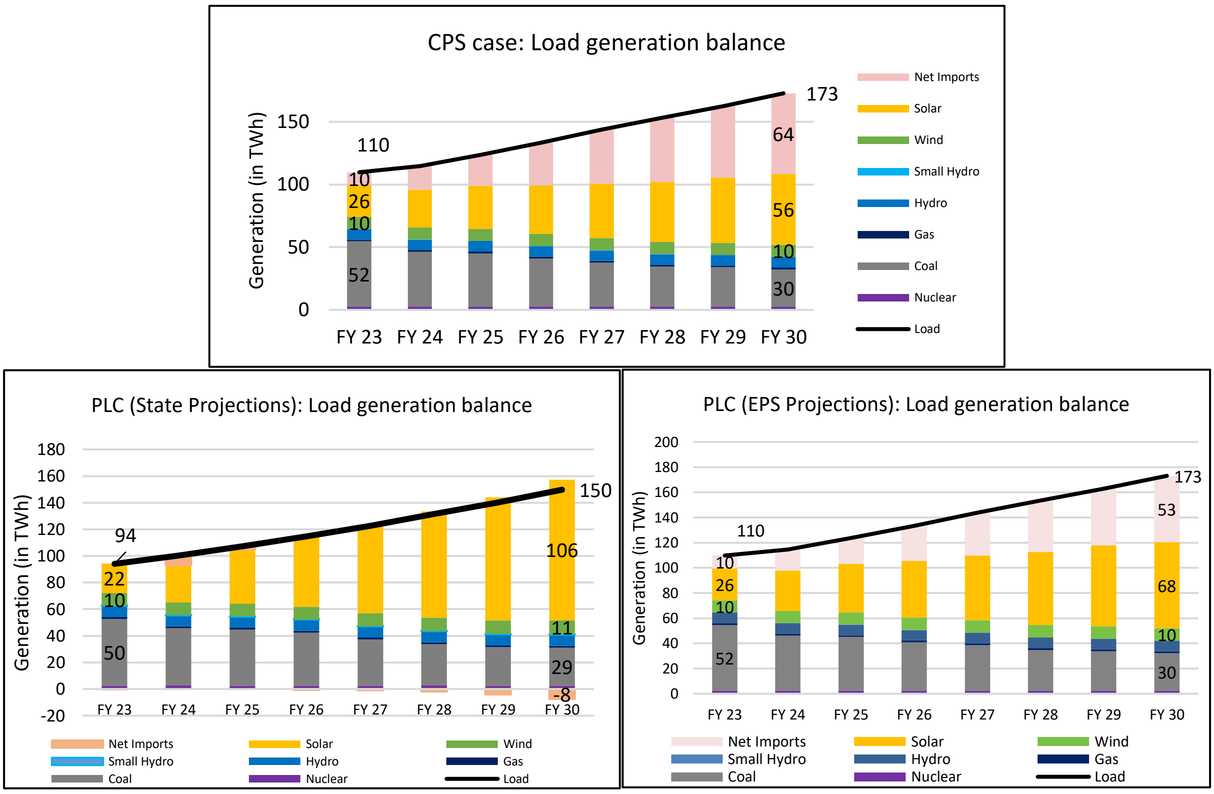

Figure 15: Annual Generation and Load by Resource Type in CPS (top), Primary Least Cost (PLC) (State Projections) (bottom - left) and Primary Least Cost (PLC)(EPS Projections) (bottom-right) FY 2023-30

In case of current policy scenario, the import of power would increase to compensate for increasing load suggesting availability of lower cost power outside the state and the same case is with the primary least cost case (EPS projections). But in the primary least cost case (state projections) the import of power is low with lower thermal generation and increased generation from RE sources**.**

b. The average cost of electricity generation is lower than today's cost of generation

The average cost of electricity includes the fixed costs (annualized capital service and O&M) of all existing and new power plants, battery assets (including battery pack replacement costs), and the transmission network, fuel costs of thermal, biomass, and nuclear generators, and any startup/shutdown costs. A CAGR based increase in variable costs of thermal plants is considered (further details in Annexure I)

Table 5: Scenario-wise APPC for FY 2023-30

	Units	Current Policies Scenario	Primary least cost case (State Projections)	Primary least cost case (EPS Projections)
FY 2023	INR/kWh	3.95	4.11	3.95
FY 2030	INR/kWh	3.74	3.20	3.63
Decrease	**%**	**~5%**	**~22%**	**~ 8%**

In CPS case, the average cost decreases because of increase in RE generation (36 TWh to 66 TWh), for primary least cost case (EPS projections) because of increase in RE Generation (35 TWh to 78 TWh) and in primary least cost case (state projections) because of increase in RE Generation (from 32 TWh to 116 TWh).

Reasons for least cost in primary case (state projections):

1. *Plummeting costs of solar, wind, and batteries drive the system average cost down*: As generation from solar and wind increases the total cost of the system decreases.

2. *3 GW of demand response reduces the night-time baseload requirement.* Shifting of agricultural load, which is primarily supplied during night hours (10 PM to 6 AM), to solar hours would reduce significantly the night-time baseload power requirement typically met by coal power plants.

3. *Cheap grid-scale battery storage enhances the capacity value of vRE*: Batteries provide di-urinal flexibility by generating during peak hours and charging during off-peak hours. This interplay between vRE and battery also enables vRE to provide firm capacity and meet reserve requirements.

4. *Increase in export of power:* With increase in cheaper RE sources within the State, import of power decreases (from 0 TWh to 8 TWh) in primary least cost case (EPS Projections) leading to further decrease in average cost of power by 2030.

c. Emission intensity from power generation

The emission intensity decreases by 47% in current policy scenario whereas it decreases by 66% in the primary least cost scenario (state projections) and 53% in the primary least cost scenario (EPS projections). Figure below shows emission intensity for different scenarios till FY 2030.

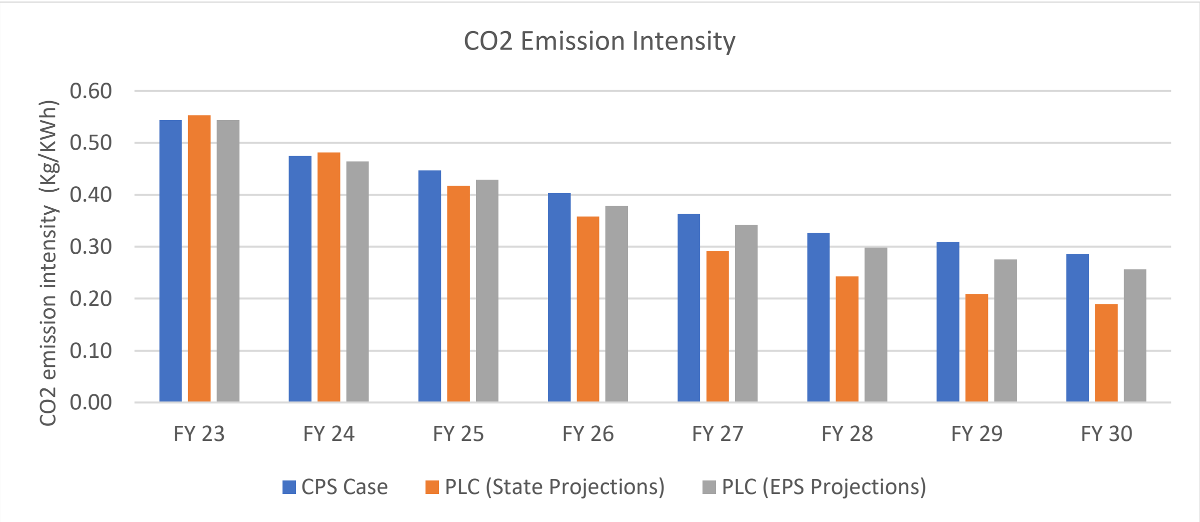

Figure 16: Co2 Emission Intensity (kg/kWh), FY 23-30

3.2 The grid is dependable even with significant RE addition

While the long-term studies for the year 2029-30 are required to assess the optimal mix in terms of investment decisions, short term generation dispatch study on hourly basis is required to assess the adequacy of the system and it validates that the optimal resource mix can meet demand in every hour of the year in 2030.

All the operational and technical parameters as discussed in chapter 3 has been considered to derive an optimum least cost hourly generation portfolio for the year 2030 for the primary least cost scenario.

Figure below shows average hourly system dispatch in FY 2030 for all months in the Primary Least Cost Case (EPS Projections).

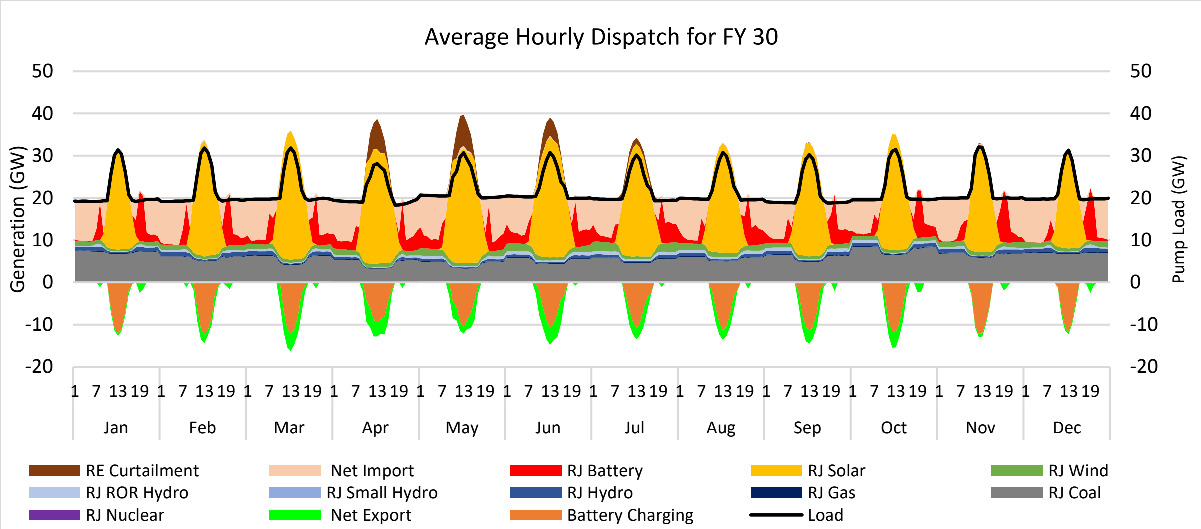

Figure 17: Monthly Average Dispatch for FY 2030

The flexible resources work in tandem to maintain grid dependability. Battery storage is critical for diurnal balancing of the grid, while variable monthly PLF of thermal plants along with import and export of power are critical for seasonal balancing.

Energy storage, including batteries and pumped hydro, charges during the day and discharges during evening and morning peak hours, while also providing the ramping support during the most critical ramp events. Thermal plants operate mostly during the low RE season (October through December) and are critical for seasonal balancing of the grid.

a. Variable monthly thermal PLF aides in seasonal balancing

Existing thermal plants operate at variable PLF providing seasonal balancing. Plants with VC greater than 4 Rs/kWh operates only during low wind/solar months and thus retiring them will increase PLF of efficient thermal plants. Figure below shows average coal generation as percentage of total generation from coal.

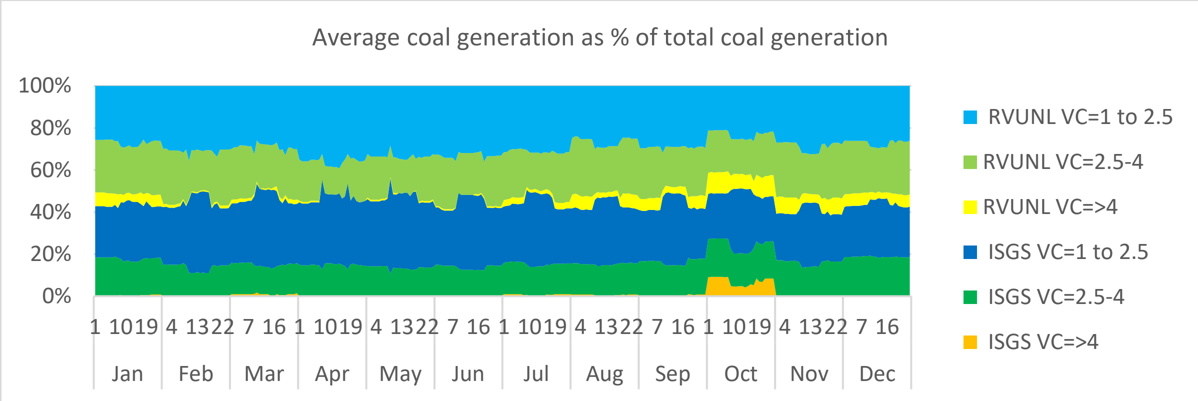

Figure 18: Average Coal Generation from Different Plants as Percentage of Total Coal Generation in the State

b. The grid has sufficient capacity to run dependably during "high-stress" periods

To understand the operation of grid during high stress periods multiple stress days were examined as mentioned below:

Table 6: Selected dispatch days

Sr. No.	Selected Day	Date
1	Max Net Load Day	1st Feb, 2030
3	Least Demand Day	8th May, 2029
6	Max vRE Day	4th June, 2029

Max Net Load Day

Peak of 36.24 GW occurred at 13:00 Hrs on 1st Feb, 2030 and is met by about ~77% RE and ~10% conventional sources and rest 12% by imported energy. During the peak day, the State imports for almost 24 hrs, coal generation provides base load.

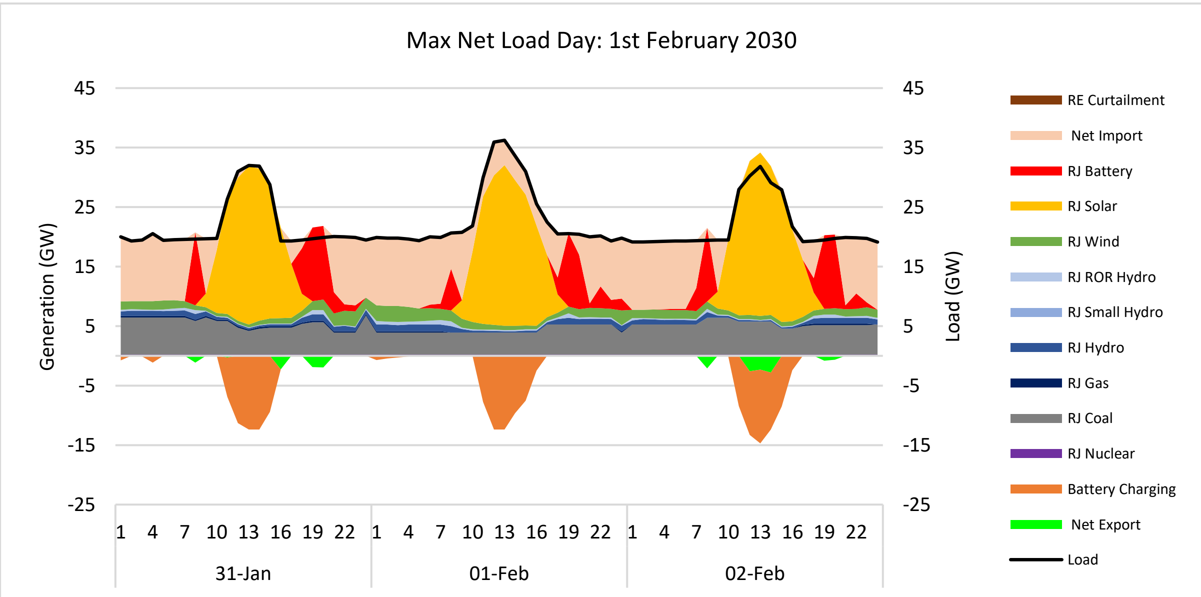

Figure 19: Max Net Load Day on 1st Feb, 2030

Lowest Demand Day

Lowest demand of ~14.14 GW is observed at 17:00 Hrs on 8th May, 2029 and as is seen in figure below the state imports throughout the day.

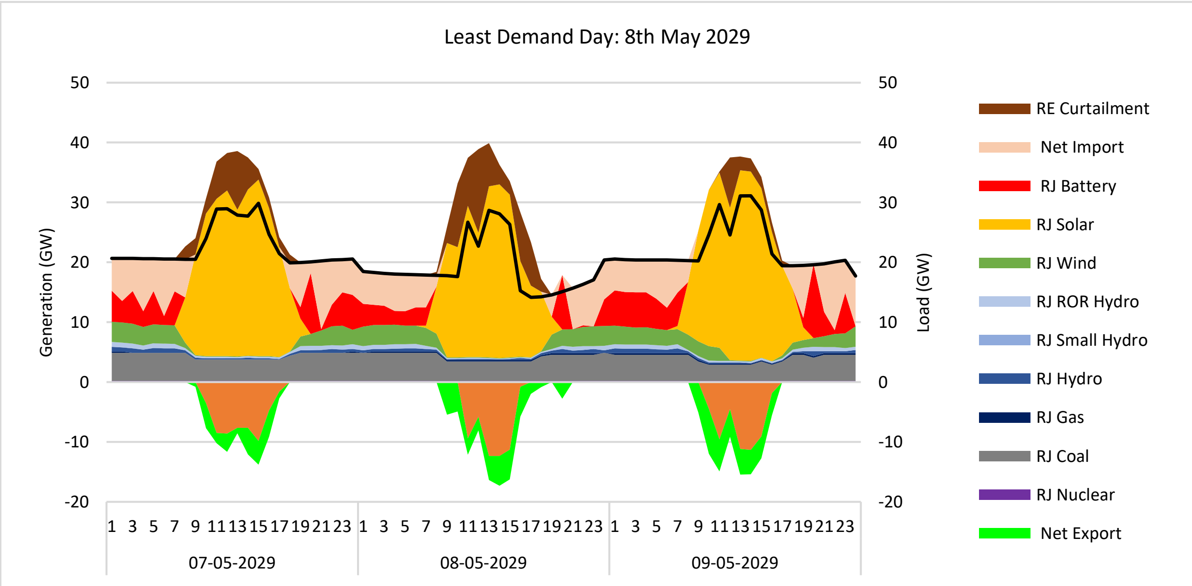

Figure 20: Least Demand Day on 8th May, 2029

Max vRE Day

System has to be resilient on the day when the maximum generation from RE (wind + solar) is likely to occur and it is observed that maximum generation from vRE sources occurs on 4th June with wind and solar contributing ~107% of peak load at 13:00 Hrs.

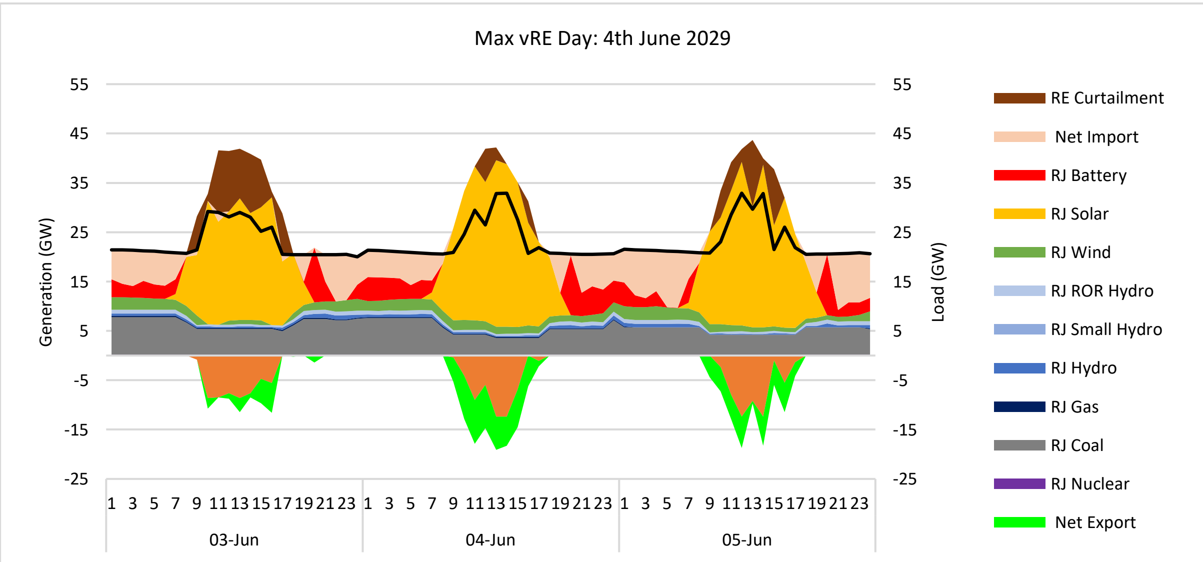

Figure 21: Highest vRE Day on 4th June 2029

It is important to understand that the study has simulated hourly grid operations using a DC Optimal Power Flow formulation. This implies that some of the operational issues that may arise in an AC power system such as reactive power compensation and impact on line voltages and grid frequency could not be assessed in this study. Deeper analyses using appropriate simulation tools (such as Power System Simulator for Engineering (PSSE)) would be needed to fully understand such impacts.

4 Sensitivity Analysis

We assess the sensitivity of our results on key assumptions of (1) clean technology costs and disruptions to the solar / batteries supply chain and (2) demand growth. Table below summarizes these alternate pathways, and key insights set forth below:

Table 7: Technology wise Installed capacity in the optimal generation mix 2030 (GW)

Scenario description	Primary least cost scenario (State Projections)	Primary least cost scenario (EPS Projections)	High RE Installation	State Sensitivity Case
Coal	10.5	10.5	10.5	10.5
Gas	0.8	0.8	0.8	0.8
Nuclear	0.5	0.5	0.5	0.5
Hydro	1.9	1.9	1.9	1.9
Solar	59.1	39.0	62.2	33.3
Wind	6.8	6.20	7.3	9.0
Small Hydro	0.03	0.03	0.03	0.03
Battery	20.8	12.4	22.2	10.0
Total	**100.4**	**71.3**	**105.4**	**66.0**

Sensitivity Case: High RE Installation

Compared to primary least cost case, it is seen that with increase in predicted demand the installed capacity increases to almost 105 GW with about 66% of vRE capacity and about 22 GW of 4-hrs of battery storage to meet.

Sensitivity Case: State Sensitivity Case

Compared to primary least cost case, it is seen that with 3000 MW Agricultural Load shift the installed capacity becomes almost 66 GW with about 64% of vRE capacity and about 10 GW of 4-hrs of battery storage to meet. Table below shows generation from different sources in all different cases considered.

Table 8: Yearly generation from different technologies for primary least cost and high RE installation scenarios by 2030

Technology wise generation	Primary least cost scenario (State Projections)	Primary least cost scenario (EPS Projections)	High RE Installation case	State Sensitivity Case
Coal	28.6	29.7	28.2	38.8
Gas	1.4	1.4	1.4	1.4
Nuclear	2.5	2.5	2.5	2.5
Hydro	8.3	8.3	8	8.3

Technology wise generation	Primary least cost scenario (State Projections)	Primary least cost scenario (EPS Projections)	High RE Installation case	State Sensitivity Case
Solar	105.6	68.4	111	57.7
Wind	10.8	9.9	12	14.3
Small Hydro	0.1	0.1	0.1	0.1
Net Import	-7.5	52.6	10.9	49.4
Total	150	173	174.3	173
APPC (Rs/KWh)	3.20	3.63	3.15	4.02

5 Conclusion

Dramatic cost reductions over the last decade for wind, solar, and battery storage position Rajasthan to have a more flexible, robust, and sustainable power system — most of which is yet to be built — for delivering affordable and reliable power to serve increasing demand. In this study, we assess a cost-effective and operationally feasible investment pathway for Rajasthan's electricity grid by enhancing system flexibility and robustness through renewable energy (RE) and a spectrum of flexible resources, such as energy storage and demand response (load shifting). The study achieves this objective by using an industry standard power system modelling platform (PLEXOS) and comprehensive electricity grid data at the individual power plant level.

5.1 Modelling Results

The study carried out through PLEXOS modelling gives Rajasthan's least cost resource mix in 2030 which is primarily consists of RE and flexible resources. These least cost mix does consider that Rajasthan will be able to shift additional ~5 GW of load from night to solar hours in state sensitivity case.

- **Current Policy Scenario (CPS):** 62 GW Solar, 7 GW of wind and 10 GW of 4-Hrs storage by 2030.
- **Primary Least Cost Scenario (EPS Projections):** 39 GW Solar, 6 GW of wind and 12 GW of 4-Hrs storage by 2030.
- **Primary Least Cost Scenario (State Projections):** 59 GW Solar, 7 GW of wind and 21 GW of 4-Hrs storage by 2030.
- **High RE Installation Scenario:** 62 GW of solar, 7 GW of wind and 22 GW of 4 Hrs storage by 2030.
- **State Sensitivity Scenario:** 33 GW of solar, 9 GW of wind and 10 GW of 4 Hrs storage by 2030.

These results imply that Rajasthan can meet its demand through 2030 largely by new investments in renewable energy and storage assets. Further, it is also seen that it is optimal to import power from other states till 2030 and thus the State should consider import of cheaper power whenever available to have a least cost scenario.

Overall, as Rajasthan's grid attains higher penetrations of renewables, balancing its variability through a spectrum of flexible resources – such as energy storage, demand response (agricultural load shifting), along with import from other States becomes increasingly important for ensuring the affordability, stability, and reliability of grid power. The flexible resources work in tandem to maintain the hourly supply-demand balance. During the high RE generation season (June through September for wind and March through June for solar), energy storage and agricultural load shifting provide diurnal grid balancing. Batteries charge during the daytime (coincident with solar generation) and discharge during the morning and evening peak periods (4-6 hours total each day). They also help to meet steep system ramps. As a result, thermal power plants are mostly dispatched as a base load resource.

5.2 Policy Recommendations

While this study indicates a direction to a least cost resource mix in 2030, critical policy and regulatory changes must be expeditiously implemented in order for Rajasthan to move on to that pathway. These changes include, among other things, a nuanced long-term resource adequacy framework for system planning and procurement, a regulatory framework for energy storage that values and compensates this resource for its full functionality, and an increase in demand management (Ag and industrial load shift). Following are some of the policy recommendations:

- Rajasthan does not exhaust its RE potential by 2030, but in long run it will need to reassess its RE potential as present RE potential assessment was carried out nearly a decade ago.
- The State higher RE curtailment, especially during high RE seasons. Both inter and intra-state transmission should be augmented.
- Results show that Rajasthan would suffer high RE curtailment during high solar season, partly because of limited demand management tools like agricultural shift. This could be avoided by adopting demand management approaches like shifting night-time load to solar hours.
- Cheaper coal power is available from States such as Chhattisgarh, Madhya Pradesh and Jharkhand.
- Nuanced resource adequacy framework required to drive planning and procurement strategies, and to avoid potential future stranded assets.
- Energy storage will play a key role and will need an appropriate regulatory framework for deployment to capture its full value.
- Focus on demand side management and other flexible resources.

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6 Appendix I: Key Assumptions, Data, and Limitations of the Model

6.1 Data Collections

With the constant support from Nodal agency i.e. RRVPNL, data collection was being made from other stakeholders such as JVVNL, JdVVNL, AVVNL, RRVUNL and RRVPNL. Modelling requires base data for Supply and Demand Side. Facilitation of various data related to financial and technical limits such as generator's installed capacity, Min stable level and variable cost etc. and for demand side, utility wise load profile, demand projections, financial contract details etc. were provided by the nodal agency.

Based on the available data certain assumptions were made to overcome issue of non-availability of data, if any. This section discusses various technical and other assumptions considered.

6.2 General Assumptions

A number of constraints related to distribution of batteries, development of wind, CEA battery and coal targets etc. are built up in the system which are shown in table below:

Table 9: Solar and Wind Build Constraints Considered

	Solar (MW)	Wind (MW)
Installed Capacity by end of 2021	10,050	5000
Max Potential (excluding the existing solar installed capacity by 2022)	128390	12700
Max Capacity that can be built in Year (PLC – EPS projections)	3500	1000
Max Capacity that can be built in Year (PLC – State projections)	7000	2500
Max capacity that can be built in a year (CPS case)	2300	1000
Max capacity that can be built in a year (High RE Installation case)	7000	2500

Further, to model technical characteristics such as such as ramp up and ramp down limits, heat rate, O&M expenses etc. the assumptions as in table below have been considered.

Table 10: General Generator Assumptions

Properties	Coal	Gas	Nuclear	Hydro	Small Hydro	RE	Biomass
Min Stable Factor (%)	55	20					
Start Cost ($)	100000	20000	10000000				
Max Ramp Up (MW/min)	0.01 * Max Capacity	0.03 * Max Capacity	0.0001* Max Capacity				
Max ramp Down (MW/min)	0.01 * Max Capacity	0.03 * Max Capacity	0.0001*Max Capacity				

Properties	Coal	Gas	Nuclear	Hydro	Small Hydro	RE	Biomass
FO&M charge ($/KW/yr)	25	15	60	10	10	10	15
Maintenance Rate (%)	5	10	15	5	5		
Forced Outage Rate (%)	10	20	15	5	5		
Outage Rating (MW)	0	0	0	0	0		
Mean Time to Repair (h)	24	24	400	24	24		
Min Time to Repair (h)	6	6	24			0	
Max Time to Repair (h)	72	72	1000			0	
WACC	8	8	8	8	8		
Economic Life (yr)	25	30	30	30	30		
Units	1	1	1	1	1		
Min Up Time (hr)	18	6	96	0	0		24
Min Down Time (h)	18	6	0	0	0		24
Firm Capacity (MW)	0.84 * Max Capacity	0.925 * Max Capacity	0.7*Max Capacity			0 for solar and 0.1*Max Capacity for wind	0.5* Max Capacity
Min Capacity Factor Month (%)			70				
Max Capacity Factor Month (%)			71				

6.3 Load Assumptions

To understand the impacts of change in load and energy requirements, predictions based on

a) Predictions based on past data and tariff order: Tariff projections (Tariff) on energy requirement and load projection are based on past and projected data as described in Tariff Order. It was considered to project future growth till 2030. State's projected energy requirement and peak demand data of 5 years i.e. from 2021-25 were used to calculate CAGR and is projected till 2030.

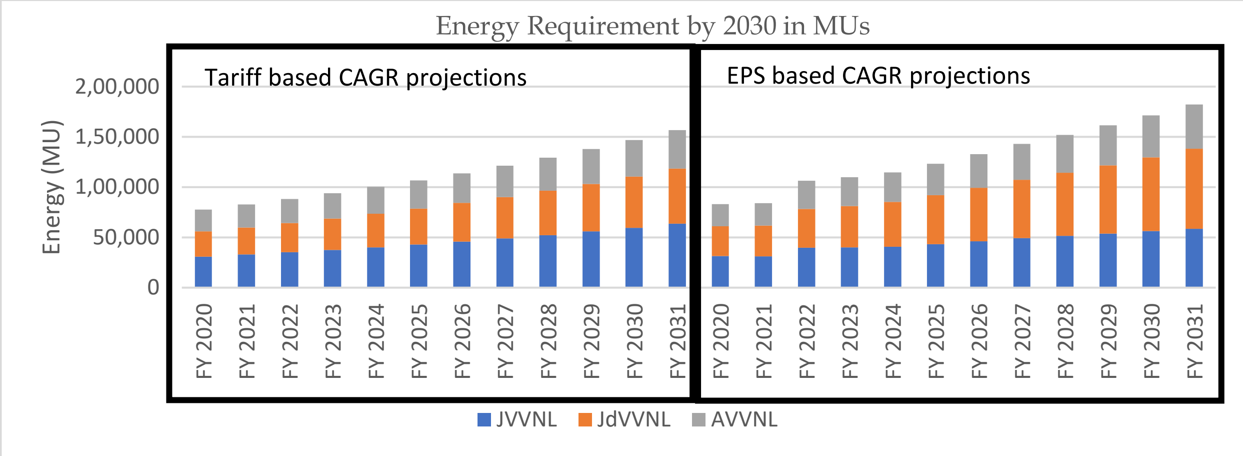


Figure 22: Tariff Orders and CEA 19th EPS Energy Requirement Projections

b) Predictions based on EPS based data: EPS based projections: EPS provides DISCOM wise energy and load projections till 2025-26, this data was used for a CAGR based projection for 2030 peak demand and energy requirement. CAGR is calculated for past 9 years i.e from FY 2017 to FY 26 and is projected till 2030.

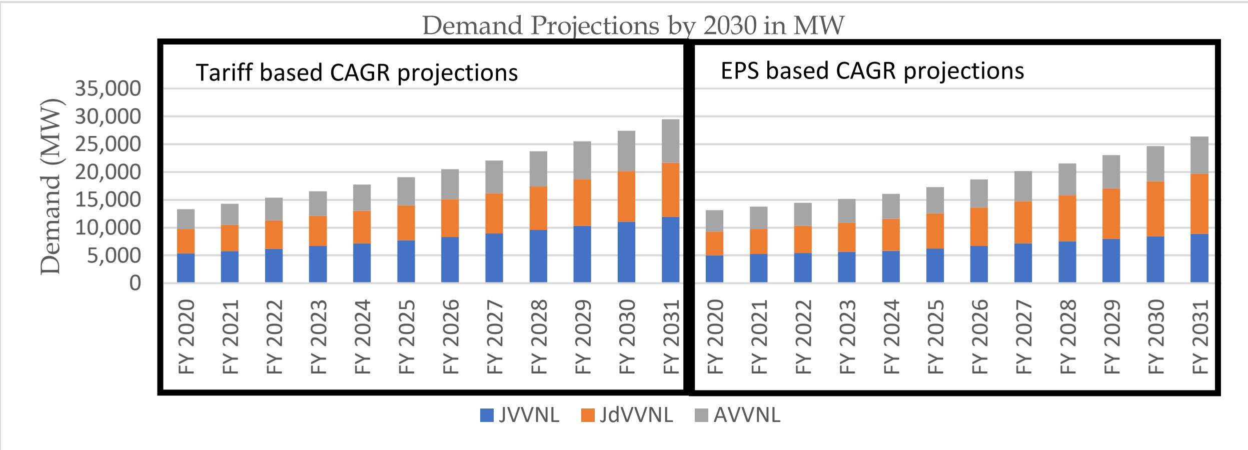


Figure 23: Demand projection from Tariff Projections and EPS projections

6.4 Cost Assumptions

Fuel cost and variable cost for future plants: It has been assumed that fuel prices for thermal power plants would increase and the following trend of fuel cost for any future addition of thermal power plants has been considered.

Table 11: Fuel costs and VC considered for future coal addition

FY	Coal Fuel Price (Rs/GJ)	Adjusted VC in (Rs/kWh) (Considering heat rate of 2300Kcal/kWh)
2023	309	2.97
2024	312	3.00
2025	315	3.03
2026	318	3.06
2027	321	3.09
2028	324	3.12
2029	328	3.15

2030	331	3.18

6.4.1 Variable costs of existing power plants

Variable cost based on plant wise CAGR from 2015-2020 has been considered as shown in table 13. This variable cost has been converted to fuel prices considering a heat rate of 9.3GJ/MWh for coal and 7.6GJ/kWh for gas-based plants shown in figure below.

Table 12: Variable Cost Projections of Existing Thermal Power Plants (Rs/kWh)

Name	Sector	FY 21	FY 22	FY 23	FY 24	FY 25	FY 26	FY 27	FY 28	FY 29	FY 30
Anta_GTPP	KPCL	4.37	4.61	4.86	5.13	5.40	5.70	6.01	6.33	6.67	7.04
Auria_GTPP	KPCL	4.22	4.46	4.71	4.98	5.26	5.55	5.86	6.19	6.54	6.90
Dadri_GTPP	KPCL	4.38	4.55	4.73	4.92	5.12	5.32	5.54	5.76	5.99	6.23
Farakka_TPS	ISGS	3.52	3.66	3.81	3.97	4.13	4.30	4.48	4.66	4.85	5.05
Kahalgaon_TPS	ISGS	2.11	2.14	2.16	2.18	2.21	2.23	2.26	2.28	2.31	2.33
Rihand_TPS	ISGS	1.50	1.66	1.84	2.03	2.25	2.49	2.75	3.04	3.37	3.72
Singrauli_TPS	ISGS	1.47	1.57	1.66	1.76	1.87	1.98	2.11	2.23	2.37	2.52
Kota_TPS	ISGS	3.31	3.54	3.78	4.03	4.31	4.60	4.91	5.25	5.60	5.99
Dholpur_CCPP	ISGS	5.38	5.59	5.81	6.04	6.28	6.53	6.79	7.06	7.35	7.64
Adani_Kawai	ISGS	2.77	2.98	3.20	3.43	3.69	3.96	4.25	4.57	4.91	5.27
UMPP_Sasan	ISGS	1.27	1.28	1.29	1.30	1.31	1.32	1.33	1.34	1.35	1.36
Maruti_Clean_DB_Power	ISGS	1.71	1.82	1.94	2.07	2.21	2.36	2.51	2.68	2.85	3.04
Ramgarh_Gas_TPP	ISGS	2.83	2.85	2.88	2.90	2.93	2.95	2.98	3.01	3.04	3.06
Unchahar_TPS_Stg_I	ISGS	3.04	3.19	3.34	3.50	3.67	3.85	4.03	4.23	4.43	4.65
Tanda_II	ISGS	2.64	2.66	2.69	2.72	2.74	2.77	2.80	2.83	2.86	2.88
Tanda_STPP_Stg_ll	ISGS	2.64	2.66	2.69	2.72	2.74	2.77	2.80	2.83	2.86	2.88
Meja_TPS	ISGS	2.71	2.74	2.76	2.79	2.82	2.85	2.87	2.90	2.93	2.96
Meja_TPS_U1	ISGS	2.71	2.74	2.76	2.79	2.82	2.85	2.87	2.90	2.93	2.96
Barsingsar_TPS	ISGS	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25
UMPP_Mundra	ISGS	2.04	2.20	2.36	2.54	2.73	2.94	3.16	3.40	3.66	3.93
Chhabra_TPS	RVUNL	2.46	2.54	2.62	2.71	2.80	2.89	2.99	3.09	3.19	3.29
Chhabra_Super_Critical_TPP	RVUNL	2.13	2.13	2.13	2.13	2.13	2.13	2.13	2.13	2.13	2.13
Kalisindh_TPP	RVUNL	2.81	2.90	3.01	3.11	3.22	3.34	3.45	3.57	3.70	3.83
Suratgarh_TPS	RVUNL	3.70	3.80	3.90	4.00	4.11	4.22	4.34	4.46	4.58	4.70
Raj_West_Power_TPS	IPP	2.71	2.93	3.17	3.43	3.72	4.02	4.36	4.72	5.11	5.53

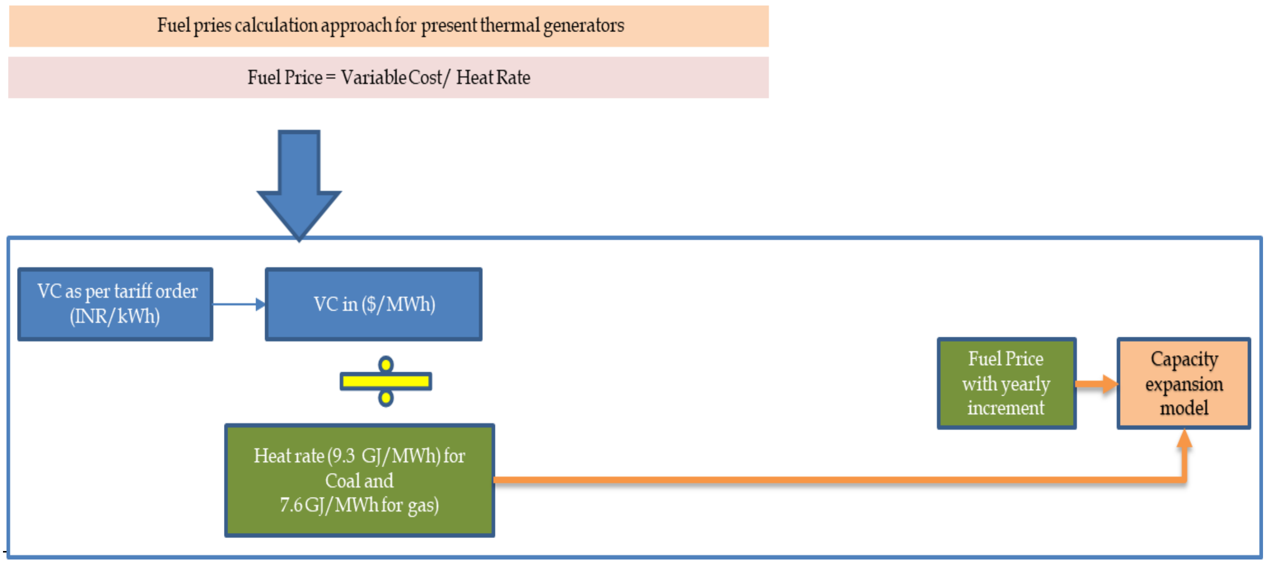
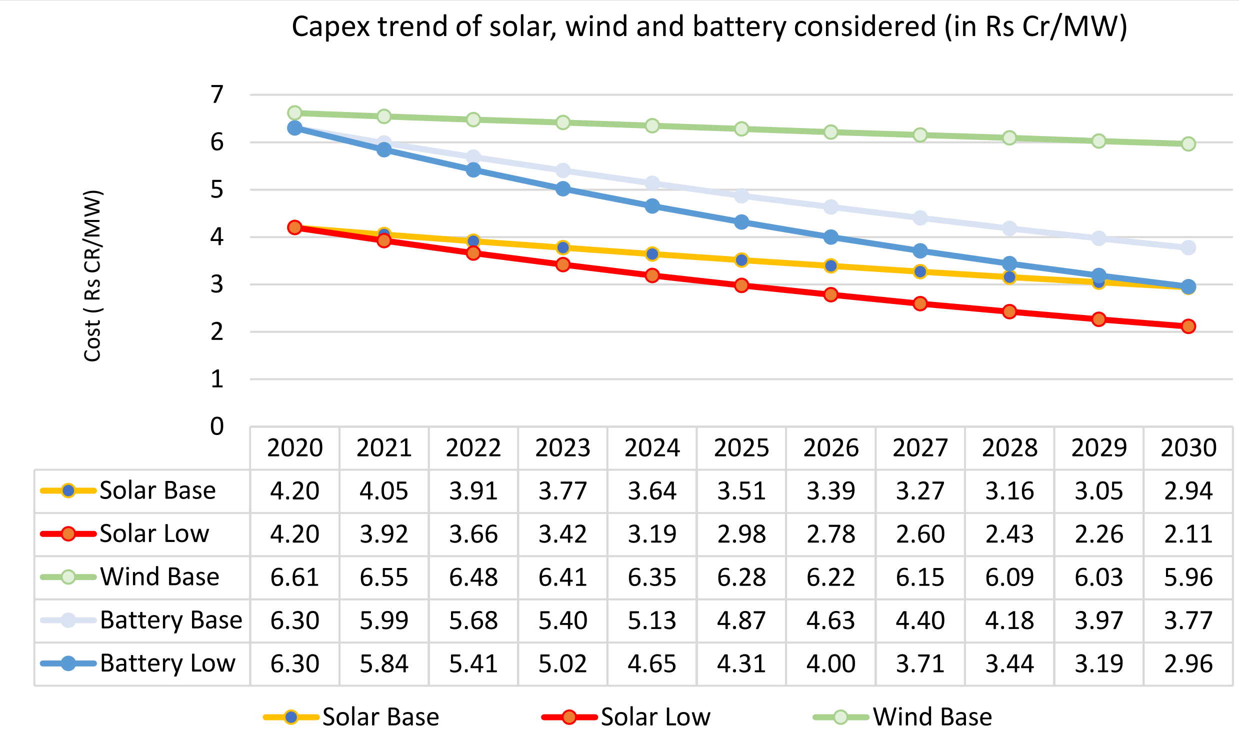


Figure 24: Future Fuel Cost Calculation for Existing Plants

6.4.2 Built Cost

New capital cost for coal and gas-based generators has been considered as 7.28 Cr/MW and 4.2 Cr/MW respectively. For solar, wind and battery two cases which are:

a) Base case with a mid-cost trajectory for solar, wind and battery cost are considered



	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Solar Base	4.20	4.05	3.91	3.77	3.64	3.51	3.39	3.27	3.16	3.05	2.94
Solar Low	4.20	3.92	3.66	3.42	3.19	2.98	2.78	2.60	2.43	2.26	2.11
Wind Base	6.61	6.55	6.48	6.41	6.35	6.28	6.22	6.15	6.09	6.03	5.96
Battery Base	6.30	5.99	5.68	5.40	5.13	4.87	4.63	4.40	4.18	3.97	3.77
Battery Low	6.30	5.84	5.41	5.02	4.65	4.31	4.00	3.71	3.44	3.19	2.96

Figure 25: Build Cost (CAPEX) of different generation technologies

6.5 Transmission Capacity

As the Rajasthan grid is connected to national grid present inter-state transmission lines has been modelled with possible increase in capacity as per optimal requirement

The Interstate transmission capacity considered to be built by year 2022 are:

From	To	Capacity (in MW)
Rajasthan	Gujarat	5,974
Rajasthan	Madhya Pradesh	5,422
Rajasthan	Haryana	4,713
Rajasthan	Punjab	2,470
Rajasthan	Uttar Pradesh	3,210

By 2022, the considered transport capacity of power from Rajasthan to other state is shown above. This will allow Rajasthan to import as well as export the power to other states. This value will also increase as per the optimisation run.

6.6 Coal Prices and Variable Costs

For existing coal power plants, we take the variable costs of existing interstate generating stations (ISGS) from reports available under the Reserves Regulation Ancillary Services (RRAS) mechanism. Variable costs for state generators and IPPs are from regulatory orders by Indian state commissions. For plants with no recent data available from regulatory orders, the variable cost data from Ministry of Power's MERIT database has been used. For power plants with no data available (less than 5 GW), the average variable costs for that technology and size in their state / region has been used. Between 2020 and 2030, a 1% per year of real increase in the variable costs has been assumed, which is half the historical growth rate of Coal India Limited's actual coal prices. Figure 26 shows the supply curve of the coal fleet (at individual unit level) for FY 2020. Each point on the chart represents a thermal power plant unit in the country; the horizontal axis shows cumulative total installed capacity of the fleet in MW while the vertical axis shows the variable cost in Rs/kWh.

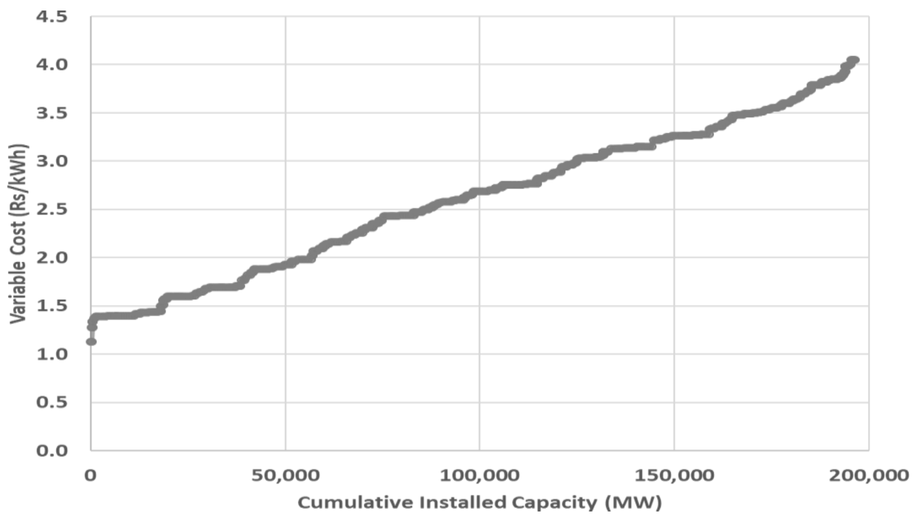


Figure 26: Supply Curve of the Existing Coal Capacity in FY 2020

It is interesting to note than in FY 2020, nearly 90 GW of the coal capacity had a variable cost of higher than Rs 2.76/kWh, the average solar reverse auction price including the safeguard duty. For new coal power plants, a pithead coal price of Rs 2000-2500/ton (incl taxes) has been assumed, which is equivalent to a variable cost of Rs 1.59/kWh, increasing at 1% per year (half the historical growth rate of Coal India Limited's actual coal prices) between 2020 and 2030. Imported coal prices are taken from global market reports at the Indonesian hub. Average delivered price imported coal is assessed to be $70/ton in FY 2020 increasing at 1% per year, which is equivalent to a variable cost of Rs 3.5/kWh for coastal power plants, after accounting for the improvement in heat rates due to imported coal.

6.7 Gas Prices and Supply Constraints

It has been assumed that the total domestic gas availability for power sector will remain constrained at the 2020 levels (8.4 bcm/yr or 23 mmscmd). Total LNG import capability would increase from 15 million tons per annum (MTPA) in 2020 to 50 MTPA in 2030. Domestic gas price in 2030 is assumed to remain almost the same as 2020 ($4.2/mmbtu). LNG price in 2020 is assumed to be $3.5/mmbtu

(FOB) or \$4.5/mmbtu (landed). For 2030, two LNG price scenarios are examined: 1) Base LNG price: landed price of \$5.5/MMBTU (plus regasification cost of \$0.6/mmbtu and pipeline charges, as applicable), and 2) Low LNG price: landed price of \$4.5/MMBTU (plus regasification cost of \$0.6/mmbtu and pipeline charges, as applicable).

6.8 Heat Rate

Actual heat rate data is used for every power plant using several sources such as regulatory filings, CEA Thermal performance review, CEA CO2 Emissions Baseline etc. The heat rate is modeled as a function of generator loading, meaning that as the power generation from a unit drops, the heat rate will increase. The heat rate function is taken from the CERC regulations on compensating the generators for partial load operations. Figure 27 shows the heat rate function used for a new 660 MW super-critical power plant.

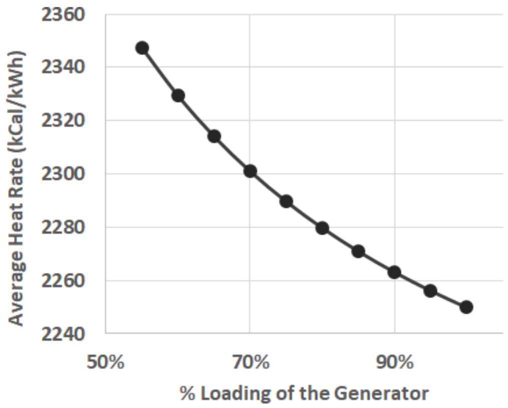


Figure 27: Average heat rate of a coal unit (660 MW super-critical) as a function of unit loading

At technical minimum level of 55%, the heat rate increases by over 4% of the design heat rate at rated capacity.

6.9 Limitations of the Model

- The Rajasthan state is built as an integrated model within the National grid, but other states/UTs generation capacities are lumped together based on technology.
- Intra-State transmission and distribution constraints are not considered.
- Power is distributed by 3 Discoms i.e. JVVNL, AVVNL, JdVVNL. These Discoms are clubbed together to form a single Rajasthan region, hence utility scale analysis is not undertaken.