How can India Meet its Rising Power Demand?

Pathways to 2030

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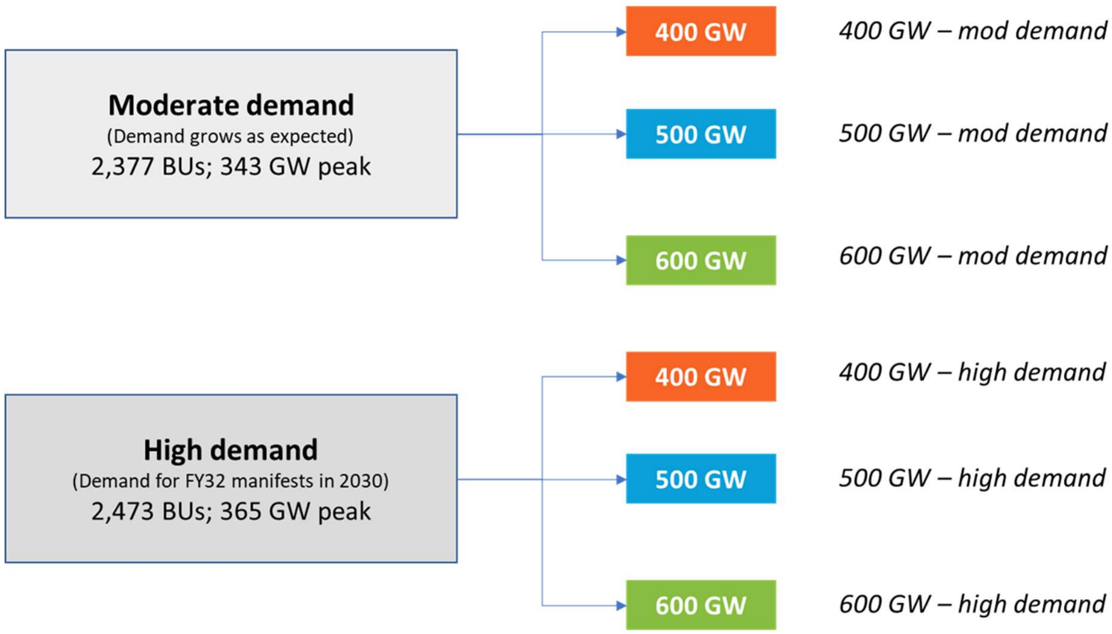
1. Modelling inputs and assumptions

We modelled India's power system to understand how the country should plan for adequate resources to meet the electricity demand for 2030. We perform national-level despatch simulations for 2030, considering the uncertainties in demand growth and the rate of non-fossil capacity deployment. We considered these uncertainties across six scenarios, elaborated in Figure 1. We conducted these simulations using GE Vernova's PlanOS' production cost optimisation model.

Figure 1: A set of six scenarios considered, accounting for demand and supply-side uncertainties for 2030



Source: Authors' analysis
Note: Moderate demand is considered as per the 20th Electric Power Survey (EPS) for 2030 CEA (2022c), and high demand is considered as per the 20th EPS, but with FY32 demand manifesting in 2030

1.1. Simulation tool and model architecture

We simulated each scenario in collaboration with GE Vernova's consulting services. We used PlanOS' production cost optimisation model (formerly known as multi-area production simulation [MAPS]) (GE Vernova, n.d.). The tool is a security-constrained linear optimisation model. We simulated India's power system at the sub-hourly (15-minute time block) level to understand the system's flexibility and reserve at every time block.

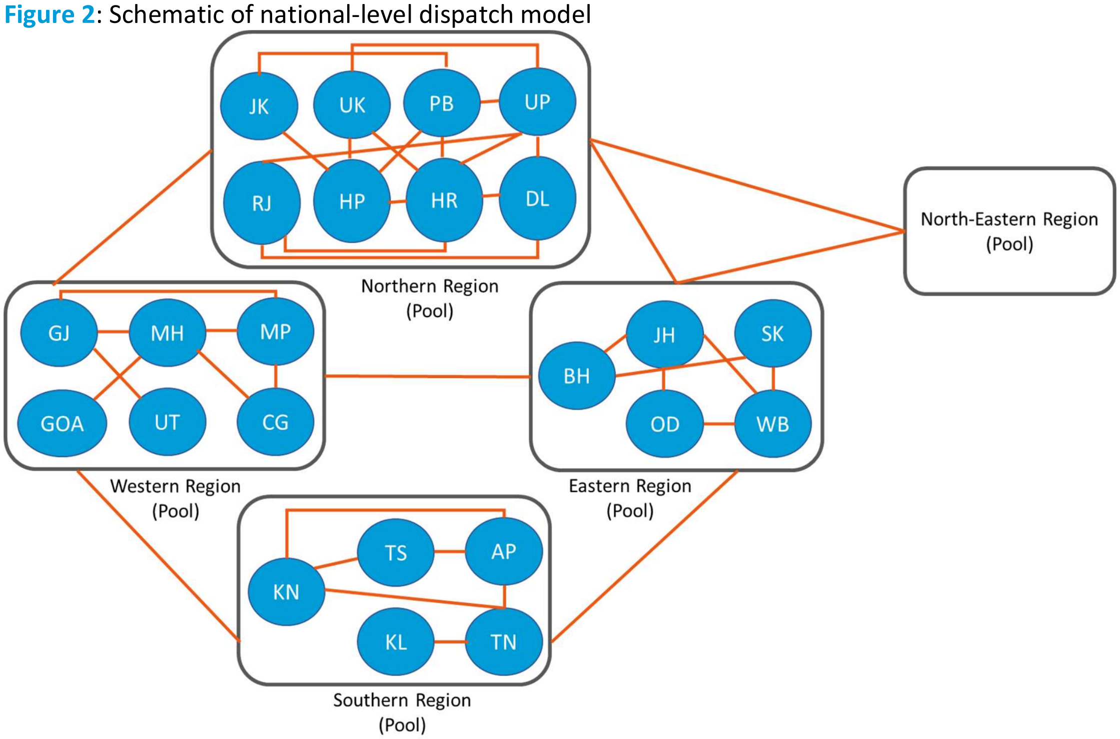
We modelled each state as a distinct node in its regional pool (as represented in Figure 2), except the northeastern states (which are pooled as a single node) and the union territories (clubbed with their nearest states).[1] Five regional pools represent the five Indian electricity regional grids -

[1] Puducherry is clubbed with Tamil Nadu, Chandigarh with Punjab, Dadra and Nagar Haveli and Daman and Diu are clubbed together as western union territories as a separate node in western region and Ladakh is clubbed with Jammu and Kashmir in the northern region pool.

Northern, Western, Southern, Eastern and North-eastern. All nodes and regional pools are connected through interstate and interregional transmission linkages. Electricity is free to flow from one node to the other subject to the power-carrying capabilities of the transmission linkages (i.e. transmission constraints).

The model is designed to emulate a market-based economic dispatch (MBED)[2] system in 2030 to ensure efficiency in scheduling and dispatch. The model utilises the detailed representation of all generation resources, individual state-level demand profiles, and interstate and interregional transmission linkages to conduct a production cost simulation, meeting the demand in a cost-effective manner.

Figure 2: Schematic of national-level dispatch model



Source: Authors' depiction of analysis

Note: All union territories in the western region are clubbed to a single node, called UT, in the western pool.

1.2. Inputs and assumptions

We used the model to integrate more than 1,400 power-generating units, 23 demand profiles, and about 38 interregional and interstate transmission linkages for 2030. We benchmarked our model for 2022 as a base year for existing capacities, generation and demand profiles. We considered the following set of inputs and assumptions to model the demand, generation capacities and transmission network in the model:

[2] MBED is a scheduling mechanism, where all generation capacities are scheduled at national level via market mechanism (MoP 2021)

A. Demand growth and profile

We consider 15-minute demand profiles for each node, observed in 2022, as base demand profiles (MoP, n.d.). We use the cumulative annual growth rate (CAGR) for energy requirement and peak demand for each node to scale up and adjust the base demand profile to meet the annual energy requirement and peak demand as per CEA's 20th *electric power survey* (EPS) for 2030 (CEA 2022c). For high-demand scenarios, we consider the demand projections for FY32 to come early in 2030. Accordingly, we scaled each node's base year demand profiles to meet the annual energy requirement and peak demand as per the 20th EPS for FY32.

B. Reliability constraints

We ran each scenario in PlanOS' production cost optimisation model with these system constraints – (i) normalised energy not served (NENS) (also known as unmet demand) between 0.05 and 0.1 per cent (MoP 2023), and (ii) vRE curtailment below 5 per cent annually.

C. Capacity additions for all scenarios

We defined each state as a node, as illustrated in Figure X1. Each node has a unique demand profile, existing and upcoming RE generation profiles and generators located or planned in the state's geographical periphery.

Coal: India has an installed capacity of around 211 GW of coal-based capacity as of December 2022 (CEA 2022a). As per the National Electricity Plan (NEP), 26.9 GW of capacity is under construction and expected to come online by 2030.[3] However, we excluded 3.9 GW of coal capacity, which has been non-operational since FY19 due to capacity being under outage for reserve shutdown (RSD) and uneconomic reasons (NPP 2023).[4] We added new coal units in case the supply is inadequate to meet the demand within reliability levels. We consider the planned and candidate plant's list (CEA 2023a) as a master list to add new coal units.

Gas: As of December 2022, India has installed 24 GW of gas capacity. We have not considered any further additions to gas capacity.

Non-fossil capacity addition: For the 500 GW and 600 GW scenarios, we consider adding 14.8 GW of under-construction hydro capacity (CEA 2023a) beyond 47 GW operational capacity as of December 2022. 4.5 GW of imported hydro capacity is also considered in the mix, totalling up to 62 GW (as represented in Figure 3). Similarly, we consider adding 13 GW planned capacity for nuclear, along with the operational 7 GW capacity.
In the 400 GW scenarios, we consider a delayed addition of hydro and nuclear capacities. We assume the capacity planned for FY27 will be commissioned by 2030, i.e. resulting in 58 GW of hydro and 14 GW of nuclear capacity.

[3] We have not considered any capacity to go under retirement as per PIB (2023).

[4] The capacity considered to be non-operational is removed because the units are under RSD (3336 MW) and other units are uneconomical (600 MW capacity) since FY19.

Figure 3: Distribution of non-fossil-based capacity across scenarios

400 GW non-fossil capacity	
Solar	229 GW
Wind	98 GW
Hydro	60 GW
Nuclear	14 GW

500 GW non-fossil capacity	
Solar	302 GW
Wind	123 GW
Hydro	62 GW
Nuclear	20 GW

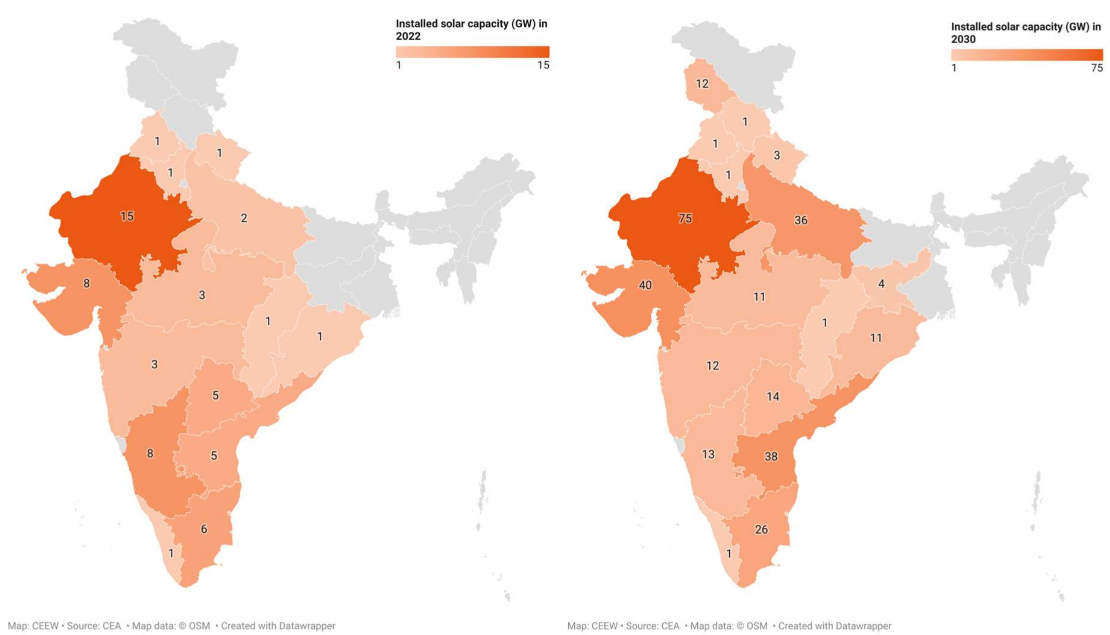
600 GW non-fossil capacity	
Solar	377 GW
Wind	148 GW
Hydro	62 GW
Nuclear	20 GW

Source: Authors' analysis

Variable renewable energy (vRE) capacity addition

- **500 GW scenarios**: We consider 425 GW vRE capacity as a part of the 500 GW non-fossil capacity mix. This includes 302 GW of solar and 123 GW of wind distributed across the states, as shown in Figure 4 and Figure 5, respectively. We collated the central plans (CEA 2022d) and stated RE policies for eight states.[5] As of December 2022, India has 61 GW and 42 GW of solar and wind capacities, respectively (CEA 2022a).

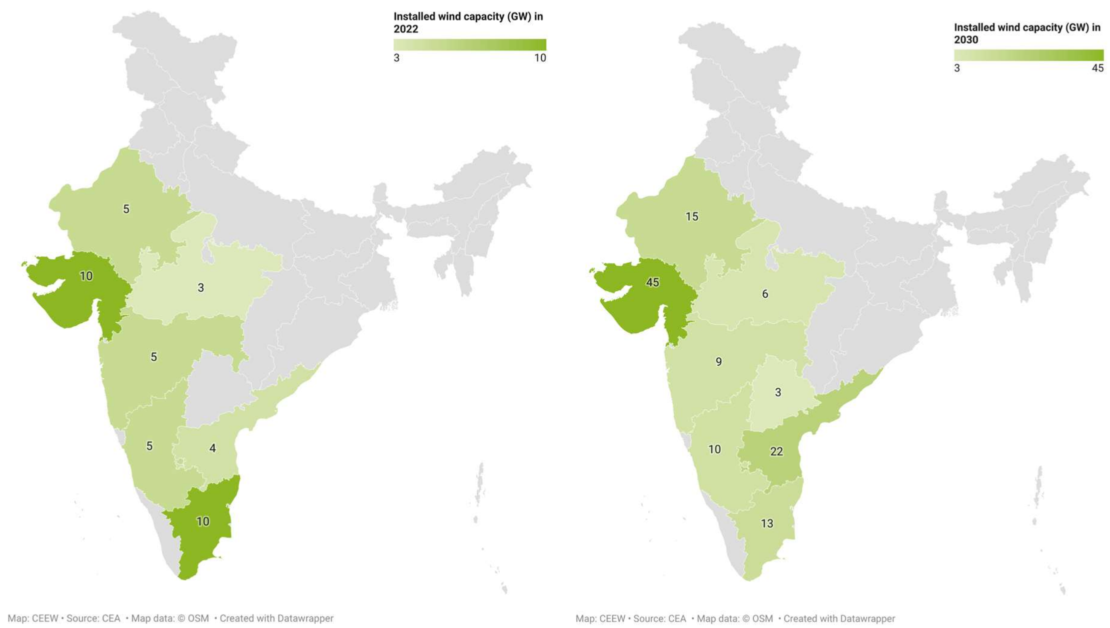
Figure 4: Solar capacity distribution in 2022 and 2030 to meet the 500 GW non-fossil target



Source: Authors' analysis based on CEA's transmission expansion plan and state RE targets as per state policies

[5] State RE policies: Rajasthan (Govt. of Rajasthan 2023); Karnataka (KREDL 2022); Uttar Pradesh (UPNEDA 2022); Odisha (Energy Department Odisha 2022); Jharkhand (JREDA 2022); Uttarakhand (Invest Uttarakhand 2023); and Tamil Nadu (Govt. of Tamil Nadu, 2023)

Figure 5: Wind capacity distribution in 2022 and 2030 to meet the 500 GW non-fossil target

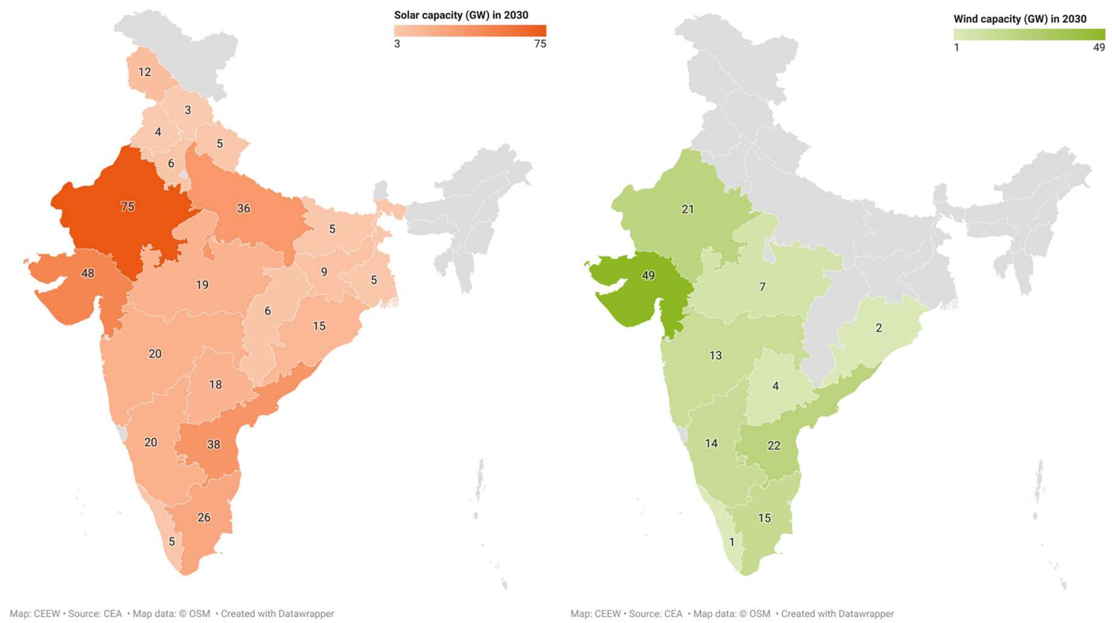


Source: Authors' analysis based on CEA's transmission expansion plan and state RE targets as per state policies

- **400 GW of non-fossil capacity**: Here, we consider only 75 per cent of the capacity addition required to meet the 500 GW non-fossil capacity target will come by 2030. Thus, we consider 181 GW of solar and 61 GW of wind addition to occur by 2030. We consider a uniform reduction in each state.

- **600 GW of non-fossil capacity**: Beyond the 425 GW of vRE capacity (in 500 GW scenarios), we added 100 GW of solar and wind capacity in a geographically diverse manner. We consider the temporal distribution of unmet demand and transmission congestion to identify the need for suited technology - solar or wind. Once identified, we utilise the RE potential, capacity targets, and current installed capacity to site the capacity in each state. A detailed approach is discussed in Box 1, and solar and wind capacity addition across states is elaborated in Figure 6.

Figure 6: Distribution of 525 GW vRE capacity across states in 600 GW scenarios



Source: Authors' analysis

Box 1: Approach for 100 GW vRE capacity addition

1. We identified the vRE capacity requirement to meet the renewable purchase obligation (RPO) for the moderate demand. With the planned (500 GW) RE capacity, it will only make 32 per cent of the total generation mix, whereas, India has a set target of meeting 39 per cent of demand with RE generation (MoP 2022).
2. CEEW's study on "Implications of a Net-Zero Target for India's Sectoral Energy Transitions and Climate Policy" identified the optimal energy mix India needs every 5 years to achieve its net zero goal 2070 (CEEW 2021). We used the technological diversification of solar and wind to be in the ratio of 3:1 in 2030. Considering this, we identified that India needs an additional 75 GW of solar and 25 GW of wind capacities to meet the RPO target.
3. We analysed the temporal instances when there is a demand-supply imbalance due to interstate transmission congestion. For instance, we observed that states like Karnataka and Kerala will face significant shortages with the existing, under-construction, and planned capacities in case the demand grows higher due to insufficient in-house generation and limited import capabilities. We identified 15 and 9 states to add solar and wind capacities, respectively.
4. Further, we distribute the 25 GW wind capacity in the nine selected states (Gujarat, Rajasthan, Karnataka, Maharashtra, Tamil Nadu, Madhya Pradesh, Telangana, Kerala and Odisha). We consider a weighted distribution based on the difference between states' wind installed capacity and their wind potential (NIWE 2023).[6]
5. We distribute 75 GW solar capacity among 17 states[7] as the weighted ratio of the reciprocal of the

[6] Considering ambitious targets set for Andhra Pradesh, we distributed 2.45 GW of capacity (which would have come in Andhra Pradesh otherwise using the weighted distribution approach) equally between Kerala and Odisha.

[7] 75 GW solar capacity is distributed in Rajasthan, Gujarat, Tamil Nadu, Karnataka, Odisha, Jharkhand, Uttarakhand, Maharashtra, Madhya Pradesh, Telangana, Punjab, Himachal Pradesh, Kerala, Haryana, and Chhattisgarh

state's solar share in India's total installed capacity (as of 2022). Uttar Pradesh and Andhra Pradesh are not considered for solar capacity addition due to their existing ambitious targets, and solar addition is restricted in some states due to technical constraints.[8] This differential capacity[9] is equally distributed in other states based on the following criteria:

a. **30%** of the differential capacity is equally distributed in states with lesser capacity, like Odisha, Jharkhand, and Telangana
b. **70%** of the differential capacity is equally distributed in states with higher capacity like Gujarat, Karnataka, Maharashtra, and Madhya Pradesh

Source: Authors' analysis

Note: This is not based on an optimised capacity-expansion exercise. This is one of the many solutions simulated to understand the need and value of diversified RE deployment.

Pumped storage hydro (PSH): As per Feb 2024 CEA's status report for PSH (CEA 2024c), we have considered 4.7 GW of already constructed on-river capacity, 3.9 GW of under construction on-river capacity, 2.6 GW of on-river capacity under survey and investigation (both reservoirs exist) and 1.2 GW of off-river capacity that is under construction. Thus, we consider 12.5 GW of PSH in 500 GW and 600 GW scenarios. For 400 GW scenarios, we consider only existing and actively under construction on-river capacity, i.e., 6 GW of PSH.

D. Transmission constraints

The import capability of the state is determined by the available transfer capacity *(*ATC) limit published by Grid India's monthly ATC reports (Grid India, n.d.). We compiled ATC limits for 2022 based on Grid India's monthly ATC intraregional reports (long- and medium-term open access). We consider 2022 TTC limits, mentioned in Table 1, as ATC for 2030 (import limits for the states). We further relaxed these import ATC limits to meet the unserved demand observed in a few states due to higher congestion.

Table 1: Import limits for the states: 2022 and 2030

Import limits (MW)	2022 ATC	Expected 2030 ATC
Rajasthan	3,400	7,000
Uttar Pradesh	8,420	14,500
Punjab	6,500	8,900
Haryana	5,000	8,500
Uttarakhand	2,500	2,500
Delhi	4,500	6,880
Himachal Pradesh	1,400	1,400
Maharashtra	9,904	9,904
Gujarat	10,568	12,450
Madhya Pradesh	10,924	10,924
Chhattisgarh	3,448	3,448
Karnataka	3,500	3,500
Andhra Pradesh	6,000	6,000
Telangana	7,200	7,200
Kerala	2,812	2,812
Tamil Nadu	10,450	10,450

[8] Solar addition is limited due to technical constraints in Punjab, Himachal Pradesh, Bihar, and West Bengal

[9] Differential Capacity here is the difference between capacity to be added as per weighted ratio of reciprocal of the state's solar capacity share minus capacity limits in Punjab, Himachal Pradesh, Bihar, and West Bengal

West Bengal	2,612	6,991
Bihar	7,721	7,721
Jharkhand	1,820	2,443
Odisha	2,675	3,743
Sikkim	109	175
North-East	600	1,290

Source: Authors' compilation based on Grid India monthly ATC reports

Note: We consider 2022 TTC limits to be the expected ATC limits for 2030 ATC

The model does not allow interregional transfers to breach the defined limits under any circumstances. However, it allows interstate transfers beyond the defined limits for a few time blocks, as in the real system. Table 2 lays out the import and export limits for all regions and between the regions.

Table 2: Regional import and export limits: 2022 and 2030

Region/Link limits (MW)	Import (2022)	Export (2022)	Import (2030)	Export (2030)
North-east region	600	258	1,470	-
Western region	-	-	-	-
Southern region	7,000	6,000	16,300	12,000
Eastern region	-	-	-	-
Northern region	15,500	3,300	24,400	7,600
S1 to (S2 and S3)	3,795	-	8,500	-
ER - SR	3,250	-	5,400	-
WR - SR	6,500	1,500	10,950	7,000
WR - NR	11,000	1,232	18,500	3,100
ER - NR	4,854	2,900	7,600	2,900
ER - WR	4,500	-	4,500	-
NE - ER	258	455	2,910	1,790
NE - NR	-	-	-	-

Source: Authors' compilation

As per our consultations with Grid India and CTUIL planning reports, we understand these are conservative assumptions. The system may have more enhanced limits going forward.

We have discussed other modelling constraints and assumptions in Annexure 1 of the main report.

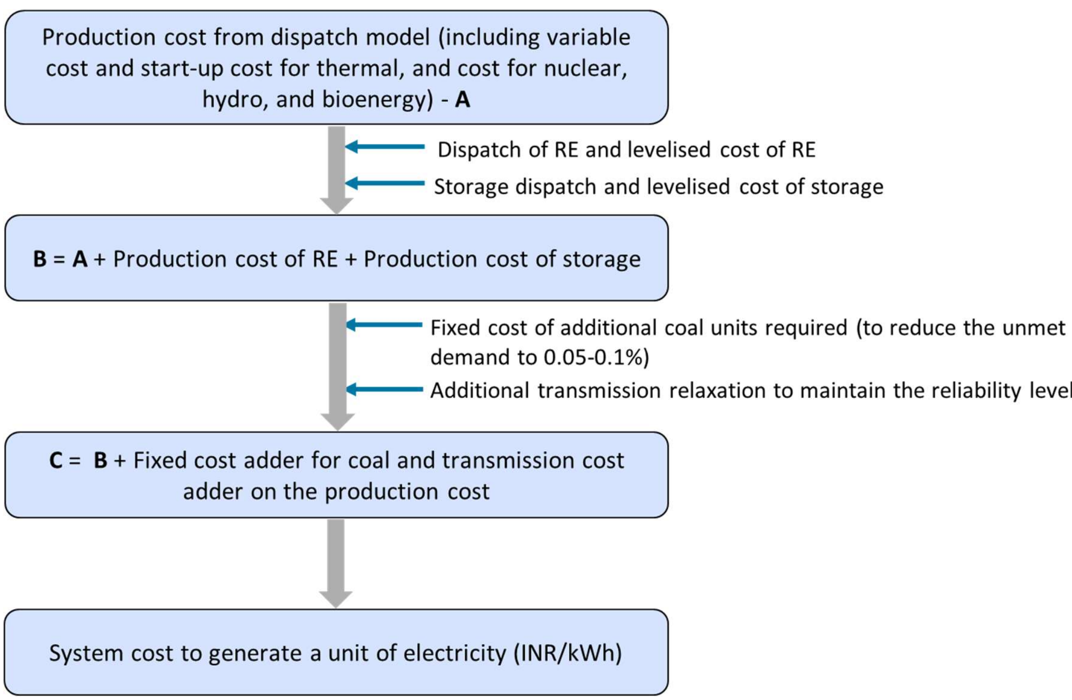
2. Inputs and assumptions for exogenous outcomes

2.1 System cost calculations and assumptions

We calculated the system cost using a step-wise approach, as shown in Figure 7. To determine the system cost, we added various cost components to the production cost estimated from the dispatch model. These components include the production cost of renewable energy, storage costs, a fixed cost adder for additional thermal plants (required beyond the planned capacity to ensure reliability across different scenarios), and a transmission cost adder to account for the extra infrastructure needed to maintain system reliability. The dispatch model's production cost includes variable costs (VC), startup costs for thermal generation, and costs for nuclear, hydro, and bioenergy.

We estimated the variable cost (VC) of a thermal power plant by accounting for heat rate degradation and fuel costs. In this study, we have considered only cold start-ups. We derived the startup cost from CEA's study on flexible operation (CEA 2023b), factoring in the increased operation and maintenance expenses due to accelerated wear and tear of plant components and higher fuel consumption.

Figure 7: Flowchart explaining approach for system cost calculation



Source: Authors' analysis

We developed a comprehensive financial model to calculate these costs. This model incorporates capital expenditure (CAPEX), operational expenditure (OPEX), and the cost of capital (including both debt and equity). It also accounts for the technical life of assets, salvage value, and efficiency parameters to compute the levelized cost of energy (LCOE) or associated cost adders. Detailed parameters for each technology, including the assumptions considered to compute the cost adders are mentioned in Tables 3, 4, and 5.

Table 3: Assumptions to calculate LCOE for vRE generation technologies

Parameter	Solar	Wind
Capex cost (INR million/MW)	32	65
O&M cost (INR million/MW/year)	1% of capex	1% of capex
Annual increase in O&M cost (%)	3.5	3.5
Technical life (years)	25	25
Annual degradation (%)	0.5	0.5
Capacity Utilisation Factor (%)	20%	27%
Capital structure		
Debt:Equity ratio	75:25	75:25
Cost of debt (%)	8	8
Cost of equity (%)	12	12
Debt term (years)	16	16
LCOE of solar (INR/kWh)	**2.44**	**3.70**

Source: Authors' compilation based on stakeholder consultations

Table 4: Assumptions to calculate LCOS for storage technologies

Computation of Battery storage LCOS	BESS	PSH
Capital cost	112 USD/kWh	60 INR million/MW
Storage duration (E to P ratio) at 100% DoD (hours)	4	8
Storage round trip efficiency (%)	88	75
Depth of Discharge (%)	90	-
No. of cycles per day	1	-
End of life capacity relative to initial capacity (%)	0.7	-
Storage cycle life (cycles)	5000	-
Inverter efficiency (%)	96	-
O&M cost	-	3.5% of capex
Annual increase in O&M cost (%)	-	4.77
Aux consumption (%)	-	1.2%
Capital structure		
Debt:Equity ratio	70:30	70:30
Cost of debt (%)	9	9
Debt term (years)	10	12
Cost of equity (%)	15.0	16.5
Levelised cost of storage (INR/kWh)	**3.84**	**4.60**

Source: Authors' compilation based on (IECC 2024, ICRA 2023) and stakeholder consultations

Table 5: Assumptions to calculate fixed cost adder for coal plants and transmission cost adder

Parameters	Coal plants	Transmission
Capital cost (INR million per MW)	96.4 (for USC unit)	10
	89.7 (for SC unit)	
Technical life (Years)	25	35
Capital structure		
Debt:Equity	70:30	70:30
Cost of debt (%)	9	9
Cost of equity (%)	15	15

Source: Authors' analysis based on CEA (2024b), Niti Aayog (2015) and stakeholder consultation
Note: SC and USC refers to supercritical and ultra-supercritical coal power units

2.2 Considerations for socioeconomic and environmental outcomes

India's ambitious clean energy pathway will impact lives and livelihoods by creating jobs, attracting investments, mitigating carbon emissions, and alleviating air pollutants. We considered the approach discussed below to evaluate these socio-economic and environmental benefits.

a. Employment numbers

We evaluated the full-time equivalent[10] (FTE) jobs created by solar, wind, and coal power capacities added between October 2024 and 2030. The new FTE jobs and respective employment factors for these technologies are considered across different stages of deployment: Survey and Investigation (S&I), Construction and Installation (C&I), and Operation and Maintenance (O&M). For solar and wind employment factors, we refer to Malik et al. (2021) and for coal employment factors we refer to Norms for Manpower Requirement in Thermal Power Sector, 2022 (CEA 2022b).

Solar capacity of 42 GW and wind capacity of 15 GW will be deployed each year between 2024 and 2030 to reach 500 GW of non-fossil capacity. We consider a one-year gestation period for solar and wind capacities. This will thus create the same C&I jobs every year, and incremental O&M jobs with increased deployment every year. However, we assume coal capacity will take 5-6 years to deploy. Thus, between 2024 and 2030, for addition of 29 GW of coal in the *500 GW-high demand scenario,* more than 23,000 FTE jobs will be generated to conduct S&I, C&I and O&M. Table 6 provides the FTE coefficients and jobs created for each technology for *500 GW-high demand* and *600 GW-high demand* scenarios.

Table 6: FTE jobs for 500 and 600 high-demand scenarios

Parameter	500 GW high demand			600 GW high demand		
	Solar	Wind	Coal	Solar	Wind	Coal
Additional capacity compared to 2024 (GW)	210	75	29	285	100	23
Employment factors						
C&I phase (including S&I)	1.37	0.76	0.38	1.37	0.76	0.38
O&M phase	0.31	0.39	0.42	0.31	0.39	0.42

[10] The full time equivalent (FTE) coefficient or job-year is a ratio of the time spent by an employee on a particular project/task in a given year to the standard total working hours in that particular year (CEEW-NRDC 2017)

FTE jobs	**1,23,082**	**40,859**	**23,287**	**1,67,040**	**54,479**	**18,469**

Source: Authors' analysis

b. Investment

Each of the scenarios could attract investments based on the mix of generation resources. We calculate the investment numbers based on the generation mix across various scenarios in Table 7. We considered the capex for coal (CEA 2024b), nuclear and hydro (CEA 2022e), solar and wind,[11] BESS (IECC 2024), PSH (ICRA 2023) and transmission (NITI Aayog 2015).

Table 7: High RE pathways could attract more than INR 23 lakh crore in investments

Generation source	Capex (INR crore/MW	Investment across scenarios (INR lakh crore)					
		400 BAU	500 BAU	600 BAU	400 HD	500 HD	600 HD
Coal - SC	8.97	1.4	1.1	1.1	1.8	1.3	1.1
Coal - USC	9.64	1.3	0.7	0.7	1.5	1.1	0.7
Gas	NA	0.0	0.0	0.0	0.0	0.0	0.0
Nuclear	15	1.0	1.8	1.8	1.0	1.8	1.8
Hydro	8.3	0.7	0.9	0.9	0.7	0.9	0.9
Solar	3.2	4.6	7.0	9.4	4.6	7.0	9.4
Wind	6.5	3.3	5.0	6.6	3.3	5.0	6.6
Bio	NA	0.0	0.0	0.0	0.0	0.0	0.0
Battery (4hr)	3.6	0.2	1.2	2.0	0.2	0.8	2.5
PSH	6	0.4	0.8	0.8	0.4	0.8	0.8
Transmission	1	0.4	0.2	0.2	0.7	0.4	0.3
INR lakh crore		**13**	**19**	**23**	**14**	**19**	**24**
USD billion		**159**	**223**	**280**	**169**	**227**	**288**

Source: Authors' analysis

c. Carbon dioxide emissions

We calculate the CO_2 emissions for each scenario by multiplying the fuel consumption (model output) with the emission factor (gCO_2/MJ) for the respective fuels. The emission factors considered (gram CO_2 per megajoules) for the respective fossil fuels are mentioned in Table 8 (CEA 2024a).

Table 8: Calculation of CO_2 emissions in 500 GW and 600 GW high-demand scenarios

Parameters	500 GW high demand	600 GW high demand
Fuel consumption		
Emission factors		
Coal (gCO_2/MJ)	90.6	
Gas (gCO_2/MJ)	49.4	
Oil (gCO_2/MJ)	71.9	

[11] Based on the stakeholder consultations

CO2 emissions (= fuel consumption x emission factor)		
Coal (MTCO2)	1,289	1,138
Gas (MTCO2)	19	11
Oil (MTCO2)	0.01	0.002
Total	**1307**	**1149**

Source: Authors' analysis

d. Air quality

To understand how each of the scenarios impacts the overall air quality, we compare the PM2.5, PM10, SO2 and NOx emissions due to thermal generation. Table 9 gives the emissions determining air quality based on the emission factors (Cropper et al. 2021) and thermal generation.

Table 9: PM2.5, PM10, SO_2, and NO_X emissions across scenarios

Emission factors (gram/kWh)	0.65	0.68	4.12	2.17
Scenarios	**Emissions** (in million tonnes)			
	PM2.5	**PM10**	**SO_2**	**NO_X**
400 GW-mod demand	0.93	0.98	5.89	3.11
500 GW-mod demand	0.80	0.85	5.10	2.69
600 GW-mod demand	0.70	0.73	4.42	2.33
400 GW-high demand	0.98	1.03	6.20	3.27
500 GW-high demand	0.86	0.91	5.46	2.89
600 GW-high demand	0.75	0.79	4.78	2.52

Source: Authors' analysis

3. Additional results from the model

3.1 Distribution of new coal capacity across states

Table 10: Highest coal capacity addition, beyond planned, is likely to come in the western region

Region	States	Additional coal capacity (GW)		
		500 GW-high demand	400 GW-high demand	400 GW-mod demand
Western	Maharashtra	2.0	2.0	2.0
	Gujarat	0.8	0.8	0.8
	Chhattisgarh	1.6	3.7	1.6
	Madhya Pradesh	0.0	2.9	0.0
Northern	Uttar Pradesh	1.6	2.9	1.6
	Haryana	0.0	1.6	1.6
	Rajasthan	0.0	2.1	2.1
Total		**6.0**	**16.0**	**9.7**

Source: Authors' analysis

3.2 BESS distribution across states for all scenarios

Table 11: Almost 50% of the BESS capacity in high-RE scenarios would have to be deployed in Rajasthan, Uttar Pradesh and Andhra Pradesh

States	Storage capacity (GW)						
	400 GW-mod demand	500 GW-mod demand	600 GW-mod demand (with DF)	600 GW-mod demand (without DF)	400 GW-high demand	500 GW-high demand	600 GW-high demand
Madhya Pradesh	0.53	0.14	2.15	4.55	0.53	0.04	3.53
Andhra Pradesh	2.55	4.91	7.48	11.88	2.55	2.81	9.10
Karnataka	2.00	0.11	1.77	3.42	2.00	0.07	2.92
West Bengal	1.00	0.00	0.20	0.36	1.00	0.00	0.25
Tamil Nadu	0.50	2.65	3.57	5.63	0.50	1.72	5.70
Maharashtra	0.08	0.00	0.69	1.12	0.08	0.02	0.78
Gujarat	0.00	2.51	3.19	4.53	0.00	1.21	5.39

Himachal Pradesh	0.00	0.12	0.75	0.95	0.00	0.04	0.66
Jammu and Kashmir	0.00	2.43	3.59	4.33	0.00	1.37	3.48
Jharkhand	0.00	0.04	1.63	2.55	0.00	0.03	2.08
Odisha	0.00	0.38	3.10	4.41	0.00	0.37	4.55
Punjab	0.00	0.06	0.49	0.60	0.00	0.05	0.56
Rajasthan	0.00	12.60	11.73	17.66	0.00	8.12	12.51
Telangana	0.00	0.19	0.96	2.17	0.00	0.16	1.97
Uttarakhand	0.00	0.21	0.82	1.06	0.00	0.10	0.75
Uttar Pradesh	0.00	6.67	10.19	15.42	0.00	5.88	12.07
Bihar	0.00	0.00	0.60	0.96	0.00	0.00	0.67
Chhattisgarh	0.00	0.00	1.04	1.76	0.00	0.00	1.40
Haryana	0.00	0.00	0.75	1.01	0.00	0.01	1.02
Kerala	0.00	0.00	0.31	0.63	0.00	0.00	0.64
BESS Total	**7**	**33**	**55**	**85**	**7**	**22**	**70**

Source: Authors' analysis

Note: DF here stands for demand flexibility

3.3 State-wise distribution of coal plants selected for MTL lowering across scenarios

Table 12: Coal capacity of around 145 GW will have to be flexibilised in the high-RE scenarios

States	Coal capacity flexibilised (GW)					
	400 GW-mod demand	500 GW-mod demand	600GW-mod demand	400 GW-high demand	500 GW-high demand	600 GW-high demand
Uttar Pradesh	12	21	21	11	15	21
Haryana	4	5	5	3	5	5
Punjab	1	3	5	1	4	6
Rajasthan	8	9	9	8	9	9
Gujarat	12	14	14	12	14	14
Madhya Pradesh	5	8	11	4	8	11
Chhattisgarh	7	10	15	5	10	16
Maharashtra	2	2	6	1	2	6

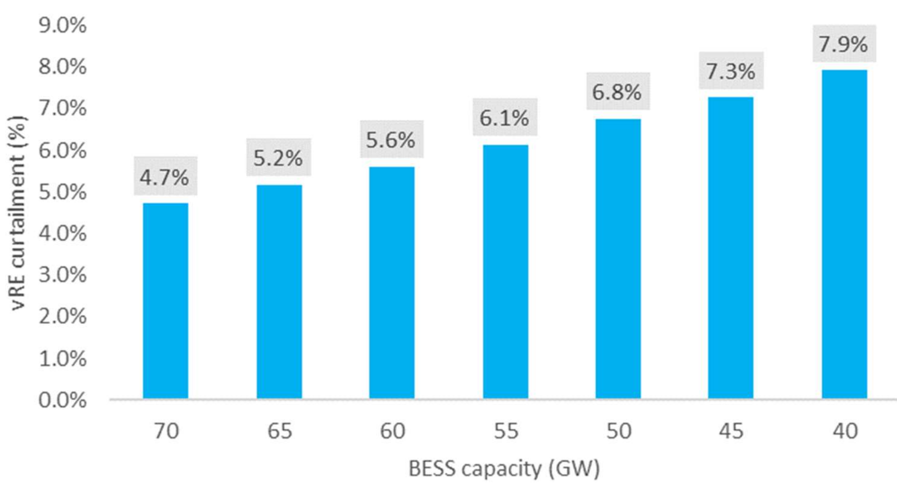
Tamil Nadu	9	10	10	8	10	10
Karnataka	6	9	9	7	9	8
Andhra Pradesh	8	11	11	7	11	11
Telangana	2	4	7	1	4	7
Bihar	1	3	6	1	3	7
West Bengal	3	5	7	2	4	7
Jharkhand	1	2	3	1	2	3
Odisha	0	2	7	0	3	7
Northeast (Aggregated)	0	1	1	0	1	1
Total	**82**	**119**	**144**	**71**	**112**	**145**

Source: Authors' analysis

3.4 BESS sensitivities for *600 GW-high demand* scenario varying from 40 to 70 GW

In the *600 GW-high demand* scenario, we require 70 GW of BESS to manage the vRE curtailment within 5 per cent level. Further, our sensitivity analysis with varying BESS capacity and its impact on vRE curtailment and system cost shows that reducing BESS capacity by every 5 GW from 70 GW to 40 GW increases the vRE curtailment by 0.4–0.7 per cent (figure 8), while decreasing the system cost by 0.1–0.2 paise per kWh.

Figure 8: Impact of varying BESS capacity on vRE curtailment levels



Source: Authors' analysis

3.5 Assumptions and implications of deviations from assumptions

Table 13: Implications of study results on deviation from assumptions

<table>
<tr><th rowspan="2">Assumption</th><th colspan="2">Deviation from assumption</th><th colspan="6">Impact on results</th></tr>
<tr><th>Nature of Deviation</th><th>Likelihood of deviation</th><th>Unmet demand</th><th>Storage needs</th><th>RE curtailment</th><th>Transmission needs</th><th>Additional capacity requirements</th><th>System cost</th></tr>
<tr><td>Market-based economic despatch (MBED) by 2030</td><td>Long-term power contracts and scheduling from portfolio generators</td><td>Moderate</td><td>↑↑</td><td>↑↑</td><td>↑</td><td>↑</td><td>↑↑</td><td>↑↑</td></tr>
<tr><td>40% MTL by 2030 for 71-145 GW coal capacity in different scenarios</td><td>Plants operate at 55% MTL</td><td>High</td><td>↑</td><td>↑↑</td><td>↑↑</td><td>↑</td><td>-</td><td>↑</td></tr>
<tr><td>Cold starts considered</td><td>Plants can and do perform hot, warm, and cold starts</td><td>High</td><td>↓ (slightly)</td><td>↓</td><td>↓</td><td>-</td><td>-</td><td>Needs evaluat-ion</td></tr>
<tr><td>Cost assumption</td><td>The prices for solar, wind, and storage do not go down as expected</td><td>Low</td><td colspan="6">The system cost will increase slightly, but the high RE (600 GW) pathway remains cost-effective, with a 10% higher capex</td></tr>
<tr><td>Demand profile variation</td><td>The demand profile may vary from the base year (2022)</td><td>High</td><td colspan="6">The high RE (600 GW) pathway has more headroom available from coal to address this variation. However, coal capacity is stressed in other scenarios.</td></tr>
</table>

Source: Authors' compilation based on multiple simulations, secondary research, and stakeholder discussions

Acronyms

ATC	Available Transfer Capacity
BESS	Battery Energy Storage System
C&I	Construction & Installation
CAGR	Cumulative Annual Growth Rate
CAPEX	Capital Expenditure
CEA	Central Electricity Authority
CTUIL	Central Transmission Utility of India Limited
EPS	Electric Power Survey
FTE	Full-Time Equivalent
ICRA	Investment Information and Credit Rating Agency
IECC	India Energy & Climate Center
JREDA	Jharkhand Renewable Energy Development Agency
KREDL	Karnataka Renewable Energy Development Limited
LCOE	Levelised Cost of Energy
LCOS	Levelised Cost of Storage
MAPS	Multi Area Production Simulation
MBED	Market Based Economic Dispatch
MoP	Ministry of Power
MTL	Minimum Technical Level
NENS	Normalised Energy Not Served
NIWE	National Institute of Wind Energy
NO_X	Nitrogen Dioxide

NPP	National Power Portal
O&M	Operation & Maintenance
OPEX	Operational Expenditure
PSH	Pump Storage Hydro
RSD	Reserve Shut Down
S&I	Survey & Investigation
SC	Super Critical
SO_2	Sulphur Dioxide
TTC	Total Transfer Capacity
UPNEDA	Uttar Pradesh New and Renewable Energy Development Agency
USC	Ultra Super Critical
VC	Variable Cost
vRE	Variable Renewable Energy

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