INTEGRATING
RENEWABLE ENERGY MODELLING WITH POWER SECTOR PLANNING FOR INDIA

PRODUCTION & RELIABILITY SIMULATIONS FOR 2022

SHAKTI
SUSTAINABLE ENERGY FOUNDATION

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1. EXECUTIVE SUMMARY

1.1 PROJECT OVERVIEW

Traditionally, the electricity generation mix of India has been dominated by thermal and hydro power. With an increased focus of the national government on greening the power sector, India targets to install 175 GW of grid-connected RE by 2022., This is expected to be around 37% of the installed capacity in 2022.

Successful operation of large quantum of variable RE capacity can only be possible if its integration and interaction with the rest of the grid is smooth. Today, RE is about 16% of India's installed capacity base. And, many stakeholders cite congestion as a primary blockage to greater RE deployment. Some stakeholders claim that congestion occurs at the intra-state level, blocking the evacuation of electricity from power plants; others say that congestion of the inter-state transmission system (ISTS) is blocking the wheeling of power further in times of local surplus. Balancing the state grid with available conventional resources is also cited as a challenge.

It remains unclear where congestion is occurring, which resources are called for rescuing the grid surges and how, what does system balancing cost to a state under the current operations, what is the extent and cause of curtailment (technical or market). In discussions, these aspects are confused. These are critical areas for analysis, and should have high priority, as it will have bearing on new grid needs that will take time to deliver.

It is encouraging to note that all around the world, countries including India, are adopting various techniques to ensure the stability of the grid with the evolving demand and supply sides. Such techniques include sophisticated grid modelling, upgradation of physical grid infrastructure, improving demand and supply forecasting, demand side management, expansion of current grid balancing areas, holistic transmission planning, flexible operation of generation assets including mechanisms for compensation, and a variety of other changes inherently useful for power system operations, whether RE accounts for a large share or not.

From experiences known so far, it is becoming clear that these techniques require new forms of collaboration and coordination among various government ministries, agencies, and stakeholders in general. More so when the roles and responsibilities affecting the development of the power sector are spread across several entities, as is the case with many countries including India. However, to India's advantage, it is uniquely positioned to tackle the complexity of the new power system, as the demand is expected to grow at a rate much faster compared to the developed economies. Therefore, new and existing capacities will have to co-exist in most environmentally and economically efficient ways.

With this context, our effort began in early 2016, to model India's power sector considering the renewable energy targets as an integral component of the overall expansion plans. The objective of this exercise was to highlight strategies that can be implemented by the Central and State Governments to optimize power sector plans and minimize the cost of RE integration.

The analysis was designed to answer these key questions:

- Given planned RE and non-RE capacity additions by 2022, will the system succeed in integrating new RE while meeting load (i.e. 24*7 affordable power for all)?
- What are the technical/infrastructure options (e.g. flexible generation, advanced grid operation protocols, expanded control areas, demand-side management, optimized transmission, etc.) for minimizing the cost of integrating RE while meeting load?

1.2 KEY FEATURES OF THE STUDY

With ambitious RE targets and other emerging technologies/applications such as e-mobility, battery storage, and super-efficient appliances, it is a pertinent time to look at other systems around the world in order to accurately understand the impacts or disruptions caused by such interacting factors. This study was commissioned and carried out considering the need to identify key factors which are going to have an impact on large-scale integration of RE in the Indian system, and at the same time finding possible solutions to concerns of implementing agencies. Some of the key concerns being:

- capturing the fixed costs associated with thermal power projects in the production simulation model,
- estimating capacity value of individual RE sources
- impact of different RE penetration levels on the power system reliability
- estimation of 'Saturation effect' of RE additions

Under this study, we undertook a power sector integrated resource planning exercise, integrating renewable energy resources with the current power sector planning framework. This was achieved by developing Multi Area Production Simulation (MAPS) and Multi Area Reliability Simulation (MARS) models for pan India integrated system and separate models for the Western, Northern, Southern, Eastern, and North-Eastern regions. The regional models were prepared based on:

- the existing and upcoming installed generation capacity in the constituent states of that region (both conventional and renewable capacities),
- the demand projections for individual constituent states of the region which was used to determine the coincidental demand to be satisfied (used as an input to the MAPS model), and
- the proposed inter-regional transmission connections to run various sensitivity cases in terms of transmission limits at an all India level in 2022.

The team undertook the following tasks:

- Developed a framework for generation planning considering recent significant RE deployment targets.
- Quantified and qualified the role of various renewable energy options in meeting energy and capacity demand.
- Identified the conventional generation capacity (coal, gas) etc. which can be avoided by deploying RE resources.

- Identified the cost-effectiveness of a range of technology and policy options available to improve the flexibility of the power system that can accommodate large-scale renewables.
- Identified most strategic use of existing and planned assets with an objective to support a flexible system and grid security in view of increasing RE sources as well as demand fluctuations.
- Generated insights for generation expansion planning for the region in conjunction with strategies for optimal and flexible system operation.
- Identified additional transmission capacity required for integrating higher amounts of solar and wind in the region

1.3 STUDY SCENARIOS

The study utilized the GE Concorda Suite Multi-Area Production Simulation (GE-MAPS) model for estimating production costs, and the GE Multi-Area Reliability Simulation (GE-MARS) model for reliability analysis and wind capacity valuation.

GE MAPS is a nodal, security-constrained, unit commitment and economic dispatch model with detailed realistic representation of all generation types and the underlying transmission grid. It is a proven tool that has been used in previous renewable (wind and solar) integration studies performed by GE and its partners in the course of the last 10 years. GE MARS is based on a sequential Monte Carlo simulation, which provides for a detailed representation of the hourly loads, generating units, and interfaces between the interconnected areas.

The study undertook the development of MAPS and MARS Models for each region separately, and an All India Integrated Model represented India as a single integrated system (subject to constraints explicitly listed to study the sensitivity cases). The various study cases considered for MAPS Model are as follows:

Cases	Inter State Limits	Inter-Regional Limits	Wheeling Charge ($/MWh)	2022 RE additions	Remarks
Case-1	No Limits	No Limits	NIL	100%	Copper sheet model to assess power Exchange requirement between regions
Case-1B	No Limits	No Limits	NIL	0%	Assess production cost savings on comparing CASE-1 and CASE-1B
Case-2	No Limits	No Limits	25$	100%	Increasing wheeling charges to impose constraints on transmission flows between regions
Case-3	Max flows for Inter State lines from Case-1	Limits based on CEA Transmission Capacity as per CEA transmission plan 2016-2036	10,000$	100%	Assess the congestion and augmentation requirements by implementing proposed CEA transmission limits
Case-3B			10,000$	0%	To assess coal ramp up/ ramp down requirements due to RE penetration

Table ES 1 : Study Cases considered in MAPS model

Similarly, the various study cases considered by the GE Energy Consulting team during the analysis using the MARS Models were:

Case	Case Title	Scope	Intent
Transmission Planning	Case-1	Transmission constraints as per CEA limits for inter-regional and intra-region connections. 100% RE capacity in 2022 (160GW – Wind + Solar).	Compute LOLE, inter-regional maximum flows and the number of limiting hours for all cases
	Case-1B	Transmission constraints as per Case-1 with no RE capacity addition considered	
Generation Planning	Case-2A	Simulate Case-1 with 70% Planned RE capacity addition	
	Case-2B	Repeat Case-1 for 50% planned RE capacity addition	
Capacity Value of RE	N/A	- Calculate capacity value of renewable generation for the year 2022 - Evaluate perfect capacity v/s LOLE with no additional RE considered - Plot LOLE v/s perfect capacity - Simulate 100%, 70% and 50% RE case and evaluate LOLE - Identify capacity value of renewable for 50%, 70% and 100% cases from plot generated in step above	Capacity value for 100%, 70% and 50% RE planned capacity addition

Table ES 2 : Study Cases considered in MARS Model

1.4 STUDY ASSUMPTIONS AND MODELING APPROACH

The modelling approach followed was a 'building-block' approach, wherein individual regions were modelled initially, stitching the results of completed regions into a consolidated model which eventually resulted in the integrated all India model. This approach was based on similar studies conducted by GE Energy Consulting, where a key take-away has been that the balancing area[1] footprint must be as large as feasible.

[1] The 'Balancing Area(s)' are responsible for balancing load and generation within a defined area and manage the power flows with other such balancing areas. Thus, the bigger the balancing area, the more options are available to the operator to balance the intermittency or variability associated with the variable renewable generation sources (especially wind, and to a lesser extent, solar).

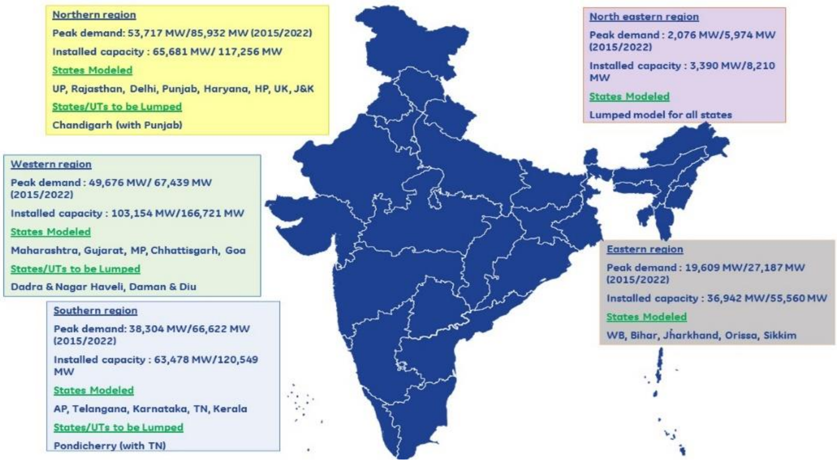


Figure ES 1 : Modelling of all regions in MAPS

The basic modelling assumptions and considerations in the preparation of the regional MAPS models and consequently the All India MAPS Model are given below:

Study time-horizon related	The analysis was performed for two calendar years, i.e. 2015 & 2022, only. The year 2015 values were used as benchmark for calibrating the models, while the 2022 values were obtained utilizing the 2022 projections as per public domain information (wherever available) or extrapolating the 2015 inputs parameters with the historical growth factors.
Existing/ Planned Capacity related	Entire Indian Power System in terms of the current and upcoming generation capacity(s), Inter-regional transmission capacity and inter-state transmission capacity has been modelled. However, intra-regional transmission constraints have not been considered.
	All data required for the analysis has been gathered from the publicly available information from the websites and reports of various Central and State Agencies.
	The Thermal Generation (Coal, Gas) capacity upcoming was considered as per the projections of the CEA, along with the '24x7 Power for All' Document for the States. It may be noted that the additions considered were only the firm additions at the time of model preparations. Further, capacity retirements have not been considered in the models. Each unit of these thermal project have been modelled, with specific parameters (as far as available).
	Under the model(s), the installed capacity for a particular State (current and upcoming) is considered as the total generation capacity within the physical boundary of that State.
	The target of Government of India is to include 175 GW of RE into the Indian system by 2022. Wind & Solar combined contribution is expected to be 160 GW, while the remaining 15 GW would be from Small Hydro, Biomass etc. This 15 GW capacity has not been modelled in the study.
	The 100 GW solar target includes the Utility-scale solar and roof-top solar targets. For the purpose of our model, there is no differentiation made between utility-scale solar and roof-top solar generation, and both have been categorized under a single category.
Power Plant Operations related	Some of the Coal based thermal power plants have been assigned 'must-run' status under the regional model.
	As per the current provisions pertaining to the dispatch of wind and solar projects in India, these projects have also been designated the 'must-run' status. There is no spilled energy considered for these plants.
	The model provides that nuclear plants would not cycle to accommodate additional variable wind and/or solar energy. This means the nuclear plants are modelled to perform at a given level without too many ramp-up or ramp-down events.
	The production simulation analysis assumed that all units were economically committed and dispatched while respecting existing and new transmission limits, generator cycling capabilities, and minimum turndowns, with exceptions made for any must-run unit or units with operational constraints.
	Potential increase in operations and maintenance (O&M) cost of conventional thermal generators due to increased ramping and cycling were not included.
	Renewable energy plant O&M costs were not included.
	The hydro projects were modelled based on the design energy data available for the projects from the public domain.

Table ES 3 : Modelling assumptions and considerations in the MAPS model

Regarding the MARS model, key reference points are mentioned below:

Study time-horizon related	The MARS analysis was performed for year 2022.
Existing/ Planned Capacity related	Generation unit's details are considered from the production cost (GE MAPS) database. Thermal generation units are classified into 5 categories. They are represented in the MARS database with a two-state model with an expected forced outage rate (EFOR). EFORs are assumed based on the generation technologies. Hydro generation assumed to generate with their full capacity without any restrictions.
Power Plant Operations related	No demand response program or other emergency operating procedures were modeled in the system.

Table ES 4 : Modelling assumptions and considerations in the MARS model

1.5 KEY FINDINGS

The key findings of the production simulation study conducted using GE-MAPS are broadly in the areas of transmission flows and the operational impact on generating stations due to high renewable energy penetration.

1.5.1 TRANSMISSION FLOWS IN PRODUCTION SIMULATION MODEL FOR YEAR 2022

To estimate the impact of transmission constraints on the production cost, two cases were simulated for the year 2022 with 100% planned RE capacity additions being considered.

- With unlimited inter-regional transmission capacity, and
- With inter-regional transmission capacity, as per CEA transmission planning document.

The Table ES 5 below indicates the total production cost for the two cases.

Region	Unlimited transmission capacity (Copper sheet model)		Inter-region transmission capacity as per CEA document	
	Rs Crores	Rs/kWh	Rs Crores	Rs/kWh
Eastern Region	60300	2.85	61495	2.88
North Eastern Region	4268	1.25	4262	1.25
Northern Region	56268	1.63	77281	1.99
Southern Region	50330	1.50	50305	1.50
Western Region	148579	2.08	132203	1.97
All India	319744	1.95	325546	1.98

Table ES 5 : Comparison of results of production costs

As can be observed, transmission constraints increase the production cost by about 0.03 Rs. /kWh.

The average inter-regional transmission flows in the two cases are as shown in Figure below.

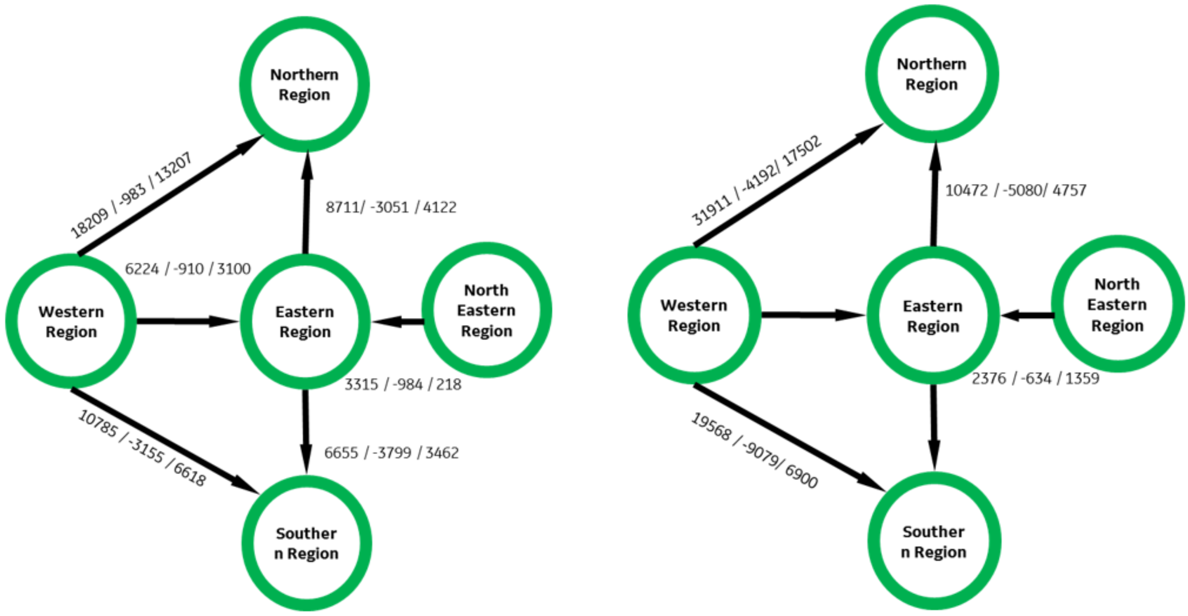


Figure ES 2: Inter-regional average annual flows – CEA limits case (left) & Copper sheet model (right)

In both scenarios, Western region is the major exporting region and Northern region is a major importer of power. Western region on average exports about 23GW of power in the CEA planning case and the Northern region imports on an average about 17GW. Other key findings on the inter-region transmission flows are as below:

- Southern Region is a net importer with significant exports occurring during the High wind and solar months, exporting a maximum of ~7GW to eastern and western regions. Maximum import during the high demand months is ~17GW. Despite significant capacity addition within the region, demand growth by 2022 makes the southern region a net importer from the western and eastern region.

- Western Region is a net exporter to the other regions in the Indian grid. Majority of exports are to the northern region. Western Region imports power from southern region (MAX ~3GW) and eastern region (MAX ~0.9GW) during periods of high renewable penetration.
- Northern region is a net importer in the system. The region has one of the highest demand in 2022 in the Indian system with the third highest capacity installations. Northern region is connected to the western and eastern regions. The region predominantly imports power from the western region. The system imports a maximum of 24.8 GW in the 2022 simulation.
- Eastern Region is a net exporter in the 2022 simulation, predominantly exporting to the Southern and the northern regions. There is an exchange in power between western (imports a maximum of ~6.2 GW) and north-eastern regions. The region does receive imports (Max ~3.8GW) from the southern region during period of high renewable penetration in the Southern Region.
- North Eastern region is predominantly Hydro based. Exports and imports are dictated by the availability of Hydro generation in the region. The region is connected to the rest of the country through the eastern region.

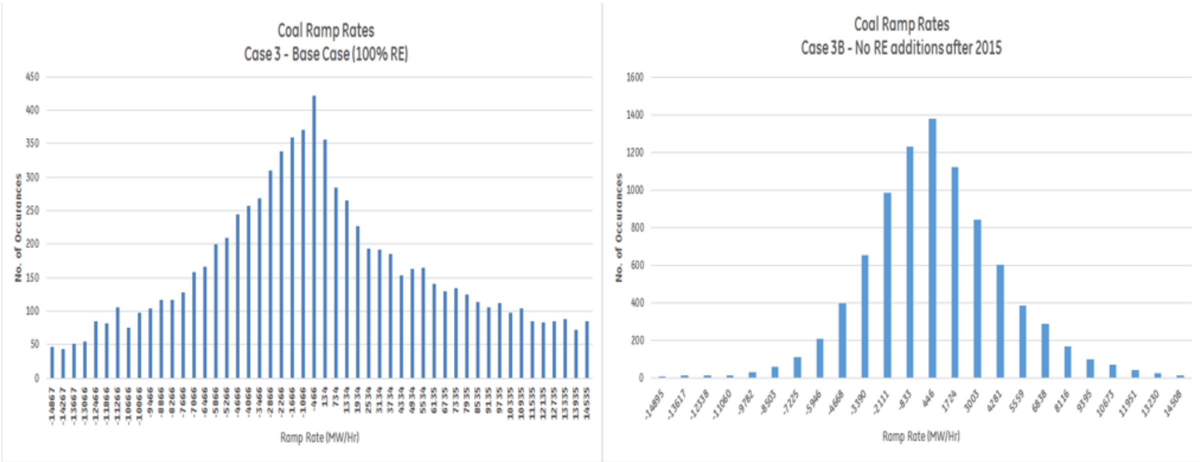
1.5.2 OPERATIONAL ANALYSIS FOR YEAR 2022

To assess the impact of RE on production cost, two cases were simulated for the year 2022. One with no RE additional after 2015 and the 2nd case with 100% planned RE capacity addition. Table 26 depicts the production cost comparison between the two cases. The results show a reduction in production costs by 0.63 Rs/kWh due to the impact of RE capacity additions.

Region	100% RE additions		No RE additions beyond 2015	
	Rs Crores	Rs/kWh	Rs Crores	Rs/kWh
Eastern Region	60300	2.85	75282	3.31
North Eastern Region	4268	1.25	4534	1.37
Northern Region	56268	1.63	86793	2.48
Southern Region	50330	1.50	71894	2.45
Western Region	148579	2.08	184484	2.50
All India	319744	1.95	422987	2.58

Table ES 6 : Production Cost Comparison between Case-1 & Case-1B

The impact of RE penetration on the ramp rate requirements was also analyzed for the above two cases and the findings are as shown in the Figure ES 3 below.



Ramp Rate Requirement – Events Case3		
Ramp Up	Greater than 5000 MW/Hr.	2141
Ramp Down	Greater than - 5000 MW/Hr.	2025

Ramp Rate Requirement – Events Case3B		
Ramp Up	Greater than 5000 MW/Hr.	1104
Ramp Down	Greater than - 5000 MW/Hr.	453

Figure ES 3 : Ramp Rates for Coal Plants - 2022 (Case-3)

Figure ES 4 below depicts the change in Plant Load Factors (PLF) and generation of power stations for the years 2015 and 2022. The contribution of more efficient and higher capacity coal plants increases in 2022 and the utilization levels of sub-critical coal plants reduces. Addition of wind and solar capacity increases contribution of RE generation in the generation mix and the increase in demand in all regions requires gas units to increase their generation in the system.

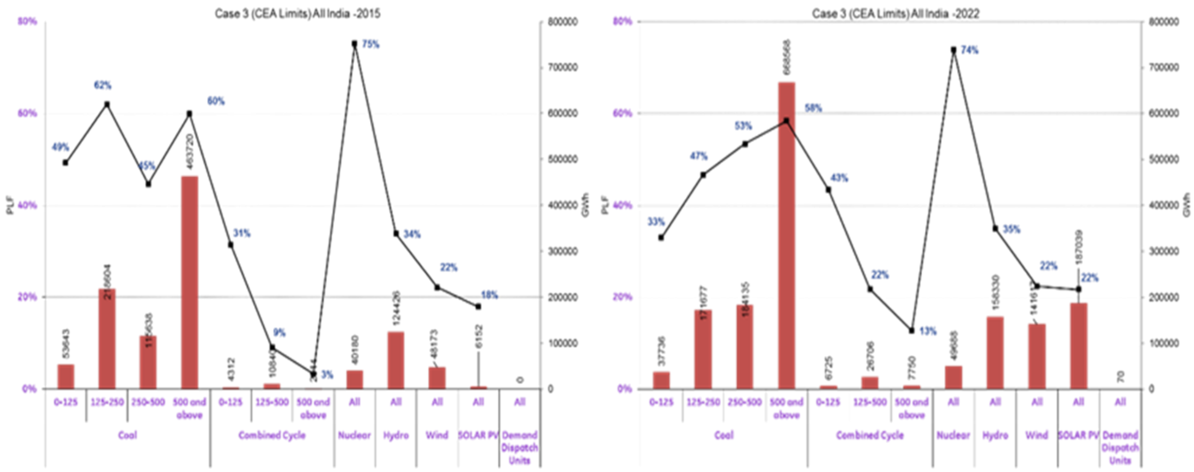


Figure ES 4 : Comparison of PLF & Generation for 2015 & 2022

Snapshot of key findings is given in the following Table ES 7 : . The detailed process followed for arriving at these conclusions along with the possible reasons behind these findings can be found in the respective sections.

Region	MAPS Findings (CEA limits case)	MARS Findings (All cases)
Eastern Region	→ Eastern region is a net exporter, supporting Northern and Southern Region, and is shown to be importing power from Southern Region during high RE generation periods in 2022 → Coal plants incur a start/stop on average every 996 hours	→ No LOLE as the region has large installed capacity versus the region load → LOLE values for 70% RE addition case are generally higher with same trend as compared to 100% RE addition case due to lower renewable capacity
Northern Region	→ In the 2022 simulation, Northern region remains a net importer (from western & eastern region) → Critical coal units operate at higher PLF 2022 and an increased contribution of gas based units in meeting the high demand in 2022 → Coal plants experience start/stop on average every 146 hours in 2022	→ States in the Northern Region experience significant LOLE due to limitation of transmission capacity between states → The State of Jammu & Kashmir interconnected with only Punjab hit the limit for ~1800 hours/ year → High demand in Northern Region makes it a net importer, putting pressure on the inter-region transmission lines such as lines connecting Gujarat to Haryana and Rajasthan → Punjab and Rajasthan are the states which have a considerable amount of LOLE
Southern Region	→ In the 2022 simulation, Southern region remains a net importer (from western & eastern region) → PLF of Coal plants in Southern Region decreases in 2022 owing to large RE generation in 2022 → Coal plants experience a start/stop every 114 hours in 2022	→ State of Tamil Nadu and Kerala have the Highest LOLE requirements in Southern region → Entire Southern Region shows relatively high LOLE at 694 hours / annum,
Western Region	→ Western region is a net exporter, providing support to Northern, Southern, and Eastern regions → Despite large additions of renewable capacity by 2022 the region's critical coal units operate at high PLF's to export power → coal plants experience a start/stop on average every 644 hours in 2022	→ High installed capacity of Thermal and Renewables capacity in Western region ensures stability in the region → Net exporter to Southern and Northern Regions → Limited transmission connectivity to Goa and the Union Territory of DD and DNH is reflected in the LOLE values for Western Region

Table ES 7 : Summary of key findings of MAPS & MARS Analysis

1.6 SCOPE FOR IMPROVEMENT

In this study, the intention was to cover every possible area of concern with relation the high RE integration in the India power system. However, during the course of study and subsequent discussions upon the topic in the various forums in the power sector, we feel that the following topics/areas (which were outside the purview of this study) are ripe for further detailed analysis.

- ✓ Refinement of the current Regional and All India Models with accurate data and figures. Currently the models were prepared based on the information available in the public domain, and the fidelity of the models can be enhanced using the latest available data which may not be available in the public domain at the time of preparation of these models.

- ✓ The fixed costs for each of around 950 thermal units currently modelled in this study can be incorporated in the current Regional and All India Models. Using this information, the model can better illustrate the dispatch profiles of the thermal projects in 2022.

- ✓ Simulation of the current Regional & All India Models with revised installed capacity (based on the emission control equipment schedule) published by CEA. This will include the most recent retirement schedule by CEA.

- ✓ Estimating the value of forecasting of RE resources. In the current simulation (2022 case) only one profile is used for commitment and dispatch of RE plants.

- ✓ Quantification of additional O&M costs due to frequent start stops and cyclic operations of the thermal power plants owing to high RE penetration, and estimating its impact on total production cost.

- ✓ Detailed models for year 2032 covering the following –
    - Copper sheet model to assess the ideal power exchange requirement between the regions assuming unlimited transmission capability and zero wheeling charges. Indication of requirement of inter-region transmission capacities in an ideal scenario for minimum production cost. This can then be compared with the proposed inter-region transmission capacities proposed in the CEA perspective transmission plan.
    - Review of line flows with CEA proposed limits to assess congestion of inter-regional lines in the year 2032 to recommend any further augmentation requirement of inter-region transmission capacity.
    - Assessment of coal Ramp up/down requirements on account of increased RE Penetrations

- ✓ Simulations for 2032 case with projected demand to estimate the capacity addition requirements to gauge if there is any shortfall in meeting the demand projections for 2032, and consequently whether there is any need for thermal capacity additions between 2022 and 2032

- ✓ Estimation of capacity value of individual RE resource viz. utility level solar PV, Rooftop solar PV, Onshore wind (and offshore wind if any)

- ✓ Impact of different levels of RE penetration (e.g. 25%, 15% and 10%) on reliability of the power system

- ✓ Consideration of load uncertainty for estimation of reliability indices

2. INTRODUCTION

India has steadily climbed the ladder of top electricity producers in the world over the past decade, which has coincided with the growth it has achieved as a country. All analysts have repeatedly highlighted the tight correlation between a country's energy security/adequacy and its economic growth, and this has been evident in India's growth over the past. However, even if India ranked as high as 3rd amongst the top electricity producers of the world in 2016[2] (as shown in Figure 1), its per-capita electricity consumption is way below the top countries in that aspect. As per the report 'Growth of electricity sector in India from 1947-2017' published by CEA in May 2017, the per-capita consumption of electricity on All-India basis was 1122 kWh during FY2016-17[3]. This is way below the per-capita consumption of developed countries such as Canada & USA, and is the least amongst the BRICS countries. A similar trend is observed in the corresponding figures for electricity consumption, which has a natural correlation with the electricity production figures, with an additional variable being the various losses in the system.

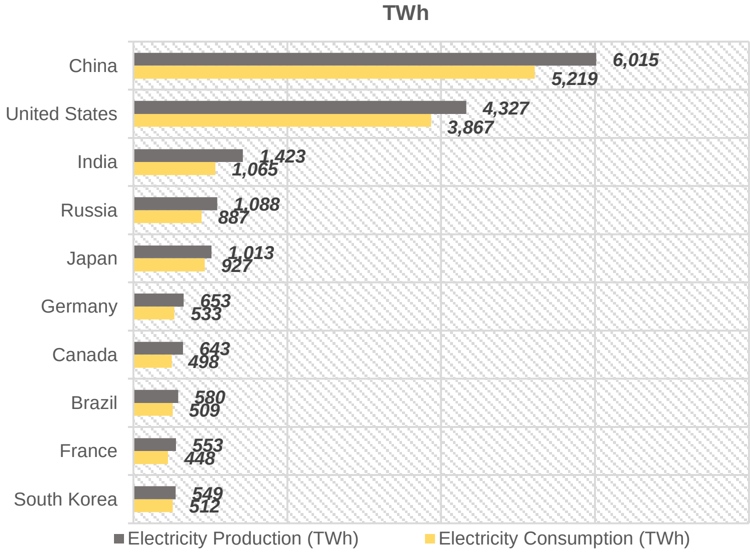


Figure 1: Top 10 Electricity Producers and their electricity consumption in 2016

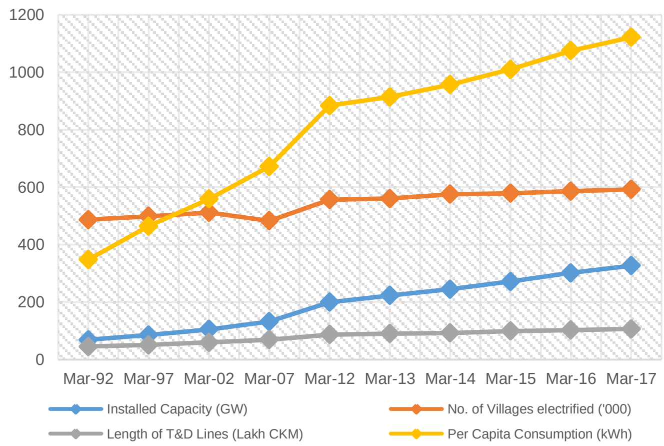


Figure 2: India Power Sector Growth (1992-2017)

Since independence in 1947, India's power sector has come leaps and bounds to where it is now, and has especially seen rapid growth since 1992. As Figure 2 shows, there has been significant additions in terms of the installed generation capacity with the private players leading the way once their participation was allowed. The village electrification has been growing at a sedate but gradual pace, with the central government bringing about some schemes recently to give them a necessary impetus. However, the most significant increase has been witnessed in terms of the per capita electricity consumption. As discussed above, even

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[2] https://yearbook.enerdata.net/electricity/world-electricity-production-statistics.html

[3] http://www.cea.nic.in/reports/others/planning/pdm/growth_2017.pdf

though the per-capita consumption is on the lower side, it has still shown significant increase since 1992 when it was a meagre 348 kWh.

Another important trend has been observed in the power supply position at an All-India Level, which has shown a consistently downward incline during the past decade (Figure 3). A major attributor to this trend could be the establishment of a vibrant power market in India, especially the nurturing of the trading activities of the various power sector entities. It was around 2008 when the power market in India began to take a definitive shape, in terms of well-defined contracts and the issuance of standardized bidding guidelines and procedures for the State Utilities to follow. This greatly incentivized the market participation by the private developers and has in turn provided the State Utilities with options to procure power at competitive rates from various avenues.

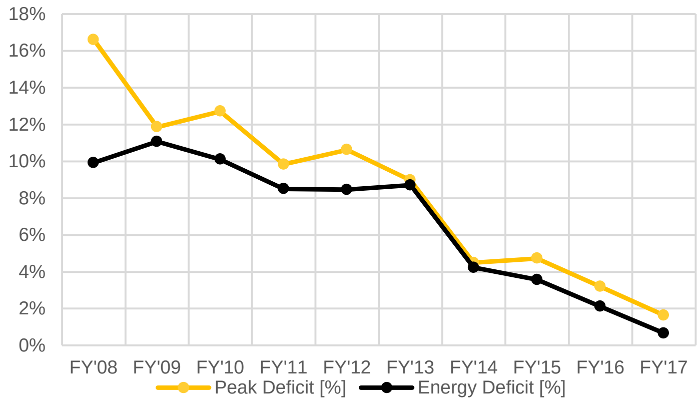


Figure 3: All India Power Supply Position (FY'08-FY'17)

In the wake of the recent focus being directed towards the need for sustainable development and carbon emissions, most of the Countries around the world are looking towards increasing the share of renewable energy sources such as wind, solar, biomass, small hydro etc. in their electricity generation and energy mix. European countries such as Germany and France are leading the way in terms of the contribution of renewable energy in the electricity production, so are countries such as Brazil, China, US, Canada, Russia etc. As shown in Figure 4, India has a share of around 15%, with plenty of positive intent towards the shift to RE.

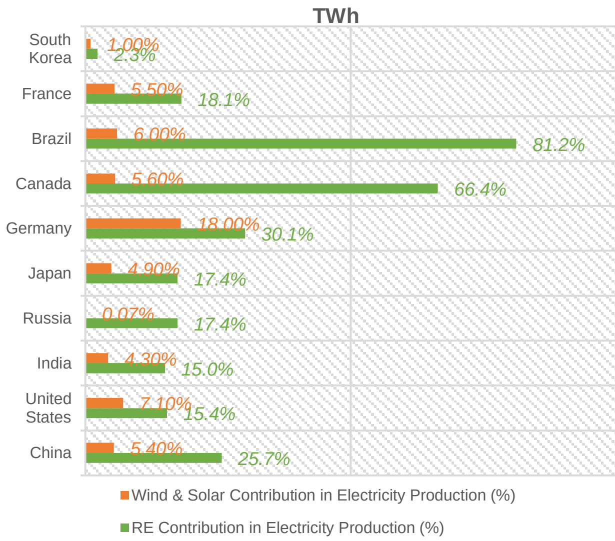


Figure 4: Contribution of Renewable Energy & Wind-Solar combined in Electricity Production (2016)

Traditionally, the electricity generation mix of the Indian Power Sector has been dominated by thermal power (i.e. coal and gas based projects), followed by large hydro projects. With a focus of encouraging the sustainable development goals set by the Federal Government, India is poised to witness a huge growth in the installed base of Renewable Energy (RE) projects in its energy mix. The plan is to incorporate a total of 175 GW of RE installed capacity in the country's installed power generation base by 2022, which is expected to be around 37% of the installed power generation capacity in 2022.

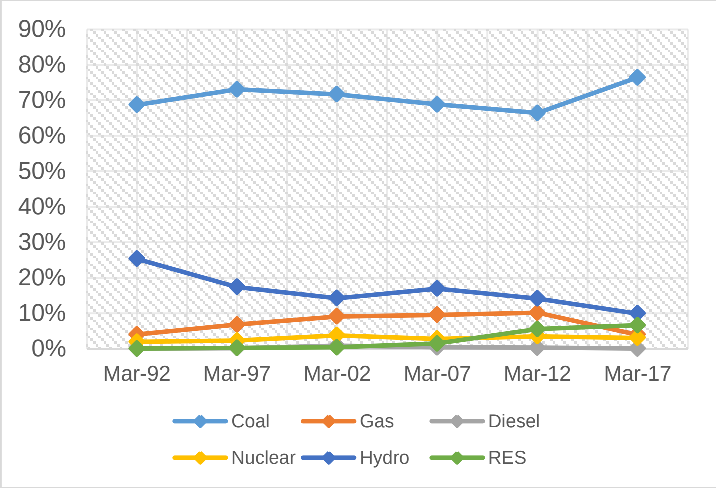


Figure 5: Contribution from various generation sources to India's Electricity mix

Variable Renewable Energy (VRE) Sources in any system's energy mix throws up unique challenges in terms of Grid Management to the System Operators. As has been seen in other established markets around the world, effective and targeted mitigation strategies are necessary to allay and counter these challenges, thereby enabling a smooth transition from fossil fuel based energy generation towards more environment friendly and sustainable energy generation.

These challenges posed by the uncertainty and intermittency of the renewable energy (especially wind & solar) will be particularly visible in case of a big power system such as India. The targets set for 2022 (60 MW Wind and 100 MW Solar) may appear too steep, however, the prerequisites for successful achievement of these targets are acute planning and robust supporting infrastructure, along with the regulatory and political will. It is still long way to go, but a positive intent will ensure the achievement of the targets, however steep they may be. Also, the overall targets for Wind and Solar are further divided into individual state-level targets. The following Figure 6 & Figure 7 show the region-wise targets for Wind and Solar installed capacity by 2022 respectively. The individual state-wise targets are also given in Section 10.3.

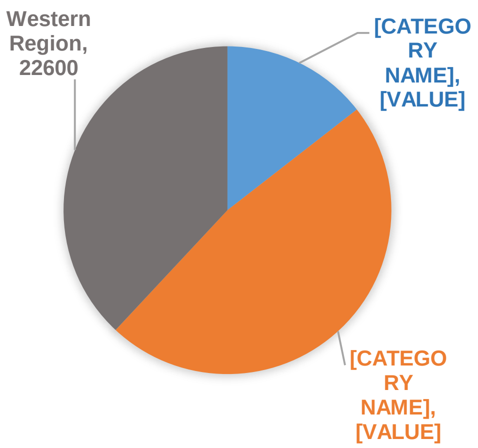


Figure 6: All India Wind Target for 2022 - Region Wise

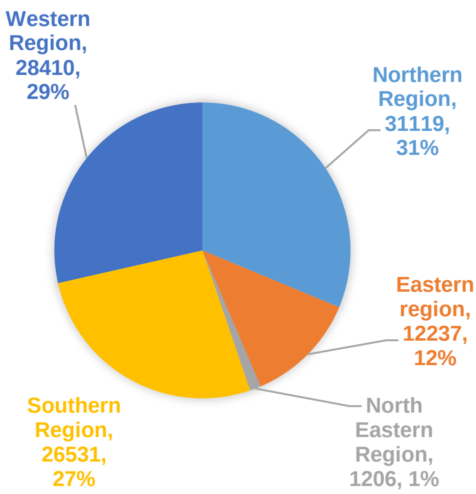


Figure 7: All India Solar Target for 2022 - Region Wise

It is an established theory that despite the RE generation increase, the unique inherent advantages offered by other technologies of power generation to aid the grid operators in maintaining a stable grid shall still be relevant and required. Therefore, for India to achieve its ambitious and laudable RE targets, it is imperative to determine the optimum mix between various technologies which would act in consonance to counter the variability and uncertainty associated with the RE technologies.

This study effort began in early 2016 as an attempt towards answering the questions posed by the increased RE penetration in India by 2022. It was intended to investigate whether the addition of planned conventional and RE capacities in the system will aid the goal of meeting the load at affordable prices, and to explore the options (technical and/or infrastructure) available for minimizing the cost of RE integration while meeting the loads. The study purview was to model the individual regions and subsequently the All India model. The step-wise approach followed for the study to cover all regions, is shown in Figure 8 below:

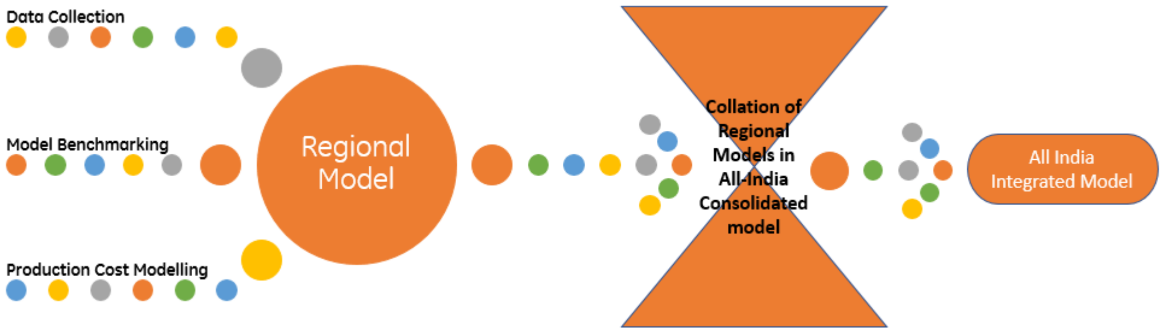


Figure 8: Model Preparation steps

The following sections would cover in detail the process followed for the preparation of regional & All-India MAPS & MARS Models, the assumptions considered, the data collection process, the various sensitivity cases considered, and any other specific input pertaining to the All-India Model.

3. OBJECTIVES AND SCOPE OF THE STUDY

3.1 KEY OBJECTIVES OF THE STUDY

Considering the targets for integration of 160 GW of Solar and Wind generation in the India Grid, it would be worthwhile to adopt some best practices from the countries who have successfully integrated a high percentage of RE in their system. This study was conceptualized and carried out keeping the focus to identify the key factors which would potentially impact the large-scale integration of RE in the Indian system. The study was designed to answer the key questions, such as:

- Given planned RE and non-RE capacity additions by 2022, will the system succeed in integrating new RE while meeting load (i.e. 24x7 affordable power for all)?
- What are the technical/infrastructure options (e.g. flexible generation, advanced grid operation protocols, expanded control areas, demand-side management, optimized transmission, etc.) for minimizing the cost of integrating RE while meeting load?

This study was commissioned and carried out keeping considering the need to identify the key factors which are going to have an impact on the large-scale integration of RE in the Indian system, and at the same time finding possible solutions to concerns of implementing agencies. Some of the key concerns being:

- capturing the fixed costs associated with thermal power projects in the production simulation model,
- estimating capacity value of individual RE sources
- impact of different RE penetration levels on the power system reliability
- estimation of 'Saturation effect' of RE additions

Under this study, we undertook a power sector integrated resource planning exercise, integrating renewable energy resources with the current power sector planning framework. This was achieved by developing MAPS and MARS models for separate models for the Western, Northern, Southern Eastern, and North-Eastern regions and an overall All India integrated system model.

3.2SCOPE OF THE STUDY

The scope of this study covered the development of MAPS and MARS Models for the Regions (i.e. Northern Region, Eastern Region, Western Region, Southern Region, and North-Eastern Region), and integrating them into an All India Model representing India as a single integrated system (subject to constraints explicitly listed to study the sensitivity cases). The regional models were prepared based on:

- the existing and planned installed generation capacity by 2022 in the constituent states of that region (both conventional and renewable capacities),
- the demand projections for individual constituent states of the region which was used to determine the coincidental demand to be satisfied (used as an input to the MAPS model), and

– the proposed inter-regional transmission connections to run various sensitivity cases in terms of transmission limits at an All India Level in 2022.

The team undertook the following tasks:

- Developed a framework for generation planning considering recent significant RE deployment targets.
- Quantified and qualified the role of various renewable energy options in meeting energy and capacity demand.
- Identified the conventional generation capacity (coal, gas) etc. which can be avoided by deploying RE resources.
- Identified the cost-effectiveness of a range of technology and policy options available to improve the flexibility of the power system that can accommodate large-scale renewables.
- Identified most strategic use of existing and planned assets with an objective to support a flexible system and grid security in view of increasing RE sources as well as demand fluctuations.
- Generated insights for generation expansion planning for the region in conjunction with strategies for optimal and flexible system operation.
- Identified additional transmission capacity required for integrating higher amounts of solar and wind in the region

Further, in order to understand the adequacy of the transmission system at an All India level, several sensitivity cases were identified and run as part of the scope. The details of these transmission sensitivity cases analyzed for All India Model is as given in Table 1 and they are further discussed in detail under Section 5.1.

Cases	Inter State Limits	Inter-Regional Limits	Wheeling Charge ($/MWh)	2022 RE additions	Remarks
Case-1	No Limits	No Limits	NIL	100%	Copper Sheet model to assess power Exchange requirement between regions
Case-1B	No Limits	No Limits	NIL	0%	Assess production cost savings on comparing CASE-1 and CASE-1B
Case-2	No Limits	No Limits	25$	100%	Increasing wheeling charges to impose constraints on transmission flows between regions
Case-3	Max flows for Inter State lines from Case-1	Limits based on CEA Transmission Capacity as per CEA transmission plan 2016-2036	10,000$	100%	Assess the congestion and augmentation requirements by implementing proposed CEA transmission limits
Case-3B			10,000$	0%	To assess coal ramp up/ ramp down requirements due to RE penetration

Table 1: Simulated cases under GE-MAPS All Model for year 2022

3.3 METHODOLOGY AND MODELING TOOLS

The core analysis of this study required detailed production simulation analysis and reliability analysis. The study utilized the GE Concorda Suite Multi-Area Production Simulation (GE-MAPS) model for production costing analysis, and the GE Multi-Area Reliability Simulation (GE-MARS) model for reliability analysis and wind capacity valuation. A brief overview of the GE-MAPS & GE-MARS process is given in the following Sections 3.4 & 3.5, and a detailed description of the capabilities of the GE-MAPS and GE-MARS software are given under Section 10.

The Indian power grid is an extremely large and complex system, and the underlying model included representation of the five electrical regions of India along with an integrated model of India power grid as single system. In other words, the representation of the power systems was not limited just to the individual states comprising the regions, and included the entire All India model with all regions interconnected and synchronized with each other directly or indirectly.

3.4 HOURLY PRODUCTION SIMULATION ANALYSIS (GE MAPS)

The GE team utilized GE Concorda Suite Multi-Area Production Simulation (GE MAPS) model to perform simulation of the All India and regional models. GE MAPS is a proven tool that has been used in previous renewable (wind and solar) integration studies performed by GE and its partners in the course of the last 10 years, including the 'Pan-Canadian Wind Integration Study (PCWIS)' conducted for the Canadian Wind Energy Association (CanWEA) and completed as recently as in October 2016, and the 'Western Wind & Solar Integration Study' conducted for the National Renewable Energy Laboratory (NREL) U.S. DoE completed in 2010.

GE MAPS is a nodal, security-constrained, unit commitment and economic dispatch model with detailed realistic representation of all generation types and the underlying transmission grid. Generation of all types, including existing and future thermal, hydro, wind, and solar plants were represented as connected to nodes or buses (substations) on the grid. The model provided detailed hourly outputs of operational and economic performance of all generation units. The modeling results also provide hourly information on transmission flows, binding transmission constraints, shadow prices, and congestion costs.

The modeling provides detailed information on inter-regional and intra-country power flows, based on a nodal based realistic representation of the regional and national power systems in India. The model was run for each modeled interconnection (i.e., Regions with its constituent states), with the degree of detail based on all publicly available information that the GE team was able to collect and incorporate in the GE-MAPS model.

The production simulation results quantified impacts of various factors on grid operation under different scenarios on an hourly basis, including, but not limited to:

- Electricity generation by each defined generation resource and unit type

- Operational performance of generation resources
- System-wide operational costs (so-called production costs)
- Power flows and congestion on monitored transmission tie-lines
- Regulation and reserve requirements
- Load-following performance
- Load not served (Demand Side Management (DSM) and involuntary interruptions)
- Variable operating costs
- Starts, stops, peaking unit utilization

A detailed description of the capabilities of the GE-MAPS can be found under Section 10.1.

3.5 RELIABILITY ANALYSIS AND CAPACITY VALUE OF RENEWABLE SOURCES (GE MARS)

GE MARS is the software program which performs the reliability evaluation of the power system. Reliability evaluations are based on the key inputs like load shapes, renewables (RE) input shapes, thermal plant parameters and transmission system details. The GE team utilized the GE Concorda Suite Multi-Area Reliability Simulation (GE MARS) model to perform reliability analysis (loss of load expectation, LOLE) and wind capacity valuation (effective load carrying capability, ELCC).

GE MARS is based on a sequential Monte Carlo simulation, which provides for a detailed representation of the hourly loads, generating units, and interfaces between the interconnected areas. In the sequential Monte Carlo simulation, chronological system histories are developed by combining randomly generated operating histories of the generating units with the inter-area transfer limits and the hourly chronological loads. Consequently, the system can be modelled in great detail with accurate recognition of random events (e.g., equipment failures), as well as deterministic rules and policies, which govern system operation, without the simplifying or idealizing assumptions often required in analytical methods.

GE MARS uses state transition rates rather than state probabilities, to describe the random forced outages of the thermal units. State probabilities give the probability of a unit being in a given capacity state at any particular time, and can be used if one assumes that the unit's capacity state for a given hour is independent of its state at any other hour. Sequential Monte Carlo simulation recognizes the fact that a unit's capacity state in each hour is dependent on its state in previous hours and influences its state in future hours. It thus requires the additional information that is contained in the transition rate data.

In this study, MARS is used to evaluate reliability of the system from three perspectives:

1. **Transmission Planning** – Evaluation of system reliability considering transmission infrastructure sufficiency
2. **Generation Planning** - Evaluation of system reliability from the generation capacity aspect
3. **Capacity value –** Evaluation of capacity value of renewable generation

A loss of load expectation (LOLE) reliability evaluation was performed for each of the different cases as highlighted under Section 5.2. The GE MARS model was used to calculate following reliability indices:

a. Daily LOLE (days/year) [Loss of Load Expectation]
   - At time of each area's daily peak, or
   - At time of coincident peak for a specified area or pool
   - All hours of the day
b. Hourly LOLE (hours/year) [Loss of Load Expectation]
c. LOEE (MWh/year) [Loss of Energy Expectation]
d. Frequency (of outage) (outages/year)
e. Duration (of outage) (hours/outage)

Indices were calculated for area and pool on isolated and interconnected basis. A detailed description of the capabilities of the GE-MAPS can be found under Section 10.2.

4. MODELING ASSUMPTIONS

4.1 MODEL FOOTPRINT

As highlighted earlier, this study was conceptualized to analyze the India Power system from the point of view of integration of the target RE capacity (wind + solar) by 2022. The scope included the model preparation for analysis at regional levels, and thereby preparing an All India integrated model to study the impact of integrating 160 GW of wind and solar in the system by 2022.

With this objective, the process followed was a 'building-block' approach, wherein the analysis of individual regions was performed at the start, all the while stitching the results of completed regions into a consolidated model which will eventually take its place as the integrated All India Model. This approach also made sense from similar studies for other power systems conducted in the past by GE Energy Consulting, where a key take-away has been that the balancing should be done at least on the largest area feasible, which in India's case would be on a regional basis (if not on state level). The 'Balancing Area(s)' are responsible for balancing load and generation within a defined area and manage the power flows with other such balancing areas. Thus, the bigger the balancing area, the more options are available to the operator to balance the intermittency or variability associated with the variable renewable generation sources (especially wind, and to a lesser extent, solar).

Figure 9 shows related to the demand and installed capacity considered in the model preparation. Further, it also shows considerations with respect to the States/UTs incorporated individually or lumped together under the respective regional models.

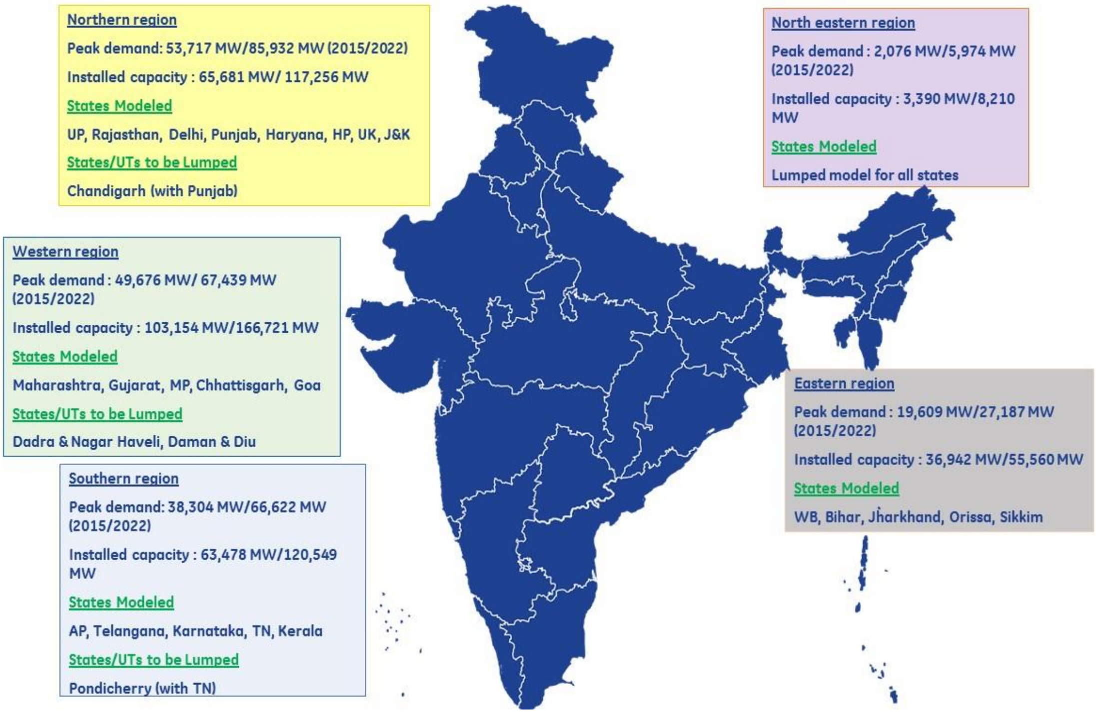


Figure 9: Region level modelling details

The following sections describe in detail the methodology and considerations under the regional models and All India model with regards to the MAPS and MARS inputs parameters.

4.2 REGIONAL MODEL

The basic conceptual process for the development of the regional models is as depicted in Figure 10 below.

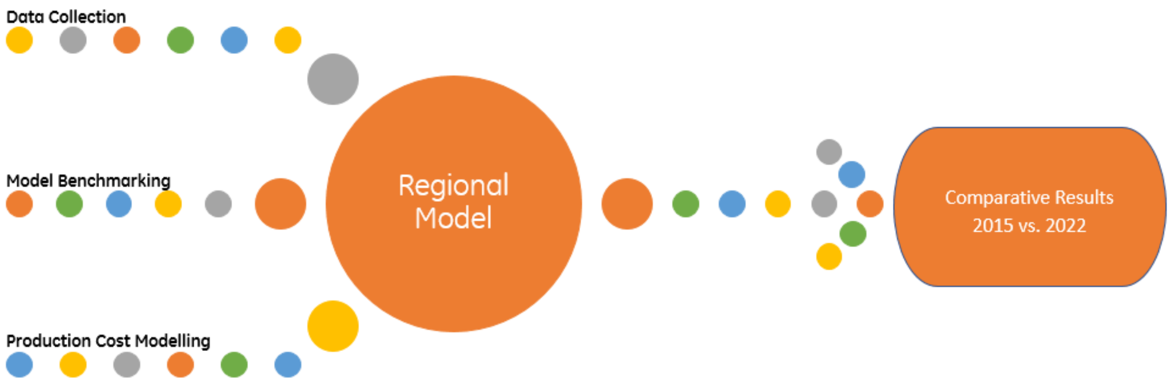


Figure 10: Regional Model preparation process

The first step towards preparation of the regional models undertaken by the GE Team was to collect, collate and arrange the data for individual states within that region. This data pertaining to the current demand, installed capacity, transmission capacity etc. was collected from various sources available in the public domain such as the State Utility's website, reports published by various central agencies such as CEA, POSOCO, Power Grid, NTPC, NHPC, DVC, THDC to name a few. The details considered for the above is mentioned in the subsequent paragraphs.

The next step was to prepare the model for the base year, i.e. 2015, by utilizing the details gathered above. This model was then benchmarked with the actual outputs as available from the above-mentioned sources, to increase the model's fidelity. This step is essential to ensure that the assumption considered in inputs reflect the fairly accurate outputs for the base year, and thus would produce reasonably accurate results for future years.

The third step was to use the planning data to prepare the model for 2022. The production cost model was run, and the outputs were analyzed to generate the results for year 2022 for the regions and their constituent states. The data used for this purpose was either used directly from the projections available in the public domain, or extrapolating the information available presently in the public domain. The demand projections for future years up to 2019; were used from the data available in the '24x7 Power for All' reports of the respective states, and then extrapolated the same up to 2022. Also, the projections under the 18th Electric Power Survey report issued by CEA for the demand scenario were considered for the study. This is also discussed in detail in the sections to come.

4.3 ALL INDIA MODEL

Upon the preparation of the regional models for Eastern, North-Eastern, Northern, Southern & Western Region, they were combined to achieve the All-India Integrated model. For this purpose, the most important consideration was the inter-regional transmission capacity which will play a critical role in the dispatch of surplus power from one region to the other. These inter-regional transmission capacities were considered as per the CEA perspective transmission plan (2016-2036) report[4].

[4] http://www.cea.nic.in/reports/others/ps/pspa2/ptp.pdf

Figure 11 shows a bare-bones representation of the integration of the Regional Models into the All India Model.

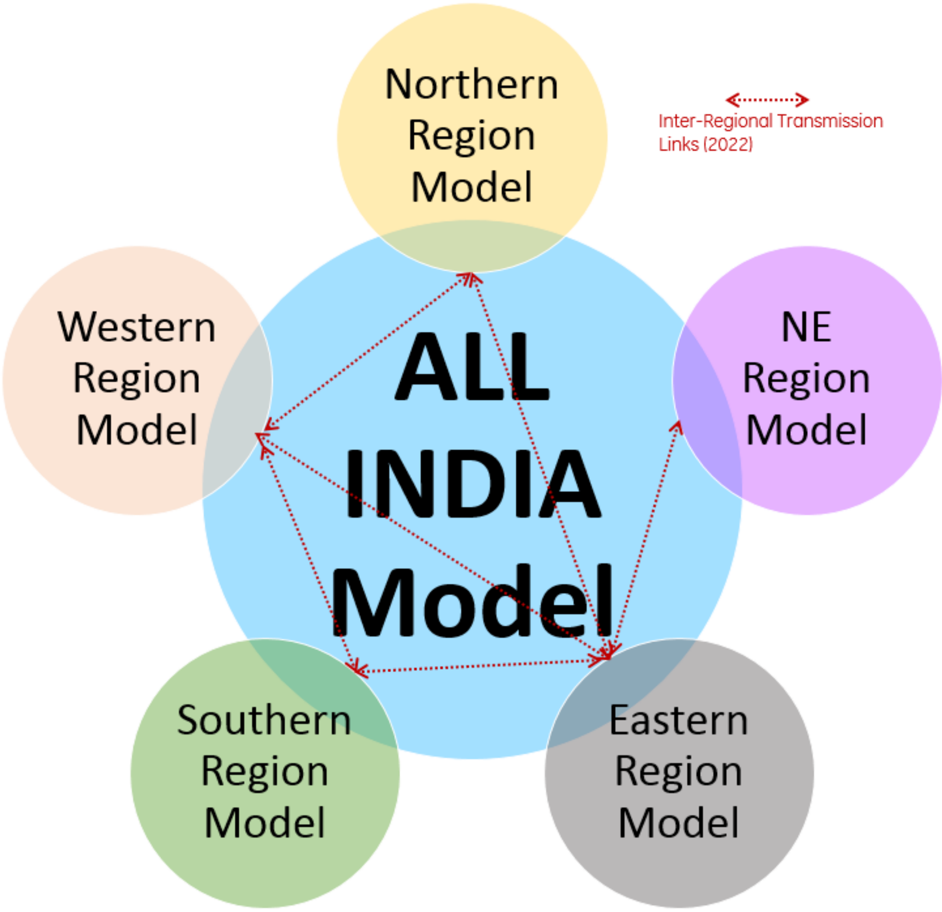


Figure 11: Integrating Regional Models into All-India Model

4.4 GENERAL MODELING ASSUMPTIONS - MAPS

The basic modelling assumptions and considerations in the preparation of the Regional MAPS Models and consequently the All India MAPS Model are as given below:

Study time-horizon related	The analysis was performed for two calendar years, i.e. 2015 & 2022, only. The year 2015 values were used as benchmark for calibrating the models, while the 2022 values were obtained utilizing the 2022 projections as per public domain information (wherever available) or extrapolating the 2015 inputs parameters with the historical growth factors.
Existing/ Planned Capacity related	Entire Indian Power System in terms of the current and upcoming generation capacity(s), Inter-regional transmission capacity and inter-state transmission capacity has been modelled. However, intra-regional transmission constraints have not been considered.
	All data required for the analysis has been gathered from the publicly available information from the websites and reports of various Central and State Agencies.
	The Thermal Generation (Coal, Gas) capacity upcoming was considered as per the projections of the CEA, along with the '24x7 Power for All' Document for the States. It may be noted that the additions considered were only the firm additions at the time of model preparations. Further, capacity retirements have not been considered in the models. Each unit of these thermal project have been modelled, with specific parameters (as far as available).
	Under the model(s), the installed capacity for a particular State (current and upcoming) is considered as the total generation capacity within the physical boundary of that State.
	The target of Government of India is to include 175 GW of RE into the Indian system by 2022. Wind & Solar combined contribution is expected to be 160 GW, while the remaining 15 GW would be from Small Hydro, Biomass etc. This 15 GW capacity has not been modelled in the study.
	The 100 GW solar target includes the Utility-scale solar and roof-top solar targets. For the purpose of our model, there is no differentiation made between utility-scale solar and roof-top solar generation, and both have been categorized under a single category.
Power Plant Operations related	Some of the Coal based thermal power plants have been assigned 'must-run' status under the regional model.
	As per the current provisions pertaining to the dispatch of wind and solar projects in India, these projects have also been designated the 'must-run' status. There is no spilled energy considered for these plants.
	The model provides that nuclear plants would not cycle to accommodate additional variable wind and/or solar energy. This means the nuclear plants are modelled to perform at a given level without too many ramp-up or ramp-down events.
	The production simulation analysis assumed that all units were economically committed and dispatched while respecting existing and new transmission limits, generator cycling capabilities, and minimum turndowns, with exceptions made for any must-run unit or units with operational constraints.
	Potential increase in operations and maintenance (O&M) cost of conventional thermal generators due to increased ramping and cycling were not included.
	Renewable energy plant O&M costs were not included.
	The hydro projects were modelled based on the design energy data available for the projects from the public domain.

Table 2: Modelling assumptions and considerations in the MAPS model

4.5 GENERAL MODELLING ASSUMPTIONS – MARS

For this analysis, Indian power system (grid) is represented in the similar manner as GE MAPS model. In the Indian system, 5 regions are represented as pools while states in the regions are represented as areas. Interconnections and the overall modelling approach is shown in Figure 12**.**

Figure 13 shows the interstate transmission links and value of the transmission limits. The Inter region transmission capacity is based on the CEA 20-year (2016-36) Perspective Transmission planning report. Inter-state limits are as per power flow simulation results for 2021-22 from the CEA planning report. Maximum values from the four quarterly values has been considered for simulations

Regarding the MARS model, key reference points are mentioned below:

Study time-horizon related	The MARS analysis was performed for year 2022.
Existing/ Planned Capacity related	Generation unit's details are considered from the production cost (GE MAPS) database. Thermal generation units are classified into 5 categories. They are represented in the MARS database with a two-state model with an expected forced outage rate (EFOR). Details are mentioned in Table 4 and Table 5 below. EFORs are assumed based on the generation technologies. Hydro generation assumed to generate with their full capacity without any restrictions.
Power Plant Operations related	No demand response program or other emergency operating procedures were modeled in the system.

Table 3 : Modelling assumptions and considerations in the MARS model

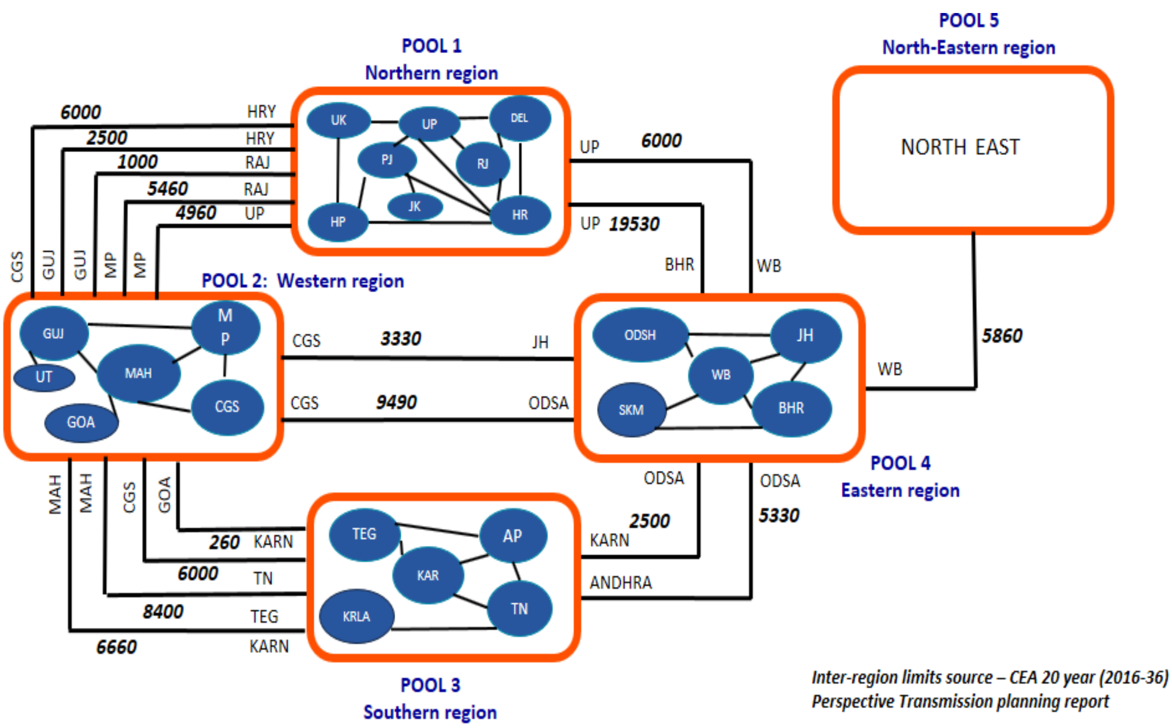


Figure 12: Inter region transmission assumptions in GE MARS model

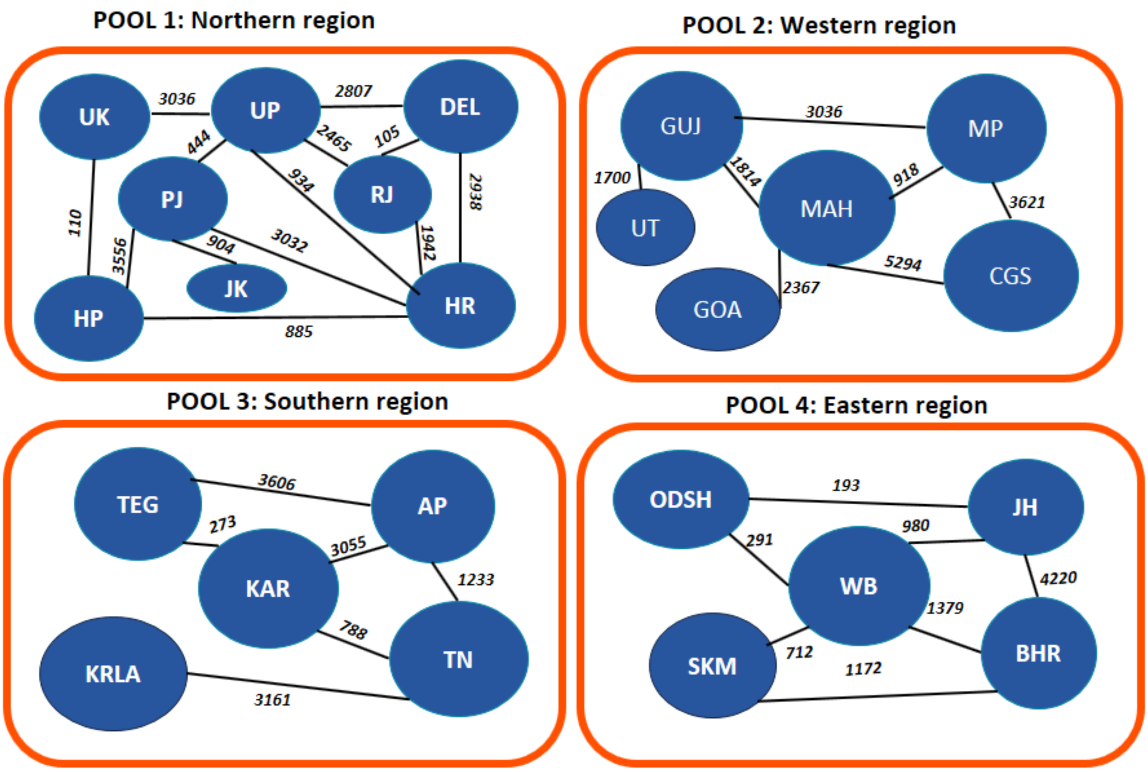


Figure 13: Inter-state transmission limits considered for MARS analysis

Sr No.	Technology	Number of Capacity States	Capacity States	
			1	2
1	Gas Open Cycle	2	100%	0%
2	Coal	2	100%	0%
3	Gas Combined Cycle	2	100%	0%
4	Diesel	2	100%	0%
5	Nuclear	2	100%	0%

Table 4: Number states for thermal generation technologies

Sr No.	Technology	Number of Capacity States	Forced Outage Rates (FOR)	
			1	2
1	Gas Open Cycle	2	2.96%	0%
2	Coal	2	4.00%	0%
3	Gas Combined Cycle	2	3.33%	0%
4	Diesel	2	2.96%	0%
5	Nuclear	2	8.10%	0%

Table 5 : Forced outage rates for thermal generation based on technologies

4.5.1 LOAD SHAPES

GE MARS used the same load model (shapes) as developed for GE MAPS study. Details are mentioned in Section 4.12.

4.5.2 RENEWABLE GENERATION PATTERN

GE MARS used the same wind shapes and solar shapes developed for GE MAPS study. Details can be found in Sections 4.6 and 4.7 below.

4.6 WIND DATA SET DEVELOPMENT ASSUMPTIONS

The Wind Power Density map of India as per the National Institute of Wind Energy (NIWE) is as shown[5] in Figure 14. As may be seen from this figure, wind generation capacity is majorly available in the Southern, Western, and Northern region states of India, i.e. a total of 8 States throughout India, including 4 Southern Region States, 3 Western Region States & 1 Northern Region State.

The targeted wind generation capacity by 2022 is 60 GW, which is divided into the potential states of these three regions only. Southern Region States have the largest cumulative target of 28 GW, followed by Western Region (22.6 GW) and Northern Region (8.6 GW). With regards to the individual State targets, Tamil Nadu (11.9 GW) is the highest, followed by Gujarat (8.8 GW), Rajasthan (8.6 GW) and Maharashtra (7.6 GW).

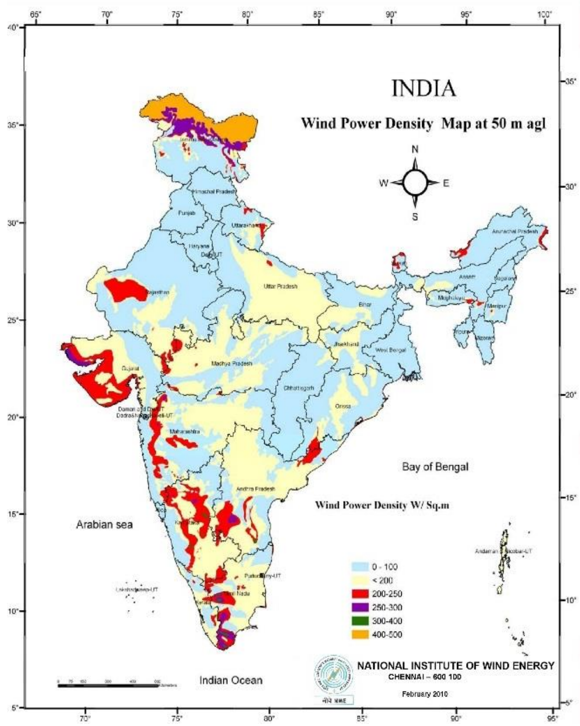


Figure 14: India Wind Power Density (W/m^2) Map

The details of the data-set development of Southern, Western, and Northern Region are given as below.

4.6.1 SOUTHERN REGION

The Wind generation potential is available in the states of Andhra Pradesh, Telangana, Tamil Nadu, and Karnataka in the Southern Region. For the state of Andhra Pradesh, the wind profiles as available from the Andhra Pradesh State Load Dispatch Centre (APSLDC) website were used for 2015 model benchmarking, with a total capacity of 793 MW. For year 2022, same profile was considered against the state's targeted wind installed capacity of 8100 MW as per the GOI target for 2022.

For the state of Karnataka, Shakti Sustainable Energy Foundation provided the hourly wind generation profile for the Gadag site located in the Chitradurg District of Karnataka. For the purpose of creating the profile for GE MAPS input, we have considered the machine curve of a 600-kW class machine. This profile shape was then used for 2015 model calibration with a total installed

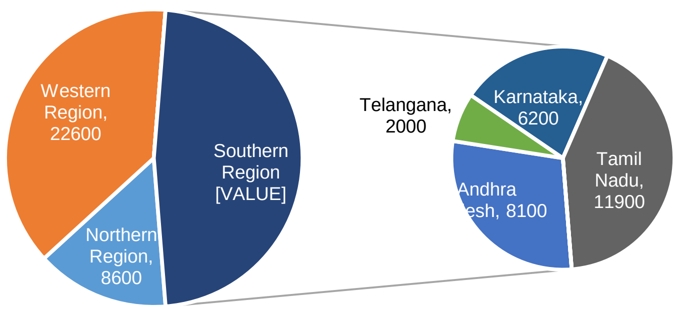


Figure 15: State-Wise Wind Target for Southern Region by 2022

5 http://niwe.res.in/assets/img/comman/WPD_Map.jpg

capacity of 2640 MW for the state of Karnataka in 2015. This was then projected to meet with the GOI target of an installed capacity of 6200 MW by 2022.

Similar process was followed for Tamil Nadu, perusing the data provided by Shakti Sustainable Energy Foundation for the site at Mupandal in the Coimbatore district. Again, a machine curve of 600 kW class machine was considered, and was calibrated against the state's installed capacity of 7458 MW. The GOI target for the state of Tamil Nadu in terms of wind capacity by 2022 is 11,900 MW, which was used to scale up the profiles and sites for 2022. The targeted wind installed capacity for the Southern Region states is about 28,000 MW by 2022, and a detailed breakup of this targeted installed capacity state-wise considered in our model is as given in Figure 15.

4.6.2 WESTERN AND NORTHERN REGIONS

The Wind generation potential is available in the states of Gujarat, Maharashtra and Madhya Pradesh only in the Western Region. The preparation of Wind generation profiles for the Western Region was done as described below.

For the State of Gujarat, the data available on the website of Gujarat State Load Dispatch Center was used. This data was available for each time block (i.e. 15-minute period), and this data was used to develop the representative profile for each month of the year. One such profile is considered for each of the three RE rich districts of Jamnagar, Kutch, and Rajkot in Gujarat. This was then used in the benchmarking of the 2015 model, and the model for 2022 was obtained by scaling the profiles to the targeted installed capacity of 8800 MW for the state of Gujarat in 2022. For the state of Maharashtra, the hourly wind generation data was taken from the daily systems report available at Maharashtra State Load Dispatch Center (MahaSLDC) website. This profile was then used to prepare the benchmarked model for 2015, and the installed capacity was scaled up to 7600 MW which is the targeted wind installed capacity for Maharashtra by 2022. The data for Madhya Pradesh was prepared assuming the wind generation profile exactly similar to the profile taken for the district of Rajkot in Gujarat. This was done as the generation data for Madhya Pradesh was not available when this model was being prepared. The model can be modified and updated in case the exact generation profiles are made available. The wind installed capacity target for Madhya Pradesh by 2022 is 6200 MW, which was included in the model for 2022.

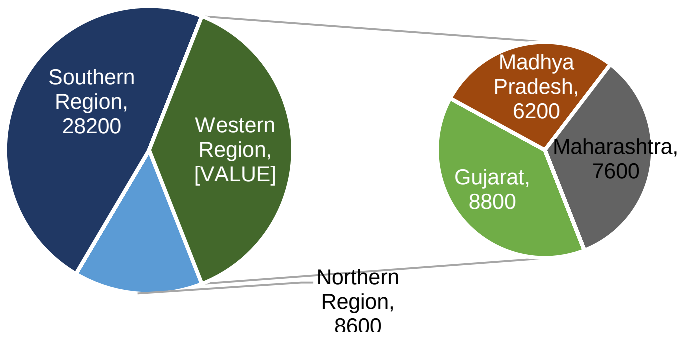


Figure 16: State-wise Wind target for Western Region by 2022

In the Northern Region, only the state of Rajasthan has the potential for wind generation, targeted to touch the tune of 8600 MW by 2022. For preparing the data set of the benchmarked model for 2015, the hourly generation profile was obtained from the 'Report on green energy corridors – PGCIL (Vol-1)'[6]. One shape was considered for each month of the year. Further, the daily peak wind

[6] http://www.powergridindia.com/sites/default/files/Our_Business/Smart_Grid/Vol_1.pdf

generation for the year was obtained from the Rajasthan Rajya Vidyut Prasaran Limited (RRVPNL) daily reports and scaled based on the profiles as obtained above.

4.7 SOLAR DATA SET DEVELOPMENT ASSUMPTIONS

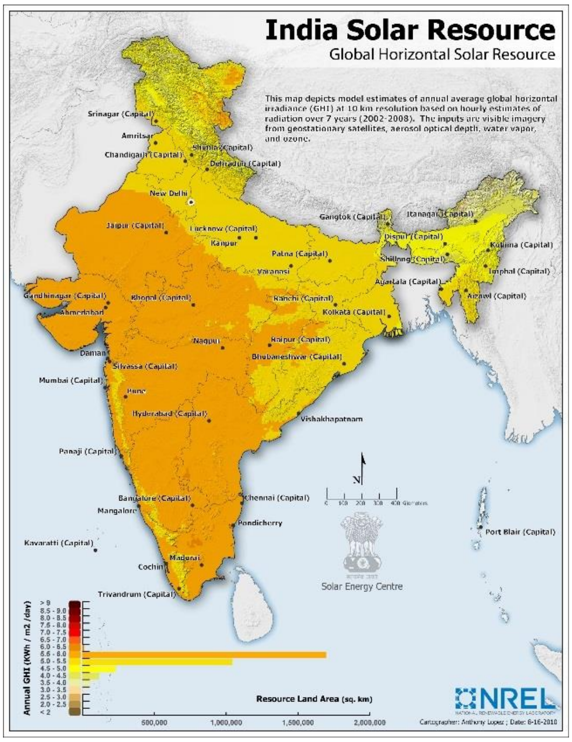


Figure 17: India Solar Resource Map (GHI basis)

India is well endowed with a huge solar potential, spread almost everywhere in the country to varying degrees. A map depicting the Global Horizontal Solar Resource of India[7] reinforces this fact, wherein it can be observed that more than half of the country has an annual average Global Horizontal Irradiance (GHI) range of 5.5-6 kWh/m^2/day, while the majority of the remaining area of the country shows a GHI range of 5-5.5 kWh/m^2/day.

Almost all States/UTs of India have been given a share of targeted capacity of 100 GW solar by 2022. It may also be noted that the target of 100 GW solar includes both Utility-scale solar as well as roof-top solar. The region-wise solar targets are as given in Figure 7 earlier. The Northern Region collectively have the highest target capacity of about 31 GW by 2022, followed by Western Region (28 GW), Southern Region (26 GW), Eastern Region (12 GW) and North-Eastern Region (1 GW). The individual State with the highest targeted solar installed capacity by 2022 are Maharashtra (11.9 GW), Uttar Pradesh (10.7 GW), Tamil Nadu (8.8 GW) and Gujarat (8 GW).

For the preparation of the Solar data set for the MAPS model, the National Renewable Energy Laboratory (NREL) data converted from hourly GHI values to corresponding kW values in 'HOMER' (Hybrid Optimization Model for Multiple Energy Resources) software was utilized. GE Energy Consulting Team has a license to use this software for modelling purposes and the same was perused under this study. The HOMER microgrid software by HOMER Energy is the global standard for optimizing microgrid design. It was originally developed at the National Renewable Energy Laboratory (NREL), and enhanced and distributed by HOMER Energy[8].

4.8 THERMAL GENERATOR MODELING

[7] http://mnre.gov.in/sec/GHI_Annual.jpg

[8] https://www.homerenergy.com/HOMER_pro.html

Since India’s power generation is heavily dependent on the thermal power projects (mainly coal), a considerable time was spent in assimilating and collating the relevant data pertaining to the thermal power projects for inclusion in the MAPS Model. The thermal generating stations were modelled based on the publicly available data including state-wise installed capacity, years in operation, planned capacity additions as per the planning documents. The thermal generating units modeling included all capacity that was operating, restarted, standby, or under construction at the time of the data preparation. The captive power generation was not modelled, as the same was also not included in the thermal installed capacity reports published by CEA.

Power plants were modeled at individual unit level to ensure proper simulation of operation. Combined cycle gas units were modeled as a single unit, aggregating the gas turbines and steam turbine into a single generator. Some of the thermal (mainly coal based) projects were assigned ‘Must-run’ status in the model, to closely mimic their actual operations in benchmarking the model and hence the model for year 2022. Any unit with the forced commitment (must-run) property must be online at all times, with the exception of planned and forced maintenance events. When committed, the units must be producing at or above the unit’s minimum power rating, regardless of economics. The capacity assigned the ‘must run’ status by region and type is given in Table 6 below:

Region	Type	Gross Installed Capacity (MW)	Generation (TWh)
Eastern Region	GTGT	130.00	8.39
	STST	25756.41	132598.15
North-Eastern Region	CCCC	391.00	2914.54
	GTGT	358.20	1762.44
	ICIC	36.36	0.00
	STST	750.00	4747.50
Southern Region	GTGT	127.58	0.00
	ICIC	699.67	0.00
	STST	2920.22	11710.79
Western Region	STST	14291.54	79095.50
Northern Region	none	0.00	0.00
All India Total		**45460.98**	**232837.32**

Table 6: Capacity assigned 'Must-Run' status under the GE-MAPS model

Other parameters defined for thermal plants as required in GE MAPS include the following:

- **Primary Fuel:** Each unit was assigned to a primary fuel type. Although units may have dual fuel capability, this study only considered and evaluated a primary fuel for each unit. The fuel assignment is used to calculate total fuel cost and evaluate fuel consumption.
- **Maximum (Max) Capacity:** The max capacity (MW) represents the maximum amount of power a given unit can produce in the economic production cost simulations. Please note that the “net” capacity i.e. capacity after the auxiliary consumption of the unit was used as a model input. The auxiliary consumption assumed for the different type of projects is as given below:

Plant Type	Aux. (%)

Coal-based	9.5%
Combined Cycle Gas	3%
Open Cycle Gas	1%
Nuclear	12%
IC engine	2%

Table 7: Auxiliary consumption assumed for thermal units

- **Minimum Rating (P-Min Operating):** Minimum rating refers to the minimum stable power output for each unit. The number of MW between the minimum rating and maximum rating represents the unit's operating range. In addition, once a unit is committed and online, it must operate at least at the minimum rating.
- **Heat Rate Curves:** The incremental heat rate curves provided for each generator are used to calculate fuel consumption based on loading level.
- **Variable O&M (VOM):** Variable operations and maintenance cost is also modeled during the production cost optimization. The maintenance cost is dependent on the unit's utilization and represents ancillary maintenance costs associated with running a unit that are accrued when the unit is running. This includes, but is not limited to, things such as maintenance on turbine parts, water consumption, lubricating oils, etc.
- **Planned Outage Rate:** Planned outage represents the percent of time the generating unit is unavailable to serve the system load in order to conduct planned and scheduled routine maintenance. These maintenance outages are scheduled optimally by the model.
- **Forced Outage Rate:** In order to account for unexpected and random generator outages, each unit is assigned a forced outage rate dictating the amount of time that the unit is unavailable to produce energy. This outage rate is in addition to any planned or scheduled maintenance or fixed operating schedules.
- **Min Down Time & Min Run Time:** In order to constrain the operational flexibility of a unit due to thermal cycling constraints, each generator is assigned a minimum down time and minimum run time in hours.
- **Start-Up Energy:** Start-up energy is the amount of fuel consumption required to start up a unit. If multiplied by the fuel cost, the resulting value represents the total start-cost for the unit. This cost is applied every time the unit comes online.

4.9 HYDRO GENERATOR MODELING

The data for the hydro generation projects was collated from various publicly available sources and was used as an input in the model. The design energy of the hydro projects (wherever available) was used to determine the monthly energy generation expected from each hydro project. Therefore, the generation assumptions would be same as the assumptions taken while determining the design energy of the hydro project. Also, in case of the planned hydro projects where this information was not publicly available, the design energy profile to be similar to a project having the same size and/or located in the same area was considered.

In the GE MAPS model, each hydro plant is characterized, at a minimum, by the following information:

- **Monthly Minimum Hourly Generation (MW):** Minimum power plant rating in MW, which represents any run-of-river portion of the plant, or water flow that must occur with or without generating power (spillage).
- **Monthly Maximum (MW):** Maximum power plant rating in MW, usually represents the capacity of the plant, but can be limited by seasonal, environmental, or other factors.
- **Monthly Energy (MWh):** This represents the total available energy that the plant can produce in the given month.
- **Company, Area, Pool Scheduling:** By default, the hydro plants were scheduled against the Area (State) load where they reside. As a result, they were only scheduled against that pool's unique load shape.

4.10 RENEWABLE GENERATING STATION MODELING (WIND AND SOLAR PV)

RE resources (Wind and Solar) were assumed to have zero fuel and O&M costs, and hence are assumed to be available at no cost (or 'Free' resource) in the dispatch stack. The model does not take into account any power purchase agreement (PPA) based prices of independent power producers (IPP) in dispatch of wind and solar resources. However, payments to IPPs can be post-processed.

All RE units were modeled as hourly load modifiers in GE MAPS and follow a pre-defined hourly generation pattern. These generation patterns were based on the hourly wind generation values available at either the SLDC or the RLDC Websites. Also, data for hourly wind generation was provided by Shakti Sustainable Energy Foundation, which was used wherever applicable. These values were perused to create the 8760 values for the wind generation for the particular state.

As mentioned under Section 4.7, the licensed HOMER software was used for development of the solar data at pre-specified sites in the states. The HOMER software requires the GHI values for a particular site as an input, which were sourced from the publicly available information at NREL database. These values were then used in HOMER with a template kW size of the solar project (say 1 kW) and was targeted against a pre-specified load to be met (say 1 kW). The HOMER model would, under these plant size and load assumptions, deliver the hourly outputs for the year (8760 values), which would be the solar generation profile for a particular site. These hourly values were then scaled up based on the Solar energy targets for a particular state to arrive at the solar generation profile corresponding to the targeted capacity in 2015 (if any) and 2022.

It is important to distinguish between the available generation profiles (GE MAPS inputs) and the actual dispatched generation profiles (GE MAPS outputs). The hourly dispatched generation is an output from the GE MAPS algorithm that takes into account any necessary curtailment. Wind generation are the last resources to be curtailed (i.e., spilled) during the low load and high supply periods. In such times, GE MAPS uses a priority order, whereby the more expensive thermal unit operations are reduced first up to their minimum load (they were still kept online if already committed). If no more thermal generation is available for backing down, then GE MAPS uses an assigned priority order to curtail the remaining wind and hydro resources. The last in the priority order is typically non-grid scale distributed solar generation, assumed to be not responsive to system operators' curtailment commands.

4.11 FUEL PRICE PROJECTIONS

The primary fuel prices considered on unit basis was an essential input in the model, as the same would be the deciding criteria of the variable cost of operation of the unit and hence will directly impact the ranking in the dispatch priority. It may be noted that the fuel prices considered were obtained from the public domain information, and are not indicative of the recent policy level changes (such as coal rationalization policy) aimed to reduce the fuel costs of the thermal power stations. Also, as far as the gas power projects are considered, the gas prices are considered based on the actual generation of the gas project and in some places, are intentionally set high to limit the generation for the purpose of benchmarking the 2015 model.

The following table provides the 2022 weighted average coal prices and gas prices in USD/MMBTU for Eastern, Northern, Southern and Western Region considered in the model.

Region	2022 Weighted Average Coal Price	2022 Gas Price
Eastern Region	5.08	8.5
Northern Region	5.17	8.5
Southern Region	5.46	9.2
Western Region	3.82	8.5

Table 8: Weighted Average Coal & Gas Prices considered for 2022 ($/MMBTU)

4.12 LOAD PROJECTIONS

For the purpose of benchmarking the model to 2015 values, the state-wise monthly/yearly peak load and energy generation values were taken from the 'Power Supply Position' reports published by CEA. The values considered are given as below:

Region	Peak Demand (MW)			Energy Requirement (GWh)		
	2015	2022	Avg Yr-on-Yr Growth	2015	2022	Avg Yr-on-Yr Growth
SOUTH	38,304	66,622	10.60%	274,618	422,798	7.71%
WEST	49,676	67,439	5.10%	340,886	471,643	5.48%
NORTH	53,717	85,932	8.60%	330,049	539,604	9.07%
EAST	19,609	27,187	5.50%	129,845	175,800	5.06%
NORTH EAST	2,076	5,974	26.80%	12,370	32,086	22.77%
ALL INDIA	153,232	238,370	7.90%	1,087,768	1,641,931	7.28%

Table 9: Region-Wise Peak Demand & Energy Requirement for 2015 & 2022

Apart from the values for monthly/yearly peak demand and energy generation, the GE MAPS model also requires the load shapes for each hour of the year as an input for the base year, which is this case was 2015. These 8760 values are used to define the load shape in the model, and the same shape (with suitable increase in the peak demand) may then be used to obtain the hourly demand values for the future years, in this instance 2022.

The method employed by the team to obtain the yearly load shape for 2015 are described as below:

SOUTHERN REGION

- → The hourly values in public domain from respective State Load Dispatch Center website for the states of Karnataka & Tamil Nadu.
- → For the state of Andhra Pradesh, hourly values were provided by APSLDC for the period from July 2014 to March 2015. The team extrapolated data for April to June 2014 based on the ratio of monthly peaks.
- → The same profile was assumed for the state of Telangana, with scaling based on peak load.
- → For the state of Kerala, only peak and off-peak daily shape for each month was available. Therefore, the team extrapolated the hourly profile assuming average day load for Kerala to be 80% of the peak day and 2 peak days, 8 off-peak days and 20 average load days per month. Then, scaled the hourly demand pattern based on the daily peak demand values.

WESTERN REGION

- → For the state of Maharashtra, Hourly state demand taken from the Maharashtra SLDC's 'Daily Systems report' which was available on their website[9]
- → For the state of remaining states in the Western Region (Gujarat, Madhya Pradesh, Chhattisgarh, Goa, and UTs) only peak and off-peak daily shape for each month was available. Therefore, the team extrapolated the hourly profile assuming average day load to

[9] http://mahasldc.in/reports/daily-reports/

be 80% of the peak day and 2 peak days, 8 off-peak days and 20 average load days per month. Then, scaled the hourly demand pattern based on the daily peak demand values.

NORTHERN REGION

- For all the states in Northern Region, Peak and off-peak daily shape for each month made available by Shakti foundation. The team utilized these values to extrapolate the hourly profile assuming average day load to be 80% of the peak day and 2 peak days, 8 off-peak days and 20 average load days per month.
- These values were then scaled based on the daily peak demand values, which were obtained from the 'Power Supply Position' report by CEA, and from paid third-party databases subscribed by GE Energy Consulting team.

EASTERN REGION

- For the states in the Eastern Region (West Bengal, Bihar, Jharkhand, Orissa and Sikkim) only peak and off-peak daily shape for each month was available from the respective SLDC websites. Therefore, the team extrapolated the hourly profile assuming average day load to be 80% of the peak day and 2 peak days, 8 off-peak days and 20 average load days per month. Then, scaled the hourly demand pattern based on the daily peak demand values.

NORTH EASTERN REGION

- For the North-eastern region, loads for all the constituent states have been lumped together in the model. The hourly load values for the year 2012 were provided by Shakti Foundation and the same were perused for the preparation of the composite load shape for the North-eastern region.

In order to obtain the values of peak demand and energy requirement for the year 2022, yearly power demand growth was assumed as per the demands projected up to 2019 in respective state 'Power for all' reports, and extrapolated with CAGR of demand growth between 2012 to 2019 to obtain the values for the year 2022.

5 SCENARIOS

5.1MAPS SIMULATION CASES CONSIDERED IN THE STUDY

The following cases are considered for the MAPS analysis on regional basis as well as All India basis in this study.

5.1.1 CASE-1

Case-1 under the MAPS analysis represents a copper sheet model to assess the ideal power exchange requirement between the regions assuming unlimited transmission capability and zero wheeling charges. Indication of requirement of inter-region transmission capacities in an ideal scenario for minimum production cost. It is modelled with the following assumptions as shown in Figure 18.

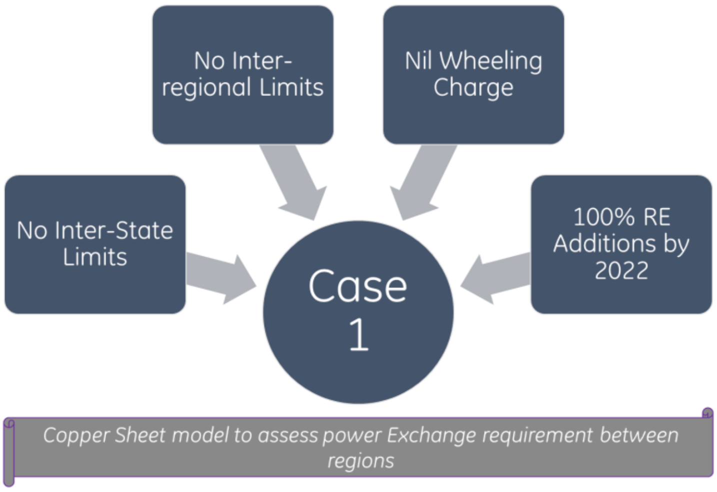


Figure 18: Details of Case-1 of MAPS Analysis

5.1.2 CASE-1B

Case-1B under the MAPS analysis was simulated to show the production cost reduction w.r.t. Case-1, which gives a measure of the savings in production cost. Additional simulation with energy charge for RE gives the increase in total cost due to high RE penetration (Figure 19).

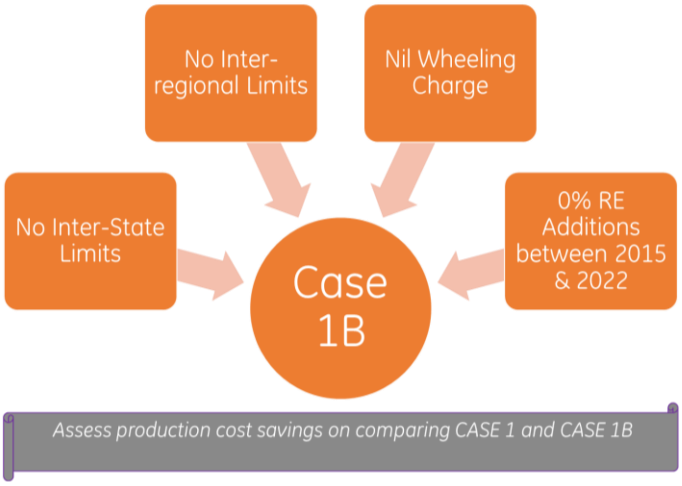


Figure 19: Details of Case-1B of MAPS Analysis

5.1.3 CASE-2

Case-2 under the MAPS analysis was simulated to apply constraint on power transfer between pools by increasing wheeling charges. The highest wheeling charge would have the maximum impact on inter-regional power transfer and give an indication of the minimum level of inter-region exchange which would be required (Figure 20).

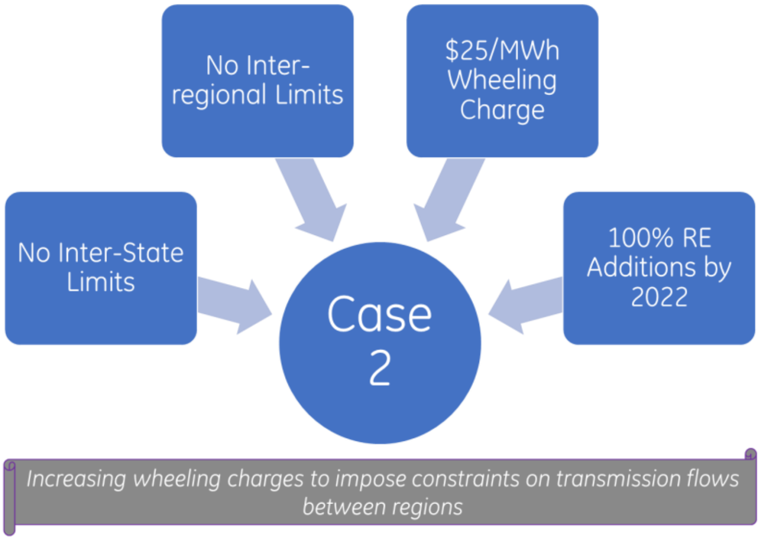


Figure 20: Details of Case-2 of MAPS Analysis

5.1.4 CASE-3

Case-3 was simulated for review of line flows with CEA proposed limits to assess congestion of inter-regional lines in the year 2022 and any further augmentation requirement of inter-region transmission capacity (Figure 21).

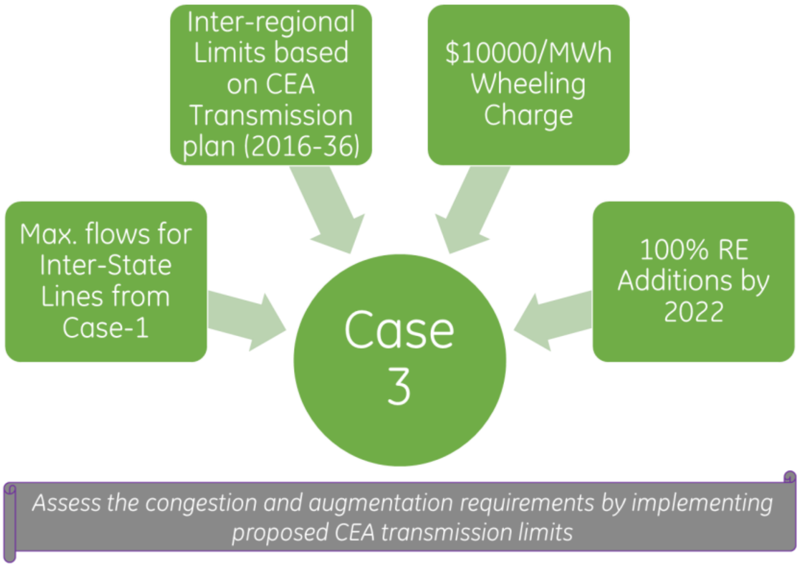


Figure 21: Details of Case-3 of MAPS Analysis

5.1.5 CASE-3B

Case-3B was simulated to assess coal ramp up/ ramp down requirements due to RE penetration. (Figure 22).

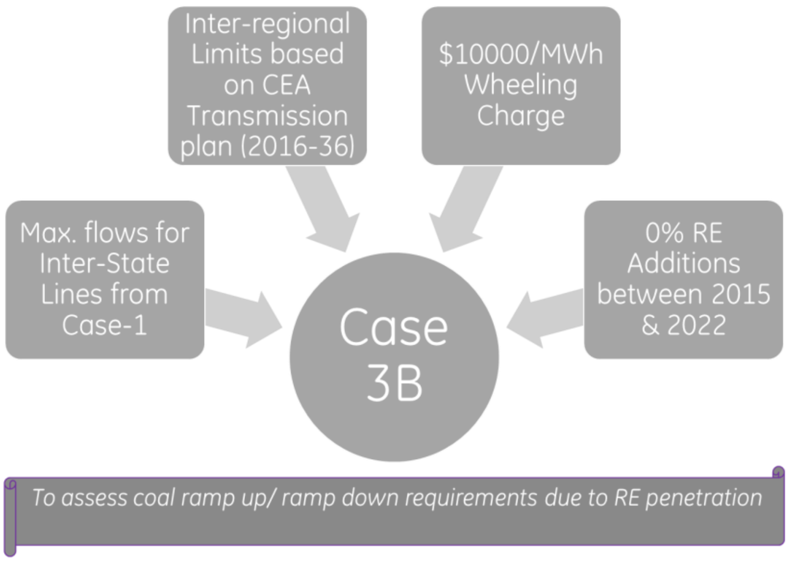


Figure 22: Details of Case-3B of MAPS Analysis

5.2 MARS SIMULATION CASES CONSIDERED IN THE STUDY

Scenario based analysis was performed by running different scenarios to estimate reliability of the system by calculating reliability indices. Case details, intent and type of reliability indices calculated are as stated in following sub-sections.

5.2.1 TRANSMISSION ADEQUACY ASSESSMENT

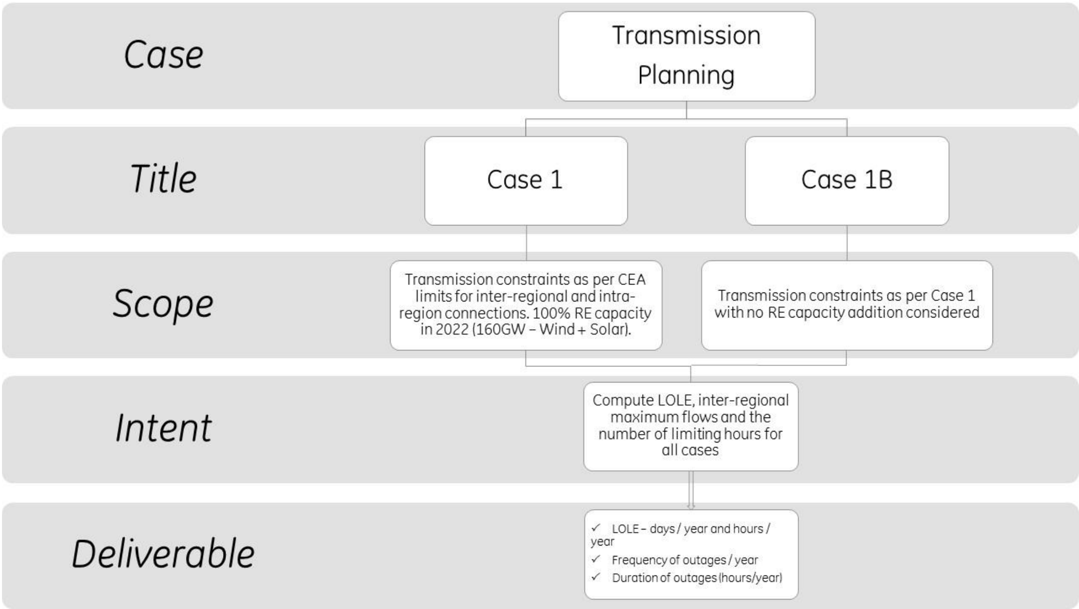


Figure 23: MARS - Transmission Planning Cases overview

5.2.2 GENERATION ADEQUACY ASSESSMENT

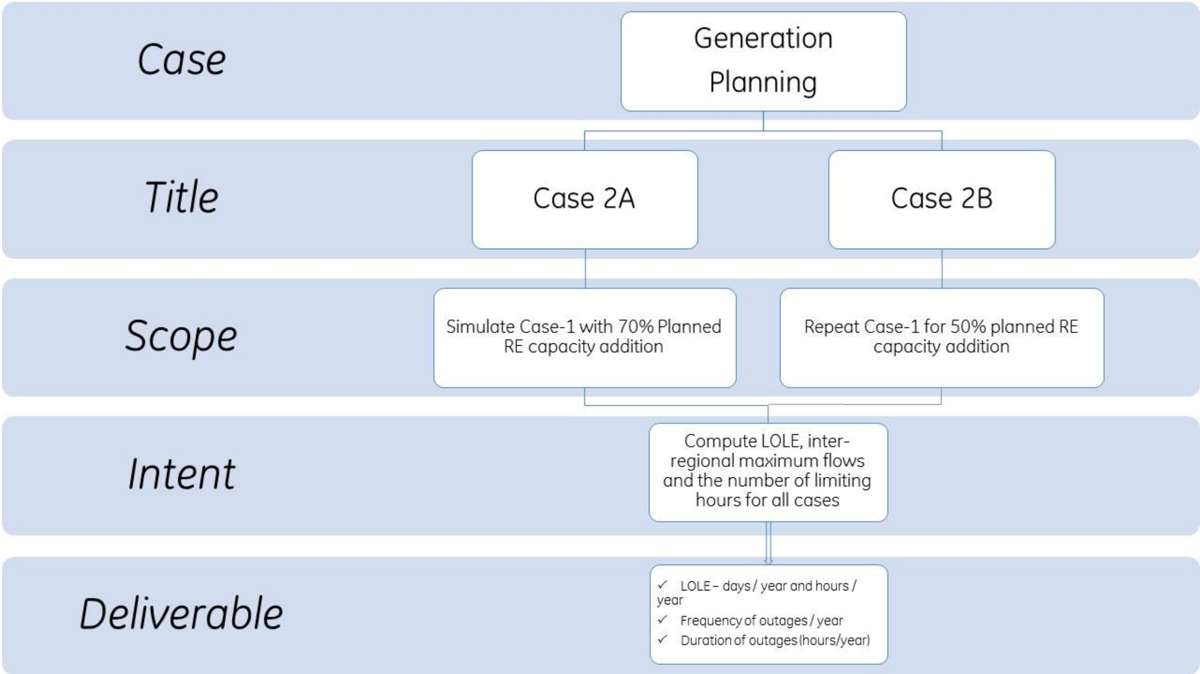


Figure 24: MARS - Generation Planning Cases Overview

5.2.3 CAPACITY VALUE OF RE

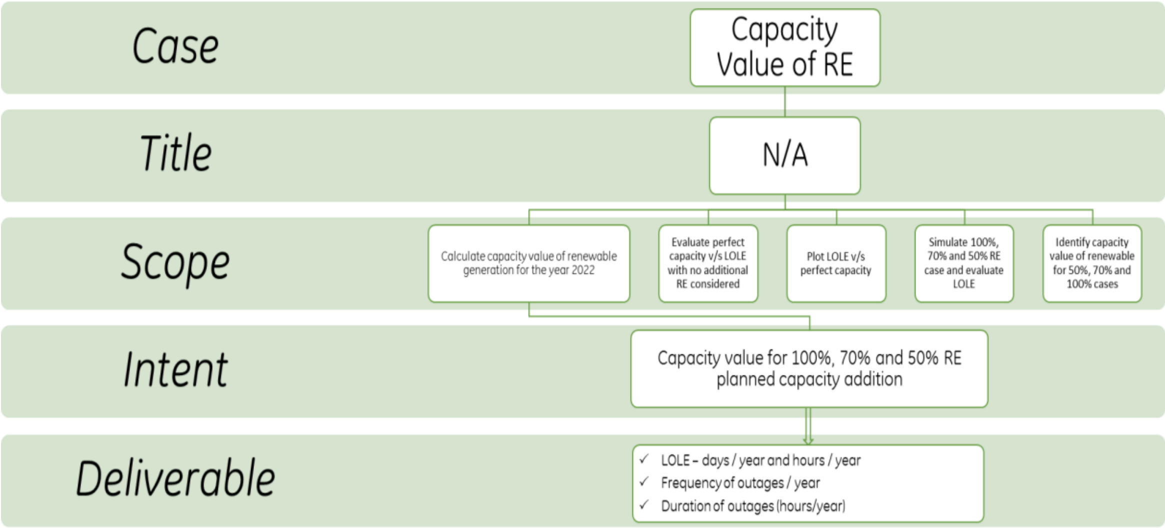
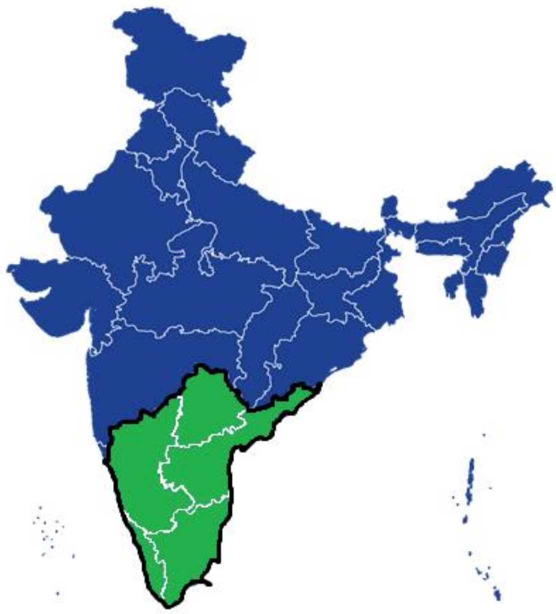


Figure 25: Capacity Value of RE Cases overview

6 REGIONAL PRODUCTION SIMULATION MODELS USING GE-MAPS

6.1 REGIONAL MODEL – SOUTHERN REGION (2022)



The Southern Region of India comprises the states of Tamil Nadu, Kerala, Karnataka, Andhra Pradesh, Telangana, and the Union Territory of Puducherry. For development of the region model using GE-MAPS, the territory of Puducherry is combined with Tamil Nadu.

Southern Region has a renewable energy target of 54 GW of solar and wind capacity addition by 2022. Andhra Pradesh, Telangana and Tamil Nadu have the most capacity addition of solar and wind.

Coal is the dominant conventional capacity as in the rest of India in the southern region. Most of which are concentrated in Andhra Pradesh and Tamil Nadu.

Figure 26: Southern Region States as highlighted in Green

Major load centers in the south are the states of Tamil Nadu, Karnataka, and Andhra Pradesh.

6.1.1 DEMAND ASSUMPTIONS

Figure 27 illustrates the peak demand and energy requirement projections for the Southern Region. It may be noted that the peak demand for the Southern Region is expected to grow at 10.6% YoY between 2015 and 2022, while the energy requirement is expected to grow at7.71% YoY for the same period.

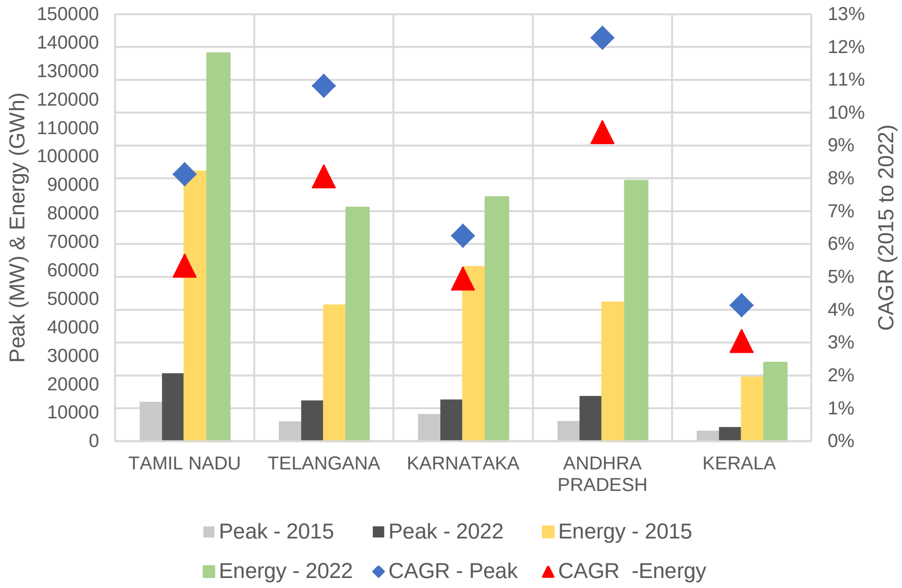


Figure 27: Southern Region State-wise Peak & Energy Comparison - 2015 vs. 2022

Southern Region States	2015		2022		CAGR	
	Peak (MW)	Energy (GWh)	Peak (MW)	Energy (GWh)	Peak (MW)	Energy (GWh)
TAMIL NADU	13766	94681	23773	136190	8%	5%
TELANGANA	6920	47716	14196	82023	11%	8%
KARNATAKA	9549	61154	14595	85665	6%	5%
ANDHRA PRADESH	7032	48743	15809	91406	12%	9%
KERALA	3641	22324	4832	27514	4%	3%

Table 10: State-wise Demand Growth in Southern Region - 2015 up to 2022

As per Table 10 above, Tamil Nadu has the highest peak and energy demand among the states in the southern region. Andhra Pradesh and Telangana have the highest growth rate for demand and peak.

Based on data provided by the 18th EPS, growth among states in the southern region follow an average CAGR of 8% peak and 6% in energy demand growth rate.

6.1.2 GENERATION CAPACITY ASSUMPTIONS

Southern Region is coal dominated with the largest capacity located in Tamil Nadu and Andhra Pradesh. Wind and solar will be the next highest installed capacity by 2022 at 23% and 21% of the capacity mix in the southern region. Among the other regions, southern region has the second highest installed capacity. Table 11 shows the state-wise capacity of each generation technology for 2022 in the Southern Region.

Southern Region	2022 Gross Installed Capacity (MW)							
	COAL	COMBINED CYCLE	OPEN CYCLE GAS	INTERNAL COMBUSTION	NUCLEAR	HYDRO	SOLAR	WIND
ANDHRA PRADESH	11435	4702	0	0	0	1798	4917	8100
KARNATAKA	9900	0	0	228	1000	3426	5697	6200

KERALA	0	523	0	240	0	1885	1870	0
TAMIL NADU	15428	929	128	446	3205	2094	9130	11900
TELANGANA	7185	0	0	56	0	2211	4917	2000

Table 11: State-wise projected Installed Capacity in Southern Region - 2022

Thermal builds between 2015 and 2022 was obtained from third party subscribed databases and planning documents of various Central/State Government agencies and only projects under construction were considered as a part of the installed capacity.

Southern Region States	2015-2022 Gross Capacity Additions (MW)					
	Coal	Combined Cycle	Internal Combustion	Nuclear	Solar	Wind
ANDHRA PRADESH	2671	382	0	0	4917	6945
KARNATAKA	5120	0	0	0	4697	3320
KERALA	0	0	0	0	1870	0
TAMIL NADU	3741	0	0	1568	9130	4245
TELANGANA	1492	0	56	0	4917	1999

Table 12: State-Wise Generation Capacity Additions in Southern Region between 2015 & 2022

As shown in Table 12, the capacity additions in between 2015 and 2022 were predominantly coal plants and the addition of renewable capacity as per the MNRE target for respective states.

6.1.3 TRANSMISSION CAPACITY ASSUMPTIONS

Southern region is linked to the western region through transmission lines connecting the states of Maharashtra to Karnataka and Telangana, Chhattisgarh to Tamil Nadu and Karnataka to Goa. Eastern region is linked to southern region through the transmission lines linking Odisha to Karnataka and Andhra Pradesh. The transmission capacity in 2022 for these lines was considered as per the “CEA Perspective Transmission Plan 2016-2036” with capacities mentioned in Table 13.

Transmission Interconnection	From and To State	CEA Transmission Capacity (MW)
West to South Transmission links	MAHARASHTRA TO KARNATAKA	6660
	MAHARASHTRA TO TELANGANA	8400
	CHHATTISGARH TO TAMIL NADU	6000
	GOA TO KARNATAKA	260
South to East Transmission links	KARNATAKA TO ODISHA	2500
	ANDHRA PRADESH TO ODISHA	5330

Table 13: Inter-Regional Transmission Interconnections & Capacity for Southern Region in 2022

In so far as the inter-state transmission capacity between the constituent states of southern region are concerned, Figure 28 depicts the transmission interconnections between each state. Transmission capacity between states was taken from the copper sheet model simulation using GE-MAPS.

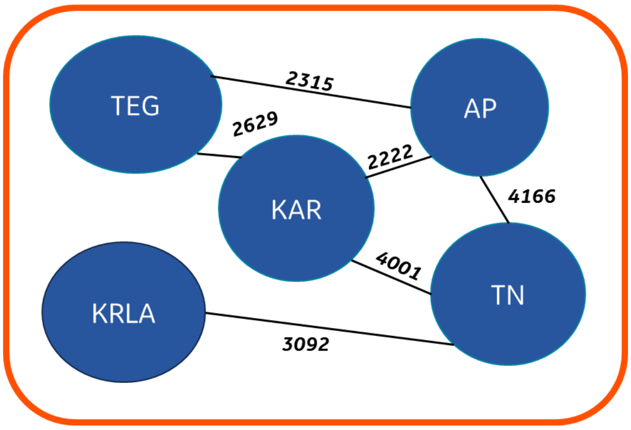


Figure 28: Transmission capacity between Southern Region States in 2022

6.1.4 OPERATIONAL PERFORMANCE OF WIND AND SOLAR RESOURCES

The combined wind and solar generation for the southern region is illustrated by using a Carpet Plot, as shown in Figure 29. The carpet plot is obtained by using the average values corresponding to each hour of the day for each month of the year. The combined wind and solar generation for the year 2022 for southern region shows that the combined generation is at its peak during the mid-day period in the months of June (and some parts of May) and, on an average, is around 33-36GW. This may be attributed to the fact that during July the wind generation is at its peak and the solar generation is also available. Further, the lowest combined generation (about 2-3 GW) is during the night and early morning hours in the month of September-October, when the wind is low and solar is not available.

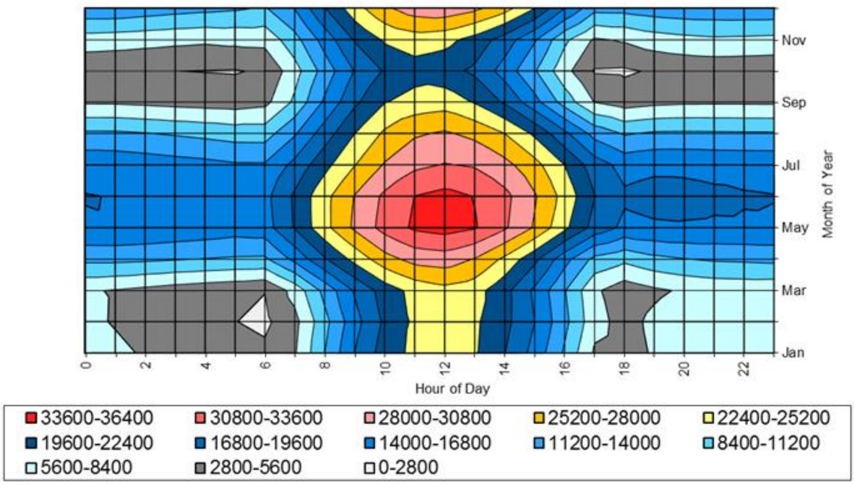


Figure 29: Combined Wind & Solar Generation Forecast for 2022 - Southern Region

6.1.5 OPERATIONAL PERFORMANCE OF THERMAL POWER PLANTS

Figure 30 shows the operational performance of all units installed in the southern region states during the year 2022, under the assumptions for Case-3 and Case-1 respectively. Transmission limits implemented in Case-3 pushes local gas units to increase generation to help in meeting demand as shown in Figure 30. Gas units are competitive as compared to other regions.

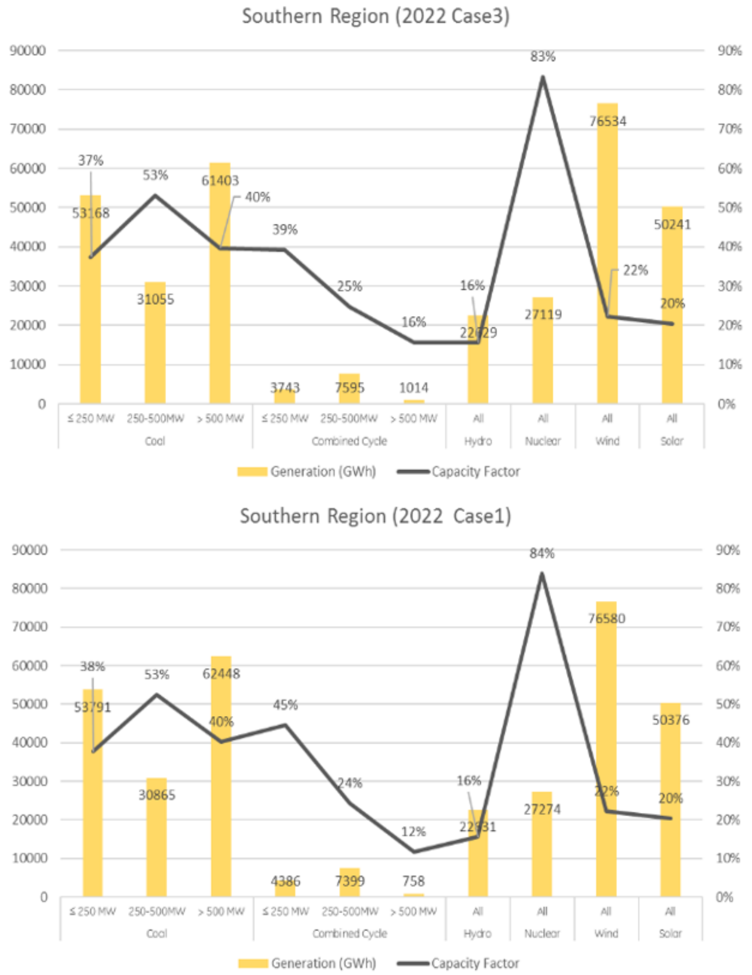


Figure 30: Generation and Capacity Factor for Southern Region - 2022 (Case-1 vs. Case-3)

As seen from Figure 31, thermal units in the southern region operate (average hours online) similarly between Case-1 and Case-3. The critical thermal units (>250MW) will have more starts on average in Case-3 due to reduced imports compared to Case-1. The average number of starts for gas based units on average is ~9 starts/month for both Case-3 and Case-1. While coal plants have an average number of starts of ~3/month.

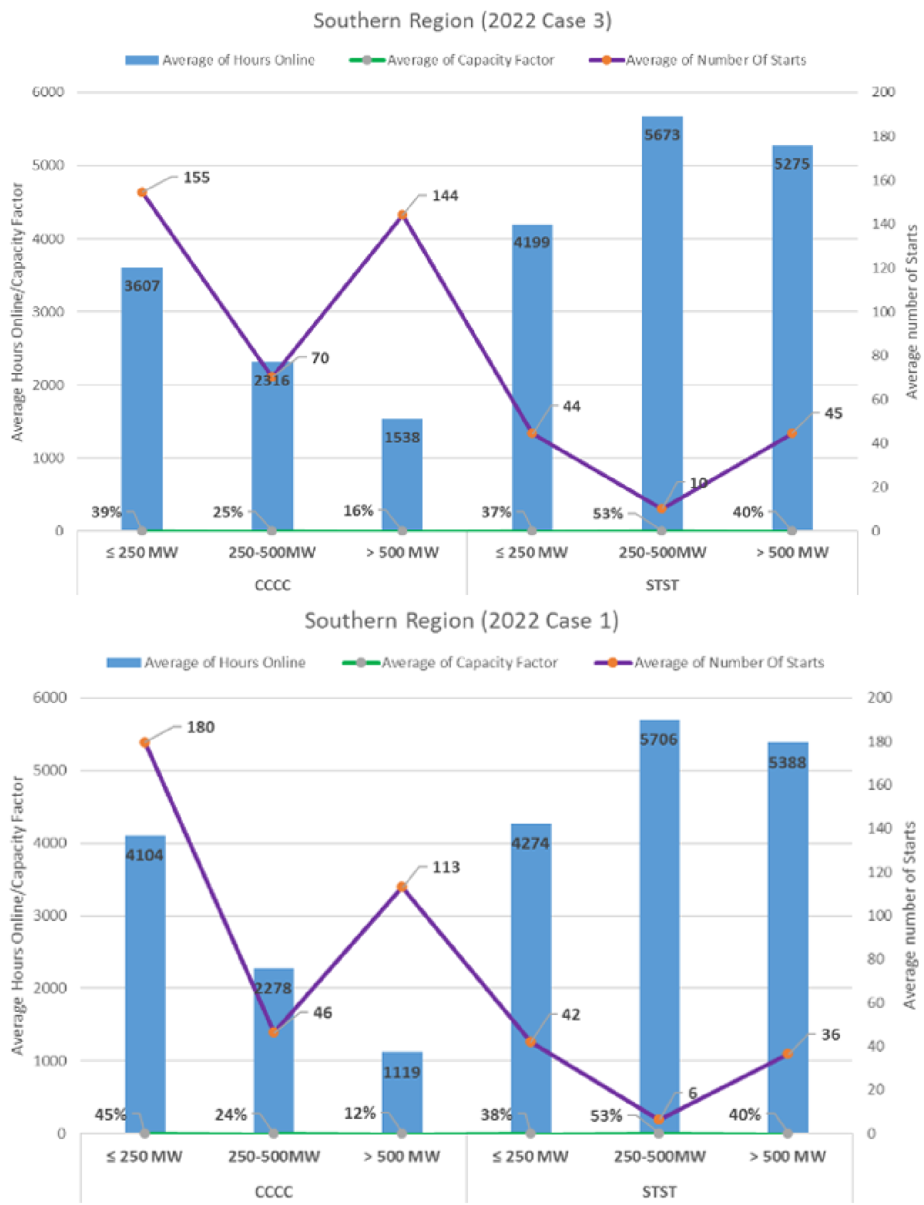


Figure 31: Operational performance of Thermal Plants in 2022 - Case-3 vs. Case-1

The "N" ratio or the number of hours between every start /stop of the unit was computed, the lower this ratio, the more the cyclical operations of the units. By this yardstick, combined cycle plants in the southern region are the most affected, having an average N-ratio of 26 to 27 between Case-3 and Case-1 respectively. This means on an average they are expected to experience a start/stop every 26 hours during their operations in 2022. For coal based plants the N ratio is significantly different between Case-1 and Case-3 ,127 and 114 respectively. This signifies the impact of imported power as critical coal units have more starts on average in Case-3 compared to Case-1.

6.2 REGIONAL MODEL – WESTERN REGION

The Western Region of India comprises the states of Maharashtra, Gujarat, Madhya Pradesh, Chhattisgarh, and the Union Territories of Daman & Diu and Dadra & Nagar Haveli. For development of the region model using GE-MAPS, the union territories in Western Region were combined into a single region.

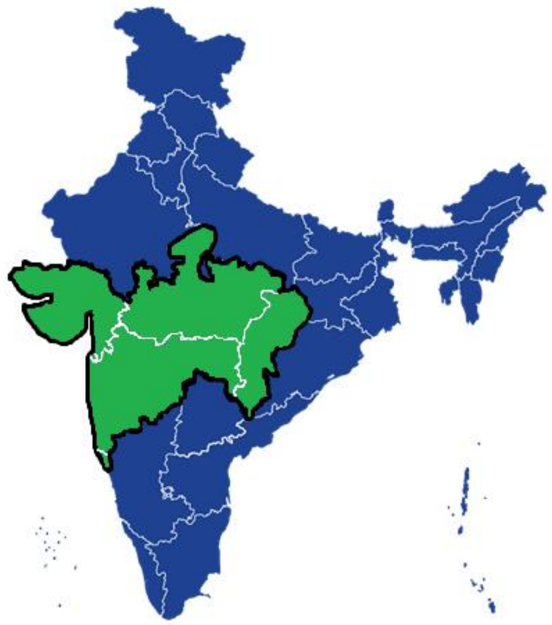


Figure 32: Western Region States as highlighted in Green

Western Region has a renewable energy target of 51 GW of solar and wind capacity addition by 2022. Maharashtra and Gujarat have the most capacity addition of solar and wind by 2022.

Coal is the dominant conventional capacity as in the rest of India in the western region, although it has significant gas based capacity as well. Coal capacity is the largest installed capacity in all the states with Chhattisgarh having the largest installations. Planned Solar and wind capacity additions as per MNRE targets are highest in Maharashtra and Gujarat. Load centers in the west are the states of Maharashtra, Gujarat, and Madhya Pradesh.

6.2.1 DEMAND ASSUMPTIONS

Figure 33 illustrates the peak demand and energy requirement projections for the western region. It may be noted that the peak demand for the western region is expected to grow at 5.1% YoY between 2015 and 2022, while the energy requirement is expected to grow at 5.5% YoY for the same period.

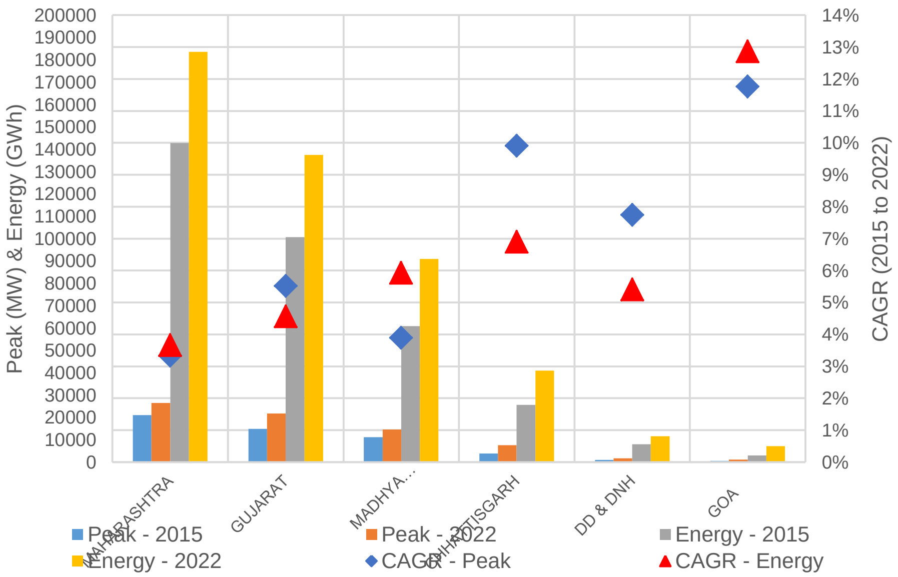


Figure 33: Western Region State-wise Peak & Energy Comparison - 2015 vs. 2022

As shown in Figure 33 and detailed in Table 14, Maharashtra has the highest peak and energy demand among the states in the western region. Chhattisgarh and the union territories have the highest growth rates in the western region. As per the data provided by the 18th EPS, growth among states in the western region follows an average CAGR of 7% peak and energy demand growth rate.

Western Region States	2015		2022		CAGR	
	Peak (MW)	Energy (GWh)	Peak (MW)	Energy (GWh)	Peak (MW)	Energy (GWh)
MAHARASHTRA	21064	26489	142783	183610	3%	4%
GUJARAT	14886	21683	100638	137523	6%	5%
MADHYA PRADESH	11114	14522	60783	90942	4%	6%
CHHATTISGARH	3898	7550	25620	40884	10%	7%
DD & DNH	1038	1750	8031	11614	8%	5%
GOA	548	1194	3031	7070	12%	13%

Table 14: State-wise Demand Growth in Western Region - 2015 up to 2022

6.2.2 GENERATION CAPACITY ASSUMPTIONS

Western region is coal dominated with the largest capacity located in Maharashtra and Chhattisgarh. Wind and solar will be the next highest installed capacity by 2022 at 14% and 17% of the capacity mix in the western region. Among the other regions, western region has the highest installed capacity.

Western Region States	2022 Cumulative Capacity (MW)							
	COAL	COMBINED CYCLE	OPEN CYCLE GAS	INTERNAL COMBUSTION	NUCLEAR	HYDRO	SOLAR	WIND
CHHATTISGARH	29658	0	0	0	0	137	1783	0
GOA	0	48	0	0	0	0	358	0
GUJARAT	18098	7101	67	0	438	1995	8020	8800
MAHARASHTRA	26166	2865	0	0	1407	3313	11926	7600
MADHYA PRADESH	21155	0	0	0	0	2681	5675	6200
DD & DNH	0	0	0	0	0	0	648	0

Table 15: State-wise projected Installed Capacity in Western Region - 2022

Thermal builds between 2015 and 2022 was obtained from third party/ planning documents and only projects under construction were considered as part of the installed capacity. As per Table 16, the capacity additions in western region states between 2015 and 2022 were predominantly coal plants and the addition of renewable capacity as per the MNRE target for respective states.

Western Region States	2015-2022 Capacity Additions (MW)				State Total
	Coal	Hydro	Solar	Wind	
Chhattisgarh	11494	0	1710	0	13204
Goa	0	0	358	0	358
Gujarat	2249	0	6914	4870	14033
Maharashtra	5633	80	11564	2938	20215
Madhya Pradesh	4836	400	4877	4995	15108
Total	24212	480	25423	12803	62918

Table 16: State-Wise Generation Capacity Additions in Western Region between 2015 & 2022

6.2.3 TRANSMISSION CAPACITY ASSUMPTIONS

Western region is linked to the Southern, Northern, and Eastern region. The transmission capacity of these lines was considered as per the CEA Perspective Transmission Plan 2016-2036 with capacities mentioned in Table 17.

Transmission Interconnection	From and To State	CEA Transmission Capacity
West to South Transmission links	MAHARASHTRA TO KARNATAKA	6660
	MAHARASHTRA TO TELANGANA	8400
	CHHATTISGARH TO TAMIL NADU	6000
	GOA TO KARNATAKA	260
North to West Transmission Links	RAJASTHAN TO GUJARAT	1000
	RAJASTHAN TO MADHYA PRADESH	5460
	HARYANA TO GUJARAT	2500
	HARYANA TO CHHATTISGARH	6000
	UTTAR PRADESH TO MADHYA PRADESH	4960
West to East Transmission Links	CHHATTISGARH TO JHARKHAND	3300
	CHHATTISGARH TO ODISHA	9490

Table 17: Inter-Regional Transmission Interconnections & Capacity for Western Region in 2022

As far as the inter-state transmission capacity between the constituent states of western region are concerned, Figure 34 depicts the transmission interconnections between each state. Transmission capacity between states was taken from the copper sheet model simulated using GE-MAPS.

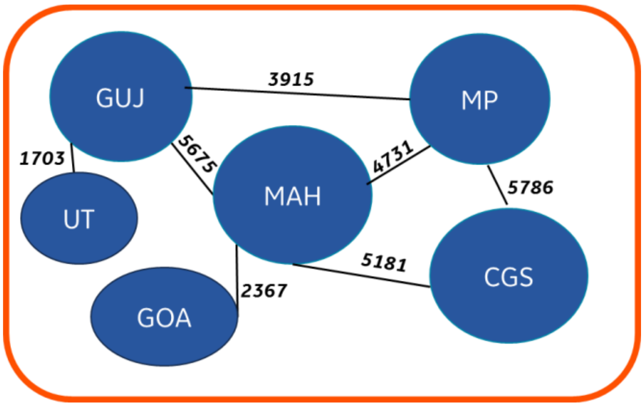


Figure 34: Transmission capacity between Western Region States in 2022

6.2.4 OPERATIONAL PERFORMANCE OF WIND AND SOLAR RESOURCES

The combined wind and solar generation for the western region is illustrated by using a Carpet Plot, as shown in Figure 35. The carpet plot is obtained by using the average values corresponding to each hour of the day for each month of the year. The combined wind and solar generation for the year 2022 for western region shows that the combined generation is at its peak during the mid-day period in the months of July (and some parts of May-June) and, on an average, is around 25-27GW. This may be attributed to the fact that during July the wind generation is at its peak and the solar generation is also available. Further, the lowest combined generation (about 2-4 GW) is during the night and early morning hours in the month of September-November, when the wind is low and solar is not available.

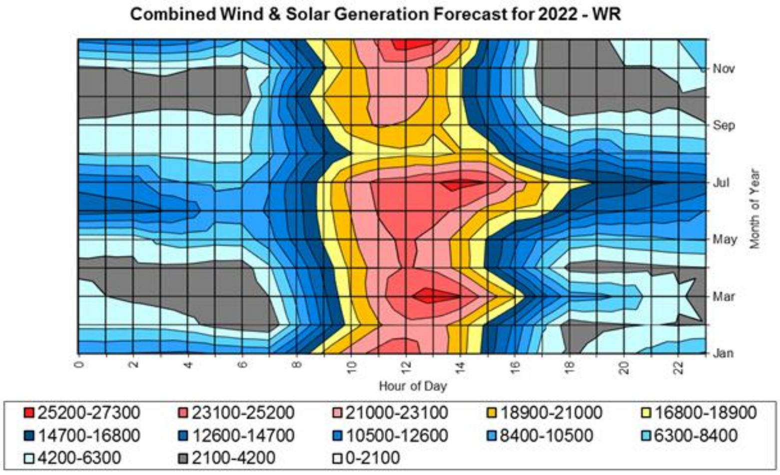


Figure 35: Combined Wind & Solar Generation Forecast for 2022 - Western Region

6.2.5 OPERATIONAL PERFORMANCE OF THERMAL POWER PLANTS

Figure 36 shows the operational performance of all units installed in the western region states during the year 2022, under the assumptions for Case-3 and Case-1 respectively. Western region is a dominant exporter in the Indian grid. Critical coal plants (>250 MW) operate at high PLF's to meet local demand as well as supply power to neighboring regions.

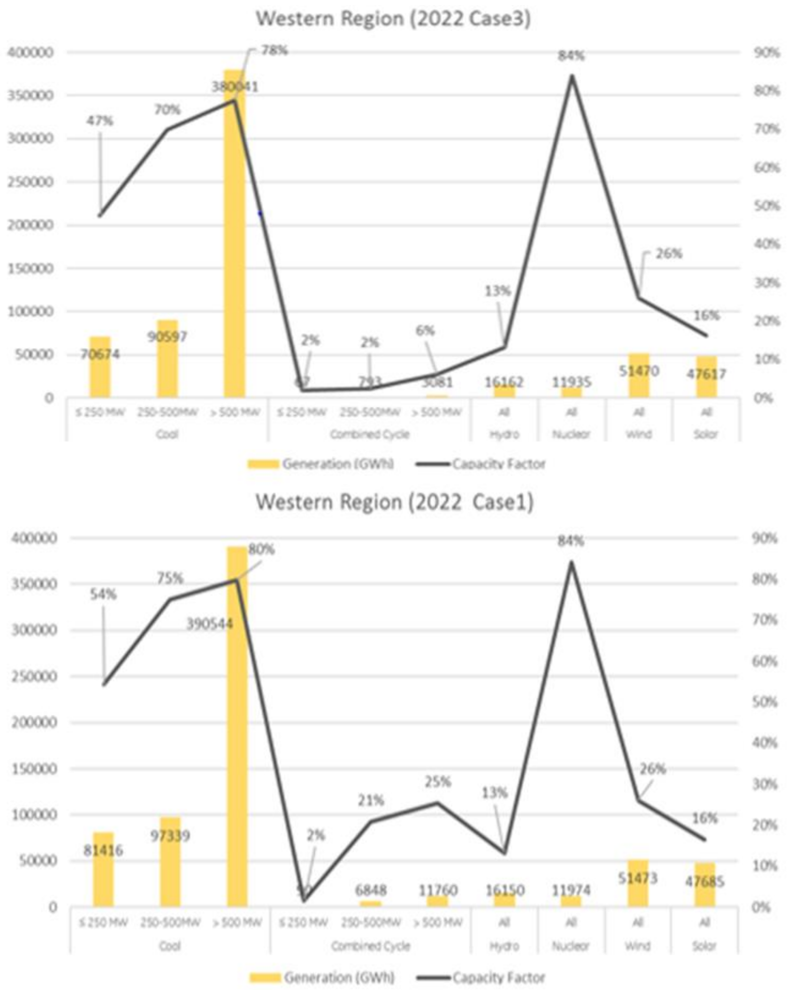


Figure 36: Generation and Capacity Factor for Western Region - 2022 (Case-1 vs. Case-3)

As observed from Figure 37 below, gas based units operate lower in Case-3 due to reduction in power being exported. The average number of starts for gas based units on average is ~5 starts/month for Case-3 and ~ 15 starts/month for Case-1. Increased exports in Case-1 requires gas units to ramp up and down, as coal units in the region supply power to neighboring regions. Introduction of transmission limits reduces the exports putting less strain on western region gas fleet. Coal plants have an average number of starts of ~1/month as coal units dispatch to supply power to regional load and exports.

Figure 37: Operational performance of Thermal Plants in Western Region in 2022 - Case-3 vs. Case-1

The “N” ratio or the number of hours between every start /stop of the unit was computed, the lower this ratio, the more the cyclical operations of the units. Combined cycle plants in the Western Region has an average N-ratio of 5.6 to 8.5 between Case-3 and Case-1 respectively. This means on an average they are expected to experience a start/stop every 5 to 8 hours during their operations in 2022. For coal based plants the N ratio is significantly different between Case-1 and Case-3, 625 and 423 respectively. This signifies the impact of exports as critical coal units have more starts on average in Case-3 compared to Case-1 as the amount of exports reduce in Case-3.

6.3 REGIONAL MODEL – NORTHERN REGION

The Northern region of India comprises the states of Rajasthan, Haryana, Punjab, Himachal Pradesh, Uttarakhand, Uttar Pradesh, Jammu & Kashmir and the Union territories of Delhi and Chandigarh. For development of the region model using GE-MAPS, the union territory of Delhi was modelled as a state and Chandigarh was combined with the state of Punjab.

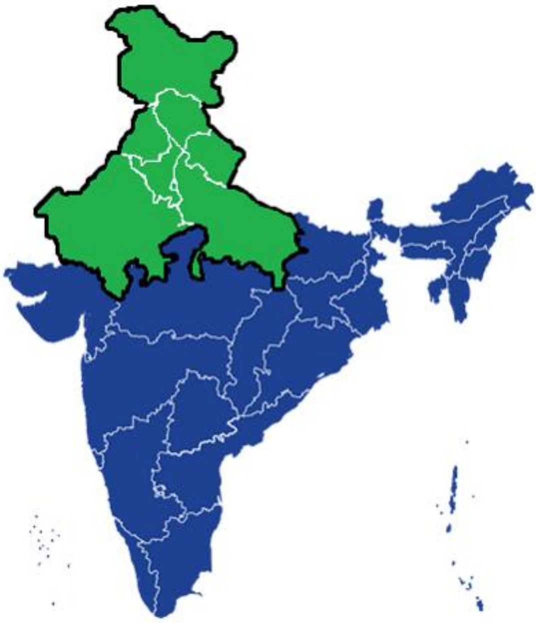


Figure 38: Northern Region States as highlighted

Northern Region has a renewable energy target of 39 GW of solar and wind capacity addition by 2022. Most of the renewable capacity addition are solar technology based with wind capacity installed only in the state of Rajasthan.

Coal is the dominant conventional capacity as in the rest of India in the northern region with significant gas based capacity also. Coal capacity is the largest installed capacity in the larger states such as Uttar Pradesh and Rajasthan. Planned solar capacity additions as per MNRE targets are highest in Uttar Pradesh and Rajasthan. Load centers in the north are the states of Uttar Pradesh, Rajasthan, and Punjab. Delhi also has a large load compared to the regions installed capacity.

6.3.1 DEMAND ASSUMPTIONS

Figure 39 illustrates the peak demand and energy requirement projections for the northern region. It may be noted that the peak demand for the northern region is expected to grow at 8.6% YoY between 2015 and 2022, while the energy requirement is expected to grow at 9.1% YoY for the same period.

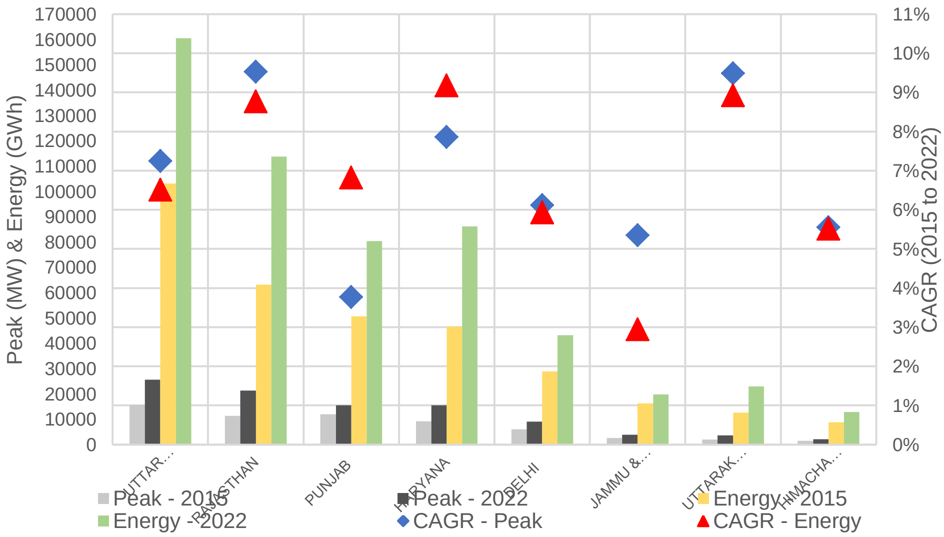


Figure 39: Northern Region State-wise Peak & Energy Comparison - 2015 vs. 2022

As shown in Figure 39 and detailed in Table 18, Uttar Pradesh has the highest peak and energy demand among the states in the northern region.

As per the data provided by the 18th EPS, growth among states in the northern region follows an average CAGR of 7% peak and energy demand growth rate.

Northern Region States	2015		2022		CAGR	
	Peak (MW)	Energy (GWh)	Peak (MW)	Energy (GWh)	Peak (MW)	Energy (GWh)
UTTAR PRADESH	15670	103179	25570	160480	7%	7%
RAJASTHAN	11268	63171	21312	113764	10%	9%
PUNJAB	11929	50598	15455	80334	4%	7%
HARYANA	9152	46615	15544	86212	8%	9%
DELHI	6006	28848	9105	43177	6%	6%
JAMMU & KASHMIR	15670	103179	25570	160480	7%	7%
UTTARAKHAND	11268	63171	21312	113764	10%	9%
HIMACHAL PRADESH	11929	50598	15455	80334	4%	7%

Table 18: State-wise Demand Growth in Northern Region - 2015 up to 2022

6.3.2 GENERATION CAPACITY ASSUMPTIONS

As shown in Table 19, northern region is coal dominated with the largest capacity located in Uttar Pradesh and Rajasthan. Solar will be the next highest installed capacity by 2022 at 27% of the capacity mix in the northern region. Among the other Regions, Northern Region has the third highest installed capacity.

Northern Region States	2022 Cumulative Capacity (MW)							
	COAL	COMBINED CYCLE	OPEN CYCLE GAS	INTERNAL COMBUSTION	NUCLEAR	HYDRO	SOLAR	WIND
DELHI	830	2199	0	0	0	0	2762	0
HIMACHAL PRADESH	0	0	0	0	0	10636	776	0
HARYANA	6199	430	0	32	0	62	4142	0
JAMMU & KASHMIR	0	0	175	25	0	3089	1155	0
PUNJAB	6604	0	0	2	0	1298	4925	0
RAJASTHAN	10407	1027	0	0	1176	430	5761	8600
UTTARAKHAND	0	0	0	0	0	5951	900	0
UTTAR PRADESH	24452	1567	0	0	440	508	10697	0

Table 19: State-wise projected Installed Capacity in Northern Region - 2022

Thermal builds between 2015 and 2022 was obtained from third party/planning documents and only projects under construction were considered part of the installed capacity. As per Table 20, capacity additions in between 2015 and 2022 were predominantly Coal & Hydro plants and the addition of renewable capacity as per the MNRE target for respective states.

Northern Region	2015-2022 Capacity Additions (MW)	State Total

	COAL	COMBINED CYCLE	HYDRO	SOLAR	WIND	
DELHI	0	0	0	2755	0	2755
HIMACHAL PRADESH	0	0	2176	776	0	2952
HARYANA	0	0	0	4112	0	4112
JAMMU & KASHMIR	0	0	450	1155	0	1605
PUNJAB	1897	0	0	4720	0	6617
RAJASTHAN	2696	0	0	4508	5300	12504
UTTARAKHAND	0	0	2160	895	0	3055
UTTAR PRADESH	7251	98	0	10626	0	17975
Total	11844	98	4786	29547	5300	51575

Table 20: State-Wise Generation Capacity Additions in Northern Region between 2015 & 2022

6.3.3 TRANSMISSION CAPACITY ASSUMPTIONS

Northern region is linked to the Western, and Eastern region through transmission lines connecting states. The transmission capacity of these lines was considered as per the CEA 2016-2027 transmission planning document with capacities mentioned in Table 21.

Transmission Interconnection	From and To State	CEA Transmission Capacity
North to West Transmission Links	RAJASTHAN TO GUJARAT	1000
	RAJASTHAN TO MADHYA PRADESH	5460
	HARYANA TO GUJARAT	2500
	HARYANA TO CHHATTISGARH	6000
	UTTAR PRADESH TO MADHYA PRADESH	4960
North to East Transmission Links	UTTAR PRADESH TO WEST BENGAL	6000
	UTTAR PRADESH TO BIHAR	19530

Table 21: Inter-Regional Transmission Interconnections & Capacity for Northern Region in 2022

Within northern region, Figure 40 depicts the transmission interconnections between each state. Transmission capacity between states was taken from the copper sheet model simulated using GE-MAPS.

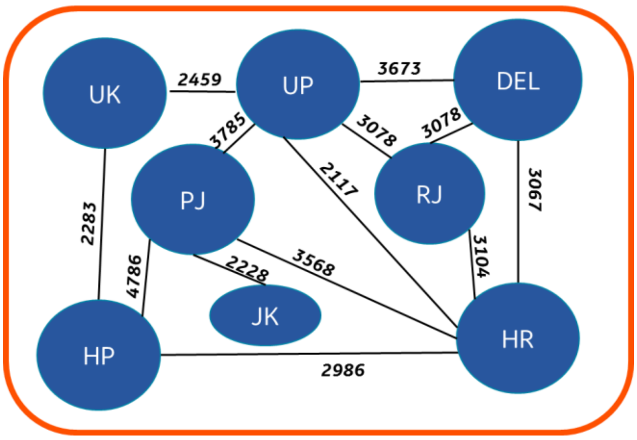


Figure 40: Transmission capacity between Northern Region States in 2022

6.3.4 OPERATIONAL PERFORMANCE OF WIND AND SOLAR RESOURCES

The combined wind and solar generation for the Northern Region is illustrated by using a Carpet Plot, as shown in Figure 41 below. The Combined wind and solar generation for the year 2022 for Northern Region shows that the combined generation is at its peak during the mid-day period in the months of February-May and, on an average, is around 28-30GW. Further, the lowest combined generation (about 0-2 GW) is during the night and early morning hours, when the wind is low and solar is not available.

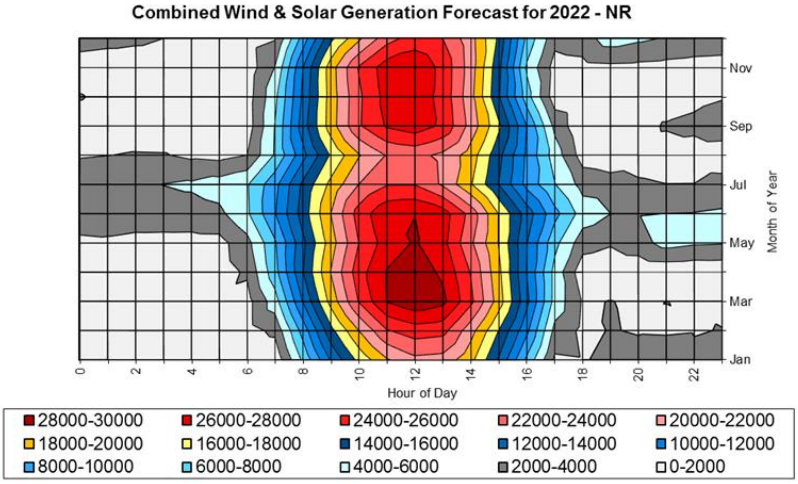


Figure 41: Combined Wind & Solar Generation Forecast for 2022 - Northern Region

6.3.5 OPERATIONAL PERFORMANCE OF THERMAL POWER PLANTS

Figure 42 shows the operational performance of all units installed in the Northern Region States during the year 2022, under the assumptions for Case-3 and Case-1 respectively. Northern Region is a net importer. From Figure 42, operation of gas based units increases in Case-3 due to reduced support from neighboring regions. In Case-1 as there are no transmission limits, coal units operate lower as cheaper power is imported. Northern region has expensive coal units compared to western and eastern regions.

Figure 42: Generation and Capacity Factor for Northern Region - 2022 (Case-1 vs. Case-3)

Further, as seen in Figure 42 above, it is observable that external support in the form of imported power impacts the operational performance of thermal units in the northern region. Gas based units operate for more hours (>250MW) ad have increased number of starts on average in Case-3 due to reduction in imported power. The average number of starts for gas based units on average is ~21 starts/month for Case-3 and ~ 7 starts/month for Case-1. Increased imports in Case-1 forces local thermal units to operate less. Coal plants have an average number of starts of ~2 to 3/month between Case-1 and Case-3 as critical coal units dispatch to supply power to regional load.

Figure 43: Operational performance of Thermal Plants in Northern Region in 2022 - Case-3 vs. Case-1

The “N” ratio or the number of hours between every start /stop of the unit was computed, the lower this ratio, the more the cyclical operations of the units. Combined cycle plants in the Northern Region has an average N-ratio of 11 to 5 between Case-3 and Case-1 respectively. This means on an average they are expected to experience a start/stop every 5 to 11 hours during their operations in 2022. For coal based plants the N ratio is significantly different between Case-1 and Case-3, 205 and 146 respectively. This signifies the impact of imports as critical coal units have more starts on average in Case-3 compared to Case-1 as the amount of imports reduce in Case-3.

6.4 REGIONAL MODEL – EASTERN REGION & NORTH-EASTERN REGION

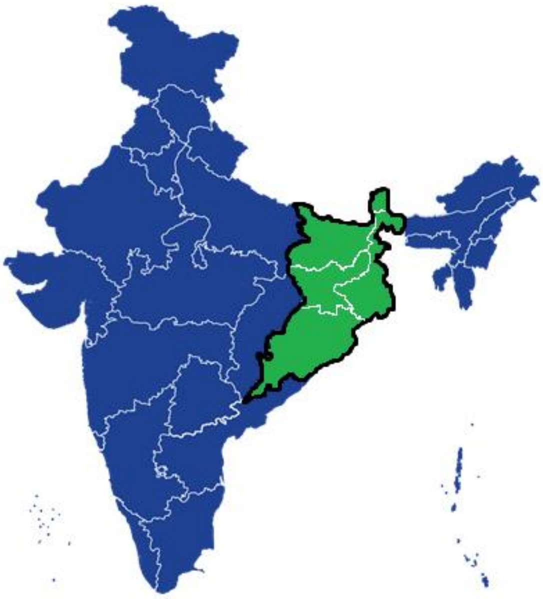


Figure 44: Eastern Region States as highlighted in Green

The Eastern region of India comprises the states of Bihar, Jharkhand, West Bengal, Odisha, and Sikkim. Eastern region has a renewable energy target of 12 GW of solar capacity addition by 2022.

Coal is the dominant conventional capacity as in the rest of India in the eastern region. Coal capacity is the largest installed capacity in the larger states of West Bengal, Bihar, and Jharkhand. Planned solar capacity additions as per MNRE targets are highest in West Bengal.

Load centers in the eastern region are the states of West Bengal, Odisha, and Bihar.

The North-Eastern region of India comprises of the states of Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, and Tripura modelled in GE-MAPS as a single region with no separation of states.

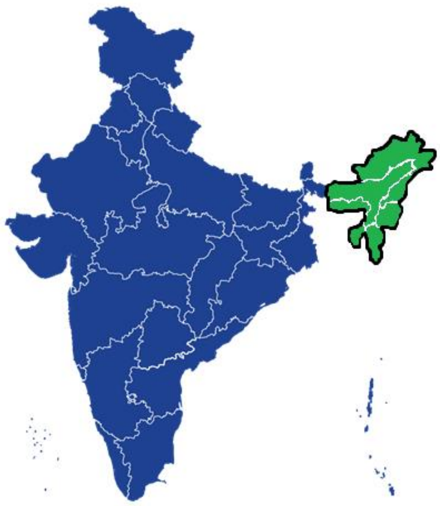


Figure 45: North-Eastern Region States highlighted

North-Eastern Region has a renewable energy target of 1.2 GW of solar capacity addition by 2022, the lowest among all other regions in India.

Hydro is the dominant conventional resource in the region. Furthermore, there is tremendous potential for the development of hydro power projects in the North-East. States such as Arunachal Pradesh have already seen interest from private developers regarding setting up of Hydro projects in the area. Central Agencies such as North Eastern Electric Power Corporation Limited (NEEPCO) are also tasked with the job of developing hydro projects in the North-Eastern states. Construction activities have already commenced for some of the projects. There are issues faced by the project developers in the region such as site accessibility, transmission system etc., but efforts are being made to alleviate these issues and facilitate the development of the hydro projects.

6.4.1 DEMAND ASSUMPTIONS

Figure 46 illustrates the peak demand and energy requirement projections for the eastern and north-eastern region. It may be noted that the peak demand for the eastern region is expected to grow at 5.5% YoY between 2015 and 2022, while the energy requirement is expected to grow at

5.1% YoY for the same period. The corresponding growth rates for north-eastern region are 26.8% in terms of peak demand, and 22.77% in terms of energy requirement.

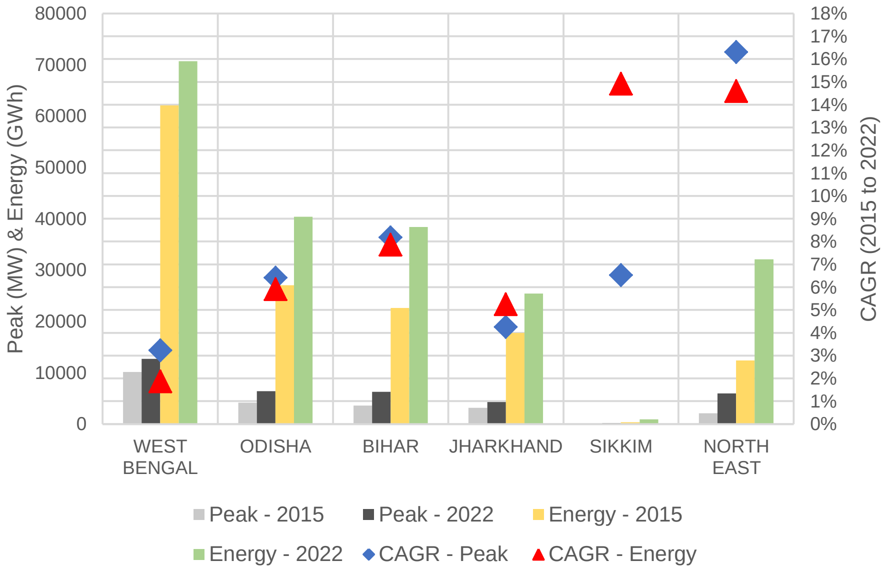


Figure 46: Eastern Region State-wise & North-Eastern Region Composite Peak & Energy Comparison - 2015 vs. 2022

As per Table 22, West Bengal has the highest peak and energy demand among the states in the eastern region. All states in the north-eastern Part of the country were combined into a single region (Non-Coincident peak). As per data provided by the 18th EPS, growth among states in the eastern region follows an average CAGR of 7% peak and energy demand growth rate.

Eastern Region States & NE Composite	2015		2022		CAGR	
	Peak (MW)	Energy (GWh)	Peak (MW)	Energy (GWh)	Peak (MW)	Energy (GWh)
WEST BENGAL	10151	62090	12680	70690	3%	2%
ODISHA	4148	27031	6410	40390	6%	6%
BIHAR	3608	22602	6258	38374	8%	8%
JHARKHAND	3186	17778	4264	25436	4%	5%
SIKKIM	122	344	190	910	7%	15%
NORTH EAST	2076	12370	5974	32086	16%	15%

Table 22: State-wise Demand Growth in Eastern Region - 2015 up to 2022

6.4.2 GENERATION CAPACITY ASSUMPTIONS

Eastern region is coal dominated with the largest capacity located in West Bengal, Odisha, and Bihar. Solar will be the next highest installed capacity by 2022 at 22% of the capacity mix in the eastern region. North-eastern region is predominantly hydro with significant gas based generation units.

North East & Eastern Region	2022 Cumulative Gross Capacity (MW)							
	COAL	COMBINED CYCLE	OPEN CYCLE GAS	INTERNAL COMBUSTION	NUCLEAR	HYDRO	SOLAR	WIND
BIHAR	7460	0	0	0	0	0	2493	0
JHARKHAND	5935	0	0	0	0	130	1995	0
ODISHA	9580	0	0	0	0	2142	2377	0
SIKKIM	0	0	0	0	0	2194	36	0

North East & Eastern Region	2022 Cumulative Gross Capacity (MW)							
	COAL	COMBINED CYCLE	OPEN CYCLE GAS	INTERNAL COMBUSTION	NUCLEAR	HYDRO	SOLAR	WIND
WEST BENGAL	13882	0	170	0	0	1420	5336	0
NORTH EAST	750	1354	462	59	0	4231	1205	0

Table 23: Eastern Region State-wise & North-East Region composite projected Installed Capacity - 2022

Thermal builds between 2015 and 2022 was obtained from third party/planning documents and only projects under construction were considered part of the installed capacity.

As per Table 24, capacity additions in between 2015 and 2022 were predominantly Coal & Hydro plants and the addition of renewable capacity as per the MNRE target for respective states.

North East & Eastern Region	2015-2022 Gross Capacity Additions (MW)				State Total
	COAL	COMBINED CYCLE	HYDRO	SOLAR	
Bihar	3175	0	0	2493	5668
Jharkhand	507	0	0	1995	2502
Odisha	1050	0	0	2377	3427
Sikkim	0	0	1489	36	1525
West Bengal	0	0	160	5336	5496
ER Total	4732	0	1649	12237	18618
North East	750	100	2770	1200	4820

Table 24: State-Wise Generation Capacity Additions in Eastern Region & NE Region between 2015 & 2022

6.4.3 TRANSMISSION CAPACITY ASSUMPTIONS

Eastern Region is linked to Western, Northern, Southern, and North-Eastern region through transmission lines connecting respective states. The transmission capacity of these lines was considered as per the CEA 2016-2036 transmission planning document with capacities mentioned in Table 25.

Transmission Interconnection	From and To State	CEA Transmission Capacity
North to East Transmission Links	UTTAR PRADESH TO WEST BENGAL	6000
	UTTAR PRADESH TO BIHAR	19530
South to East Transmission Links	KARNATAKA TO ODISHA	2500
	ANDHRA PRADESH TO ODISHA	5330
West to East Transmission Links	CHHATTISGARH TO JHARKHAND	3300
	CHHATTISGARH TO ODISHA	9490
East to North-East Transmission Links	WEST BENGAL TO NORTH EAST	5860

Table 25: Inter-Regional Transmission Interconnections & Capacity for Eastern & North-Eastern Region in 2022

Within eastern region, Figure 47 depicts the transmission interconnections between each state. Transmission capacity between states was taken from the copper sheet model ran using GE-MAPS.

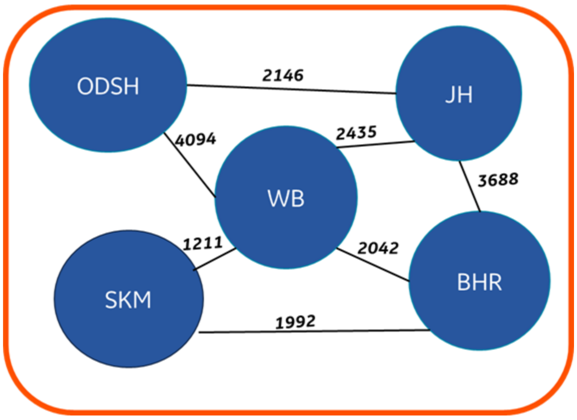


Figure 47: Transmission capacity between Eastern Region States in 2022

6.4.4 OPERATIONAL PERFORMANCE OF WIND AND SOLAR RESOURCES

The combined wind and solar generation for the year 2022 for eastern region shows that the combined generation is at its peak during the mid-day period in the months of March-April and, on an average, is around 9.5-11GW. Further, since there is no wind present in the eastern region, the lowest combined generation (about 1-2 GW) is naturally during early morning and late evening hours throughout the year.

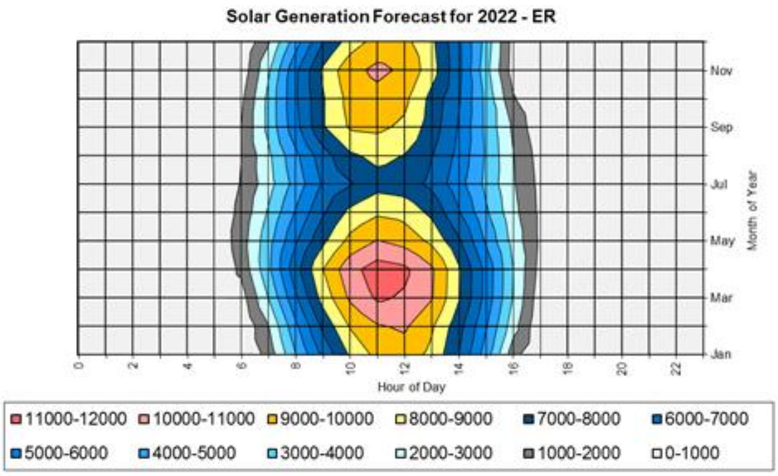


Figure 48: Combined Wind & Solar Generation Forecast for 2022 - Eastern Region

Similarly, for the North-Eastern Region, the maximum generation is generally in the range of around 1-1.5 GW achieved during the summer months of March-April.

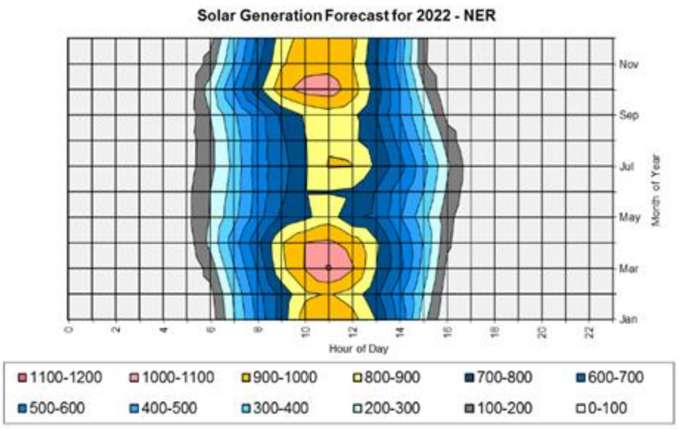


Figure 49: Combined Wind & Solar Generation Forecast for 2022 - North-Eastern Region

6.4.5 OPERATIONAL PERFORMANCE OF THERMAL POWER PLANTS

Figure 50 shows the operational performance of all units installed in the eastern region states during the year 2022, under the assumptions for Case-3 and Case-1 respectively. Eastern region is connected to all regions in the Indian grid. Coal is the only thermal technology present in the region. Between Case-1 and Case-3, coal units operate on a similar level under both cases.

Figure 50: Generation and Capacity Factor for Eastern Region - 2022 (Case-1 vs. Case-3)

Eastern region coal units have 7 starts annually in the 2022 simulation for Case-3, and 3 starts annually in Case-1. With such low number of starts, the regional coal units have very low cyclical operations.

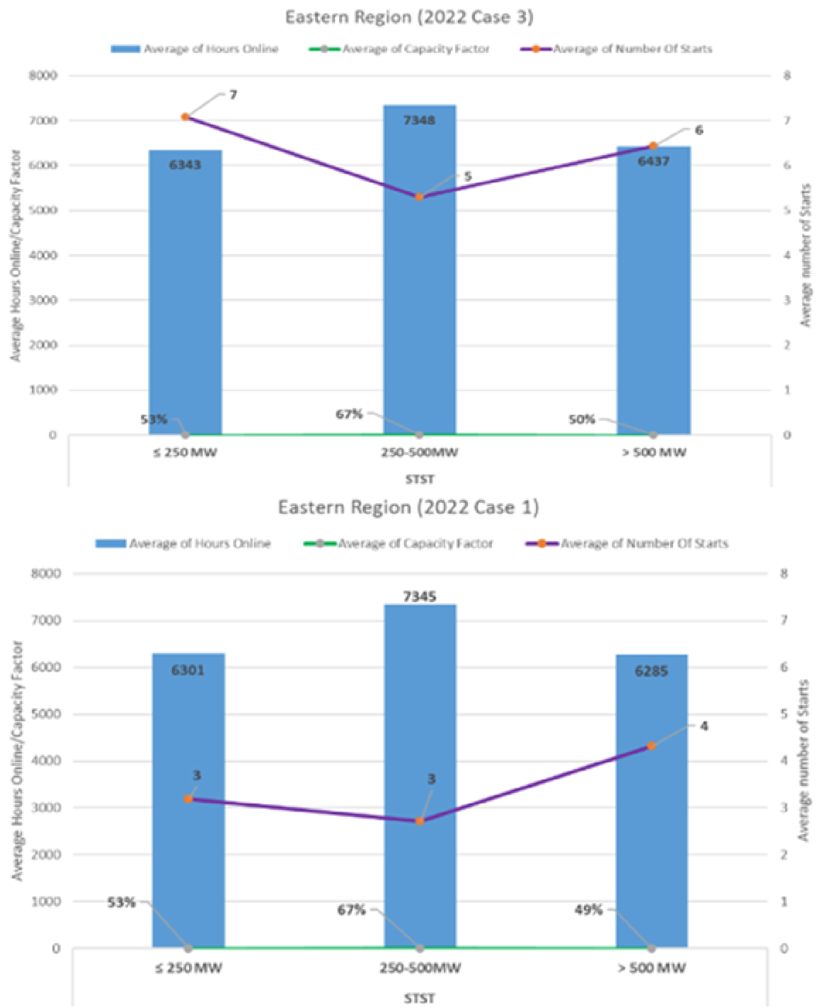


Figure 51: Operational performance of Thermal Plants in Eastern Region in 2022 - Case-3 vs. Case-1

In case of the North-Eastern Region, it is a hydro dominated region with some gas units. The region is connected only to eastern region and depends on imports from the eastern region to meet its demand. The region is dependent on local thermal fleet to operate when hydro unit generation is lower. Gas unit operations in both cases operate similarly (i.e. Case-1 and Case-3). The region is dependent on local units more than imports.

Figure 52: Generation and Capacity Factor for North-Eastern Region - 2022 (Case-3)

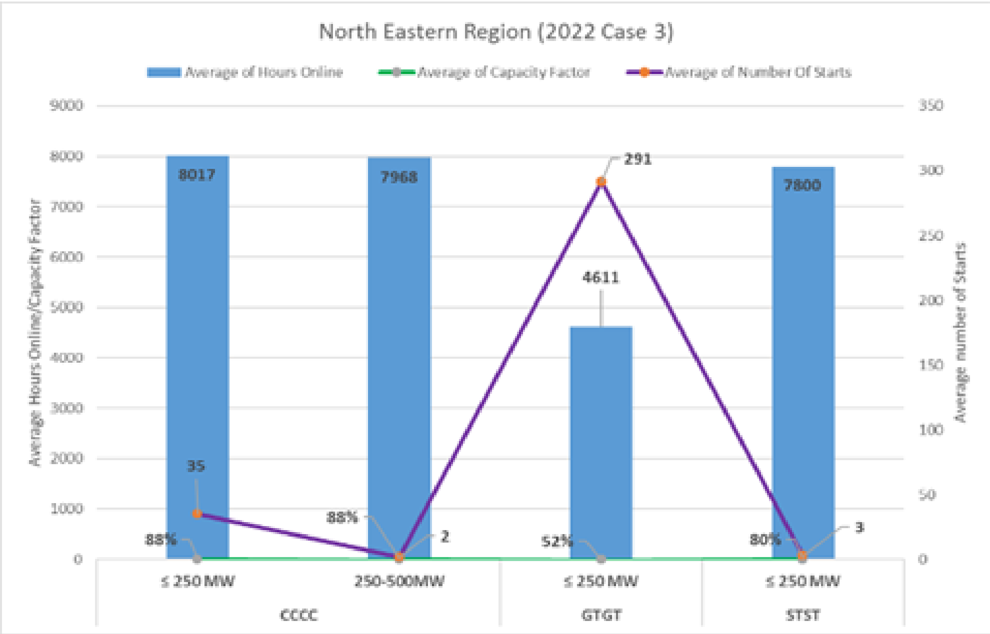


Figure 53: Operational performance of Thermal Plants in North-Eastern Region in 2022 - Case-3

7 ALL INDIA PRODUCTION SIMULATION MODELS USING GE-MAPS

7.1 INTER-REGIONAL TRANSMISSION FLOWS

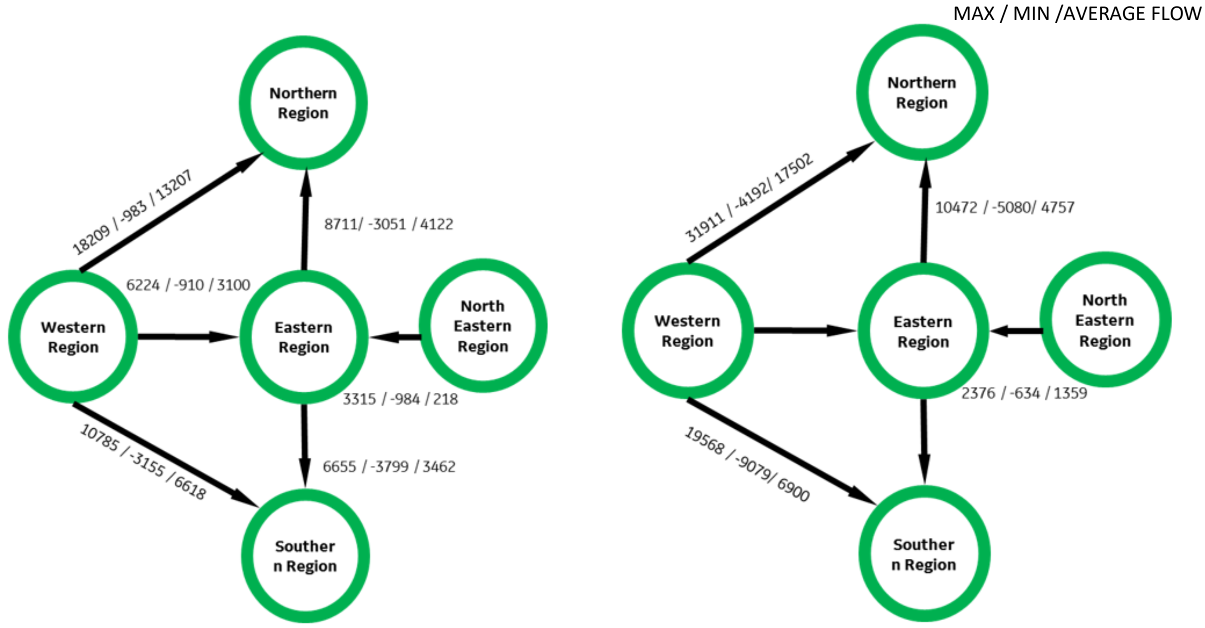


Figure 54: Inter-regional average annual flows - Case-3 (left) & Case-1 (right)

In order to understand the dynamics of inter-regional transmission flows, two significant cases were simulated for the year 2022 with full RE capacity projections-

- Case-1: Simulation assuming unlimited inter-regional transmission capacity, and
- Case-3: Simulation assuming inter-regional transmission capacity as per CEA transmission planning document.

The copper-sheet model (Case-1) gives a high-level estimate on the inter-regional and inter-state transmission capacity requirements for the system for the lowest production cost. Case-3 simulates the impact of transmission limits on the inter-regional transmission capacity as per the CEA transmission planning 2016-2036 document. The transmission limits between states within the region for Case-3 were considered as the maximum flows occurring between states in the copper-sheet model (Case-1). The inter-regional transmission flows were analyzed during high and low demand periods and during high solar and wind periods.

In both the cases, the western region is the major exporting region. In Case-1, western region is exporting ~27GW of power to eastern, northern, and southern regions as compared to ~23GW when transmission limits are considered (Case-3). Northern region is the largest importing region in the system importing on an average ~22GW without any transmission constraints (Case-1). With the introduction of transmission limits (Case-3), it imports on average ~17 GW. The impact of the transmission capacity in Case-3 is seen on the Western-Northern Interconnection in Figure 55. Hence, it is required to increase the local thermal generation in northern region due to constraint in transferring power from western region to northern region.

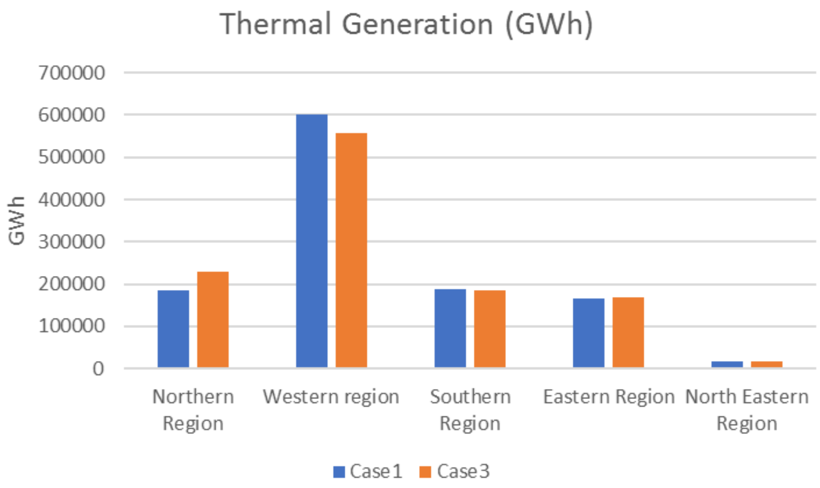


Figure 55: Region-wise Thermal Generation under Case-3 and Case-1

In the 2022 simulations, the regions experience low demand in the month of February and high demand in the month of October. In the high demand period, the Northern region requires a maximum power import of ~23 GW received from the western and eastern regions in Case-3 (Figure 56). This will have significant impact on the performance of thermal units in export oriented regions. The transmission network between western and northern region is utilized more than the eastern and northern transmission links.

FEBRUARY (Low Demand Month) -> MAX / MIN /AVERAGE FLOW

OCTOBER (High Demand Month)-> MAX / MIN / AVERAGE FLOW

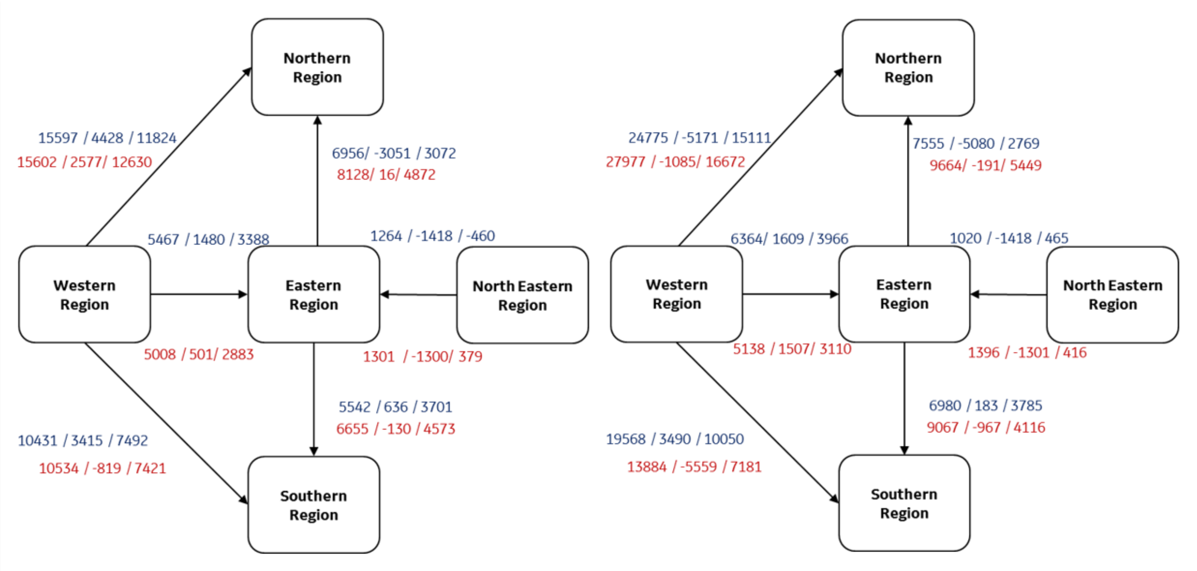


Figure 56: Transmission flows in February & October 2022 - Case-3 (left) and Case-1 (right)

The western region has some of the cheapest sources of coal power in the Indian system. It has an average export of 29 GW to northern, eastern, and southern regions in the month of February and 27 GW in the month of October if no transmission constraints are considered (Case-1). However, there is a significant drop in exports with the transmission limits considered (Case-3). The exports drop to 22.7 GW in February and 22.9 GW in October for western region.

The southern region on an average import around 13.8GW and 11.2GW in February and October respectively. The coal based stations in the region are significantly more expensive than the stations operating in western and eastern regions. Considering the transmission limits (Case-3), the import drops to ~11GW in February and October. High renewable penetration in the month of October also causes a significant drop in imports for southern region in both cases.

Northern region is a net importer throughout the year, in both the cases. The imports increase in October compared to February due to higher demand in both Case-1 and Case-3.

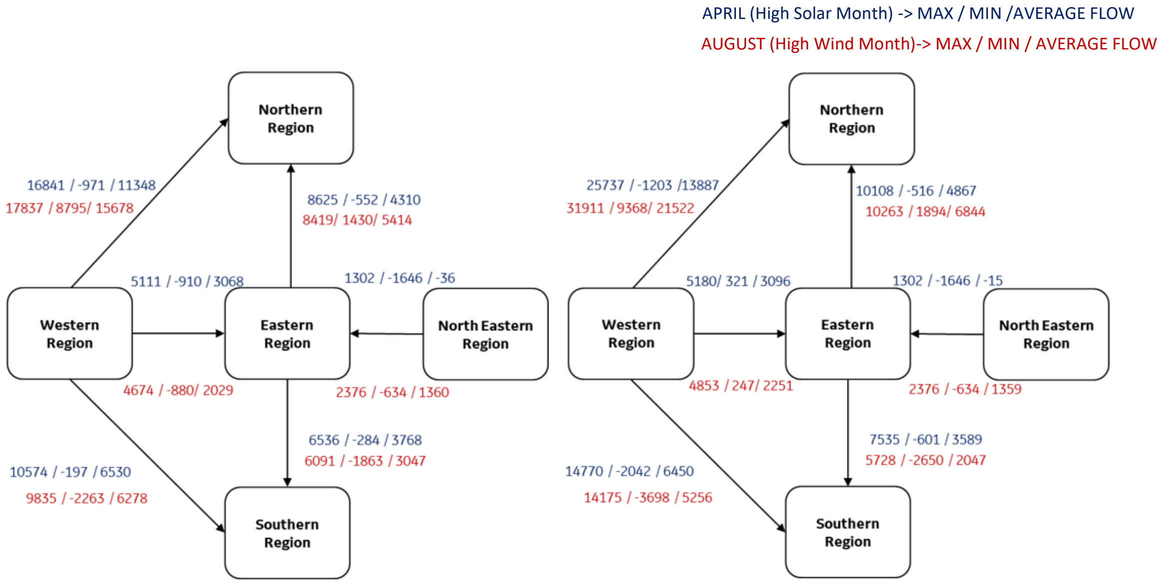


Figure 57: Transmission flows in April & August 2022 - Case-3 (left) and Case-1 (right)

Figure 57 shows the simulation results considering high renewable penetration, such as in the months of April (high Solar) and August (High Wind). As can be observed:

- The western region exports on an average 23GW and 29GW to its neighboring regions in the months of April and August respectively (Case-1). With transmission limits simulated in Case-3, the exports drop to around 20.9GW and 23.9GW in the months of April and August respectively.
- The southern region imports around 10GW in April and 7GW in August per copper sheet simulation (Case-1). The import is 10GW and 9GW in the same months under Case-3. High wind generation in August reduces the need to import power form neighboring regions. During high renewable penetration, there are significant hours when southern region exports to western and eastern regions.
- Northern region is a net importer. The average import during high RE penetration especially the month of April (high solar) is 18.7GW as compared to the 29GW and 27GW during February and October in Case-1 simulations. Considering the transmission limits (Case-3) simulations, the import reduces to 15.6GW in April and to 17.8GW and 22GW in February and October. High Solar installations as per MNRE targets in northern region impacts the net imports in the month of April.

Figure 58 to Figure 62 in the following section present the details on the inter-regional power transfer for hourly basis. Further, Figure 63 presents the summary of inter-regional transfer for 2022.

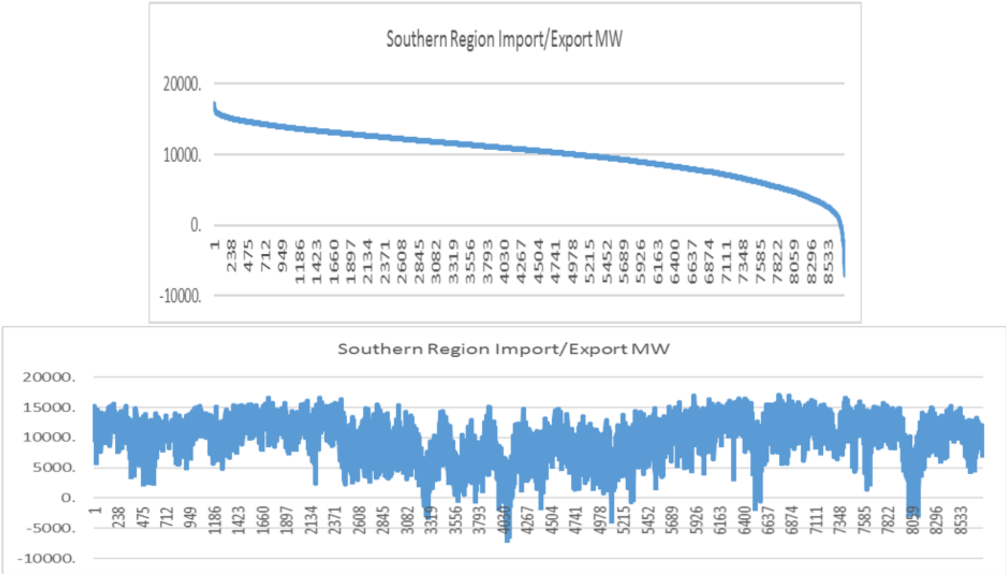


Figure 58: Southern Region Import/Export in 2022

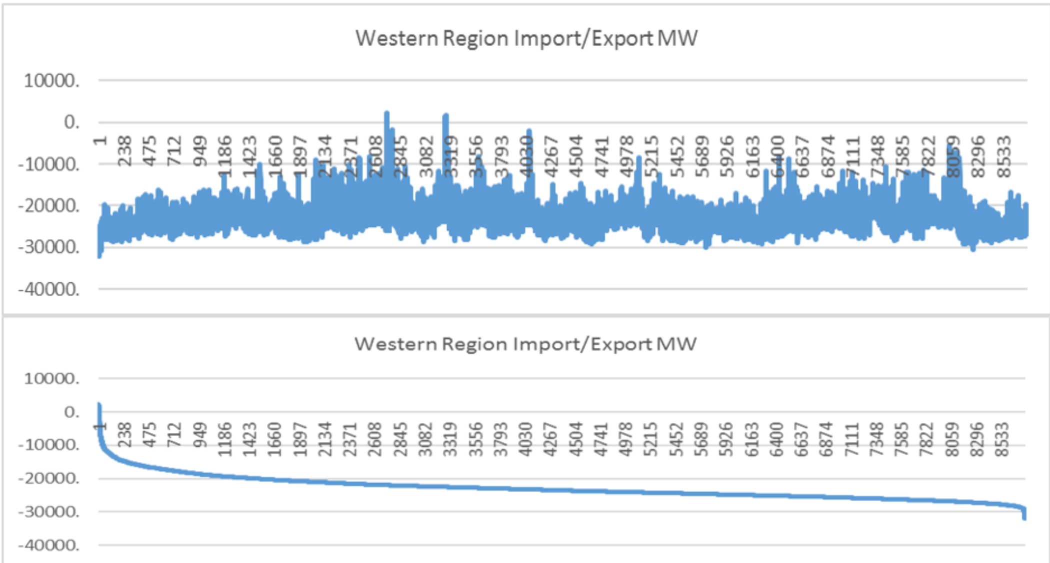


Figure 59: Western Region Import/Export in 2022

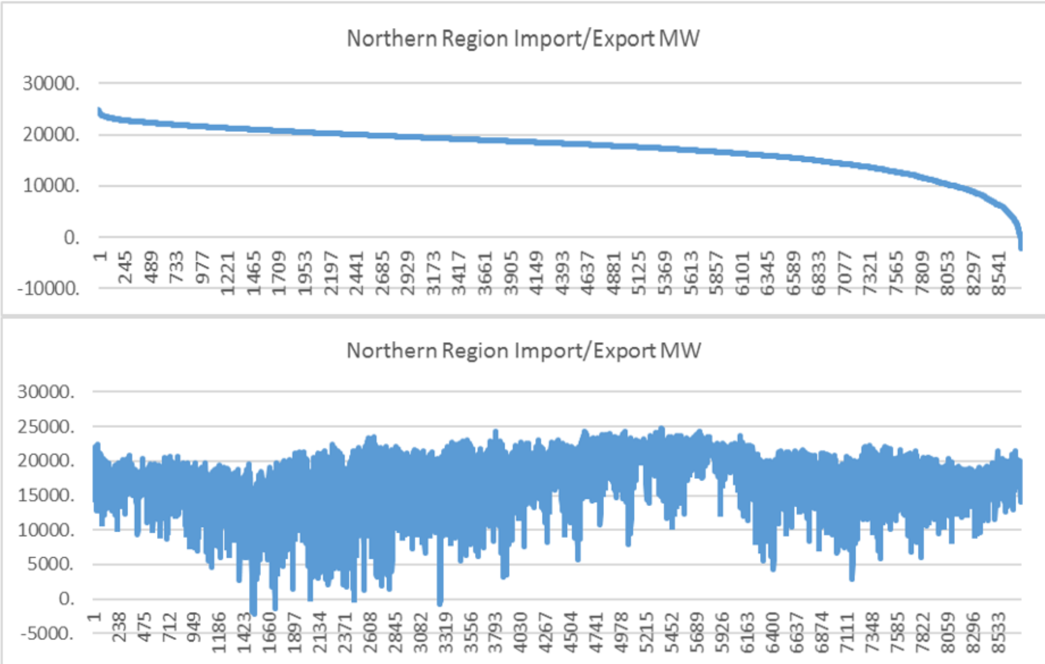


Figure 60: Northern Region Imports/Exports in 2022

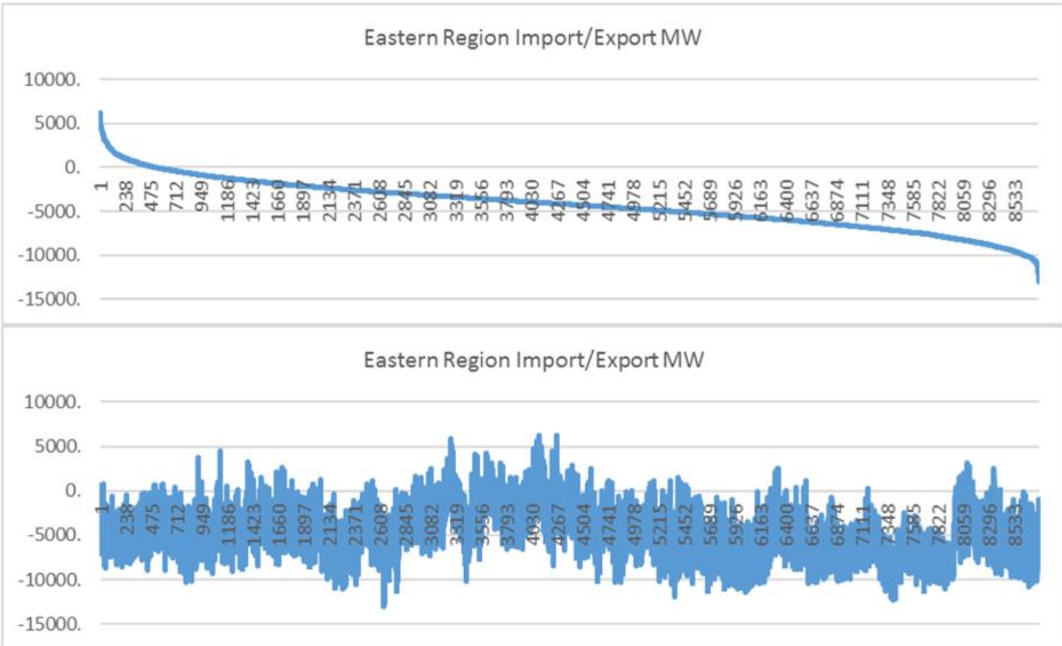


Figure 61: Eastern Region Imports/Exports in 2022

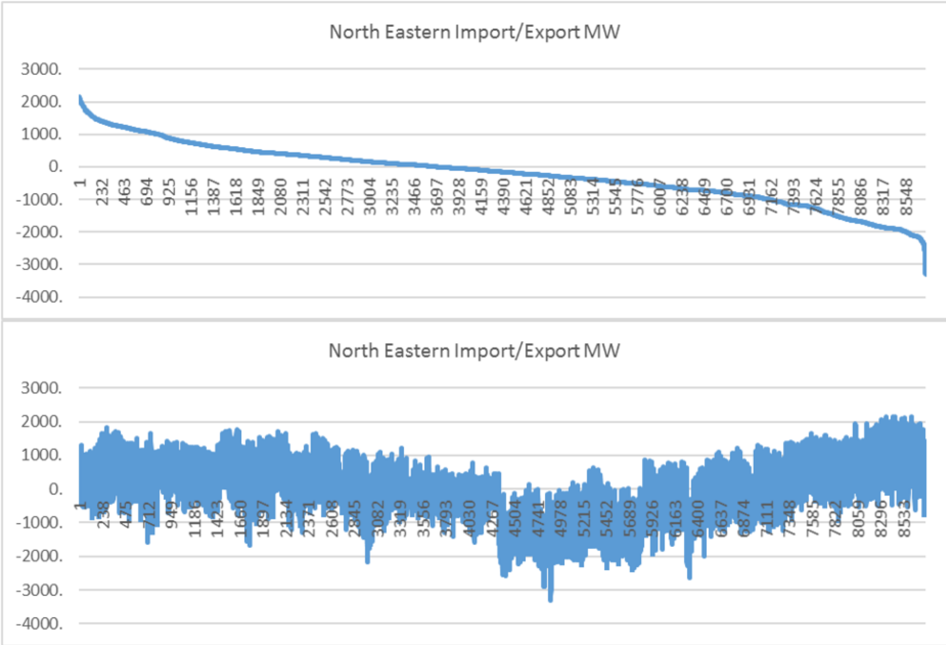


Figure 62: North-eastern Region Import/Export in 2022

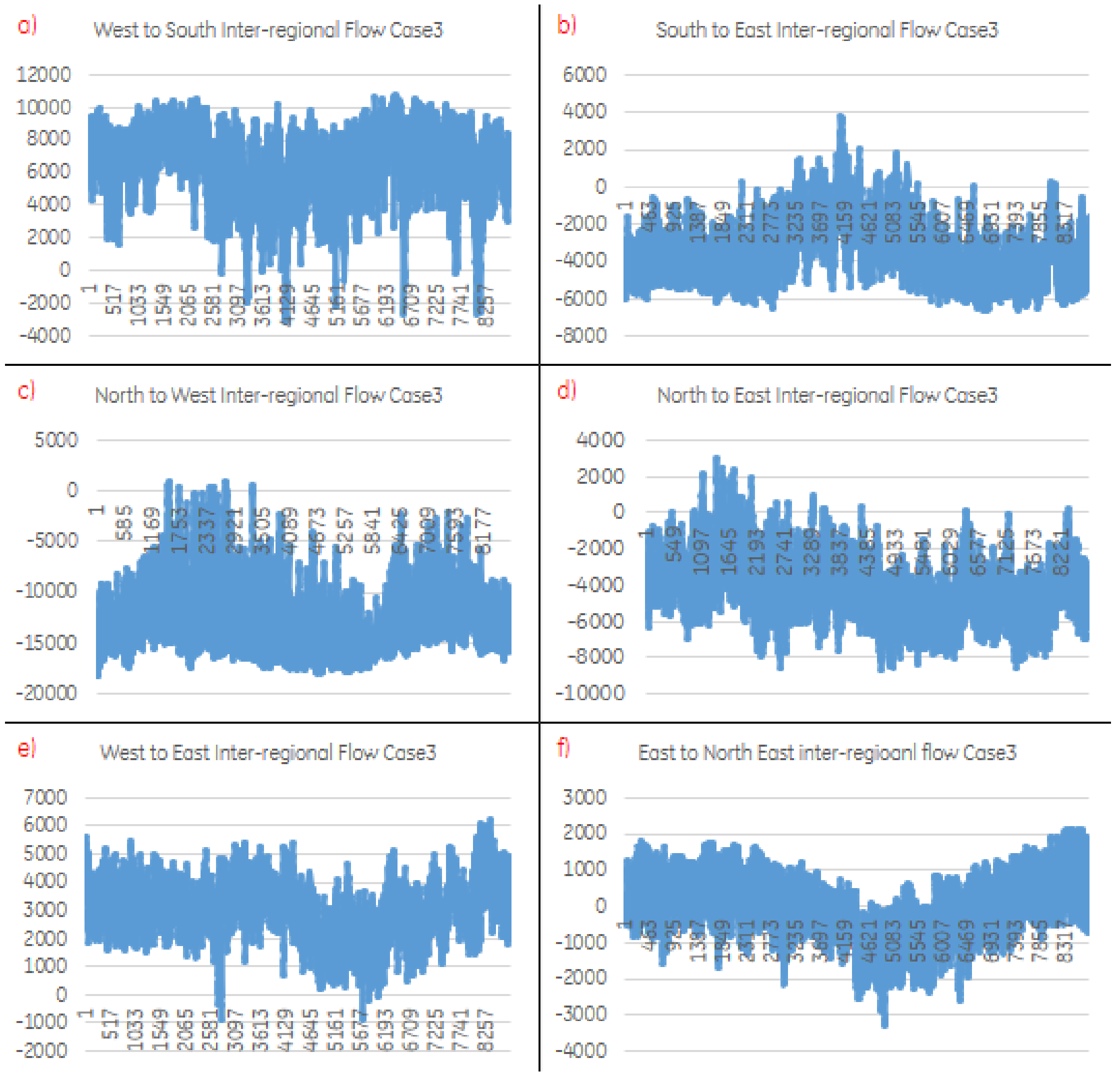


Figure 63: Inter-regional transfer of Power - 2022

As observed from Figure 58 to Figure 62:

- Southern Region is a net importer with significant exports occurring during the High wind and solar months, exporting a maximum of ~7GW to eastern and western regions. Maximum import during the high demand months is ~17GW. Despite significant capacity addition within the region, demand growth by 2022 requires southern region to be a net importer from the western and eastern region.
- Western Region is a net exporter to the other regions in the Indian grid. Majority of exports are to the northern region. Western Region imports power from southern region (MAX ~3GW) and eastern region (MAX ~0.9GW) during periods of high renewable penetration.
- Northern region is a net importer in the system. The region has one of the highest demand in 2022 in the Indian system with the third highest capacity installations. Northern region is connected to the western and eastern regions. The region predominantly imports power from the western region. The system imports a maximum of 24.8 GW in the 2022 simulation.
- Eastern Region is a net exporter in the 2022 simulation, predominantly exporting to the Southern and the northern regions. There is an exchange in power between western

(imports a maximum of ~6.2 GW) and north-eastern regions. The region does receive imports (Max ~3.8GW) from the southern region during period of high renewable penetration in the Southern Region.

- North Eastern region is predominantly Hydro based. Exports and imports are dictated by the availability of Hydro generation in the region. The region is connected to the rest of the country through the eastern region.

Summary of inter-regional Power Flows:

(i). The Southern region exports power to eastern region during periods of high renewable generation. Western region is a net exporter to all regions it is connected to. Northern region is a net importer.

(ii). Western region exports power to Southern throughout the year and exports a maximum of ~10GW in the month of September (Figure 63 (a)&(b)). Western region does import power from southern region, maximum import ~3GW during high RE periods. Southern region exports power to eastern region, a maximum export of ~3.7 GW during high RE period of June-July and imports a maximum of ~6.6 GW during high demand period of October.

(iii). Northern region imports power from western region throughout the year. Northern region imports a maximum of 18 GW from western region and 8 GW from the eastern region (Figure 63 (c)&(d)). The region is dependent on imports for meeting demand and imports from southern region during high wind season and from the eastern region during the summer season of April. Exports to eastern region is a maximum of 6 GW during high demand periods in the eastern region.

(iv). The north-east region is hydro rich and is connected to the rest of the Indian grid through eastern region. The North-eastern region exports a maximum of 3 GW to the eastern region especially during periods of high hydro generation. The region imports a maximum of 2 GW from eastern region (Figure 63 (f)).

7.2 OPERATIONAL ANALYSIS FROM ALL INDIA MAPS MODEL – RESULTS

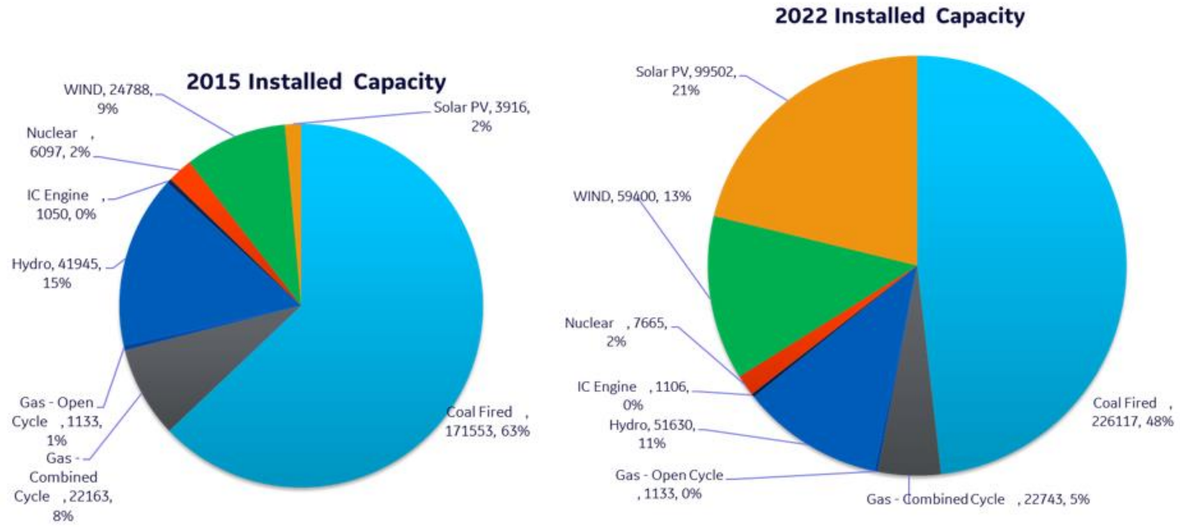


Figure 64: All India Installed Capacity - 2015 and 2022

The total installed capacity on All India basis is considered as 469 GW by 2022 in the MAPS Model (Figure 64). Out of this capacity, the coal based capacity will make up 48% of the total installed capacity, with only minor gas capacity additions by 2022 (if at all). As per the MNRE targets of renewable capacity (wind and solar) RE capacity will be the second largest installed capacity by 2022 making up 34% followed by Hydro (11%).

7.2.1 OVERALL SYSTEM PERFORMANCE FOR 2022 V/S 2015

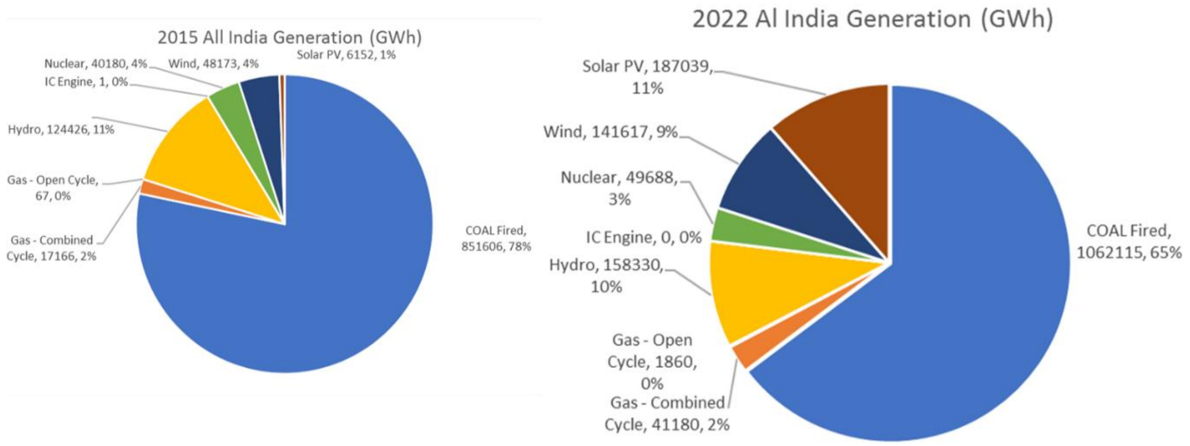


Figure 65: All India Energy Generation - 2015 and 2022

As observed from Figure 65, there is a reduction in contribution of coal generation in the grid and an increase in RE generation from 2015 to 2022, due to addition of RE capacity (160 GW) as per MNRE renewable energy targets by 2022. Gas unit contribution remains at similar levels in the generation mix.

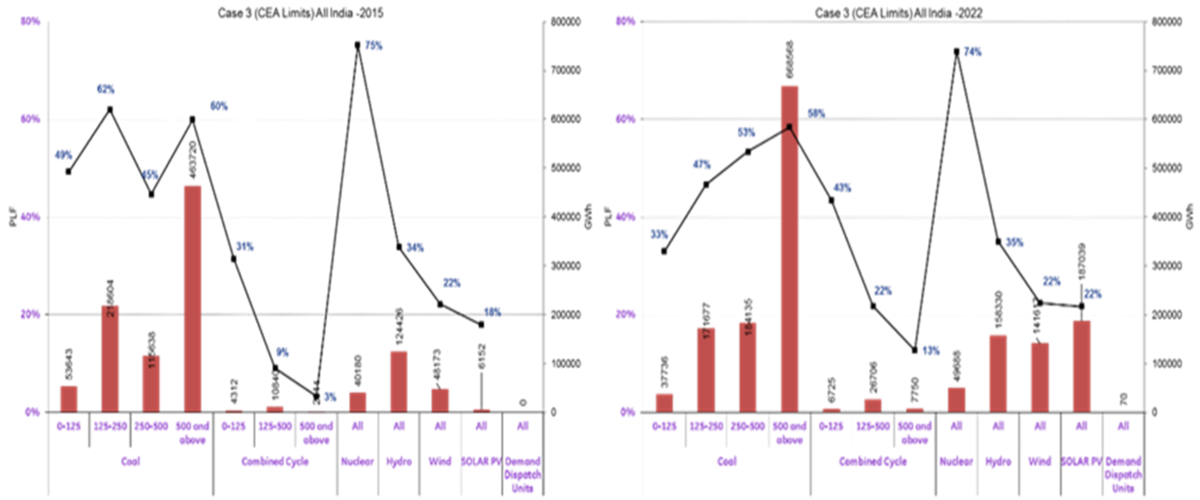


Figure 66: All India PLF and Generation as per Case-3

Figure 66 depicts the change in Plant Load Factors (PLF) and generation of power stations between 2015 to 2022. Critical coal plants will increase the generation in 2022 due to demand growth. Addition of wind and solar capacity increases contribution of RE generation in the generation mix. Increase in demand in all regions requires gas units to increase their generation in the system.

7.2.2 IMPACT OF RE & TRANSMISSION LIMITS ON PRODUCTION COST

Table 26 depicts the production cost comparison between 100% of targeted RE additions in 2022 (Case-1) and no RE additions beyond 2015 (Case-1B). The results show a reduction in production costs by 0.63 Rs/kWh due to the impact of RE capacity additions.

Region	Case-1 (100% RE additions)		Case-1B (0% RE additions)	
	Rs Crores	**Rs/kWh**	**Rs Crores**	**Rs/kWh**
Eastern Region	60300	2.85	75282	3.31
North Eastern Region	4268	1.25	4534	1.37
Northern Region	56268	1.63	86793	2.48
Southern Region	50330	1.50	71894	2.45
Western Region	148579	2.08	184484	2.50
All India	319744	1.95	422987	2.58

Table 26: Production Cost Comparison between Case-1 & Case-1B

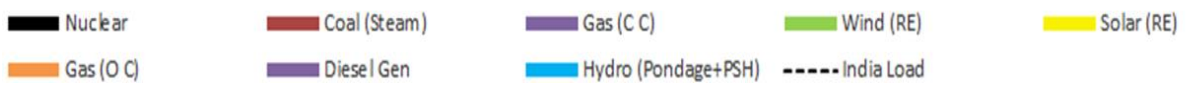
Impact of transmission limits and wheeling charges are shown in Table 27. By imposing a wheeling charge of 25$/MWh (~1.5 Rs/kWh) results in increase in production cost by 1 paise/ kWh between Case-1 and Case-2. Regions such as western region which is a major exporter, observes a drop-in production costs due to the reduced generation of its units to export power to its neighbors. Regions such as south and north must depend on their own generating stations to meet demand as the cost of importing power becomes more expensive with the introduction of a wheeling charge. With the inclusion of inter-regional transmission limits (as per CEA planning 2016-2035 document) sees an increase in production costs by 3 paise/kWh between Case-1 and Case-3.

Region	Case-1		Case-2 – Case-1 with 25$/MWh wheeling charge		Case-3 (CEA Limits)	
	Rs Crores	Rs/kWh	Rs Crores	Rs/kWh	Rs Crores	Rs/kWh
Eastern Region	60300	2.85	59996	2.84	61495	2.88
North Eastern Region	4268	1.25	4294	1.26	4262	1.25
Northern Region	56268	1.63	70033	1.86	77281	1.99
Southern Region	50330	1.50	56659	1.6	50305	1.50
Western Region	148579	2.08	130667	1.96	132203	1.97
All India	319744	1.95	321650	1.96	325546	1.98

Table 27: Impact of Transmission limits and Wheeling Charges

7.2.3 DISPATCH SIMULATION

Dispatch stack (generation) for all India is shown in Figure 67 to Figure 70 for four representative days in the month of February (low demand), April (high Solar), July (high wind) and October (high demand) respectively. Due to increased penetration of wind and solar by 2022, it is expected that the net load requirements would have a high ramp up and ramp down rate primarily due to the increase/decrease in RE generation (solar). Gas based plants such as the combined cycle units would be of importance during the initial period of ramp up requirement in view of the longer start up time for the coal plants.



7.2.3.1 LOW DEMAND

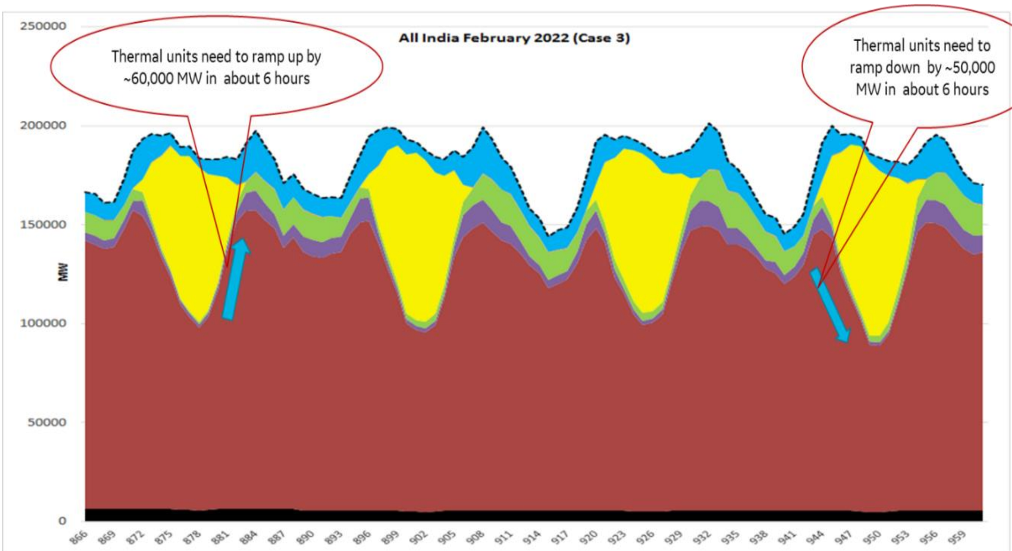


Figure 67: All India Dispatch for February 2022 (Case-3)

High ramp up and ramp down requirements for thermal units due to the impact of solar generation. Solar generation in the northern and southern regions requires ramping of thermal units to meet demand (Figure 67).

7.2.3.2 HIGH SOLAR

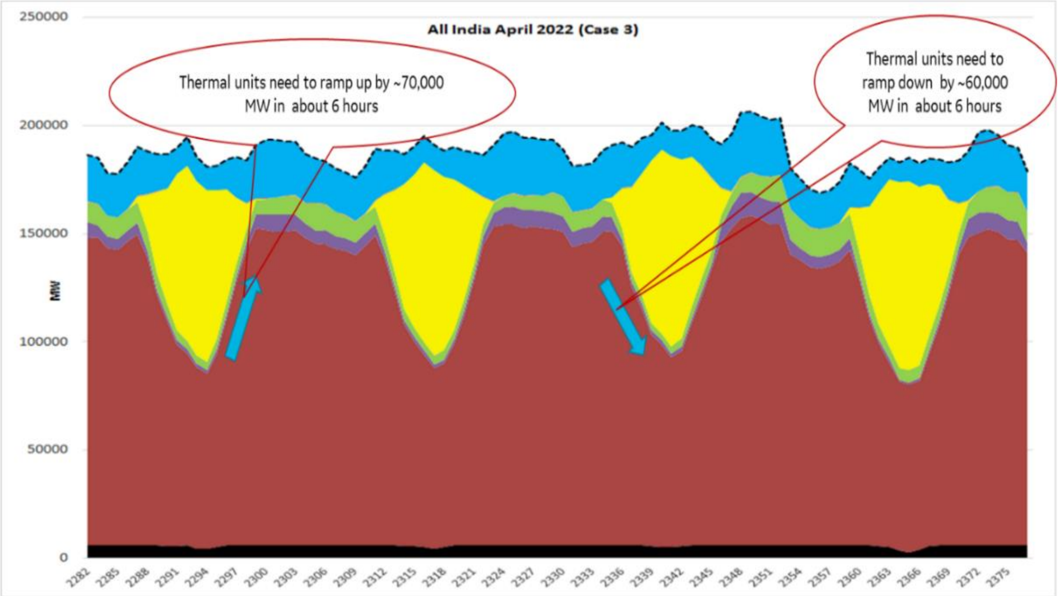


Figure 68: All India Dispatch for April 2022 (Case-3)

As observed in Figure 68, high solar generation increases the ramping requirements of thermal units. Solar generation in the northern and southern regions increases ramping requirements along with increased import requirements in the southern region increases the ramping requirements in the exporting regions (west and eastern regions).

7.2.3.3 HIGH WIND

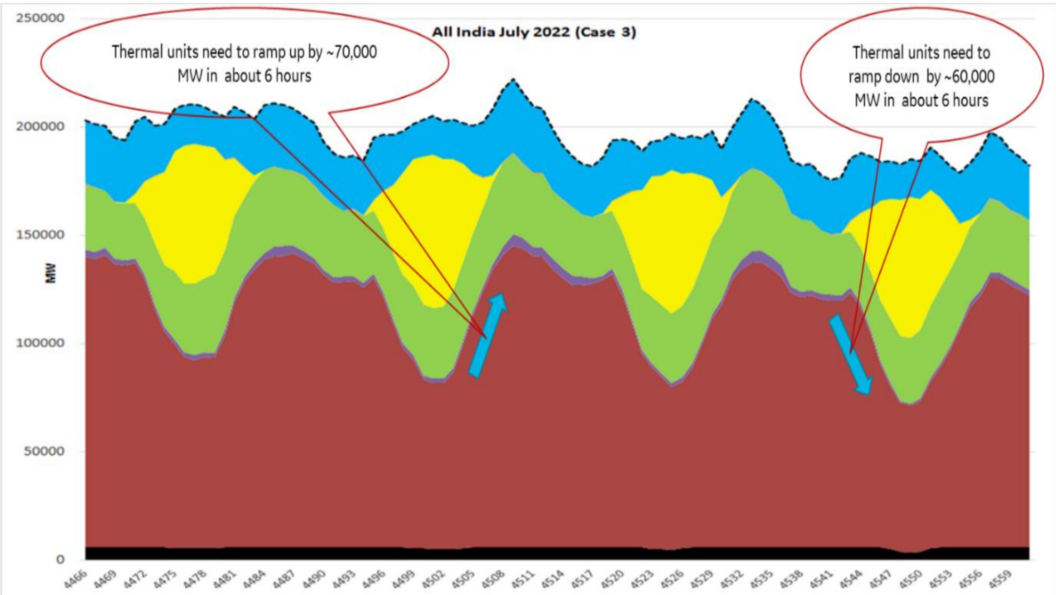


Figure 69: All India Dispatch for July 2022 (Case-3)

Similar to the observations in case of high solar, high wind generation increases ramping requirements of thermal units (ramp up of ~70,000 MW in 6hrs) to ~10500 MW ramp up every hour vs 10000 MW ramp down requirement (~60,000 MW in 6hrs). High wind generation in the western and southern regions contributes to the ramping requirements of thermal units in the region.

7.2.3.4 HIGH DEMAND

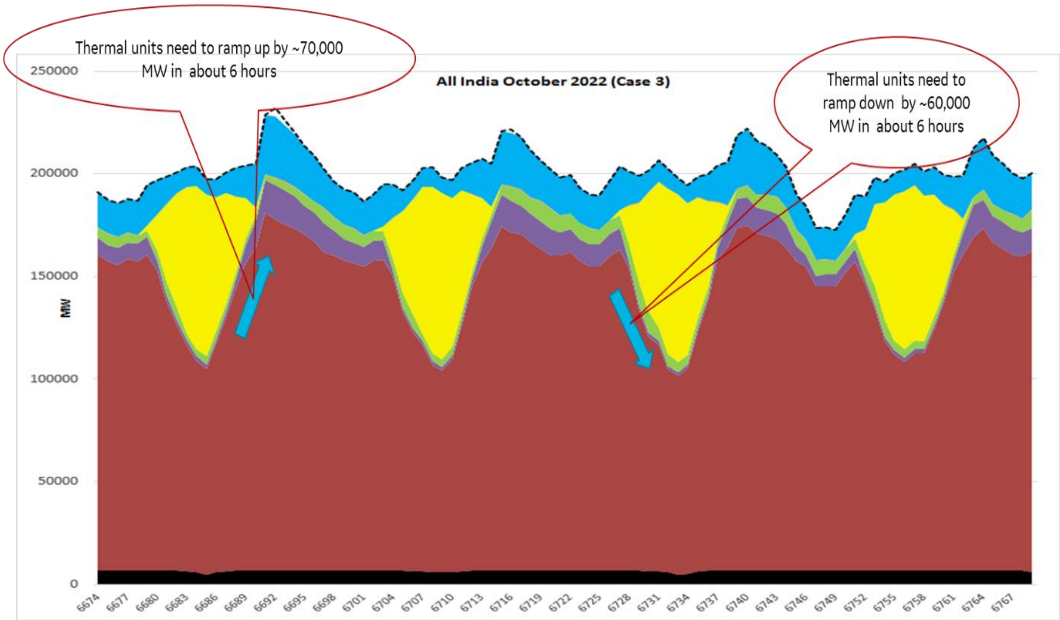
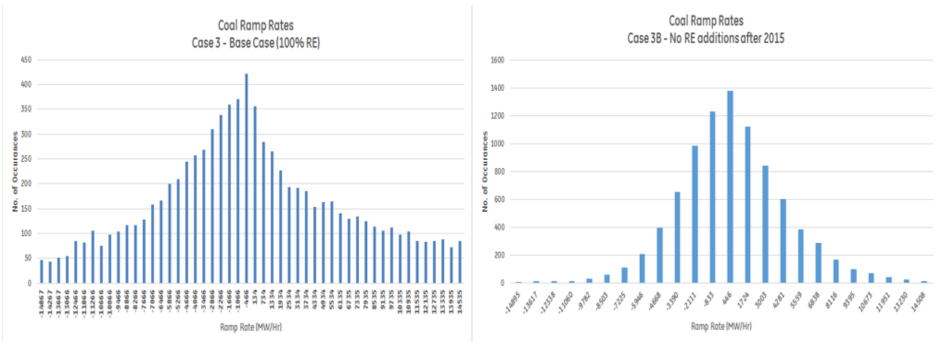


Figure 70: All India Dispatch for October 2022 (Case-3)

Ramping requirements for thermal units lie in the range of 10,000MW per hour due to high demand across all regions in the Indian grid (Figure 70). Solar generation contributes to the ramping requirements of thermal plants.

7.2.4 THERMAL PLANT OPERATIONS IN 2022 VS 2015 – RAMP RATES

Ramp up requirement for coal plants reduces significantly due to the absence of the full renewable capacity as per MNRE targets. With only the existing renewable capacity available (Case-3B) there is lower variation of thermal generation as the renewable generation is lower in the system mix as seen in Figure 71.



Ramp Rate Requirement – Events Case3		
Ramp Up	Greater than 5000 MW/Hr.	2141
Ramp Down	Greater than -5000 MW/Hr.	2025

Ramp Rate Requirement – Events Case3B		
Ramp Up	Greater than 5000 MW/Hr.	1104
Ramp Down	Greater than -5000 MW/Hr.	453

Figure 71: Ramp Rates for Coal Plants - 2022 (Case-3)

8 MULTI AREA RELIABILITY SIMULATION (MARS) MODEL – ALL INDIA

8.1 SIMULATION RESULTS FOR 2022

Results of MARS cases mentioned in Section 5.2 are discussed in this section. Results of Case-1 and Case-2A are discussed in detail. Cases 1B and 2B are used in estimation of capacity value of RE in Indian grid and are considered in the section of 'Capacity Value of RE'.

Though MARS has an ability to calculate reliability indices (LOLE, LOEE etc.) for each area on isolated basis; in this section LOLE calculation results are represented only on interconnected basis.

8.1.1 TRANSMISSION ADEQUACY ASSESSMENT

This is the case for transmission adequacy evaluation. For the case under consideration, transmission constraints are as per CEA limits for inter-regional and intra-region connections. 100% RE capacity in 2022 (160GW – Wind + Solar) is considered. The purpose of this case is to compute LOLE, inter-regional maximum flows and the number of limiting hours for all cases. LOLE values are shown in Table 28 to Table 31. Key observations from results are:

- LOLE values seen in Goa and UT mainly due to transmission limitations
- Kerala and Tamil Nadu have reliability issues for <10% time annually in southern region
- LOLE values seen in northern region mainly in the state of J&K
- Eastern and NE regions have surplus capacity; thus, no LOLE values are indicated

WESTERN REGION States	Interconnected				
	LOLE (Days / year)	LOLE (Hours/year)	LOEE (MWh/year)	Frequency (outage/ year)	Duration (Hours / outage
MAHARASHTRA	0	0	0	0	0
GUJARAT	0	0	0	0	0
MADHYA PRADESH	0	0	0	0	0
CHHATTISGARH	0	0	0	0	0
GOA	128	269	9859	108	2
UNION TERRITORY WEST	17	12	44	12	1
WESTERN REGION	139	280	9904	118	2

Table 28: Case-1 results for Western region

SOUTHERN REGION States	Interconnected				
	LOLE (Days / year)	LOLE (Hours/year)	LOEE (MWh/year)	Frequency (outage/ year)	Duration (Hours / outage
KARNATAKA	0	**0**	0	0	0
ANDHRA PRADESH	0	**0**	0	0	0
TELENGANA	0	**0**	0	0	0
KERALA	44	**694**	240514	207	3
TAMIL NADU	39	**358**	422054	105	3
SOUTHERN REGION	44	**694**	662568	207	3

Table 29: Case-1 results for Southern Region

NORTHERN REGION States	Interconnected				
	LOLE (Days / year)	LOLE (Hours/year)	LOEE (MWh/year)	Frequency (outage/ year)	Duration (Hours /outage
UTTAR PRADESH	0	**0**	0	0	0
RAJASTHAN	16	**37**	20253	25	2
PUNJAB	42	**281**	152490	69	4
HARYANA	33	**166**	96051	44	4
UTTARAKHAND	0	**0**	0	0	0
DELHI	37	**195**	74447	50	4
HIMACHAL	0	**0**	0	0	0
JAMMU & KASHMIR	182	**2413**	1532882	241	10
NORTHERN REGION	196	**2588**	1876123	264	10

Table 30: Case-1 results for Northern Region

EASTERN REGION States	Interconnected				
	LOLE (Days / year)	LOLE (Hours/year)	LOEE (MWh/year)	Frequency (outage/ year)	Duration (Hours / outage
WEST BENGAL	0	**0**	0	0	0
BIHAR	0	**0**	0	0	0
JHARKHAND	0	**0**	0	0	0
ODISHA	0	**0**	0	0	0
SIKKIM	0	**0**	0	0	0
EASTERN REGION	0	**0**	0	0	0

Table 31: Case-1 results for Eastern Region

Figure 72 shows the regional links (Northern and Western regions) where flows are getting limited. Majority of the power flows between the states of Gujarat - Rajasthan and Gujarat – Haryana in Northern and Western region. Lines highlighted in RED had limiting flows for more than 10% of time in a year.

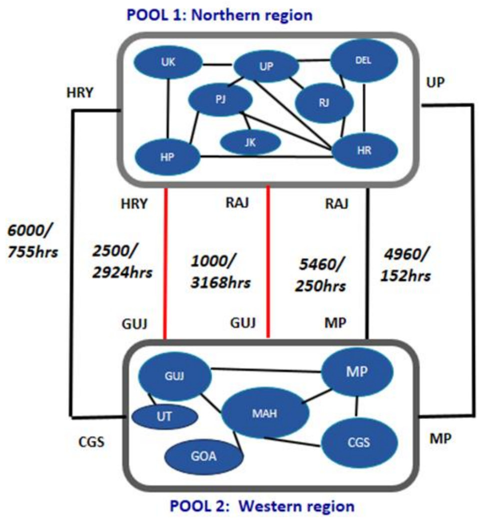


Figure 72: Inter region limiting hours for regional links (Values: Line capacity/hours limited)

Figure 73 shows the hours for which interstate transmission lines in Northern region are limited or hitting the higher limit (line rating) in terms of flows.

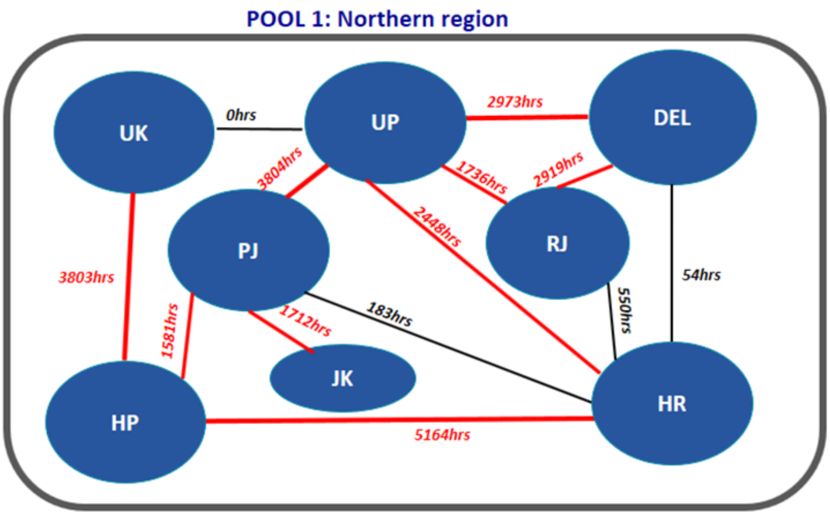


Figure 73: Inter-state limiting hours for Northern region

For this case:

- The Inter region transmission capacity is based on the CEA 20-year (2016-36) Perspective Transmission planning report.
- Inter-state limits are as per power flow simulation results for 2021-22 from the CEA planning report

8.1.2 GENERATION ADEQUACY ASSESSMENT

This is the case for generation adequacy evaluation. For the case under consideration, transmission constraints are as per CEA limits for inter-regional and intra-region connections. 70% RE capacity in 2022 is considered. The purpose of this case is to compute LOLE, inter-regional maximum flows and the number of limiting hours for all cases if partial RE installation target is achieved. LOLE values are shown in Table 32 to Table 35. Key observations from results:

- LOLE values seen in Goa and UT mainly due to transmission limitations
- Kerala and Tamil Nadu have reliability issues, LOLE values higher than in Case-1 due to lower RE levels
- LOLE values seen in northern region mainly in the state of J&K
- Eastern and NE regions have surplus capacity; thus, no LOLE values are indicated

WESTERN REGION States	Interconnected				
	LOLE (Days / year)	LOLE (Hours/year)	LOEE (MWh/year)	Frequency (outage/ year)	Duration (Hours / outage
MAHARASHTRA	0	**0**	0	0	0
GUJARAT	0	**0**	0	0	0
MADHYA PRADESH	0	**0**	0	0	0
CHHATTISGARH	0	**0**	0	0	0
GOA	128	**281**	10387	112	3
UNION TERRITORY WEST	18	**12**	48	12	1
WESTERN REGION	140	**292**	10435	122	2

Table 32: Case-2A results for Western region

SOUTHERN REGION States	Interconnected				
	LOLE (Days / year)	LOLE (Hours/year)	LOEE (MWh/year)	Frequency (outage/ year)	Duration (Hours / outage
KARNATAKA	0	**0**	0	0	0
ANDHRA PRADESH	0	**0**	0	0	0
TELENGANA	0	**0**	0	0	0
KERALA	52	**790**	280787	225	4
TAMIL NADU	46	**480**	537537	134	4
SOUTHERN REGION	52	**790**	818324	225	4

Table 33: Case-2A results for Southern Region

NORTHERN REGION States	Interconnected				
	LOLE (Days / year)	LOLE (Hours/year)	LOEE (MWh/year)	Frequency (outage/ year)	Duration (Hours /outage
UTTAR PRADESH	0	**0**	0	0	0
RAJASTHAN	16	**44**	24015	27	2
PUNJAB	42	**294**	159434	69	4
HARYANA	33	**169**	97457	45	4
UTTARAKHAND	0	**0**	0	0	0
DELHI	37	**200**	75729	52	4
HIMACHAL	0	**0**	0	0	0
JAMMU & KASHMIR	183	**2641**	1667129	211	13
NORTHERN REGION	197	**2829**	2023763	235	12

Table 34: Case-2A results for Northern Region

EASTERN REGION States	Interconnected				
	LOLE (Days / year)	LOLE (Hours/year)	LOEE (MWh/year)	Frequency (outage/ year)	Duration (Hours / outage
WEST BENGAL	0	**0**	0	0	0
BIHAR	0	**0**	0	0	0
JHARKHAND	0	**0**	0	0	0
ODISHA	0	**0**	0	0	0
SIKKIM	0	**0**	0	0	0
EASTERN REGION	0	**0**	0	0	0

Table 35: Case-2A Results for Eastern Region

Figure 74 shows the regional links (Northern and Western regions) where flows are getting limited. Majority of the power flows between the states of Gujarat - Rajasthan and Gujarat – Haryana in Northern and Western region. Lines highlighted in RED had limiting flows for more than 10% of time in a year.

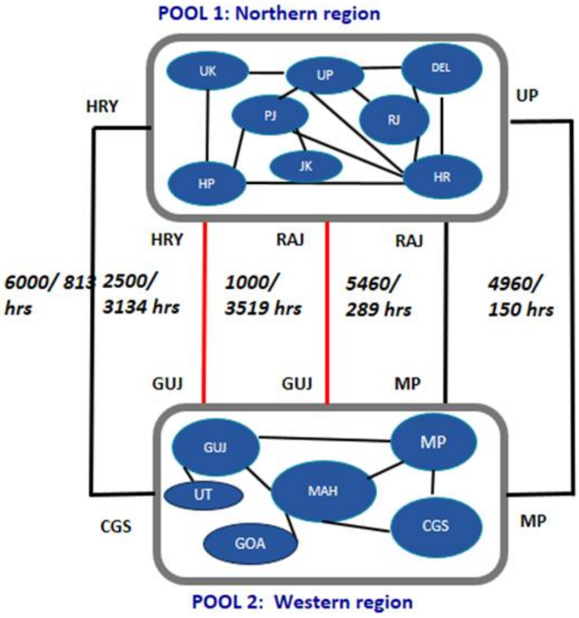


Figure 74: Inter region limiting hours for regional links (Values: Line capacity/hours limited)

Figure 75 shows the hours for which interstate transmission lines in Northern region are limited or hitting the higher limit (line rating) in terms of flows.

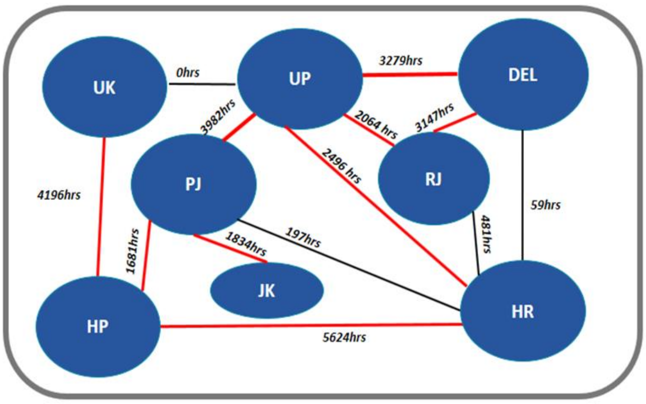


Figure 75: Inter-state limiting hours for Northern region

For this case:

- The Inter region transmission capacity is based on the CEA 20-year (2016-36) Perspective Transmission planning report.
- Inter-state limits are as per power flow simulation results for 2021-22 from the CEA planning report

8.2 CAPACITY VALUE OF RE FOR 2022

Capacity value and LOLE are the main indicators of reliability of the system in this study. As per CEA standard, recommended (design) value of LOLE is 0.2% time of the year or 17.5 hrs./year. For rest of the year, system should maintain reliability i.e. load – generation balance should be maintained. However, it is to be noted that, in this study transmission aspect is also considered along with load-generation. Thus, reliability is dependent on generation as well as transmission system availability.

In the previous sections of the report, LOLE analysis was discussed; this section describes the concept of capacity value, calculation methodology and key findings.

'Capacity factor' and 'Capacity value' are the two common terms used in renewable energy domain to describe renewable resources. However, it is to be noted that both terms are distinct. Definitions of both terms are given below:

- → Capacity value is the contribution of renewable generation to resource adequacy and generally depends on its output during the riskiest hours of the years
- → Capacity factor is the measure of average renewable generation and depends on its output throughout the year

Thus, two terms may not be used interchangeably.

The capacity of a system to reliably serve its load can be quantified through resource adequacy studies. Capacity value is the contribution of any resource in the system to meet that goal and maintain a reliable supply of power.

The key difference in the capacity value evaluation of thermal generation and RE generation is explained in following points:

- → Thermal generation is available (in terms of capacity) throughout the year. Fuel supply, planned maintenance periods and forced outages (based on historical events) can be used to define availability of thermal generation correctly to moderate accuracy levels. Thus, capacity value estimation for such generation resources is not complicated.
- → Renewable resources generation (wind and solar) is intermittent as it depends on weather conditions (wind speed and solar radiations). Thus, RE resource nameplate capacity might rarely be fully available to contribute to resource adequacy.

In this study, capacity value estimation considers wind and solar generation profiles for a year. However, RE generation during peculiar hours influences the capacity value findings. These are the hours where system is at the risk of loss of load and these hours usually corresponds to net load (load minus RE generation)

8.2.1 METHODOLOGY FOR CAPACITY VALUE CALCULATION

This study uses the method of 'perfect capacity' addition to calculate capacity value of RE generation. Perfect capacity is defined as "availability of a firm and consistent amount of capacity for every hour in the year".

The procedure followed to estimate capacity value is explained in brief:

- The LOLE of the system is calculated without any RE resource. It is called as LOLE1 of the base system.
- LOLE of the system is calculated with RE resources in the system (LOLE2)
- All RE resources are removed in the system and fraction of 'perfect capacity' is added to system; LOLE 3 is noted.
- Above step is repeated for several perfect capacities and subsequent LOLE 4, LOLE 5, LOLE 6 are noted.
- A graph is plotted for perfect capacity Vs corresponding LOLE values.
- LOLE2 is located on this graph; corresponding perfect capacity is also noted down.
- The capacity value of RE resource is –

  (perfect capacity as found in above step) / (RE capacity)

Graphical representation of the methodology is shown in Figure 76. Example illustrates estimation of capacity value for 300 MW of wind. Base case LOLE is 1.27 days/year. Perfect capacities are added (with no RE) in the steps of 100 MW and resulting LOLEs are plotted as shown. 1.27 days is located on the graph. With the corresponding value of perfect capacity on x-axis, capacity value of wind is estimated as 19%.

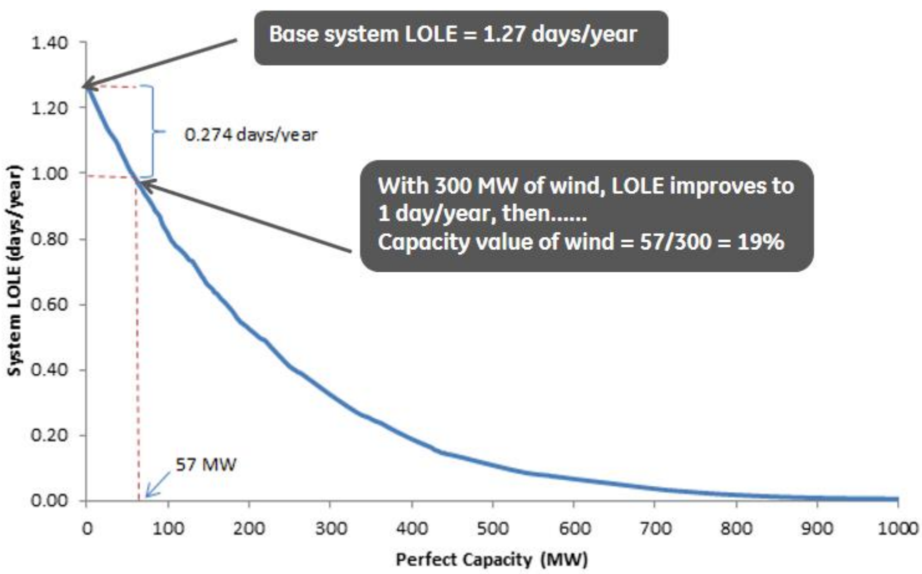


Figure 76: Calculation methodology of Capacity value of Wind

9 KEY FINDINGS AND CONCLUSIONS

9.1 GE MAPS RESULTS

The results from the MAPS analysis are given in the following sections.

9.1.1 OPERATIONAL STUDY, GENERATION

Southern Region

Southern region remains a net importer in 2022 MAPS simulations. In 2015, combined wind and solar capacity was 11 GW and 54 GW by 2022 (as per MNRE targets). Such large addition of renewable capacity will have a significant impact on the region’s thermal operations:

- In 2015, critical coal plants are operating with a PLF of ~61%, which significantly drops to ~46% in 2022 due to increased RE generation as seen in Figure 77**.** The average operating hours per start drops from 1230 hours to 114 hours during the same period indicating a shift from base load to mid merit operations.
- Gas plants experience a slight increase in PLF and cyclical operations due to higher ramping requirements, the average number of starts increasing from ~2/month to ~9/month as seen in Figure 78.

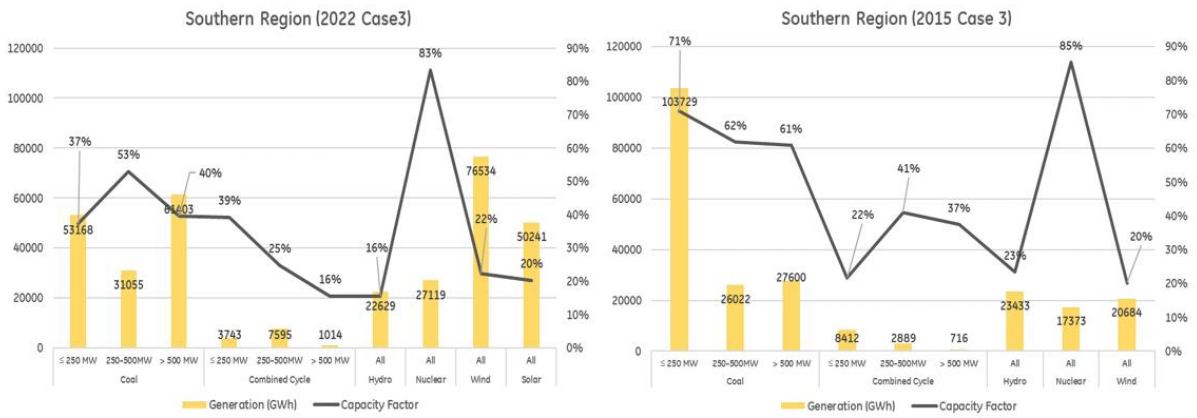


Figure 77: Southern Region Generation and Capacity Factor Comparison - 2015 vs. 2022

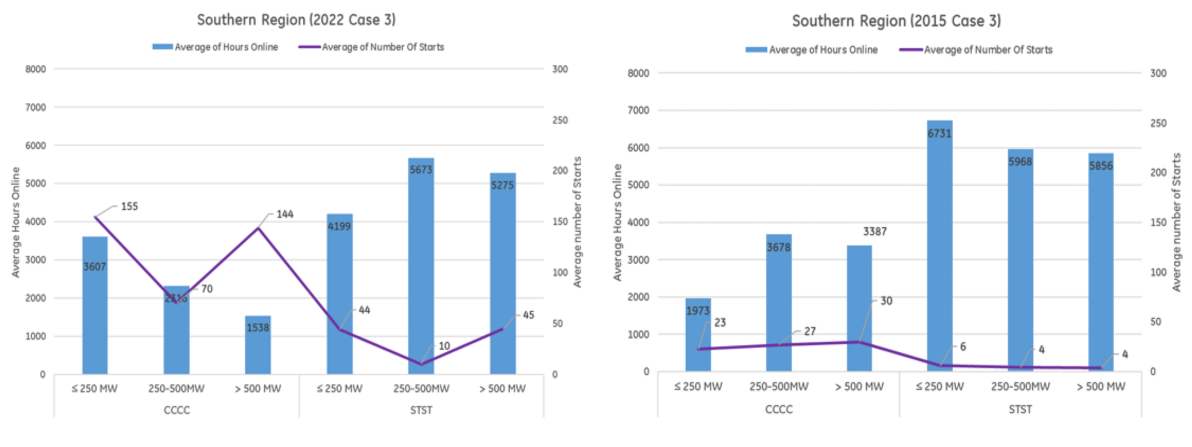


Figure 78: Southern Region Thermal Units Starts & Hours online Comparison - 2015 vs. 2022

Western Region

Western region remains a net exporter in 2022 simulations. In 2015, combined wind and solar capacity was 12 GW and 51 GW by 2022 (as per MNRE targets).

The regions critical coal units operate at high PLF's as shown in Figure 79. The average operating hours per start increases from 422 hours to 644 hours. High RE installations in the region, do not negatively impact coal plant operations (Figure 80). Coal units in western region are the most cost competitive in the Indian region.

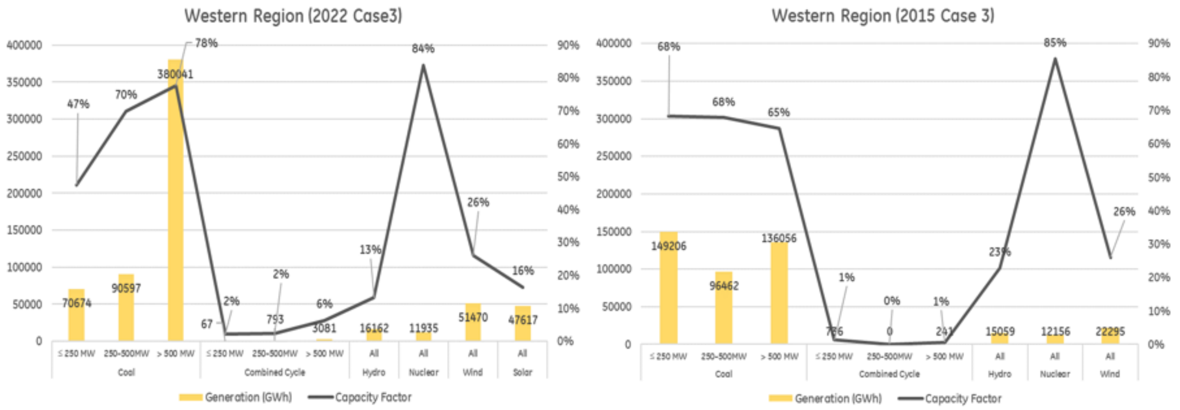


Figure 79: Western Region Generation and Capacity Factor Comparison - 2015 vs. 2022

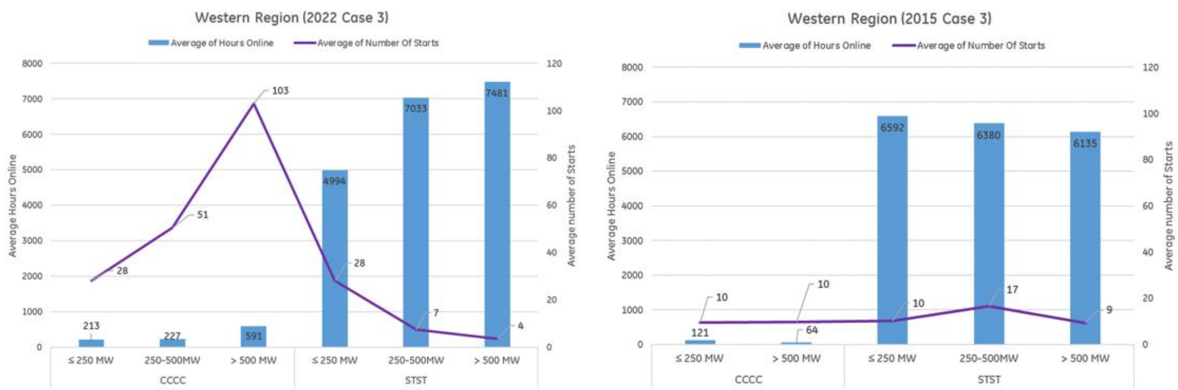


Figure 80: Western Region Thermal Units Starts & Hours online Comparison - 2015 vs. 2022

Northern Region

Northern region remains a net importer in 2022 simulations. In 2015, combined wind and solar capacity was 5 GW and 39 GW by 2022 (as per MNRE targets). Majority of RE additions in the region are solar but there is wind capacity planned only in the state of Rajasthan:

- Critical coal units operate at higher PLF both in 2015 and 2022 and an increased contribution of gas based units in meeting the high demand in 2022 as shown in Figure 81. The average operating hours per start drops from 210 hours to 146 hours during the same period indicating a shift from base load to mid merit operations.
- Increased variation in renewable generation impacts gas units to assist in ramping requirements for regional demand variation. The average number of starts increase to

~21/month whereas in the 2015 simulation gas units do not contribute significantly to regional demand (Figure 82).

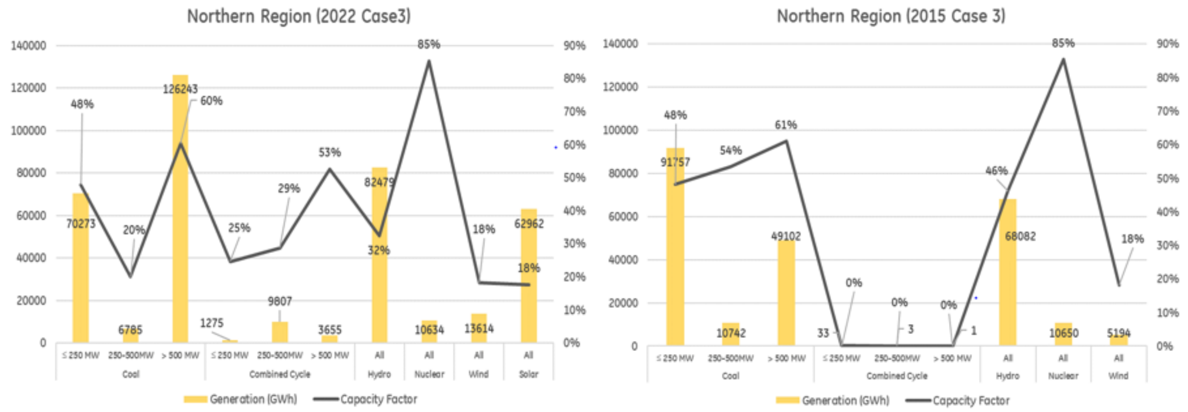


Figure 81: Northern Region Generation and Capacity Factor Comparison - 2015 vs. 2022

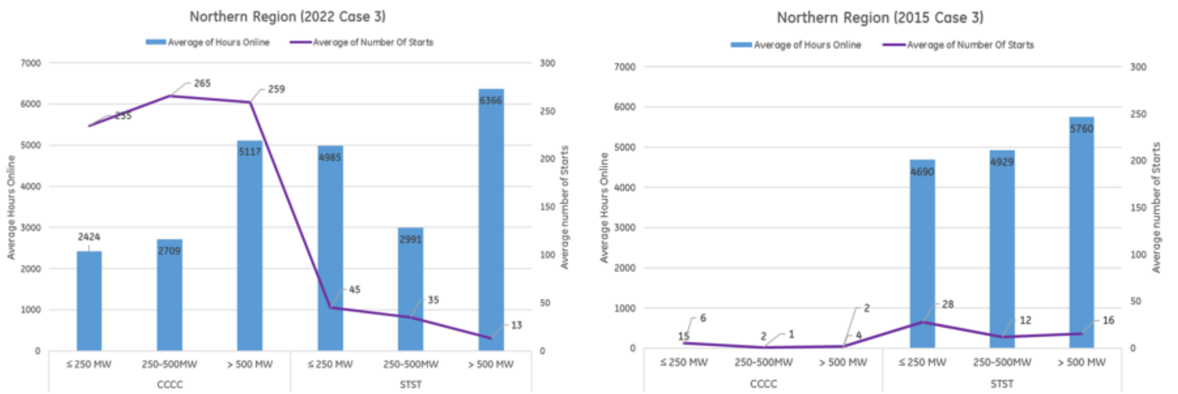


Figure 82: Northern Region Thermal Units Starts & Hours online Comparison - 2015 vs. 2022

Eastern Region

Eastern region remains a net exporter in 2022 MAPS simulations. The region has 12 GW of solar capacity additions by 2022 as per MNRE targets.

Eastern region is a coal and hydro dominated region as seen in Figure 83 and has the second cheapest coal sources. The average operating hours per start increases from 751 hours to 996 hours. The region is electrically interconnected with all other regions serving as a bridge between hydro rich north-east and the rest of the country.

Figure 83: Eastern Region Generation, Capacity Factor, Starts & Hour of operation comparison - 2015 vs. 2022

9.1.2 PRODUCTION COST ANALYSIS

Case-1 Vs Case-1B

Production cost is the variable cost incurred for meeting the load in an area, which includes fuel, emissions, and variable O&M. In the analysis under this study, the impact on production cost is only due the fuel costs, as inputs related to emissions are not included in the model.

Typically, in the absence of RE generation, the load in the area is met with costly thermal generation and imports. This would be the instance where no RE additions take place beyond 2015. However, the increased RE generation displaces the costly thermal generation bringing down the overall production cost.

Large RE additions occur in the southern region resulting in highest savings on a Rs/kWh basis as it displaces expensive regional thermal generating units. However, this trend is not observed in Western region despite large RE capacity additions as western region is net exporter.

Northern region being a net importer is dependent on imports from eastern and western regions. Additions of RE capacity (primarily solar) displaces expensive units. Coal generating units in the northern region utilize expensive coal fuel. Displacement of these expensive units by the large addition of RE capacity, and as the region is a net importer, the region observes high savings due to addition on RE capacity.

Case-1 vs Case-2 and Case-1 vs Case-3

Case-1 was run as a copper sheet model with no transmission limits between the states. Case-2 introduces a wheeling charge of 25$/MWh (~1.5 Rs/KWh) which means a charge of 25$ for every MW transferred on the transmission lines interconnecting regions, and Case-3 was implemented using the transmission limits set by the CEA in the transmission planning document. The impact of these transmission constraints is seen in Table 36 & Table 37.

Increasing the cost or constraining transmission capacity between regions force regions to depend more on local generation than external support. Regions such as Northern and Southern which are net importers for the simulated year of 2022 observe an increase in production cost. Northern region being the most dependent on external support incurs the most losses in terms of production costs between Case-1, Case-2 and Case-3.

Introduction of a wheeling charge in Case-2, observes a production cost increase on an all India level by 1 paise/kWh and by 3 paise/kWh in Case-3 with transmission limits.

Region	Case-1 (full RE)		Case-1B (no RE additions betwenn 2015 to 2022)		Case-2 – Case-1 with 25$/MWh wheeling charge		Case-3 (CEA Limits and full RE)	
	Rs Crores	Rs/kWh	Rs Crores	Rs/kWh	Rs Crores	Rs/kWh	Rs Crores	Rs/kWh
Northern Region	56268	1.63	86793	2.48	70033	1.86	77281	1.99
Western Region	148579	2.08	184484	2.5	130667	1.96	132203	1.97
Southern Region	50330	1.5	71894	2.45	56659	1.6	50305	1.5
Eastern Region	60300	2.85	75282	3.31	59996	2.84	61495	2.88
North Eastern Region	4268	1.25	4534	1.37	4294	1.26	4262	1.25
All India	319744	1.95	422987	2.58	321650	1.96	325546	1.98

Table 36: Savings comparison in various cases - Regional and All India Basis

Region	Case-1 vs Case-1B Savings		Case-1 vs Case-2 Savings		Case-1 vs Case-3 Savings	
	Rs Crores	Rs/kWh	Rs Crores	Rs/kWh	Rs Crores	Rs/kWh
Northern Region	30525	0.85	-13765	-0.23	-21013	-0.36
Western Region	35905	0.42	17912	0.12	16376	0.11
Southern Region	21564	0.95	-6329	-0.1	25	0
Eastern Region	14982	0.46	304	0.01	-1195	-0.03
North Eastern Region	266	0.12	-26	-0.01	6	0.000
All India	103243	0.63	-1906	-0.01	-5802	-0.03

Table 37: Comparison of savings in Case-1 with other cases

(+ values indicate savings, -ve indicate loses)

9.1.3 TRANSMISSION ANALYSIS

Southern region is not a net exporter, but exports power to eastern region during high renewable generation periods (June) as seen in Figure 84. Further, net exports from eastern region to southern region are around 30.3 TWh under Case-3 and 25.8 TWh in Case-1. The increase of about 4.5 TWh in southern region imports from eastern region between Case-3 and Case-1 compensates the decrease in imports from western region which implies that transfer capability between eastern and southern region is adequate and is being fully utilized in 2022.

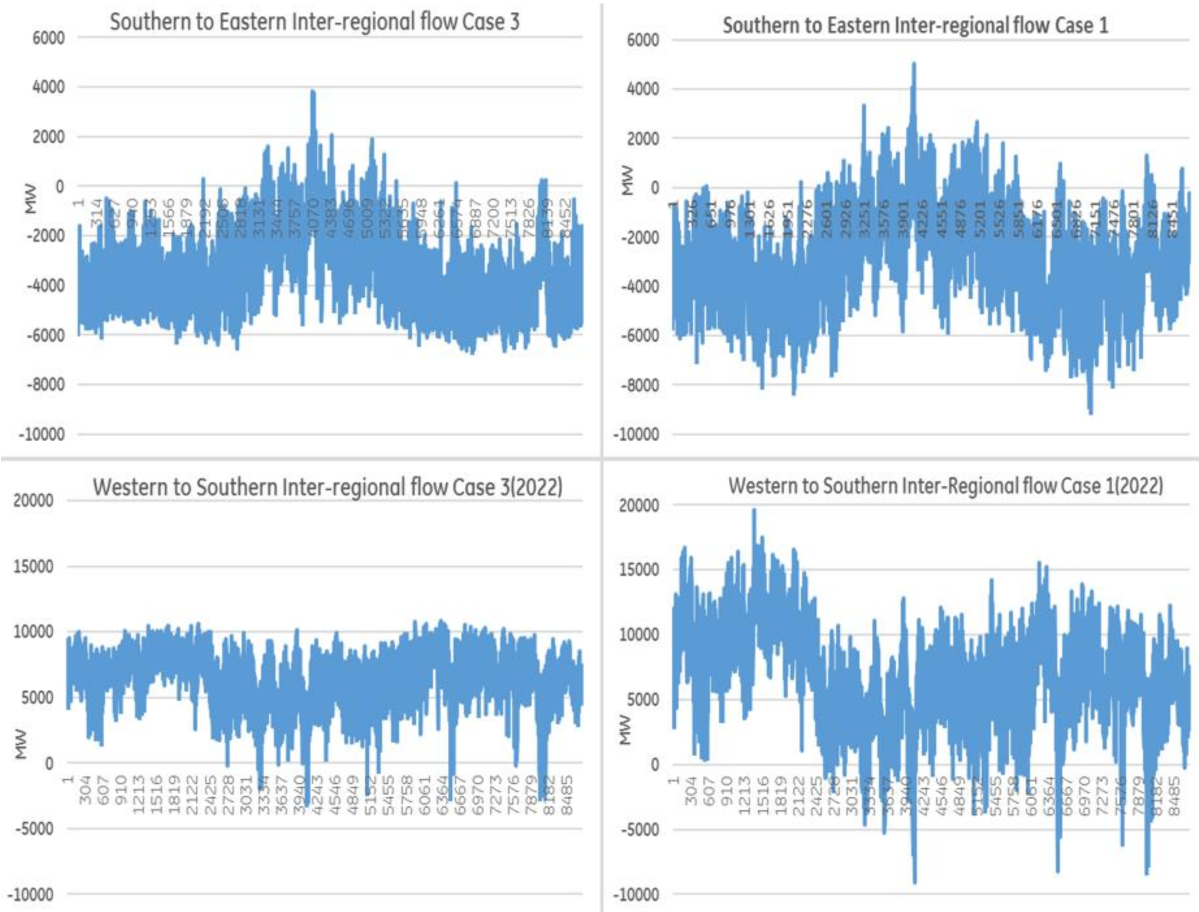


Figure 84: Southern Region power transfer with WR & ER for 2022: Case-3 & Case-1

Again, in case of inter-regional transfers between western and southern region there are some instances of exports from southern region to western region in high RE periods, but such instances are still lesser than the instances seen with export from southern region to eastern region during similar periods. Net exports from western region to southern region are about 57.9 TWh under Case-3 and 60.4 TWh in Case-1. The instances of southern region importing to western region are higher in Case-1 than in Case-3, which is also natural because restrictions imposed by the transmission limits implemented in Case-3 as tabulated in Table 13.

Referring to (Figure 30), interregional transmission capacity limits (Case-3) do not significantly affect the utilization of thermal plants in Southern region.

Northern region is set to remain a net importer in 2022, under both Case-1 and Case-3. The import from western region are significantly higher than the imports from the eastern region. Northern region imports a maximum of 18 GW from western region under Case-3 and 31.9 GW in Case-1. The net regional imports a total of 116 TWh from western region under Case-3 and 153 TWh in Case-1 which is an average import of 13207 MW in Case-3 and 17502 MW in Case-1. The decrease in the total imports is attributed to the restrictions imposed by the transmission limits implemented in case. Given the reduction in imports between the two cases, due to the transmission limits, the regional units need to increase generation to meet demand. Northern region exports power to western region during summer periods but is limited to less than 0.2% of the year.

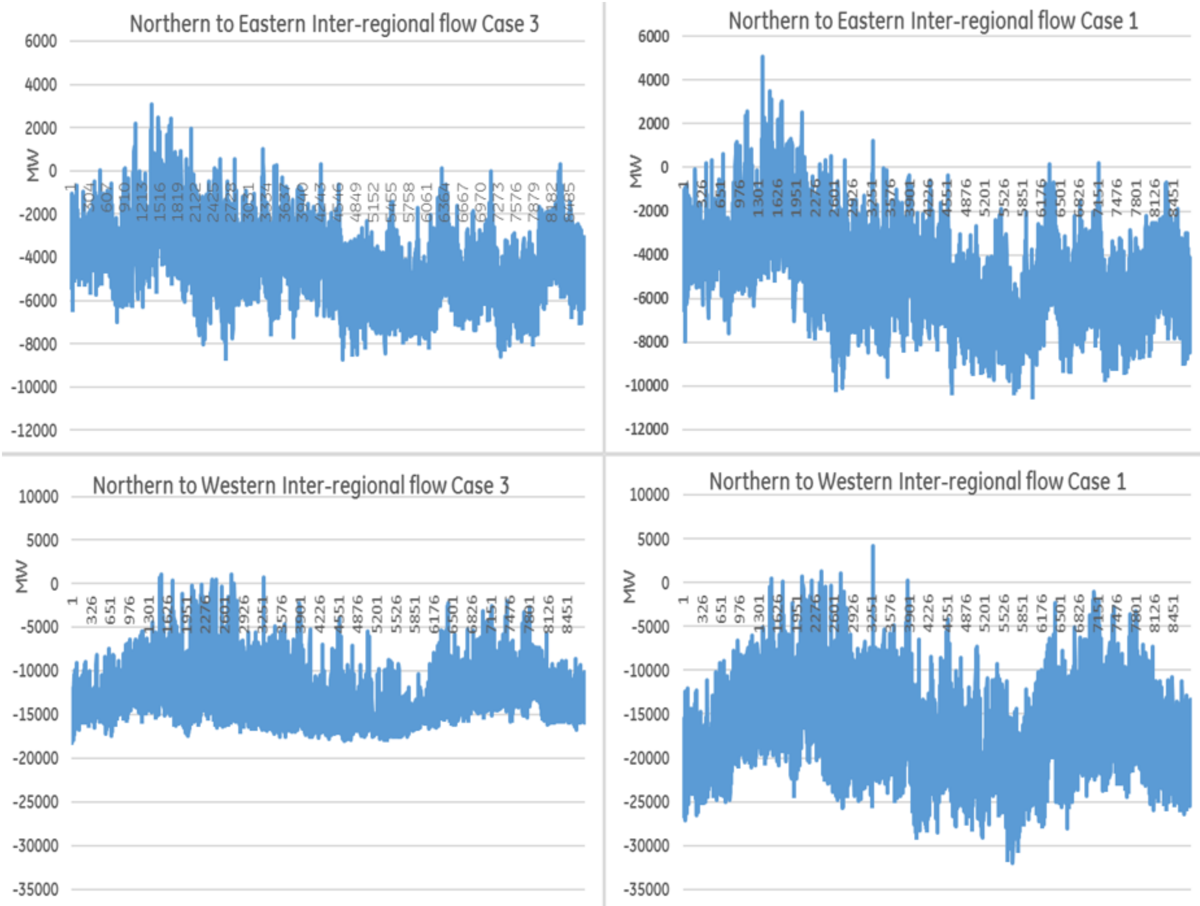


Figure 85: Northern Region power transfer with WR & ER for 2022: Case-3 & Case-1

Northern region imports a maximum of 8.7 GW from eastern region under Case-3 and 10.4 GW in Case-1. The net regional imports a total of 36 TWh from eastern region under Case-3 and 42 TWh in Case-1 which is an average import of 4122 MW in Case-3 and 4757 MW in Case-1. The decrease in the total imports is attributed to the restrictions imposed by the transmission limits implemented in Case-3. Given the reduction in imports between the two cases, due to the transmission limits, the regional units need to increase generation to meet demand. Northern region exports power to eastern region during summer periods but is limited to less than 2% of the year with a maximum export of 3GW in Case-3 and 5 GW in Case-1.

Northern region is a net importer in 2022 for both Case-1 and Case-3. The northern region is significantly impacted by the transmission limits implemented as per Table 21.

9.2 GE MARS RESULTS

9.2.1 KEY FINDINGS FROM TRANSMISSION AND GENERATION PLANNING CASES

Cases 1 and 2A were run with CEA Transmission Limits Inter and Intra State limits. Following are the key findings from these runs:

a) **Northern Region**
   - → States in the Northern Region experience significant LOLE due to limitation of transmission capacity between states
   - → The State of Jammu & Kashmir interconnected with only Punjab hit the limit for ~1800 hours/ year
   - → High demand in Northern Region makes it a net importer, putting pressure on the inter-region transmission lines such as lines connecting Gujarat to Haryana and Rajasthan

b) **Western Region**
   - → High installed capacity of Thermal and Renewables capacity in Western region ensures stability in the region
   - → Net exporter to Southern and Northern Regions
   - → Limited transmission connectivity to Goa and the Union Territory of DD and DNH is reflected in the LOLE values for Western Region

c) **Southern Region**
   - → State of Tamil Nadu and Kerala have the Highest LOLE requirements in Southern region

d) **Eastern Region**
   - → No LOLE as the region has large installed capacity versus the region load
   - → LOLE values for Case-2A are generally higher with same trend as in Case-1 due to lower renewable capacity

9.2.2 KEY FINDINGS FROM THE CAPACITY VALUE ANALYSIS

Capacity value of RE resources (wind + solar) is estimated for following cases:

1. Case-1 – 100% RE target is achieved by 2022
2. Case-2 – 70% RE target is achieved by 2022
3. Case-3 – 50% RE target is achieved by 2022

By year 2022, India will have huge installed capacity of RE which will be dispersed in large geographical area. Thus, for perfect capacity addition (capacity value calculations) only such areas were chosen which showed considerable LOLE and have remarkable presence of RE installations. These area / regions are Southern Region, Punjab, and Rajasthan. Details of perfect capacity added in each area is given in Table 39, Table 40 and Table 41 as below.

Results for capacity value are tabulated in Table 38.

Case	Parameter	Southern Region	Punjab	Rajasthan
100% RE Case	**RE capacity addition**	43.9	4.72	9.81
	RE Capacity Value	8.65%	7.20%	5.61%
70% RE Case	**RE capacity addition**	30.13	3.31	6.69
	RE Capacity Value	12.28%	9.08%	7.14%
50% RE Case	**RE capacity addition**	21.52	2.36	4.9
	RE Capacity Value	16.26%	12.29%	9.58%

Table 38: Capacity value of key regions/states

Figure 86 below shows the procedure of calculation for southern region.

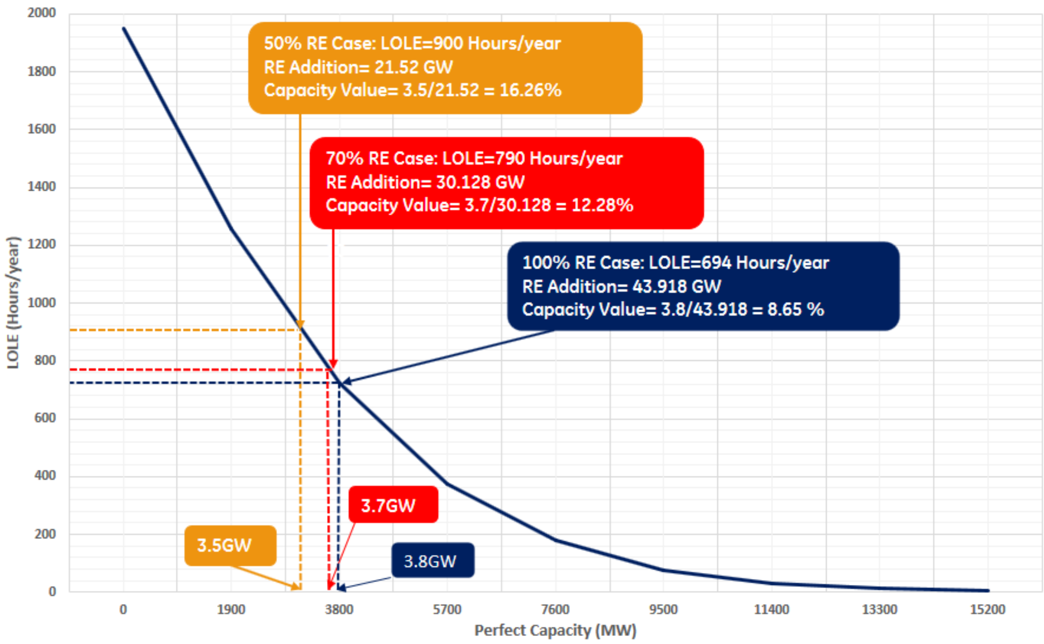


Figure 86: Calculation of capacity value of RE for Southern region

Table 39 summarizes the procedure of capacity value estimation with addition of perfect capacity for southern Region. Karnataka, Andhra Pradesh and Telangana faces no reliability issues with (0% RE i.e. 0 MW of perfect capacity). LOLE values for all RE addition cases (0%, 50%,70% and 100%) are zero. Kerala and Tamilnadu will face LOLE of 1950 Hrs./Year and 1748 Hrs./Year respectively if no RE (0 MW perfect capacity) is added to southern region. Even with 100% RE addition, these two states will face LOLE of 694 Hrs./Year and 358 Hrs./Year. MARS considers the highest LOLE of the area as pool's LOLE, thus Kerala's (area's) LOLE is indicated as Southern region's (pool's) LOLE value. These values are used to construct the graph of capacity value estimation in Figure 86 .

There were 9 iterative simulations used to construct this graph. To start with; capacity values with 0%, 50% 70% and 100% RE penetration are recorded. 0% RE addition case is same as 0MW perfect capacity case.

In successive steps, perfect capacity is added and LOLE is recorded. For 0 MW perfect capacity case, 1950 Hrs./Year LOLE is plotted. With 0% RE addition, perfect capacity was added in southern region in the steps of 1900 MW till 15200 MW. It can be observed from the Table 39 that LOLE is reduced as higher perfect capacities are added to system. With 15200 MW, LOLE is 7 Hrs./Year which is well within the desired value. On the X-axis, perfect capacities are plotted and on the Y – axis corresponding LOLE values are recorded. A resultant plot is a graph with downward trend in term of LOLE as shown in Figure 86 .

Capacity value for various RE penetration level are calculated as a next step.

For example, 70% RE addition case (30.128 GW) shows 790 Hrs./Year as LOLE value. Perfect capacity on X-axis is ~3.7 GW. Thus, capacity value for 70 %RE penetration is:

$$(3.7) \ / \ (30.128) = 12.28\%$$

As more and more RE is added to the system, capacity value is reduced. This might be since, LOLE with higher generation is lower and further addition of generation capacity will not bring much relief. As seen from the graph, lower portion indicates very slow improvement even with considerable addition of perfect capacity. This is termed as 'saturation effect'.

Capacity value of RE resources in southern region has changed in integrated (all India) model when compared to standalone Southern region simulation. For 50% RE case, southern region in standalone case has capacity value of 13.27% which improves to 16.26% in Integrated case. While 100% RE case had capacity value of 11.2% (in standalone southern region case) changes to 8.65%. The change in capacity value for both cases is due to the alignment of RE resources to only Southern India load (standalone southern India case) as compared to its alignment to load in Indian grid (all India case).

State	Perfect Capacity – LOLE (Hours/year)											
Perfect Capacity (MW)	0	1900	3800	5700	7600	9500	11400	13300	15200	50% RE	70% RE	100% RE
KARNATAKA	0	0	0	0	0	0	0	0	0	**0**	**0**	**0**
ANDHRA PRADESH	0	0	0	0	0	0	0	0	0	**0**	**0**	**0**
TELENGANA	0	0	0	0	0	0	0	0	0	**0**	**0**	**0**
KERALA	1950	1255	722	374	178	76	30	13	7	**900**	**790**	**694**
TAMIL NADU	1748	1074	578	276	120	48	18	5	1	**616**	**480**	**358**

State	Perfect Capacity – LOLE (Hours/year)											
Perfect Capacity (MW)	0	1900	3800	5700	7600	9500	11400	13300	15200	50% RE	70% RE	100% RE
SOUTHERN REGION	1950	1255	722	374	178	76	30	13	7	**900**	**790**	**694**

Table 39: Perfect capacity addition for southern region

State	Perfect Capacity – LOLE (Hours/year)											
Perfect Capacity (MW)	**0**	**500**	**1000**	**1500**	**2000**	**2500**	**3000**	**3500**	**4000**	**50% RE**	**70% RE**	**100% RE**
RAJASTHAN (LOLE)	74	39	20	9	5	2	1	0	0	**48**	**44**	**37**

Table 40: Perfect capacity addition for Rajasthan

State	Perfect Capacity – LOLE (Hours/year)											
Perfect Capacity (MW)	**0**	**200**	**400**	**600**	**800**	**1000**	**1200**	**1400**	**1600**	**50% RE**	**70% RE**	**100% RE**
PUNJAB (LOLE)	457	336	246	174	122	85	58	39	26	**307**	**294**	**281**

Table 41: Perfect capacity addition for Punjab

10 APPENDICES AND REFERENCES

10.1 GE MAPS MODEL

Application of GE MAPS

GE's Multi Area Production Simulation (GE MAPS)[10] software program is a transmission based Production cost model to be used for the execution of the wind integration study. This GE proprietary (but commercially available) modeling tool has a long history of governmental, regulatory, independent system operator and investor-owned utility applications. The production cost model provides unit-by-unit production output (MW) on an hourly basis for an entire year of production (GWh) of electricity production by each unit). The results also provide information about the variable cost of electricity production, emissions, fuel consumption, etc.

The overall simulation algorithm is based on standard least marginal cost operating practice. That is, generating units that can supply power at lower marginal cost of production are committed and dispatched before units with higher marginal cost of generation. Commitment and dispatch are constrained by physical limitations of the system, such as transmission thermal limits, minimum spinning reserve, as well as the physical limitations and characteristics of the power plants.

The primary source of model uncertainty and error for production cost simulations, based on the model, consist of:

- Some of the constraints in the model may be somewhat simpler than the precise situation dependent rules used by electricity market operators and utilities.
- Marginal production-cost models consider heat rate and a variable O&M cost. However, the models do not include an explicit heat-rate penalty or an O&M penalty for increased maneuvering that may be a result of incremental system variability due to as-available renewable resources (in future scenarios).
- The production cost model requires input assumptions like forecasted fuel price, forecasted system load, estimated unit heat rates, maintenance and forced outage rates, etc. Variations from these assumptions could significantly alter the results of the study.
- Prices that utilities pay to IPPs for energy are not in general equal to the variable cost of production for the individual unit; nor are they equal to the systemic marginal cost of production. Rather, they are governed by PPAs. The price that utilities pay to third parties can be reflected in the simulation results insofar as the conditions can be reproduced.

The simulation results provide insight into hour-to-hour operations, and how commitment and dispatch may change subject to various changes, including equipment or operating practices. Since the production cost model depends on fuel price as an input, relative costs and change in costs between alternative scenarios tend to produce better and more useful information than absolute costs. The results from the model approximate system dispatch and production, but do not necessarily identically match system behavior. The results do not necessarily reproduce accurate

[10] http://www.geenergyconsulting.com/practice-area/software-products/maps

production costs on a unit-by-unit basis and do not accurately reproduce every aspect of system operation. However, the model reasonably quantifies the incremental changes in marginal cost, emissions, fossil fuel consumption, and other operations metrics due to changes, such as higher levels of wind power.

Unique Features of GE MAPS

GE MAPS is a highly detailed model that calculates hour-by-hour production costs while recognizing constraints on the dispatch of generation imposed by the transmission system. When the program was initially developed over twenty years ago, its primary use was as a generation and transmission planning tool to evaluate the impacts of transmission system constraints on the system production cost. In the current deregulated utility environment, the acronym GE MAPS may more also stand for Market Assessment & Portfolio Strategies because of the model's usefulness in studying issues such as market power and the valuation of generating assets operating in a competitive environment.

The unique modeling capabilities of GE MAPS use a detailed electrical model of the entire transmission network, along with generation shift factors determined from a solved ac load flow, to calculate the real power flows for each generation dispatch. This enables the user to capture the economic penalties of re-dispatching the generation to satisfy transmission line flow limits and security constraints.

Separate dispatches of the interconnected system and the individual companies' own load and generation are performed to determine the economic interchange of energy between companies. Several methods of cost reconstruction are available to compute the individual company costs in the total system environment. The chronological nature of the hourly loads is modeled for all hours in the year. In the electrical representation, the loads are modeled by individual bus.

In addition to the traditional production costing results, MAPS can provide information on the hourly spot prices at individual buses and on the flows on selected transmission lines for all hours in the year, as well as identifying the companies responsible for the flows on a given line.

Because of its detailed representation of the transmission system, GE MAPS can be used to study issues that often cannot be adequately modeled with conventional production costing software. These issues include:

Market Structures – GE MAPS is being used extensively to model emerging market structures in different regions of the United States. It has been used to model the New York, New England, PJM and California ISOs for market power studies, stranded cost estimates, and project evaluations.

Transmission Access – GE MAPS calculates the hour spot price ($/MWh) at each bus modeled, thereby defining a key component of the total avoided cost that is used in formulating contracts for transmission access by non-utility generators and independent power producers.

Loop Flow or Uncompensated Wheeling – The detailed transmission modeling and cost reconstruction algorithms in MAPS combine to identify the companies contributing to the flow on a given transmission line and to define the production cost impact of that loading.

Transmission Bottlenecks – GE MAPS can determine which transmission lines and interfaces in the system are bottlenecks and how many hours during the year these lines are limiting. Next, the program can be used to assess, from an economic point of view, the feasibility of various methods, such as transmission line upgrades or the installation of phase-angle regulators for alleviating bottlenecks.

Evaluation of New Generation, Transmission, or Demand-Side Facilities – GE MAPS can evaluate which of the available alternatives under consideration has the most favorable impact on system operation in terms of production costs and transmission system loading.

Power Pooling – The cost reconstruction algorithms in GE MAPS allow individual company performance to be evaluated with and without pooling arrangements, so that the benefits associated with pool operations can be defined.

Modeling Capabilities of GE MAPS

GE MAPS has evolved to study the management of a power system's generation and transmission resources to minimize generation production costs while considering transmission security. The modeling capabilities of MAPS are summarized below:

Time Frame – One year to several years with ability to skip years.

Company Models – Up to 175 companies.

Load Models – Up to 175 load forecasts. The load shapes can include all 365 days or automatically compress to a typical week (seven different day shapes) per month. The day shapes can be further compressed from 24 to 12 hours, with bi-hourly loads.

Generation – Up to 7,500 thermal units, 500 pondage plants, 300 run-of-river plants, 50 energy-storage plants, 15 external contracts, 300 units jointly owned, and 2,000 fuel types. Thermal units have full and partial outages, daily planned maintenance, fixed and variable operating and maintenance costs, minimum down-time, must-run capability, and up to four fuels at a unit.

Network Model – Includes 50,000 buses, 100,000 lines, 145 phase-angle regulators, and 100 multi-terminal High-Voltage Direct Current lines. Line or interface transmission limits may be set using operating nomograms as well as thermal, voltage and stability limits. Line or interface limits may be varied by generation availability.

Losses - Transmission losses may vary as generation and loads vary, approximating the ac power flow behavior, or held constant, which is the usual production simulation assumption. The incremental loss factors are recalculated each hour to reflect their dependence on the generation dispatch.

Marginal Costs – Marginal costs for an increment such as 100 MW can be identified by running two cases, one 100 MW higher, with or without the same commitment and pumped-storage hydro schedule. A separate routine prepares the cost difference summaries. Hourly bus spot prices are also computed.

Operating Reserves – Modeled on an area, company, pool and system basis.

Secure Dispatch – Up to 5,000 lines and interfaces and nomograms may be monitored. Each study hour considers the effect of hundreds of different network outages.

Report Analyzer – MAPS allows the simulation results to be analyzed through a powerful report analyzer program, which incorporates full screen displays, customizable output reports, graphical displays and databases. The built-in programming language allows the user to rapidly create custom reports.

Accounting – Separate commitment and dispatches are done for the system and for the company own-load assumptions, allowing cost reconstruction and cost splitting on a licensee-agreed basis. External economy contracts are studied separately after the base dispatch each hour.

Bottom Line – Annual fuel plus O&M costs for each company, fuel consumption, and generator capacity factors.

10.2 GE MARS MODEL

The Multi-Area Reliability Simulation software program (GE MARS)[11] enables the electric utility planner to quickly and accurately assess the reliability of a generation system comprised of any number of interconnected areas.

GE Mars Modeling Technique

A sequential Monte Carlo simulation forms the basis for MARS. The Monte Carlo method provides a fast, versatile, and easily-expandable program that can be used to fully model many different types of generation and demand-side options.

In the sequential Monte Carlo simulation, chronological system histories are developed by combining randomly-generated operating histories of the generating units with the inter-area transfer limits and the hourly chronological loads. Consequently, the system can be modeled in great detail with accurate recognition of random events, such as equipment failures, as well as deterministic rules and policies which govern system operation, without the simplifying or idealizing assumptions often required in analytical methods.

Reliability Indices Available from Mars

The following reliability indices are available on both an isolated (zero ties between areas) and interconnected (using the input tie ratings between areas) basis:

- Daily LOLE (days/year)
- Hourly LOLE (hours/year)
- LOEE (MWh/year)
- Frequency of outage (outages/year)
- Duration of outage (hours/outage)

[11] http://www.geenergyconsulting.com/practice-area/software-products/mars

- Need for initiating emergency operating procedures (days/year)

The use of Monte Carlo simulation allows for the calculation of probability distributions, in addition to expected values, for all of the reliability indices. These values can be calculated both with and without load forecast uncertainty.

Description of Program Models

Loads - The loads in MARS are modeled on an hourly, chronological basis for each area being studied. The program has the option to modify the input hourly loads through time to meet specified annual or monthly peaks and energies. Uncertainty on the annual peak load forecast can also be modeled, and can vary by area on a monthly basis.

MARS has the capability to model the following different types of resources:

- Thermal
- Energy-limited
- Cogeneration
- Energy-storage
- Demand-side management

An energy-limited unit can be modeled stochastically as a thermal unit with an energy probability distribution (Type 1 energy-limited unit), or deterministically as a load modifier (Type 2 energy-limited unit). Cogeneration units are modeled as thermal units with an associated hourly load demand. Energy-storage and demand-side management are modeled as load modifiers.

For each unit modeled, the user specifies the installation and retirement dates and planned maintenance requirements. Other data such as maximum rating, available capacity states, state transition rates, and net modification of the hourly loads are input depending on the unit type.

The planned outages for all types of units in MARS can be specified by the user or automatically scheduled by the program on a weekly basis. The program schedules planned maintenance to levelize reserves on an area, pool, or system basis. MARS also has the option of reading a maintenance schedule developed by a previous run and modifying it as specified by the user through any of the maintenance input data. This schedule can then be saved for use by subsequent runs.

Thermal Units - In addition to the data described previously, thermal units (including Type 1 energy-limited units and cogeneration) require data describing the available capacity states in which the unit can operate. This is input by specifying the maximum rating of each unit and the rating of each capacity state as a per-unit of the unit's maximum rating. A maximum of eleven capacity states are allowed for each unit, representing decreasing amounts of available capacity as a result of the outages of various unit components.

Because MARS is based on a sequential Monte Carlo simulation, it uses state transition rates, rather than state probabilities, to describe the random forced outages of the thermal units. State probabilities give the probability of a unit being in a given capacity state at any particular time, and can be used if you assume that the unit's capacity state for a given hour is independent of its state at any other hour. Sequential Monte Carlo simulation recognizes the fact that a unit's capacity state in a given hour is dependent on its state in previous hours and influences its state in future hours. It thus requires the additional information that is contained in the transition rate data.

For each unit, a transition rate matrix is input that shows the transition rates to go from each capacity state to each other capacity state. The transition rate from state A to state B is defined as the number of transitions from A to B per unit of time in state A:

$$TR\ (A\ to\ B) = \frac{Number\ of\ Transitions\ from\ A\ to\ B}{Total\ Time\ in\ State\ A}$$

If detailed transition rate data for the units is not available, MARS can approximate the transitions rates from the partial forced outage rates and an assumed number of transitions between pairs of capacity states. Transition rates calculated in this manner will give accurate results for LOLE and LOEE, but it is important to remember that the assumed number of transitions between states will have an impact on the time-correlated indices such as frequency and duration.

Energy-Limited Units - Type 1 energy-limited units are modeled as thermal units whose capacity is limited on a random basis for reasons other than the forced outages on the unit. This unit type can be used to model a thermal unit whose operation may be restricted due to the unavailability of fuel, or a hydro unit with limited water availability. It can also be used to model technologies such as wind or solar; the capacity may be available, but the energy output is limited by weather conditions.

Type 2 energy-limited units are modeled as deterministic load modifiers. They are typically used to model conventional hydro units for which the available water is assumed to be known with little or no uncertainty. This type can also be used to model certain types of contracts. A Type 2 energy-limited unit is described by specifying a maximum rating, a minimum rating, and a monthly available energy. This data can be changed on a monthly basis. The unit is scheduled on a monthly basis with the unit's minimum rating dispatched for all of the hours in the month. The remaining capacity and energy can be scheduled in one of two ways. In the first method, it is scheduled deterministically so as to reduce the peak loads as much as possible. In the second approach, the peak-shaving portion of the unit is scheduled only in those hours in which the available thermal capacity is not sufficient to meet the load; if there is sufficient thermal capacity, the energy of the Type 2 energy-limited units will be saved for use in some future hour when it is needed.

Cogeneration - MARS model’s cogeneration as a thermal unit with an associated load demand. The difference between the unit's available capacity and its load requirements represents the amount of capacity that the unit can contribute to the system. The load demand is input by specifying the hourly loads for a typical week (168 hourly loads for Monday through Sunday). This load profile can be changed on a monthly basis. Two types of cogeneration are modeled in the program, the difference being whether or not the system provides back-up generation when the unit is unable to meet its native load demand.

Energy-Storage and DSM - Energy-storage units and demand-side management are both modeled as deterministic load modifiers. For each such unit, the user specifies a net hourly load modification for a typical week which is subtracted from the hourly loads for the unit's area.

Transmission System

The transmission system between interconnected areas is modeled through transfer limits on the interfaces between pairs of areas. Simultaneous transfer limits can also be modeled in which the total flow on user-defined groups of interfaces is limited. Random forced outages on the interfaces are modeled in the same manner as the outages on thermal units, through the use of state transition rates.

The transfer limits are specified for each direction of the interface or interface group and can be input on a monthly basis. The transfer limits can also vary hourly according to the availability of specified units and the value of area loads.

Contracts

Contracts are used to model scheduled interchanges of capacity between areas in the system. These interchanges are separate from those that are scheduled by the program as one area with excess capacity in a given hour provides emergency assistance to a deficient area.

Each contract can be identified as either firm or curtailable. Firm contracts will be scheduled regardless of whether or not the sending area has sufficient resources on an isolated basis, but they can be curtailed because of interface transfer limits. Curtailable contracts will be scheduled only to the extent that the sending area has the necessary resources on its own or can obtain them as emergency assistance from other areas.

Emergency Operating Procedures

Emergency operating procedures are steps undertaken by a utility system as the reserve conditions on the system approach critical levels. They consist of load control and generation supplements which can be implemented before load has to be actually disconnected. Load control measures could include disconnecting interruptible loads, public appeals to reduce demand, and voltage reductions. Generation supplements could include overloading units, emergency purchases, and reduced operating reserves.

The need for a utility to begin emergency operating procedures is modeled in MARS by evaluating the daily LOLE at specified margin states. The user specifies these margin states for each area in terms of the benefits realized from each emergency measure, which can be expressed in MW, as a per unit of the original or modified load, and as a per unit of the available capacity for the hour.

The user can also specify monthly limits on the number of times that each emergency procedure is initiated, and whether each EOP benefits only the area itself, other areas in the same pool, or areas throughout the system. Staggered implementation of EOPs, in which the deficient area must initiate a specified number of EOPs before non-deficient areas begin implementation, can also be modeled.

Resource Allocation among Areas

The first step in calculating the reliability indices is to compute the area margins on an isolated basis, for each hour. This is done by subtracting from the total available capacity in the area for the hour the load demand for the hour. If an area has a positive or zero margins, then it has sufficient capacity to meet its load. If the area margin is negative, the load exceeds the capacity available to serve it, and the area is in a loss-of-load situation.

If there are any areas that have a negative margin after the isolated area margins have been adjusted for curtailable contracts, the program will attempt to satisfy those deficiencies with capacity from areas that have positive margins. Two methods are available for determining how the reserves from areas with excess capacity are allocated among the areas that are deficient. In the first approach, the user specifies the order in which an area with excess resources provides assistance to areas that are deficient. The second method shares the available excess reserves among the deficient areas in proportion to the size of their shortfalls.

The user can also specify that areas within a pool will have priority over outside areas. In this case, an area must assist all deficient areas within the same pool, regardless of the order of areas in the priority list, before assisting areas outside of the pool. Pool-sharing agreements can also be modeled in which pools provide assistance to other pools according to a specified order.

Output Reports

The following output reports are available from MARS. Most of the summaries of calculated quantities are available for each load forecast uncertainty load level and as a weighted-average based on the input probabilities.

- ⇨ Summary of the thermal unit data.
- ⇨ Summary of installed capacity by month by user-defined unit type.
- ⇨ Summary of load data, showing monthly peaks, energies, and load factors.
- ⇨ Unit outage summary showing the weeks during the year that each unit was on planned outage.
- ⇨ Summary of weekly reserves by area, pool, and system.
- ⇨ Annual, monthly, and weekly reliability indices - by area and pool, isolated and interconnected.
- ⇨ Expected number of days per year at specified margin states on an annual, monthly, and weekly basis.
- ⇨ Annual and monthly summaries of the flows, showing for each interface the maximum and average flow for the year, the number of hours at the tie-line limit, and the number of hours of flow during the year.
- ⇨ Annual summary of energy and hours of curtailment for each contract.
- ⇨ Annual summary of energy usage for the peaking portion of Type 2 energy-limited units.
- ⇨ Replication year output, by area and pool, isolated and interconnected, showing the daily and hourly LOLE and LOEE for each time that the study year was simulated. This information can be used to plot distributions of the indices, which show the year-to-year variation that actually occurs.
- ⇨ Annual summary of the minimum and maximum values of the replication year indices.
- ⇨ Detailed hourly output showing, for each hour that any of the areas has a negative margin on an isolated basis, the margin for each area on an isolated and interconnected basis.
- ⇨ Detailed hourly output showing the flows on each interface.

Program Dimensions

All of the program dimensions in MARS can be changed at the time of installation to size the program to the system being studied. Among the key parameters that can be changed are the number of units, areas, pool, and interface

10.3 TENTATIVE STATE-WISE BREAK-UP OF RE TARGET BY 2022 (MW)[12]

State/UTs	Solar	Wind	Small Hydro	Biomass
Delhi	2762.00	0.00	0.00	0.00
Haryana	4142.00	0.00	25.00	209.00
Himachal Pradesh	776.00	0.00	1500.00	0.00
Jammu and Kashmir	1155.00	0.00	150.00	0.00
Punjab	4772.00	0.00	50.00	244.00
Rajasthan	5762.00	8600.00	0.00	0.00
Uttar Pradesh	10697.00	0.00	25.00	3499.00
Uttarakhand	900.00	0.00	700.00	197.00
Chandigarh	153.00	0.00	0.00	0.00
Northern Region	**31119.00**	**8600.00**	**2450.00**	**4149.00**
Goa	358.00	0.00	0.00	0.00
Gujarat	8020.00	8800.00	25.00	288.00
Chattisgarh	1783.00	0.00	25.00	0.00
Madhya Pradesh	5675.00	6200.00	25.00	118.00
Maharashtra	11926.00	7600.00	50.00	2469.00
D. & N. Haveli	449.00	0.00	0.00	0.00
Daman & Diu	199.00	0.00	0.00	0.00
Western Region	**28410.00**	**22600.00**	**125.00**	**2875.00**
Andhra Pradesh	9834.00	8100.00	0.00	543.00
Telangana		2000.00	0.00	0.00
Karnataka	5697.00	6200.00	1500.00	1420.00
Kerala	1870.00	0.00	100.00	0.00
Tamil Nadu	8884.00	11900.00	75.00	649.00
Puducherry	246.00	0.00	0.00	0.00
Southern Region	**26531.00**	**28200.00**	**1675.00**	**2612.00**
Bihar	2493.00	0.00	25.00	244.00
Jharkhand	1995.00	0.00	10.00	0.00
Orissa	2377.00	0.00	0.00	0.00
West Bengal	5336.00	0.00	50.00	0.00
Sikkim	36.00	0.00	50.00	0.00
Eastern region	**12237.00**	**0.00**	**135.00**	**244.00**
Assam	663.00	0.00	25.00	0.00
Manipur	105.00	0.00	0.00	0.00
Meghalaya	161.00	0.00	50.00	0.00
Nagaland	61.00	0.00	15.00	0.00
Tripura	105.00	0.00	0.00	0.00
Arunachal Pradesh	39.00	0.00	500.00	0.00
Mizoram	72.00	0.00	25.00	0.00
North Eastern Region	**1206.00**	**0.00**	**615.00**	**0.00**
Andaman & Nicobar Islands	27.00	0.00	0.00	0.00
Lakshadweep	4.00	0.00	0.00	0.00
Other (New States)	0.00	600.00	0.00	120.00
All India	**99534.00**	**60000.00**	**5000.00**	**10000.00**

Table 42: Tentative State-Wise breakup of RE Target by 2022

[12] http://mnre.gov.in/file-manager/UserFiles/Tentative-State-wise-break-up-of-Renewable-Power-by-2022.pdf

LIST OF FIGURES/TABLES

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