Resource Adequacy Planning for the State of Rajasthan – Modeling Approaches and Results

Prepared By

Idam
Enabling Carbon Minimal World!

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Abbreviations

APPC:	Average Power Procurement Cost	MoP:	Ministry of Power
APR:	Annual Performance Review	RSLDC:	Rajasthan State Load Dispatch Centre
ARR:	Annual Revenue Requirement	NENS:	Normalized Energy Not Served
ARIMA:	Auto-Regressive Integrated Moving Average	NLDC:	National Load Dispatch Centre
BESS:	Battery Energy Storage Systems	NEP:	National Electricity Plan
CAGR:	Compound Annual Growth Rate	PRM:	Planning Reserve Margin
CC:	Capacity Crediting	PSP:	Pumped Storage Hydro
CEA:	Central Electricity Authority	PUShP:	Portal for Utility Statistics for Health of Power Distribution
CERC:	Central Electricity Regulatory Commission	RA:	Resource Adequacy
DERs:	Distributed Energy Resources	RAR:	Resource Adequacy Requirement
DLs:	Distribution Licensees	RE:	Renewable Energy
EENS:	Expected Energy Not Served	RPO:	Renewable Purchase Obligation
ELCC:	Expected Load Carrying Capability	RTC:	Round-The-Clock
EPS:	Electricity Power Survey	SERC:	State Electricity Regulatory Commissions
ESS:	Energy Storage Systems	SLDC:	State Load Dispatch Centres
EVs:	Electric Vehicles	ST-DRAP:	Short-Term Distribution Resource Adequacy Plan
FoR:	Forum of Regulators	ST-NRAP:	Short-Term National Resource Adequacy Plans
LOLP:	Loss of Load Probability	STOA:	Short Term Open Access
LT-DRAP:	Long-Term Distribution Resource Adequacy Plan	STU:	State Transmission Utilities
LT-NRAP:	Long-Term National Resource Adequacy Plans	UPS:	Uninterruptible Power Supply
RERC:	Rajasthan Electricity Regulatory Commission	vRE:	variable Renewable Energy
MoD:	Merit Order Dispatch		

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1. Introduction

India has set five ambitious clean energy targets for its economy, also known as five nectar elements or "Panchamrit", as follows:

1. Reach non-fossil energy capacity of 500 GW by 2030.
2. Meet 50% of its energy requirements from renewable energy (RE) by 2030.
3. Reduce the total projected carbon emissions by one billion tons from now untill 2030.
4. Reduce the carbon intensity of its economy by less than 45% by 2030.
5. Achieve the target of Net Zero by 2070.

Between FY15 and November 2024, India's RE (including hydro) capacity increased around five times from 40 GW to almost 205 GW[1], supplying nearly 23% of the total electricity generated as November 2024[2]. Various studies suggest a significant rise in RE's share over the next decade. Rajasthan, Gujarat, Karnataka, Maharashtra, and Tamil Nadu stand out as RE-rich states in India, collectively possessing about 50% of total RE installed capacity.

1.1. Background

Rajasthan boasts of 32,246.38 MW of installed RE capacity, including 26,489.65 MW of solar and 5,195.82 MW of wind as of December 2024[3]. It has a total potential of 142 GW solar and 284 GW (at 150 meter) wind, underlining its pivotal role in India's RE landscape and in achieving India's clean energy aspirations.

As Rajasthan embarks on this transition, its electricity sector faces several challenges, such as:

- Intermittency at multiple levels (day/night, seasonal etc.)
- Unavailability during peak demand periods
- Increased ramping from conventional plants
- Creation of "duck curve" situations

Such a fast-evolving grid with ever increasing RE penetration requires adoption of measures of resource adequacy (RA) which would include flexible resources (storage, load shift etc.). RA involves the planning of generation and transmission resources to reliably meet the projected demand in compliance with specified reliability standards for serving the load with an optimal generation mix. It also provides the tools to determine whether there are enough resources and, if not, what type of resource is needed to meet reliability needs and how to contract these capacities. At the same time, any surplus resulting in the analysis would facilitate the trading of the same with other constituents ensuring optimal capacity utilization.

Well-designed system planning and RA frameworks, coordinated with state-level resource planning and procurement and supported by market mechanism, are critical to scaling RE deployment with less curtailment and less financial and operational stress on conventional assets. System planning and RA analysis can help facilitate generation capacity sharing among states, increasing the utilization of existing generation assets.

Further, ensuring sufficient firm capacity on the grid is crucial to meet the load reliably. Procuring thermal capacity without considering RE or flexible resources can lead to an oversized system and higher costs. Therefore, system simulation studies and optimization are essential to meet ramping needs and load curves cost-effectively.

Key measures to address resource adequacy challenges include the implementation of demand-side management (DSM) strategies and load-shifting mechanisms. Load shifting helps optimize electricity

1 NPP Dashboard

2 NPP Dashboard

3 MNRE

consumption patterns by encouraging consumers to shift demand from peak periods to times of surplus generation, enhancing system reliability. Additionally, accurate demand forecasting and flexible generation resources play a crucial role in balancing supply and demand. These measures collectively strengthen the power system's ability to maintain reliability and meet electricity demand, especially with the increasing share of variable renewable energy (vRE) in the generation mix.

1.2. Objectives & Scope

RA is being implemented by various states across India as per the mandate of the Ministry of Power (MoP), which requires State Electricity Regulatory Commissions (SERCs) to notify Regulations and states to ensure their effective implementation. Given the critical role of RA in power sector planning, while also recognizing that it is a relatively new concept, this initiative was undertaken to conduct detailed studies and organize a capacity-building workshop for Rajasthan.

The workshop covered all aspects of RA, providing state agencies and utilities with the necessary training and material to facilitate successful implementation. A separate report has been prepared documenting the workshop proceedings, while this report focuses on the detailed RA modeling studies.

This study aims to undertake "**Resource Adequacy Planning – Modeling Approaches and Results**" for the state of Rajasthan. By applying energy modeling and optimization techniques, it aims to demonstrate an optimal and cost-effective resource mix through FY34 that meets projected demand and also maintains reliability standards. It seeks to help Rajasthan maximize its RE potential and serve as a scalable, sustainable model for other RE-rich states in India.

To achieve this objective, the following key activities have been undertaken:

- **Data Collection**: Gathering, consolidating, and validating data related to hourly demand profiles, future peak and energy projections, existing and contracted resources with their technical and financial parameters, hourly RE generation profiles, and RPO targets.
- **System Configuration**: Setting up and configuring the collected inputs.
- **Simulations and Iterations**: Running simulations through FY34 to check outputs such as capacity expansion, dispatch, storage characteristics, total system cost, as well as reliability metrics of net energy not served and loss of load probability.
- **Output Analysis and Inferences**: Analyzing output parameters to draw conclusions on meeting RPO targets, required RE and storage, operational reliability, planning reserve margin (PRM), cost of generation/system, and average power procurement cost (APPC).

1.3. Structure of the Report

This report is structured into six main chapters as follows:

Chapter 2 provides an overview of the demand and supply scenario in Rajasthan.

Chapter 3 explores the concept of RA in detail, emphasizing its role in planning of generation and transmission resources to meet projected demand reliably. It covers key features guiding principles, and key steps in RA framework.

Chapter 4 provides an overview of the Forum of Regulators (FoR) model Regulations for Resource Adequacy Framework, 2023 covering key steps, roles and responsibilities.

Chapter 5 presents an overview of various tools and methodologies that can be applied for RA studies and also gives an insight into the modeling approach undertaken for this study.

Chapter 6 outlines the key input assumptions used in this modeling study, from existing and contracted resources with their technical and financial characteristics, RPO requirements, hourly solar and wind generation profiles, hourly demand profile, demand projections, stochastics etc.

Chapter 7 covers key outputs and outcomes derived from the energy modeling study. It highlights year-on-year (YoY) trends in installed capacity and generation, battery energy storage requirements, average

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hourly generation patterns, unserved and dump energy metrics, reliability indicators, and APPC. These findings offer a comprehensive view of the future energy landscape and the performance of Rajasthan's power system under RA framework.

Chapter 8 presents a high-level synthesis of RA study published by Central Electricity Authority (CEA) for the state of Rajasthan, to provide the state with comprehensive set of outputs and pathways for its future development.

Chapter 9 provides concluding remarks

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2. Rajasthan State Overview

Rajasthan, the largest state both by area and by population[4], spans 342,239 square kilometers in the northwestern part of the country. As of the 2011 Census, it had a population of approximately 68.5 million, which has grown to around 75.3 million in recent estimates. The state has a population density of about 220 people per square kilometer. The sex ratio in 2011 was 928 women for every 1,000 men, slightly below the national average. The median age in Rajasthan is 22.4 years, with males at 21.9 years and females at 23 years. The state has a significant rural population, with many residents living in villages and small towns. It boasts of a vibrant economy with an actual Gross State Domestic Product (GSDP) of 15.7 lakh crores and projected GSDP of ₹ 15,28,385 crore for FY24, reflecting a 12.5% growth over FY23[5] which highlights its economic strength and progress. It is a key player in India's power industry, particularly in renewable energy, with significant contributions from solar and wind power.

Figure 1: Map of Rajasthan[6]

Rajasthan's abundant natural resources and vast solar potential have significantly contributed to the expansion of its power sector, meeting the energy needs of industrial, residential, agricultural, commercial and institutional consumers. Its power mix is diverse, including thermal, hydro, solar, and wind power plants, underscoring its commitment to sustainable energy. Innovative policies such as incentives for renewable energy adoption and the integration of cutting-edge technologies such as hybrid RE systems, and offshore wind have positioned Rajasthan at the forefront of India's green energy transition. Through continuous innovation and collaborative efforts, the power sector continues to advance, aiming to fulfil the growing energy demands of its population while paving the way towards a more sustainable and prosperous future.

2.1. Demand Scenario

Rajasthan saw a peak demand of 18,128 MW in the month of January in FY24, and total energy requirement in FY24 was 1,07,422.38 MUs. The following Figure 2 shows the monthly peak demand for FY24:

4 UIDAI; List of states and union territories of India by area - Wikipedia

5 RBI

6 Geographical analysis online | District Map

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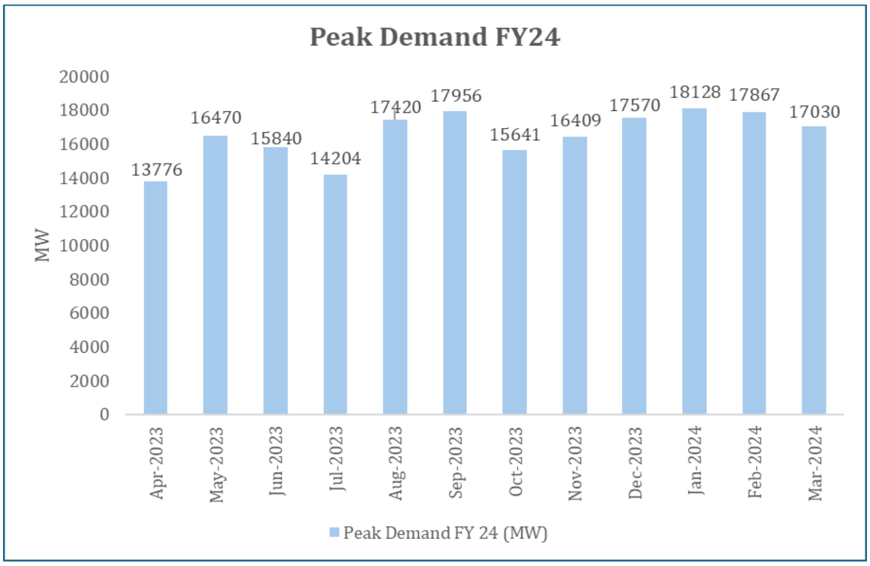

Figure 2: Rajasthan Month-wise Peak Demand of FY24[7]

It was observed that the actual peak demand in FY22 was marginally lower than CEA projections while in FY23 exceeded the projections outlined in CEA's 20th Electric Power Survey (EPS). The variance for FY22 was relatively small, FY23 was a bit larger and FY24 saw a substantial increase in peak demand only. Table 1 below provides a detailed comparison of actual and EPS projections:

Table 1: Actual v/s EPS Peak Demand and Energy Requirement[8]

Year	Energy Requirement (MUs)		Peak Demand (MW)	
	20th EPS	Actual	20th EPS	Actual
FY22	89,918	89,814	15,803	15,784
FY23	1,01,757	1,01,801	16,291	17,399
FY24	1,12,368	1,07,422	17,906	18,128

2.2. Supply Scenario

Rajasthan's energy landscape is defined by a diverse mix of energy sources. As of FY24, coal had an installed capacity of 14,429 MW, contributing 48% to the total installed capacity. On the other hand, RE contributed 39% to the total installed capacity, with 6,721 MW of solar and 4,935 MW of wind[9]. This RE-rich resource mix underscores Rajasthan's commitment to sustainability and a transition towards cleaner and more resilient power generation. With abundant solar and wind resources, the state continues to lead in renewable energy development, fostering a greener and more sustainable energy future. On the generation side, as of FY24, coal makes up 69% of the total generation, with RE contributing 20%. The following **Error! Reference source not found.** shows Rajasthan's installed capacity and generation mix:

7 CEA Dashboard- Rajasthan state

8 20th EPS, CEA Dashboard- Rajasthan state

9 Received from state, MERIT order updated

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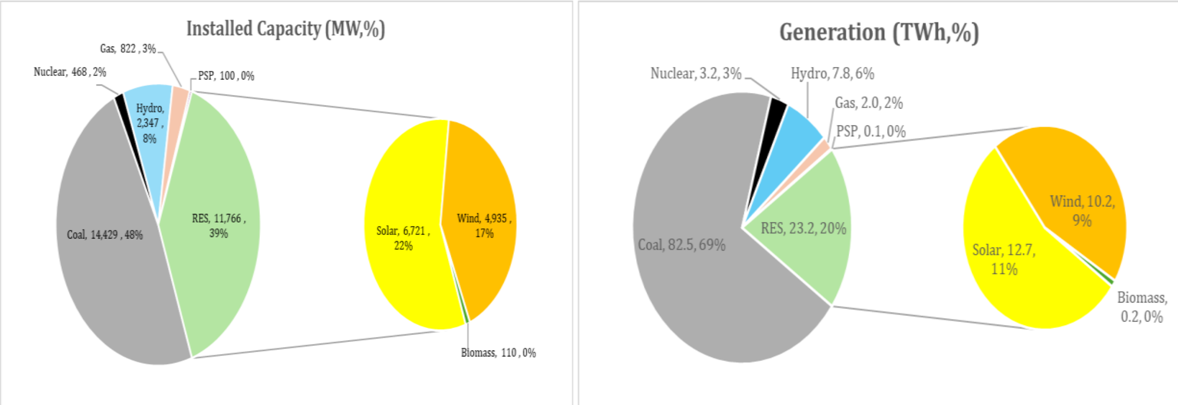

Figure 3: Installed Capacity[10] & Generation Mix of Rajasthan for FY24[11]

Given the rapidly growing demand and increasing share of renewable energy (RE), Rajasthan is set to emerge as a national leader in solar power generation, renewable energy development and continues to harness its vast natural resources to diversify its energy portfolio. Therefore, it is crucial for Rajasthan to prepare for vRE and its associated challenges by implementing RA. The following chapter provides an overview of RA, highlighting its key aspects and the reliability metrics involved.

10 Received from state

11 Received from state

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3. Resource Adequacy: A New Paradigm

Resource Adequacy (RA) entails the planning of generation and transmission resources for reliably meeting the projected demand in compliance with specified reliability standards for serving the load with optimum generation mix. This would also facilitate the scaling of RE while considering the need, inter alia, for flexible resources, storage systems for energy shift, and demand response measures for managing the intermittency and variability of RE sources. RA analysis provides the tools to determine whether there are enough resources and, if not, what type of resource is needed to meet reliability needs and contract these capacities. At the same time, any surplus resulting from the analysis would facilitate the trading of the same with other entities ensuring optimal capacity utilization.

3.1. Why do we need Resource Adequacy (RA)?

The evolving power sector necessitates a robust and adaptive framework to ensure resource adequacy and grid reliability. Several critical factors highlight the need for RA:

- **Transition to RE:** The energy sector is undergoing an aggressive shift towards RE sources like solar and wind. While these sources are clean and sustainable, they introduce challenges such as intermittency and variability, which can disrupt grid stability. A reliable planning framework is essential to effectively integrate RE while ensuring consistent power supply.
- **Changing grid dynamics:** With the rise of RE, conventional thermal power plants are now required to operate more flexibly, frequently ramping up or down to balance vRE generation. Additionally, modern grids experience bidirectional power flows due to distributed energy resources like rooftop solar. This complexity necessitates a more dynamic and resilient planning approach.
- **Diverse energy mix and emerging demand drivers:** India's energy mix is becoming increasingly diverse and variable, with contributions from coal, gas, nuclear, hydro, and renewables. Simultaneously, new demand drivers such as electric vehicles (EVs), data centers, green hydrogen production, and solar technologies are reshaping energy consumption patterns. Climate and weather variability also significantly impact energy demand and renewable generation, requiring adaptive planning tools to account for these fluctuations. This has introduced dual variability in both supply and demand, presenting a new phenomenon that needs to be effectively addressed for ensuring grid reliability and stability.
- **Coincident peak challenges:** One significant challenge is managing coincident peak demands, where the combined peak demand of multiple states exceeds the national peak. For example, individual state peaks may occur at different times, creating complexities in resource allocation, capacity sharing, and transmission planning. Without proper coordination, this can lead to either resource under-utilization or excessive capacity additions. Addressing these challenges requires a structured approach like RA to align state and national grid planning effectively.
- **Limitations of current demand forecasting:** Existing forecasting methods, such as those based on the Compound Annual Growth Rate (CAGR), are insufficient to capture the dynamic and region-specific changes in demand patterns. This can result in either underestimation or overestimation of resource requirements, leading to inefficiencies.
- **Planning gaps and lack of synergy:** A significant challenge in the current energy planning framework is the disconnect between long-term planning, as outlined in the National Electricity Plan (NEP), and short-term planning, as reflected in the Load Generation Balance Report (LGBR). This misalignment results in inadequate coordination between capacity addition, transmission infrastructure development, and overall resource planning. Such gaps can lead to inefficiencies, delays in project implementation, and insufficient infrastructure to support growing energy demands. Ultimately, this lack of synergy poses a risk to grid stability, especially as the power system evolves to accommodate higher shares of renewable energy and more complex operational

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requirements. Addressing this disconnect is critical to ensuring a resilient, and reliable electricity grid.

- **Grid reliability and security:** Ensuring grid stability under all conditions, especially during stress scenarios, requires a forward-looking framework. As the power system becomes more complex and interconnected, RA plays a vital role in maintaining grid security and meeting demand reliably.

3.2. Key Features of RA

Some of the key features of resource adequacy are discussed as follows:

- **Tool for resource assessment**: RA provides framework to evaluate the adequacy of the existing resource mix and identify gaps in capacity.
- **Addressing coincident peak challenges:** RA specifically addresses the complexities of coincident peaks, ensuring that capacity planning accounts for both state-level and national-level peak demands. By optimizing resource sharing among states and aligning resource planning, it avoids overbuilding or underutilization.
- **Shared responsibility:** RA encourages collaboration between states, utilities, grid operators, regulators, and other stakeholders, enabling efficient sharing of generation capacity and reducing costs.
- **Maximizing resource utilization:** RA focuses on increasing the utilization of existing infrastructure, reducing waste, and enhancing cost-effectiveness.
- **Transmission and capacity alignment:** Transmission infrastructure often lags capacity additions, creating bottlenecks. RA emphasizes synchronized planning to ensure transmission systems can support new capacity efficiently.

Implementing RA helps stakeholders ensure a reliable balance of supply and demand, maintain grid security, and optimize resource utilization. It also provides a forward-looking perspective, enabling power systems to adapt to emerging challenges, including fluctuating demand, resource availability, and system stress.

3.3. Guiding Principles of RA

Figure 4: Guiding Principles of RA

Ensuring RA in power systems requires a structured approach guided by key principles that balance reliability, cost-efficiency, and adaptability. These guiding principles provide a comprehensive framework for addressing capacity shortfalls while fostering sustainable energy solutions. Below is an elaboration on the critical aspects of RA:

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- **Assessment of RA**

A thorough and comprehensive assessment of RA involves quantifying the size, frequency, duration, and timing of potential capacity shortfalls. This detailed evaluation is essential to design effective resource solutions.

  - **Size:** Identifying the magnitude of the capacity gap during peak and off-peak periods helps prioritize investments and procurement strategies.
  - **Frequency:** Understanding how often capacity shortages occur enables system operators to plan for recurring events and avoid over-provisioning.
  - **Duration:** The length of time a shortfall persists directly impacts the type of resources required, such as fast-ramping capabilities or long-duration storage.
  - **Timing:** The seasonal, daily, or hourly nature of shortfalls provides insights into resource alignment with demand patterns, allowing for more precise capacity planning.

By systematically assessing these parameters, utilities can tailor their resource portfolios to address gaps effectively without overbuilding infrastructure.

- **Static vs. Dynamic Approaches**

The traditional static approach of designing systems to meet peak demand using a fixed Planning Reserve Margin (PRM) is becoming outdated in today's dynamic energy landscape. Modern RA planning requires a shift toward dynamic methodologies that better reflect evolving grid conditions.

  - **Dynamic RA Planning:** Following methodology from the RA guidelines, will give us more dynamic PRM value which meets the other reliability criteria, thus catering for contingencies.
  - **Scenario-Based Analysis:** Dynamic approaches leverage scenario modeling to simulate various future outcomes, ensuring the system remains reliable under diverse conditions.

- **Resource Diversity**

The diversity of energy resources plays a pivotal role in achieving optimal and least-cost resource adequacy. Each resource type brings unique capabilities that contribute to system stability and flexibility.

  - **Renewable Resources:** Solar and wind offer clean, cost-effective energy but require complementary resources due to their variability.
  - **Energy Storage:** Battery storage systems provide critical support by balancing short-term fluctuations and enhancing grid stability.
  - **Demand Response:** Demand-side management helps align consumption with resource availability, reducing peak load pressures.
  - **Flexible Generation:** Conventional plants with flexible ramping capabilities support the integration of intermittent resources.

  By strategically combining diverse resources, planners can create a balanced portfolio that maximizes system efficiency while minimizing costs and emissions

- **Sharing of Resources**

Isolated planning and operation of resources can lead to overcapacity and inefficient operations. A collaborative approach to resource sharing is essential for reducing overall system costs and enhancing regional reliability.

3.4. Key Steps in RA

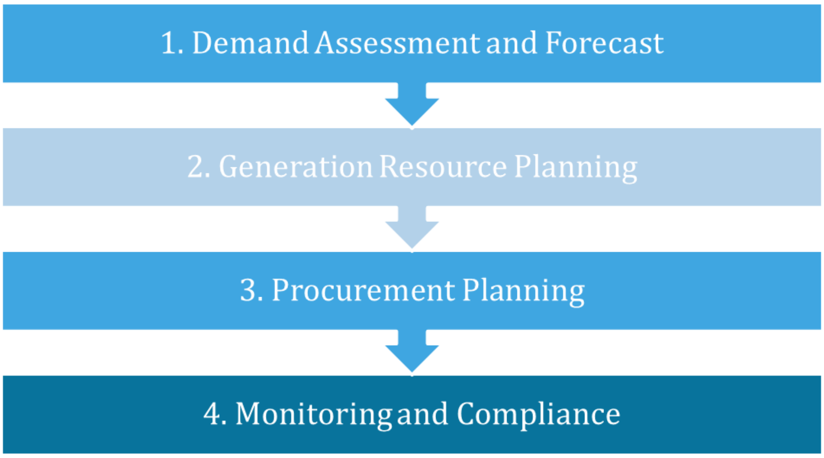

Figure 5: Key Steps in RA

Below are the steps in RA:

1 **Demand Assessment and Forecasting:**

- Purpose: Forecast peak demand (MWs) and energy requirement (MUs) over short (1 year), medium (5 years), and long-term (10 years) horizons considering various input parameters.
- Prevailing Practices:
  - Current Methods: Non-uniform and simplistic across discoms and states, often relying on CAGR-based calculations.
  - Need for Scientific Approach: An analytical approach with detailed hourly resolution is essential for realistic planning, considering demands such as electric vehicles (EVs), distributed energy resources (DERs), and weather changes.
- Methodology:
  - Use weather data, historical consumption, categories of consumer, econometric data, policies, and other drivers.
  - Distribution licensees should conduct hourly demand assessment and forecasting for rolling short-term and medium-term horizons, using the latest Electricity Power Survey (EPS) as a base.
  - State Transmission Utilities (STU) and State Load Dispatch Centres (SLDC) should aggregate forecasts and submit state-level short-term and medium-term forecasts to the Central Electricity Authority (CEA) and National Load Dispatch Centre (NLDC).

2 **Generation Resource Planning:**

- **Capacity Crediting (CC):**
  - Definition: CC represents the amount of power a resource can provide during peak hours.
  - Methodology:
  - Top Demand Hours: Capacity credit is estimated by averaging a generator's historical contribution during peak demand hours. The number of peak hours considered may vary by region.
  - Top Net Load Hours: Focuses on system stress when high demand coincides with low renewable generation. Net load, calculated as total demand minus

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renewable generation, is used as a better proxy for system stress. Capacity credit is averaged during these critical hours.

- Expected Load Carrying Capability (ELCC): A detailed method using hourly demand and generation data, incorporating random generator outages based on historical and expected conditions

- **Planning Reserve Margin (PRM):**
    - Definition: PRM is the percentage of resources available over the peak demand to ensure reliability.
    - Metrics: Loss of Load Probability (LOLP) and Expected Energy Not Served (EENS) are used to gauge reliability.
- **RA Requirement and Allocation:**
    - Calculate RA requirements based on forecasted demand, existing resources (discounted by their capacity credit), and PRM. Optimize these requirements at the national/regional level and allocate them down to states and demand-serving entities.
    - Formulations:
        - State Peak with PRM: RA Requirement = State Peak (1 + PRM)
        - Regional Peak with PRM: RA Requirement = Coincident Peak Demand (1 + PRM)

3 Procurement Planning:

- Procurement Resource Mix:
    - Objective: Identify the resource mix to meet RA requirements and Renewable Purchase Obligations (RPO), ensuring reliability and avoiding stranded assets by using optimization and least-cost energy modeling techniques.
- Procurement Type and Tenure:
    - Objective: Ensure the type and duration of procurement contracts
- Capacity Trading/Sharing Constructs:
    - Objective: To optimize resource utilization and minimize costs

4 Monitoring and Compliance:

- Objective: Develop an overarching framework to ensure smooth implementation of the RA framework.
- Components: Monitoring and reporting, verification and regulatory oversight, and treatment for shortfalls in short-term and medium-term compliance.
- Recommendation: STUs/SLDCs should communicate state-level shortfalls to SERCs. Distribution licensees should address shortfalls through national capacity auctions or bilateral contracts. SERC can determine non-compliance charges for shortfalls against RA requirements.

3.5. Reliability Metrics[12]

To ensure a reliable power system, various reliability metrics are employed to assess the adequacy of generation resources. These metrics quantify the system's ability to meet demand under normal and contingency conditions. Below is a detailed explanation of the key reliability metrics:

- **Loss of Load Probability (LoLP)** measures the likelihood that electricity demand may exceed available generation capacity at any given time during the year. It serves as a key indicator of supply shortages due to insufficient capacity or unexpected outages. A typical reliability target for LoLP is less than 0.2%, meaning that the risk of supply inadequacy is acceptable only for a very

12 CEA Guidelines: RA Framework

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small portion of the year. This metric is critical for planning the balance between supply and demand to minimize load shedding risks.

- **Expected Energy Not Served (EENS)** quantifies the total energy shortfall (in megawatt-hours) that is anticipated over a year due to supply inadequacies. Unlike LoLP, which measures the probability of a shortfall, EENS captures its severity by estimating the amount of unmet demand.
- **Normalized Energy Not Served (NENS)** builds on EENS by normalizing the energy shortfall against the system's total demand, providing a percentage-based measure of reliability. A system is generally considered reliable if NENS remains below 0.05%, indicating that only a very small fraction of total demand is unmet. NENS is particularly useful for comparing reliability across systems with varying sizes and demand profiles.
- **Planning Reserve Margin (PRM)** represents the percentage of additional generation capacity maintained above the system's peak demand. This buffer ensures reliability during unexpected events, such as generator outages or demand surges. While higher PRMs improve system reliability, they also increase costs, necessitating a careful balance to achieve optimal performance. PRM serves as an essential planning tool to account for uncertainties and maintain system resilience.

RA plays a pivotal role in ensuring the reliability of power systems, especially in an era of increasing renewable energy integration and evolving grid dynamics. The detailed analysis of RA not only highlights its importance but also underscores the necessity of comprehensive planning to address challenges like intermittency, coincident peak demands, and grid reliability.

Building on this foundational understanding, the following sections delve into the FOR State Model Regulations for RA framework which applies to every state, and was introduced in June 2023. These regulations align with national directives and aim to establish a robust framework for resource planning.

4. FoR Model Regulations for RA Framework

The Forum of Regulators (FoR) has notified the Resource Adequacy Framework for State model Regulations, June 2023. The Regulations aim to ensure reliable electricity supply by planning generation and transmission resources to meet projected demand, while also optimizing the generation mix and integrating renewable energy sources.

- **Scope and Applicability:**

It explicitly identifies the entities that are subject to these regulations which include:

  - Generating Companies: Businesses involved in electricity production.
  - Distribution Licensees: Entities responsible for distributing electricity to consumers.
  - State Load Dispatch Centre (SLDC): The entity responsible for maintaining real-time grid balance and reliability.
  - State Transmission Utility (STU): The utility responsible for developing and maintaining the state's transmission infrastructure.
  - Other Grid-Connected Entities: Any other organizations directly connected to the electricity grid.
  - Stakeholders within the State: any other relevant stakeholders within the State.

- **Core Concept of Resource Adequacy Framework:**
  - The RA framework is fundamentally about proactive planning for generation and transmission resources.
  - The goal is to guarantee the reliable fulfillment of projected electricity demand.
  - This must be achieved while adhering to established reliability standards.
  - It also highlights the importance of optimizing the generation mix, potentially favoring cleaner and more efficient energy sources.

- **Key Steps in RA process:**

This outlines the essential components of a successful RA framework:

  - Demand Assessment and Forecasting: Accurately predicting future electricity needs.
  - Generation Resource Planning: Strategically planning for the generation resources required to meet demand.
  - Procurement Planning: Planning how to acquire the necessary resources, whether through new construction, contracts, or other mechanisms.
  - Monitoring and Compliance: Continuously monitoring the system to ensure it remains adequate and that all participants comply with the regulations.

- **Time Horizons: Planning for the Future:**

The regulations define two key planning timeframes:

  - Medium Term: A period extending up to five years, allowing for strategic planning and resource development.
  - Short Term: A period of up to one year, focusing on near-term resource adequacy and operational considerations.

- **Distribution Licensee Responsibilities: Front-line Planning:**
  - This places a specific obligation on distribution licensees.
  - They are required to develop and maintain both Medium-Term Distribution Resource Adequacy Plans (MT-DRAPs) and Short-Term Distribution Resource Adequacy Plans (ST-DRAPs). This ensures that those closest to the end consumers are actively involved in resource adequacy planning.

- In the following sub-sections key chapters from FOR Chapter are covered.
  - Demand Assessment and Forecasting
  - Generation Resource Planning

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- Power Procurement Planning
- Monitoring and Compliance
- Roles and Responsibilities

4.1. Demand Assessment and Forecasting

This section provides detailed guidance on how distribution licensees should forecast electricity demand, a critical foundation for effective resource planning.

4.1.1. Long-term and Medium-term Demand Forecast

- Importance: Emphasizes that accurate demand forecasting is a cornerstone of resource adequacy. If demand is underestimated, the system may face shortages; if overestimated, resources may be underutilized, leading to economic inefficiencies.
- Granularity: Specifies that demand assessment and forecasting should be conducted at an hourly or even sub-hourly level. This granular approach is essential for capturing peak demand periods and accurately modeling the variability of electricity consumption.
- Responsibility: Clearly assigns the responsibility for demand forecasting (both in terms of MW and energy MWh) to the distribution licensee within its defined control area.
- Consumer Categories: Requires separate load forecasts for each distinct consumer category that has its own retail tariff. This allows for a more tailored and accurate prediction of demand based on the specific characteristics of different customer groups (e.g., residential, commercial, industrial).

- **Demand Forecasting Methodologies:**

Distribution licensees are tasked with preparing demand forecasts for their respective areas. This includes historical data maintenance and consumer category-specific load forecasts, as per the Commission's guidelines. To determine the forecast, licensees can use various methodologies, including:

- Compounded Average Growth Rate (CAGR): A simple method that projects future demand based on historical growth rates.
- End Use or Partial End Use: A more detailed approach that models demand based on the specific end uses of electricity (e.g., lighting, appliances, heating).
- Trend Analysis: Identifying and extrapolating historical trends in electricity consumption.
- Auto-regressive Integrated Moving Average (ARIMA): A statistical time series model that captures the autocorrelation in historical demand data.
- AI including machine learning, ANN techniques: Using advanced AI and machine learning techniques to identify patterns and predict future demand.
- Econometric Modeling: Building statistical models that relate electricity demand to economic factors (e.g., GDP, population, employment).

These methodologies must align with the guidelines issued by the Authority and demonstrate statistical reliability through low standard deviations and high R-squared values.

- **Method Selection:**

Stresses the importance of statistical analysis in selecting the most appropriate forecasting method. The method with the lowest standard deviation and highest R-squared value (indicating a good fit to historical data) should be chosen.

- **Comprehensive Data Utilization:**

Distribution licensees must adopt state-of-the-art tools and consider diverse datasets, such as:

- Weather data
- Demographic and econometric data
- Consumption profiles
- Policy impacts

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  - This data-driven approach ensures the forecasts are accurate and context-sensitive.

- **Load Modifications and Influences:**

Forecasts must account for permanent impacts on demand due to factors like:

  - Demand-Side Management (DSM): Programs designed to reduce or shift electricity demand.
  - Open Access: The ability for consumers to choose their electricity supplier, which can affect load patterns.
  - Distributed Energy Resources (DER): Small-scale generation sources located close to consumers (e.g., solar panels, microgrids).
  - Electric Vehicles (EVs): The growing adoption of EVs can significantly increase electricity demand.
  - Tariff Signals: The design of electricity tariffs can influence consumer behavior and demand patterns.
  - Changes in specific energy consumption: Improvements in energy efficiency can reduce overall demand.
  - Increase in commercial activities with electrification: Increasing the electrification of business and commercial operations.
  - Increase in the number of agricultural pumps sets and its solarization: Greater use of electric pumps for irrigation.
  - Changes in consumption patterns from seasonal consumers: Changes to seasonal loads.
  - Availability of supply: Impact of supply availability on demand
  - Policy influences: Government policies related to 24x7 power for all, promotion of LED lighting, efficient appliances, electrification policies, distributed generation, energy storage, and the National Hydrogen Mission.

- **Refinement Based on Load Research:**

This allows for the refinement of medium-term load profiles based on detailed load research analysis.

- **Load Forecast Calculation:**

This describes how to calculate the overall load forecast for the licensee. This involves summing the energy forecasts for all consumer categories and adjusting for factors such as captive generation, prosumer activity, and open access.

- **Loss Trajectory:**

Specifies that an approved loss trajectory (representing electricity losses in the distribution system) must be added to the energy forecast.

- **Peak Demand Determination:**

Explains how to determine peak demand, which is crucial for resource adequacy planning. This involves using load factors, diversity factors, and seasonal variations to estimate the maximum electricity demand that the system will experience.

- **Sensitivity and Probability Analysis:**

Requires that distribution licensees conduct sensitivity and probability analysis to assess the uncertainty in their demand forecasts. This involves developing multiple scenarios (e.g., most probable, business as usual, aggressive) to account for different potential outcomes.

4.1.2. Short term (Hourly/Sub-hourly) Demand Forecast and State level Aggregation

The distribution licenses must submit hourly/sub-hourly 1-year short-term (ST) and 5-year medium-term (MT) forecasts to SLDC by April 30th each year.

The SLDC aggregates these forecasts, ensuring considerations like load diversity, seasonal variations, and voltage-level distinctions. The aggregated demand forecasts, with detailed breakups and loss trajectories, are submitted to NLDC, SRLDC, and other relevant authorities by May 31 each year.

This systematic process ensures that the demand forecast is not only accurate but also resilient to variability, paving the way for effective resource adequacy planning.

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4.2. Generation Resource Planning

Generation resource planning is the second key step after demand assessment and forecasting. It focuses on evaluating existing and contracted generation resources, determining their effective capacity (capacity crediting), identifying any capacity gaps relative to forecasted demand, and developing plans to acquire the necessary additional resources. This process also incorporates the crucial aspect of planning for a reserve margin to ensure system reliability.

4.2.1. Key Steps in Resource Planning

The generation resource planning process can be broken down into three primary stages:

- **Capacity Crediting of Generation Resources:** This involves determining the actual contribution of each generation resource (existing and planned) to meet peak demand. It acknowledges that the nominal capacity of a power plant may not always be fully available due to factors like maintenance, weather conditions (for renewables), or fuel availability.
- **Assessment of Planning Reserve Margin (PRM):** The PRM is a percentage of peak load that represents the extra generation capacity required to maintain system reliability. It acts as a buffer against unforeseen events such as unexpected outages, forecast errors, and fluctuations in renewable energy generation.
- **Ascertaining Resource Adequacy Requirement and Allocation:** This stage involves comparing the available capacity (after capacity crediting) plus the planned reserve margin with the forecasted demand. Any difference represents the resource gap that needs to be addressed. This gap is then allocated to different entities within the control area (regional/state), defining their responsibility for acquiring new generation resources.

4.2.2. Resource Mapping and Characteristics

A fundamental component of generation resource planning is the creation of a detailed inventory of all contracted generation resources. This "resource map" should encompass existing resources, those currently under construction or planned, and those slated for retirement. It is crucial to consider both long-term and medium-term horizons. For each resource, the following characteristics must be documented:

- Thermal Power Plants: Heat rate (efficiency), auxiliary power consumption, ramp-up and ramp-down rates (how quickly they can change output), fuel type, and emissions profile.
- Hydropower Plants: Hydrology data (water availability), reservoir capacity (for storage-based hydro), turbine characteristics, and environmental impacts.
- Renewable Energy Sources (RES): Capacity factors or CUFs (Capacity Utilization Factors – representing the actual energy produced as a percentage of potential energy), intermittency characteristics (variability of solar and wind resources), location-specific resource availability, and land use requirements.

This detailed characterization is essential for accurate modeling and analysis of the power system.

4.2.3. Constraint Identification

Generation resource planning must operate within a set of constraints that influence decision-making. These include:

- Penalties for Unmet Demand: Financial penalties for failing to supply electricity to consumers.
- Forced Outages: The unplanned unavailability of generation resources due to equipment failures.
- Spinning Reserve Requirements: Capacity that must be online and immediately available to respond to sudden changes in demand or generation.
- System Emission Limits: Regulations on emissions of pollutants from power plants (e.g., NOx, SOx, particulate matter). These are typically set by environmental agencies.
- Grid Stability and Reliability: Constraints related to maintaining voltage stability, frequency stability, and overall grid security.

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4.2.4. Planning Reserve Margin (PRM) Assessment:

The PRM is a critical element of resource planning. It is designed to ensure a certain level of reliability, typically expressed in terms of metrics like:

- Loss of Load Probability (LOLP): The probability that the system will be unable to meet demand at some point in time.
- Normalized Energy Not Served (NENS): The expected amount of energy that will not be supplied due to capacity shortages.

The appropriate PRM level is determined by considering the desired reliability level, the variability of demand and renewable generation, and the potential for forced outages. It is often set by regulatory authorities.

4.2.5. Capacity Crediting of Generation Resources

Capacity crediting is a crucial step to accurately reflect the contribution of each generation resource. The net load-based approach, as described in the provided text, is a common method for determining capacity credits for variable renewable energy sources (VRE) like solar and wind. It accounts for the fact that these resources may not be available during peak demand periods.

- Net Load Approach Details: The method compares the system load with and without the VRE generation. By analyzing the top load hours, it determines how much the VRE actually contributes during periods of high demand. This contribution is then used to calculate the capacity credit.
- Hydro and Thermal Capacity Crediting: For hydropower, capacity crediting considers water availability and the type of hydro plant (run-of-river vs. storage). Thermal power plants are assessed based on their historical performance, including forced outage rates and fuel availability.

4.2.6. Resource Adequacy Requirement and Allocation

Once capacity credits are determined and the PRM is established, the resource adequacy assessment can be performed.

- Resource Gap Calculation: The projected demand, including the PRM, is compared to the available capacity from existing and planned resources (after capacity crediting). Any difference is the resource gap.
- Scenario Analysis: It's essential to conduct scenario analysis to account for uncertainties in demand growth, fuel prices, technology costs, and regulatory changes. Multiple scenarios (e.g., low growth, base case, high growth) should be considered.
- Medium-Term and Short-Term Planning: Resource adequacy plans are typically developed for both the medium term (several years out) and the short term (the next year). These plans outline how the resource gap will be addressed, including the procurement of new generation resources, demand-side management programs, and other measures.
- Allocation of Resource Adequacy Requirements: The responsibility for meeting the identified resource gap is often allocated to different entities, such as distribution licensees or other load-serving entities. This allocation may be based on their contribution to peak demand or other factors.
- Regulatory Oversight and Approval: The generation resource planning process is typically subject to regulatory oversight. Distribution licensees are required to submit their resource plans to the relevant regulatory commission for review and approval. The commission ensures that the plans are consistent with regulatory requirements and are in the best interests of consumers.

4.3. Power Procurement Planning

Power procurement planning involves identifying the optimal mix of generation resources, determining appropriate procurement types and durations, and engaging in capacity trading or sharing to mitigate risks of resource shortfalls while minimizing stranded capacity.

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4.3.1. Procurement of Resource Mix

A crucial element of procurement planning is identifying the optimal generation resource mix. This mix should:

- Facilitate RE Integration: Prioritize resources that enable the smooth integration of renewable energy sources (RES) into the overall portfolio. This requires considering the intermittency of RES and ensuring sufficient dispatchable generation to balance fluctuations.
- Minimize Costs and Avoid Stranded Assets: Employ optimization techniques and least-cost modeling to identify the most cost-effective resource mix and avoid investments in generation assets that may become underutilized or obsolete (stranded assets). The distribution licensee must demonstrate the use of these techniques in their procurement plan submitted for approval.
- Align with National Policies**:** Procurement decisions must be consistent with the overall national electricity plan and relevant policies issued by the government.

4.3.2. Procurement Type and Tenure:

Distribution licensees must carefully consider the type and duration of their procurement contracts.

- Prioritize Regional Resources: Initially, available generation capacity within the region should be optimized. Procurement from outside the region should only be considered if it offers a lower cost alternative, considering transmission constraints and costs.
- Long-Term, Medium-Term, and Short-Term Strategies: A comprehensive procurement strategy must address all three horizons:
  - Long-Term: Focus on securing reliable capacity for future demand growth, often through long-term power purchase agreements (PPAs) for base-load generation.
  - Medium-Term: Address anticipated changes in demand or generation availability, potentially through medium-term contracts or capacity auctions.
  - Short-Term: Manage short-term fluctuations in demand and generation, utilizing mechanisms like spot markets or bilateral trading.
- Emphasis on Long and Medium-Term Arrangements: Greater emphasis should be placed on long and medium-term contracts to ensure resource adequacy and price stability.
- Annual Rolling Plan: An annual rolling plan should assess incremental capacity addition requirements, considering existing and planned procurement initiatives.
- Timelines: Capacity contracting should be completed by November 30th each year. The Annual Rolling Plan must be submitted to the STU/SLDC by December 31st. State-level aggregated plans are submitted to RLDCs by January 31st, and regional plans are submitted to the NLDC by the same date.

4.3.3. Sharing of Capacity

Capacity sharing can play a significant role in optimizing resource utilization and minimizing costs.

- Short-Term Capacity Sharing: Distribution licensees should incorporate the possibility of short-term capacity sharing into their resource adequacy plans.
- Inter-State Capacity Sharing/Trading: Utilize available platforms for inter-state capacity sharing or trading to optimize capacity costs.
- Information Sharing: Contracted capacity information must be submitted to the SLDC and STU for compliance verification.

The procurement plan and the Annual Rolling Plans require approval from the relevant regulatory commission. This ensures transparency and oversight of the procurement process.

- Submission of Agreements: New or amended long/medium-term power purchase agreements must be approved by the Commission. Distribution licensees must submit a list of all existing power purchase agreements to the Commission along with the Resource Adequacy plan.

4.4. Monitoring and Compliance

Monitoring and Reporting

Effective monitoring and reporting are essential for tracking progress toward resource adequacy and identifying potential shortfalls.

- Role of STU and SLDC: The State Transmission Utility (STU) and the State Load Dispatch Centre (SLDC) play a crucial role in monitoring resource adequacy at the state level.
- Communication of Shortfalls: Based on the Medium-Term Distribution Resource Adequacy Plan (MT-DRAP) and the Short-Term Distribution Resource Adequacy Plan (ST-DRAP), the STU and SLDC are responsible for identifying and quantifying any state-aggregated capacity shortfalls.
- Reporting to the State Commission: The STU and SLDC must communicate these identified shortfalls to the State Electricity Regulatory Commission by September 30th of each year for the following year(s). This report should provide a clear picture of the projected resource gap and its potential impact on system reliability.
- Advising Distribution Licensees: In addition to reporting to the Commission, the STU and SLDC will also advise the distribution licensees regarding the need to commit additional generation capacity to address the identified shortfalls. This communication should be timely and provide specific guidance on the amount of capacity required.

Treatment for Shortfall in RA Compliance

Maintaining resource adequacy is a critical obligation for distribution licensees. Clear consequences for non-compliance are necessary to ensure that licensees take the necessary steps to secure sufficient resources.

- Obligation to Comply: Distribution licensees are obligated to comply with the RA requirements established by the Commission. This includes procuring sufficient generation capacity to meet their share of the forecasted peak demand plus the required planning reserve margin.
- Non-Compliance Charges: If a distribution licensee fails to meet the RA requirements, appropriate non-compliance charges will be applied to the shortfall. These charges serve as a financial penalty for failing to maintain adequate resources and incentivize compliance.
- Calculation of Charges: The methodology for calculating non-compliance charges should be clearly defined by the Commission. It might consider factors such as the magnitude of the shortfall, the duration of the shortfall, and the potential impact on system reliability.
- Use of Funds: The revenue generated from non-compliance charges could be used for purposes that benefit the electricity system or consumers, such as supporting the development of renewable energy projects, funding energy efficiency programs, or reducing consumer electricity rates.
- Transparency and Enforcement: The monitoring, reporting, and enforcement of RA compliance should be conducted in a transparent manner. Clear guidelines and procedures should be established and made publicly available. The Commission plays a vital role in overseeing compliance and ensuring that non-compliance charges are applied consistently and fairly.

4.5. Roles, Responsibilities and Timelines

Effective implementation of RA requires clear roles and responsibilities among various stakeholders, along with well-defined timelines for data sharing and planning. Coordination between distribution licensees, State Load Dispatch Centers (SLDCs), State Transmission Utilities (STUs), and regulatory bodies is essential to ensure accurate demand forecasting, capacity planning, and compliance with RA requirements. This section outlines the key responsibilities of different entities, the data-sharing framework, and the timelines for submission and assessment of RA plans.

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4.5.1. Data Requirement and Sharing Protocol

Accurate and comprehensive data is fundamental to informed decision-making in resource planning. A clear data sharing protocol ensures that relevant information is available to all stakeholders.

Data Sharing by Distribution Licensees (with STU/SLDC): Distribution licensees are responsible for maintaining and sharing a wide range of data related to demand assessment and forecasting. This includes:

- Consumer Data: Detailed information about their customer base, including demographics, consumption patterns, and load profiles.
- Historical Demand Data: Past electricity consumption data, including hourly, daily, and seasonal variations.
- Weather Data: Historical and projected weather data, including temperature, humidity, and solar irradiance.
- Demographic and Econometric Variables: Data on population growth, economic activity, and other factors that influence electricity demand.
- T&D Losses: Data on transmission and distribution losses.
- Actual Energy Requirement and Availability: Information on actual electricity demand and supply, including any curtailments or outages.
- Peak Demand Data: Data on peak electricity demand and the time at which it occurs.
- Demand Profile Changes: Information on any changes in demand patterns, such as shifts in agricultural practices, time-of-use tariffs, or changes in industrial activity.
- Historical Hourly Load Shape: Hourly electricity consumption profiles for different customer segments.

Data on Policies and Drivers: Distribution licensees must also maintain and share data on factors influencing electricity demand, including:

- Penetration of Energy-Efficient Technologies: Data on the adoption of LED lighting, efficient fans, and other energy-saving appliances.
- Electrification Trends: Information on the increasing use of electric appliances for cooking and other purposes.
- Commercial Activity Growth: Data on the growth of commercial activities in different areas.
- Agricultural Pumping and Solarization: Information on the number of agricultural pumps and the adoption of solar-powered irrigation.
- Changes in Specific Energy Consumption: Data on changes in energy consumption per unit of output in different sectors.
- Consumption Patterns of Seasonal Consumers: Data on the electricity consumption of seasonal consumers, such as tea plantations.
- Demand-Side Management (DSM) and Distributed Energy Resources (DERs): Information on the impact of DSM programs and the adoption of DERs (e.g., rooftop solar).
- Electric Vehicle (EV) and Open Access (OA): Data on the growth of EVs and the impact of open access on electricity demand.
- National Hydrogen Mission: Information on any initiatives related to the National Hydrogen Mission and their potential impact on electricity demand.
- AT&C Loss Reduction: Data on efforts to reduce Aggregate Technical and Commercial (AT&C) losses.

Historical Consumption Data: Distribution licensees must maintain at least 10 years of historical consumption data for various consumer categories:

- Domestic: Residential customers.
- Commercial: Businesses and commercial establishments.

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- Public Lighting: Street lighting and other public lighting.
- Public Water Works: Water pumping and distribution facilities.
- Irrigation: Agricultural pumping.
- LT Industries: Small-scale industries.
- HT Industries: Large-scale industries.
- Railway Traction: Electricity used for railway operations.
- Bulk (Non-Industrial HT Consumers): Large non-industrial consumers.
- Open Access: Customers who purchase electricity directly from the market.
- Captive Power Plants: Power plants owned and operated by industries for their own use.
- Load Survey Insights: Data and insights derived from load surveys.
- Contribution to Peak Demand: The contribution of each consumer category to peak demand.
- Seasonal Variation Aspects: Seasonal variations in electricity consumption for each category.

Data Sharing by SLDC: The SLDC is responsible for maintaining and sharing aggregated demand assessment and forecasting data at the state level. This data is shared with the State Electricity Regulatory Commission and the National Load Dispatch Centre (NLDC).

Generation Capacity Data: Distribution licensees share information about their existing and contracted generation capacities, including technical and financial characteristics and hourly generation profiles, with the STU and SLDC. This data is used for calculating state-level capacity credit factors and preparing state-level resource assessments.

Aggregated Generation Data: The SLDC and STU aggregate generation data and share state-level assessments with the State Commission and the NLDC for RA assessment.

RA Requirement Allocation: The STU communicates the allocation of regional and national RA requirements to the distribution licensees.

4.5.2. Implementation Timelines

Adherence to the following timelines is crucial for effective resource planning and RA assessment:

- Demand Forecast Submission (by Distribution Licensees to SLDC): April 30th of each year.
- State-Level Forecast Submission (by SLDC to Commission and NLDC): May 31st of each year.
- MT-DRAP and ST-DRAP Exercise (by Distribution Licensees): August 31st of each year.
- State-Level Aggregated Plan Submission (by STU and SLDC to NLDC): January of each year.

With the establishment of the foundational framework for RA through the FoR State Model Regulations, the focus now shifts to the practical methodologies employed in evaluating and ensuring resource adequacy. The following chapter provides a detailed examination of the various approaches and modeling philosophies utilized in the development of a capacity build model. This includes an exploration of both spreadsheet-based and detailed modeling approaches, with an emphasis on their respective roles in maintaining a reliable and cost-effective power system.

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5. Modeling Tools & Approaches

The following section outlines various tools and methodologies that can be applied for undertaking Resource Adequacy (RA) studies. With a primary objective of minimizing total system costs while ensuring the reliability and adequacy of the power system, this section provides an in-depth exploration of the principles guiding the modeling process.

5.1. Modeling Tools[13]

For comprehensive modeling, a variety of tools are available, each with their own unique capabilities. These tools are generally divided into three main categories: Capacity Expansion Models, Production Cost Models, and Generation Resource Adequacy Models. Each category has a specific function, depends on inputs, and produces distinct outputs.

1) **Capacity Expansion Models**
The primary focus of capacity expansion models is to guide decisions about future investments in power generation and transmission infrastructure. These models evaluate various factors, such as projected demand growth, available and planned generation assets, and evolving regulatory frameworks. By analyzing cost trends, fuel availability, and technological advancements, these models help stakeholders identify the optimal mix of investments. In addition to determining where new capacity is needed, they also help identify which existing assets may need to be retired, ensuring a cost-effective and sustainable energy supply.
2) **Production Cost Models**
Production cost models are designed to simulate the real-time operations of the power grid. These models analyze the performance of the power system under different conditions, factoring in demand patterns, fuel prices, and operational constraints. By considering elements such as network topology and regulatory policies, they offer insights into key operational metrics. These include the generation dispatch stack, system congestion, and the associated costs. Additionally, they assess the impact of renewable energy curtailments, emissions, and system reliability by measuring the potential loss of load.
3) **Generation Resource Adequacy Models**
Ensuring the availability of sufficient resources to meet demand is the focus of generation resource adequacy models. These tools analyze the system's capability to handle various scenarios, including unexpected outages and variable renewable energy generation. Using inputs such as demand profiles, network data, and outage statistics, these models calculate key adequacy metrics. Metrics such as Loss of Load Expectation (LOLE), Loss of Load Probability (LOLP), and Expected Energy Not Served (EENS) provide a comprehensive view of the system’s reliability.

The tools which can do all the above objectives are:

- Open Source:
  - GridPath
- Commercial
  - BID3
  - PLEXOS
  - PowerSIMM Planner

PLEXOS has been used in the RA study for Maharashtra presented in this report.

5.2. Modeling Philosophy

Detailed optimization modeling ensures that critical aspects of system operations are captured accurately. It allows for the simulation of different scenarios, testing whether the energy demand balance is achieved

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on an hourly or sub-hourly basis under varying conditions. Randomness in generation patterns, particularly for RE sources, as well as that in load patterns is incorporated using stochastic techniques, ensuring that system reliability is assessed against real-world uncertainties. This level of analysis offers a more complete understanding of resource adequacy and helps in identifying the most efficient and reliable pathways for capacity expansion.

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

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

PLEXOS has been used to assess the pathway for clean energy investments such that CEA's reliability standards are met from FY25 to FY34 for the state of Rajasthan. The model minimizes total generation cost (fixed plus variable) for the entire system, including existing and new generation capacity.

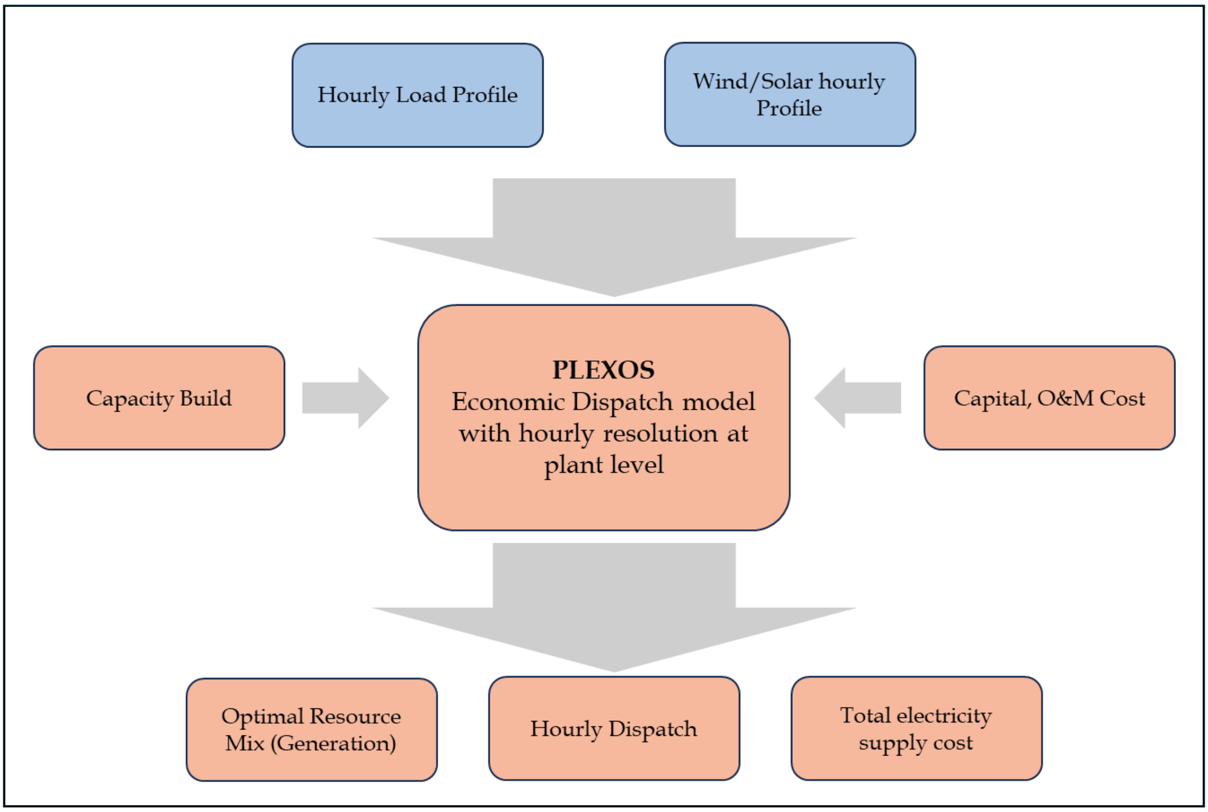

Figure 6: Modeling Philosophy

5.2.1. State Model Configuration

The Configuration model of the model in PLEXOS typically includes detailed representations of the state's power generation facilities, transmission network, demand profiles, RE integration as follows:

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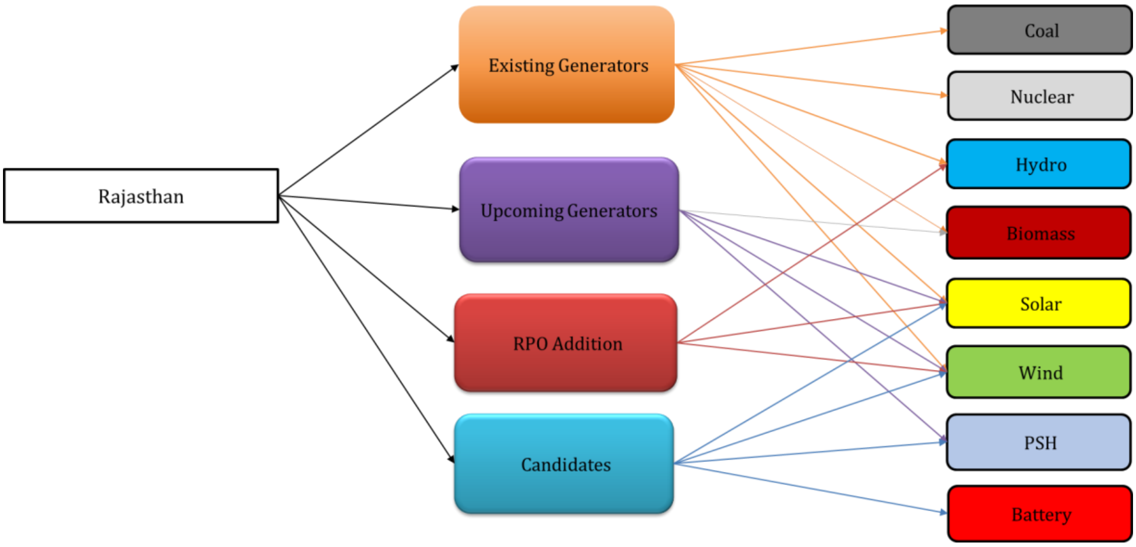

Figure 7: Rajasthan State Model Configuration in PLEXOS

5.2.2. Stage-wise Modeling

This flowchart outlines the steps involved in PLEXOS for evaluating capacity expansion and assessing YOY hourly dispatch outcomes. It emphasizes reliability criteria and ensures that the model's results align with specific standards or requirements.

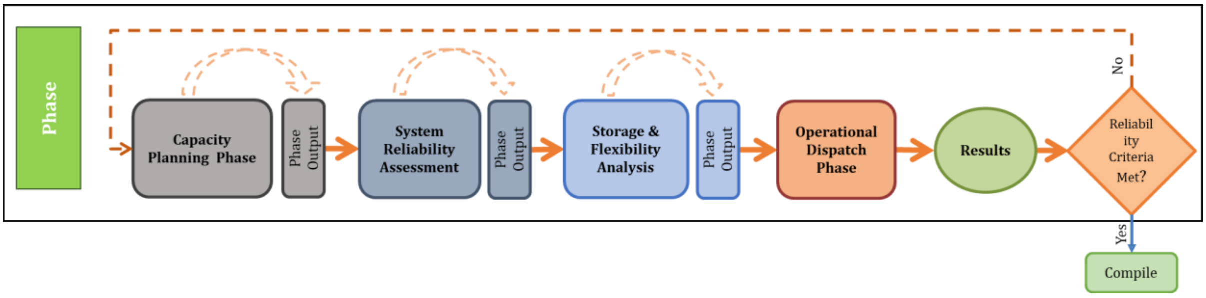

Figure 8: PLEXOS Stage-wise Modeling

1. **LT (Long Term Phase): Capacity Planning Phase**

The objective of this phase is to assess and plan the capacity expansion of the energy system, focusing on developing an optimized resource mix and strategizing the buildout of additional generation capacity to meet future energy demands. Key activities include capacity expansion modeling to identify the necessary growth in generation capacity, resource mix optimization to balance the integration of RE sources with cost-effectiveness, and system buildout planning to outline timelines and prioritize projects for implementation.

2. **PASA (Projected Assessment of System Adequacy): System Reliability Assessment**

The focus of this phase is to enhance the reliability of the power system by addressing maintenance schedules, system reliability metrics, and outage modeling. This involves developing and optimizing maintenance schedules to minimize disruptions to energy supply, evaluating reliability metrics such as LoLP to assess the system's ability to meet demand under various scenarios, and simulating potential outages to evaluate their impacts on system stability and reliability.

3. **MT (Medium Term): Storage & Flexibility Analysis**

This phase aims to evaluate medium-term operational decisions, with a focus on storage solutions and system flexibility. It involves analyzing the system's ability to adapt to variations in demand and supply, particularly with the growing integration of renewable energy. The optimization of energy storage

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systems is prioritized to effectively balance load and generation. Scenario analysis is conducted to assess the effectiveness of various storage dispatch strategies.

4. ST (Short Term): Operational Dispatch Phase

The final phase involves evaluating hourly dispatch results, with a focus on YoY variations to ensure the operational model meets predefined reliability criteria. This includes developing precise hourly models to simulate the dispatch of generating plants and assessing the outcomes against reliability standards.

5. Results & Feedback Loop

At the conclusion of the operational dispatch phase, the system's reliability is evaluated against established criteria. If the criteria are not met, the framework employs an iterative feedback loop to revisit earlier phases. This ensures continuous improvement and alignment with reliability and sustainability goals.

Having outlined the various RA approaches and the modeling philosophy employed in the development of a least-cost optimization model using PLEXOS. The subsequent chapter delves into the specifics of monthly peak demand, daily load profiles, and solar and wind input profiles, and other inputs providing a comprehensive foundation for the detailed modeling and analysis that follows.

6. Input Assumptions for Rajasthan RA Modeling

This section outlines the data, stochastic simulation techniques, and resource-specific assumptions used to carry out RA modeling and assess system reliability for Rajasthan. It details the handling of renewable energy profiles, load projections, and RPO targets, providing a comprehensive overview of the modeling framework.

6.1. Solar & Wind Input Profiles

Figure 9 illustrates the monthly average solar and wind profiles for Rajasthan, featuring an average Capacity Utilization Factor (CUF) of 23% and 23% respectively. Based on the availability of the data, FY24 solar and wind profiles were used as a basis for future projections. In addition, simulations include stochastic variations in both demand and solar and wind profiles that introduce randomness in renewable energy generation.

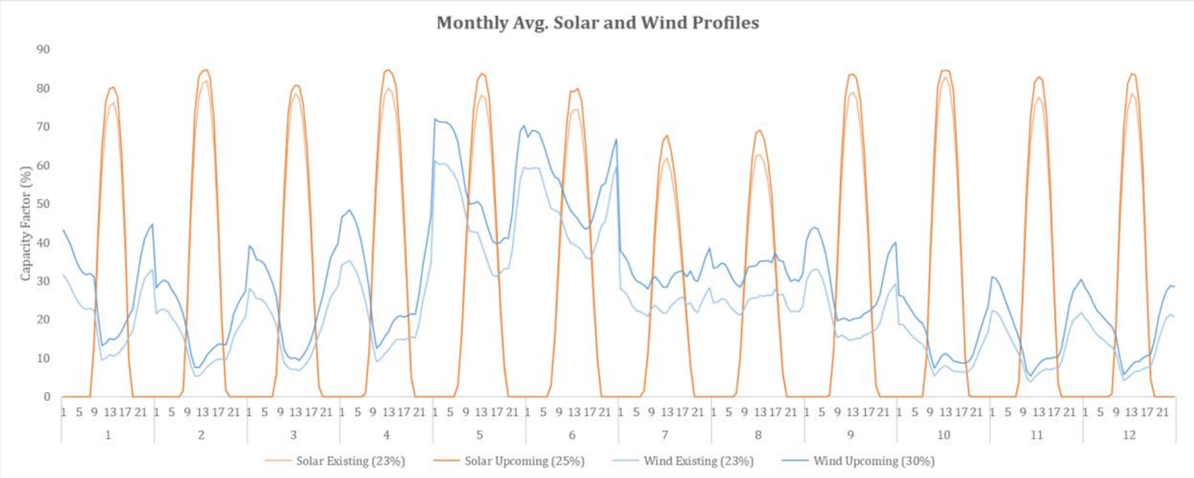

Figure 9: Monthly average Solar and Wind Profiles of Rajasthan

6.2. Stochastic Setup

Stochastic modeling is essential for addressing uncertainties in modern power grids, such as RE variability, fluctuating demand, fuel price volatility, and unplanned outages. Unlike deterministic models, it uses probability distributions and Monte Carlo simulations to represent real-world fluctuations, enabling more robust reliability assessments. By generating multiple scenarios with varying inputs like wind speed, solar irradiance, and load profiles, stochastic models estimate key reliability metrics such as LOLP and EENS. This approach supports resilient power system planning by identifying generation, storage, and transmission strategies that remain reliable under diverse conditions. Advanced tools like PLEXOS incorporate stochastic modeling to optimize decisions and ensure long-term grid stability.

RE generation is inherently variable due to its dependence on weather conditions, and electricity demand can fluctuate significantly on yearly, monthly, and hourly scales due to various factors. Accounting for these variations in grid studies is critical to ensuring grid stability and minimizing stress on both the grid and other generators. To address this, a stochastic approach adopted using historical data, where available, or alternative datasets for demand and RE generation, including solar, wind, and hydro resources.

The analysis focused on quantifying the variability in hourly data, evaluating it monthly to compute the coefficient of variation (CV) for use as an input to the model. The following systematic steps were undertaken:

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1. Variance: The variance for each month was calculated to quantify the dispersion of hourly data points. Variance provides a measure of how much the data deviates from the mean, reflecting the spread within the dataset.
2. Standard Deviation: The standard deviation, as the square root of the variance, provides an interpretable measure of the spread of data in the same units as the original dataset.
3. Determination of the Coefficient of Variation: The coefficient of variation was computed for each month as the ratio of the standard deviation to the average. This metric, expressed as a percentage, indicates the relative variability of the data compared to its means, allowing for a standardized comparison across months.

This approach provides a robust framework for assessing variability in load and RE generation data, offering valuable insights into their consistency and predictability over different months.

To illustrate, two stochastic samples of load and RE generation variability were generated:

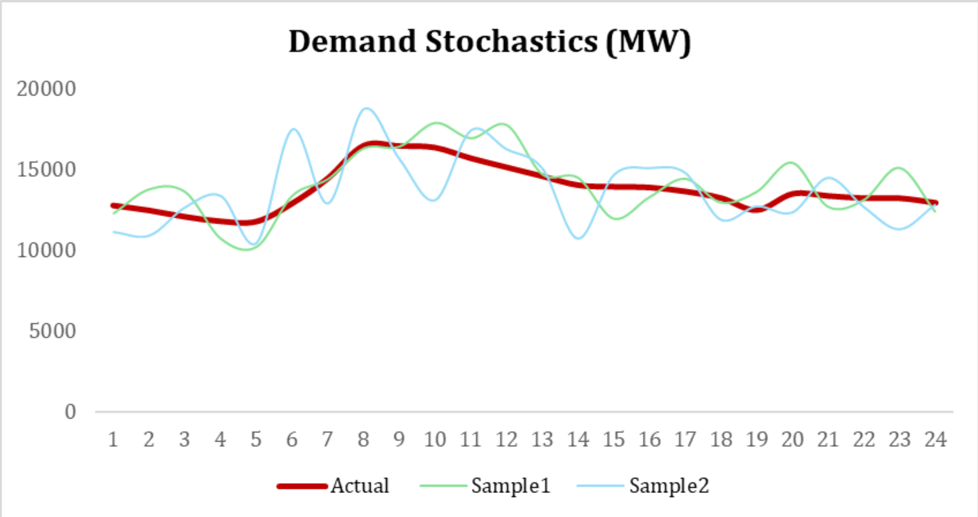

Figure 10: Demand Stochastics (MW)

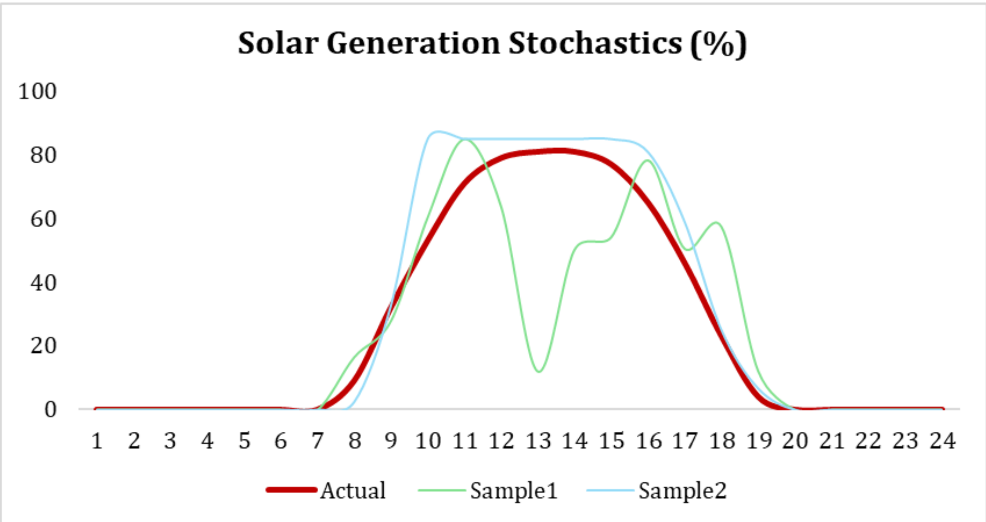

Figure 11: Solar Generation Stochastics (%)

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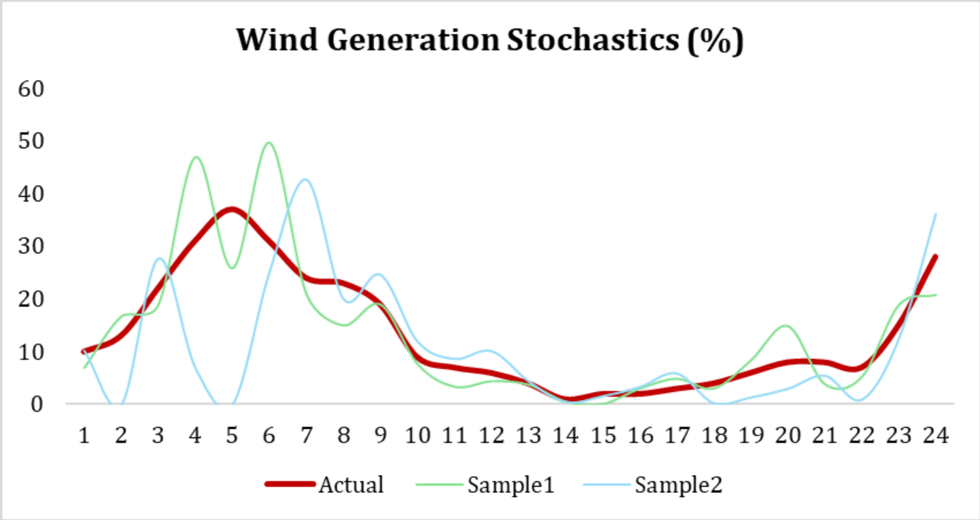

Figure 12: Wind Generation Stochastics (%)

For hydro plants, monthly generation data from the previous year was sourced from the Central Electricity Authority (CEA) website. Each plant's maximum and minimum Capacity Utilization Factor (CUF) for every month was determined, and the standard deviation was incorporated into the model. As expected, hydro generation was observed to peak during the monsoon months (June, August to October). The graph below shows the average hourly CUF for hydro plants monthly, highlighting seasonal patterns.

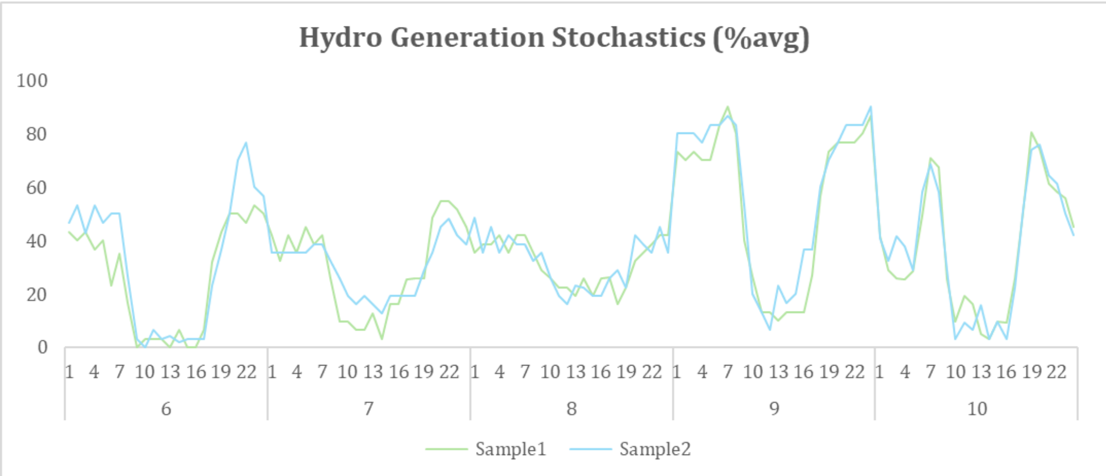

Figure 13: Hydro Generation Stochastics (%avg)

6.3. Resource-wise Input Assumptions

The power generation model outlined above provides a comprehensive overview of the existing and planned capacities across various energy sources within the Rajasthan region. Each type of generator, whether coal, nuclear, hydro, solar, wind, biomass, or pumped storage hydro, is meticulously characterized based on operational parameters[1], including allocated capacities, heat rates, PLFs, start costs, VO&M, FO&M, forced and planned outages, minimum up/down time, and maximum ramp up/down etc. Notably, the model incorporates upcoming capacity additions for renewable sources, such as solar, hydro and wind, in alignment with regulatory obligations. Furthermore, the inclusion of battery technologies underscores a proactive approach towards addressing intermittent challenges associated with renewables, thereby enhancing the overall resilience and reliability of the power system. The Table 2 shows the Resource-wise Input Assumptions as below:

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Table 2: Resource-wise Input Assumptions

Resource Type	Existing Capacity (MW)	Upcoming Contracted Capacity (Allocated) (MW)	Cost Escalation/Reduction Assumptions
Coal	14,429	FY27 – 1,600 FY29 – 2,245	1% increase
Gas	822	-	3% increase
Nuclear	468	FY25 – 350	1% increase
Hydro	2,347	FY25 - 56	Constant
Solar	6,721	300 MW in FY25 3,000 MW in FY26	Constant
Wind	4,935	-	Constant
Biomass	110	123 MW in FY25	3% increase
Pumped storage hydro (PSH)	100	-	3% increase
Battery Energy Storage System (BESS)	-	-	-

The Table 3 below shows the upcoming contracted capacity additions included in the model, the plants with the commissioning date were considered in the model:

Table 3: Upcoming Capacity with Date of Commissioning

Plant Name	Total Capacity (MW)	Allocated Capacity (MW)	Type	Commissioning Year
NTPC Singrauli TPP Stage III	2x800	1600	Coal	FY27
RRVUNL Chhabra TPP U7 &8	2x660	1320	Coal	FY29
RRVUNL Gurha TPP	1x125	125	Coal	FY29
RRVUNL Kalisindh TPP	1x800	800	Coal	FY29
NPCIL RAPP U8	1x350	350	Nuclear	FY25
NTPC Tapovan Vishnugard HEP	1x56	56	Hydro	FY25

In the PLEXOS model, some candidate capacity of solar and wind plants was considered for different years to meet the required reliability level i.e., UE less than 0.05%, LoLP less than 0.2%.

To ensure a reliable power supply, it is essential to meet reliability criteria. Hence, the study has considered solar, wind and BESS 4h candidate requirements.

- **Solar Candidate:** The solar candidate capacity represents additional solar power capacity that can be installed to ensure the system meets reliability standards.
  - **VOM:** 2.5 Rs/kWh for FY25, reducing at 2% YoY till FY30, then reducing at 1% and reaching 2.17 Rs/kWh by FY34.
  - **CUF:** 25%

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- **Wind Candidate:** The wind candidate capacity includes additional wind power plants that can be developed to enhance system reliability.
  - **VOM:** Starting at ₹2.89/kWh for FY25, then reduced by 2% YoY until FY30, remaining constant thereafter through FY34.
  - **CUF:** 30%
- **BESS 4-hr:** 4-hour battery energy storage system will mitigate contingency risks and facilitate the efficient storage of excess renewable energy.
  - **VOM:** 5.71 Rs lakhs/MW/month for FY25, reducing at 5% YoY till FY30, then at 2% and reaching 4.07 Rs lakhs/MW/month by FY34.

6.4. Renewable Purchase Obligation (RPO)

Rajasthan has mandated the RPO till 2030 and the same percentage has been retained till FY34 and same is shown in Table 4.

Table 4: Renewable Purchase Obligation[14]

FY	Other RPO	New Wind RPO	New DRE RPO	New Hydro RPO
2024-25	27.35%	0.67%	1.50%	0.38%
2025-26	28.24%	1.45%	2.10%	1.22%
2026-27	29.94%	1.97%	2.70%	1.34%
2027-28	31.64%	2.45%	3.30%	1.42%
2028-29	33.10%	2.95%	3.90%	1.42%
2029-30	34.02%	3.48%	4.50%	1.33%
2030-31	34.02%	3.48%	4.50%	1.33%
2031-32	34.02%	3.48%	4.50%	1.33%
2032-33	34.02%	3.48%	4.50%	1.33%
2033-34	34.02%	3.48%	4.50%	1.33%

As per this above RPO mandates, and considering existing and upcoming contracted capacities, additional capacities required to meet these RPO mandates were calculated, it is as per below table:

FY	Solar (MW)	Wind (MW)	Hydro (MW)	Total
2024-25	451	63	16	530
2025-26	1972	405	157	2535
2026-27	1644	685	171	2501
2027-28	1778	741	185	2705
2028-29	1811	754	189	2754
2029-30	1713	714	178	2606
2030-31	1132	472	118	1721
2031-32	779	325	81	1185
2032-33	770	321	80	1171
2033-34	1224	510	127	1861
Total	**13274**	**4989**	**1303**	**19567**

14 RPO Targets | MoP

6.5. Monthly Peak Demand and Daily Load Profile

The base year for this study is taken as FY24. In this fiscal year, the highest peak demand was recorded in January, at 18,128 MW. The Figure 14 below shows Rajasthan's monthly peak demand for FY24:

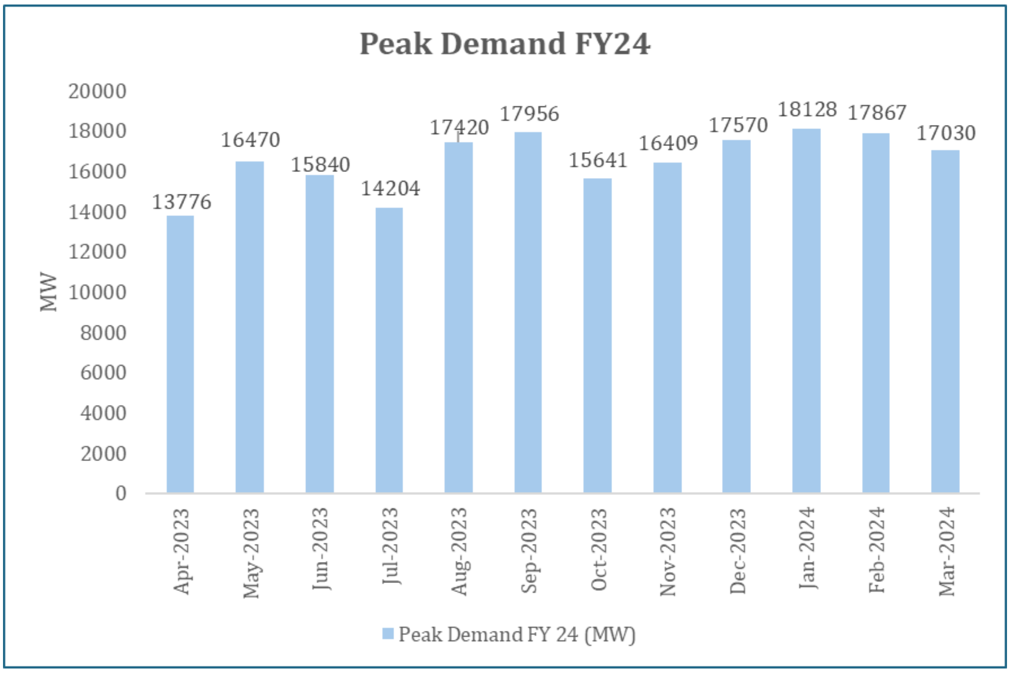

Figure 14: Rajasthan's Monthly Peak Demand for FY24

Considering the hourly load profile for FY24, the hourly load profile for future years is projected through PLEXOS without change in the load shape. The monthly average hourly profile shown in the Figure 15 below:

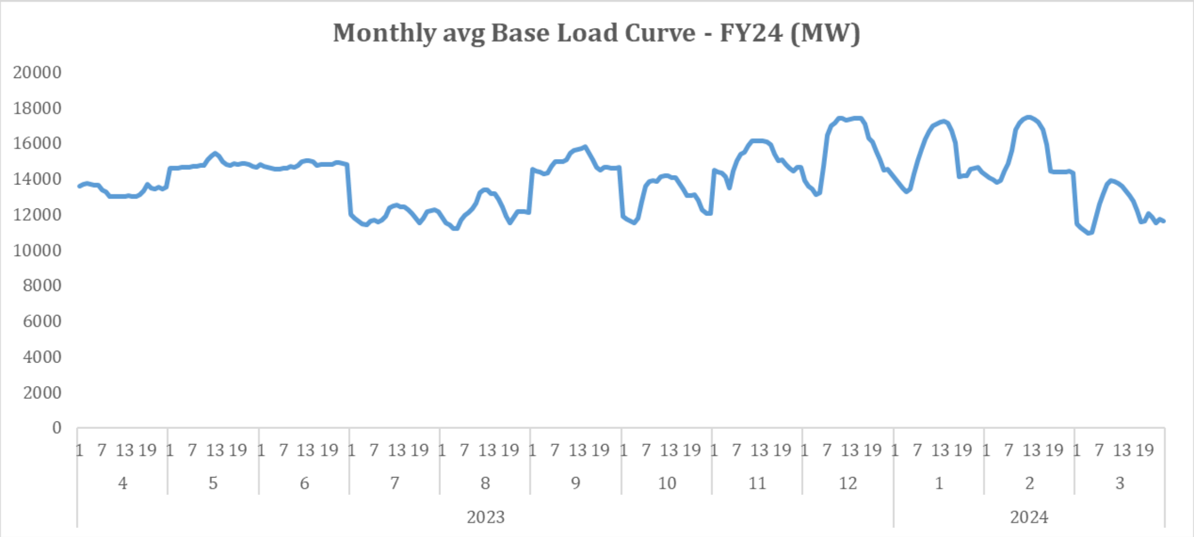

Figure 15: Monthly average Hourly Load Profile for FY24

6.6. Demand Projection Considered

FY24 was considered as base year and annual peak and energy projections from the 20th EPS were utilized from FY25 to FY34.

- **20th EPS**: Projections from the 20th EPS report were used where energy requirement grows by CAGR of 5.56% and peak demand by 5.37%.

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Table 5: Scenario Matrix of Rajasthan

20th EPS Projections			RUVNL Projections	
FY	**Energy Projections (MUs)**	**Peak Projections (MW)**	**Energy Projections (MUs)**	**Peak Projections (MW)**
FY24	1,12,368	17,906	1,02,369	18,979
FY25	1,19,167	18,959	1,08,696	20,284
FY26	1,26,118	20,030	1,15,413	21,680
FY27	1,33,550	21,175	1,22,546	23,172
FY28	1,41,260	22,358	1,30,119	24,766
FY29	1,49,303	23,590	1,38,161	26,470
FY30	1,58,836	25,048	1,46,699	28,291
FY31	1,65,398	26,048	1,55,309	30,237
FY32	1,71,883	27,032	1,64,424	32,317
FY33	1,82,192	28,597	1,74,074	34,540
FY34	1,93,119	30,252	1,84,291	36,917
FY35	2,04,702	32,003	1,95,107	39,456

By considering the 20th EPS projections which are available up to FY32, the projections have been computed up to FY34.

The energy (in MU's) and peak demand (in MW's) projections required to model are shown for 20th EPS and RUVNL in the Figure 16 below:

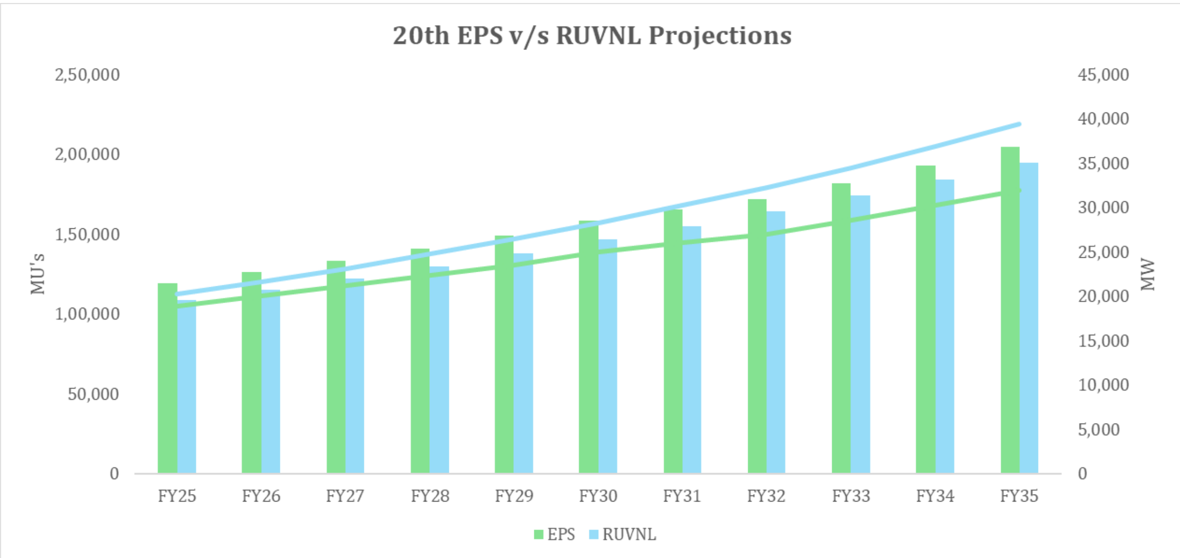

Figure 16: Rajasthan's YoY Peak and Energy projections – 20th EPS and RUVNL

Having detailed Rajasthan RA modeling, study findings derived from energy modelling are analyzed. The following chapter summarizes the output parameters, such as unserved and dump energy, reliability metrics, YoY resource-wise installed capacity and generation, battery energy storage capacity, resource-wise average hourly generation, and (APPC). These findings provide critical insights into the performance and reliability of the power system.

7. Study Findings

This chapter presents the findings derived from the study based on the inputs discussed in previous chapters. The key insights extracted from the analysis for 20th EPS projections are summarized in the following sub-sections:

1. YoY resource-wise installed capacity
2. YoY resource-wise generation
3. Resource-wise average hourly generation
4. Unserved and dump energy
5. Reliability metrics
6. Average Power Purchase Cost

7.1. YoY Resource-wise Installed Capacity

The Figure 17 below illustrates the YOY resource-wise installed, upcoming contracted, and candidate capacity mix for Rajasthan, with the corresponding data provided in tabular form in the annexure.

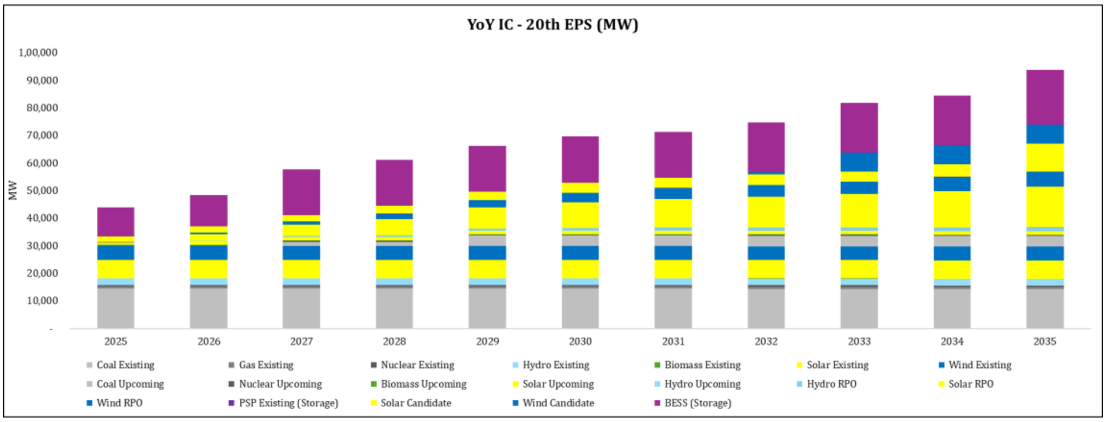

Figure 17: YoY Installed Capacity and Additional Capacity Required – 20th EPS

- From the above Figure 17 it can be observed that RE (upcoming & RPO) capacities show substantial growth.
- Coal Decline: Gradual reduction from 14,429 MW (2025) to 14,222 MW (2034), signaling a transition away from coal.
- Renewable Growth: Solar and wind shows significant increase, with solar RPO rising from 451 MW (2025) to 14,572 MW (2035) and wind RPO from 63 MW to 5,530 MW.
- Energy Storage & PSP: BESS grows from 10,341 MW (2025) to 17,938 MW (2034), supporting grid stability, while PSP remains at 100 MW.
- Nuclear & Biomass: Nuclear stays at 468 MW, with a 350 MW upcoming contracted in 2025, while biomass remains at 123 MW annually.

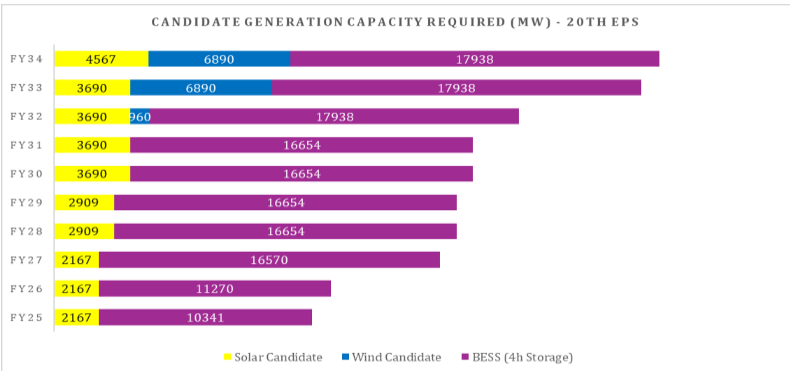

Figure 18: Candidate Capacity Required (MW) – 20th EPS

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- To meet the LoLP and PRM limits, candidate capacities from Solar, Wind and BESS will be required throughout the horizon.

7.2. YoY Resource-wise Generation

Below is graph of resource-wise generation and capacity factor resource wise YoY:

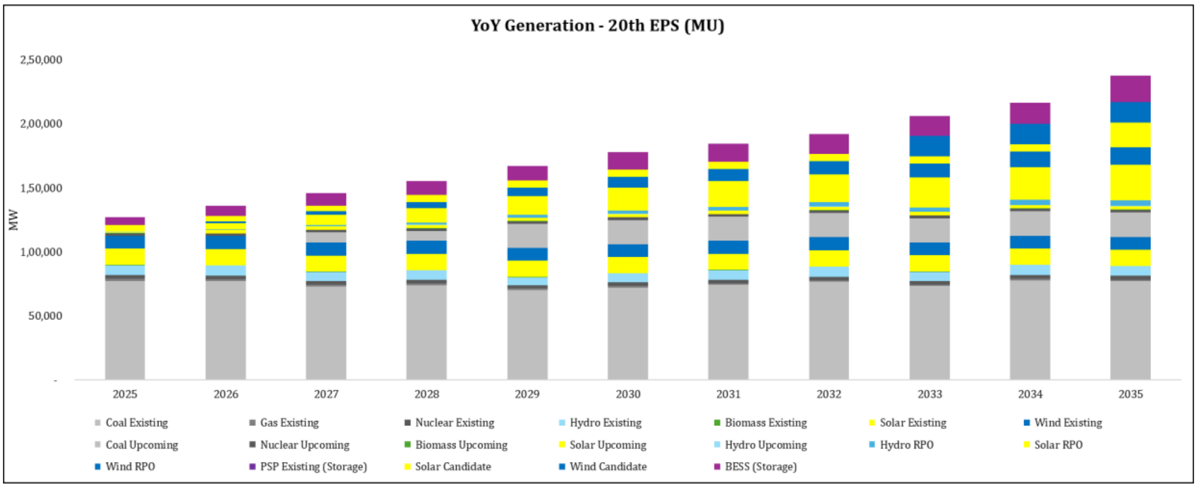

Figure 19: YoY Generation – 20th EPS (MUs)

- It can be observed that coal share generation has higher contribution compared to RE generation.

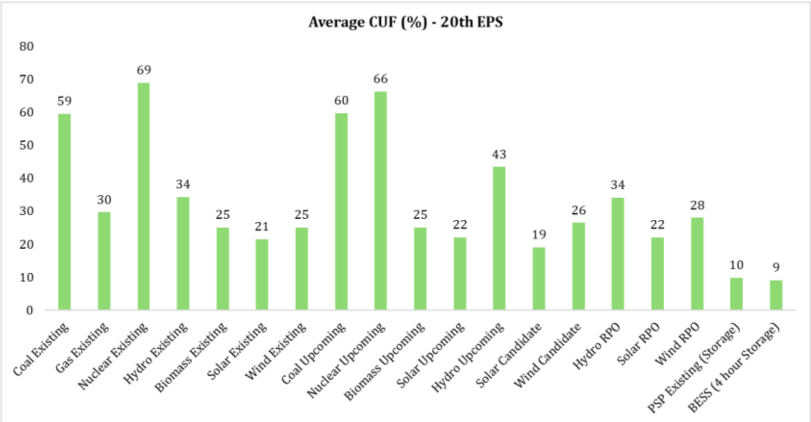

Figure 20: Average CUF (%) - 20th EPS

- It can be observed that coal plants CUF have reduced to 59% and Nuclear is running at 69%.
- The capacity of solar and wind candidate is not running near to its maximum CUF and getting curtailed.
- There is an opportunity to trade this extra capacity with other states.

7.3. Average Hourly Generation

The following Figure 21 shows the average hourly generation for terminal year of FY34:

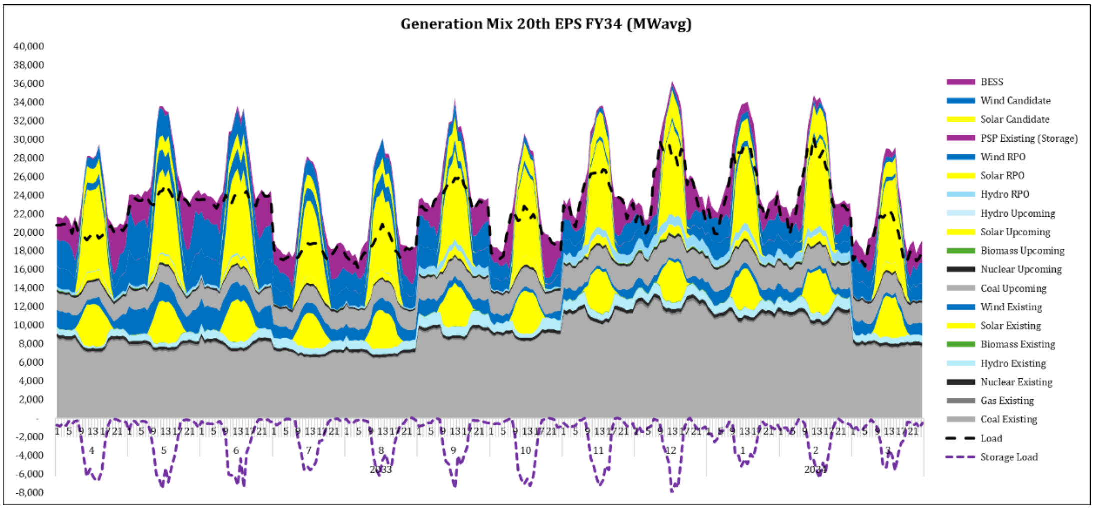

Figure 21: Generation Mix 20th EPS - FY34

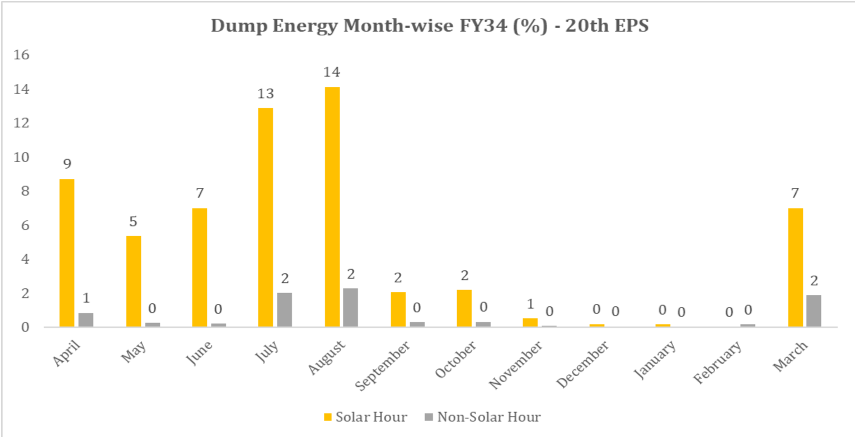

Figure 22: DE Month-wise FY34 (%) – 20th EPS

- It is observed from Figure 22 that in the months of April-August, and March, the dump energy is high during solar hours, thus energy can be traded with other states during these months.
- Rest of the months, the DE is low during solar hours.

7.4. Unserved and Dump Energy

The following Table 6 shows YoY unserved and dump energy resulting from the buildout and dispatch:

Table 6: Unserved Energy and Dump Energy

FY	Unserved Energy Factor (%)		Dump Energy Factor (%)		Dump Energy (Mus)	
	Existing + Planned	Existing + Planned+ Candidate	Existing + Planned	Existing + Planned+ Candidate	Existing + Planned	Existing + Planned+ Candidate
25	0.49	0	2.54	0.5	4,252	1,025
26	0.74	0	3.36	0.57	5,885	1,259
27	0.38	0	3.87	0.75	7,542	1,917
28	0.62	0	4.52	0.91	9,132	2,388
29	0.3	0	5.39	1.83	12,245	5,216
30	0.54	0	5.46	1.23	12,759	3,693
31	0.72	0	5.62	1.16	13,391	3,541
32	1.1	0	5.67	0.9	13,695	2,905

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FY	Unserved Energy Factor (%)		Dump Energy Factor (%)		Dump Energy (Mus)	
	Existing + Planned	Existing + Planned+ Candidate	Existing + Planned	Existing + Planned+ Candidate	Existing + Planned	Existing + Planned+ Candidate
33	1.71	0	5.48	2.13	13,370	7,108
34	2.57	0	5.05	1.56	12,564	5,259

- Due to high solar capacity from existing and planned capacities, there is significant amount of dump energy during solar hours. However, with the addition of storage candidate capacities, this dump energy is utilized during non-solar hours, thereby reducing the overall dump energy.
- It can be observed that unserved energy is high during non-solar hours. However, with the addition of storage candidate capacity, the overall unserved energy is reduced.

7.5. Reliability Metrics

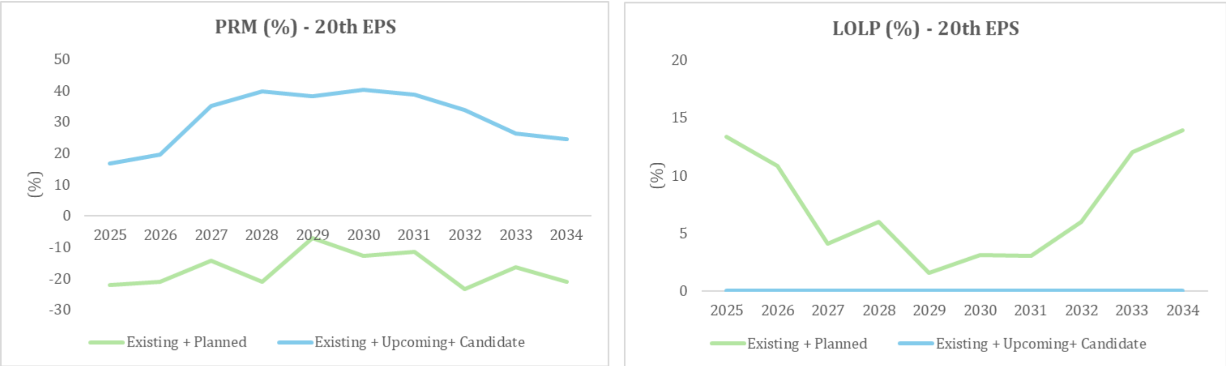

Figure 23: PRM & LoLP - 20th EPS

- The above Figure 23 shows reliability metrics without and with consideration of candidate capacity (over and above existing and planned).
- The PRM with existing and planned capacities lies between -7% to -28%. After adding candidate plants capacities, the reliability criteria met the standards.
- The LOLP decreased till FY29 and afterwards it goes increasing, thus candidate plants will be required to meet standard limits i.e. (below or equal to 0.2%).

The following Table 7 shows YoY reliability metrics of capacity margin and LoLP:

Table 7: Reliability Metrics for 20th EPS

FY	Planning Reserve Margin (MW)	Planning Reserve Margin (%)	LOLP (%)
25	4,831	16.66	0
26	6,329	19.63	0
27	11,723	35.03	0
28	13,612	39.78	0
29	14,248	38.29	0
30	15,285	40.22	0
31	15,313	38.7	0
32	14,301	33.75	0
33	11,768	26.38	0
34	11,967	24.48	0

7.6. Average Power Purchase Cost

The following Table 8 shows YoY APPC resulting from the buildout and dispatch:

Table 8: APPC – 20th EPS

FY	Coal Existing	Gas Existing	Nuclear Existing	Hydro Existing	Biomass Existing	Solar Existing	Wind Existing	Coal Upcoming	Nuclear Upcoming	Biomass Upcoming	Solar Upcoming	Hydro Upcoming	Solar Candidate	Wind Candidate	Hydro RPO	Solar RPO	Wind RPO	PSP Existing (Storage)	BESS (Storage)	System Cost
25	4.71	4.26	3.40	2.28	7.35	2.86	4.47	0.00	5.00	7.35	2.60	2.58	2.50	0.00	6.45	3.28	4.81	7.52	11.55	**4.88**
26	4.75	4.36	3.44	2.28	7.57	2.86	4.48	0.00	5.05	7.57	2.60	2.58	2.45	0.00	6.45	3.28	4.86	8.62	9.06	**4.84**
27	4.89	4.69	3.48	2.28	7.80	2.86	4.47	5.57	5.10	7.80	2.60	2.58	2.40	0.00	6.45	3.28	4.91	8.43	10.54	**5.01**
28	4.90	4.81	3.51	2.29	8.03	2.86	4.48	5.60	5.15	8.03	2.60	2.59	2.35	0.00	6.45	3.28	4.96	9.29	8.89	**5.00**
29	5.08	4.88	3.55	2.37	8.27	2.86	4.48	5.52	5.20	8.27	2.60	3.01	2.30	0.00	6.45	3.28	5.00	9.15	8.14	**5.02**
30	5.03	4.94	3.58	2.29	8.52	2.86	4.48	5.53	5.26	8.52	2.60	2.59	2.26	0.00	6.45	3.28	5.06	9.85	6.53	**4.98**
31	5.00	5.15	3.61	2.30	8.78	2.86	4.47	5.57	5.31	8.78	2.60	2.59	2.23	0.00	6.45	3.28	5.11	10.60	6.08	**5.04**
32	4.98	5.29	3.65	2.29	9.04	2.86	4.48	5.60	5.36	9.04	2.60	2.59	2.21	0.00	6.45	3.28	5.16	14.91	5.97	**5.32**
33	5.11	5.48	3.69	2.32	9.31	2.86	4.48	5.67	5.41	9.31	2.60	2.60	2.19	2.75	6.45	3.28	5.21	18.08	5.72	**5.40**
34	5.03	5.57	3.72	2.30	9.59	2.86	4.48	5.71	5.47	9.59	2.60	2.58	2.17	2.75	6.45	3.28	5.26	14.82	5.26	**5.24**
35	5.09	6.00	3.76	2.32	9.88	2.86	4.47	5.74	5.52	9.88	2.60	2.58	2.15	2.75	6.45	3.28	5.31	17.53	4.56	**5.41**

- Coal and nuclear costs are assumed to increase by 1% annually, while for gas, biomass, PSP costs are assumed to increase by 3% and for other resources remain constant.
- The system cost decreased to 4.84 Rs/kWh in FY26 due to the introduction of more affordable resources. However, in FY27, the system cost rose as substantial coal capacity was installed, which is more expensive. This led to underutilization of storage capacity, causing an increase in its costs and ultimately resulting in a higher overall system cost.
- Storage costs fluctuate yearly based on UE and DE.

Having the key study findings, the comparative assessment of resource adequacy plans published by CEA and Idam's RA studies are analyzed. The following chapter comprehensively compared the key differences in unserved energy, capacity projection mix, and additional requirements to meet reliability of the power system.

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8. Key Insights from CEA's RA Study

The CEA has published a Resource Adequacy (RA) report for the state of Rajasthan, which provides an assessment of the state's electricity demand and the required generation capacity to ensure a reliable power supply. This section presents a high-level analysis of the study, highlighting key findings, and insights.

Unserved Energy (MUs) for FY30 (monthly) from CEA's and Idam's RA studies are depicted as follows:

Table 9: Unserved Energy (MUs) for FY30

CEA		Idam	
Month	**ENS (MU)**	**ENS (MU)**	**ENS (%)**
Apr-29	71	9	0.08
May-29	0	46	0.34
Jun-29	36	52	0.41
Jul-29	0	0	0
Aug-29	0	8	0.09
Sep-29	0	89	0.66
Oct-29	0	0	0
Nov-29	49	92	0.66
Dec-29	459	248	1.65
Jan-30	306	145	1.03
Feb-30	417	100	0.76
Mar-30	53	2	0.02
Total	**1391**	**791**	

The comparison of UE for FY30 between CEA's and Idam's RA studies, highlights key differences in energy shortfall estimation:

Total ENS:

- CEA estimates a total ENS of 1,391 MU, whereas Idam projects 791 MU.

Peak Shortfall Months:

Both studies indicate that the highest ENS occurs during November to February, with December experiencing the most severe shortfall:

- CEA: 459 MU in December, 417 MU in February, and 306 MU in January.
- Idam: 248 MU in December, 145 MU in January, and 100 GWh in February.

Months with Zero ENS:

- CEA's study shows zero ENS in May, July, August, September, and October, while Idam reports minor ENS for these months (e.g., 0.34% in May, 0.09% in August, and 0.66% in September).

Key Insights:

- The concentration of ENS in winter months aligns with Rajasthan's seasonal demand variations, where higher electricity consumption occurs due to agricultural and heating needs.

The Capacity Mix Projections (MW) from CEA and Idam are shown as follows:

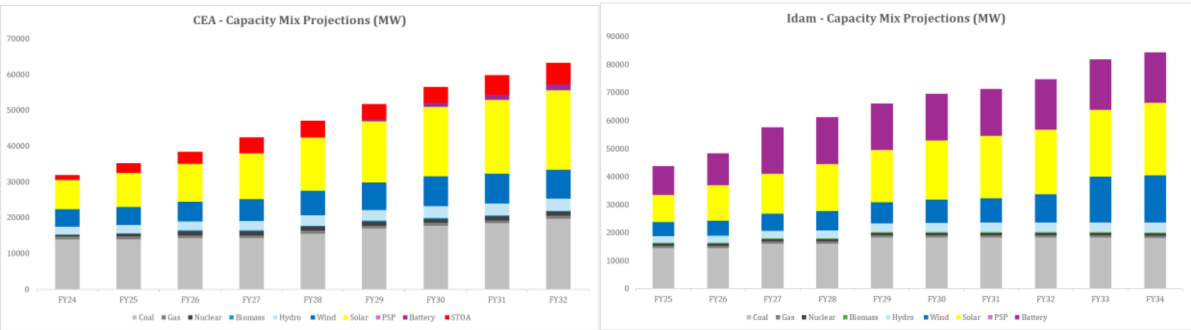

Figure 24: CEA & Idam - Capacity Mix Projections (MW)

The capacity mix projections for Rajasthan from CEA and Idam show significant differences in the planned coal, RE, hydro, and BESS capacity additions over the forecast period.

Key Comparisons:

Coal Capacity:

- CEA projects a steady increase in coal capacity, reaching 19,710 MW by FY32.
- Idam estimates a peak of 18,231 MW by FY32 but declines to 18,067 MW in FY34.

Nuclear and Biomass:

- CEA's nuclear projected capacity increases to 1,157 MW by FY26, while Idam's nuclear capacity reaches 818 MW.
- Biomass capacity is fixed at 111 MW in CEA, whereas Idam considered 233 MW starting from FY27 onward.

Hydro and Wind:

- CEA projects hydro capacity to grow from 2,181 MW (FY24) to 3,344 MW (FY32), while Idam considers an increase, reaching 3,706 MW by FY34.
- Wind projected capacity under CEA is 8,103 MW in FY32 while Idam's wind projected capacity 16,814 MW in FY34.

Solar Capacity:

- CEA's solar capacity reaches 22,132 MW by FY32, whereas Idam estimates 25,862 MW by FY34.

Battery storage & PSP:

- CEA projects battery storage only from FY29 onward (gradually increasing to 1,642 MW by FY32), whereas Idam estimates a much higher battery capacity starting earlier (11,270 MW in FY25, increasing to 17,938 MW by FY34).
- Idam's high battery storage estimates reflect a push for grid flexibility and renewable integration.

The Planned capacity, additional, market and candidate capacities requirement from CEA and Idam are shown as follows:

Table 10: CEA- Planned capacity, additional and market capacity requirement

CEA													
FY	Coal		Nuclear	Biomass	Hydro		Wind		Solar		PSP	Storage (4hours)	STOA
	Planned	Additional	Planned	Planned	Planned	Additional	Planned	Additional	Planned	Additional	Planned	Additional	Market
FY24	281	0	0	0	179	0	1201	0	3359	0	0	0	1369
FY25	0	0	350	123	56	91	0	194	300	1378	100	0	2718
FY26	300	0	350	0	0	165	0	622	1000	1119	0	0	3390

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CEA													
FY	Coal		Nuclear	Biomass	Hydro		Wind		Solar		PSP	Storage (4hours)	STOA
	Planned	Additional	Planned	Planned	Planned	Additional	Planned	Additional	Planned	Additional	Planned	Additional	Market
FY27	0	0	0	0	0	153	0	709	0	2167	0	0	4480
FY28	1320	0	0	0	0	181	0	789	0	2203	0	0	4600
FY29	925	447	0	0	0	203	0	861	0	2155	0	439	4347
FY30	0	788	0	0	0	209	0	868	0	2281	0	696	4409
FY31	0	683	0	0	0	53	0	217	0	1261	0	152	5490
FY32	0	1328	0	0	0	52	0	214	0	1548	0	355	6000

Table 11: Idam - Planned capacity, additional and candidate capacity requirement

Idam											
FY	Coal	Nuclear	Biomass	Hydro		Wind		Solar			Battery
	Planned	Planned	Planned	Planned	Additional	Additional	Candidate	Planned	Additional	Candidate	Candidate
FY25	0	350	123	56	16	63		300	451	2167	10341
FY26	0	0	0	0	157	405		1,000	1972	2167	11270
FY27	1600	0	0	0	171	685		0	1644	2167	16570
FY28	0	0	0	0	185	741		0	1778	2909	16654
FY29	2,245	0	0	0	189	754		0	1811	2909	16654
FY30	0	0	0	0	178	714		0	1713	3690	16654
FY31	0	0	0	0	118	472		0	1132	3690	16654
FY32	0	0	0	0	81	325	960	0	779	3690	17938
FY33	0	0	0	0	80	321	6890	0	770	3690	17938
FY34	0	0	0	0	127	510	6890	0	1224	4567	17938

The capacities for planned and candidate plants for Rajasthan is different for CEA and Idam due to variations in the data received and the approach to meet reliability metrics. CEA envisions capacity mix with continued coal additions and STOA requirements, whereas Idam considers RE additions with substantial battery storage support.

Key Comparisons:

Coal Capacity:

- CEA planned coal additions until FY32, peaking at 1,320 MW in FY28 and 1,328 MW in FY32.
- In this study, the increase in coal capacity as candidate buildout has not been considered.

Renewable Energy Expansion:

- CEA's additional wind capacity is relatively modest, increasing in small increments, whereas Idam estimates wind candidate capacity, with 6,890 MW until FY34, starting from FY30.
- Solar capacity in CEA increases significantly every year, with additions peaking at 3,359 MW in FY24 and remaining above 2,000 MW in subsequent years.

Hydro and Biomass:

- Both projections include limited hydro additions, with Idam slightly more in capacity additions than CEA.
- Biomass is only planned in FY25 under both projections.

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Battery Storage & PSP:

- CEA projects battery storage capacity starting from FY29 with 439 MW until FY32 with 355 MW.
- Idam estimates battery candidate capacity, reaching 17,938 MW by FY34.

Market Requirements:

- CEA includes short-term market participation projections, showing an increasing reliance on market-based solutions to manage demand fluctuations.
- This study does not consider market.

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9. Conclusion

This study undertook a comprehensive Resource Adequacy (RA) assessment for the state of Rajasthan, with the objective of exploring and evaluating the multifaceted aspects of RA and its associated metrics. The overarching goal was to ensure a reliable and cost-effective power supply while adhering to established RA guidelines.

Key Findings:

- **FY25 Capacity Adequacy:** The analysis indicates that in the fiscal year 2025, the existing contracted capacity will not be sufficient to meet the defined reliability metrics. This presents Rajasthan with strategic options: either to procure additional power from the market or to invest in the development of new generation facilities.
- **Cost Reduction with RE:** The increasing integration of RE sources, particularly solar and wind, is shown to contribute to a reduction in overall system costs over time.
- **Reliability Metric Compliance:** The study successfully demonstrated compliance with key reliability metrics, including Loss of Load Probability (LoLP) and Normalized Energy Not Served (NENS), validating the robustness of the modeling approach.

Key Recommendations

- **Increased RE Integration:** Given Rajasthan's high solar and wind potential, the state should prioritize renewable energy expansion while ensuring sufficient storage capacity to mitigate intermittency.
- **Enhancing Grid Flexibility:** Investments in battery storage and pumped hydro storage should be encouraged to enhance grid stability and accommodate vRE generation.
- **Capacity Expansion Planning:** Regular assessment of capacity addition requirements is needed to avoid under- or over-investment in power generation assets.
- **Cost-Effective Solar Integration:** The economic viability of solar energy will provide substantial benefits to the state in the coming years.
- **Adherence to Resource Adequacy Guidelines:** Reliability metrics, such as PRM, LoLP and NENS, should be consistently monitored to align with CEA's recommendations.

By adopting these strategies, Rajasthan can ensure a sustainable, cost-effective, and reliable power supply, supporting its long-term economic and energy transition goals.

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10. Appendix

10.1. List of Existing Plants

List and details of existing plants considered in the model:

Table 12: Existing Coal Plants

Plant Type	Plant Name	Installed Capacity (MW)	Allocated Capacity (MW)
Central Generating Station Coal	Meja STPP	66	66
	NLC TPP (Barsingsar)	250	250
	NTPC Farakka STPS	11	11
	NTPC Feroz Gandhi TPP U1 (UNCHAHAR)	25	25
	NTPC Feroz Gandhi TPP U2 (UNCHAHAR)	57	57
	NTPC Feroz Gandhi TPP U3 (UNCHAHAR)	32	32
	NTPC Feroz Gandhi TPP U4 (UNCHAHAR)	79	79
	NTPC Kahalgoan STPS U1	23	23
	NTPC Kahalgoan STPS U2	101	101
	NTPC NCTPP Dadri TPP U1	179	179
	NTPC NCTPP Dadri TPP U2	50	50
	NTPC Rihand STPS U1	132	132
	NTPC Rihand STPS U2	144	144
	NTPC Rihand STPS U3	164	164
	NTPC Singrauli STPS	370	370
	NTPC Tanda II TPS	88	88
State Generating Station Coal	RRVUNL Chhabra TPP U1-4	1000	1000
	RRVUNL Chhabra TPP U5&6	1320	1320
	RRVUNL Kalisindh TPP U1&2	1200	1200
	RRVUNL Kota TPP U1&2	220	220
	RRVUNL Kota TPP U3-5	630	630
	RRVUNL Kota TPP U6&7	390	390
	RRVUNL Suratgarh TPP U1-6	1500	1500
	RRVUNL Suratgarh TPP U7&8	1320	1320
	Adani Power TPP	1320	1320

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Private Generating Station Coal	CGPL- UMPP TPP	380	380
	JSW Energy TPP	1080	1080
	PTC- DB TPP	311	311
	PTC- MCCPL TPP	195	195
	Sasan UMPP TPP	372	372
	SKS Power TPP	100	100

Table 13: Existing Gas Plants

Plant Type	Plant Name	Installed Capacity	Allocated Capacity
Central Generating Station Gas	NTPC Anta GTPS	83	83
	NTPC Auriya GTPS	61	61
	NTPC Dadri GTPS	77	77
State Generating Station Gas	RRUVNL Dholpur CCPP GTPS	330	330
	RRUVNL Ramgarh CCPP GTPS U1&2	111	111
	RRUVNL Ramgarh CCPP GTPS U3	160	160

Table 14: Existing Nuclear Plants

Plant Name	Installed Capacity (MW)	Allocated Capacity (MW)
NPCIL NAPP U1&2	44	44
NPCIL RAPP U2	200	200
NPCIL RAPP U3&4	125	125
NPCIL RAPP U5&6	87.74	87.74

Table 15: Existing Hydro Plants

Plant Type	Plant Name	Installed Capacity (MW)	Allocated Capacity (MW)
Central Generating Station Hydro	Bhakra- Dehar- Pong HEP	671	671
	Chambal- Satpura HEP	193	193
	NHPC Chamera I HEP	105	105
	NHPC Chamera II HEP	35	35
	NHPC Chamera III HEP	29	29
	NHPC Dhauliganga HEP	32	32
	NHPC Dhulasti HEP	49	49
	NHPC Prabati HEP	65	65

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	NHPC Salal HEP	20	20
	NHPC Sewa II HEP	15	15
	NHPC Tanakpur HEP	11	11
	NHPC Tehri HEP	86	86
	NHPC URI I HEP	42	42
	NHPC URI II HEP	27	27
	NTPC Koldam HEP	91	91
	NTPC Singrauli MMH	2	2
	RFF HEP	25	25
	SJVNL Nathpa-Jhakri HEP	128	128
	SJVNL Rampur HEP	36	36
	THDC Koteshwar HEP	38	38
State Generating Station Hydro	RRVUNL Mahi HEP	140	140
	RRVUNL Mahi MMH HEP	1	1
	RRVUNL Mangrol MMH HEP	6	6
	RRVUNL STPS MMH HEP	16.89	17
Private Generating Station Hydro	PTC- Karchem Wangtoo HEP	104	104
	PTC- Teesta HEP	100	100
Cross Border	PTC-Tala HEP	100	100

Table 16: Existing Pumped Hydro Storage Plant

Plant Name	Installed Capacity (MW)	Allocated Capacity (MW)
Tehri PSP	100	100

10.2. YoY Installed Capacity

Data of YoY Installed Capacity results for 20th EPS scenarios:

Table 17: YoY Installed Capacity (MW) – 20th EPS Scenario

FY	Coal Existing	Gas Existing	Nuclear Existing	Hydro Existing	Biomass Existing	Solar Existing	Wind Existing	Coal Upcoming	Nuclear Upcoming	Biomass Upcoming	Solar Upcoming	Hydro Upcoming	Solar Candidate	Wind Candidate	Hydro RPO	Solar RPO	Wind RPO	PSP Existing (Storage)	BESS (Storage)
25	14,429	822	468	2,347	110	6,721	4,935	-	350	123	300	56	2,167	-	16	451	63	100	10,341
26	14,429	822	468	2,347	110	6,721	4,935	-	350	123	1,300	56	2,167	-	173	2,423	468	100	11,270
27	14,418	822	468	2,347	110	6,721	4,935	1,600	350	123	1,300	56	2,167	-	344	4,068	1,153	100	16,570
28	14,418	822	468	2,347	110	6,721	4,935	1,600	350	123	1,300	56	2,909	-	530	5,846	1,894	100	16,654

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29	14,418	822	468	2,347	110	6,721	4,935	3,845	350	123	1,300	56	2,909	-	718	7,657	2,649	100	16,654
30	14,418	822	468	2,347	110	6,721	4,935	3,845	350	123	1,300	56	3,690	-	897	9,370	3,363	100	16,654
31	14,418	822	468	2,347	110	6,721	4,935	3,845	350	123	1,300	56	3,690	-	1,015	10,502	3,834	100	16,654
32	14,386	822	468	2,347	110	6,721	4,935	3,845	350	123	1,300	56	3,690	960	1,096	11,281	4,159	100	17,938
33	14,386	822	468	2,347	110	6,721	4,935	3,845	350	123	1,300	56	3,690	6,890	1,176	12,051	4,479	100	17,938
34	14,222	822	468	2,347	110	6,721	4,935	3,845	350	123	1,300	56	4,567	6,890	1,303	13,274	4,989	100	17,938

10.3. YoY Generation

Data of YoY Generation results for 20th EPS scenarios:

Table 18: YoY Generation (BUs) - 20th EPS Scenario

FY	Coal Existing	Gas Existing	Nuclear Existing	Hydro Existing	Biomass Existing	Solar Existing	Wind Existing	Coal Upcoming	Nuclear Upcoming	Biomass Upcoming	Solar Upcoming	Hydro Upcoming	Solar Candidate	Wind Candidate	Hydro RPO	Solar RPO	Wind RPO	PSP Existing (Storage)	BESS (Storage)
25	77	2	3	8	0	13	10	0	2	0	1	0	4	0	0	1	0	0	6
26	77	2	3	8	0	13	10	0	2	0	3	0	4	0	1	5	1	0	8
27	73	1	3	7	0	13	10	8	2	0	3	0	4	0	1	8	3	0	10
28	74	1	3	8	0	13	10	8	2	0	3	0	6	0	2	11	5	0	11
29	70	1	3	6	0	13	10	19	2	0	2	0	6	0	2	15	6	0	11
30	72	1	3	7	0	13	10	19	2	0	2	0	6	0	3	18	8	0	14
31	74	1	3	7	0	12	10	19	2	0	2	0	6	0	3	20	9	0	14
32	77	1	3	8	0	13	10	19	2	0	3	0	6	0	3	22	10	0	15
33	73	1	3	7	0	13	10	19	2	0	3	0	6	16	4	23	11	0	16
34	78	1	3	8	0	13	10	19	2	0	2	0	6	16	4	25	12	0	17
35	77	1	3	7	0	13	10	19	2	0	2	0	19	16	4	28	14	0	21

10.4. Additional Capacity Required

Table 19: Additional Capacity Required (GW)

FY	Solar Candidate	Wind Candidate	BESS (4h) Candidate
25	2	0	10
26	2	0	11
27	2	0	17
28	3	0	17
29	3	0	17
30	4	0	17
31	4	0	17
32	4	1	18
33	4	7	18
34	5	7	18