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

Prepared By

Enabling Carbon Minimal World!

Technopolis Knowledge Park, 5th Floor, Mahakali Caves Road,

Chakala, Andheri East, Mumbai- 400 093 INDIA

Tel: + (91) 22 68620300,

Email: contact@idaminfra.com, Website: www.idaminfra.com

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Idam Infrastructure Advisory Pvt. Ltd.
5th Floor, Technopolis Knowledge
Park, Mahakali Caves Road,
Chakala, Andheri East, Mumbai – 400 093
Phone: +91 (22) 68620300
Email: contact@idaminfra.com

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Idam Infrastructure Advisory Pvt. Ltd.
5th Floor, Technopolis Knowledge
Park, Mahakali Caves Road,
Chakala, Andheri East, Mumbai – 400 093
Phone: +91 (22) 68620300
Email: contact@idaminfra.com

Table of Contents

Idam Infrastructure Advisory Pvt. Ltd.
5th Floor, Technopolis Knowledge
Park, Mahakali Caves Road,
Chakala, Andheri East, Mumbai – 400 093
Phone: +91 (22) 68620300
Email: contact@idaminfra.com

List of Figures

Idam Infrastructure Advisory Pvt. Ltd.
5th Floor, Technopolis Knowledge
Park, Mahakali Caves Road,
Chakala, Andheri East, Mumbai – 400 093
Phone: +91 (22) 68620300
Email: contact@idaminfra.com

List of Tables

Idam Infrastructure Advisory Pvt. Ltd.
5th Floor, Technopolis Knowledge
Park, Mahakali Caves Road,
Chakala, Andheri East, Mumbai – 400 093
Phone: +91 (22) 68620300
Email: contact@idaminfra.com

Abbreviations

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

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5th Floor, Technopolis Knowledge
Park, Mahakali Caves Road,
Chakala, Andheri East, Mumbai – 400 093
Phone: +91 (22) 68620300
Email: contact@idaminfra.com

1. Introduction

India has set five ambitious clean energy targetsfor 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 percent of its energy requirements from renewable energy (RE) by 2030.
3. Reduce the total projected carbon emissions by one billion tonnes from now onwards till 2030.
4. Reduce the carbon intensity of its economy by less than 45 percent 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 significant increase in share of RE in the next 10 years. Karnataka, Maharashtra, Rajasthan, Gujarat, and Tamil Nadu stand out as RE-rich states in India, collectively possessing around 50% of total RE installed capacity.

1.1. Background

Karnataka boasts of 22,602 MW of installed RE capacity, including 8,986 MW of solar and 6,731 MW of wind as of December 2024[3]. It has a total potential of 154 GW, underlining its pivotal role in India's RE landscape and in achieving India's clean energy aspirations.

As Karnataka 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 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

1 NPP Dashboard
2 NPP Dashboard
3 MNRE

their effective implementation. Given the criticality 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 capacity-building workshop for Karnataka.

The workshop covered all aspects of RA, providing state agencies and utilities with the necessary training and material to facilitate a 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 Karnataka. 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. It seeks to help Karnataka 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, unserved energy, storage characteristics, 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 Karnataka.

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 Karnataka Electricity Regulatory Commission (Framework for Resource Adequacy) Regulations, 2024 covering key steps, roles and responsibilities, and timelines.

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 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 Karnataka'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 Karnataka, to provide the state with comprehensive set of outputs and pathways for its future development.

Chapter 9 provides concluding remarks.

2. Karnataka State Overview

Karnataka, located in Southern India, is the 6th largest state by both area and by population[4]. It boasts of a vibrant economy with an actual Gross State Domestic Product (GSDP) of ₹ 25.7 lakh crores and projected GSDP of ₹ 25,69,99 crore for FY24, reflecting a 10% growth over FY23[5] which highlights its economic strength and progress. It is a key player in India's industrial and technological landscape, home to numerous major public sector industries and renowned research institutions.

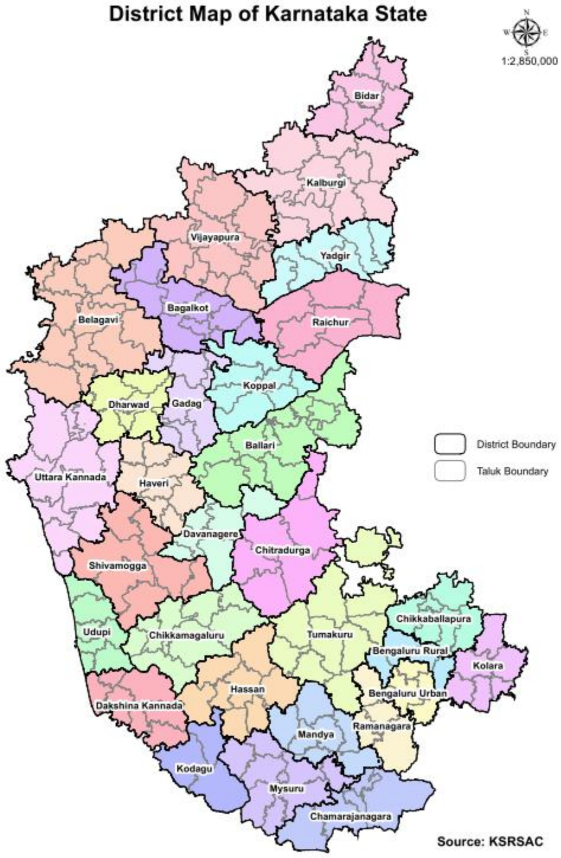

Figure 1: Map of Karnataka[6]

Karnataka's strategic coastal location and strong industrial base have 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 and the integration of cutting-edge technologies have positioned Karnataka 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.

4 UIDAI; List of states and union territories of India by area - Wikipedia
5 RBI
6 KSRSAC | District Map

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5th Floor, Technopolis Knowledge
Park, Mahakali Caves Road,
Chakala, Andheri East, Mumbai – 400 093
Phone: +91 (22) 68620300
Email: contact@idaminfra.com

2.1. Demand Scenario

Karnataka saw a peak demand of 17,220 MW in the month of February in FY24, which was a 9% increase from FY23. Its total energy requirement in FY24 was 95,141 MUs. The following Figure 2 shows the monthly peak demand for FY24 and FY23:

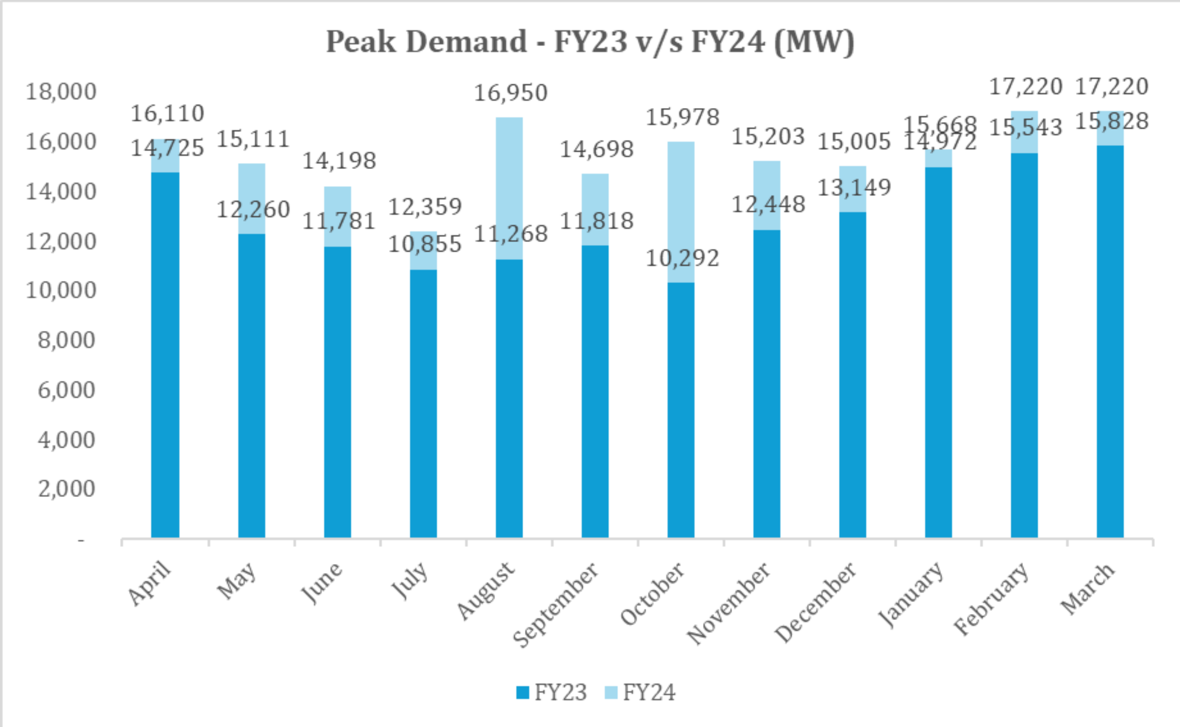

Figure 2: Karnataka Month-wise Peak Demand of FY23 and FY24[7]

It was observed that the actual peak demand over the past two years consistently exceeded the projections outlined in CEA's 20th Electric Power Surbey (EPS). The variance for FY23 was relatively small, FY24 saw a substantial increase in both peak demand and energy requirements. Table 1 below provides a detailed comparison of actual values against 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	72,799	72,417	14,841	14,830
FY23	74,748	75,071	15,167	15,828
FY24	77,629	94,133	15,768	17,212

2.2. Supply Scenario

Karnataka's energy landscape is characterized by a diverse mix of energy sources. As of FY24, coal had an installed capacity of 9,610 MW, contributing 32% to the total installed capacity. On the other hand, RE contributed 53% to the total installed capacity, with 5,237 MW of wind and 7,972 MW of solar[9]. On the generation side, as of FY24, coal makes up 48% of the total generation, with RE contributing 34%. This RE-rich resource mix underscores Karnataka's commitment to sustainability and a transition towards cleaner and more resilient power generation. The following Figure 3 shows Karnataka's installed capacity mix and generation mix.

7 Received from state
8 20th EPS, Received from state
9 Received from state

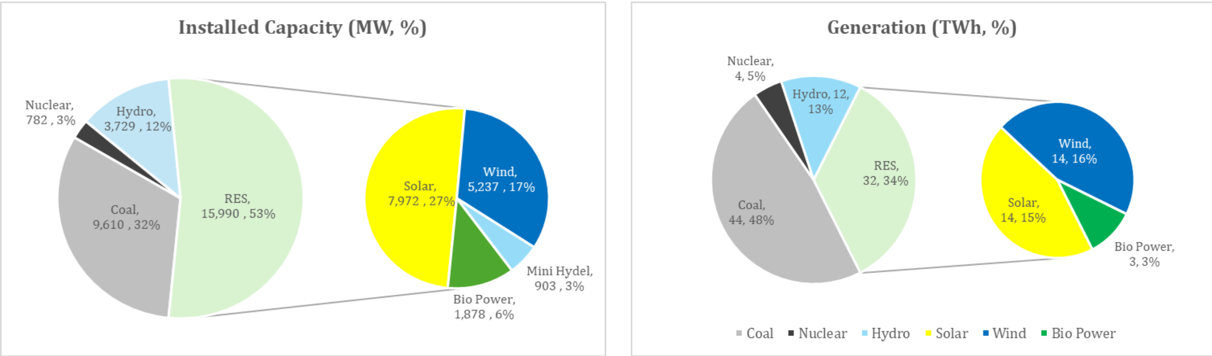

Figure 3: Installed Capacity Mix[10] and Generation Mix of Karnataka for FY24[11]

Given the rapidly growing demand and increasing share of renewable energy (RE), Karnataka is set to remain a leading state in RE. Therefore, it is crucial for Karnataka to prepare for vRE and its associated challenges by implementing measures like RA. The following chapter provides an overview of RA, highlighting its key aspects and the reliability metrics involved.

10 NPP Dashboard
11 NPP Dashboard

Idam Infrastructure Advisory Pvt. Ltd.
5th Floor, Technopolis Knowledge
Park, Mahakali Caves Road,
Chakala, Andheri East, Mumbai – 400 093
Phone: +91 (22) 68620300
Email: contact@idaminfra.com

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 utilisation.

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:

1. **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.
2. **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.
3. **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 a dual variability in both supply and demand, presenting a new phenomenon that needs to be effectively addressed for ensuring grid reliability and stability.
4. **Coincident peak challenges:** One significant challenge is managing coincident peak demand, 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 underutilization or excessive capacity additions. Addressing these challenges requires a structured approach like RA to align state and national grid planning effectively.
5. **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.
6. **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 requirements. Addressing this disconnect is critical to ensuring a resilient, and reliable electricity grid.
7. **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

- **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 and entities like 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 behind 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

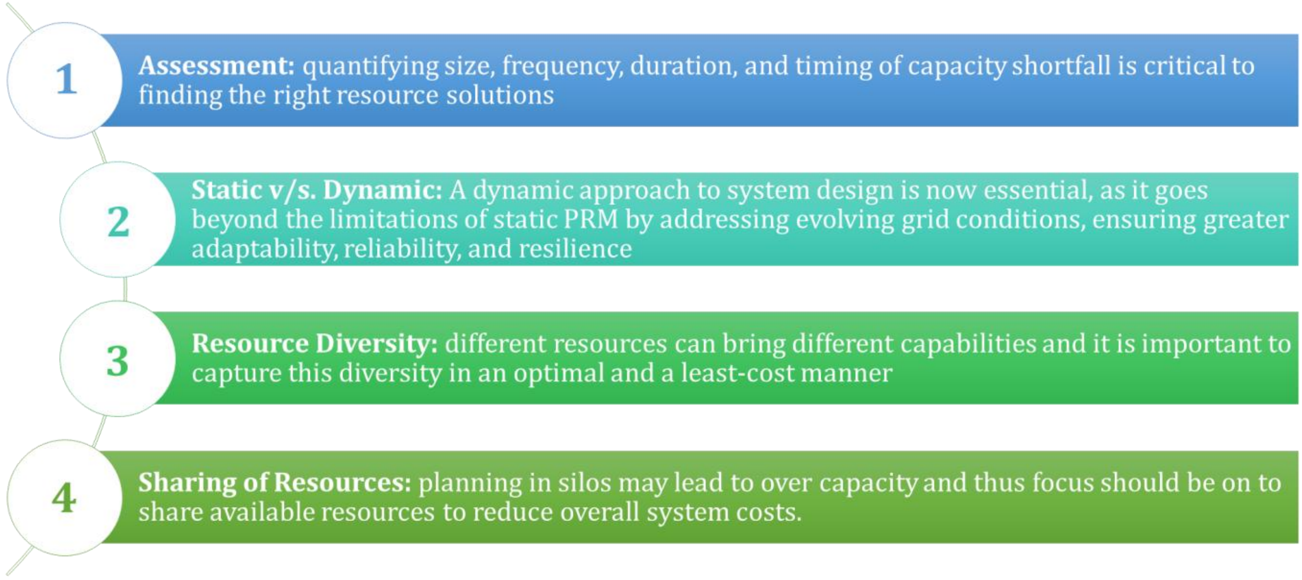

Figure 4: Guiding Principles of RA

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:

1) **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.

2) **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:** Dynamic RA planning, based on the established RA guidelines, produces a dynamic PRM (Planning Reserve Margin) that satisfies reliability requirements and accommodates contingencies.
  - **Scenario-Based Analysis:** Dynamic approaches leverage scenario modeling to simulate various future outcomes, ensuring the system remains reliable under diverse conditions.

3) **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

4) **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

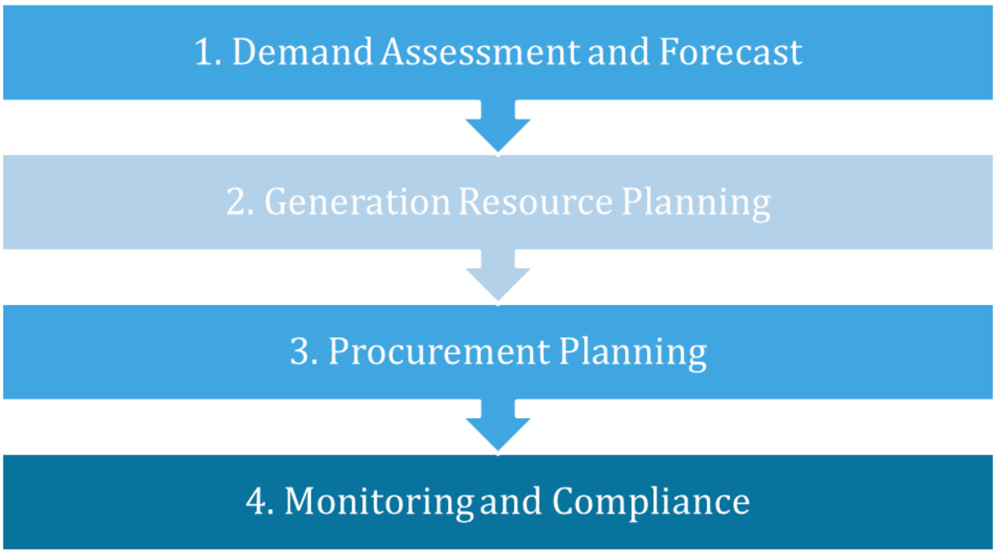

Figure 5: Key Steps in RA

Idam Infrastructure Advisory Pvt. Ltd.
5th Floor, Technopolis Knowledge
Park, Mahakali Caves Road,
Chakala, Andheri East, Mumbai – 400 093
Phone: +91 (22) 68620300
Email: contact@idaminfra.com

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 demand drivers 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 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.
    - 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.

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Phone: +91 (22) 68620300
Email: contact@idaminfra.com

- Components: Monitoring and reporting, verification and regulatory oversight, and treatment for shortfalls in short-term and medium-term compliance.

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:

1. **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 small portion of the year. This metric is critical for planning the balance between supply and demand to minimize load shedding risks.
2. **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.
3. **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.
4. **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 specifics of Karnataka's approach to RA, guided by its recently introduced Resource Adequacy Regulations, 2024. These regulations align with national directives and aim to establish a robust framework for resource planning.

12 CEA Guidelines: RA Framework

Idam Infrastructure Advisory Pvt. Ltd.
5th Floor, Technopolis Knowledge
Park, Mahakali Caves Road,
Chakala, Andheri East, Mumbai – 400 093
Phone: +91 (22) 68620300
Email: contact@idaminfra.com

4. KERC RA Regulations

The Karnataka Electricity Regulatory Commission (KERC) has notified the Framework for Resource Adequacy Regulations, 2024, (referred as KERC RA Regulations in this report), in alignment with the national directives to ensure reliable, cost-effective, and sustainable electricity supply in the state. These Regulations aim to enhance power system reliability by optimizing resource planning and addressing the challenges posed by the evolving energy landscape.

4.1. Background

Background and Legislative Framework

The Resource Adequacy framework derives its legal foundation from the Electricity Act, 2003, which empowers the Ministry of Power (MoP), Government of India, to issue amendments and rules for the effective regulation of the power sector. As part of this mandate:

- The Electricity (Amendment) Rules, 2022, issued by the MoP on 29th December 2022, provided the legal provisions for developing a Resource Adequacy Planning Framework.
- Under Rule 16(1) of these Rules, the MoP, in consultation with the Central Electricity Authority (CEA), issued the Guidelines for Resource Adequacy Planning Framework for India on 28th June 2023.
- Rule 16(2) further mandates State Electricity Regulatory Commissions (SERCs) to frame state-specific Resource Adequacy regulations based on the MoP guidelines and any model regulations prepared by the Forum of Regulators (FoR).

To facilitate uniformity and effective implementation, the Forum of Regulators developed a set of Model Regulations for the Resource Adequacy Framework, published in June 2023. These model regulations provided the foundation for state commissions to develop tailored frameworks suited to their unique grid conditions and demand-supply dynamics.

Adoption of Resource Adequacy in Karnataka

In compliance with the national directives and model regulations, the Hon'ble Karnataka Electricity Regulatory Commission (KERC) issued the KERC Framework for Resource Adequacy Regulations, 2024, through its notification (KERC/F-30/Vol-10/690) on 23rd September 2024. The regulations were subsequently published in the Karnataka Gazette on 24th September 2024.

Regulatory Implications and Compliance

The regulations require:

- Distribution Licensees (DLs): To submit long-term and short-term resource adequacy plans in accordance with the framework.
- System Operators (SLDCs/STUs): To assess resource adequacy compliance and identify gaps in capacity or infrastructure.
- Coordination with Regional and National Frameworks: To align state-level planning with the national framework and ensure compliance with central guidelines.

The KERC regulations are expected to serve as a model for other states, demonstrating a proactive approach to modernizing power system planning and fostering energy security for all stakeholders.

In following sub-sections key chapters from KERC Chapter is covered.

- Demand Assessment and Forecasting
- Generation Resource Planning
- Power Procurement Planning
- Monitoring and Compliance
- Roles and Responsibilities

4.2. Demand Assessment and Forecasting

This section describes the demand forecasting process, a crucial component of resource adequacy assessment. It details the methodologies, data utilization, scenario planning, and aggregation procedures used to generate reliable demand projections for both short-term and long-term planning.

4.2.1 Short-term and Long-term Demand Forecast

Demand assessment and forecasting form a pivotal step in the Resource Adequacy assessment. This process requires meticulous attention to detail and involves hourly, sub-hourly, or time-interval assessments as notified by the Commission. The forecasting spans short-term and long-term planning horizons using a combination of comprehensive data, scientific modeling tools, and policy frameworks.

4.2.2 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 Annual Growth Rate (CAGR)
- End-use or Partial End-use Analysis
- Trend Analysis
- Auto-regressive Integrated Moving Average (ARIMA)
- AI and Machine Learning Techniques
- Time Series/Econometric Methods

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

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
- 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
- Open access
- Distributed energy resources
- Demand response measures
- Electric vehicle penetration
- Tariff signals
- Changes in energy consumption patterns

For each factor, trajectories based on economic and policy parameters must be developed, ensuring robust scenario planning.

4.2.3 Scenario Planning

To address uncertainties, licensees must develop forecasts under at least three scenarios:

- Most Probable
- Business as Usual
- Aggressive Growth

These scenarios undergo sensitivity and probabilistic analysis, providing a spectrum of outcomes. The most suitable scenario is then submitted to SLDC by April 30 each year.

4.2.4 State-Level Demand Aggregation

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.

Idam Infrastructure Advisory Pvt. Ltd.
5th Floor, Technopolis Knowledge
Park, Mahakali Caves Road,
Chakala, Andheri East, Mumbai – 400 093
Phone: +91 (22) 68620300
Email: contact@idaminfra.com

4.3. Generation Resource Planning

Generation resource planning forms a crucial step following demand assessment and forecasting. It involves evaluating the existing and contracted generation resources, considering their capacity credits, and determining the incremental capacity required to meet the forecasted demand, including the planning reserve margin.

4.3.1 Data Requirements

To develop a comprehensive Resource Adequacy Plan, the following data elements are essential:

- Planning Reserve Margin (PRM): Defined by the Central Electricity Authority (CEA) at the national level or as determined by the distribution licensee, subject to optimal limits and regulatory approval.
- Historical Demand Data: Hourly demand met by the state or distribution licensee over the past five years.
- Load Growth Estimates: Projected load growth during the planning period.
- Conventional Generation Parameters: Technical details of conventional plants, including capacity, auxiliary consumption, ramp rates, availability factors, and more.
- Under-Construction and Retiring Capacity: Status of projects under construction, retirements, bilateral contracts, and associated timelines.
- Investment Options: Feasibility of new technologies, gestation periods, and asset lifespans.
- Renewable Generation: Capacities and generation profiles of renewable resources.
- Cost Parameters: Capital, variable, and operational costs of generators, along with start-up and shutdown costs.
- Historical Outage Data: Forced and planned outage rates of generation facilities.
- Transmission and Distribution Plans: Tie-line details and expansion plans for transmission and distribution infrastructure.
- Spinning Reserves: Requirements for maintaining operational flexibility.
- Regulatory Obligations: Renewable Purchase Obligations (RPO) and energy storage targets.

4.3.2 Demand and Supply Modeling

Demand projections for future years, based on hourly or sub-hourly time intervals, form the basis of the resource adequacy model. The chosen generation expansion planning model must simulate the system's behaviour, including ramping of conventional resources, renewable energy profiles, and storage characteristics. The optimization exercise minimizes the total system cost while adhering to power system constraints:

- Resource Adequacy Requirement (RAR): Ensures sufficient generation capacity to meet demand plus the planning reserve margin.
- Portfolio Balance Constraints: Guarantees the generation within a control area matches demand, exports, curtailments, and energy not served.
- Renewable Energy Constraints: Generation from solar and wind resources is aligned with their hourly profiles based on historical data.
- Conventional Generation Constraints: Dispatchable resources are limited by technical and operational parameters, such as ramp rates and minimum uptime.
- Renewable Purchase Obligations (RPO): Ensures compliance with renewable energy targets.
- Storage Constraints: Models energy storage to account for efficiency losses, state of charge, and charge/discharge cycles.
- Operating Reserve Constraints: Provides reserves to address demand variability and renewable intermittency.
- Demand Response: Incorporates potential load shifting or demand response measures.
- Transmission and Distribution Constraints: Accounts for infrastructure limits and associated costs.

4.3.3 Capacity Crediting of Generation Resources

Firm capacity represents the dependable power a generator can provide, expressed as a percentage of its installed capacity. This is critical for integrating variable renewable resources like wind and solar.

- **Top Demand Hours:** In this approach, capacity credit is estimated by averaging the historical performance of a generator or generator class during peak demand hours. The number of peak demand hours considered can vary depending on the region.
- **Top Net Load Hours:** This method takes into account periods of system stress, which occur when high demand aligns with low renewable energy generation. The 'net load' metric, defined as the total renewable energy generation subtracted from overall demand, must be met by dispatchable resources like thermal and hydro plants. Due to the system stress caused by the duck curve, net load is a more accurate indicator of system stress for new capacities than peak demand. Capacity credit is calculated by averaging the contribution of a generator or generator class during the top net load hours.
- **Expected Load Carrying Capability (ELCC):** This method uses an hourly time-series demand data for a specific period and considers the availability of different generation resources each hour of the year. It also accounts for random outages of generators based on historical and expected conditions. Supply matching is used to determine the Loss of Load Probability (LOLP) of the system.

4.3.4 Regulatory Compliance and Future Directions

Distribution licensees must adhere to regulatory requirements for resource adequacy, including compliance with RPOs and storage obligations. Emerging methodologies like ELCC will become more prominent as data capabilities improve. Utilities must transparently document deviations from prescribed methods and justify their approaches.

4.3.5 Ensuring Resource Adequacy and Its Allocation for Control Areas

Every year, by the end of May, the State Load Dispatch Centre (SLDC) takes on the responsibility of gathering and providing crucial data to the Authority, NLDC, and SRLDC. This data includes demand forecasts for the next decade, an assessment of current generation resources, and any other necessary details. This information is essential for creating both the Long-Term and Short-Term National Resource Adequacy Plans (LT-NRAP and ST-NRAP) as outlined in the CEA RA Guidelines.

By the end of July, the Authority and NLDC publish their respective reports. The LT-NRAP report, issued by the Authority, offers guidance on the national Planning Reserve Margin (PRM) for states and union territories. It also outlines the optimal generation mix needed over the next ten years to ensure the national system remains resource adequate while meeting demand at the lowest cost. Additionally, it provides capacity credits for different types of resources on a regional basis and details each state or union territory's contribution to the national peak demand.

The ST-NRAP report, published by the NLDC, includes various parameters such as demand forecasts, resource availability based on the status of new projects under construction, planned maintenance schedules, historical forced outage rates, and decommissioning plans.

Once the LT-NRAP is published, the SLDC has 15 days to allocate each distribution licensee's share of the national peak demand. Each distribution licensee then plans to contract the necessary capacities to meet their Resource Adequacy Requirement (RAR) during the national peak. They must demonstrate that they have secured 100% of the required capacity for the first year and at least 90% for the second year. This is done through a mix of long-term, medium-term, and short-term contracts, although power procurement through exchanges like the Day-Ahead Market is not considered for RAR.

Each distribution licensee must also develop a 10-year Resource Adequacy Plan (LT-DRAP) to meet their peak and energy requirements. This plan is validated by the Authority and submitted to the CEA by the end of September each year. By the end of November, the validated plan is then submitted to the Commission for approval.

The Commission reviews and approves the distribution licensee's contracting plan by the end of December each year. This plan must ensure that the licensee can meet both their own peak and energy requirements as well as their contribution to the national peak.

The LT-DRAP is updated annually, optimizing for any additional capacity needed. Distribution licensees must demonstrate that they have secured 100% of the required capacity for the first year and at least 90% for the second year.

By the end of January each year, distribution licensees submit details of their contracted capacities to the SLDC. The SLDC aggregates this information and submits it to the SRLDC by mid-February. The SRLDC then

Idam Infrastructure Advisory Pvt. Ltd.
5th Floor, Technopolis Knowledge
Park, Mahakali Caves Road,
Chakala, Andheri East, Mumbai – 400 093
Phone: +91 (22) 68620300
Email: contact@idaminfra.com

aggregates the regional data and submits it to the NLDC by the end of February. The NLDC checks for compliance with the ST-NRAP and identifies any shortfalls. If there are shortfalls, the NLDC may facilitate a national-level auction to procure the balance capacity.

The SLDC also prepares a one-year look-ahead Short-Term Resource Adequacy Plan (ST-DRAP) based on the LT-DRAP results. This plan is reviewed on a daily, weekly, monthly, and quarterly basis to ensure compliance and address any shortfalls.

To determine the optimal Planning Reserve Margin (PRM), metrics such as Loss of Load Probability (LOLP) and Normalized Energy Not Served (NENS) are used. Multiple future scenarios are created using stochastic models to account for uncertainties. Demand-supply matching simulations are performed to assess the duration of loss of load events and energy not served. This iterative process continues until the desired LOLP/NENS levels are achieved, balancing system costs and reliability.

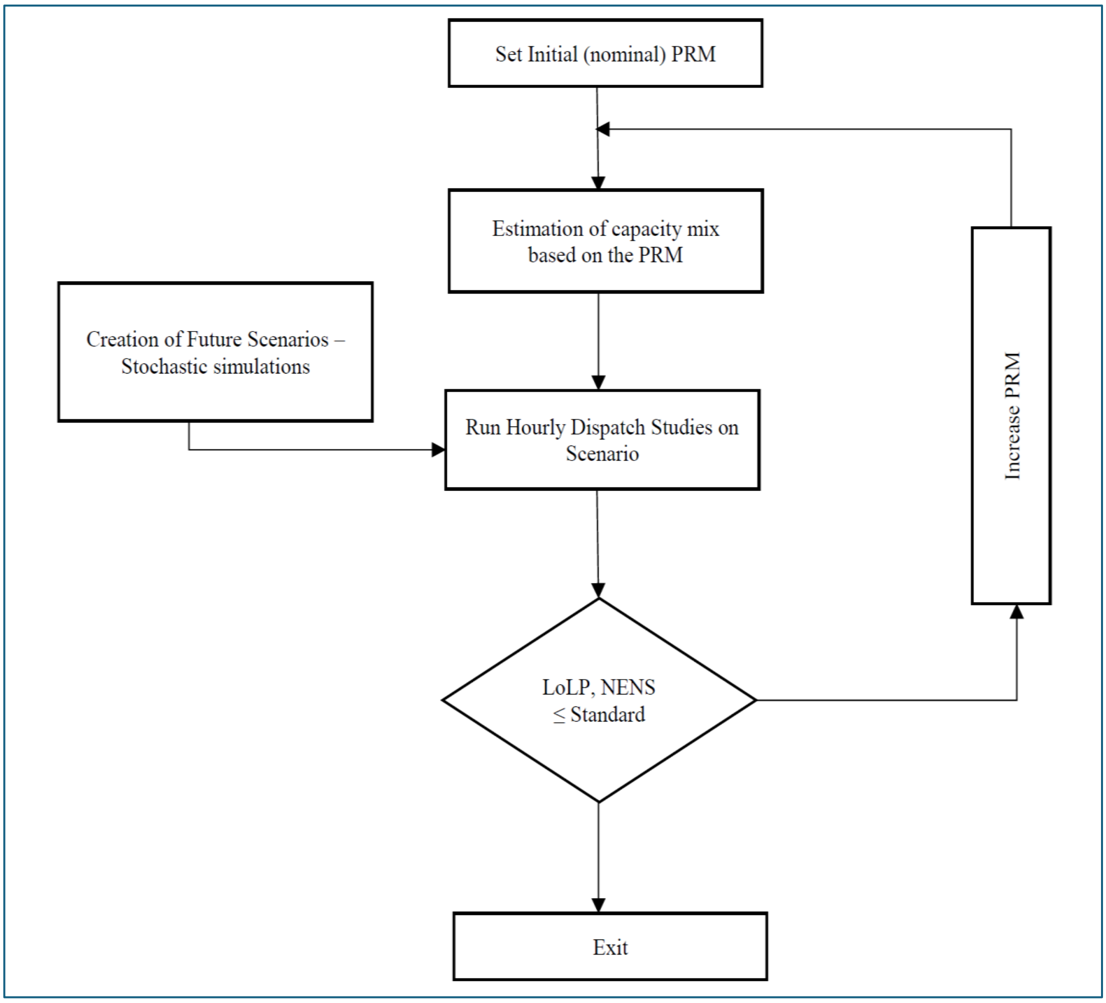

Figure 6: Flow chart of Optimal Reserve Margin Study

4.4. 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.

4.4.1 Procurement of Resource Mix

The responsibilities of distribution licensees in identifying optimal resource mixes, contracting resources, and utilizing various power procurement channels. It emphasizes the importance of strategic decision-making, considering long-term planning studies, renewable energy targets, and the necessity of obtaining Commission approvals for new capacity arrangements.

Idam Infrastructure Advisory Pvt. Ltd.
5th Floor, Technopolis Knowledge
Park, Mahakali Caves Road,
Chakala, Andheri East, Mumbai – 400 093
Phone: +91 (22) 68620300
Email: contact@idaminfra.com

Optimal Resource Mix

- Distribution licensees must identify an optimal mix of generation resources to ensure smooth integration of renewable energy (RE) while meeting reliability standards.
- Optimization techniques and least-cost modeling should be used to avoid asset stranding. These techniques must be demonstrated in the power procurement planning submitted to the Commission for approval.
- Procurement must align with the identified resource mix and national electricity plans and policies.
- The outcomes of Resource Adequacy Studies should define the type and quantum of generation resources required. The capacity mix may include existing, planned, and additional resources to meet growing demand, considering the appropriate gestation periods for new generation assets.

Contracting Resources

- Contract an optimal portfolio of resources based on long-term (LT-NRAP) study outputs.
- Use long-, medium-, and short-term firm contracts to meet Resource Adequacy Requirements (RAR), excluding reliance on short-term power exchange procurements.
- Procure additional resources based on the LT-DRAP study for meeting peak demand, subject to regulatory approval.
- Procurement from renewable sources to meet Renewable Purchase Obligation (RPO) targets should consider the state's RE potential and fungibility within RE resources.
- Procurement guidelines for wind, solar PV, wind-solar hybrid, and round-the-clock (RTC) power projects must be followed.
- Storage capacity can be contracted based on LT-DRAP requirements, following guidelines for competitive bidding for energy from Battery Energy Storage Systems (BESS).

Power Procurement Channels

- Power can be procured through central agencies, intermediaries, traders, aggregators, power exchanges, bilateral agreements, banking arrangements, or capacity sharing with other distribution licensees.
- Short-term and medium-term procurement can be done through DEEP and PUShP portals.

Timely Procurement Execution

Procurement processes must align with projected requirements, ensuring sufficient lead time for capacity readiness. The following table specifies the timelines for completing procurement processes:

Resource Type	Long Term (Years)	Medium Term (Years)
Coal/Lignite	7	2
Hydro	9	2
Solar	2	1
Wind	3	1
Pump Hydro Storage (PSP)	5	3
Other Storage	2	1
Nuclear	9	3

Special Provisions

- Uniform Tariff Provisions: When uniform tariffs are required across distribution licensees, a collective Resource Adequacy Plan may be developed with approval from the Commission and the Authority.
- Granular Planning Horizons: Distribution utilities may adopt more granular timeframes for formulating LT-DRAP, in line with LT-NRAP guidelines, to enhance accuracy and reliability.

Commission Approval

- Commission Approval: Any new capacity arrangement or tie-up requires prior Commission approval, considering the necessity, cost reasonableness, and efficiency.
- 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.

Idam Infrastructure Advisory Pvt. Ltd.
5th Floor, Technopolis Knowledge
Park, Mahakali Caves Road,
Chakala, Andheri East, Mumbai – 400 093
Phone: +91 (22) 68620300
Email: contact@idaminfra.com

Variation in Power Purchase

The licensee may undertake additional procurement under these circumstances:

- Additional power procurement may be undertaken during the year if there is an unanticipated increase in demand, a shortfall in supply, or if sourcing from existing tied-up sources becomes costlier.
- Short-term arrangements can be made during emergencies or as directed by SLDC/SRLDC/NLDC to prevent grid failure, with details submitted to the Commission within 15 days.

4.5. Monitoring and Compliance

Monitoring and Reporting

The distribution licensees, SLDC, and utilities shall adhere to the timelines, procedures, and methodologies specified under these regulations. The SLDC is tasked with monitoring the entire process and must submit monthly compliance reports to the Commission.

Treatment for Shortfall in RA Compliance

Distribution licensees are required to meet their Resource Adequacy (RA) requirements. In the event of non-compliance, penalties will be imposed as follows:

- Non-compliance charges equivalent to the higher of Marginal Capacity Charge (Rs/kW/month) or 1.25 times the Average Capacity Charge (Rs/kW/month) for power procurement under the distribution licensee's APR/Tariff Order for the relevant financial year.
- Such charges will be disallowed by the Commission in the Annual Performance Review (APR) and cannot be recovered through future ARR/APRs.

4.6. Roles and Responsibilities and Timelines

To ensure adherence to regulatory guidelines and maintain a reliable power system, a robust framework for data management and information sharing is essential. This section outlines the data requirements, sharing protocols, and operational procedures for distribution licensees and the SLDC. It also details the establishment of dedicated cells for planning and power exchange, as well as the key implementation timelines for resource adequacy planning and execution.

4.6.1 Data Requirement and Sharing Protocol

Distribution licensees must maintain and share comprehensive data with the SLDC for demand assessment and forecasting. Key data elements include:

- Consumer data, historical demand data, and weather variables.
- Demographic and econometric factors influencing demand.
- Transmission and Distribution (T&D) losses and actual energy availability.
- Historical hourly load shapes and demand profile changes.
- Statistics on energy efficiency measures, demand-side management, and appliance penetration.
- Data on specific consumer categories, seasonal demand variations, and trends in electric vehicle adoption.
- Information on contracted capacities and technical and financial characteristics of generation assets.

The SLDC must:

- The SLDC maintains and aggregates demand assessment and forecasting data for the state and shares it with the Authority and NLDC for national assessment.
- The SLDC also aggregates generation data and communicates the allocation of national RA requirements to distribution licensees.

Distribution licensees and SLDC must use authenticated and realistic data for the RA plan, including demand forecasting. Penalties are imposed for using unauthentic or unrealistic data, and these penalties cannot be passed on in the tariff.

a) Publication of Information on Website
Distribution licensees and SLDCs must publish the following information on their websites:

Idam Infrastructure Advisory Pvt. Ltd.
5th Floor, Technopolis Knowledge
Park, Mahakali Caves Road,
Chakala, Andheri East, Mumbai – 400 093
Phone: +91 (22) 68620300
Email: contact@idaminfra.com

- Distribution licensees and SLDC must publish monthly, weekly, day-ahead, and intraday power procurements/sales and generator schedules on their websites within 15 days of such transactions. The data should be easily accessible and downloadable.
- The SLDC must also publish the monthly Merit Order Dispatch (MoD) stack with the per-unit variable cost of each generating station on its website.

a) Constitution of dedicated Cells by Distribution Licensee

- **Planning Cell**: Distribution licensees must establish a 'Planning Cell' for Resource Adequacy within one month of the regulations coming into force. This cell should have the capability and tools for demand forecasting, capacity planning, and RE integration.
- **Power Exchange Cell**: A dedicated 'Power Exchange Cell' must be established for real-time power purchase/sale and intra-day, day-ahead, and week-ahead power procurement through power exchanges or other means. Guidelines for the operation of these cells must be framed and submitted to the Commission within one month of the regulations coming into force.
- Consultation for Resource Adequacy Plan: The Resource Adequacy Plan must be made in consultation with state sector generating companies, other distribution licensees (in case of state-wide uniform tariff), central sector generating companies, transmission companies, and load dispatch centres.

4.6.2 Resource Adequacy Implementation Timeline

Key implementation timelines include:

- 30th April: Submission of demand forecasts by distribution licensees to SLDC
- 31st May: SLDC's submission of state-level assessments to the Authority, NLDC, and SRLDC.
- 31st July: Publication of LT-NRAP and ST-NRAP by the Authority and NLDC.
- 30th September: Submission of LT-DRAP by distribution licensees to CEA for vetting.
- 30th November: Approval of LT-DRAP by the Commission.
- 31st December: Commission approval of contracting plans for national and state-level peaks.
- 31st January: Submission of contracted capacity details by distribution licensees to SLDC.
- 15th February: SLDC's aggregation of contracted capacities at the state level and submission to SRLDC.
- 28th February: Regional aggregation of capacities by SRLDC and submission to NLDC.
- March: Completion of contracting for capacity shortfalls through national-level auctions.

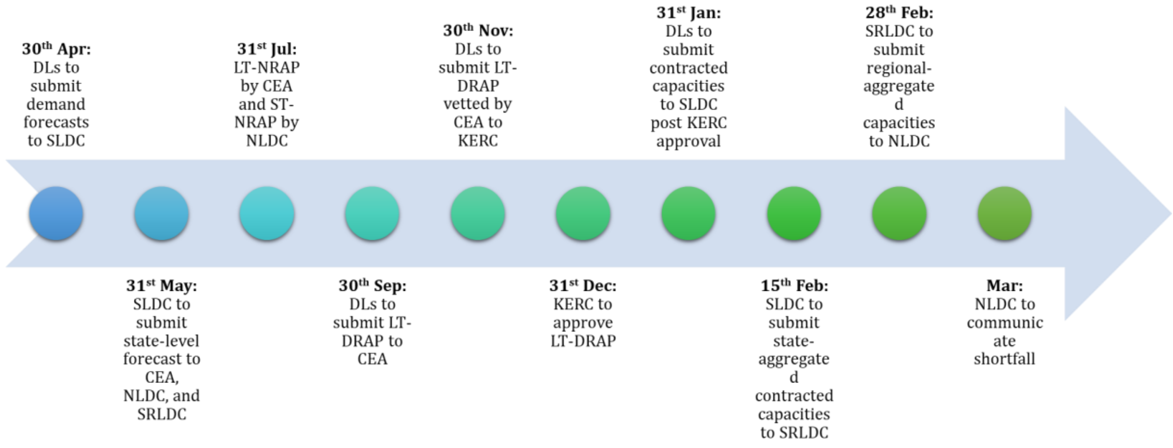

Figure 7: RA Implementation Timelines

With the establishment of the foundational framework for resource adequacy through the KERC 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.

Idam Infrastructure Advisory Pvt. Ltd.
5th Floor, Technopolis Knowledge
Park, Mahakali Caves Road,
Chakala, Andheri East, Mumbai – 400 093
Phone: +91 (22) 68620300
Email: contact@idaminfra.com

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 its 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 particular 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 are capable of doing all the above objectives are:

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

PLEXOS has been used in the RA study for Karnataka 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 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

13 AFRY

Idam Infrastructure Advisory Pvt. Ltd.
5th Floor, Technopolis Knowledge
Park, Mahakali Caves Road,
Chakala, Andheri East, Mumbai – 400 093
Phone: +91 (22) 68620300
Email: contact@idaminfra.com

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-Optimisation, 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 Karnataka. The model minimizes total generation cost (fixed plus variable) for the entire system, including existing and new generation capacity.

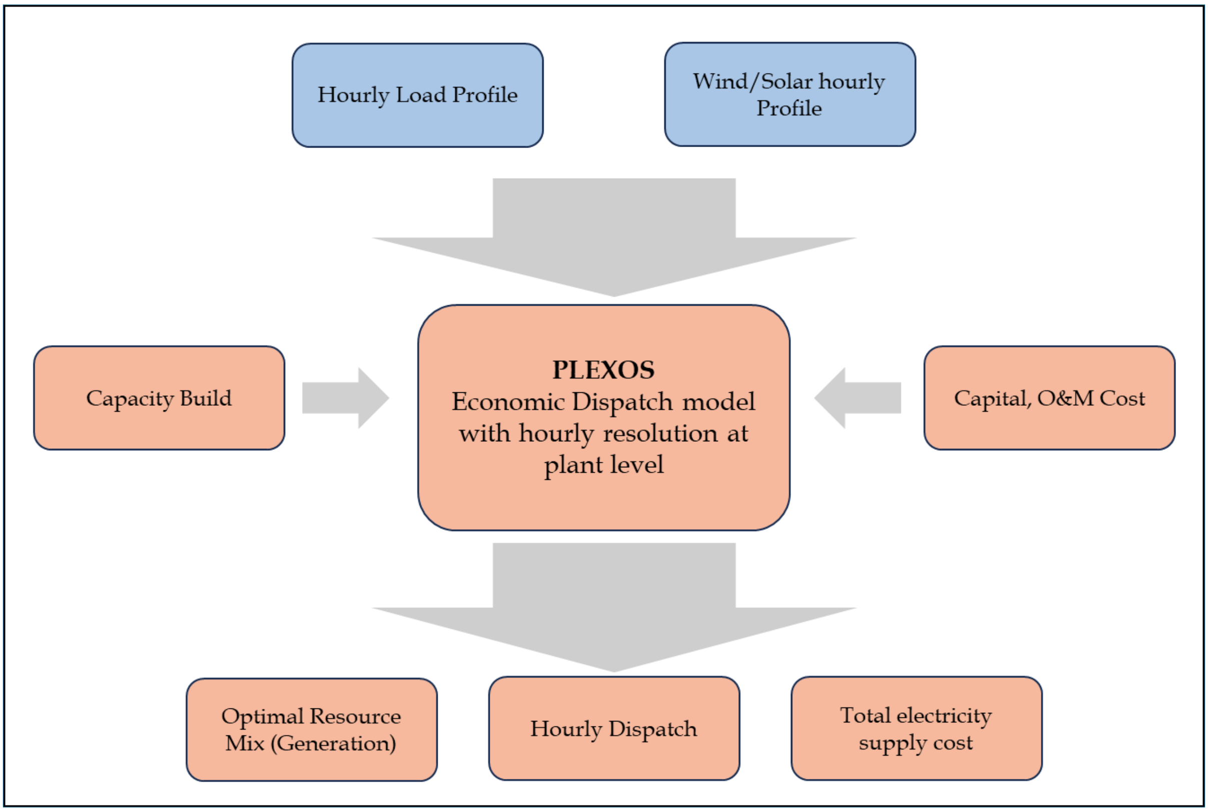

Figure 8: Modeling Philosophy

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5th Floor, Technopolis Knowledge
Park, Mahakali Caves Road,
Chakala, Andheri East, Mumbai – 400 093
Phone: +91 (22) 68620300
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5.2.3 State Model Configuration

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

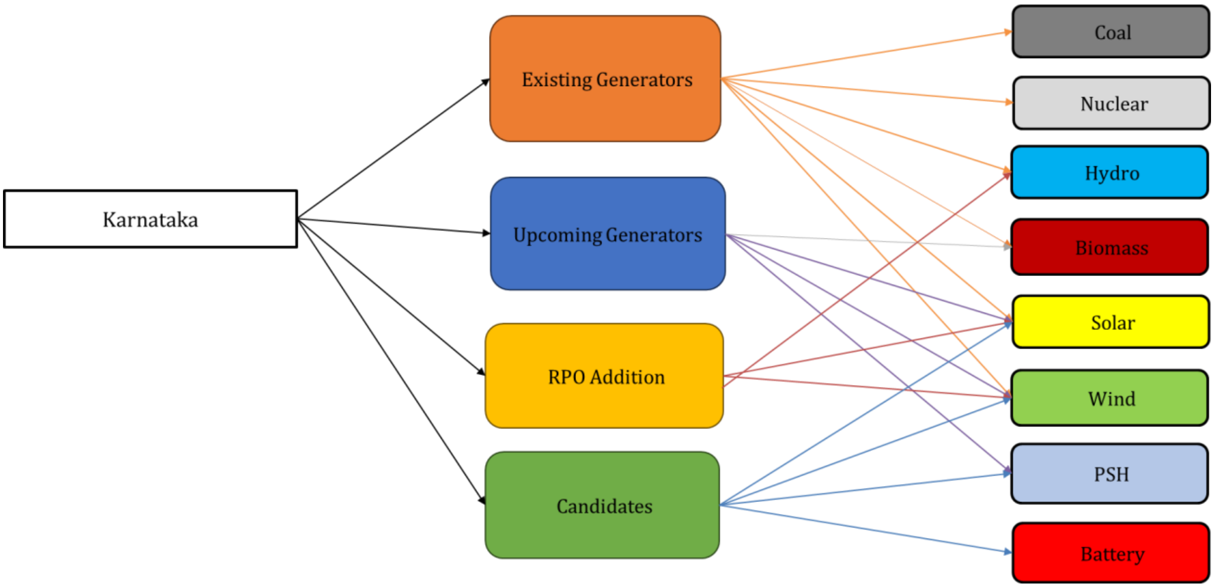

Figure 9: Karnataka State Model Configuration in PLEXOS

5.2.4 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.

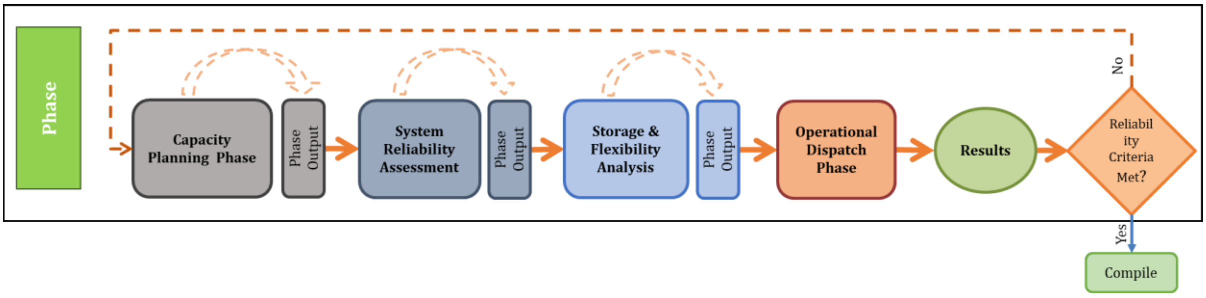

Figure 10: PLEXOS Stage-wise Modeling

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 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.

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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.

Idam Infrastructure Advisory Pvt. Ltd.
5th Floor, Technopolis Knowledge
Park, Mahakali Caves Road,
Chakala, Andheri East, Mumbai – 400 093
Phone: +91 (22) 68620300
Email: contact@idaminfra.com

6. Input Assumptions for Karnataka 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 Karnataka. It details the renewable energy profiles, load projections, and RPO targets, providing a comprehensive overview of the modeling framework.

6.1. Solar & Wind Input Profiles

Figure 11 illustrates the monthly average solar and wind profiles for Karnataka, featuring an average Capacity Utilization Factor (CUF) of 20% and 33% 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.

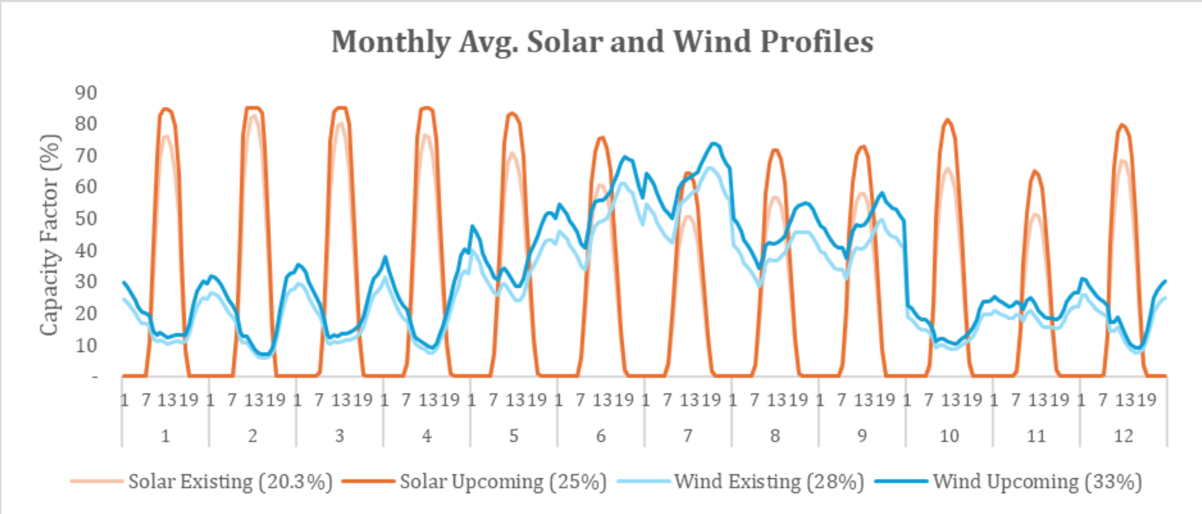

Figure 11: Monthly Average Solar and Wind Profiles of Karnataka

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 fluctuates 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 is 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 on a monthly basis to compute the coefficient of variation (CV) for use as an input to the model. The following systematic steps were undertaken:

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,

Idam Infrastructure Advisory Pvt. Ltd.
5th Floor, Technopolis Knowledge
Park, Mahakali Caves Road,
Chakala, Andheri East, Mumbai – 400 093
Phone: +91 (22) 68620300
Email: contact@idaminfra.com

indicates the relative variability of the data compared to its mean, 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, five stochastic samples of load and RE generation variability were generated:

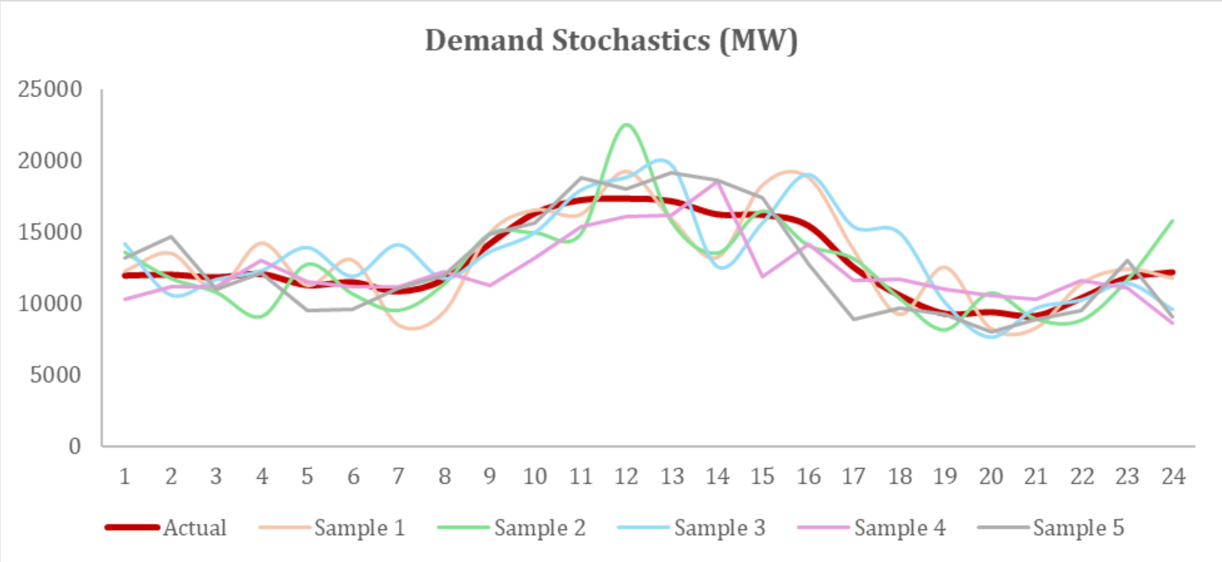

Figure 12: Demand Stochastics (MW)

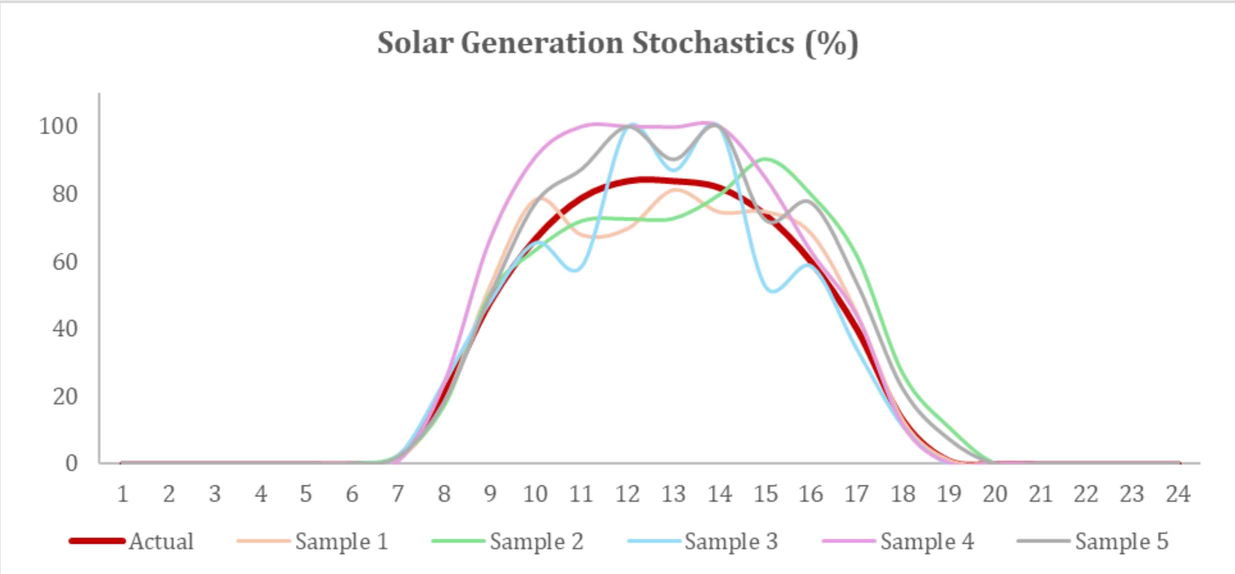

Figure 13: Solar Generation Stochastics (%)

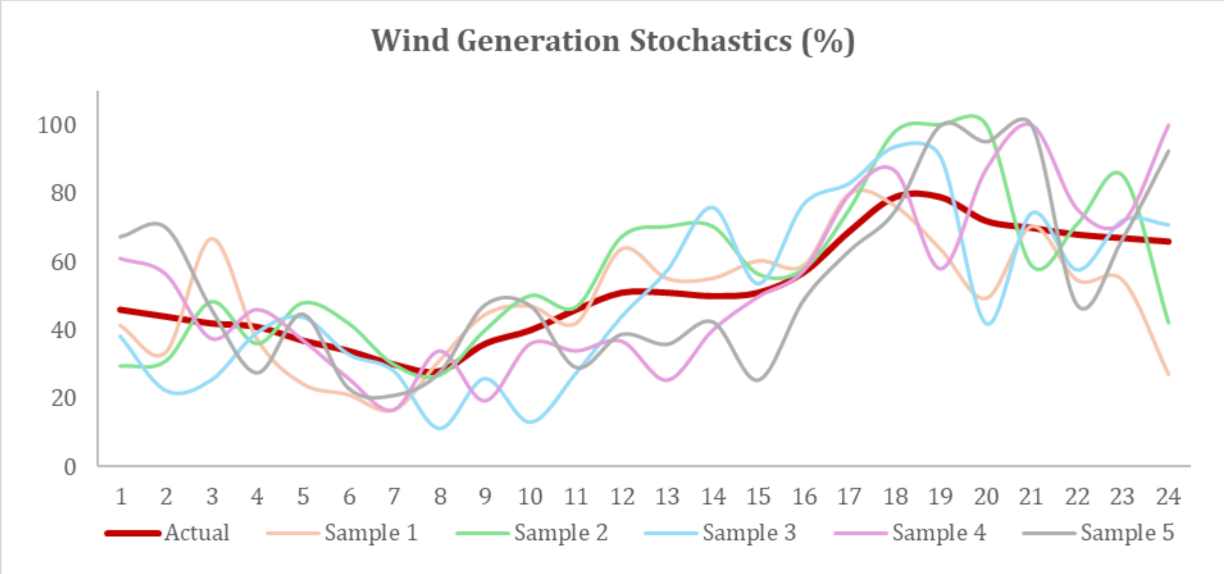

Figure 14: Wind Generation Stochastics (%)

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 (July to October). The graph below showcases the average hourly CUF for hydro plants on a monthly basis, highlighting seasonal patterns.

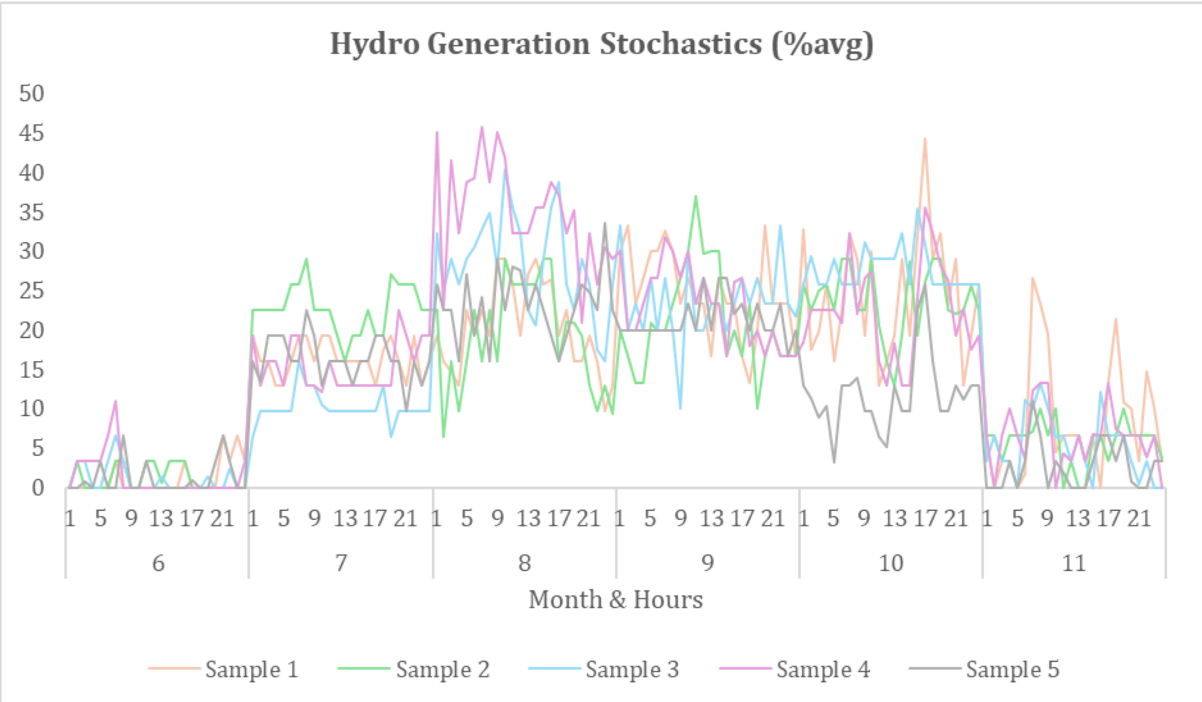

Figure 15: Hydro Generation Stochastics (%avg)

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 Karnataka 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 and wind, in

Idam Infrastructure Advisory Pvt. Ltd.
5th Floor, Technopolis Knowledge
Park, Mahakali Caves Road,
Chakala, Andheri East, Mumbai – 400 093
Phone: +91 (22) 68620300
Email: contact@idaminfra.com

alignment with regulatory obligations. Furthermore, the inclusion of battery technologies underscores a proactive approach towards addressing intermittency challenges associated with renewables, thereby enhancing the overall resilience and reliability of the power system. The Table 2 shows the Resource-wise Model Input Assumptions as below:

Table 2: Resource-wise Model Input Assumptions

Resource Type	Existing Capacity (MW)	Upcoming Capacity (Allocated) (MW)	Cost Escalations/Reduction Assumptions
Coal	9,610	FY28 – 1,900	2% increase
Gas	0	FY25 – 370 MW	Constant
Nuclear	782	FY27 – 442 FY29 – 700	Constant
Hydro	5,009	-	Constant
Solar	8,500	753 MW in FY25 2,040 MW in FY26 1,500 MW in FY27 1,000 MW in FY28 200 MW in FY29 1,000 MW in FY30 1,000 MW in FY31	Constant
Wind	6,000	1,000 MW in FY27 1,000 MW in FY28 200 MW in FY29 1,000 MW in FY30 1,000 MW in FY31	Constant
Biomass & Others	1,867	12 MW in FY25	Constant
Pumped storage hydro (PSH)	-	2,000 MW in FY30 1,500 MW in FY31	3% increase
Battery Energy Storage System (BESS)	-	2 MW in FY25 600 MW in FY27 500 MW in FY28 50 MW in FY29 50 MW in FY30 50 MW in FY31 50 MW in FY32 50 MW in FY33 50 MW in FY34	-

Table 3 below shows the upcoming contracted capacity additions included in the model, the plants with the commissioning date was considered in the model and the plants which are uncertain were not considered:

Table 3: Upcoming Capacity with Date of Commissioning

Plant Name	Total Capacity (MW)	Allocated Capacity (MW)	Type	Commissioning Year
Godhna TPS	2x800	1600	Coal	FY29
Yelahanka CCPP	4x93	370	Gas	FY25
KKNP Unit 3 & 4	2000	442	Nuclear	FY27
Kaiga Unit 5 & 6	1400	700	Nuclear	FY29
DVC KTPS Phase-II	2x800	300	Coal	FY29
Sharavathy PSP	8x250	2,000	PSP	FY30
Varahi PSP	6x250	1,500	PSP	FY31

Table 4: Upcoming Contracted Capacity Additions - Uncertain

Name of the Project	Resource	Capacity (MW)
NHPC Kiru	Hydro	624
NHPC Kwar	Hydro	540
NHPC Pakaldul	Hydro	1,000
NHPC Teesta-VI	Hydro	500
NHPC Dugar	Hydro	500
NHPC Dibang	Hydro	2,880
Netravathy PSP-I	PSP	1,500
Netravathy PSP-II	PSP	2,500

In the PLEXOS model, some additional capacity of short term and medium-term contracts 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 and wind 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%
- **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 reduces by 2% YoY until FY30, remaining constant thereafter through FY34.
    - **CUF:** 33%
- **BESS 2-hr:** 2-hour battery energy storage system will mitigate contingency risks and facilitate the efficient storage of excess renewable energy.
    - **VOM:** 3.56 Rs lakhs/MW/month for FY25, reducing at 5% YoY till FY30, then at 2% and reaching 2.49 Rs lakhs/MW/month by FY34
- **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.

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5th Floor, Technopolis Knowledge
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Phone: +91 (22) 68620300
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6.4. Renewable Purchase Obligation (RPO)

Karnataka has mandated the RPO till 2030 and the same percentage has been retained till FY34 and same is shown in Table 3.

Table 5: Renewable Purchase Obligation[14]

FY	Other RPO	New Wind RPO	New DRE RPO	New Hydro RPO
2025	27.35%	0.67%	1.50%	0.38%
2026	28.24%	1.45%	2.10%	1.22%
2027	29.94%	1.97%	2.70%	1.34%
2028	31.64%	2.45%	3.30%	1.42%
2029	33.10%	2.95%	3.90%	1.42%
2030	34.02%	3.48%	4.50%	1.33%
2031	34.02%	3.48%	4.50%	1.33%
2032	34.02%	3.48%	4.50%	1.33%
2033	34.02%	3.48%	4.50%	1.33%
2034	34.02%	3.48%	4.50%	1.33%

Based on the above RPO target, additional solar & wind capacity will not be required till FY34 as it is meeting the obligations.

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 March, peaking at 17,220 MW. The below figure shows Karnataka's monthly peak demand for FY24:

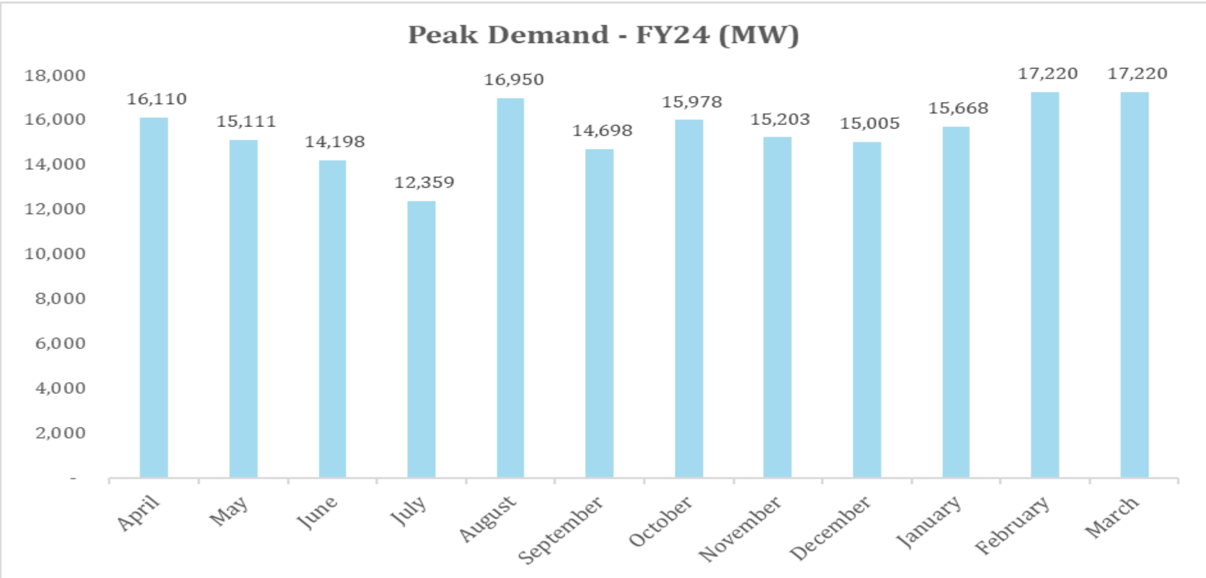

Figure 16:Karnataka's Monthly Peak Demand for FY24

Considering the hourly load profile for FY24, 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 17 below:

14 RPO Targets | MoP

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Phone: +91 (22) 68620300
Email: contact@idaminfra.com

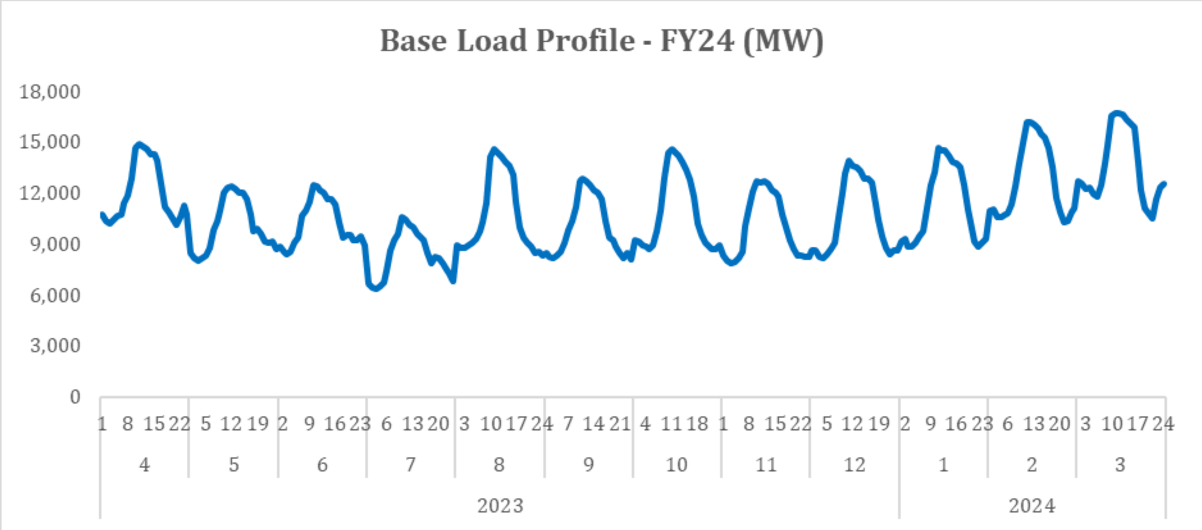

Figure 17: Monthly average Hourly Load Profile for FY24

By considering the KPTCL projections which are available up to FY 2031-32, the projections have been computed up to FY34 in accordance with the agreed horizon.

The energy (in MU's) and peak demand (in MW's) projections required to model for this study are taken from KPTCL as shown in Figure 18 below:

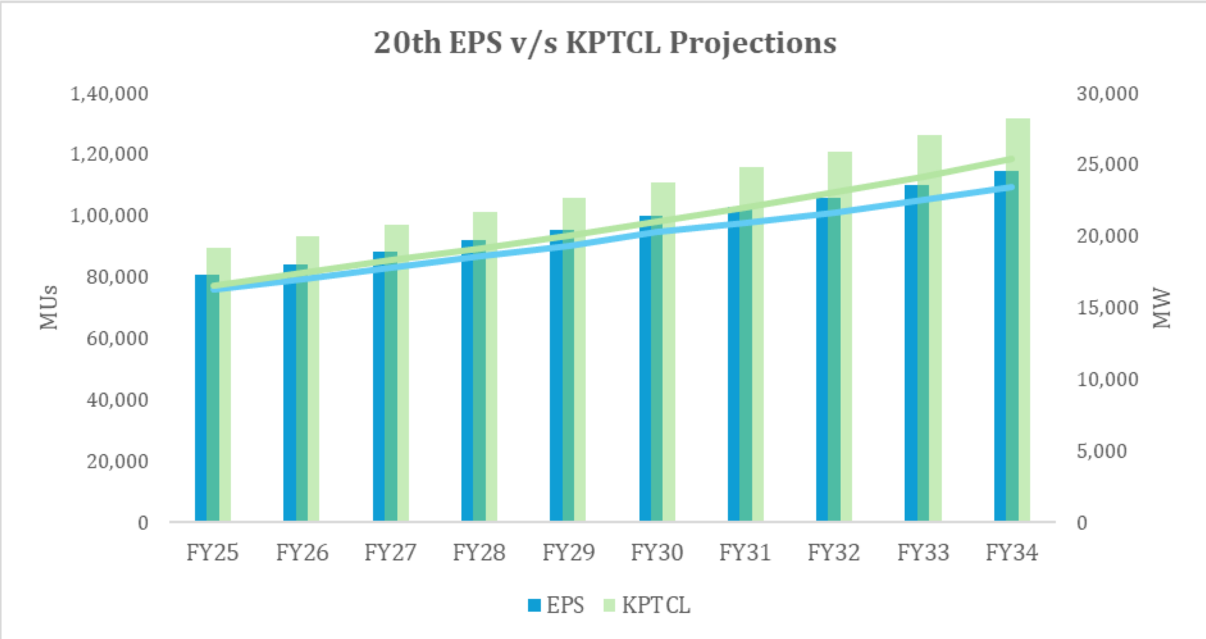

Figure 18: Karnataka's YoY Peak and Energy projections - 20th EPS and KPTCL

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Phone: +91 (22) 68620300
Email: contact@idaminfra.com

6.6. Demand Projection Considered

FY24 was considered as a base year and annual peak and energy projections from the KPTCL were utilized from FY25 to FY34.

KPTCL: Projections from the State KPTCL were used as compared to 20th EPS projection. The energy projection grows by CAGR of 4.3% and peak demand by 4.8%.

Table 6:Scenario Matrix of Karnataka

Year	20th EPS		KPTCL	
	Energy Projections (MUs)	Peak Projections (MW)	Energy Projection (MUs)	Peak Projections (MW)
FY25	80,922	16,277	89,496	16,580
FY26	84,132	16,947	93,194	17,439
FY27	88,232	17,810	97,095	18,353
FY28	91,852	18,578	1,01,233	19,135
FY29	95,486	19,352	1,05,943	20,025
FY30	99,758	20,254	1,10,941	20,970
FY31	1,02,973	20,954	1,15,755	21,990
FY32	1,05,970	21,613	1,20,778	23,058
FY33	1,10,130	22,506	1,26,018	24,179
FY34	1,14,453	23,435	1,31,486	25,355

Having detailed the input assumptions, we now move on to the key findings derived from the energy modeling. The following chapter summarizes the output parameters, such as unserved and dump energy, reliability metrics, year-over-year (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.

Idam Infrastructure Advisory Pvt. Ltd.
5th Floor, Technopolis Knowledge
Park, Mahakali Caves Road,
Chakala, Andheri East, Mumbai – 400 093
Phone: +91 (22) 68620300
Email: contact@idaminfra.com

7. Study Findings

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

1. YoY Resource-wise Installed Capacity
2. YoY Resource-wise Generation
3. Average Hourly Generation
4. Unserved and dump energy
5. Reliability Metrics
6. Average Power Purchase Cost

7.1. YoY Resource-wise Installed Capacity

The graph below illustrates the year-on-year resource-wise installed, upcoming, and additional capacity mix for Karnataka, with the corresponding data provided in tabular form in the annexure.

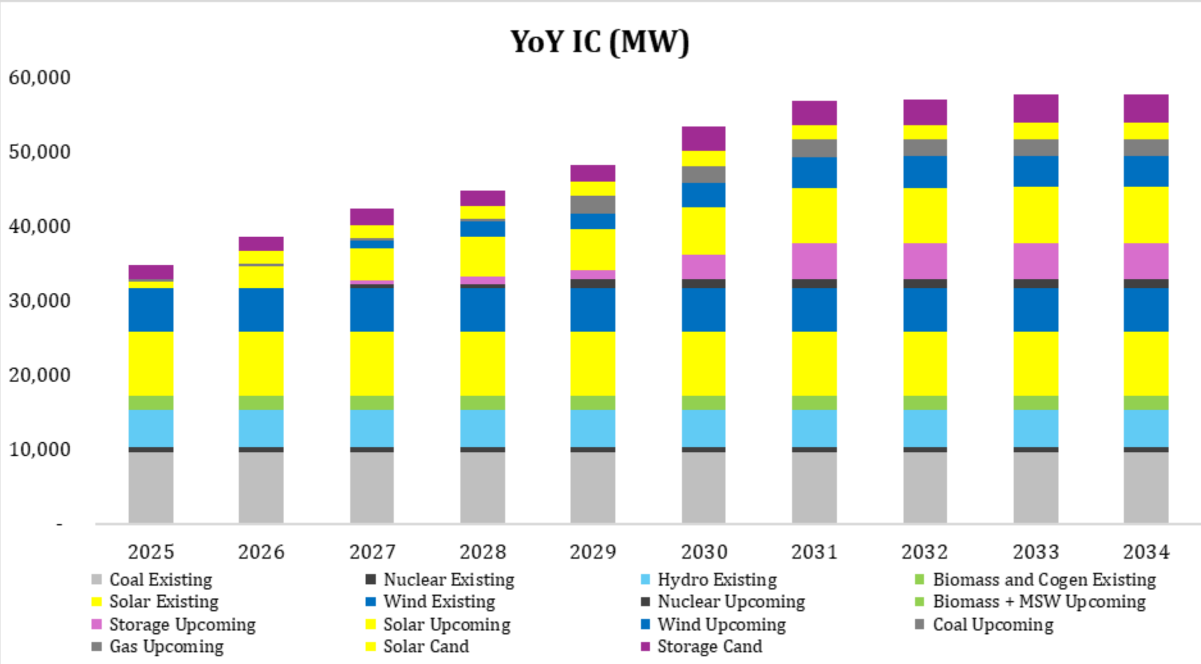

Figure 19: YoY Installed Capacity

- From above two graphs it can be observed that solar capacities are double of coal capacity.
- In FY29, significant amount of coal and nuclear plant is upcoming.
- RE and storage upcoming capacities are significantly added in FY30.

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5th Floor, Technopolis Knowledge
Park, Mahakali Caves Road,
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Email: contact@idaminfra.com

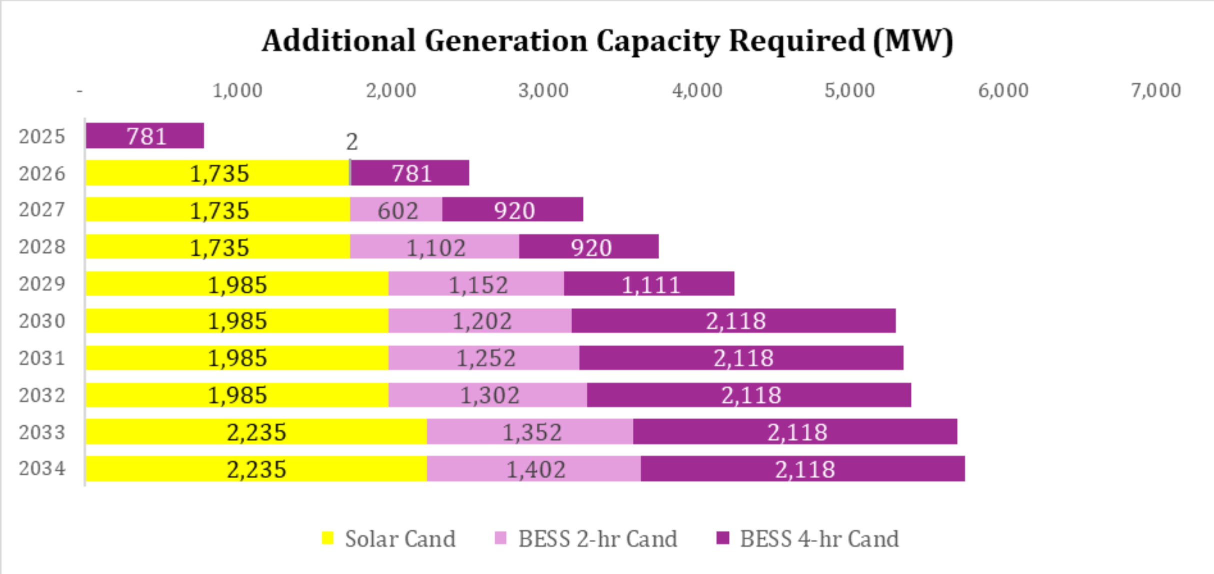

Figure 20: Additional Capacity Required (MW)

- To meet the LoLP limits, solar and storage candidate capacities are getting build.
- No new wind candidate capacity was build as its cost is higher than that of solar energy. Additionally, wind power would contribute to surplus energy during non-peak times, whereas peak demand is during solar hours, and thus soalr candidates got build.

7.2. YoY Resource-wise Generation

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

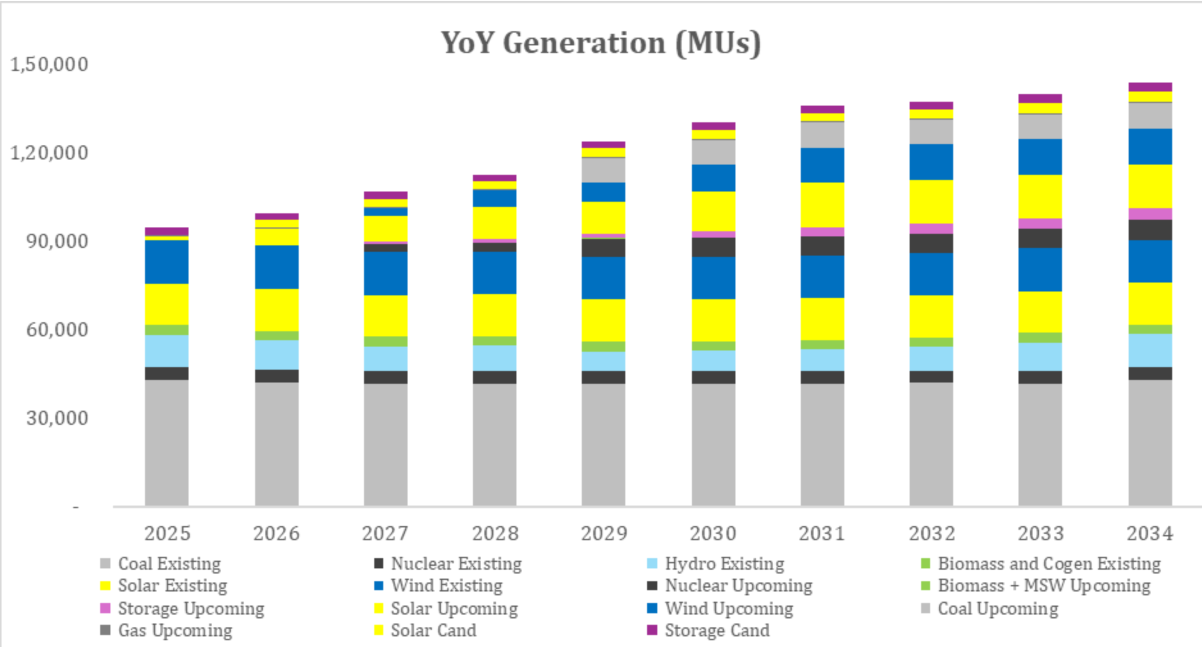

Figure 21: YoY Generation (MUs)

- It is evident that, despite the installed capacity of RE surpassing that of coal, contribution of coal generation continues to be significant.

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Phone: +91 (22) 68620300
Email: contact@idaminfra.com

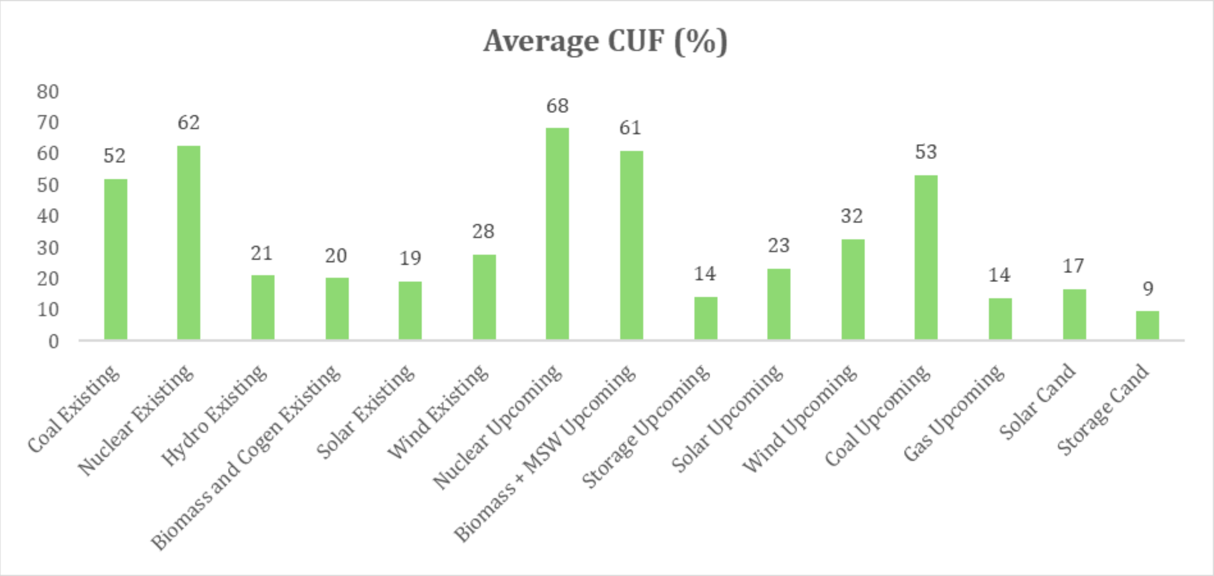

Figure 22: Average CUF (%)

- It can be observed that conventional plants are not running at their maximum capacity and getting curtailed.
- There is an opportunity to trade this extra capacity can be traded with other states.
- In storage upcoming, both BESS and PSP were considered; the resultant CUF of BESS is on higher side as compared to PSP.

7.3. Average Hourly Generation

The following graph shows average hourly generation for terminal year of FY30:

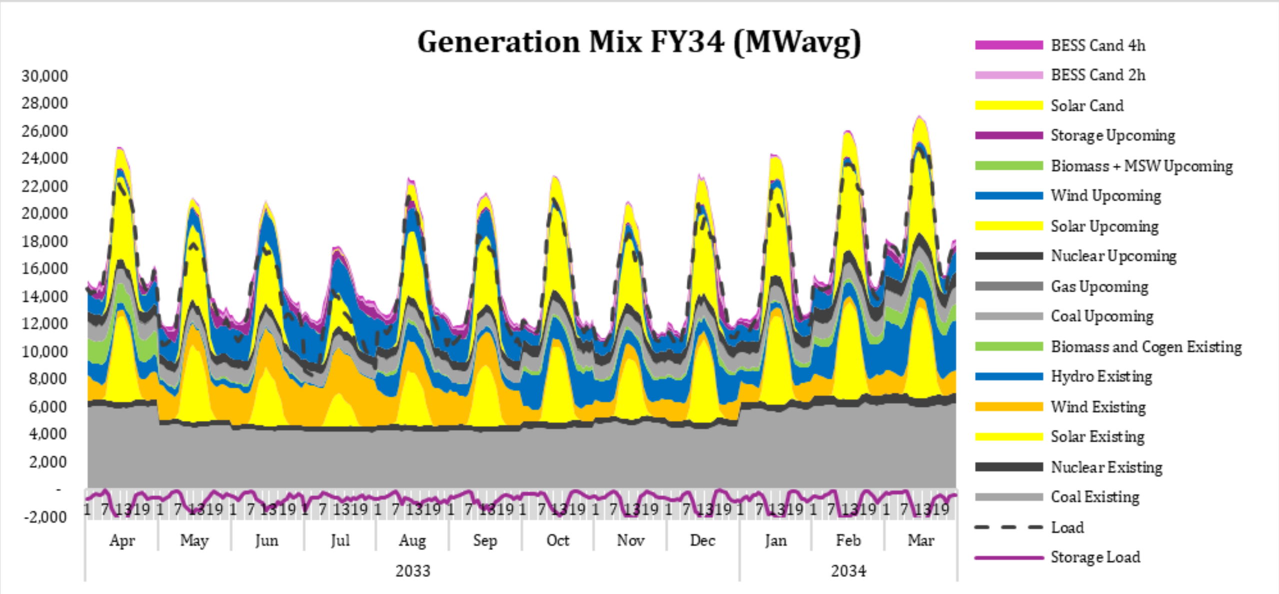

Figure 23: Generation Mix- FY34

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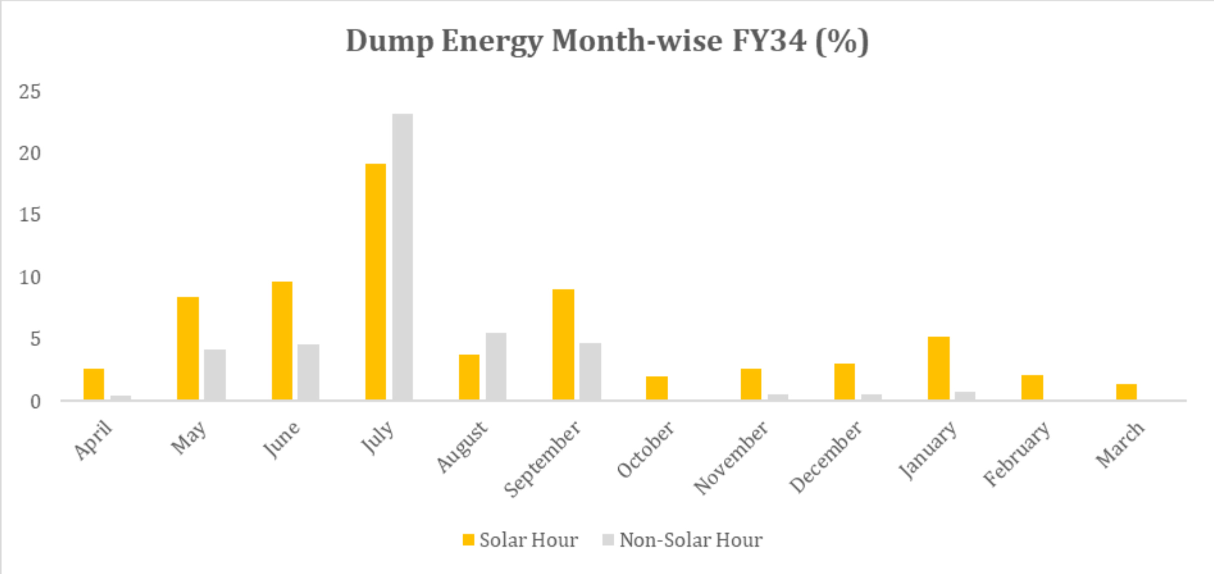

Figure 24: DE Month-wise FY30 (%)

- It is observed that in months of May to September the dump energy is high for solar hours, as the load is on lower side. This energy can be traded with other states during these months.
- Only in July the DE is high for non-solar hour, as in July the demand is low and generation of wind is high during non solar hours.
- Rest of the months, the DE is high during solar hours and very less during non-solar hour.

7.4. Unserved and Dump Energy

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

Table 7: Unserved Energy and Dump Energy

FY	Unserved Energy Factor (%)		Dump Energy (%)		Dump Energy (MUs)	
	Existing + Planned	Existing + Planned + Candidate	Existing + Planned	Existing + Planned + Candidate	Existing + Planned	Existing + Planned + Candidate
25	0	0	2.64	1.58	4,167	2,541
26	0.01	0	2.88	2.28	4,671	3,869
27	0	0	4.19	3.48	7,189	6,377
28	0.01	0	4.69	3.83	8,288	7,323
29	0	0	7	6.57	13,858	14,042
30	0	0	6.03	5.89	13,240	13,891
31	0	0	5.59	5.52	13,183	13,940
32	0	0	4.1	3.9	9,691	9,911
33	0	0	2.94	2.6	6,914	6,653
34	0.01	0	2.3	1.67	5,405	4,268

- Karnataka has enough existing resources and upcoming resources to meet projected demand, due to which high dump energy and very low unserved energy is observed (less than 0.01%).

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7.5. Reliability Metrics

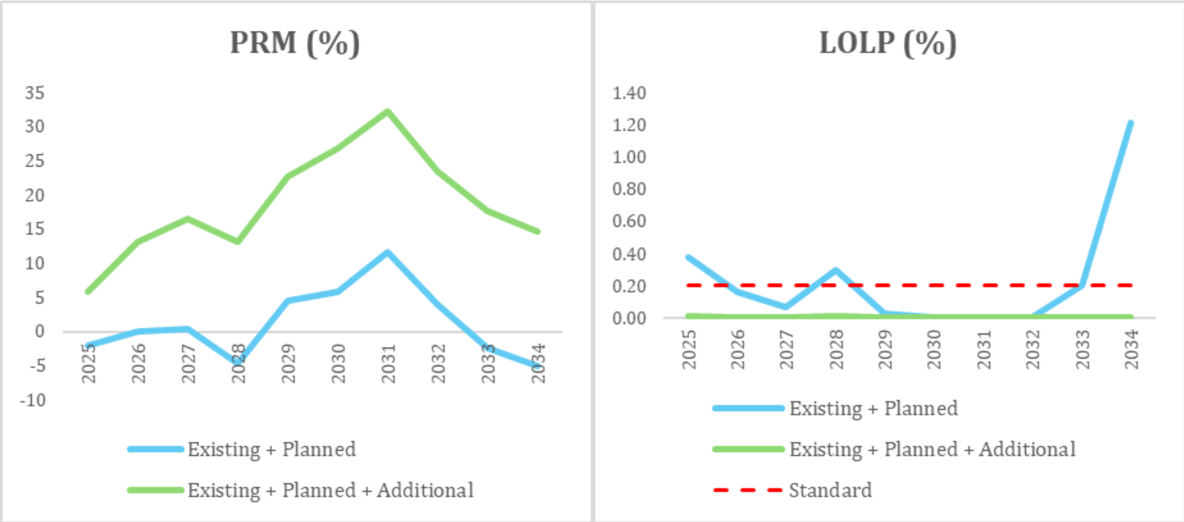

Figure 25: PRM and LoLP

- Figure 25 shows reliability metrics without and with consideration of candidate capacity (over and above existing installed and upcoming contracted capacity).
- In the initial and later years, the PRM is lower and the LoLP is higher due to insufficient installed capacity during those periods, while peak demand remains elevated. Consequently, additional plants will be necessary to fulfill the reliability requirements..

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

Table 8: Reliability Metrics for all Scenarios

FY	Planning Reserve Margin (MW)	Planning Reserve Margin (%)	LoLP (%)
25	1,352	5.77	0.01
26	3,128	13.07	0.15
27	4,000	16.59	0.03
28	3,441	13.07	0.01
29	6,199	22.7	0
30	7,844	26.82	0
31	9,676	32.31	0
32	7,553	23.43	0
33	5,785	17.58	0
34	5,136	14.7	0.04

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5th Floor, Technopolis Knowledge
Park, Mahakali Caves Road,
Chakala, Andheri East, Mumbai – 400 093
Phone: +91 (22) 68620300
Email: contact@idaminfra.com

7.6. Average Power Purchase Cost

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

Table 9: APPC

FY	Coal Existing	Nuclear Existing	Hydro Existing	Biomass and Cogen Existing	Solar Existing	Wind Existing	Nuclear Upcoming	Biomass + MSW Upcoming	Storage Upcoming	Solar Upcoming	Wind Upcoming	Coal Upcoming	Gas Upcoming	Solar Cand	Wind Cand	Storage Cand	**System Cost**
25	4.91	4.76	1.46	5.56	3.92	3.93	0.00	2.07	3.87	2.60	0.00	0.00	7.80	0.00	0.00	4.80	**4.15**
26	5.00	4.80	1.46	5.73	3.92	3.93	0.00	2.10	3.66	2.60	0.00	0.00	8.05	2.45	0.00	4.74	**4.04**
27	5.07	4.84	1.52	5.90	3.92	3.93	3.14	2.13	3.22	2.60	3.10	0.00	7.94	2.40	0.00	4.74	**3.89**
28	5.12	4.88	1.53	6.08	3.92	3.93	3.14	2.13	2.77	2.60	3.10	0.00	8.11	2.35	0.00	4.99	**3.90**
29	5.17	4.92	1.73	6.26	3.92	3.93	3.20	2.14	2.80	2.60	3.10	5.01	8.30	2.30	0.00	4.95	**4.02**
30	5.20	4.96	1.72	6.45	3.92	3.93	3.20	2.14	4.14	2.60	3.10	5.04	8.35	2.26	0.00	5.17	**4.15**
31	5.25	5.00	1.68	6.64	3.92	3.93	3.21	2.14	4.66	2.60	3.10	5.06	8.84	2.24	0.00	5.13	**4.23**
32	5.29	5.04	1.62	6.84	3.92	3.93	3.20	2.13	4.47	2.60	3.10	5.12	8.41	2.21	0.00	4.92	**4.19**
33	5.34	5.09	1.54	7.04	3.92	3.93	3.20	2.11	4.27	2.60	3.10	5.18	8.33	2.19	0.00	4.73	**4.17**
34	5.32	5.12	1.60	7.26	3.92	3.93	3.17	2.07	4.15	2.60	3.10	5.19	8.34	2.17	0.00	4.36	**4.15**

- 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 3.9 Rs/kWh in FY27 due to the introduction of more affordable resources. However, in FY29, 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.

8. Key Insights from CEA's RA Study

The CEA has published a Resource Adequacy (RA) report for the state of Karnataka, 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.

The Unserved Energy (MUs) for different years from CEA's and Idam's RA studies are depicted as follows:

Table 10: Unserved Energy from FY25-34 (MUs)

Month	CEA		Idam	
	ENS (MU)	ENS (%)	ENS (MU)	ENS (%)
2024-25	32	0.03	3.7	0
2025-26	100	0.1	10.1	0.01
2026-27	318	0.32	2.5	0
2027-28	850	0.83	9.6	0.01
2028-29	1,823	1.72	0.8	0
2029-30	2,499	2.25	1.1	0
2030-31	3,919	3.38	1.2	0
2031-32	6,574	5.44	0.9	0
2032-33			3.8	0
2033-34			15.9	0.01

The comparison between CEA and Idam's projections for unserved energy (ENS) based on KPTCL projections highlights significant differences in anticipated energy shortages. CEA's projections show a steadily increasing ENS from 32 MU in 2024-25 to 6,574 MU in 2031-32, indicating growing energy deficits. In contrast, Idam's projections estimate substantially lower ENS values, remaining under 16 MU throughout the period, suggesting a more optimistic resource adequacy scenario.

Key Insights:

- Divergence in ENS Estimates – CEA projects a higher ENS, peaking at 5.44% in 2031-32, whereas Idam maintains near-zero ENS throughout.
- Impact of Planning Methodologies – The difference may stem from variations in installed capacity, and assumptions regarding renewable energy integration.

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

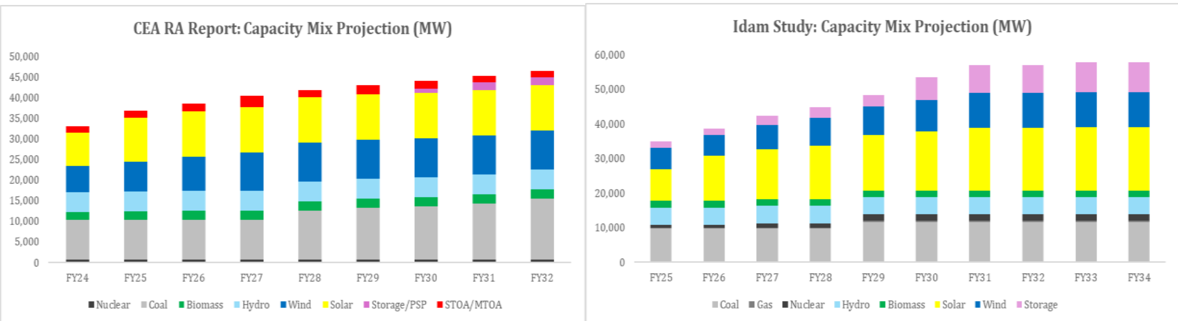

Figure 26: CEA & Idam - Capacity Mix Projections (MW)

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

Table 11: CEA- Planned capacity, additional and market capacity requirement

CEA								
FY	Coal	PSP	Wind	Solar	Biomass	STOA/MTOA	Total	
	Additional	Planned	Planned	Planned	Planned	Additional	Planned	Additional
FY24	0	0	1,000	506	72	1,457	1,578	1,457
FY25	0	0	1,000	2,494	141	1,693	3,635	1,693
FY26	0	0	1,000	366	117	1,958	1,483	1,958
FY27	0	0	974	0	0	2,799	974	2,799
FY28	2,222	0	230	0	0	1,823	230	4,045
FY29	686	0	0	0	0	2,211	0	2,897
FY30	435	1,000	0	0	0	1,826	1,000	2,261
FY31	593	1,000	0	0	0	1,393	1,000	1,986
FY32	1,205	0	0	0	0	1,553	0	2,758

Table 12: Idam - Planned capacity, additional and candidate capacity requirement

Idam											
FY	Coal	Gas	Nuclear	Biomass	Solar		Wind	Storage		Total	
	Planned	Planned	Planned	Planned	Planned	Candidate	Planned	Planned	Candidate	Planned	Candidate
FY25	0	370	0	12	750	0	0	2	1,843	1,134	1,843
FY26	0	0	0	0	2,040	1,735	0	0	129	2,040	1,863
FY27	0	0	442	0	1,500	0	1,000	600	138	3,542	138
FY28	0	0	0	0	1,000	0	1,000	500	0	2,500	0
FY29	1,900	0	700	0	200	250	200	50	191	3,050	441
FY30	0	0	0	0	1,000	0	1,000	2,050	1,007	4,050	1,007
FY31	0	0	0	0	1,000	0	1,000	1,550	0	3,550	0
FY32	0	0	0	0	0	0	0	50	0	50	0
FY33	0	0	0	0	0	250	0	50	384	50	634
FY34	0	0	0	0	0	0	0	50	0	50	0

The capacities for planned and candidate plants for Karnataka is different for CEA and Idam due to variations in the data received and the approach to meet reliability metrics. CEA has also considered coal and market capacity to meet reliability metrices, whereas Idam has only considered solar, wind, and BESS to meet the metrices.

Idam Infrastructure Advisory Pvt. Ltd.
5th Floor, Technopolis Knowledge
Park, Mahakali Caves Road,
Chakala, Andheri East, Mumbai – 400 093
Phone: +91 (22) 68620300
Email: contact@idaminfra.com

Key Comparisons:

Coal Capacity:

- CEA plans for additional coal capacity, with incremental additions reaching 1,205 MW by FY32.
- Idam, on the other hand, has limited coal additions, with a peak of 1,900 MW in FY29 but no further expansion in later years.

Renewable Energy Expansion:

- Solar: Idam estimates high solar capacity expansion, reaching 3,550 MW by FY31, while CEA's planned additions peak at 2,494 MW in FY25.
- Wind: CEA includes consistent wind additions of 1,000 MW annually till FY26, while Idam's planned wind additions are lower but include candidate wind capacity in later years.
- Biomass: Both CEA and Idam include minimal biomass capacity, with planned additions stopping after FY26 for CEA and FY29 for Idam.

Storage Capacity:

- Idam projects significant PSP and battery storage additions, peaking at 1,550 MW in FY31.
- CEA considers PSP additions of up to 1,000 MW, but its reliance on storage remains lower compared to Idam.

Market requirement:

- 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.

The capacity additions from CEA and Idam present two distinct approaches to RA planning, with variations in coal, renewable energy, and storage deployment.

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Chakala, Andheri East, Mumbai – 400 093
Phone: +91 (22) 68620300
Email: contact@idaminfra.com

9. Conclusion

This study undertook a comprehensive Resource Adequacy (RA) assessment for the state of Karnataka, 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:

- **Contracted Capacity Sufficiency:** Karnataka's existing contracted capacity is projected to meet future demand. However, additional capacity is necessary to address contingencies and meet comprehensive Resource Adequacy (RA) metrics.
- **Potential for Energy Export:** With capacity exceeding contracted levels, Karnataka has the potential to become a significant energy exporter to neighboring states.
- **Renewable Purchase Obligation (RPO) Compliance:** The state's planned renewable energy (RE) capacity additions ensure compliance with its RPO targets.
- **Impact on Conventional Power Plants:** Increased RE generation results in conventional power plants operating at minimum capacity levels.
- **Reliability Metrics Compliance**: The study demonstrated successful compliance with key reliability metrics, including Loss of Load Probability (LoLP) and Normalized Energy Not Served (NENS), validating the modeling approach.

Key Recommendations:

- **Investment in Storage Capacity:** Significant investment in energy storage capacity is crucial. This will not only benefit Karnataka by managing excess energy and addressing contingencies but also provide valuable support to neighboring states during periods of need.
- **Continued Solar Integration:** The state should continue to prioritize the integration of cost-effective solar energy, which will provide substantial economic benefits in the coming years.

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

Idam Infrastructure Advisory Pvt. Ltd.
5th Floor, Technopolis Knowledge
Park, Mahakali Caves Road,
Chakala, Andheri East, Mumbai – 400 093
Phone: +91 (22) 68620300
Email: contact@idaminfra.com

10. Appendix

10.1. List of Existing Plants

List and details of existing plants considered in the model:

Table 13: Existing Coal Plants

Plant Type	Plant Name	Installed Capacity (MW)	Allocated Capacity (MW)	CUF (%)
CGS Coal	DVC Koderma U1&2 TPS	236	236	52
	DVC Mejia U7&8 TPS	189	189	52
	Kudgi U1-3 Stg I TPS	1,200	1,200	50
	NLC I Expansion TPS	92	92	53
	NLC II Expansion TPS	110	110	53
	NLC II Stg I TPS	84	84	53
	NLC II Stg II TPS	115	115	52
	NN TPS	66	66	53
	NTPL Tuticorin U1 TPS	158	158	51
	Ramagundam Stg I TPS	99	99	52
	Ramagundam Stg II TPS	246	246	52
	Ramagundam U7 Stg III TPS	87	87	51
	Simhadri Stg II TPS	176	176	52
	Talcher Stg II TPS	350	350	53
	UPCL TPS	1,200	1,200	40
	Vallur U1-3 TPS	111	111	51
SGS Coal	BTPS U1 TPS	500	500	51
	BTPS U2 TPS	500	500	52
	BTPS U3 TPS	700	700	51
	RPCL YTPS TPS	1,600	1,600	50
	RTPS U1-7 TPS	1,470	1,470	52
	RTPS U8 TPS	250	250	51
	NTPC NVVN Bundled	70	70	50

Table 14: Existing Nuclear Plants

Plant Name	Installed Capacity (MW)	Allocated Capacity (MW)	CUF (%)
BHAVINI	500	84	70
Kaiga U1&2 APS	108	108	60
Kaiga U3&4 APS	119	119	60
Kudankulam U1&2 APS	442	442	60
Madras APS	29	29	60

Table 15: Existing Hydro Plants

Plant Name	Installed Capacity (MW)	Allocated Capacity (MW)	CUF (%)
Jurala+TB+Hampi HEP	117	117	30
Almatti Dam HEP	290	290	30
Bhadra HEP	26	26	30
Gerusoppa HEP	240	240	30
Ghataprabha HEP	32	32	30

Idam Infrastructure Advisory Pvt. Ltd.
5th Floor, Technopolis Knowledge
Park, Mahakali Caves Road,
Chakala, Andheri East, Mumbai – 400 093
Phone: +91 (22) 68620300
Email: contact@idaminfra.com

Plant Name	Installed Capacity (MW)	Allocated Capacity (MW)	CUF (%)
Kadra HEP	150	150	30
Kali HEP	900	900	30
Kodasalli Dam HEP	120	120	30
Linganamakki HEP	55	55	30
MGHE Jogfalls HEP	139	139	30
Munirabad HEP	28	28	30
Sharavathi HEP	1,030	1,030	30
Shivasamudram HEP	42	42	30
Supa HEP	100	100	30
Varahi HEP	460	460	30

Table 16: Existing Pumped Hydro Storage Plants

Plant Name	Installed Capacity (MW)	Allocated Capacity (MW)	CUF (%)
Sharavathy PSP	2000	2000	5 to10
Varahi PSP	1500	1500	5 to10

10.2. YoY Installed Capacity

Data of YoY Installed Capacity results for all the three scenarios:

Table 17: YoY Installed Capacity (MW)

FY	Coal Existing	Nuclear Existing	Hydro Existing	Biomass and Cogen Existing	Solar Existing	Wind Existing	Nuclear Upcoming	Biomass + MSW Upcoming	Storage Upcoming	Solar Upcoming	Wind Upcoming	Coal Upcoming	Gas Upcoming	Solar Cand	Storage Cand
25	9,610	782	5,009	1,867	8,500	6,000	0	12	2	750	0	0	370	0	1,843
26	9,610	782	5,009	1,867	8,500	6,000	0	12	2	2,790	0	0	370	1,735	1,972
27	9,610	782	5,009	1,867	8,500	6,000	442	12	602	4,290	1,000	0	370	1,735	2,110
28	9,610	782	5,009	1,867	8,500	6,000	442	12	1,102	5,290	2,000	0	370	1,735	2,110
29	9,610	782	5,009	1,867	8,500	6,000	1,142	12	1,152	5,490	2,200	1,900	370	1,985	2,301
30	9,610	782	5,009	1,867	8,500	6,000	1,142	12	3,202	6,490	3,200	1,900	370	1,985	3,308
31	9,610	782	5,009	1,867	8,500	6,000	1,142	12	4,752	7,490	4,200	1,900	370	1,985	3,308
32	9,610	782	5,009	1,867	8,500	6,000	1,142	12	4,802	7,490	4,200	1,900	370	1,985	3,308
33	9,610	782	5,009	1,867	8,500	6,000	1,142	12	4,852	7,490	4,200	1,900	370	2,235	3,692
34	9,610	782	5,009	1,867	8,500	6,000	1,142	12	4,902	7,490	4,200	1,900	370	2,235	3,692

10.3. YoY Generation

Data of YoY Generation results for both scenarios:

Table 18: YoY Generation (BUs)

FY	Coal Existing	Nuclear Existing	Hydro Existing	Biomass and Cogen Existing	Solar Existing	Wind Existing	Nuclear Upcoming	Biomass + MSW Upcoming	Storage Upcoming	Solar Upcoming	Wind Upcoming	Coal Upcoming	Gas Upcoming	Solar Cand	Storage Cand
25	43	4	11	3	14	15	0	0	0	2	0	0	0	0	2
26	42	4	10	3	14	15	0	0	0	6	0	0	0	3	2
27	42	4	9	3	14	15	3	0	1	9	3	0	0	3	2
28	42	4	9	3	14	15	3	0	1	11	6	0	0	3	2
29	42	4	7	3	14	14	6	0	1	11	6	9	0	3	2
30	42	4	7	3	14	15	6	0	2	13	9	9	0	3	3
31	42	4	7	3	14	15	6	0	3	15	12	9	0	3	3
32	42	4	8	3	14	14	6	0	3	15	12	9	0	3	3
33	42	4	10	3	14	15	6	0	3	15	12	9	0	3	3
34	43	4	11	3	14	15	7	0	4	15	12	9	0	3	3

10.4. Additional Capacity Required

Table 19: Additional Capacity Required (GW)

FY	Solar Cand	Storage Cand
25	0	6
26	0	6
27	0	6
28	0	6
29	0	6
30	0	6
31	3.5	6
32	3.5	6
33	3.5	6
34	3.5	6