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THEORETICAL HANDBOOK **2025**

INTEGRATED RESOURCE ADEQUACY ASSESSMENT FRAMEWORK

A holistic approach to power system reliability and resilience

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Foreword

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FOREWORD

Today, India stands at a defining moment in its energy transition journey. With ambitious targets of achieving 500 GW of renewable energy capacity by 2030 and moving toward net-zero emissions by 2070, the power system is undergoing rapid and complex transformation. This transition is not only characterized by the growing integration of variable renewable energy sources like solar and wind (both large scale and distributed), but also by the emergence of new and unpredictable demand segments—such as data centers, electric vehicles, and green hydrogen production via electrolyzers. These developments coupled with the increasing frequency of extreme weather events introduce a new layer of variability and uncertainty, both on the supply and demand sides, making the task of ensuring Resource Adequacy (RA) significantly more challenging.

In this context, an Integrated Resource Adequacy Assessment Framework is not merely desirable—it is the need of the hour. The dynamic interplay between generation variability and evolving consumption patterns needs to be duly factored. The recent peak demand of 250 GW recorded in May 2024, driven by extreme weather conditions along with demand growth, underlines the urgency of adopting more holistic and adaptive planning mechanisms.

The "Integrated Resource Adequacy Assessment Framework: A Holistic Approach to Power System Reliability and Resilience," is a timely contribution towards this goal. This handbook is a useful guide for navigating the adequacy challenges in the evolving power sector of the country.

This handbook introduces a more comprehensive approach through the Integrated Resource Adequacy Assessment (I-RAA) Framework. It consolidates global insights and provides a structured process that enables stakeholders to integrate technical and operational dimensions. The framework encompasses all essential components: demand assessment, energy mix, generation adequacy, transmission system, and the increasingly significant role of electricity markets. Crucially, it reshapes the concept of resource adequacy by highlighting two key aspects: reliability— the consistent delivery of services under normal circumstances —and resilience—the system's capacity to endure, adapt, and recover from disruptions. This layered understanding is vital for effective planning, ensuring that our systems can "keep the lights on" in an ever-changing environment.

The Ministry of Power and Central Electricity Authority (CEA) have already issued the guidelines on resource adequacy and this handbook provides a conceptual foundation on the subject.

I commend the authors for this comprehensive work and encourage all stakeholders to make best use of the handbook.

(Samir Chandra Saxena)

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Glossary

Abbreviations	Description
AC	Alternating Current
ACE	Area Control Error
AGC	Automatic Generation Control
AI	Artificial Intelligence
ALFC	Automatic Load Frequency Control
AMI	Advanced Metering Infrastructure
ARIMA	Auto-Regressive Integrated Moving Average
ARMA	Auto-Regressive Moving Average
ATC	Available Transfer Capability
AVR	Automatic Voltage Regulator
BAA	Balancing Area Authority
BAU	Business-as-usual
BEE	Bureau of Energy Efficiency
BEFI	Building Energy Flexibility Index
BESS	Battery Energy Storage System
BPS	Bulk Power System
CA	Capacity Auction
CAIDI	Customer Average Interruptions Duration Index
CAIFI	Customer Average Interruptions Frequency Index
CAISO	California Independent System Operator
CBM	Capacity Benefit Margin
CC	Capacity Credit
CDRI	Coalition for Disaster Resilient Infrastructure
CEA	Central Electricity Authority
CEM	Capacity Energy Margin
CERC	Central Electricity Regulatory Commission
CF	Capacity Factor
CfD	Contracts for Differences
CO	Capacity Obligation
CP	Capacity Payment
CPP	Critical Peak Pricing
CPUC	California Public Utilities Commission
CRM	Capacity Remuneration Mechanism

CSP	Concentrating Solar Power
CTU	Central Transmission Utility
CUF	Capacity Utilisation Factor
CVaR	Conditional Value at Risk
DA	Distribution Automation
DAM	Day-ahead Market
DC	Direct Current
DEEP	Discovery of Efficient Electricity Price
DER	Distributed Energy Resources
DG	Distributed Generation
DGQI	Data Governance Quality Index
DIRE	Disturbance and Impact Resilience Evaluation
DISCOM	Distribution Companies
DLC	Direct Load Control
DR	Demand Response
DSM	Demand-side Management
DSO	Distributed System Operator
EC	The European Commission
ECP	Equivalent Conventional Power
ED-CPP	Extreme Day Critical Peak Pricing
EDP	Extreme Day Pricing
EE	Energy Efficiency
EENS	Expected Energy Not Served
EFC	Equivalent Firm Capacity
EFOR	Equivalent Forced Outage Rate
EFORd	Equivalent Forced Outage Rate – Demand
EFORp	Equivalent Forced Outage Rate – Peak
ELCC	Effective Load Carrying Capability
EMO	Energy Market Operator
EMR	Electricity Market Reform
EMS	Energy Management System
EMT	Electro Magnetic Transient
ENTSO-E	European Network of Transmission System Operators for Electricity
EOM	Energy-only Market
EPS	Electricity Power Survey

EPSC	Electric Power Survey Committee
ERAA	European Resource Adequacy Assessment
ERCOT	Electric Reliability Council of Texas
ERM	Energy Reserve Margin
ERO	Electric Reliability Organization
ESC	Energy Supply Chain
ESCO	Energy Saving Company
EU	The European Union
EUE	Expected Unserved Energy
EUR	Expected Unserved Ramping
EV	Electric Vehicle
FAI	Flexibility Area Index
FERC	Federal Energy Regulatory Commission
FGMO	Free Governor Mode of Operation
FMEA	Failure Mode and Effect Analysis
FOR	Forced Outage Rate
FoR	Forum of Regulators
FOT	Front Office Transaction
FRAS	Fast Response Ancillary Services
FRC	Frequency Response Characteristics
FRP	Frequency Response Performance
FSI	Floor Space Index
FVPP	Financial Virtual Power Plant
GDP	Gross Domestic Product
GEP	Generation Expansion Planning
GHG	Green House Gas
GNA	General Network Access
GRT	Grid Recovery Time
GW	Gigawatt
GWh	Gigawatt-hour
HILF	High Impact, Low Frequency
HPX	Hindustan Power Exchange Limited
HT	High Tension
HVDC	High-Voltage Direct Current
Hz	Hertz

I-RAA	Integrated Resource Adequacy Assessment
ICAP	Installed Capacity
IDM	Intra-day Market
IEA	International Energy Agency
IEX	Indian Energy Exchange
IMD	Indian Meteorological Department
Intra-STS	Intra-State Transmission System
IoT	Internet of Things
IPP	Independent Power Producer
IRP	Integrated Resource Planning
IRRE	Insufficient Ramping Resource Expectation
ISGS	Inter-State Generation Station
ISO	Independent System Operator
ISTS	Inter-State Transmission System
JERC	Joint Electricity Regulatory Commission
KW	Kilowatt
KWh	Kilowatt-hour
LDC	Load Despatch Centre
LFC	Load Frequency Control
LMP	Locational Marginal Pricing
LNG	Liquified Natural Gas
LOL	Loss of Load
LOLD	Loss of Load Days
LOLE	Loss of Load Expectation
LOLEv	Loss of Load Events
LOLH	Loss of Load Hours
LOLP	Loss of Load Probability
LOLY	Loss of Load Years
LORP	Lack of Ramp Probability
LSE	Load Serving Entity
LT-DRAP	Long-Term Distribution Licensee Resource Adequacy Plan
LT-NRAP	Long-Term National Resource Adequacy Plan
m/s	Metre per second
MBED	Market-Based Economic Despatch
ML	Machine Learning

MoP	Ministry of Power
MTTF	Mean Time to Failure
MU	Million Units
MVAR	Mega Volt-Ampere Reactive
MW	Megawatt
MWe	Megawatt-electrical
MWh	Megawatt-hour
MWth	Megawatt-thermal
NATC	Non-recallable Available Transfer Capability
NATF	North American Transmission Forum
NDC	Nationally Determined Contribution
NDGFP	National Data Governance Framework Policy
NENS	Normalised Energy Not Served
NERC	National Electric Reliability Council
NEUE	Normalised Expected Unserved Energy
NGO	Non-Governmental Organisation
NLDC	National Load Despatch Centre
nm	Nanometre
NOAR	National Open Access Registry
NPAF	Normative Plant Availability Factor
NRAS	Network Reserve Ancillary Services
NREL	National Renewable Energy Laboratory
NSGM	National Smart Grid Mission
NSMC	Non-Sequential Monte Carlo
NSSO	National Sample Survey Office
NYISO	New York Independent System Operator
OPF	Optimal Power Flow
OTC	Over the Counter
PBP	Price Based Programmes
PEUM	Partial End-Use Methodology
PFCAS	Power Flow Control Ancillary Services
PFD	Periods of Flexibility Deficit
PNNL	Pacific Northwest National Laboratory
PPA	Power Purchase Agreement
PRAS	Primary Reserve Ancillary Service

PRM	Planning Reserve Margin
PS	Performance Score
PUShP	High Price Day Ahead Market and Surplus Power
PV	Photo-voltaic
PX	Power Exchange
PXI	Power Exchange India Limited
RA	Resource Adequacy
RAR	Resource Adequacy Requirement
RATC	Recallable Available Transfer Capability
RCSE	Ramping Capability Shortage Expectation
RDSS	Revamped Distribution Sector Scheme
REGS	Renewable Energy Generating Stations
REP	Resilient Energy Platform
RES	Renewable Energy Sources
RLDC	Regional Load Despatch Centre
RO	Reliability Option
ROCOF	Rate of Change of Frequency
RPN	Risk Priority Number
RRAS	Reserve Regulation Ancillary Service
RSI	Resilience to Stress Index
RT	Response Time
RTO	Regional Transmission Organisation
RTP	Real-time Pricing
RWG	Resilience Working Group
SAIDI	System Average Interruptions Duration Index
SAIFI	System Average Interruptions Frequency Index
SCADA	Supervisory Control and Data Acquisition
SCED	Security Constrained Economic Despatch
SCR	System Capability Ramp
SEM	Standard Error to Mean
SERC	State Electricity Regulatory Commission
SG	Synchronous Generator
SLDC	State Load Despatch Centre
SMC	Sequential Monte Carlo
SO	System Operator

SR	Strategic Reserve
SRAS	Secondary Reserve Ancillary Service
ST-DRAP	Short-Term Distribution Licensee Resource Adequacy Plan
ST-NRAP	Short-Term National Resource Adequacy Plan
STU	State Transmission Utility
T-GNA	Temporary General Network Access
TCM	Transfer Capability Margin
TEP	Transmission Expansion Planning
TOU	Time-of-use
TRANSCOM	Transmission Company
TRAS	Tertiary Reserve Ancillary Service
TRM	Transmission Reliability Margin
TTC	Total Transfer Capability
TVPP	Technical Virtual Power Plant
UK	The United Kingdom
USA	The United States of America
UT	Union Territory
VAT	Value Added Tax
VCAS	Voltage Control Ancillary Services
VER	Variable Energy Resource
VOLL	Value of Lost Load
VPP	Virtual Power Plant
VPPA	Virtual Power Purchase Agreement
VRE	Variable Renewable Energy
W/m^2	Watts per square metre
WEM	Winter Energy Margin

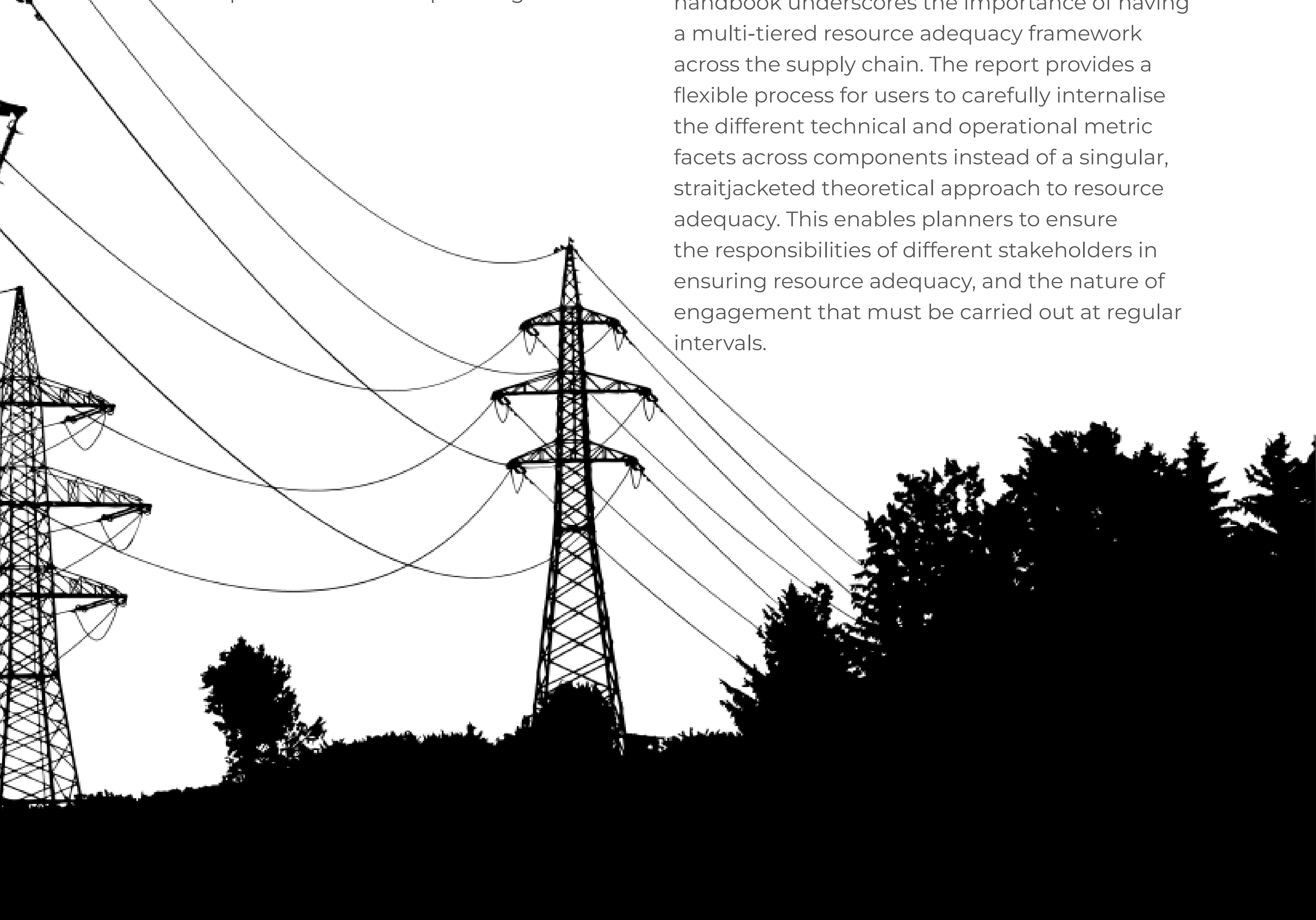
Executive Summary

The *"Integrated Resource Adequacy Assessment Framework: A Holistic Approach to Power System Reliability and Resilience"* is a theoretical exercise involving a comprehensive, framework-based approach towards the concept of resource adequacy and the practical implications of power system components in ensuring supply reliability, particularly in the context of increasing reliance on renewable energy sources and the challenges posed by climate change.

By outlining the historical context and evolution of resource adequacy metrics, the report introduces readers to a holistic resource adequacy approach that encompasses transmission, distribution, and demand-side resources in addition to the standard generation capacity measurement. It highlights significant global events that have exposed vulnerabilities in the evolution of power systems, underscoring the importance of robust planning and resilience in electricity supply and operations. The handbook consolidates the learnings from global developments on resource adequacy and presents an integrated framework approach to incorporate various components.

The Integrated Resource Adequacy Assessment Framework (I-RAA) integrates various components of the power system, including demand assessment, fuel adequacy, generation adequacy, network adequacy and the roles of electricity markets. The framework also aims to provide metrics for evaluating the reliability and resilience of power systems, ensuring that they can meet both current and future energy demands. The various metrices and attributes captured under each of the headers of the I-RAA framework and can help facilitate discussions on determining the best approach for a given country based on their evolving priorities.

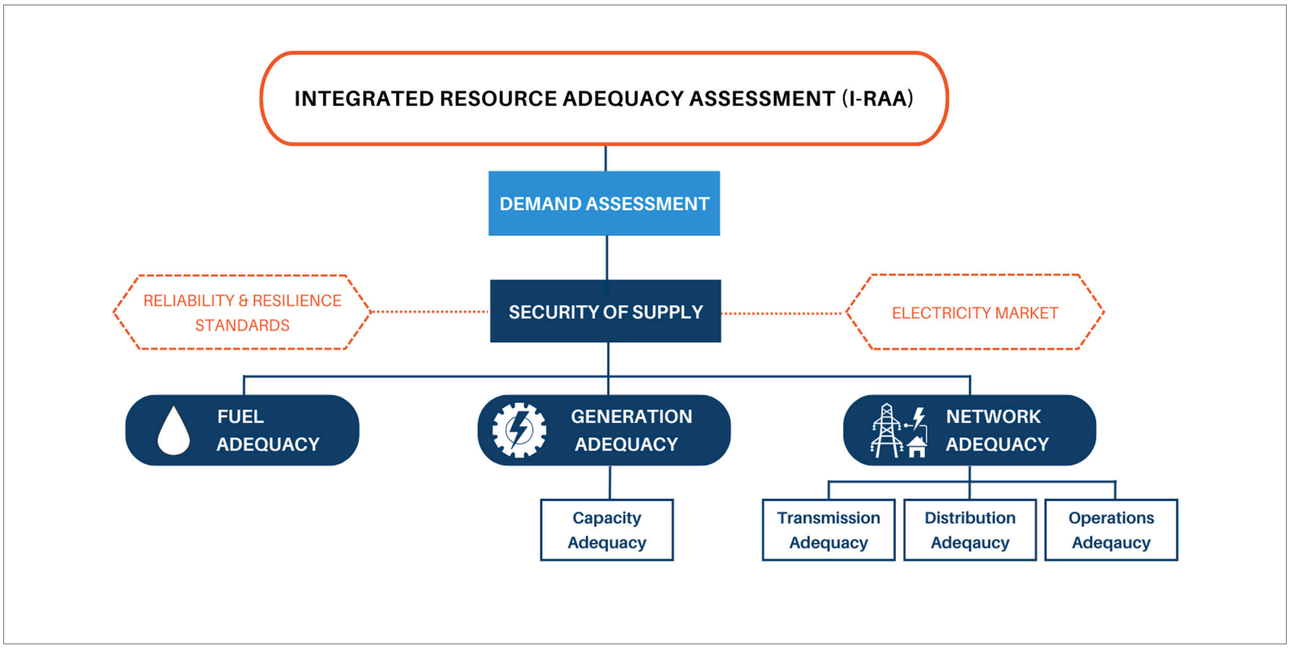
Offering useful insights and a chronological guide to integrate resource adequacy planning for different stakeholders, this theoretical handbook underscores the importance of having a multi-tiered resource adequacy framework across the supply chain. The report provides a flexible process for users to carefully internalise the different technical and operational metric facets across components instead of a singular, straitjacketed theoretical approach to resource adequacy. This enables planners to ensure the responsibilities of different stakeholders in ensuring resource adequacy, and the nature of engagement that must be carried out at regular intervals.



Chapter 1: Introduction

The concept of resource adequacy (RA) is significant in the context of a rapidly changing power sector, particularly the need to effectively balance supply due to the integration of renewable energy sources. Discussing the historical evolution of RA and its role in ensuring reliable electricity supply amidst increasing environmental concerns and extreme weather events, the chapter highlights significant power outages globally, such as the power outage in Texas in February 2021 due to fuel shortages and extreme cold, which underscored the fragility of energy infrastructure, the January 2021 power grid failures across Europe affecting many households, load shedding in China due to rapid industrial demand and equipment failures, India's record power demand in May 2024 driven by extreme temperatures, illustrating the global challenges faced in maintaining reliable energy supply amidst increasing demand and adverse conditions, and the Iberian power outage in countries like Portugal and Spain in April 2025, caused by a cascading voltage instability event and insufficient reactive power control that led to tripping of multiple generation units and total system collapse. This calls for a review of the existing discourse surrounding RA and its ability to ensure security of supply in the long run despite the constraint of supply variability. The chapter discusses how usually RA is defined as the assurance that utilities have sufficient generation capacity to meet demand at any given time, particularly as traditional thermal generation is increasingly replaced by renewables. It also critiques traditional RA metrics for their limitations in assessing the complexities of modern power systems and advocates for a more comprehensive approach that includes resilience and flexibility.

Exploring the evolution of planning approaches in the energy sector and the advancements like Integrated Resource Planning (IRP) and Distributed Energy Resources (DER) that works on integrating the demand and supply-side elements, the chapter discusses the challenges faced by current systems that hinder effective resource adequacy assessments. The chapter calls for a holistic approach to resource adequacy that encompass all aspects of power system planning. This includes robust supply chain management, resilient infrastructure, and effective load management strategies to adapt to emerging challenges. It asserts that stakeholders can better prepare for the complexities of modern energy systems and ensure reliable electricity supply by adopting a more integrated and comprehensive framework in an increasingly dynamic environment.



I-RAA Framework

Chapter 2: Resource Adequacy Framework

Expanding on the holistic approach towards RA, this chapter delves into the proposed Integrated Resource Adequacy Assessment Framework (I-RAA), which integrates various components of the power system to ensure adequacy. The framework coalesces the indicators of reliability across the components of demand and supply to better highlight the impact of these indicators on resource adequacy. It defines resource adequacy and outlines the two major components of the I-RAA framework: Demand Assessment and Security of Supply. Briefly discussing the concepts of market, reliability and resilience standards on the periphery, the chapter elucidates the taxonomy of the developed framework by reviewing the definitions across different components of supply and demand including fuel adequacy, generation adequacy, and network adequacy, detailing how these elements interact to establish equilibrium. In addition to demand-supply equilibrium, the chapter also discusses the need for resilience in power systems to withstand and recover from disruptions, highlighting the distinction between reliability (consistent electricity delivery) and resilience (ability to recover from unexpected events).

Components of the I-RAA Framework

- **Resource Adequacy:**
  Resource Adequacy is a measure of the power system as a whole to optimise resources (including generation, transmission, distribution, storage and responsive demand) to be able to balance and meet the unconstrained demand.

- **Security of Supply:**
  It considers both the short-term needs from a system security point of view through network adequacy and the mid-term to long-term needs through generation adequacy, which in turn is dependent on fuel adequacy. Complementing this would be the market adequacy where the power system interacts with the electricity market to serve the needs of any of the subcomponents under I-RAA framework.

  - **Fuel Adequacy:** Fuel Adequacy deals with the continued availability and provision of primary fuels assuming that all means of transport, transformation and conversion exist to get the energy flux from the producer to the consumer.

  - **Generation Adequacy:** A power system would be generation adequate if sufficient capacity was available to meet projected peak demand plus a reserve margin to hedge against inaccuracies in projected demand, unexpected outages, and other operational deviations.

  - **Network Adequacy:** Network adequacy is a measure of its ability to transmit power from generation sources to distribution interface and the distribution system to meet the demand and energy requirements of the customer, taking into account reliability and resilience standards.

    - **Transmission Adequacy:** Transmission adequacy is the ability to transfer power from the generation sources to the distribution interfaces taking into account reliability and resilience standards.

    - **Distribution Adequacy:** Distribution adequacy is the ability to supply power from the distribution interfaces to the end consumer taking into account reliability and resilience standards.

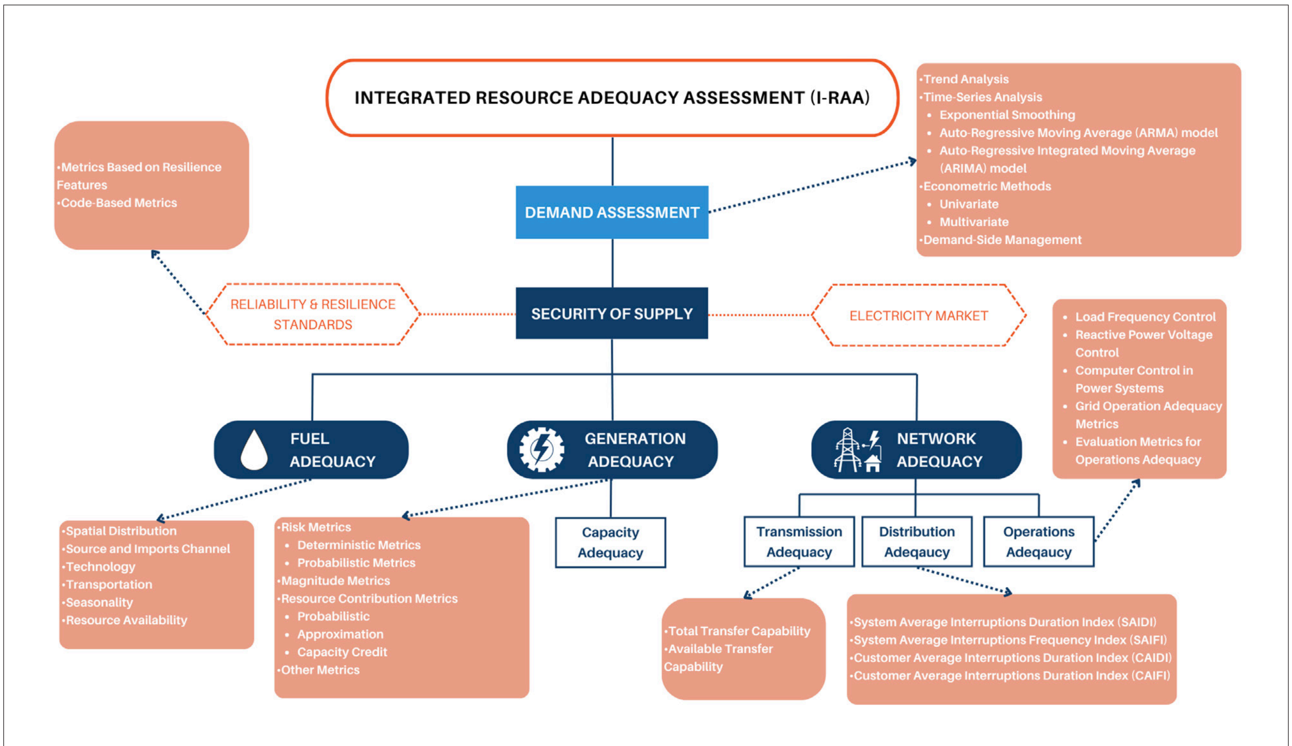
    - **Operations Adequacy:** Operations adequacy is the ability to optimise and balance power between generation and demand taking into account reliability and resilience standards and supported by interoperability.

- **Demand Assessment:**
  Demand assessment is achieved through a hybrid combination short-term estimations

and long-term forecasting that measures demand using baseline corrections from historical demand data, assumptions from actual trends, inclusion of seasonal variations, and forecasts for future growth. The framework recognises the importance of integrating demand-side resources (like energy efficiency and demand response) into planning processes to enhance overall system reliability.

Chapter 3: Adequacy Metrics

This technical extension to Chapter 2 deals with traditional and modern metrics for assessing resource adequacy in detail. The metrics mapped under these components are largely reliability metrics and are classified further based on their risks, magnitude and resource contribution. These categorisations further help in explaining their relevance in evaluating the adequacy of generation, transmission, and distribution systems. Additionally, it examines conventional metrics for their inability to capture the complexities of modern power systems, particularly with the integration of variable renewable energy sources and introduces new metrics that assess the risks associated with different resources and the methods of demand assessment in forecasting electricity needs. The resource adequacy framework also introduces readers to resilience metrics, as an effort to measure the ability of integrated power systems to recover from disruptions and impacts caused by unforeseen events.



Resource Adequacy in the I-RAA Framework

The I-RAA framework expands over traditional metrics by incorporating additional dimensions, including fuel adequacy, network adequacy, and demand-side resources along with metrics for resilience. The chapter discusses the metrics for each component:

Fuel Adequacy Metrics

The metrics discussed in this section are used for measuring fuel adequacy in alignment with the established definition in the I-RAA framework. Attributes of fuel adequacy, such as resource availability, sustainability, and reliability, are evaluated using metrics tailored to different fuel sources, including traditional power generation (coal, natural gas, nuclear) and renewable power generation (solar, wind, hydro).

Generation Adequacy Metrics

The section discusses various methods for assessing the reliability and sufficiency of electricity generation resources within a power system. It categorises metrics into deterministic and probabilistic approaches. Deterministic metrics, such as the Planning Reserve Margin (PRM), provide a straightforward snapshot of adequacy by comparing total available capacity against peak demand but may oversimplify the complexities of resource availability. In contrast, probabilistic metrics, including Loss of Load Expectation (LOLE) and Loss of Load Probability (LOLP), account for uncertainties in generation and demand, offering a more nuanced evaluation of risk by estimating the likelihood and frequency of insufficient supply to meet demand. Additionally, the section highlights magnitude metrics like Expected Unserved Energy (EUE), which quantify the total expected shortfall in energy supply, and resource contribution metrics that assess how different generation resources contribute to overall system reliability. Additionally, metrics of capacity credit and other combination metrics are also discussed to incorporate the generation of variable resources. This comprehensive framework allows for a detailed understanding of generation adequacy, essential for effective planning and management of electricity supply systems.

Network Adequacy Metrics

The limits on transfer capability, frequency, and voltage in addition to generational losses are widely discussed in this section. The network adequacy metrics are classified by transmission, distribution, and operations of the power network. In addition, metrics such as the flexibility metrics are discussed to understand system responsiveness in demand changes. Deterministic and stochastic factors play a huge role in maintaining the thermal, voltage and frequency stability of power networks. Limits to the latter largely affect the components of network adequacy. At the transmission level, the framework measures the transfer capability of interconnected transmission lines and the risks arising out of deterministic and stochastic factors through capacity and reliability margin contributions. Factors that affect network imbalances are measured under transmission adequacy since voltage and power flow affect transmission and transfer capability. As far as operations adequacy is concerned, the section maps the metrics that measure frequency and imbalances and briefly highlights the role of ancillary services in restoring frequency and ensuring network reliability. The distribution adequacy metrics measures the average interruptions and duration of these interruptions while serving the customers.

Demand Assessment

Factors affecting demand assessment, such as economic growth, population changes, and technological advancements, are discussed along with data requirements and time horizons. The chapter reviews existing methodologies for demand assessment, including a variety of techniques like trend analysis, time-series analysis, econometric and end-use methods comprising of top-down and bottom-up approaches, and highlights the importance of considering the impact of demand-side management (DSM) programs.

Resilience Metrics

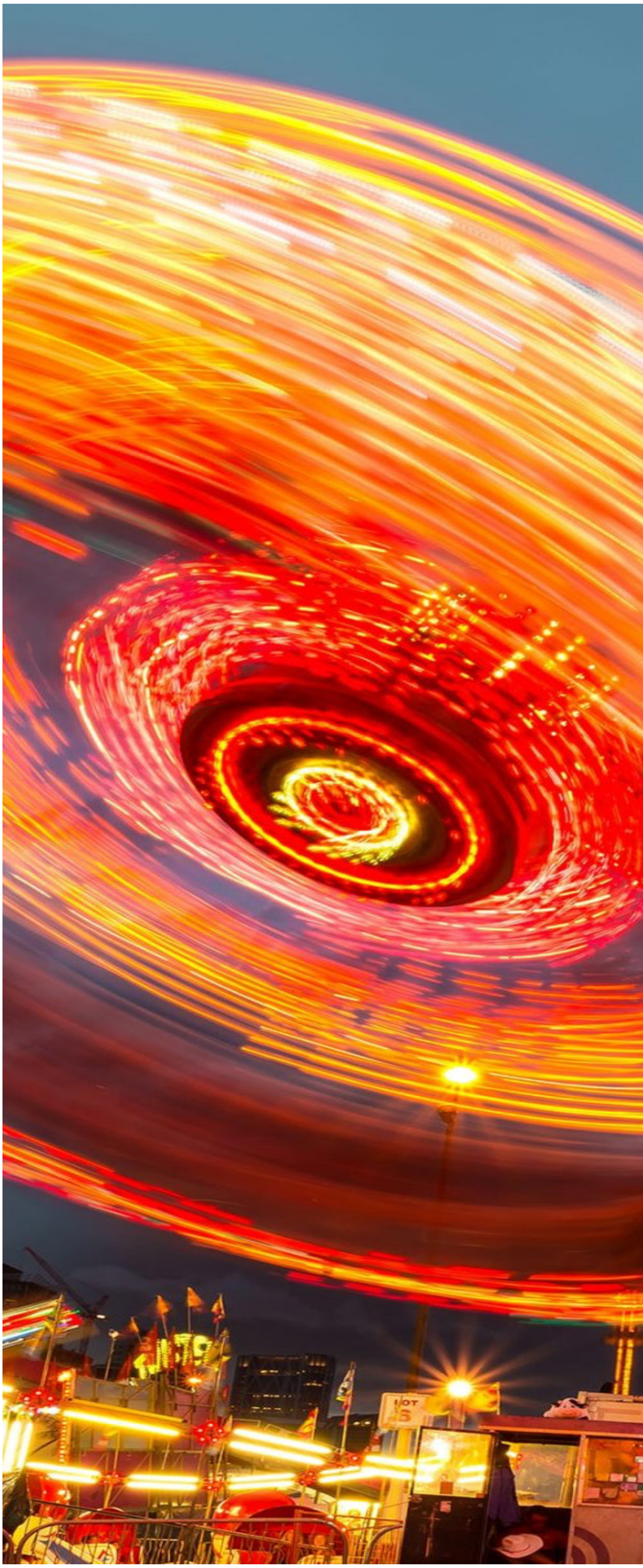
The concepts of grid and power system resilience are introduced, assessing the ability of the power system to withstand and recover from extreme events. Resilience metrics are categorised into two: one being metrics based on resilience features and two being code-based resilience metrics. Different assessment approaches and the resilience curves are presented to evaluate the system's ability to maintain critical functions during and after disruptive events. To provide an idea of grid resilience to readers, the chapter briefly explains the resilience bow-tie method used in Hawaiian Electric and the steps involved in measuring the pre and post-event effects.

Chapter 4: Electricity Markets

The chapter enlightens the readers by introducing them to electricity markets, their instruments and operations, and their ability to ensure resource adequacy within the market. The readers are exposed to the various regulatory models and their implications for market efficiency and reliability. It examines international best practices in resource adequacy assessments and their applicability to India, emphasising the need for integrated market mechanisms that support resource adequacy.

The chapter discusses three main regulatory models for electricity markets: the Single Buyer Model, where a single entity is responsible for purchasing electricity from generators and selling it to consumers; the Wholesale Market Model, which involves the creation of a competitive wholesale market where generators sell electricity to retailers or large consumers, with prices determined by supply and demand and generators dispatched based on their bids; and the Wholesale & Retail Market Model, which builds upon the wholesale market model by also introducing competition at the retail level, allowing consumers to choose their electricity supplier and retailers to compete for customers based on price, service, and other factors. These models establish the roles and interaction of market participants that are useful to ensure smoother engagement and trade.

This chapter on market also introduces the time sequence to the electricity markets categorised based on the time sequence of transactions into several distinct types: Forward (Long-term) Markets, which facilitate the trading of electricity contracts for future delivery, providing price stability and risk management; Spot (Short-term) Markets, where electricity is traded for immediate or near-term delivery, typically within a day; Balancing Markets – Ancillary Services, which ensure system reliability by managing real-time supply and demand imbalances through services like frequency regulation; Redespatch and Flexibility Markets, which address transmission congestion by adjusting



generator dispatch and trading flexibility services such as demand response; and Capacity Markets, which incentivise generators to be available to produce electricity when needed, thus ensuring resource adequacy and long-term system reliability.

The chapter highlights several factors that influence the role of markets in resource adequacy, the importance of transmission pricing, congestion management, and despatch models in ensuring efficient electricity distribution. It addresses the need to mitigate the "missing money" problem, which can deter investment in necessary capacity, and underscores the significance of tracking front office transactions (FOTs) to understand market dynamics. Understanding capacity contributions from various generation sources is crucial for effective planning, as is addressing the value of lost load, which reflects the economic impact of outages on consumers. Additionally, limiting market power and manipulation is essential to maintain fair competition and integrity within the market. Finally, the role of smart grids is increasingly recognised as vital for enhancing resource adequacy by improving system flexibility and responsiveness to demand changes.
The chapter also provides an overview of resource adequacy mechanisms in global electricity markets, focusing on the United States, the European Union (EU), and India and how each approach energy resource adequacy with distinct strategies tailored to their unique challenges and goals.

The report underscores the need for a resource adequacy framework that would standardise the theoretical intersections surrounding the concept. It provides a suggestive way forward in realising the objectives of an ideal power system by highlighting the different levels or degrees of resource adequacy: the first being resource adequacy itself, the second being reliability, and the third being resilience. These aspects are important to understand the capabilities of different power systems and would help planners to incorporate policies and actionable insights for smoother implementation.

Additionally, the report also provides different theoretical and application requirements like comprehensive data standards, modelling infrastructure, framework optimisation techniques, stakeholder engagement, regional and sub-regional demand dynamic studies and integrated planning approach to better incorporate the resource adequacy report in power system planning. It also specifically elaborates a step-by-step process for stakeholders to ensure the effective implementation of the report into their respective power system planning process at different temporal granularities, highlighting the possible productive outcomes of the exercise.

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1. INTRODUCTION

1. INTRODUCTION

In recent times as a result of growing environmental awareness and the dynamic and fast-changing landscape of electricity generation with the expansion of renewable energy, new concerns and questions regarding how the sector should evolve have emerged. There are also related challenges such as increased global average temperatures and increased frequency and intensity of extreme weather events which impact the power system. In mid-February 2021, Texas, United States of America (USA), faced power outage due to fuel shortages and cold weather, which exposed vulnerabilities in the energy supply chain and infrastructure. Similarly, on January 8, 2021, a breakdown of power grids in southern, central, and western Europe left several thousands of households without power, caused by equipment failure exacerbated by weather conditions and high demand (CREA 2022). In China, between the end of 2020 and mid-January 2021, load shedding was implemented in Hunan and Jiangxi due to rapid industrial power consumption growth and equipment failures (CREA 2022). On 30 May 2024, India registered a record maximum power demand of 250GW owing to extreme summer temperatures (Ministry of Power 2024). Countries in the Iberian Peninsula such as Portugal and Spain, faced a blackout event on April 28, 2025, that was caused by a cascading voltage instability triggered by a forced oscillation from a photovoltaic plant, inadequate reactive power control by multiple generators, and the inappropriate tripping of generation units, ultimately leading to a total system collapse (Red Eléctrica 2025). These events underscore the importance of a comprehensive approach to power sector planning, including robust supply chain management, resilient infrastructure, and effective load management strategies. As extreme weather events become more frequent, it is crucial for power systems to be able to respond effectively to sudden surges in demand and potential equipment failures.

Highlights

- *The introduction provides a comprehensive overview of the evolving landscape of resource adequacy (RA) in the electricity sector.*
- *The chapter highlights the importance of a holistic approach that considers factors beyond peak demand and traditional reliability metrics.*
- *It explores the historical evolution of RA, the limitations of existing methodologies, and the need for a more comprehensive framework.*

It is no surprise then that one such subject which has increasingly gained attention within the electricity policy circles is that of resource adequacy (RA). The concept of RA in itself is not new, as early as the 1870s since electricity was commercialised, electrical system planning has involved ensuring adequate generation to meet the load obligations of load serving entities (LSEs). Resource adequacy (RA) has been defined as “the knowledge that the utilities or load serving entities (LSEs) that supply electricity to customers - within an explicitly defined region has accumulated sufficient generation to meet the total load (electricity demand) of that region at any given time” (Eckstrom & Shen, 2018). Such calculations require a deep knowledge of both LSE generating capacity and load expectations or load forecasts. This becomes even more important in the current scenario where we see traditional power generation such as thermal generation being replaced with more renewable energy generation, combined with the need to ensure flexibility and availability of generation resources to meet demand at all times.

1.1 ORIGIN AND EVOLUTION OF RESOURCE ADEQUACY

The traditional concept of resource adequacy assessment was more of a response to outage situations, which focused on providing for maximum capacity during annual peak demand periods (Carden et al. 2011). Planners forecast the approximate annual peak demand during the planning horizon and utilities then estimate their load obligations and determine the capacity needed to serve the demand. The peak demand forecast is usually produced based on some combination of historical load data as well as geographic, economic, and forward-looking climate change factors. And on the supply side, resource adequacy is provided by the electricity generation along with the transmission and distribution network that delivers power for final consumption. Typical supply side resources are categorised by the fuel type or generation technology such as coal, natural gas, hydro, nuclear, wind and solar; and could be either self-owned or contracted, serve as baseload, variable or as peaking generator, all of which correlate with resource availability and their capacity to meet the peak demand. Due to uncertainty of the supply resources and accurate estimation of demand, electricity system operators have to plan for reserves such as planning reserve – which is the additional capacity procured beyond the amount required to satisfy the expected peak demand and the operating reserve – which are ancillary services that operators procure during daily operations on timescales of minutes to hours.

The analysis of the bulk power system’s (BPS) resource adequacy traditionally focused on the generation capacity during peak time periods. This assessment emphasised the comparison of capacity reserve levels to peak demand, assuming that resources were generally despatchable and available when needed, except for unit outages and de-rates (NERC 2020). However, a power system must also have adequate transmission and distribution lines to deliver power to load points and consider demand-side resources.

Integrated Resource Planning (IRP) emerged in the 1980s in the United States of America (USA) as a response to a changing energy landscape. The oil embargoes of the 1970s highlighted the need for diverse energy sources, while repeated instances of unnecessary and overbudget power plants exposed the limitations of traditional planning based on constant load growth. Prior to the 1970s, planners relied on assumptions of unwavering load growth fuelled by the post-war baby boom (5-7% per year) (Weston 2009). However, as birth rates stabilised and load growth plateaued, this model became outdated. Many massive nuclear power plants under construction faced cancellation due to a lack of actual demand. Utilities needed a new approach to future resource procurement, moving beyond the ‘increasing economies of scale’ mentality. Regulators, too, sought a system that did not simply guarantee utilities could recoup costs through rate hikes. IRP was born out of this necessity, offering a more comprehensive and adaptable planning framework.

IRP practices empower both utilities and consumers to manage risk effectively. By evaluating long-term (10-25 years) procurement strategies, IRP helps identify the most cost-effective solutions to meet future energy needs. This includes anticipating peak demand and ensuring sufficient reserve margins. IRP matured significantly by the early 1990s, evolving into robust planning frameworks with well-defined criteria (Wilson and Biewald 2013). This coincided with a wave of change in the energy sector. New technologies like large-scale wind turbines, advanced solar panels, and cogeneration were entering the market, challenging traditional fossil fuel generation. IRP guidelines played a critical role in smoothing the transition from the pre-1978, vertically integrated market to the more diverse post-Federal Energy Policy Act of 1992 market. These guidelines helped minimise risks associated with integrating these new technologies and fostering a more diversified electricity sector.

Another important change in resource planning was the inclusion of demand-side resources in addition to transmission and generation. The "Integrated" in IRP is in reference to the integration of both demand- and supply-side resources in the utility planning process. Demand-side resources can also be referred to as distributed energy resources (DER). DERs are usually small-scale, geographically dispersed, and directly connected to the local distribution network, such as rooftop solar panels (U.S. Department of Energy 2018). The definition of DER has evolved to more broadly cover resources that are deployed at the distributional level, including energy storage, electric vehicles (EV), demand response (DR) initiatives, and energy efficiency (EE) technologies. With advancements in computer modelling technology, LSEs have been able to enhance the accuracy of their load forecasts and better reflect Distributed Energy Resources (DER) improvements.

While all load serving entities (LSEs) incorporate regional transmission planning along with their IRPs, the depth of these analyses varies significantly. Some utilities conduct very detailed assessments of future transmission requirements. These transmission analyses often reveal that existing transmission networks are sufficient to maintain reliability in the current and near-term future (copperplate), meaning they are not currently acting as a constraint (Carvallo et al. 2020). However, transmission planning under reliability or resource adequacy studies under IRP was often designed with respect to capacity/resource contribution and co-optimises transmission capacity in performing least-cost optimisation (California Public Utilities Commission 2019). Moreover, attributes of supply-side options in IRP only consider the efficiency of net amount of electricity produced per unit of fuel input, in terms of generation. As for transmission and distribution, efficiency is measured as the percentage of power or energy lost during transmission or distribution (The Tellus Institute, n.d.-a).

RA assessments had been mandatory for utilities in the US, often studied separately for reliability assessment, or implicitly included under Integrated Resource Planning (IRP). An IRP captures more factors than a standard RA assessment in the sense that utilities also use IRP to develop actionable insights and plans to achieve cost-optimal generation expansion, equal treatment of demand and supply-side resources, complying with environmental regulations with increased stakeholder participation.

Originally, RA planning, largely in the USA was done by balancing area authorities (BAAs) or balancing responsibility parties (BRPs), who were the utilities. However, over time, Independent System Operators (ISOs) have adopted the balancing role for the load serving entities (LSEs) in the regions in which they operate. When compared to individual LSEs' RA assessments, regional RA programs can exploit resource, load, and transmission diversity given their expansive footprints and achieve cost savings by pooling capacity resources. A comprehensive RA assessment is fundamental to IRP because it ensures that the resource portfolios considered by the utility for future investments satisfy the necessary reliability standards (Carvallo et al. 2020).

Countries like India began assessing electricity demand immediately after independence in 1947, recording a per capita consumption of just 16 kWh. This laid the foundation for structured forecasting exercises like the Central Electricity Authority's (CEA) Electric Power Surveys, which periodically projected future demand to guide infrastructure planning. The Electricity (Supply) Act of 1948 further institutionalised power development by creating State Electricity Boards (SEBs) to manage generation and distribution (Barbar et al. 2021).

The 1950s saw the prioritisation of electrification as part of India's planned development, with significant government contribution in the power sector. By the early 1960s, regional power systems were introduced, enabling inter-state electricity transmission. This period also witnessed the establishment of central generation companies like National Thermal Power Corporation (NTPC) and National Hydroelectric Power Corporation (NHPC) in the 1970s to address growing demand.

In early 2000s, India's National Electricity Policy (NEP) that came into effect also aimed to ensure the supply of reliable and quality power of specified standards in an efficient manner and at reasonable rates as one of its core objectives. This alongside the continued development of national grid for inter-state transmission and periodical assessment plans were crucial elements that paved for the development of resource adequacy and IRP processes in India in the subsequent years that followed.

India now has one of the largest synchronously interconnected electric grids in the world. Since the interconnection of all the regional grids across the country in December 2013, India achieved 'One Nation, One Grid, One Frequency', creating a significant milestone in ensuring interconnected and efficient power network across all regions. This integration facilitated seamless power transfer across regions, ensuring reliable electricity supply and promoting optimal resource utilisation. It also supported uniform electricity pricing across the country at the exchange level, fostering economic growth and energy security.

1.2 GENERAL RA METRICS

A variety of reliability metrics are used to determine the level of resource adequacy of a power system. The RA assessments undertaken by regulators and utilities generally use a combination of deterministic metric such as Planning Reserve Margin (PRM) and probabilistic metrics such as Loss of Load Hours (LOLH), Loss of Load Probability (LOLP), Loss of Load Events (LOLE), Expected Unserved Energy (EUE) etc. (Rachel Wilson and Peterson 2011), to account for load obligations over determined timeframe. Countries majorly or partly involved in traditional power generation use the planning reserve margin (PRM) to measure resource adequacy. PRM is defined as the is defined as the difference between the total installed generation capacity and the peak load, divided by the peak load (EPRI, n.d.). Also, increasingly used for renewable power generation, the Loss of Load (LOL) standard measures the frequency of events where the load exceeds generation over different time periods. Whereas EUE measures the expected (i.e., average) amount of unserved energy per year, averaged across all resource adequacy simulations (Stenclik 2024).

The first steps towards comprehensive resource adequacy standards in the USA began by 1947 with the studies like those of Giuseppe Calabrese who proposed the criterion of limiting outage events to one every ten years (1-in-10 LOLE) (Carden et al. 2011). A series of events ushered improvements in resource adequacy standards, for example in November of 1965, a disruption caused by a misoperation in the Northeast US and Canada led 30 million people to lose power for an extended period (Eckstrom and Shen 2018a). As a result of this outage, electric utilities joined forces to prevent another outage of similar scale and created the National Electric Reliability Council (NERC) in 1968 (At present, NERC's name is the North American Electric Reliability Corporation). NERC took steps to ensure that all member utilities were upholding the 1-in-10 years outage standard (Carden et al. 2011). Today, NERC serves as the Electric

Reliability Organization (ERO) of the United States, as certified by Federal Energy Regulatory Commission (FERC) according to the Federal Energy Policy Act of 2005. In 2006, FERC made NERC responsible for upholding reliability standards across the country. Although it gained recognition from the 1960s, the wider acceptance was realised only around 2011 (Toth and Schwartz 2024).

To ensure 1-in-10 LOLE, reserve margins were planned to ensure that the deficiency in generation capacity to meet daily peak demand (known as loss of load expectation or loss-of-load probability) would occur no more than once in ten years. These margins were calculated using probabilistic analysis, considering generating unit forced outage rates based on random equipment failures from historical data. The targeted level historically aimed for one event in ten years, based on daily peaks rather than hourly energy obligations (NERC 2020). Additional insights were traditionally gained by calculating loss-of-load hours and expected unserved energy based on mean-time-to-repair unit averages.

The evolution of resource adequacy metrics globally has undergone significant transformations, particularly in response to the increasing penetration of variable renewable energy sources. While resource adequacy metrics have been in practice since the late 1940s, we present below an approximate timeline that highlights key developments in resource adequacy metrics, emphasising the shift from deterministic approaches to probabilistic and resilience-focused methodologies.

Timeline of Resource Adequacy Metrics Evolution

1970s-1980s:
Usage of Initial Metrics

The primary metric for assessing resource adequacy was the Loss of Load Expectation (LOLE), which quantified the average expected shortfall in electricity supply over a specified period. Initiated as a 1-in-10 years outage standard by NERC shortly after the 1965 power disruption in Northeast USA and Canada, this method provided a simplistic view of reliability but lacked depth regarding the nature and frequency of outages.

1990s:
Introduction of Enhanced Metrics

As energy systems evolved, additional metrics such as Loss of Load Hours (LOLH) and Expected Unserved Energy (EUE) began to

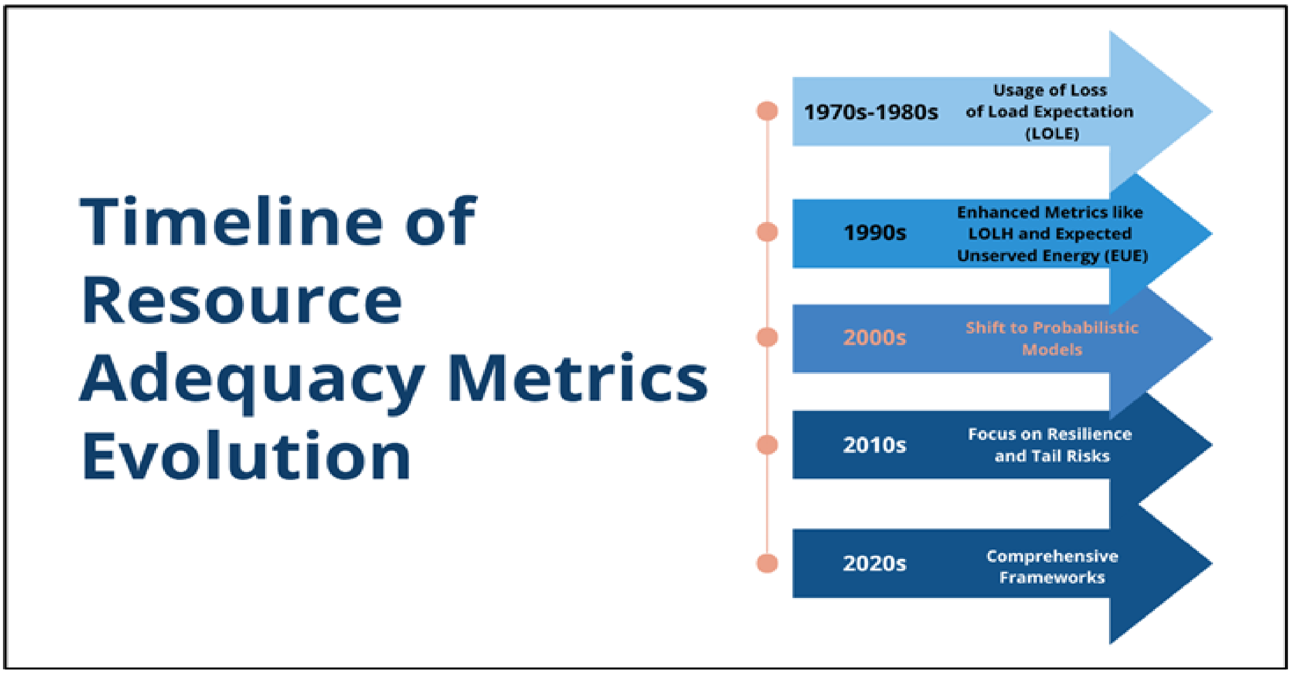


Figure 1 : Timeline of Resource Adequacy Metrics, Source: Authors

gain traction. These metrics aimed to provide more detail on the duration and magnitude of shortfalls, although they still operated within a deterministic framework.

2000s:
Shift Towards Probabilistic Methods
Utilities and system planners began adopting probabilistic reliability-based methods, utilising computer simulations to model various operational scenarios. This shift allowed for a more nuanced understanding of resource contributions to adequacy, accounting for variability in demand and generation from renewable sources.

2010s:
Focus on Resilience and Tail Risks
The increasing integration of renewable energy led to a greater emphasis on resilience-focused metrics. New methodologies emerged that not only considered average performance but also tail risks (low-probability but high impact events) associated with extreme weather events or unexpected outages. Metrics like Conditional Value at Risk (CVaR) were introduced to better assess the impact of rare but severe shortfall events.

2020s:
Comprehensive Resource Adequacy Frameworks
Recent guidelines, such as those issued by the Government of India in 2023, emphasise a multi-metric approach that incorporates both traditional and new metrics to ensure reliable power supply amid growing demand and renewable integration. This includes frameworks that assess not just capacity but also the timing and duration of potential shortfalls.
Countries *(Figure 2)* across the world use a mix of traditional resource adequacy metrics for their resource adequacy assessments. Besides the metrics discussed above some of the other metrics that countries use include Normalised Expected Unserved Energy (NEUE), Energy Reserve Margin (ERM), Winter Energy Margin (WEM) and Capacity Energy Margin (CEM). These metrics measure the level of outage risk and its magnitude to ensure reserve capacities through traditional and renewable generation combined with energy storage to meet the growing demand.

Some of the traditional RA metrics have specific limitations with respect to their measurement. The PRM effectively focuses on peak demand, and the traditional PRM metrics do not account for each generator's specific contribution to

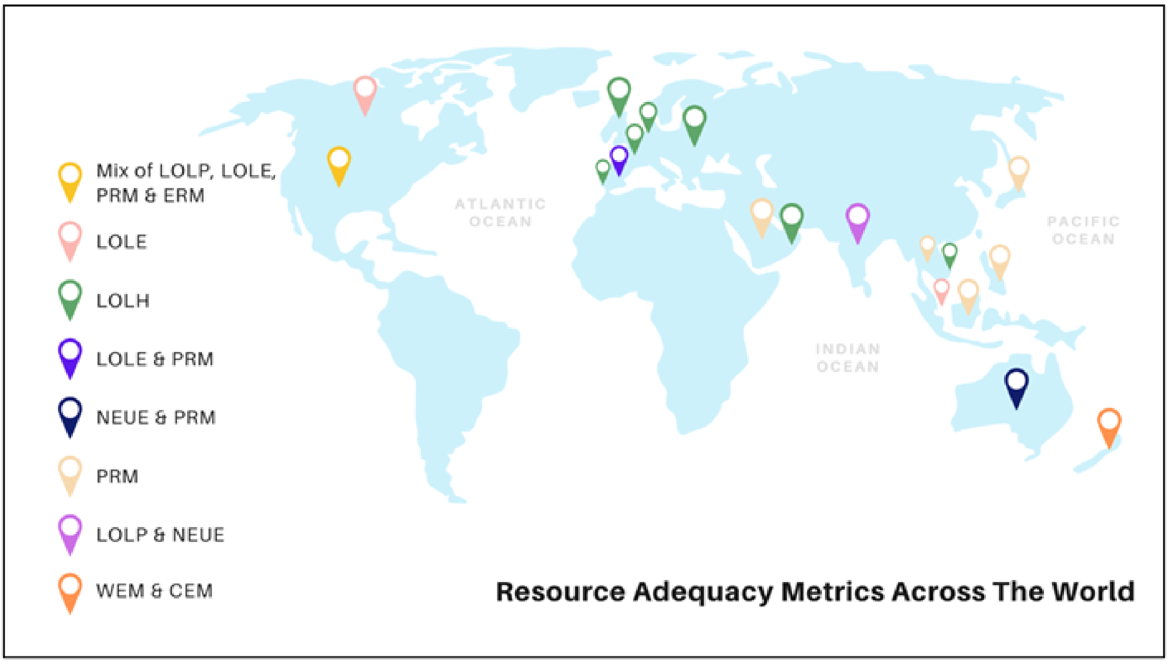


Figure 2 : Types of Resource Adequacy Metrics Across Countries, Source: Aothors, based on (Stenclik 2024)

meeting load during the periods of highest LOLP. For very detailed resource adequacy analysis, probabilistic methods, such as loss of load expectation (LOLE), are preferred because they account for thermal unit forced outage rates, wind and solar capacity values, and the highest LOLP times (Reimers, Cole, and Frew 2019). Moreover, PRM uses nameplate or installed capacity of generators along with peak load to calculate the margin. Counting variable generators' nameplate capacity and using it to calculate PRM would be unacceptable because this overestimates their contributions to meeting peak demand (Eckstrom and Shen 2018b). In the case of LOL, the single criterion approach is criticised for its inability to differentiate among the size, frequency, duration, and timing of shortfalls. Generally, damages associated with power system shortfalls are non-linear. The LOL metric not only omits such shortfalls but also fails to treat them differently. Longer and larger disruptions lead to disproportionately greater damages, yet the LOLE metric treats all resource adequacy short- falls equally (Stenclik 2024).

Some planners also suggest the need to measure the magnitude of LOL events that would best reflect the action plan for regulators and utilities. Another metric that is usually paired to the LOL metric is the expected unserved energy (EUE) that measures the magnitude of LOL events. While many find this as a significant density metric, others argue that the metric is limited in scope as a risk metric. Many regulators, utilities and operators have also added capacity contribution metrics- the share of contribution of different capacity resources in ensuring reliable supply. This helps in planning for future demand and load events while also helping understand the level of resource that needs to be added to restore existing load or outage event.

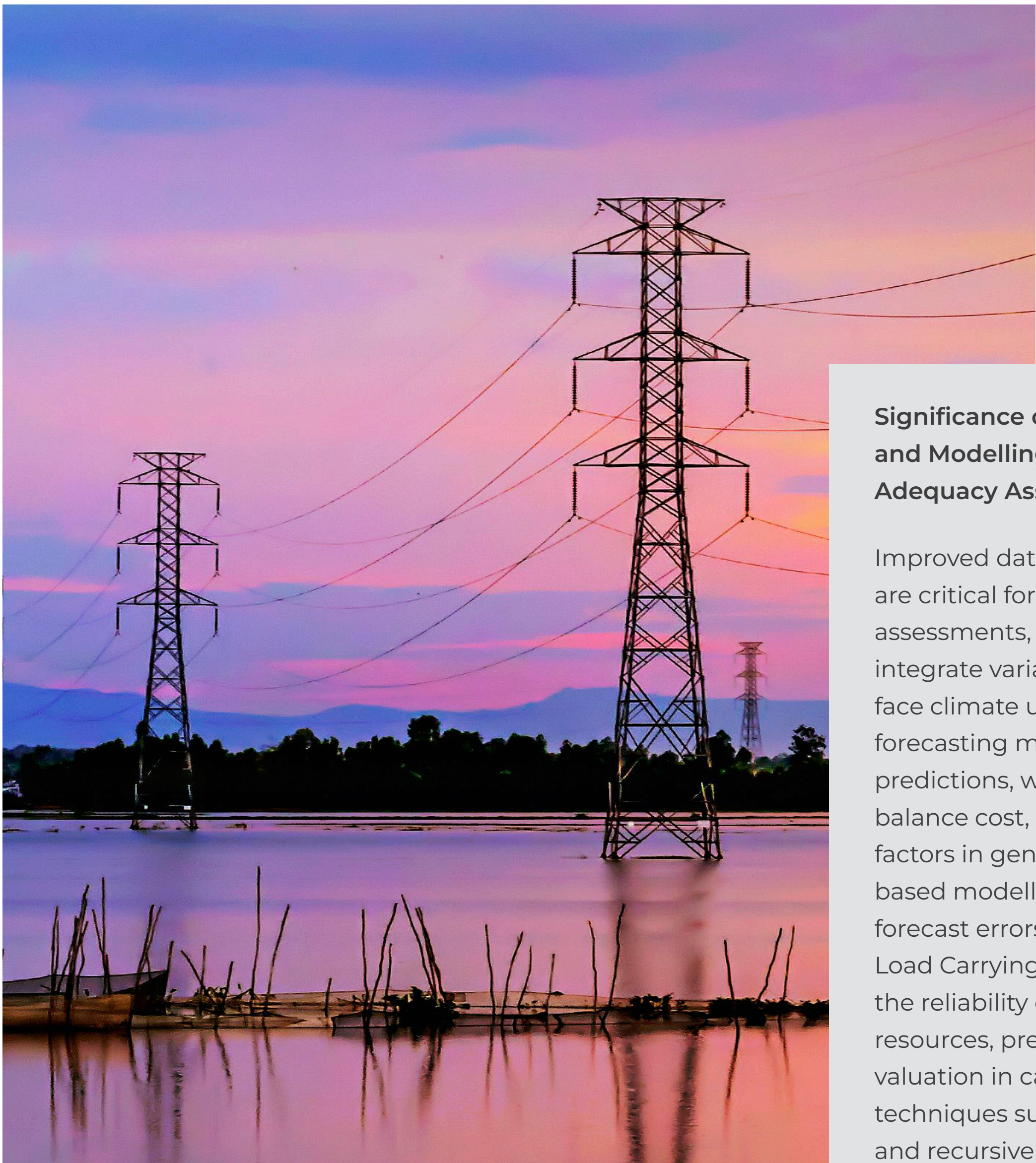
While these reliability metrics assessment helps in averting future risks, some argue that it might not be completely helpful in ensuring reliability and security of the grid. Critical literature on resource adequacy cites how the traditional metrics are limited by their ability to measure risk only from a generative standpoint. It suggests that a model resource adequacy assessment in general should capture the high-risk conditions during off-peak demand periods in addition to peak periods; and that the RA metrics must also measure reliability in generation, transmission and distribution and mapping tail risks to ensure resilience (Carvallo et al. 2023).

1.3 A HOLISTIC APPROACH TO RA

In the mid- to late 1990s, the electric industry underwent restructuring, shifting utilities from traditional resource planning to a market-based approach for providing electric supply. This change aimed for economy of planning and operations. However, today's evolving landscape presents new challenges, including climate change, national security concerns, and volatility in fuel and commodity markets. These factors can complicate the determination of the optimal approach for supplying electricity to consumers.

System planning, especially in terms of assessing adequacy, must innovate and evolve to ensure power systems can continue to provide secure and affordable electricity supply throughout energy transitions. The bulk power system (BPS) is experiencing an unprecedented transformation, necessitating a re-evaluation of how generating capacity, energy supply, and load serving needs are conceptualised (NERC 2020). This transformation will lead to a power sector that looks vastly different from today's, requiring us to rethink how we plan for a secure electricity system. Our approach to understanding demand must encompass more than just peak demand patterns, while our understanding of supply must go beyond the installation of despatchable capacity and the risk of outages during peak demand periods (IEA 2022a). In essence, it is no longer adequate to focus solely on the system's ability to maintain balance during specific tight moments.

Conventional power sector planning practices involve load forecasts that try to balance the burgeoning demand with supply at all points in time without any provision for storages as it might not prove to be cost-effective. The conventional methodologies used around the world to forecast demand are primarily based on



medium to long-term Gross Domestic Product (GDP) growth forecasts. Such economic growth predictions multiplied by 'electricity elasticity' would eventually lead to demand projections that would outstrip the real electrical demand (Greacen et al. 2013).

In addition to its general peak demand calculation to measure generation requirement, traditional planning approaches have a major limitation in their risk assessment. They lock in a single cost scenario, often fuel costs, and optimise the plan based on that assumption. This creates a plan that only works well if the future closely resembles the initial guess. Unfortunately, the conventional method offers little to no insight into how sensitive the chosen plan is to changes in those key assumptions.

Significance of having Improved Data and Modelling Approaches in Resource Adequacy Assessments

Improved data and modelling approaches are critical for robust resource adequacy assessments, particularly as power systems integrate variable renewable energy and face climate uncertainties. Advanced load forecasting models enable granular demand predictions, while optimisation frameworks balance cost, reliability, and environmental factors in generation planning. Scenario-based modelling addresses renewable forecast errors, and methods like Effective Load Carrying Capability (ELCC) quantify the reliability contributions of intermittent resources, preventing over or under-valuation in capacity markets. Probabilistic techniques such as Monte-Carlo simulations and recursive convolution better handle uncertainties like extreme weather or fuel supply disruptions, moving beyond outdated deterministic benchmarks. Integrating Artificial Intelligence (AI) and machine learning refines metrics like Loss of Load Probability (LOLP) by analysing real-time grid data, historical patterns, and socio-economic factors, enabling adaptive responses to dynamic conditions. Transmission planning also benefits from network optimisation models that identify bottlenecks and future infrastructure needs. These advancements, combined with climate-resilient scenario analysis, ensure frameworks remain adaptable to evolving risks like decarbonisation policies or shifting demand patterns, ultimately enhancing grid reliability amid energy transitions.

It is even worse when it comes to considering how multiple factors might change together, like a scenario with high natural gas prices, a drought, and the introduction of carbon pricing – a situation the traditional approach wouldn't effectively account for (Greacen et al. 2013). While this change in capacity with increased reliance on intermittent renewable sources has made the task of calculating resource adequacy increasingly important, it has also made it much more challenging. Uncertain fuel availability, such as unpredictable output from variable renewable energy sources, fuel location challenges, and fluctuations in forecasted load, may lead to inadequate energy supply for meeting electrical demand and ensuring reliable operation of the bulk power system (BPS) throughout the year (NERC 2020). The added layer of unpredictability to the power system along with changes in the climate make it difficult for planners to ensure reliability on the system.

Traditional IRP practices capture the power that can be transferred across an interconnected grid, focusing largely on individual line capacities and energy lost can be misleading. Unlike static line capacities, transfer capability considers the dynamic interplay within the entire network. Factors like generation availability, customer demand, and overall system configuration can significantly limit the amount of power that can be reliably transferred, even with high individual line capacities. Simply adding line capacities ignores these interactions, potentially leading to an overestimation of true transfer capability. Therefore, transfer capability, which takes a holistic view of the interconnected network, is crucial for ensuring a reliable and efficient power grid (NERC 1996).

The rapid integration of energy storage across the grid, connecting to both transmission and distribution systems, highlights the growing importance of network planning and operations. This holistic approach is crucial for efficiently delivering power to load centres in a changing grid landscape. Furthermore, the challenge of an aging transmission system is amplified as renewable energy sources, often geographically dispersed, are added to the mix. The increasing distance between generation and demand creates grid congestion. Improved network planning and operations become essential to optimise and strategically expand the transmission system to accommodate these renewable resources and ensure reliable power delivery (Ali and Banke 2022).

Climate Modelling

Why Climate Modelling: The Need for Fuel Availability with Growing Renewables and Grid Resilience for System Performance

Climate modelling in resource adequacy assessments is essential for developing a more holistic approach to resource procurement and grid resilience, particularly in the face of increasing extreme weather events driven by climate change. Traditional resource adequacy metrics often rely on historical data and deterministic methods, which may not adequately capture the complexities introduced by climate variability. By integrating granular climate risk models, such as Monte Carlo simulations, planners can better quantify the probabilistic impacts of extreme weather on resource adequacy. For instance, these simulations can model various scenarios that account for the frequency and intensity of weather events - like hurricanes in the southeastern United States, heatwaves in Europe, and cyclones or heatwaves in India- allowing for a comprehensive understanding of how these factors influence electricity supply and demand. Additionally, other extreme events might also affect the consistency of the variable supply of renewables, affecting grid reliability. Hence, climate modelling is important not only to understand the impact of tail risks on system performance, but also on the availability of energy for generation.

Incorporating Climate Impact Models

The use of advanced climate impact modeling techniques enables utilities and system operators to simulate a range of possible future conditions, including demand spikes during heatwaves or generation shortfalls during severe storms. This probabilistic approach enhances the robustness of resource adequacy assessments by acknowledging the interconnectedness of various risks, such as correlated failures across generation sources during extreme events. For example, the 2021 winter storm in Texas demonstrated how simultaneous failures in generation capacity due to cold weather could lead to widespread outages, highlighting the need for resilience strategies that consider both operational reliability and climate impacts. By adopting a holistic framework that incorporates climate impact models, energy planners can develop more effective strategies to ensure resource adequacy, ultimately leading to a more resilient and reliable power system capable of withstanding the challenges posed by climate change.

Incorporating Climate Adaptation Needs

Climate adaptation needs are increasingly critical as extreme weather events become more prevalent and varied across different regions. Each country faces unique challenges that necessitate tailored resilience planning strategies integrated into resource adequacy frameworks. For instance, in the United States, the frequency and intensity of heatwaves, hurricanes, and snowstorms have surged, prompting a need for robust infrastructure and emergency response systems to mitigate these impacts. In the European Union, countries like Germany experience severe flooding due to heavy downpours, while Mediterranean nations face droughts and heatwaves; thus, adaptation strategies must address these diverse climatic threats through localised approaches. Meanwhile, India contends with cyclones and extreme heat events, necessitating specific measures such as improved early warning systems and resilient agricultural practices to safeguard vulnerable populations. This region-specific focus on resilience planning is essential for effectively managing the risks posed by climate change, ensuring that each country can adapt to its unique environmental challenges while maintaining resource adequacy in energy supply and infrastructure.

India's unique vulnerability to extreme weather events, such as cyclones and heatwaves, necessitates a region-specific resilience planning strategy that is integrated into resource adequacy frameworks.

As climate change intensifies, these events are becoming more frequent and severe, posing significant threats to livelihoods, food security, and overall economic stability. For instance, over 80% of India's population lives in districts highly susceptible to climate-induced disasters, highlighting the urgent need for tailored adaptation measures. A comprehensive climate adaptation strategy must go beyond existing policies and Nationally Determined Contributions (NDCs) to address these challenges effectively. This involves developing binding legislation that facilitates proactive resilience-building efforts, such as enhancing infrastructure, improving water management systems, and implementing sustainable agricultural practices. By incorporating these elements into resource adequacy planning, India can better prepare for the impacts of climate change, ensuring that both energy supply and community resilience are maintained in the face of increasing environmental uncertainties.

1.4 CHARACTERISTICS OF AN IDEALLY ADEQUATE POWER SYSTEM

Balancing supply resources to meet the unconstrained demands requires a power system that is capable and flexible despite operational and system constraints. An ideally adequate power system has the following characteristics:

1. **Capacity:**
   Enough capacity to meet the forecasted peak demand such that the peak demand does not exceed capacity of supply and storage resources and available imports more often.

2. **Energy/Fuel:**
   Supply resources to have adequate access

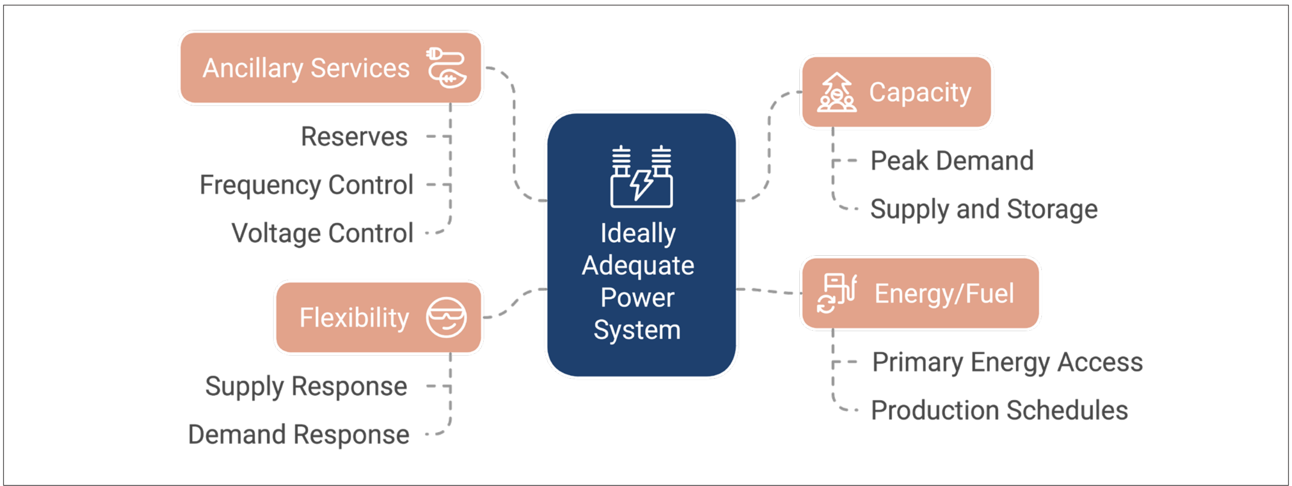


Figure 3 : Characteristics of an Ideally Adequate Power System

to primary energy/fuel resources for the production schedules to meet the demand portfolios.

3. **Flexibility:**
   The ability of the supply and demand resources to ensure sufficiency to respond to operational and non-operational uncertainty.

4. **Ancillary Services:**
   Essential ancillary services (reserves, frequency, and voltage control) provided by the resource portfolios are required to maintain power grid balance and network reliability (EPRI 2022a).

A well-designed resource adequacy framework should also consider both established reliability targets and the system's ability to bounce back from unforeseen disruptions (resilience). ***Reliability*** focuses on the power system's ability to consistently deliver electricity under normal conditions (Mijolla et al. 2022b), while resilience emphasises preparedness for and rapid recovery from unexpected events like extreme weather or cyberattacks (Executive Office of the President 2013). Current resource adequacy assessments primarily address risks with known probabilities, prioritising modelling scenarios where demand exceeds supply. Uncertainties, like the impact of a specific weather event, are managed through real-time responses once the situation unfolds. However, incorporating resilience goes beyond traditional risk assessment. While a common standard for measuring resilience is not currently established, including it in the framework offers two key benefits: improved predictability of the system's response to disruptions and potentially lower operational costs through better preparation (Carvallo et al. 2023).

In addition to reliability and resilience, the resource adequacy metrics will have to serve the purpose of balancing demand to the current supply-heavy metrics. Thus, there is also the requirement of detailed information on regional and subregional demand (load), as well as unit-level information on generating units and their ability to dependably serve load (Eckstrom and Shen 2018a). Electricity regulators can no longer reasonably assess resource adequacy within their region as nowadays the reliance is more and more on trading partnerships and short-term purchases of power across regions. An integrated policy and regulatory approach are essential to address the operational, investment, and regulatory challenges of networks effectively. This approach should enable efficient operation and timely development of networks to support liberalisation and decarbonisation goals. Effective policy should maintain competitiveness in the power generation sector, facilitate efficient market development, and ensure the timely and cost-effective deployment of renewables in suitable locations (Volk 2013).

This holistic approach creates opportunities, such as optimising investments across generation and network planning, or enabling more efficient investment through interregional planning that leverages the strengths of interconnected areas. However, maximising these benefits requires flexible contractual structures that allow stakeholders to utilise the full capabilities of the system. Additionally, as electrification increases, and different sectors become more interconnected, integrated planning across sectors like electricity and transportation will become crucial (IEA 2022a).

Developing a holistic approach towards resource adequacy becomes significant in decluttering the components and jargons surrounding resource adequacy. Moreover, it ensures proper classification and clarified approach towards the concept itself. Hence, we are developing a framework for resource adequacy assessment that combines the components along the supply chain and demand. This would serve as a literature on resource adequacy, its taxonomy and the contours of reliability and resilience across components. The framework, once developed, will be compatible for both resource adequacy assessments and resource planning for different stakeholders.

On the other hand, the objectives of the Integrated Resource Adequacy Assessment (I-RAA) Framework Handbook exercise are two-fold:

1. Theoretical standardisation of the concept of resource adequacy and its metrics

2. An all-encompassing resource adequacy framework whose scope lies beyond the traditional measures based in generation and capacity perspectives

Resource adequacy exercises across the world have primarily undertaken reliability assessments measuring the outage, loss-of-load and unserved energy probabilities over time that focuses on maintaining a specific loss-of-load standard, as discussed above. These reliability assessments were an improvement on the traditional way of increasing reserve margins, whose economic value was not just limited to avoiding physical curtailments but also in other reliability related costs (like emergency purchases) and the insurance value of reducing the likelihood of extremely high-cost outcomes.

However, with the aim of keeping the lights on and the integration of variable renewables, power stakeholders across countries are now going beyond increasing reserves, trading off between cost optimisation and reliability where the consistent balancing of demand and supply remains a costly affair.

The report provides an integrated approach that ensures reliability and resilience across components along the supply chain. The proposed framework is also inclusive of the components of demand and electricity market, while the reliability and resilience standards run through the components of the supply chain as mentioned earlier.

In ***chapter 2,*** we will be discussing the framework in detail the definitions and concepts surrounding components of resource adequacy with an extended lens into the demand and supply components. This will equip the reader with more knowledge combined with lesser ambiguity to wade through the rough waters of the theory.

In ***chapter 3,*** we discuss the adequacy metrics through the nature of measuring risks, magnitude and contribution through generation, transmission, distribution. We also provide a model design for demand assessments that explain the methods of demand estimation and forecasting for better projections.

In ***chapter 4,*** we discuss the different regulatory models and other market mechanisms surrounding resource adequacy across the world and the need to include prices and market interactions in ensuring resource adequacy.

In ***chapter 5,*** we conclude the report with discussing how countries can adapt the stylised resource adequacy menu into their planning process and the stages of achieving a certain degree of resource adequacy based on their input choice. We also provide a possible pathway for countries at least on a year-ahead basis to ensure a smooth integration of the I-RAA Framework into their resource adequacy assessment process.

How to read this Handbook?

This handbook consolidates a broad spectrum of global and regional literature on resource adequacy to provide a structured and comprehensive perspective suited to evolving power systems. Drawing upon academic research, technical reports, policy briefs, and explanatory documents, the authors synthesise key concepts and emerging trends in the field.

To bring coherence to the varied approaches in the domain, the handbook introduces a unifying conceptual framework: the Integrated Resource Adequacy Assessment (I-RAA) Framework. While traditional concepts such as resource adequacy, security of supply, reliability, resilience, demand assessment, and transmission adequacy remain central, this handbook advances the discourse by proposing a refined taxonomy. It introduces specific terms like fuel adequacy, generation adequacy, network adequacy, distribution adequacy, and operations adequacy to disaggregate and analyse the distinct components of the electricity supply chain through the lens of adequacy assessment.

For example, generation adequacy is defined as the system's capacity to generate and flexibly respond to real-time fluctuations in demand and supply. Conventional resource adequacy metrics such as planning reserve margins, loss of load probability, and expected unserved energy are repositioned here under generation adequacy, offering a more targeted articulation of a power system's generative capabilities and capacity contributions.

The subsequent chapter on the I-RAA Framework is structured to:

- Ground the analysis in established scholarly and technical literature;
- Present newly proposed classifications and definitions;
- Contextualise the relevance of each component and its associated metrics;
- Examine the implications of integrated adequacy assessments across the supply chain.

Readers are invited to engage with this handbook not merely as a reference text, but as an evolving analytical tool one that facilitates critical reflection on adequacy in the context of accelerating energy transitions and increasingly decentralised planning paradigms.

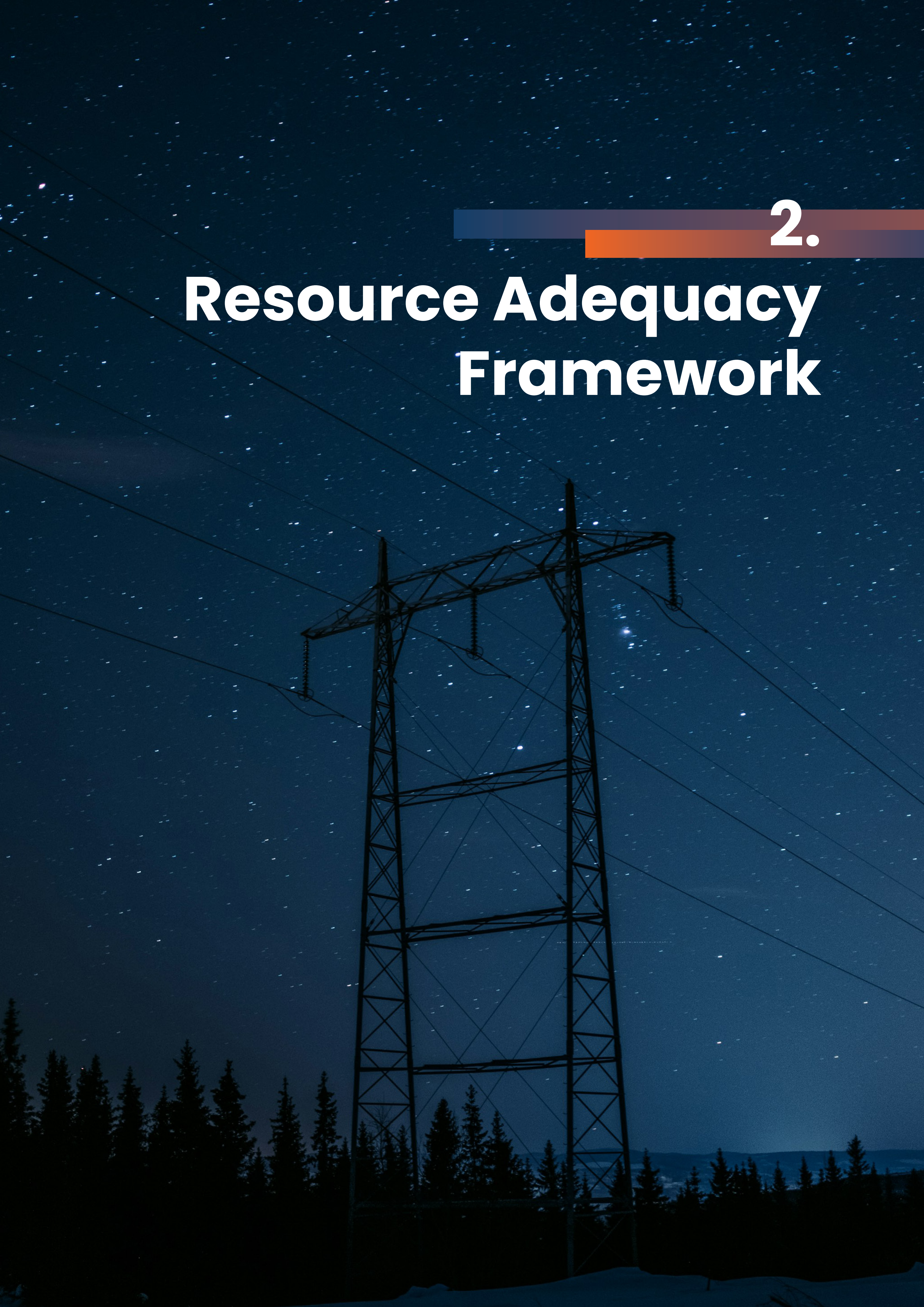
About This Series
This report is the first in a three-part series on Resource Adequacy, designed to build a comprehensive framework and enable practical application:

1. **Theoretical Handbook:**
   Establishes a standardised and integrated framework for resource adequacy, encompassing demand, supply, electricity markets, and reliability and resilience standards.

2. **Practical Report - India:**
   This forthcoming report will apply the theoretical framework to the Indian context. Developed through expert and stakeholder consultations, it will identify relevant metrics and propose recommendations to strengthen India's resource adequacy planning.

3. **Modelling Handbook - India:**
   Building on the practical report, this final volume will develop modelling tools tailored to India's needs. It will include a detailed guidebook and be supported by capacity-building efforts to promote adoption at national and sub-national levels, in collaboration with research and policy institutions.

2. Resource Adequacy Framework



2. RESOURCE ADEQUACY FRAMEWORK

Resource adequacy as a concept has evolved over the last many years. As discussed in the Chapter 1, the concept has evolved from a mere supply driven resource planning in the pre-renewables era to a more supply plus power system driven resource planning in the post-renewables era. In this chapter we try to examine how the definition of resource adequacy is addressed in different parts of the world, including taking a closer look at the sub-components of resource adequacy in order to develop a holistic "***Integrated Resource Adequacy Assessment (I-RAA)***" framework.

Highlights

- *This chapter explores the evolving concept of resource adequacy by examining global definitions and interpretations, setting the foundation for a more structured approach.*
- *This chapter introduces the Integrated Resource Adequacy Assessment (I-RAA) Framework, which disaggregates adequacy across the electricity supply chain, covering demand, fuel, generation, network, distribution, and operations, and refines or adds key terms for greater clarity.*
- *The chapter emphasises the integration of reliability and resilience standards in shaping a comprehensive adequacy assessment.*

2.1 WHAT IS RESOURCE ADEQUACY?

Different countries and institutions world over have defined resource adequacy differently and as such there is no universal definition. Listed below are some definitions to help frame the resource adequacy definition.

> "Having a sufficient overall portfolio of energy resources to continuously achieve the real-time balancing of supply and demand (Australian Energy Market Operator 2020);
>
> or "Resource adequacy is measured by the probability of an outage due to insufficient capacity. It is measured at the system level to capture the overall impact of outages of individual components including generators and transmission" (Ibanez and Milligan 2012);
>
> or "assess whether a power system has an appropriate set of resources to maintain continuous service to demand, with a desired level of certainty, given a range of operating conditions and challenges" (Mijolla et al. 2022a);
>
> or "balance between supply and demand including various flexibility sources and grid interconnections is referred to as resource adequacy" (ENTSO-E, n.d.-b);

or "An electrical power system is considered resource adequate if it has procured sufficient resources (including supply, transmission, and responsive demand) such that it runs a sufficiently low risk of invoking emergency measures (such as involuntary load shedding) due to resource unavailability or deliverability constraints" (Stephen 2021);

India defines resource adequacy as "tying up sufficient capacity to reliably serve expected demand of the consumers in the DISCOMs license area in a cost-effective manner" (MoP 2023).

Annex 1 outlines global definitions and terminologies related to resource adequacy.

To bring greater clarity and structure, this chapter introduces the Integrated Resource Adequacy Assessment (I-RAA) Framework along with a refined taxonomy. Traditional terms such as resource adequacy, security of supply, reliability, and resilience are revisited and refined, while others, such as fuel adequacy, generation adequacy, network adequacy, distribution adequacy, and operations adequacy, have been added or adapted by the authors to better reflect the distinct elements of the electricity supply chain through an adequacy lens.

Based on literature review the proposed definition for resource adequacy could be:

> Resource Adequacy is a measure of the power system's ability to ***balance and ensure sufficient resources*** (including generation, transmission, distribution, storage, and demand response) to reliably meet unconstrained demand at all times.

2.2 INTEGRATED RESOURCE ADEQUACY ASSESSMENT FRAMEWORK (I-RAA)

The development of an Integrated Resource Adequacy Assessment (I-RAA) framework would further need one to clearly define resource adequacy, taking into account the time horizons, the various elements and its interactions across the power sector value chain and an approach that requires both bottom up and top-down planning. Therefore, we present a holistic I-RAA framework who has two major components 1) Demand Assessment and 2) Security of Supply. The figure below shows a comprehensive I-RAA framework.

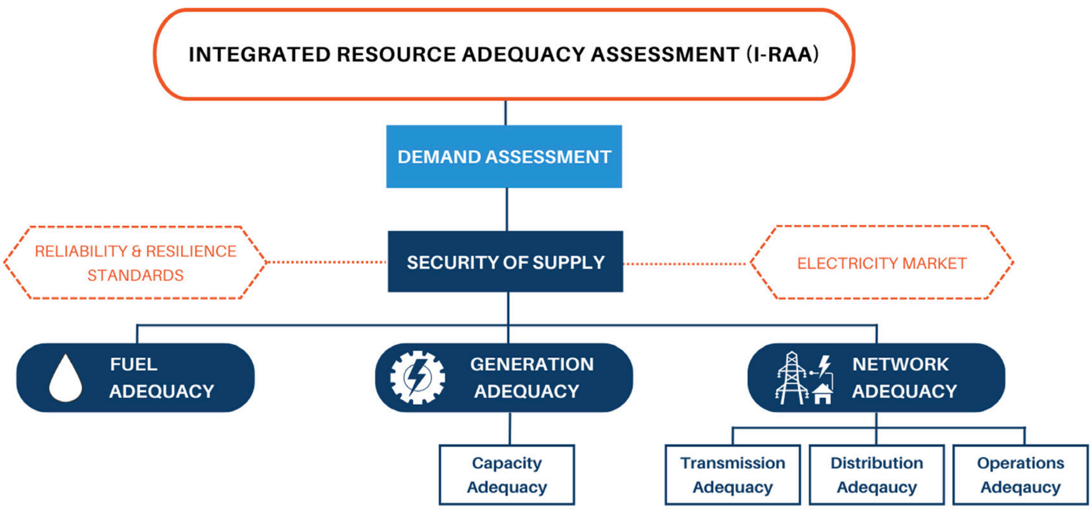


Figure 4 : Integrated Resource Adequacy Framework (I-RAA), Source: Authors

The I-RAA framework is characterised by the integration of the series of components that flow into balancing the overall supply with demand. The framework begins with demand assessment, the one of the foremost aspects of the framework for which it was created. Here, the degree of demand assessment through spatiotemporal intersections determines the short or long-term granularity of the I-RAA assessment. This helps in estimating the level of supply that can be ensured reliably to meet the unconstrained demand in a flexible manner. The supply, in turn, is affected by the adequate level of primary fuel, generation and network. Fuel adequacy ensures the availability and provision of primary fuels to generate electricity. Generation adequacy on the other hand, ensures the sufficient generation resources to meet the forecasted demand and deviations in addition to ensuring flexibility of the available capacity. Network adequacy ensures the transmission, distribution, and operational stability to adequately transfer power from producers to consumers. Network adequacy also ensures the ability of control assets to maintain operational stability among system, policies, and practices. The reliability is ensured by the continuity of the supply-side resources to meet demand whereas the resilience standards ensures that the components of supply anticipate, absorb, adapt to, and/or rapidly recover from extreme scenarios.

Demand assessment is a fairly newer concept that looks not just at demand estimation based on historical patterns, but also takes into account climate variations, demand projections linked to economic indicators and their relative impact on end-use consumption (Aliaksandr Novikau 2022). Moreover, demand assessment is a larger component that encompasses both short-term and long-term outlooks of demand estimation and demand projection respectively.

Security of supply takes into account both the short-term needs from a system security point of view through network adequacy and the mid-term to long-term needs through generation adequacy, which in turn is dependent of fuel adequacy (Schittekatte and Meeus 2021a).

Complementing this would be the market adequacy where in the power system interacts with the electricity market to serve the needs of any of the subcomponents under I-RAA framework.

The interaction of the various components within the I-RAA framework should also factor in the desired level of reliability. The reliability level is a measure of the ability of a power system to deliver electricity to all points of consumption and receive electricity from all points of supply within accepted standards and in the amount desired (Mijolla et al. 2022b).

Resilience means the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents (Executive Office of the President 2013). Grid resilience is the ability to withstand grid stress events without suffering operational compromise or to adapt to the strain so as to minimise compromise via graceful degradation. Resilience is different from reliability in the sense that the former focuses on recovering from the impact of uncertainties whereas reliability focuses on risks. In the context of power system, risk refers to situations where the outcomes are unknown, but the probabilities of different outcomes are known or can be estimated; while uncertainty involves scenarios where both the outcomes of events and their probabilities are unknown (Carvallo et al. 2023).

The concepts of reliability and resilience are often used interchangeably in the context of power systems, but they represent distinct characteristics. Reliability refers to the ability of a system to consistently deliver electricity under normal operating conditions. It is traditionally measured using frequency and duration indices such as CAIFI, SAIFI, CAIDI, and SAIDI. These metrics quantify the frequency and duration of outages. Resilience, on the other hand, is the system's ability to withstand and recover from disruptions or unexpected events. It encompasses the system's inherent ability to resist losing capabilities or gracefully degrade under stress (Taft 2017).

While reliability and resilience are interrelated, they are not synonymous. Increasing resilience can potentially improve reliability by reducing the frequency and duration of outages. However, this is not always guaranteed, as resilience changes may not directly impact the specific events that lead to reliability issues. Moreover, reliability metrics may not accurately reflect changes in resilience, as they are primarily focused on the consequences of outages rather than the system's ability to withstand them. Therefore, it is essential to distinguish between reliability and resilience and to employ appropriate metrics for each to effectively assess and enhance the performance of power systems (Taft 2017).

In power planning studies, risks are included instead of uncertainties because while the outcome of the risk is unknown, the probabilities surrounding these outcomes can be ascertained. Factoring in uncertainty involves factoring in unknown outcomes and unknown occurrences.

It is for the same reason that planning processes prioritise repeated modelling of risk events where demand exceed supply over uncertain events that assess the impact of, say, adverse weather events over the power system. This is why, in practice, uncertain events are managed through emergency responses and contingency procedures that operators can use on a short-term basis once the uncertain event and its magnitude of impact are known (Carvallo et al. 2023).

Continuing on the risk versus uncertainty (reliability versus resilience) debate, it is important to know that understanding the treatment of resilience and its impact on resource adequacy has been a point of debate across power stakeholders. A literature review by (Carvallo et al. 2023) finds that power system planning has no commonly accepted metrics to measure resilience, nor does it find any systematic treatment of the costs of extreme weather and non-weather events, resilience benefits, and resilience metrics in power planning processes.

A resource adequacy assessment framework should factor in both reliability level and resilience standards to be able to plan for future risks and to prepare effectively to respond to uncertainties and shocks. General metrics measuring resource adequacy only take into consideration the frequency and the magnitude of risk and measures the capacity value of its resources to effectively balance demand and supply. Measuring resilience, although not commonly measured till now, needs to ensure and account the degree of responsiveness of the power system and network in recouping from sudden shocks and uncertainties that threaten the steady flow of supply. Including resilience measurement onto the framework is important for two reasons: improved predictability and reduced operational expenditure.

In the proposed I-RAA Framework, ***reliability*** refers to the ability of power

system components to consistently aid in the generation, transmission, distribution, and the delivery of electricity under normal operating conditions.

The framework defines ***resilience*** as the ability of power system components to withstand and recover from generation, supply, and operation disruptions caused by extreme or unexpected events.

Our framework establishes reliability and resilience as a part of the greater I-RAA framework that ensures consistency and recovery of the power system. The reliability and resilience standards are present throughout the components; they interact with them to ensure the balance of demand and supply components (resource adequacy) and maintain consistency in balancing (reliability). Disruption of this balance caused by extreme or unexpected events would be met by swift recovery of the components (resilience).

The scope of market interactions in the framework are separate from that of the power system interactions in the sense that markets serve as the commercial platform that enables the sale of power. We discuss electricity markets and the need for unbundling at the basic level in chapter 4, and whether markets deliver resource adequacy and price stability in the energy supply chain (ESC).

An ***electricity market*** is a system that facilitates the exchange of electricity-related goods and services. It includes the set of market actors (eligible market participants and the market operator), as well as a set of standardised products that can be exchanged in the market.

I-RAA planning can again be undertaken both from a centralised and decentralised approach. A centralised approach considers an aggregated view of the various jurisdictions under a geographical area both from a system planner and system operator point of view. When done from the 'load-serving entities' perspective it is a decentralised approach, again inclusive of planning and operations.

2.3 BREAKING DOWN THE I-RAA FRAMEWORK

This section presents an explanation and defines some of the key elements of the I-RAA framework. The other aspects of the I-RAA framework such as the reliability level, resilience standards and electricity markets (as defined in the previous section) are studied in relation to these elements and are therefore explained in detail the following chapters 3 and 4.

Fuel Adequacy:
The fuel adequacy component factors in the primary fuel required for various generation units in order to ensure continued production of electricity from units. This could be in the form of procuring raw materials such as coal, gas, etc., or effectively forecasting renewables such as hydro, solar and wind.

Key to understanding fuel availability is the proximity to the source of primary fuel procurement. This is useful to reduce the time in the extraction and transportation of a resource. For instance, coal-based thermal power plants are located somewhat close to coal deposit locations to ensure faster access to primary fuel material. Similarly, solar or wind abundant region will be naturally selected to install solar or wind power plants. This aspect of fuel availability is often referred to as the resource potential of a given region.

Analysing the resource potential is also significant to measure the cost, reliability, and environmental impact of fuel procurement. The geography of a location, the presence of transmission or other logistical infrastructure, the economic viability of resource extraction, and environmental policies determine the resource potential of a region to a greater extent.

Available literature on fuel adequacy by (KU Leuven Energy Institute 2013b) defines fuel adequacy as, 'Fuel Adequacy deals with the continued availability and provision of primary fuels assuming that all means of transport, transformation and conversion exist to get the energy flux from the producer to the consumer'. Adapting from the same, our framework defines fuel adequacy as:

> Fuel Adequacy refers to the continued availability and provision of ***primary, secondary, and alternative fuels, considering the existence and reliability*** of all means of transportation, transformation, and conversion required to deliver energy from producers to consumers, ***while accounting for infrastructure, environmental, regulatory, and geopolitical risks.***

Generation Adequacy:
This component assesses the generative ability of a power system and its flexibility to respond to sudden demand and supply changes. In other words, the way in which the power system can match the evolution in electricity demand. Generation adequacy also ensures the availability of generative assets and reserves to not only cover for changing demand, but also for contingencies. From a consumption perspective, generation adequacy is also considered to be a main component since the level of generative capacity and the ability to meet peak demand would help consumers purchase electricity from utilities or power plants that are better capable of providing stable power supply.

Therefore, generation adequacy can is defined in our framework as:

> A power system would be generation adequate if sufficient capacity, including firm generation and ***variable renewable energy***, is available to meet projected peak demand plus a reserve margin that accounts for inaccuracies in projected demand, unexpected outages, ***renewable intermittency, and extreme events.***

Capacity Adequacy:
Expanding capacity takes time; the planning, permitting, and construction involved make it a long-term process. However, unlike short-term challenges that can be heavily influenced by unpredictable current events, capacity expansion offers greater predictability (Larsen and van Ackere 2023). In addition, there exist three aspects that make a power system capacity adequate:

- **Peak load:** Sufficient capacity (including demand response) to handle peak load situations.
- **Flexibility:** If the capacity has sufficient flexibility in handling the variations in load and balance the system in real-time.
- **Energy backup:** Whether there is sufficient energy backup capacity to serve demand during prolonged periods of low wind and solar generation (THEMA consulting group 2015a).

Adapting the definition from (Danish Energy Agency 2014), that defines capacity adequacy as 'an element of electricity supply, i.e. the probability that electricity is available when demanded by consumers', our framework defines capacity adequacy as:

> Capacity Adequacy refers to the ability of

> the electricity supply system to ***reliably meet consumer demand, including peak demand***, at any given time through a combination of ***generation capacity, demand-side flexibility, storage, and reserve margins.***

Network Adequacy:
Ensuring reliable supply by managing fuel and generation will not be the only qualifying criteria for a power system to be resource adequate. Network adequacy bridges the gap between generation and consumption by ensuring the continuous supply of electricity through power networks while ensuring the functioning of the power system during major outages.

Network adequacy is a combination of three other components: transmission adequacy, distribution adequacy and operations adequacy. Transmission adequacy deals with ensuring electricity supply to demand centres; distribution adequacy ensures electricity supply to the end users (Elering 2021); while operation adequacy ensures the ability of the power network to withstand contingencies.

Developing on the definition by (Yin Jie 2006) that defines network adequacy as 'a measure of its ability to supply the aggregate electric power and energy requirements of the customers within component ratings and voltage limits, taking into account planned and unplanned outages of system components', our framework defines network adequacy as:

> Network adequacy refers to the ability of the electricity transmission and distribution systems to reliably and efficiently transmit power from generation sources to end consumers, meeting demand and energy requirements in accordance with reliability and resilience standards.

Transmission Adequacy:
A critical aspect to maintaining network adequacy is the existence of an efficient network system that ensures the transfer of power from generation to consumption. Transmission is a bulk power transfer from generation to distribution substations. Transmission adequacy ensures the ability of a power grid to effectively transmit electricity to meet demand. This includes having the capacity to handle internal power flows and the flexibility to adjust for changes using connections to other grids and the ability to import or export power as needed.

Existing literature on transmission adequacy by (UCTE 2009) defines transmission adequacy as 'an assessment of the ability of a power system to manage the flow resulting from the location of both consumption and generation'. Based on the above definition, our definition defines transmission adequacy based on reliability and resilience in the following manner:

> Transmission adequacy is the ability of the transmission system to reliably and efficiently transfer power from generation sources to distribution interfaces, ensuring the system's flexibility, resilience, and reliability.

Distribution Adequacy:
The distribution networks at the substation level convert the high-voltage electricity received from the transmission networks into lower voltages for end-consumers. When the distribution networks are capable enough of receiving power from different mass generation sources as well as distributed energy sources without disrupting the steady flow of electricity, then they are adequate.

Therefore, the framework proposed distribution adequacy can be defined as:

> Distribution adequacy refers to the ability of the distribution network to reliably and efficiently deliver electricity from distribution interfaces to end consumers, while managing bidirectional power flows, ensuring resilience, and adapting to evolving demand patterns.

Operations Adequacy:

Operations adequacy, a component introduced with reference to the I-RAA Framework, ensures how secure and adequate a power system is to withstand contingencies. Power operations are required to respond quick enough to voltage fluctuations and maintain frequency levels across the grid. Operations adequacy also helps in assessing the ability of the grid to handle the real-time challenges of electricity supply and demand.

Our framework proposes the following definition:

> Operation adequacy refers to the ability to optimise and balance power between generation and demand in real-time, ensuring flexibility, reliability, and resilience, supported by seamless interoperability across system components.

Interoperability can be defined as the capability of systems to exchange and use information, enabling network communication in a seamless way (Ravi Kumar and Bakshi 2024).

Demand Assessment:
Demand for electricity is a driving force behind resource adequacy planning for load-serving entities. Accurate demand forecasts are crucial to ensure sufficient resources are available to meet future needs. When demand is expected to increase, additional generation resources or energy purchases become necessary. Two key demand types are considered in resource planning:

- **Annual Demand:** This refers to the total energy consumption (measured in Megawatt-hours or MWh) of a specific area over an entire year. Due to the influence of weather and seasonal patterns, annual demand is typically broken down by season. Understanding annual demand and its seasonal variations helps in strategically building a resource portfolio.

- **Peak Hour Demand:** This refers to the highest level of energy consumption (measured in Megawatts or MW) within a specific area during a single hour of the day or year. Identifying trends in peak hour demand helps planners anticipate changes that need to be factored into resource planning strategies.

Electricity demand assessment methods have been constantly evolving. Many utilities India were earlier exercising methods that used to extrapolate on past demand trends. However, with the advent of alternative supply-side and end-use technologies, impact of microeconomic and macroeconomic factors, demography and lifestyle changes, modelling techniques had to evolve to capture the effects of price, income, population, technology and other economic, demographic, policy, and technological variables (WEC India, n.d.).

Conventional demand assessment methodologies that used historical data, growth rates, assumptions, and scenarios to assess demand often outstripped the actual demand, leading to supply overhangs. Moreover, these methods often adopted assumptions based on roadmap figures than actual data and trends; the methodologies did not account for baseline correction that ought to factor in unserved demand to measure anomalies from baseline over years. Another drawback of such assessments was that they had forecast periodicity- a considerable time gap (5-10 years) that affects assumptions, baselines, and other such dynamic factors (WEC India, n.d.).

Demand assessment methods will have to account for non-linear relationships that may exist between dependent and independent variables; a combination of techniques that not only expresses latent demand but one that also includes sensitive parameters of weather, per capita income among other tail risks and seasonal factors that affect the baseline demand.

Demand assessment is the first and most crucial step of any resource adequacy and planning analysis. It involves the forecasting of peak (MWs) and energy (MUs) requirement for multiple horizons (short/medium/long-term) and considers various input parameters such as historical consumption, consumer categories, weather data, econometric data, policies, and drivers, etc (Forum of Regulators 2023).

The component of demand assessment in our framework undergoes another classification based on the temporal selection of the type of assessment. In the short-term, demand assessment is referred to as demand estimation whereas in the medium and long-term, the process is referred to as demand projection. This classification is useful even for traditional planning process that would help separate production-cost planning from capacity-expansion.

Demand-side resources play a crucial role in achieving balance and flexibility within the proposed I-RAA Framework, particularly as electricity demand becomes more dynamic and variable energy resources are integrated into the grid especially in the short-run. Demand-side management (DSM) strategies, especially demand response (DR) programs, incentivise consumers to adjust their electricity usage during peak periods or in response to price signals. This flexibility helps maintain grid stability by reducing demand when supply is constrained, ultimately alleviating the need for costly new generation capacity (Albadi and El-Saadany 2008).

For example, during extreme weather events that lead to spikes in energy consumption, DR can enable large consumers—such as industrial facilities or commercial buildings—to lower their usage temporarily, thus supporting the overall balance of the grid. Moreover, DSM not only enhances operational efficiency but also contributes to cost savings for both utilities and consumers by avoiding the need for additional infrastructure investments. By optimising both supply and demand through these flexible resources, the energy system can become more resilient and responsive to fluctuations, ensuring reliability in an increasingly complex energy landscape.

Another important strategy in addition to DSM is that of energy efficiency. Energy efficiency initiatives contribute further by promoting long-term reductions in energy consumption through improved technologies and practices, allowing consumers to achieve the same output with less energy (Morales-España, Martínez-Gordón, and Sijm 2022).

Our framework, hence, defines demand assessment as:

> Demand assessment is achieved through a hybrid approach that combines short-term estimations and long-term forecasting. This process utilises baseline corrections from historical demand data, assumptions from actual trends, and includes seasonal variations, while incorporating technological advancements (efficiencies), and distributed energy resources.

This section is a prelude to the next chapter that explains in detail the metrics that define the components of the framework discussed

here. While the current chapter deals with the theoretical taxonomy of these components, the next chapter sets the scene on how the metrics of different components measure the risk, their magnitude and the degree of resource availability or contribution that can potentially ensure reliability of the components and adequacy of the framework. The chapter also discusses how the metrics also factor in resilience at different levels of the supply chain.

2.4 COMPONENT INTEGRATION

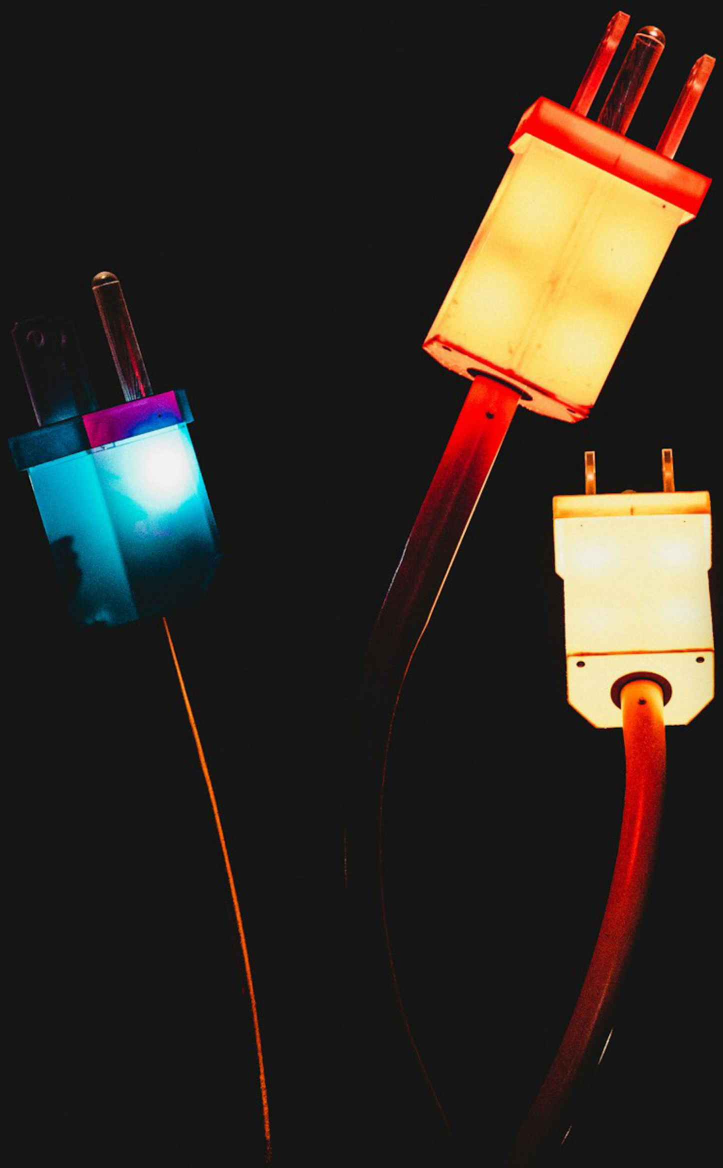
The primary objective of the I-RAA Framework is to establish a standardised assessment process across components of supply chain and integrate them into resource adequacy planning at different spatio-temporal granularities. The framework is designed in such a manner that it can be incorporated at any level of planning — be it at the central or regional level, or at any part of the vertical supply chain. This feature enables power system planners to undertake either a top-down or a bottom-up approach based on their country/regional requirements. Ultimately, the planning stage in accordance with the framework is smoothly integrated with the rest of the components to ensure flow and reduce redundancies.

In the proposed Integrated Resource Adequacy Assessment (I-RAA) Framework, Fuel Adequacy, Generation Adequacy, and Network Adequacy are intricately interconnected, each playing a vital role in ensuring a reliable and resilient power system. As defined earlier, fuel adequacy refers to the continued availability of necessary primary, secondary, and alternative fuel supplies to generate electricity, which directly impacts reserves and ancillary services. For example, during extreme weather events, such as storms or heatwaves, fuel supply chains may be disrupted, leading to shortages that affect firm generation and variable renewable capacity. The I-RAA Framework ensures contingency planning for such fuel disruptions, providing utilities the strategies to secure alternative fuel sources or enhance storage capabilities to maintain operational stability.
Generation adequacy is influenced by fuel adequacy since the type and reliability of fuel sources determine how effectively power plants can operate. For instance, during a cold snap that increases heating demand, natural gas plants may face supply constraints if gas pipelines are compromised. Countries like India currently has simultaneous heating and cooling demands in the face of geographical variation and seasonal diversity along with climate change, making cooling and heating requirement inevitable. The need for a diverse generation mix that includes renewable energy sources, which can mitigate reliance on fossil fuels but also require careful consideration of their intermittency is ensured through fuel adequacy by effectively planning for supply constraints.

Network adequacy encompasses the infrastructure required to transport electricity from generation sites to consumers. The planning of different adequacy components described so far have been taking place in silos, and this framework suggests integrating the processes to ensure effective resource adequacy planning. The very idea of network adequacy is to ensure the ability of the power grid and its transferability based on the real-time demand and generation that is fluctuating with the variable renewable resources. Complementing the above framework components are reliability and resilience standards. While the former is a single standard that runs through the framework ensuring the adequate requirement of the parameters fulfilling the adequate criteria, the latter ensures grid resilience in the face of system impact because of extreme impact events.

For electricity supply to become more effective, a holistic design that priorities component flow is needed to manage supply in the long run while simultaneously ensuring stakeholder engagement throughout the supply chain. The I-RAA framework accounts for these interdependencies. This comprehensive strategy not only enhances reliability but also supports long-term sustainability goals by promoting a balanced energy mix and efficient infrastructure development.

3.
Resource Adequacy Metrics



3. RESOURCE ADEQUACY METRICS

As discussed in Chapter 2, the I-RAA framework in general is a progressive exercise that harmonises the components of the demand and supply-side resources to achieve adequacy at every spatio-temporal level. The metrics used across these components will have to be worthy of defining the risk, measuring the magnitude, and expressing capability of a resource.

The following section will brief on the traditional metrics used to measure resource adequacy followed by metric measurements of other components defined in our framework.

Highlights

- *This chapter provides a comprehensive exploration of the metrics used to assess resource adequacy within the I-RAA framework.*
- *Then metrics are mapped by components that define the level of risk/reliability that can be assessed at each level. This includes traditional RA metrics (mostly generation) as well as other metrics of the I-RAA framework.*
- *The chapter also compiles a demand assessment metric/methodology framework for short and long term.*
- *In addition, resilience standards are introduced into the framework, providing a deeper understanding into the power system's ability to withstand extreme events.*

3.1 TRADITIONAL RESOURCE ADEQUACY METRICS

Resource adequacy is a mechanism that aims to ensure reliable and flexible supply to match any given level of flexible and inflexible demand at a certain period. To ensure a resource adequate power system, planners must be able to project the overall demand for a given time horizon and to the peak demand fluctuations happening on a regular basis (EPRI 2022a). Resource adequacy assessments in general should be capable of measuring the following:

- The frequency of load events, i.e., the number of events where the demand exceeds supply.
- The duration and/or magnitude of load events.
- Identifying the volume of resource or capacity to counter the load and maintain system balance, and their degree of efficiency.

Initial resource adequacy metrics in 1950s only used approximations to focus mainly on methods of accounting for the joint probabilities of combinations of unit outages (EPRI, n.d.).
Given the level of computing power and the wide use of traditional energy sources at that time,

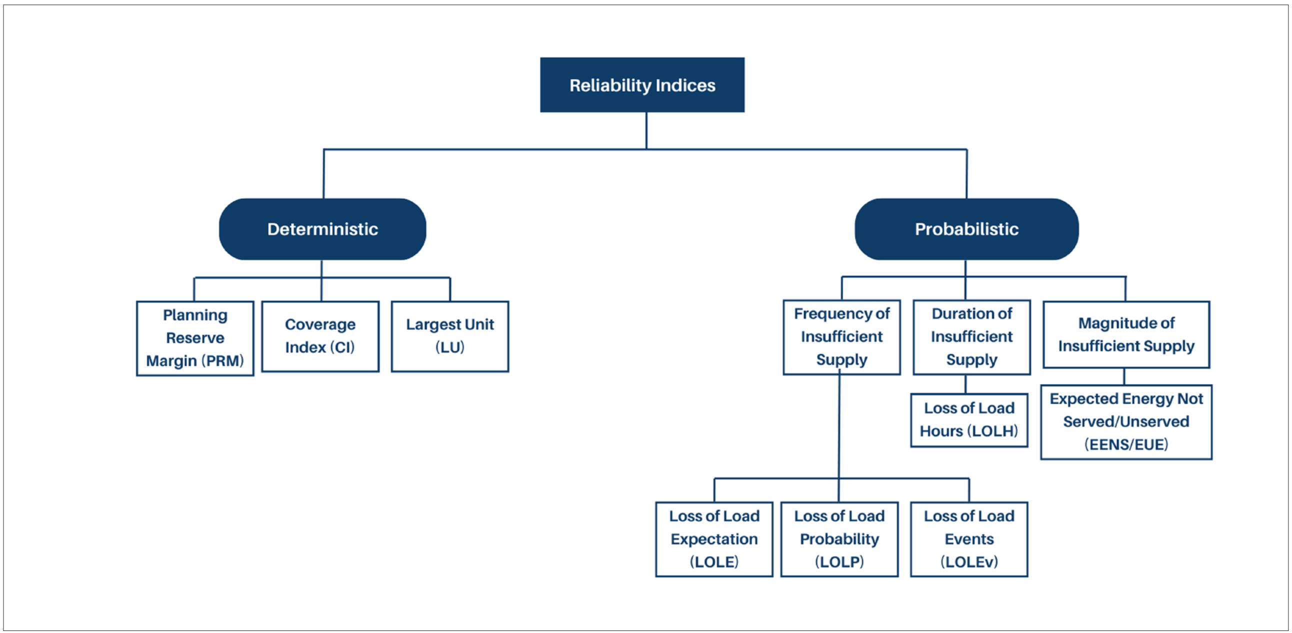


Figure 5: Traditional Resource Adequacy 'Reliability' Indices, Source: (EPRI 2022b)

these approximation methods were considered ample enough. With emerging technologies and the rise of non-despatchable resources, and with increase in computational power, new probabilistic assessment methods have evolved that involves a combination of different metrics to address the needs arising out of different situations (Mijolla et al. 2022b).

Some of the least covered deterministic indices include the coverage index (CI); the ratio between installed generation capacity and peak load, and largest unit (LU); a comparison of the difference between the available capacity and demand with the largest unit on the system (EPRI 2022b).

Metrics can capture differing aspects of the adequacy of a system. Certain metrics can capture information on system risk and magnitude, while others can inform on resource contribution.

Risk Assessment:
This assessment analyses the risk of a load event happening; it predicts the frequency and the probability of the load event happening. It is useful to study the load threshold to plan for reserves and supply in advance (EPRI, n.d.). Also, risk does not mean a shortfall will indeed occur, but that emergency measures may need to be used to mitigate or eliminate a potential shortfall (Carvallo et al. 2023).

Magnitude Metrics:
Measures the duration of an outage and its magnitude relative to the duration. Magnitude is often included as a metric under risk assessment.

Resource Contribution:
Resource contribution assessment is important to understand the share of contribution of different capacity resources in ensuring reliable supply. This helps in planning for future demand and load events while also helping understand the level of resource that needs to be added to restore existing load or outage event.

In addition to measuring the risk and resource contribution, resource adequacy assessments also include metrics that study the degree of availability of different power sources to meet the resource adequacy requirements, also known as capacity credit (CC). Capacity credit, usually expressed as a percentage relative to a resource's nameplate capacity, is an important metric widely used for resource planning and resource adequacy assessments. It quantifies the percentage capacity contribution of a specific resource to overall system adequacy relative to its nameplate capacity (Jorgenson et al. 2021).

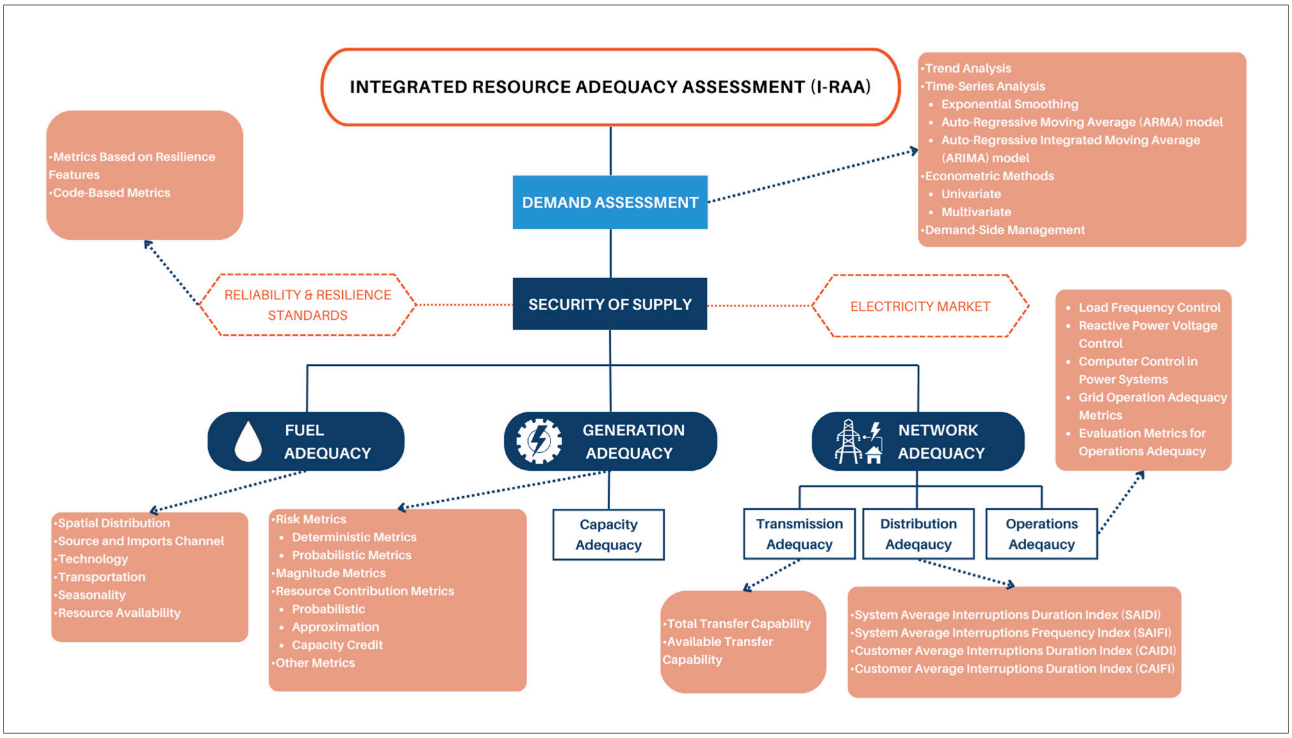


Figure 6: Integrated Resource Adequacy Framework (I-RAA) Framework – Adequacy Metrics, Source: Authors

3.2 RESOURCE ADEQUACY IN I-RAA FRAMEWORK

Traditional resource adequacy metrics only measure the risk to the generative capacities and the ability of a resource to contribute to improve capacity. Our framework rather considers these metrics to be a part of generation adequacy wherein the metrics are mapped according to the reliability standard that measures either of risk, magnitude, or resource contribution. Other metrics belonging to components of network adequacy, fuel adequacy, demand assessment and resilience are measured based on a diverse set of factors.

The metrics of fuel adequacy, for instance, are not metrics per se but the attributes that determine the availability of the respective fuel source. The network adequacy metrics on the other hand are a combination of transmission adequacy, distribution adequacy and operation adequacy metrics that operate with respect to transfer capability & limits, customer interruptions and area control error respectively. Demand assessment is further classified by short-term and long-term measurement techniques that are discussed in detail. The resilience metrics explain the need for resilience in power system, the difference between reliability and resilience, and the features of a resilient power system. This is followed by the metrics based on these resilience features, code-based metrics, resilience evaluation criteria and resilience enhancement methods that will explain in detail the different phases of power system performance during extreme events and the degree of restoration based on the level of planning and system operations.

Then how does the framework capture resource adequacy? On establishing the metric standard for every component (risk, magnitude, or resource contribution), the inputs will have to match the sufficiency criteria marked for a metric of a component. For the framework to be resource adequate, each of the risk/magnitude/resource contribution metrics within a component and across components will have to match to achieve a resource adequate power system. For instance, a risk metric of loss of load expectation (LOLE) standard of 0.1 day-in-a-year (translating to one-day-in-ten-year standard) can be affected by the resource contribution metric of effective load carrying capability (ELCC), defined as the amount by which the system's load can increase when the resource is added to the system while maintaining the same loss-of-load standard (EPRI, n.d.), and/or due to the forced outage of one or more transmission lines. Achieving reliability in this case would be to ensure the addition of a resource matching the load carrying capability to 0.1 day-in-a-year loss-of-load standard and improving the total transfer capability of the transmission line to reduce the outage rate. Similarly, other magnitude or resource contribution metrics of other components will have to match each other, resulting in a resource adequate power system.

3.2.1 FUEL ADEQUACY METRICS

A key element that serves vital to power generation is the primary source of fuel that is required to generate heat or kinetic energy that is then converted to mechanical energy using turbines and then into electricity using electromagnetic induction through generators. Fuel adequacy, as defined in the previous chapter, deals with the continued availability and provision of primary fuels if all means of transport, transformation and conversion exist to get the energy flux from the producer to the consumer. Traditional and renewable methods of power generation require consistency in resource supply to always ensure availability of the primary fuel to meet the growing power demand. Measuring fuel needs would require assessment techniques to internalise the factors that affect the level and type of fuel availability- including the transportation, sourcing and import channels, spatial distribution, technology to extract and clean, and seasonality. Theoretically, the availability and the factors that affect availability cannot be expressed as metrics that measure their proportion for two reasons: one being the fact that the strategy required to achieve fuel adequacy is localised/subjective to the entity performing the assessment; and the two being that this would be beyond the scope of theory involving modelling side assessment techniques that measure the treatment of such factors. Hence, this section limits itself in ascribing to the attributes of fuel adequacy.

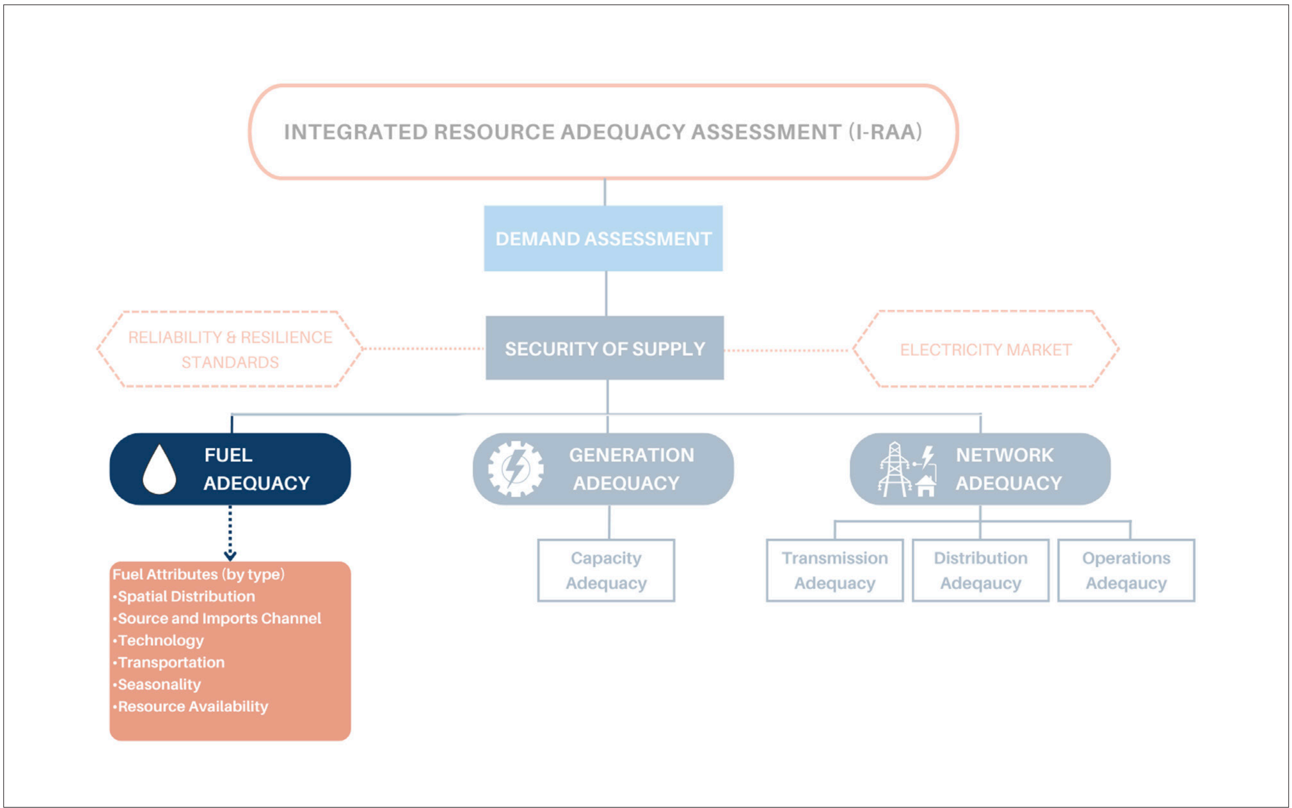


Figure 7: Integrated Resource Adequacy Framework (I-RAA) – Fuel Adequacy, Source: Authors

As the power system transitions towards cleaner energy sources with a growing reliance on variable renewable generation (VRE) like wind and solar, traditional resource adequacy metrics will have to be revaluated to account for the impact of weather events, since they affect fuel procurement, transportation prior to the process of power generation and the transmission and distribution infrastructure upon power generation. As for resource adequacy planning involving traditional power generation, the metrics only ensured sufficient despatchable generation capacity available to meet demand. However, in case of VRE, the output fluctuates relative to the weather, thus introducing a new veil of uncertainty into the equation. In addition to ensuring despatchable generation, fuel adequacy metrics will have to consider the tail risks associated with weather patterns on both traditional and renewable power generation (Mauch, Millar, and Dorris 2022).

3.2.1.1 ATTRIBUTES OF FUEL ADEQUACY

Fuel adequacy attributes help capture the level of primary fuel required for power generation and their consistency supplying the desired amount. Estimating availability of fuel is primarily subjective to the reserves or storage of a particular fuel source. This availability can be further endogenous of different variables of varied proportions of different fuel sources. For instance, the availability of water for hydro power generation might be interrupted during winter, posing difficulty to transport them across turbines respectively. Similarly, the availability of coal stock can be affected by rainfall or monsoonal factors that might restrict the movement of coal to the power station. Weather fluctuations can largely affect the harnessing of wind and solar energy and cause supply variability. Hence, the energy or fuel adequacy in our framework is measured through the attributes that affect their availability (Mauch, Millar, and Dorris 2022). Some of the attributes are described below:

Spatial Distribution:
This refers to the variation in the type of fuel resources available in each landscape or region and their volume. The spatial distribution also measures the different factors that influence the spatial distribution like geology, topography, vegetation, climate, and human activity.

Source and imports channel:
Source and imports channel of fuel focuses on the variety of ways a region or country obtains its fuel, rather than where the fuel itself is located geographically. Source diversity refers to the mix of different fuel types a region or country uses, offering energy security and reliability of fuel supply. Imports channel diversity looks at the various ways a region or country acquires fuel from external sources through imports, long-term contracts or spot market purchases and diversification of transportation channels through pipelines or maritime mode.

Technology:
Technology refers to the range of technologies used to extract, process, and utilise different fuel sources. It goes beyond simply having a variety of fuels themselves. Different fuel sources require specific methods from extraction though utilisation. For instance, oil and gas rely on drilling and pumping techniques, while coal is extracted through mining. Once extracted, fuel like crude oil needs refining into products like gasoline and diesel whereas biomass can be converted into biofuels through processes like gasification or fermentation. Once converted, power generation of these fuels depend on a variety of technologies like coal-fired plants, natural gas or biofuel fired plants. In case of renewables, the solar irradiance converted to electrical energy can be utilised for power generation (De Rosa et al. 2022).

Transportation:
The availability of transportation to move the primary resource from the site of extraction to the site of electricity generation. This is primal for all the other attributes since proximity to the source of fuel extraction can determine the availability and continued provision of the resource.

Seasonality:
Seasonality and weather changes coupled with other stochastic factors can invariably affect the

availability of variable renewable sources such as solar, wind, etc., and the procurement and transportation of traditional sources of fuel such as coal, natural gas etc.

Resource Availability:
The attribute or the metric that measures the level of availability of a resource in meeting the supply requirements. The availability is subjective of the fuel source and is invariably affected by the above attributes.

These attributes will be the defining characteristics of the fuel sources and their availability in our framework. The factors and their treatment will be subjective to the type of fuel.

3.2.1.2 ATTRIBUTES BY DIFFERENT SOURCES OF FUEL

Attribute	Spatial Distribution	Source & Imports Channel	Technology	Transportation	Seasonality	Resource Availability
Traditional Power Generation						
Coal	Low - Concentrated deposits	Limited - Domestic mining or import via ship/rail	Limited - Primarily conventional coal plants	Rail, ship, or conveyor belts (high cost)	Minimal impact	Normative Availability
Natural Gas	Moderate - Can be found onshore or offshore	High - Imports via pipeline or LNG terminals	Moderate - Varied technologies for LNG, pipelines, and storage	Pipelines or LNG terminals (moderate cost)	Minimal impact	Proved reserves
Hydropower	High - Varies based on river flow and geography	Limited - Depends on river location	Moderate - Dams, turbines, and potential for pumped storage	Minimal - Water flow within the system	Varies - River flow can be lower in dry seasons	Normative Capacity Index
Nuclear	N/A	N/A (fuel source is uranium)	High - Different reactor designs and fuel cycles	N/A (fuel is enriched uranium)	N/A	Reasonable Assured Reserves
Renewable Power Generation						
Solar	High - Sunlight available globally	N/A (no fuel import)	High - Different panel technologies and tracking systems	Minimal - Transmission lines	Varies - Sunlight intensity changes with seasons	Solar irradiance, solar constant, solar window, solar spectrum, solar insolation, and direct and diffuse radiation
Wind	High - Wind patterns vary geographically	N/A (no fuel import)	High - Different turbine designs for various wind conditions	Minimal - Transmission lines	High - Wind patterns can vary seasonally	Short-term: Realisable potential Long-term: Realistic potential
Geothermal	Moderate - Geologically limited locations	Limited - Geologically specific locations	Limited - Technology for harnessing geothermal energy	Minimal - Transmission lines	Minimal impact	Conversion efficiency ratio

Attribute	Spatial Distribution	Source & Imports Channel	Technology	Transportation	Seasonality	Resource Availability
Biomass	Moderate - Varies depending on feedstock source	Moderate - Varies depending on feedstock source	Moderate - Conversion technologies based on feedstock type	Transportation required for feedstock (varies)	Varies depending on feedstock source (e.g., wood availability)	Implementation potential
Pumped Hydropower	N/A	N/A	High - Pumped storage requires advanced pumping and generation systems	N/A (uses existing hydropower infrastructure)	N/A	

Table 1: Attributes by Different Types of Fuel, Source: Author compiled

3.2.1.3 TRADITIONAL POWER GENERATION

THERMAL POWER GENERATION

In traditional thermal power generation, fuel sources of coal or natural gas use the heat energy from combustion of these resources to boil water and transfer the steam through turbines that convert the thermal energy of the steam into mechanical energy, which is then captured by generators that use electromagnetic induction to convert them to electrical energy. Before the integration of renewable energy sources into the resource-mix, fuel availability was key to ensure adequate supply to meet demand (Kansai Electric Power, n.d.).

Coal based thermal power generation

- **Spatial Distribution:** Low, since coal deposits are concentrated in specific geographic regions. This can lead to reliance on long-distance transportation and potential supply chain disruptions.

- **Source & Imports Channel:** Limited since coal can be mined domestically if reserves are available. Otherwise, it needs to be imported via ships or rail, which can be expensive and vulnerable to geopolitical issues.

- **Technology:** Limited, since it primarily relies on conventional coal-fired power plants with established technology. Some advancements exist in clean coal technologies (under development) to capture emissions.

- **Transportation of Fuel:** High cost - Coal needs to be transported by rail, ship, or conveyor belts over long distances, adding significantly to the overall cost of electricity generation.

- **Seasonality:** Minimal impact - Coal does not experience significant seasonal variations in availability or production, although the transportation can be affected by extreme weather events like rain, snow, etc.

- **Availability:** Normative Availability is the generative ability of the seller that equals to the guaranteed minimum offtake for a certain share of the contracted capacity by the buyer over a given period (CERC, n.d.).

> Normative Availability is the generative ability of the seller that equals to the guaranteed minimum offtake for a certain share of the contracted capacity by the buyer over a given period.

When the seller falls short beyond a regulated range of normative availability, the same gets reduced in the capacity charge for the buyer. In case of a fuel shortage induced reduction in normative availability under a two-part-tariff regime, the same gets reduced from the energy charge in addition to the capacity charge (CERC 2022).

Coal Grade

Coal grade is an economic or technological classification of the relative quality of a coal for a particular use. A variety of grades of coal are defined for different uses or markets in different industries and countries, and for the needs of a particular process or by regulations concerning the process or end-use product. The terms are process- or product-specific. For example, a coal which can be used to generate steam for electricity, may not be a high-grade coal for metallurgical uses. Terms such as low-ash or low-sulphur are also examples of grade terms. Different quality grades are used in different coal markets (Kentucky Geological Survey, n.d.).

- **Steam Coal:** Steam Coal: Steam coal, as the name describes, refers to the grade of coal used in power plants that generates steam to create electricity. These coals are usually tested for heating and other quality characteristics based on the design of the boiler and the pollution-control equipment at power plants.

- **Metallurgical Coal:** Metallurgical coal, also known as met coal or coking coal, is a certain type of coal primarily used in the production of coke, a crucial raw material for steel making. Only certain coal types with particular quality characteristics are suitable for this purpose. For the coal to be classified as metallurgical grade, it must have very low levels of ash (typically less than 10 percent) and sulphur (less than 1 percent), as well as a volatile matter content between 20 and 30 percent, which corresponds to medium- to high-volatile bituminous rank. Moreover, the coal must possess an appropriate balance of reactive and inert components. In the coking industry, grade terms such as low-ash, low-sulphur, and low-volatile are commonly used to describe coals that meet these stringent requirements.

- **Chemical and Specialty Coal:** Some types of coal are suitable for producing chemicals and specialty products. These chemical and specialty coals must adhere to specifications to the particular product or chemical process in which they will be used. The required standards may involve ash and sulphur content, similar to those for steam and metallurgical coals, but can also relate to mechanical properties or detailed aspects of chemical composition. (Kentucky Geological Survey, n.d.).

NATURAL GAS BASED POWER GENERATION

- **Spatial Distribution:** Moderate - Natural gas can be found onshore or offshore, with varying degrees of accessibility.

- **Source & Imports Channel:** High - Countries can rely on domestic production via pipelines or import natural gas as Liquefied Natural Gas (LNG) through specialised terminals. This offers more flexibility compared to coal and oil but still involves potential price fluctuations and geopolitical considerations.

- **Technology:** Moderate - Requires a mix of technologies for extraction (onshore vs. offshore), transportation (pipelines vs. LNG), and storage facilities.

- **Transportation of Fuel:** Moderate cost - Pipelines offer a more cost-effective transport option compared to ships for LNG. However, infrastructure development and maintenance can be expensive.

- **Seasonality:** Minimal impact - Natural gas availability and production do not have significant seasonal variations, except transportation during extreme winter seasons.

- **Availability:** The availability of natural gas is determined by the proved reserve levels. Proved reserves are defined as 'The estimated quantities that geological and engineering information indicates with reasonable certainty can be recovered in the future from known reservoirs under existing and economic operating conditions' (Lako and Kets 2005).

HYDROPOWER GENERATION

In case of hydro power plants, water from dam or reservoir is released through channels into hydroelectric turbines that convert the potential energy of the water into mechanical energy. Like thermal power plants, generator connected to the turbine shaft converts the mechanical energy to electrical energy (US Energy Information Agency 2023).

- **Spatial Distribution:** High - Varies significantly based on river flow and geography. Suitable locations with sufficient water flow are limited and can be geographically concentrated.

- **Source & Imports Channel:** Limited - Reliant on the location of rivers and dams within a country's borders. Limited potential for import/export of hydropower electricity.

- **Technology:** Moderate - Relies on dams, turbines, and generation infrastructure. Potential for pumped storage technology to store excess energy for later use.

- **Transportation of Fuel:** Minimal or no cost - Hydropower plants do not incur fuel procurement costs. Unlike thermal power plants that require continual purchases of coal, gas, or biomass as fuel, hydropower plants use water as their energy source, which is generally available at no direct cost.

- **Seasonality:** Varies - River flow can be lower during dry seasons, impacting electricity generation capacity.
- **Availability:** The normative capacity index of a power plant is the capacity index of that power plant whose maximum availability capacity depend on values of purely run-of-the-river hydro stations and/or pondage/storage-type hydro generating stations (CERC 2004).

Like thermal generation, the normative capacity index is used to measure the fuel adequacy in hydro power generation (CERC, n.d.). Here, the capacity of the power plant to generate to its full potential is more important than its availability factor since water shortages or other normative factors restrict the plant to operate at maximum capacity.

Capacity index of a power plant refers to the ratio of Declared Capacity (MW) to the Maximum Available Capacity (MW) (CERC 2008).

Declared Capacity for any day is the maximum MW (ex- bus) which the generating station can generate, as declared by the generating company, considering the head and the availability of water and availability of machines on that day. The maximum available capacity in MW (ex-bus) is the maximum MW which the hydro-electric generating station could have generated had all its installed units been available, under the prevailing conditions of head and the availability of water (CERC 2008). As per CERC the normative capacity index is as defined below (CERC 2004).

> The normative capacity index of a power plant is the capacity index of that power plant whose maximum availability capacity depend on values of purely run-of-the-river hydro stations and/or pondage/storage-type hydro generating stations.

The capacity charge levied on the buyer would reduce when the available capacity reduces to that of the declared capacity.

NUCLEAR POWER GENERATION

Nuclear power plants utilise the principle of controlled nuclear fission to generate electricity. Within the reactor core, enriched uranium fuel undergoes a fission reaction when struck by neutrons. This fission process releases a significant amount of thermal energy. The heat generated from nuclear fission is used to convert water into pressurised steam within the reactor's closed-loop steam system. This high-pressure steam is then channelled through turbines, causing them to rotate. The rotating turbines are coupled to electrical generators, where the mechanical energy is converted into electricity through the principles of electromagnetic induction (US Energy Information Administration, n.d.).

The core of a nuclear reactor houses fuel assemblies containing numerous fuel rods. These fuel rods consist of ceramic pellets fabricated from enriched uranium ore. Each pellet generates a substantial amount of energy, comparable to the energy content of approximately 150 gallons of oil (US Energy Information Administration, n.d.).

- **Spatial Distribution:** Not Applicable - Nuclear power plants do not rely on a specific fuel source geographically. However, safety regulations and public perception can limit the number of locations suitable for nuclear plants.

- **Source & Imports Channel:** Not Applicable - Nuclear power does not require a continuous fuel source. Enriched uranium fuel is used, and the supply chain can be complex, involving international trade and regulations.

- **Technology:** High- Different reactor designs and fuel cycles are available, each with varying levels of efficiency and waste management approaches.

- **Transportation of Fuel:** Not Applicable - Nuclear power plants have relatively low fuel costs compared to their total operating expenses, with the majority of costs stemming from capital investment rather than fuel procurement.

- **Seasonality:** Not Applicable - Nuclear power plants are not affected by seasonal variations, except for force majeure events.

- **Availability:** The availability of nuclear power is determined by the Reasonably Assured Reserves (RAR). These 'proved' reserves have a high assurance of existence. These reserves are defined in terms of uranium recoverable from mineable ore, allowing for mining and processing losses. Resource estimates are expressed in terms of tonnes of recoverable uranium (Lako and Kets 2005).

Small Modular Reactors (SMRs)

Small Modular Reactors (SMRs) are advanced nuclear fission reactors with a power capacity of up to 300 megawatts electric (MWe) per unit, significantly about one-third of the generating capacity of traditional nuclear power reactors.

SMRs produce a large amount of low-carbon electricity. They are modular in design, meaning that it allows for factory assembly of major components, which can then be transported to the installation site as a unit for rapid deployment and scalability. SMRs operate on the same fundamental principle as conventional reactors wherein the nuclear fission of fuel (typically uranium) is used to generate heat, which is in turn used to produce steam and drive turbines for electricity generation.

Fuel procurement for SMRs generally follows established nuclear practices. Most SMRs are designed to use low-enriched uranium (LEU), similar to that used in large light water reactors. Some advanced SMR designs may require high-assay low-enriched uranium (HALEU) or alternative fuels such as mixed oxide (MOX) or thorium-based fuels, depending on the reactor type. The modular and standardised nature of SMRs facilitates streamlined fuel logistics, as fuel assemblies can be manufactured in specialised facilities and delivered as needed to the reactor site. As SMR deployment increases, expansion of enrichment and fuel fabrication capacities—especially for advanced fuels—will be necessary to ensure consistent fuel availability for diverse SMR technologies (Liou 2023).

3.2.1.4 RENEWABLE POWER GENERATION

SOLAR POWER GENERATION

Solar energy is vast and ubiquitous, they can be harnessed in any place that receives sunlight. Every hour, the Earth's surface receives an amount of solar insolation exceeding total global energy consumption annually. However, numerable factors like geography, time of day, and weather conditions, all affect the volume of energy that can be harnessed for electricity production or heating (Center for Climate and Energy Solutions 2020).

Solar energy can be harnessed for electricity generation through two primary methods:

a. **Photovoltaics (PV):** These systems utilise solar cells that convert sunlight directly into electricity via the photoelectric effect. PV installations are commonly found on rooftops of residential and commercial buildings.

b. **Concentrating Solar Power (CSP):** In CSP plants, lenses or mirrors concentrate sunlight into an intense beam, heating a fluid that generates steam to drive a turbine and produce electricity. Compared to residential or commercial PV, CSP projects are larger-scale and often owned and operated by electric utilities (Center for Climate and Energy Solutions 2020).

While utility-scale CSP plants predated the widespread commercialisation of photovoltaics, the latter technology's cost reductions have led to its dominance in the solar electricity market.

Solar photovoltaics are the fastest growing electricity source producing almost 5.53% of the world's electricity as of 2023 (Ritchie, Rosado, and Roser 2023a). Latest available data on global solar capacity addition as recent as 2022 shows an addition of around 191.52GW, bringing the total to about 1053.12GW (Ritchie, Rosado, and Roser 2023c).

For solar photo-voltaic (PV) plants, measuring the standard test conditions to measure their solar irradiance efficiency becomes crucial. Using further limits on the power supplied by the Sun to the electricity produced, the efficiency of a PV module is calculated (Navitassolar, n.d.).

- ◇ **Spatial Distribution:** High - Sunlight is available globally, but the intensity varies depending on latitude, weather patterns, and daylight hours. Areas with higher solar irradiance are more suitable for large-scale solar power generation.

◇ **Source & Imports Channel:** Not Applicable- Solar energy is harnessed locally through solar panels or concentrated solar power plants. No fuel import or export is involved.

◇ **Technology:** High - Different photovoltaic (PV) panel technologies exist (e.g., monocrystalline, polycrystalline, thin-film) with varying efficiencies and costs. Tracking systems can be integrated to maximise sunlight capture.

◇ **Transportation of Fuel:** Minimal or no cost - Solar power generation does not require any fuel procurement, as sunlight is free and abundantly available.

◇ **Seasonality:** Varies - Sunlight intensity changes with seasons. In some regions, solar power generation can be significantly lower during winter months.

◇ **Availability:** The availability of solar power is determined by the level of solar irradiance, solar constant, solar window, solar spectrum, solar insolation, and direct and diffuse radiation (Jayakumar 2009).

Solar power generation relies on several key principles that determine the amount of energy captured and converted into electricity. Here's a breakdown of these principles:

a. **Solar Irradiance:** This refers to the amount of solar radiation (light and heat energy) striking a surface per unit area over a specific time. It is typically measured in Watts per square metre (W/m^2) and is the fundamental measure of solar energy available for capture.

b. **Solar Constant:** This is the average irradiance received on a surface perpendicular to the incoming rays outside the Earth's atmosphere. It is a theoretical value of approximately 1361 W/m^2 and serves as a reference point for understanding variations in solar irradiance reaching Earth's surface.

c. **Solar Window:** This is the usable portion of the electromagnetic spectrum from the sun that can be efficiently converted into electricity by solar photovoltaic (PV) cells. It typically ranges from about 300 to 1100 nanometre (nm) and encompasses visible light and some infrared and ultraviolet wavelengths.

d. **Solar Spectrum:** This refers to the entire distribution of electromagnetic radiation emitted by the sun. It includes a wide range of wavelengths, from ultraviolet to infrared, with varying intensities. Only a portion of this spectrum falls within the solar window and can be effectively utilised for solar power generation.

e. **Solar Insolation:** This term describes the total amount of solar radiation received over a specific period on a tilted surface at a particular location. It is influenced by factors like solar irradiance, geographical location (latitude), time of day, season, and tilt angle of the solar panels. Solar insolation data is crucial for designing efficient solar power systems.

f. **Direct Radiation:** This is the sunlight that reaches the Earth's surface directly from the sun, without being scattered or absorbed by the atmosphere. It typically has the highest intensity and is the most valuable component for solar power generation.

g. **Diffuse Radiation:** This is sunlight that has been scattered or reflected by atmospheric components like clouds, dust, and water vapor. It has a lower intensity compared to direct radiation but still contributes to overall solar insolation (Jayakumar 2009).

WIND POWER GENERATION

The level of wind energy remains a primary energy source to achieve fuel adequacy in a wind farm. Wind turbines work by converting the kinetic energy in the wind first into rotational kinetic energy in the turbine and then electrical energy that can be supplied. The energy available for conversion mainly depends on the wind speed and the swept area of the turbine (Sarkar and Kumar Behera 2012).

The global share of wind energy in electricity production grew from 7.3% in 2022 to 7.8% in 2023 (Ritchie, Rosado, and Roser 2023b). As of 2022, the global wind energy capacity addition amounted for 74.65GW, increasing the total installed wind energy capacity to 898.82GW (Ritchie, Rosado, and Roser 2023d).

Wind farm capacity reflects the maximum electricity generation possible under ideal wind conditions. However, wind's variable nature means actual production often falls below capacity. Though wind energy has been harnessed for centuries, modern turbines represent a significant leap forward technologically, even compared to those of just a decade ago. While wind power generation boasts the advantage of zero greenhouse gas emissions, wind farms necessitate vast areas of land due to the need for numerous, widely spaced turbines (Center for Climate and Energy Solutions 2020).

The amount of electricity produced from wind plants depends on three factors:

a. **Wind Speed:** The power available from the wind is a function of the cube of the wind speed. Therefore, if the wind blows at twice the speed, its energy content will increase eight-fold. Turbines at a site where the wind speed averages 8 m/s produce around 75-100% more electricity than those where the average wind speed is 6 m/s.

b. **Wind Turbine Availability:** This is the capability to operate when the wind is blowing, i.e. when the wind turbine is not undergoing maintenance. This is typically 98% or above for modern machines.

c. **Wind Turbine Arrangement:** Wind farms are laid out so that one turbine does not take the wind away from another. However other factors such as environmental considerations, visibility and grid connection requirements often take precedence over the optimum wind capture layout (Sarkar and Kumar Behera 2012).

Fuel Attributes of Wind Energy

- **Spatial Distribution:** High - Wind patterns vary geographically; strong and consistent winds are crucial for efficient wind power generation, limiting suitable locations.

- **Source & Imports Channel:** Not Applicable- Wind energy is harnessed locally through wind turbines. No fuel import or export is involved.

- **Technology:** High - Different wind turbine designs are available, suited for various wind speeds and environments (e.g., onshore vs. offshore). Technological advancements are improving turbine efficiency and blade size.

- **Transportation of Fuel:** Minimal or no cost - Wind power generation does not require fuel procurement in the conventional sense, as wind itself is a free renewable resource.

- **Seasonality:** High - Wind patterns can vary seasonally. Some regions might experience lower electricity generation during specific times of the year.
- **Availability:** The wind power availability can be defined in two-time horizons – short-term and long term. The realisable potential considers the extent to which a technology is constrained by lead times, maximum deployment, growth rates, etc., in the short-term. In the long-term, the realisable potential is theoretically equal to the realistic potential. The realistic potential then takes into account considerations of spatial planning, environmental impacts (e.g. bird casualties), public acceptance, etc, but not costs (Lako and Kets 2005).

The primary availability of wind energy can be assessed by its harnessing potential that can be categorised in the following manner:

a. **Theoretical Potential:** This represents the total kinetic energy available in the wind resource, considering all wind speeds across a given area. It's essentially the raw, unharnessed energy potential of the wind.

b. **Technical Potential:** This takes into account the efficiency of wind turbine technology to convert wind energy into electricity. It also acknowledges limitations imposed by unsuitable land areas, such as urban centres, where wind farm development wouldn't be practical.

c. **Realistic Potential:** This further refines the technical potential by incorporating real-world constraints like spatial planning considerations (e.g., designated conservation areas), potential environmental impacts (e.g., bird migration patterns), and public acceptance of wind farms in specific locations. Cost factors are not considered at this stage.

d. **Realisable Potential:** This is the most pragmatic assessment, factoring in all the limitations considered in the realistic potential, along with economic constraints like the cost of wind turbine technology, grid infrastructure development, and deployment timelines. This reflects the actual amount of wind energy that can be harnessed within a specific timeframe.

Metrics Measuring Wind Availability of Operating Projects

When assessing turbine availability, two primary calculation methods are employed: time-based and production-based availability.

Time-based Availability: This approach calculates availability as a ratio of two time durations: the total time the turbine is operational and the total project duration. While computationally simpler, it overlooks wind speed variations throughout the period. This can lead to underestimating the significance of availability during high-wind periods when energy production is maximised. The readily available data from operational wind projects makes time-based definitions easier to implement.

Time-based availability = Time available (in hours) / Total time in consideration (in hours)

Production-based Availability: This method provides a more nuanced picture of energy losses. It calculates availability as the ratio of actual energy produced to the ideal energy production based on wind speeds and site conditions. Production-based availability acknowledges that turbines may have lower availabilities during high winds due to increased production and loads, potentially leading to more faults and downtime. Additionally, it accounts for strategically scheduled maintenance during low-wind periods, allowing a turbine to generate more energy compared to one experiencing downtime during high-wind times, even if both have the same total down-hours. For this reason, project evaluations often consider production-based or energy-weighted availability.

Production-based availability = Energy produced (in kWh) / Energy potentially expected (in kWh)

However, calculating production-based availability presents greater challenges. It requires additional data and complex calculations to estimate the ideal energy production under hypothetical perfect operation. While more intricate to compute, production-based availability offers a clearer picture of turbine reliability and can deviate from time-based values by up to 2% depending on the specific definitions used.

As mentioned above, there exists two types of time-based availability:

Full-period Availability: This method calculates availability as the ratio of operational hours to the total period under consideration, typically a month or a year.

Full-period availability = Number of hours available / 8,760 hours/year

Wind-in-Limits Availability: In contrast, the WIL definition considers availability only during periods when wind speed and temperature fall within the turbine's operational limits. Additionally, it factors in grid and Balance of Plant (BoP) availability. This method provides a more nuanced picture of availability by focusing on periods when the turbine could have realistically generated power. However, it requires additional data points to assess grid and BoP availability, potentially complicating the calculation.

Wind-in-limits availability = Number of hours generating kW / Number of hours that the wind is between cut-in and cut-out

GEOTHERMAL POWER GENERATION

Traditionally, geothermal energy harnesses the Earth's natural heat, readily available near the surface in certain regions. This heat source is used for generating electricity and directly for applications like heating and cooking. Geothermal areas are typically found near tectonic plate boundaries, zones known for earthquakes and volcanoes. Historically, for centuries, people have utilised hot springs and geysers for bathing, cooking, and heating purposes (Center for Climate and Energy Solutions 2020).

Generating electricity through geothermal power typically involves drilling a well, reaching depths of one to two miles, to access rocks with temperatures ranging from 300 to 700°F. Water is pumped down this well, where the hot rocks reheat it. The heated water travels through natural cracks and rises as steam through a second well. This steam can then be used to spin a turbine for electricity generation or directly for heating and other purposes. Finding a suitable well might require drilling several possibilities, and the true extent of the geothermal resource can only be confirmed after drilling. Additionally, some water evaporates during the process, necessitating the addition of fresh water to maintain a continuous steam flow. Unlike intermittent renewable sources like wind and solar, geothermal offers the advantage of continuous electricity generation. However, there are minimal releases of carbon dioxide trapped underground during this process (Center for Climate and Energy Solutions 2020).
Enhanced geothermal systems, still under development, utilise advanced drilling and fluid injection techniques to increase the accessibility and expand the potential of geothermal resources (Office of Energy Efficiency & Renewable Energy, n.d.-a).

Fuel Attributes of Geothermal Energy

- **Spatial Distribution:** Limited - Geothermal resources are concentrated in specific geological locations with hot underground reservoirs.

- **Source & Imports Channel:** Limited - Reliant on geothermal power plants located near suitable geological features. No fuel import or export is involved.

- **Technology:** Limited - Relies on established technologies to extract geothermal heat and convert it to electricity. Some advancements are exploring enhanced geothermal systems to access deeper resources.

- **Transportation of Fuel:** Minimal or no cost - Geothermal plants harness heat directly from the earth's subsurface, which is a naturally occurring, on-site resource. As a result, there are no ongoing fuel procurement or transportation costs for geothermal power generation once the plant is operational.

- **Seasonality:** Minimal impact - Geothermal energy availability is not significantly affected by seasonal variations.

- **Availability:** The availability of geothermal power depends on the conversion efficiency of the power plant in converting the steam into electricity. The conversion efficiency is the ratio of net electric power generated (MWe) to the geothermal heat produced/ extracted from the reservoir (MWth) (Zarrouk and Moon 2014).

As for geothermal energy, the conversion efficiency ratio is important to understand the temperature and flow rate of geothermal source determine the power generation potential (Zarrouk and Moon 2014).

The conversion efficiency is the ratio of net electric power generated (MWe) to the geothermal heat produced/ extracted from the reservoir (MWth).

Geothermal power plants have lower efficiency relative to other thermal power plants, such as coal, natural gas, oil, and nuclear power stations.

BIOMASS (BIOFUEL)

Biomass, a diverse category of organic materials ranging from wood sources and agricultural residues to animal and human waste, serves multiple purposes. It can be used for facility heating, generating electricity directly, or even for combined heat and power applications (U.S. Department of Energy 2016).

Biomass conversion into electricity utilises various methods. The most common approach involves direct combustion of woody materials or agricultural waste. However, other techniques exist, including gasification, pyrolysis, and anaerobic digestion. Gasification heats biomass with limited oxygen, producing a usable synthesis gas. Pyrolysis rapidly heats biomass in an oxygen-free environment, yielding bio-oil. Finally, anaerobic digestion, where bacteria decompose organic matter without oxygen, produces renewable natural gas (U.S. Department of Energy 2016).

The choice of conversion method depends on the type of biomass. Woody materials like wood chips, pellets, and sawdust are typically combusted or gasified for electricity generation. Corn stover and wheat straw residues can be either baled for combustion or converted into gas using an anaerobic digester. Notably, very wet wastes like those from animals or humans are converted into medium-energy content gas through anaerobic digestion. Additionally, pyrolysis can transform most other types of biomasses into bio-oil, a usable fuel for boilers and furnaces (Center for Climate and Energy Solutions 2020).

Successful planning for a biomass energy system depends on three crucial aspects: resource assessment, planning, and procurement. The initial screening and feasibility analysis require a thorough identification of potential biomass sources and an estimation of the necessary fuel quantities. Ideally, a detailed assessment of potential suppliers' capabilities to produce and deliver fuel that meets the specific equipment requirements should be conducted. This in-depth process involves several steps:

a. **Determining the Load:** This involves assessing the amount of energy the system needs to provide.
b. **Identifying Potential Equipment Providers:** Researching manufacturers or vendors of biomass equipment is necessary.
c. **Collaborating with Vendors on Fuel Specifications:** Working with these vendors helps define the precise characteristics the biomass fuel needs to possess.
d. **Contacting Suppliers:** Reaching out to potential suppliers allows you to gauge their ability to meet the established fuel specifications and determine pricing (U.S. Department of Energy 2016).

Furthermore, estimating monthly and annual fuel needs, including peak usage periods, is crucial for properly sizing fuel handling and storage equipment. This comprehensive approach ensures a well-matched biomass energy system with reliable fuel sources.

Fuel Attributes of Biomass

◇ **Spatial Distribution:** Moderate - Availability of biomass feedstocks (like wood, agricultural waste) vary depending on location and land use practices.
◇ **Source & Imports Channel:** Moderate - Biomass can be sourced locally or transported from surrounding areas. The extent of reliance on imports depends on the availability and type of feedstock.
◇ **Technology:** Moderate - Conversion technologies vary depending on the type of biomass feedstock used (e.g., direct combustion, gasification).
◇ **Transportation of Fuel/Energy:** Varies - Transportation costs for biomass feedstock can vary depending on the distance and type of transport.
◇ **Seasonality:** Varies depending on the feedstock source. For example, wood availability might be lower during winter months due to harvesting limitations.
◇ **Availability:** The availability of biomass can be measured by implementation potential, or the fraction of the economic potential that can be implemented within say 50 years, considering institutional constraints and incentives (Lako and Kets 2005).

PUMPED HYDROPOWER GENERATION

Pumped hydroelectricity leverages gravity to store and generate electricity. Water is pumped uphill to a reservoir during periods of low electricity demand and prices. When demand and prices rise, this stored water is released, flowing downhill through turbines to generate electricity, and feed the grid (US Energy Information Agency 2023).

The capacity for energy storage in a pumped hydro facility depends on the size of its two reservoirs, while the power generation output is linked to the size of the turbines. There are two primary configurations for pumped hydro storage:

a. **Open Loop:** One or both reservoirs connect directly to a natural water source like a river, allowing for continuous water flow.
b. **Closed Loop:** This “off-river” design uses a closed system where water is pumped between upper and lower reservoirs without relying on significant natural inflows (International Hydropower Association, n.d.).

Closed loop pumped hydropower storage systems require significant water volume for energy storage. For a system with a 400-meter head and 90% generation efficiency, roughly 1 Gigalitre of water is needed per Gigawatt-hour (GWh) of storage capacity. This water requirement directly correlates with the head height: doubling or halving the head would respectively halve or double the water volume needed. Once reservoirs are filled, managing evaporation losses is critical. In some regions, rainfall and evaporation over the reservoir surface roughly balance out. However, in arid areas, evaporation suppressors - small floating objects that reduce wind speed and evaporation rates - can be used to tip the balance in favour of rainfall, minimising the need for additional water input (Blakers et al. 2021).

Fuel Attributes of Pumped Hydropower

- **Spatial Distribution:** Not Applicable - Pumped hydropower utilises existing hydropower infrastructure.
- **Source & Imports Channel:** Not Applicable - Pumped hydropower doesn't require a continuous fuel source. It uses electricity from other sources to pump water uphill for storage and later generation.
- **Technology:** High - Relies on advanced pumping and generation systems integrated with existing hydropower infrastructure.
- **Transportation of Fuel:** Minimal cost - The fuel used is the electricity used to pump water from a lower to an upper reservoir during periods of low electricity demand or low prices. The cost of this fuel is therefore the cost of the electricity procured from the grid, rather than any physical fuel procurement or transportation cost.
- **Seasonality:** Not Applicable - Pumped hydropower can be used strategically to address seasonal variations in electricity demand. It can store excess energy during low-demand periods and generate electricity during peak demand times.
- **Availability:** (Closed loop) Minimum water volume requirements in Gigalitres per Gigawatt-hour (GWh) minus evaporation losses.

The attributes of different types of fuel sources ascribe to the availability of the fuel; fulfilling the availability criteria helps achieve an entity achieve fuel adequacy of its resource-mix, irrespective of the proportion, type, or level of extraction of different fuel sources. The next section deals with the generative and capacity abilities of a power system and the risk, magnitude and contribution metrics used to assess and address the gaps.

3.2.1.5 CRITICAL MINERAL AVAILABILITY FOR RESOURCE ADEQUACY

The discussion surrounding critical minerals such as lithium, cobalt, and rare earth elements is increasingly vital in ensuring resource adequacy during the energy transition. As the world shifts towards renewable energy technologies, these minerals play a crucial role in the production of batteries, wind turbines, and solar panels. For instance, lithium is essential for lithium-ion batteries that power electric vehicles (EVs) and store energy from renewable sources, while cobalt and nickel enhance battery performance and longevity. Rare earth elements are critical for manufacturing permanent magnets used in wind turbines and electric motors. The International Energy Agency (IEA) projects that the demand for these minerals will surge

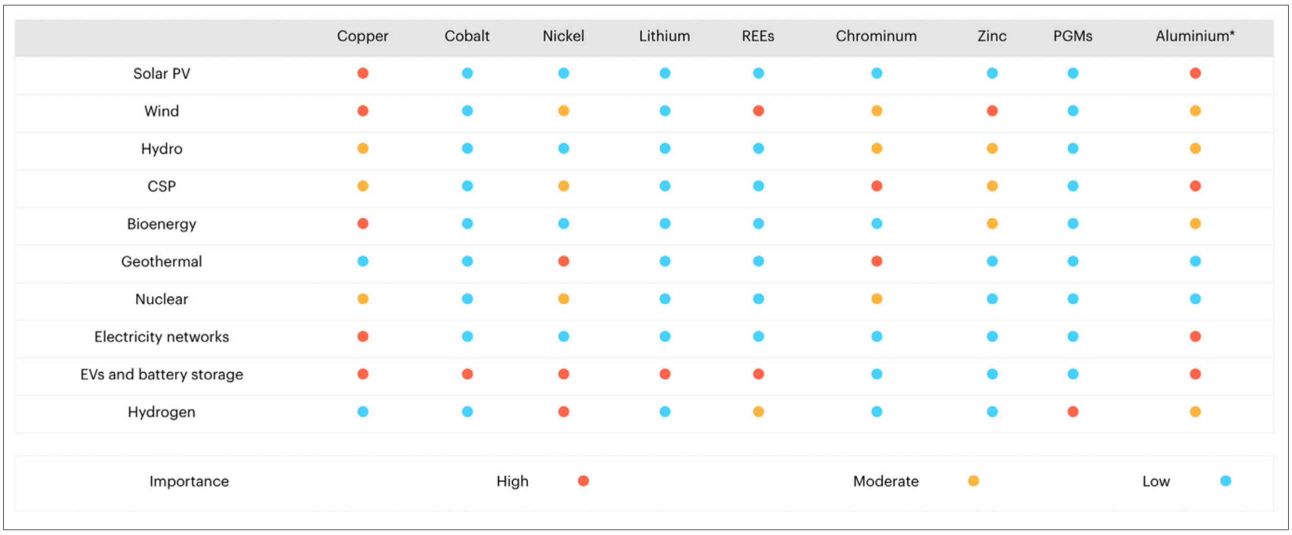


Figure 8: Critical mineral needs for clean energy technologies, Source: (IEA 2022b)

dramatically, with estimates indicating a tripling of mineral demand for clean energy technologies by 2030 and quadrupling by 2040 in scenarios aimed at achieving net-zero emissions. This escalating demand highlights the need for robust supply chains that can withstand price volatility and geopolitical tensions, ensuring that the energy transition remains resilient and secure (IEA 2023).

In contrast to traditional capacity credit methods that evaluate resource adequacy based on historical performance and reliability of fossil fuel plants, the analysis of critical minerals introduces new complexities. Traditional generation resources typically have predictable output patterns, allowing for straightforward capacity assessments. However, intermittent renewable resources depend heavily on these critical minerals for their functionality, which complicates their reliability assessment. The extraction and processing of these minerals are often concentrated in specific regions, leading to potential supply risks that could hinder the deployment of renewable technologies. As such, policymakers must consider not only the availability of these minerals but also their environmental impact, social implications, and the need for recycling strategies to mitigate resource scarcity. Addressing these challenges through comprehensive policies will be essential to ensure that the transition to a clean energy future is both sustainable and equitable (IEA 2021).

3.2.2 GENERATION ADEQUACY METRICS

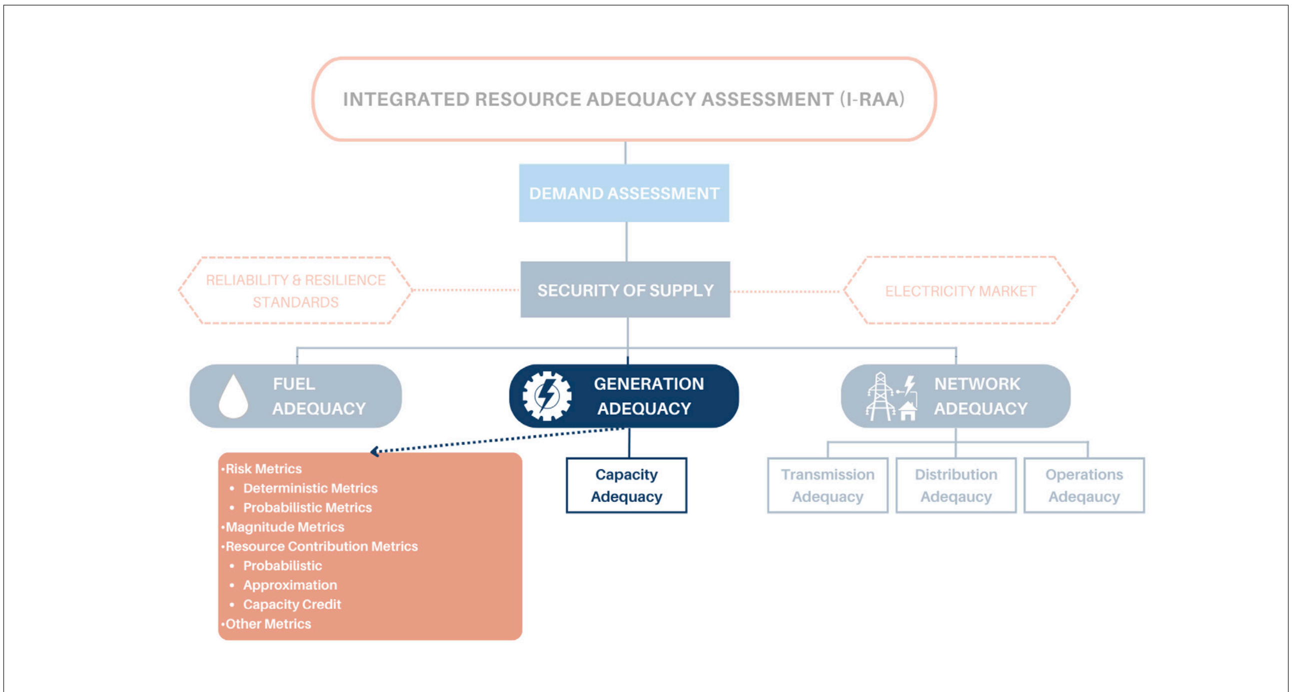


Figure 9: Integrated Resource Adequacy Framework (I-RAA) – Generation Adequacy, Source: Authors

3.2.2.1 RISK METRICS

Metrics capturing system risk can be divided into deterministic and probabilistic metrics. Deterministic metrics use a single prediction to assess adequacy at a specific time and location. They are faster to calculate but less accurate. Probabilistic approaches, on the other hand consider a range of possibilities using probabilities to account for uncertainties. While these methods are more accurate, they require more computing power.

DETERMINISTIC METRICS

Planning Reserve Margin (PRM): This is a common deterministic index that calculates the difference between total available installed capacity and peak load, divided by peak load. It provides a snapshot of adequacy by examining peak demand but may oversimplify resource adequacy analysis by not considering factors like storage state-of-charge management, demand response availability, and hourly variations in renewable resources.

However, it oversimplifies the risk by not considering chronological issues and vulnerabilities and assumes that all generation resources have the same availability and reliability. As a result, PRM may not accurately reflect the actual risk of power system inadequacy, especially when considering the increasing integration of variable renewable energy resources.

PROBABILISTIC METRICS

Loss of Load Metrics

- **Forced Outage Rates:** Forced outage rates are metrics used to evaluate the reliability of power generation units in a power system. They represent the percentage of time that a unit is unavailable due to unplanned outages or deratings. There are different types of forced outage rates, each with its own specific calculation and application.

  a. **Equivalent Forced Outage Rate (EFOR):** This applies to any time a generator fails during the year, irrespective of system load.
  b. **Equivalent Forced Outage Rate - demand (EFORd):** This captures the probability that the unit will fail completely when needed.
  c. **Equivalent Forced Outage Rate – peak (EFORp):** It captures the actual rate of complete or partial failure when plant is needed during pre-defined peak hours.

- **Loss-of-Load Expectation (LOLE):** This metric measures the expected count of event-periods per study horizon, where system resources are insufficient to meet demand. It is defined as the expected count of event-periods per study horizon, with an event-period being a period of time during which system resources are insufficient to meet demand. LOLE is often expressed in shortfall days/year (LOLD) or shortfall hours/year (LOLH) in North American or European studies, respectively.

- **Loss-of-Load Days (LOLD):** This metric is defined as the expected count of event-days per study horizon, with an event-day being a period of time during which system resources are insufficient to meet demand.

- **Loss-of-Load Hours (LOLH):** This metric is defined as the expected count of event-hours per study horizon, with an event-hour being a period of time during which system resources are insufficient to meet demand. When a study uses an LOLH metric, it usually evaluates shortfall risk for all hours of the study horizon.

- **Loss-of-Load Years (LOLY):** This metric is defined as the expected count of event-years per study horizon, with an event-year being a period of time during which system resources are insufficient to meet demand.

- **Loss-of-Load Events (LOLEv):** This metric, also called loss-of-load frequency (LOLF), estimates how often power shortages occur within a specific timeframe. It focuses on the number of these events, not how long they last or how severe they are.

- **Loss-of-Load Probability (LOLP):** Loss of Load Probability (LOLP) is a metric used in power systems to express the likelihood of encountering insufficient generation capacity to meet electricity demand. It’s important to note that LOLP is reported as a percentage of time per specified period, and both the timeframe for potential shortfall (event-period) and the total timeframe considered (horizon) need to be clearly defined when discussing LOLP values. There are different ways to calculate LOLP, depending on the focus of the analysis:

a. **One-hour LOLP:** This is the most common approach, where both the event-period (potential shortfall timeframe) and the horizon (total timeframe considered) are set to one hour. Essentially, it calculates the probability of insufficient capacity for each hour. The sum of these hourly LOLP values throughout the planning period provides a broader picture of reliability.
b. **Annual LOLP:** Here, LOLP represents the overall chance of encountering a shortfall at least once within a specific year. In this case, both the event-period and the horizon are one year.
c. **Normalised LOLP:** This method relates the expected number of event-periods (shortfall occurrences) to the total study duration. The event-period and horizon can have different values. For instance, an expected outage duration of 3 hours per year (LOLE) would translate to an LOLP of 0.82% if the event-period is one hour and the horizon is one year (representing 3 hours out of 8760 hours in a year).

3.2.2.2 MAGNITUDE METRICS

Magnitude metrics measure the duration of an outage and its magnitude relative to the duration. Some of the metrics include Expected Unserved Energy (EUE) and Normalised EUE. Magnitude is often included as a metric under risk assessment.

- **Expected Unserved Energy (EUE):** This metric is defined as the total expected amount of unserved energy, in MWh or GWh, in a given study horizon. It communicates the magnitude of shortfall events, rather than the frequency or duration.
- **Normalised Expected Unserved Energy (NEUE):** This metric expresses the total amount of unmet electricity demand as a percentage of overall system demand. This allows for comparing the risk of outages between power systems of different sizes or considering different future possibilities.
- **Energy Reserve Margin (ERM):** This metric helps with planning for electricity needs. It defines a percentage by which generating capacity should exceed expected demand in a given hour, creating a buffer for unexpected situations.

3.2.2.3 RESOURCE CONTRIBUTION METRICS

Resource contribution metrics are divided into two broad categories: probabilistic and approximation methods. Probabilistic methods for measuring resource contributions involve calculating metrics based on a range of outcomes providing a more accurate assessment of system reliability. Approximation methods for measuring resource contributions are simpler to use and explain compared to probabilistic methods. However, they are less accurate as they involve less data and analytical effort and are typically preferred by system operators and utilities for their ease of use.

PROBABILISTIC METHODS

- **Effective Load-Carrying Capability (ELCC):** The ELCC of a resource measures how much additional load a power system can handle when that resource is added, while still maintaining the same level of reliability.
- **Equivalent Firm Capacity (EFC):** The EFC of a resource estimates how much dependable power generation would be needed to replace that resource, if the power system’s ability to handle outages stays the same.
- **Equivalent Conventional Power (ECP):** The ECP of a resource estimates the amount of

generating capacity from a traditional, controllable power plant (like a natural gas turbine) that would be needed to replace the resource, if the power system's ability to handle outages stays the same.

Importance of Probabilistic Metrics in a Growing Renewable Energy Landscape

The importance of probabilistic resource contribution metrics in the growing renewable energy landscape lies in their ability to accurately assess the capacity value of variable generation sources like wind and solar. As these resources become more prevalent, traditional methods that rely on fixed capacity and average outage rates are inadequate due to the inherent variability and unpredictability of renewable energy generation. Probabilistic metrics, such as Effective Load Carrying Capability (ELCC) provide a more nuanced understanding of how these resources contribute to overall system reliability and planning reserves. By incorporating the uncertainties associated with weather patterns and generation variability, these metrics enable better decision-making for energy system operators, ensuring that renewable resources are effectively integrated into the grid while maintaining reliable power supply (Ibanez et al. 2014).

Effective Load Carrying Capability (ELCC) is a critical metric used to quantify the contribution of intermittent renewable resources, such as solar and wind, during peak demand periods. Unlike traditional capacity credit methods that primarily assess generation resources based on their nameplate capacity and historical performance, ELCC evaluates how much of that capacity can be reliably counted on to meet peak demand when it is most needed. This approach recognises the variability and intermittency of renewable resources, which do not produce energy consistently throughout the day or year. By employing loss-of-load probability modeling, ELCC provides a more nuanced understanding of how these

resources can contribute to system reliability under varying conditions, particularly during periods of high demand when renewable output may be low. This is essential for grid operators who must ensure that sufficient generation is available to meet peak loads, especially as renewable penetration increases and shifts the timing of peak demand (Ibanez et al. 2014).

In contrast, traditional capacity credit methods often rely on historical output data during peak periods to assign capacity credits to resources. This approach can misrepresent the actual reliability value of intermittent resources because it does not adequately account for their performance during critical times when demand surges. For instance, while a natural gas plant may provide consistent output during peak hours, solar and wind resources may not be available at those times due to their dependence on weather conditions. As a result, using ELCC allows for a more accurate assessment of the effective capacity that renewables can provide, considering their operational characteristics and the interactions with other generation sources. This shift in methodology is becoming increasingly important in resource adequacy planning as utilities and grid operators seek to integrate higher levels of renewable energy while maintaining system reliability.

APPROXIMATION METHODS

Capacity Based Methods

- **Installed Capacity:** It refers to the maximum amount of power a unit can generate and is often based on ideal summer conditions. It does not account for outages or reduced output, so it can overestimate a unit's true contribution.
- **Unforced Capacity:** It refers to the net amount of power a unit can generate after accounting for its forced outage rate.

Time-Period-Based Methods

These metrics consider the output availability of a resource during its peak demand or defined at-risk period. Largely useful in the case of variable resources, time-period-based methods focus only on the riskiest duration to reduce computational burden.

Resource availability is also largely affected by capacity value; years of data must be used to analyse the capacity value since annual variations over the years are significant. System planners assessing capacity value can define time periods based on either peak load times or periods with the highest Loss-of-Load Probability (LOLP).

- **Mean Available Energy Output During Peak Load:** The capacity value of a resource is defined as the mean output of its available generation during a specified peak load period. This is useful for instances where certain probabilistic metrics cannot be calculated because of time or data constraints or in systems with a high correlation between periods of peak demand or maximum system risk.
- **Exceedance Available Energy Output During Peak Load:** Referred to as the percentile method, this metric defines the capacity value of a resource as the minimum available energy output that can be produced in a certain percentage of peak load hours.
- **Mean Available Energy Output During Highest LOLP Hours:** Under this method, the capacity value of a resource is defined as its mean available energy output during peak LOLP hours. This method is useful in case where two resources that provide identical amount of annual energy to the grid might have different capacity values based on their output during high LOLP hours.

CAPACITY CREDIT METHODS

Two main approaches are used to estimate capacity credit (CC): reliability-based and approximation-based methods.

Reliability-based methods involve complex models that consider factors like hourly electricity demand, generator information, and transmission networks. They calculate metrics like loss-of-load probability (LOLP) or expected unserved energy (EUE) to assess the impact of adding a new resource on grid reliability.

Approximation-based methods are simpler and estimate CC based on a resource's capacity factor (CF), which is the ratio of its average output to its maximum capacity during a specific period. This period typically focuses on peak demand hours when the grid is stressed (Jorgenson et al. 2021). Two forms of capacity approximations are measured:

a. **Capacity credit approximation with Top Demand Hours:** In this case, a basic approximation of capacity credit can be obtained by averaging the historical contribution of a generator / generator class during peak demand hours. The selection of how many peak demand hours to include, however, often varies across geographies.
b. **Capacity credit approximation with Top Net Load Hours:** In this case, consideration is given to the fact that periods of system stress occur when high demand coincides with low renewable energy generation. A metric called 'net load' is defined as 'total renewable energy generation subtracted from overall demand', which must be met from despatchable resources like thermal plants, hydro plants, etc. In this method, capacity credit can be obtained by averaging the contribution of a generator/ generator class during top net load hours (CEA 2022a).

While easier to use, these methods might miss some factors like how adding a resource might affect peak periods or limitations of energy-limited resources.

Both methods might not consider transmission constraints, but some simulation techniques can incorporate them. Due to their comprehensiveness, reliability-based methods are preferred when data and computing power allow. However, approximation-based methods are still valuable for planning future system expansion with capacity addition models (Jorgenson et al. 2021).

Choosing the right resource adequacy metric depends on various factors- the share of resource-mix, the level of supply-side and demand-side resources, the level of dependence on conventional generation sources, the degree of integration of variable resources and the frequency of the impact of risks on the power system.

To measure resource adequacy, a considerable number of countries in the world use some form of the Loss-of-Load metrics. Much of North America largely uses Loss-of-Load-Expectation, major countries across the European Union uses Loss-of-Load-Hours, Australia uses Normalised Expected Unserved Energy and Asia uses a combination of both Planning Reserve Margin and Loss-of-Load metrics (Mijolla et al. 2022a). India, on the other hand, uses a mix of Loss-of-Load-Probability, Normalised Expected Unserved Energy and Planning Reserve Margin for its resource adequacy framework (Mijolla et al. 2022a) (CEA 2022a).

3.2.2.4 OTHER METRICS

Combination metrics: Combination metrics combine existing probabilistic metrics to provide additional insights. For example, the LOLH/ LOLD metric (expressed in hours/day) calculates the average shortfall duration per loss of load day. The EUE/LOLD metric (expressed in MWh/ day) calculates the average unserved energy per loss of load day, which is useful for sizing energy storage and demand response resources. The EUE/LOLH metric (expressed in MW) quantifies the average amount of capacity shortfall on the system, which can be used to size resource mitigations.

Full distribution metrics: Full distribution metrics consider the entire distribution of resource adequacy metrics, rather than just the average value. This is important because outlier events can have a significant impact on system adequacy. Common methods for analysing the distribution of resource adequacy

metrics include calculating the standard error to mean (SEM), percentiles (such as the 25th, 50th, and 75th percentile), and the 95th or 99th percentile. Additionally, the conditional value at risk (CVaR) metric can be used to measure the weighted average outcome of tail-end events. Visualising the risk distribution graphically can also be helpful for understanding system adequacy risks.

Characterisation metrics: Characterisation metrics provide information about the magnitude, duration, and timing of individual shortfall events. This is important because aggregate metrics, such as LOLH and LOLE, do not provide this level of detail. Characterisation metrics can be used to select and size resources to meet specific adequacy needs. For example, a characterisation metric could summarise event shortfalls by duration, size (MW), magnitude (MWh), and timing (month, season, hour of day).

Author's Note:

While traditional generation adequacy metrics primarily focus on capacity shortages, flexibility metrics are equally essential for ensuring a reliable and resilient power system. Flexibility is the system's ability to cope with variability and uncertainty in generation and demand (Cochran et al. 2014). This is particularly crucial in the context of increasing levels of variable renewable energy (VRE) sources. Flexibility adequacy, distinct from traditional capacity and energy adequacy, assesses a power system's operational manoeuvrability to handle futu§re demands. It can be evaluated independently or in conjunction with traditional adequacy studies. Unlike capacity deficits, flexibility deficits may not always necessitate additional generation capacity but rather adjustments in operational practices or the efficient utilisation of existing reserves. Hence, the metrics that ensure flexible generation are discussed under Network Adequacy metrics along with transmission, distribution and other operation metrics.

3.2.3 NETWORK ADEQUACY METRICS

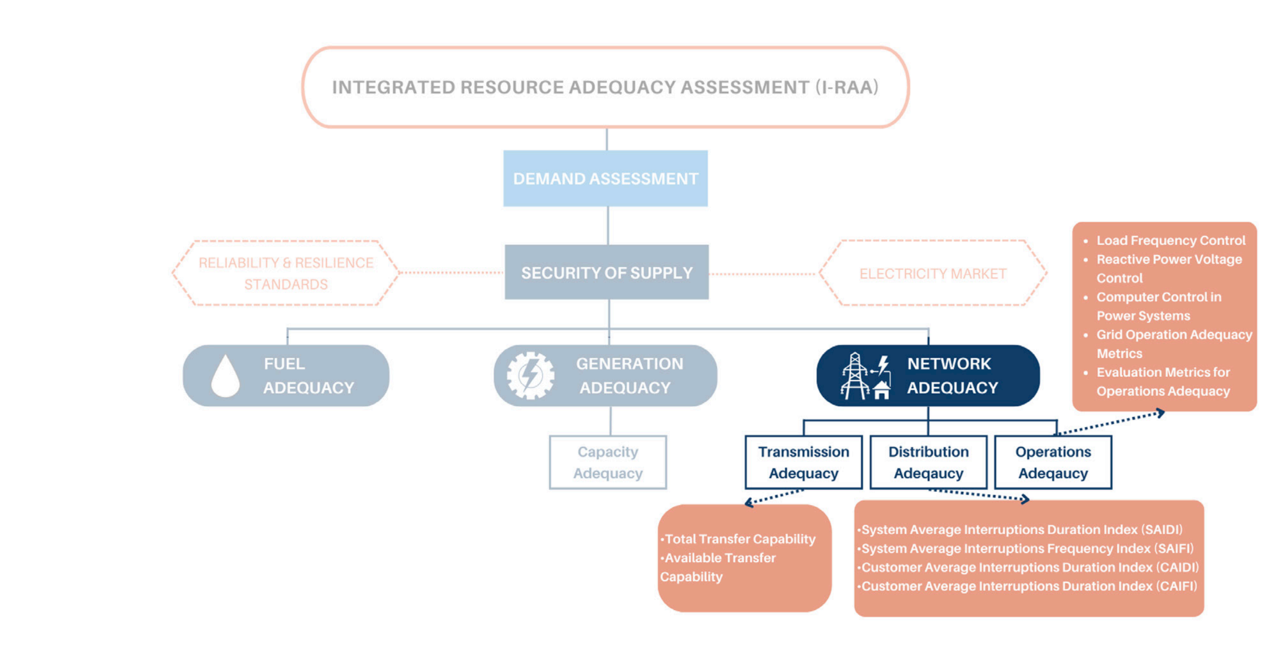


Figure 10: Integrated Resource Adequacy Framework (I-RAA) – Network Adequacy, Source: Authors

Now that the prospective reader would be familiar with the framework established in this handbook and the rationale behind it, it would be imperative to introduce the reader to the network adequacy metrics that coalesces the identified risks affecting power generation. As a combined integrated system, the network adequacy metrics will help resource adequacy assessments achieve system reliability through steady-state balancing of demand and supply through proper network operation standards through transmission and distribution. These standards are further useful in measuring the latent resilient characteristics of the power system, thus making it significant to understand the reliability-resilience relationship in later chapters.

The network adequacy metrics are classified by transmission, distribution, and operations of the power network. Deterministic and stochastic factors play a huge role in maintaining the thermal, voltage and frequency stability of power networks. Limits to the latter largely affect the components of network adequacy. At the transmission level, our framework measures the transfer capability of interconnected transmission lines and the risks arising out of deterministic and stochastic factors through capacity and reliability margin contributions. Factors that affect network imbalances are measured under transmission adequacy since voltage and power flow affect transmission and transfer capability.

As far as operations adequacy is concerned, we map the metrics that measure frequency and imbalances and briefly highlight the role of ancillary services in restoring frequency and ensuring network reliability.

The distribution adequacy metrics measures the average interruptions and duration of these interruptions while serving the customers.

3.2.3.1 TRANSMISSION ADEQUACY METRICS

Improved transmission and transfer capabilities ensure the reliable transfer of power output from generation resources to customers under a wide variety of operating conditions. Transmission adequacy metrics largely ensure the availability of transfer capability, defined as the measure of the ability of interconnected electric systems to reliably move or transfer power from one area to another over all transmission lines (or paths) between those areas under specified system conditions (NERC 1996).

Transfer capability uses a Monte-Carle method, usually simulated well beforehand that anticipates future system states. Each simulation represents a static snapshot of the network's operation based on projected factors. These simulations provide valuable insights into network performance and available transfer capability.

Some of the key factors that are used to determine transfer capability include:
Key factors considered in these simulations include:

- **Projected Customer Demands:** The simulated demand levels should reflect the system conditions and customer demand patterns being studied.
- **Generation Despatch:** The simulation should realistically model the commitment and output of utility and non-utility generators based on the specific conditions.
- **System Configuration:** The simulated network configuration should accurately represent the expected state, including planned generation and transmission outages and the activation of relevant operating procedures.
- **Base Scheduled Transfers:** The simulations should model pre-arranged electricity transfers that reflect the base system conditions under analysis.
- **System Contingencies:** A comprehensive screening of potential generation and transmission outages should be conducted, following established planning criteria, to identify the most critical contingencies that could limit transfer capability. In some cases, the analysis might consider multiple simultaneous contingencies if deemed necessary (NERC 1996).

To apply a contingency-based approach, planners simulate various equipment failures, such as a unit outage, and analyse the potential consequences on the system. By using analysis tools like load flow and short circuit studies, they identify potential overloads, under voltages, or unacceptable fault duties that might arise. To mitigate these issues, planners can upgrade equipment, change design parameters, or

implement alternative operating strategies. This process is repeated for different contingency cases, simulating various equipment failures to ensure the system's resilience and reliability under different operating conditions (Willis 2004).

To ensure system reliability, electric utilities typically design their transmission and substation facilities to withstand the loss of any one major equipment unit (N-1 capability). In some cases, more stringent criteria (N-2 or N-3) are applied, particularly in critical areas, to tolerate the loss of two or even three units. While these different contingency levels may have varying operating criteria, the overall goal is to maintain normal system operation under most conditions, even when facing equipment failures (Willis 2004).

TRANSFER CAPABILITY VERSUS TRANSFER CAPACITY

Transfer Capability refers to the maximum amount of power that can be reliably transferred between two areas of an interconnected network under specific conditions. It depends heavily on factors like generation availability, customer demand, and the overall transmission system configuration at a given time.

Transfer capacity on the other hand, represents a fixed limit associated with a specific piece of equipment, typically expressed as its thermal rating. For example, the capacity of a transmission line refers to the maximum amount of power it can safely carry under normal circumstances (NERC 1996).

Focusing solely on individual transmission line capacities can be misleading when determining how much power can be transferred between areas in an interconnected grid. Unlike static line capacities, transfer capability considers the dynamic interplay within the entire network. Factors like generation availability, customer demand, and the overall system configuration can significantly limit the amount of power that can be reliably transferred even if individual lines have high capacities. Simply adding up line capacities ignores these crucial network interactions, potentially leading to an overestimation of true transfer capability. Therefore, to ensure a reliable and efficient power grid, it's vital to measure transfer capability, which takes a holistic view of the interconnected network (NERC 1996).

In case of improving transfer capability for meeting the rise in demand, planners often find confounded between the decision to install parallel transmission lines or use series-capacitor to maintain the voltage fluctuation arising out of increased power transfer. While the former increases installation and operation costs, the latter is cost-effective and helps in stabilising the inductance. However, this would result in a sub-synchronous resonance (SSR) problem, caused by series-capacitor that creates a resonant circuit at sub-synchronous frequencies. These frequencies not only operate below the power grid's operating frequency, but also dangerous if it interacts with the turbine-generator's natural frequencies, thus causing a sustained exchange of energy between the electrical system and the shaft, leading to severe torsional stress on the shaft. For power system engineers to perform studies to identify potential SSR risks during the design and operation of the system, transfer capability metric is important (Abu-Siada and Karunar, n.d.). Hence, transfer capability is as significant a measure as transfer capacity for ensuring transmission adequacy.

Transfer capability can be measured as total transfer capability and available transfer capability.

- ◇ ***Total Transfer Capability (TTC)*** is defined as the amount of electric power that can be transferred over the interconnected transmission network in a reliable manner while meeting all of a specific set of defined pre- and post-contingency system conditions.

- ◇ ***Available Transfer Capability (ATC)*** is a measure of the transfer capability remaining in the physical transmission network for further commercial activity over and above already committed uses (NERC 1996).

Mathematically, the available transfer capability is defined as the Total Transfer Capability (TTC) less the Transmission Reliability Margin (TRM), less the sum of existing transmission commitments (which includes retail customer service) and the Capacity Benefit Margin (CBM) (NERC 1996).

Transmission Reliability Margin (TRM) refers to the amount of transmission transfer capability necessary to ensure that the interconnected transmission network is secure under a reasonable range of uncertainties in system conditions. TRM acts as a buffer of transfer capability, safeguarding the interconnected transmission network's reliability. This reserve ensures that all transmission system users benefit from dependable transmission services across a wide spectrum of potential system conditions. TRM explicitly acknowledges the inherent uncertainties associated with system conditions and their impact on available transfer capability (ATC) calculations. It also factors in the need for operational flexibility to maintain reliable system operation as these conditions fluctuate.

The capacity benefit margin (CBM) refers to the amount of transmission transfer capability reserved by load serving entities to ensure access to generation from interconnected systems to meet generation reliability requirements. CBM empowers load-serving entities (LSEs) to strategically reduce their local generation capacity. This strategy relies on interconnections and reserved transfer capability through CBM. Without CBM, LSEs might need more on-site generation to ensure reliability. CBM operates at a more localised level compared to the broader network focus of the transmission reliability margin (TRM). When an LSE implements policies to reserve transfer capability for generation reliability (through CBM), this reservation should be factored into calculations of available transfer capability (ATC). These CBM reservations remain relevant for future transmission system development planning (NERC 1996).

LIMITS TO TRANSFER CAPABILITY

The power grid's ability to reliably deliver electricity depends on several factors related to its physical and electrical properties. These factors include:

- **Thermal limits:** Thermal limits to transfer capability refer to the maximum limit of power that can be conducted by transmission lines and equipment before overheating and sustaining damage.
- **Voltage limits:** Collapsing of system voltage can lead to blackouts; it is always important to establish system voltages and voltage limits to maintain their ranges within acceptable minimum and maximum limits.
- **Stability limits:** The power grid's stability is crucial; hence, the transmission networks must withstand disruptions without losing synchronisation between generators, which operate in unison at a specific frequency. After disturbances, generators temporarily oscillate, causing fluctuations in voltage and line loads. For stability, these oscillations must quickly settle, allowing the system to reach a new stable state. Failure to do so can lead to generator desynchronisation, potentially causing widespread outages and equipment damage.

The total transfer capability and available transfer capability metrics will have to take into consideration uncertainties arising from system conditions and other external factors like projected customer demand and its distribution, generation despatch, location of future generators, future weather conditions, and available transmission facilities. This would mean that the transfer capability is also commercially affected by curtailment and recallability, the two most important factors that helps in setting aside a transfer margin to meet uncertainties.

Curtailment refers to the ability of a transmission provider to temporarily reduce or interrupt a portion of the agreed-upon transmission service. This is a last resort measure used only when limitations within the network, like congestion or emergencies, threaten system stability. Once these limitations are resolved, the curtailed service is restored. Curtailment is a response to real-time changes in the transmission network.

Recallability, on the other hand, grants transmission providers the broader right to interrupt any part of a transmission service for various reasons, including economic considerations, if it adheres to established regulations and contractual agreements. This allows for greater flexibility in managing the network, encompassing both emergency situations and potential economic benefits.

Taking uncertainties into concern, the available transfer availability will have to account for a reserve margin beyond the reliability margin and capacity margin. This would mean that the system planners will have to account for a share of ATC that can be recalled and not recalled.

NON-RECALLABLE AVAILABLE TRANSFER CAPABILITY (NATC)

It represents the portion of the transmission network's capability that can be reliably accessed and reserved for specific purposes. It is calculated by subtracting the Transmission Reliability Margin (TRM) and any non-recallable reserved transmission services (including Capacity Benefit Margin) from the Total Transfer Capability (TTC). This essentially indicates the amount of network capability available for secure and reliable power transmission under normal operating conditions and during defined contingency scenarios.

NATC = TTC – TRM – Non-Recallable Reserved Transmission Service (including CBM)

RECALLABLE AVAILABLE TRANSFER CAPABILITY (RATC)

It refers to the portion of the transmission network's capacity that can be accessed and potentially recalled for specific purposes. It is calculated by subtracting the Transmission Reliability Margin (TRM), recallable transmission service, and non-recallable reserved transmission service (including Capacity Benefit Margin) from the Total Transfer Capability (TTC). However, portions of the TRM and CBM may be made available for recallable use by the transmission provider, depending on the specific timeframe under consideration for granting additional transmission service. This flexibility allows for more efficient network management, potentially utilising spare capacity within established reliability margins.

RATC requires different considerations in planning and operational timeframes. During the planning stage, only information about recallable and non-recallable transmission service reservations is available. However, in the operational horizon, actual transmission schedules become known, potentially allowing for more precise calculations and adjustments of RATC based on real-time network conditions.

RATC = TTC – a(TRM) – Recallable Reserved Transmission Service – Non-Recallable Reserved Transmission Service (including CBM) where $0 \leq a \leq 1$ value determined by individual transmission providers based on network reliability concerns

Establishing an ATC or an NATC standard by a utility depends on the amount of transfer capability that can be recalled or curtailed based on external uncertainties beyond the changes in system conditions, contingencies, and system limits to reduce the increased stress on the network. Factoring in the real-time changes in the power grid would mean that the transmission system will have to experience multiple episodes of curtailment due to variable output or transmission congestion. Congestion occurs when the demand for transmission capacity exceeds the available transfer capacity, a condition that arises on the transmission system when one or more restrictions prevents the despatch of electric energy from serving loads (Forum of Regulators 2022). Apart from affecting the grid stability, congestion would also result in load shedding, causing the power system to depart from the planned Loss-of-Load-Expectation standard.

Network reliability is measured by the adherence of the transfer capability based on voltage control and power flow control. Measuring the network reserve ancillary services (NRAS) can be further divided into voltage control ancillary services (VCAS) and power flow control ancillary services (PFCAS). The quantum of reserves that needs to be set aside for voltage and power flow control can only be set aside by the central transmission utility (CTU) and hence is included as a measure of transmission adequacy in this handbook. We plan to include the NRAS reserves along with other stochastic residual factors in transfer capability margin (TCM), within TRM to account for residual uncertainties.

3.2.3.2 OPERATION ADEQUACY METRICS

Operations adequacy is an important concept in the field of power system operation and control, referring to the ability of a power system to meet the expected demand for electricity while maintaining reliability and stability. It encompasses the assessment of both the generation capacity and the transmission infrastructure necessary to deliver electrical energy to consumers without interruption.

As electricity demand fluctuates due to various factors such as time of day, weather conditions, and economic activity, power systems must be designed and operated to ensure that sufficient resources are available to meet these demands. Operations adequacy is a critical aspect that ensures the reliable and efficient delivery of electrical energy to meet consumer demand. It encompasses the ability of the power system to maintain stability and reliability under varying load conditions. Key components that contribute to operational adequacy include Load Frequency Control (LFC), Reactive Power Voltage Control, and Computer Control Systems. Together, these elements form a cohesive framework that enhances the performance and resilience of power systems (Reddy 2020).

LOAD FREQUENCY CONTROL (LFC)

Load Frequency Control (LFC) is a crucial aspect of power system operation that ensures the balance between power generation and consumption, maintaining the system frequency within acceptable limits. Some of the key components and their objectives are discussed below:

- **Objective:** The primary goal of LFC is to maintain the system frequency at a nominal value (e.g., 50 Hz or 60 Hz) by adjusting the output of generators in response to changes in load.

- **Control Mechanisms:**
  - d. **Automatic Load Frequency Control (ALFC):** This system automatically adjusts the power output of generators to correct frequency deviations. It operates by measuring the frequency and adjusting the generation accordingly.
  - e. **Tie-Line Control:** In interconnected systems, LFC also manages the power flow across tie-lines between different control areas, ensuring that the frequency remains stable across the entire network.

- **Components:**
  - a. **Speed Governing Mechanism:** This mechanism adjusts the fuel supply to the generator based on the frequency deviation.
  - b. **Control Area:** Each area in a power system can be treated as a separate control entity, with its own generation and load characteristics.

- **Static and Dynamic Analysis:** LFC involves both static analysis (steady-state conditions) and dynamic analysis (transient conditions) to evaluate system performance under various scenarios.

- **Integration with Economic Despatch:** LFC is often integrated with economic despatch to ensure that the generation is not only balanced but also cost-effective (Reddy 2020).

REACTIVE POWER VOLTAGE CONTROL

Reactive Power Voltage Control is essential for maintaining voltage levels within the power system, which is critical for the stability and efficiency of power delivery. Here are the main aspects:

- **Importance of Reactive Power:** Reactive power is necessary for maintaining voltage levels in the system. It supports the voltage that allows the transmission of active power (real power) through the network.

- **Voltage Control Mechanisms:**
    a. **Automatic Voltage Regulator (AVR):** This system automatically adjusts the excitation of generators to maintain the desired voltage level.
    b. **Excitation Systems:** These can be classified into:
    c. **DC Exciters:** Provide direct current to the rotor winding.
    d. **AC Exciters:** Use alternating current for excitation.
    e. **Static Exciters:** Utilize power electronics for excitation control.

- **Methods of Voltage Control:**
    a. Tap Changing Transformers: These transformers adjust the voltage levels by changing the turns ratio.
    b. Switched Capacitors: These devices inject reactive power into the system to support voltage levels and minimize transmission losses.
    c. Mega Volt-Ampere Reactive (MVAR) Injection: This involves adding reactive power to the system to maintain an acceptable voltage profile (Reddy 2020).

COMPUTER CONTROL IN POWER SYSTEMS

Computer control systems play a vital role in modern power system operation and control, enhancing efficiency, reliability, and responsiveness. Key features include:

- **SCADA Systems:** Supervisory Control and Data Acquisition (SCADA) systems are used for real-time monitoring and control of power systems. They collect data from various sensors and devices, allowing operators to make informed decisions.

- **Energy Management Systems (EMS):** These systems optimize the operation of power systems by integrating various control functions, including generation scheduling, load forecasting, and real-time monitoring.

- **Advanced Control Techniques:** Computer-based control systems utilize advanced algorithms for load frequency control, reactive power management, and fault detection. Techniques such as model predictive control and artificial intelligence are increasingly being applied.

- **Simulation and Modelling:** Computer simulations are used to model power system behaviour under different scenarios, helping engineers design more robust systems and prepare for contingencies.

- **Communication Networks:** Modern power systems rely on robust communication networks to facilitate data exchange between different components, ensuring coordinated operation and control

In summary, Load Frequency Control, Reactive Power Voltage Control, and Computer Control are integral components of Power System Operation and Control, each contributing to the stability, efficiency, and reliability of power delivery systems (Reddy 2020).

GRID OPERATION ADEQUACY METRICS

Grid operation adequacy refers to the ability of the power system to meet electricity demand reliably and securely. Some of the key metrics used to assess different timeframes within grid operations are:

DAY-AHEAD OPERATION

Unit commitment determines which generation units will be online and available to produce electricity for the next day. This considers factors like:

- **Demand Forecast:** Predicted electricity demand for the next day.
- **Unit Availability:** Status and limitations of each generation unit (e.g., minimum up/ down time, startup costs).
- **Fuel Costs:** Cost of fuel for different generation types (e.g., natural gas, coal).
- **Variable Renewable Energy (VRE) Forecast:** Predicted output from wind and solar power for the next day.

Metrics Used to Measure Unit Commitment

- **Equivalent Forced Outage Rate (EFOR):** Probability of a generation unit being unavailable due to unplanned outages.
- **Installed Capacity vs. Peak Demand:** Ratio of total generation capacity to the expected peak demand for the next day.
- **Reserve Margin:** Percentage of additional generation capacity available above the forecasted peak demand to account for contingencies (Conejo and Baringo 2018).

HOURS-AHEAD OPERATION

- **Despatch Curve:** Represents the relationship between system power output and marginal cost (cost of producing the next unit of electricity) for committed generation units.
- **Merit Order:** Ranking of committed generation units based on their increasing marginal cost. Units with the lowest cost are despatched first to meet demand.
- **System Lambda:** The marginal cost of electricity at a specific point in time, often represented by the intersection of the demand level and the despatch curve.

Metrics used

- **Load Forecast Error:** The difference between the actual demand and the forecasted demand.
- **Spinning Reserve Margin:** The amount of generation capacity that can be quickly brought online to meet an unexpected increase in demand.
- **System Lambda:** Provides an indication of the real-time cost of electricity production (Conejo and Baringo 2018).

MINUTES-AHEAD OPERATION

- **Optimal Power Flow (OPF):** Analyses the power flow across the grid in real-time to ensure efficient and secure operation.
- **Frequency Deviation:** The difference between the actual grid frequency and the scheduled frequency (typically 60 Hz or 50 Hz).

Metrics used

- **Frequency Deviation:** Indicates potential imbalances between generation and demand.
- **Voltage Levels:** Monitors voltage levels at various points in the grid to ensure they stay within acceptable limits.
- **Line Overload:** Identifies power lines that are approaching or exceeding their capacity (Conejo and Baringo 2018).

REAL-TIME CONTROL (SECONDS TO MINUTES)

Frequency Response: The automatic response of generators and loads to frequency deviations. Primary control utilizes kinetic energy stored in rotating machinery to initially stabilize frequency.

Area Control Error (ACE): A metric used by automatic generation control (AGC) to maintain system frequency and power flow balance within a control area. The frequency imbalances are measured through area control error (ACE). Changes to the scheduled interchange between interconnections could disrupt the balance established by ACE. Impacts of interchange deviations and other risks affect the system frequency. Frequency imbalances will have to be arrested by the primary, secondary and tertiary ancillary services. They respond to the synchronous inertial response (withdrawal of kinetic energy) arising out of a contingency event that causes the frequency imbalance.

Area Control Error (ACE) = Actual Interchange – Scheduled Interchange – [10 x Frequency Bias Coefficient x (Actual System Frequency – 50)] + Measurement Error

Metrics used:

- **Rate of Change of Frequency (ROCOF):** The speed at which grid frequency changes following a disturbance.
- **Time Error:** The difference between the actual time and the time measured in AC cycles. This metric is important for maintaining long-term grid synchronisation (Conejo and Baringo 2018).

These are just some of the many metrics used to assess grid operation adequacy. By monitoring and analysing these metrics, system operators can ensure reliable and secure electricity delivery.

EVALUATION METRICS FOR OPERATIONS ADEQUACY

Evaluation metrics for operations adequacy in power systems are quantitative measures used to assess the performance and reliability of power grid operations. These metrics help in determining how well a power system can maintain stability, reliability, and efficiency under various operating conditions. The key evaluation metrics include:

- **Operating Reserve:** This metric refers to the additional capacity available to meet demand fluctuations and maintain system reliability. It is defined as:

Operating Reserve = Total Operating Capacity - Electric Load

where the total operating capacity is the net electricity capacity from all generators in the system.

- **Voltage Magnitude (V_mag):** This metric assesses the voltage levels across the grid to ensure they remain within acceptable limits. Violations in voltage magnitude can lead to equipment instability and operational issues.
- **Line Loading:** This metric evaluates the loading conditions of transmission lines to ensure they do not exceed thermal and stability limits. It is crucial for preventing line overloads, which can lead to failures or outages (Liu et al. 2021).

The overall Performance Score (PS) combines these metrics to provide a single score reflecting the participant's performance during the simulation. The formula for calculating the Performance Score can vary based on the weight coefficients assigned to each metric.

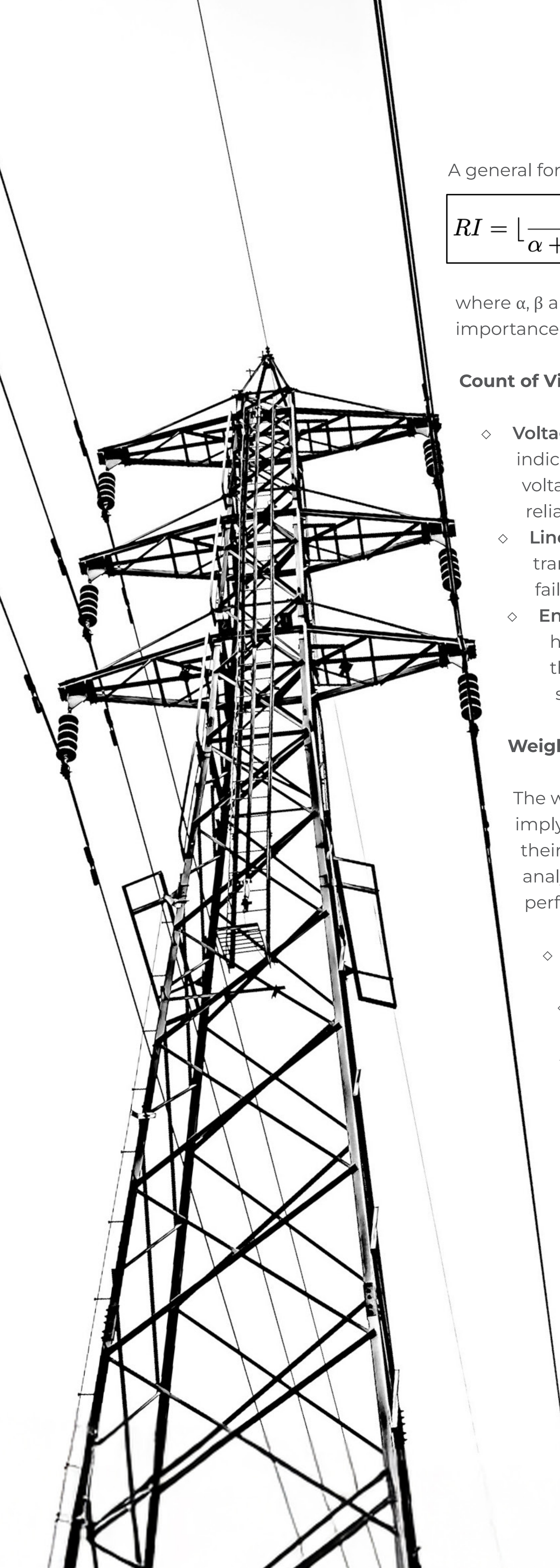
Variables in the Performance Score Formula

1. Count of Violations:

- **a:** Represents the number of buses that have voltage magnitude (Vmag) violations.
- **b:** Represents the number of transmission lines that have line loading violations.
- **c:** Denotes the ratio of energy emergency duration to total simulation duration.

2. Weight Coefficients:

- **α:** Weight coefficient for the voltage magnitude term.
- **β:** Weight coefficient for the line loading term.
- **γ:** Weight coefficient for the operating reserve term.



A general form of the Performance Score can be expressed as:

$$RI = \lfloor \frac{100}{\alpha+\beta+\gamma} \times (\alpha \mathrm{e}^{-0.05a} + \beta \mathrm{e}^{-0.05b} + \gamma\sqrt{1-c^2}) \rceil^1$$

where α, β and γ are weight coefficients that determine the importance of each metric in the overall score (Liu et al. 2021).

Count of Violations

- **Voltage Magnitude Violations (a):** A higher count indicates more significant issues with maintaining voltage levels across buses, which is critical for system reliability.
- **Line Loading Violations (b):** This reflects how many transmission lines are overloaded, which can lead to failures or outages if not managed properly.
- **Energy Emergency Ratio (c):** This ratio indicates how often energy emergencies occur relative to the total simulation time, providing insight into system reliability under stress.

Weight Coefficients

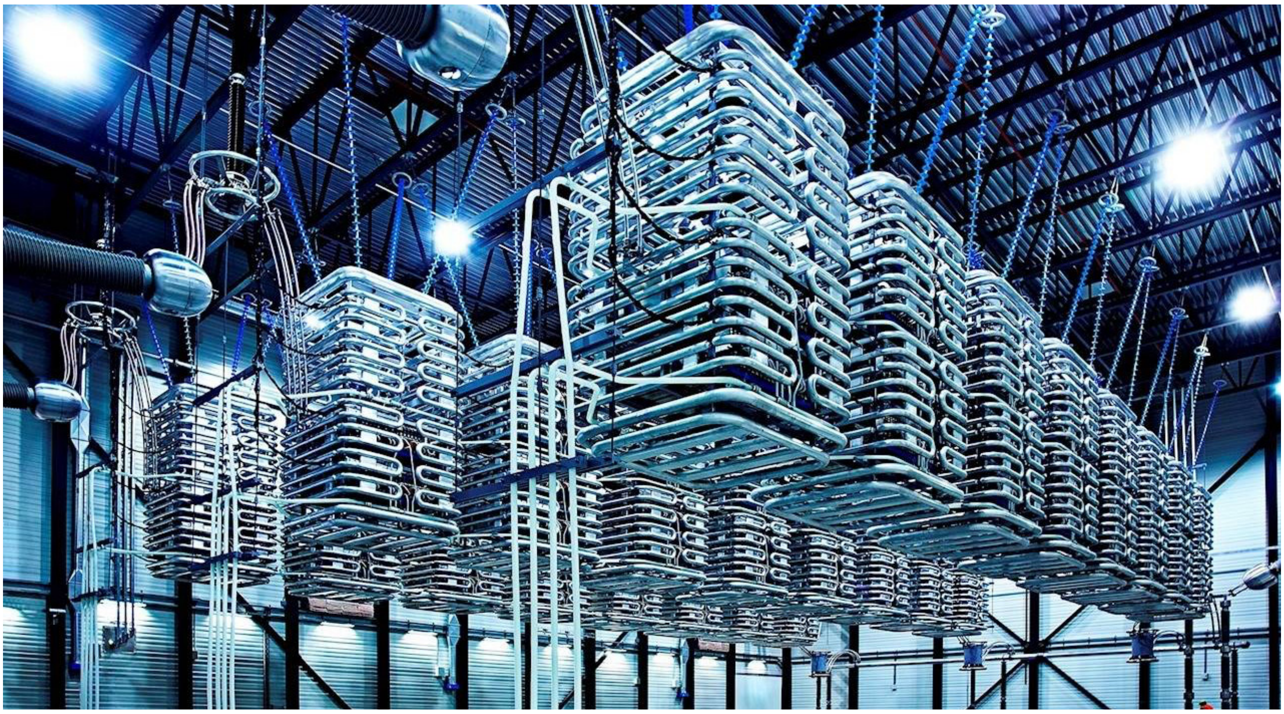
The weight coefficients α, β, γ are initially set to 1, implying equal importance for each metric. However, their values may be adjusted based on further analysis to reflect their relative significance in system performance:

- **α (Vmag):** Adjusting this weight can emphasize the importance of maintaining voltage levels.
- **β (Line Loading):** This weight can be increased if line loading issues are deemed more critical.
- **γ (Operating Reserve):** If maintaining adequate operating reserves is prioritized, this weight can be elevated.

Exponential Decay Function

The terms $e^{-0.05a}$ and $e^{-0.05b}$ apply a natural exponential decay function:

- For small values of a and b, this function decreases rapidly, imposing a larger penalty for initial violations.
- This decay function ensures that early violations have a more substantial impact on the score than later ones (Liu et al. 2021).



GAUF-HAUBRICH METHOD FOR SECONDARY AND TERTIARY RESERVE MODELLING

The Graf-Haubrich method is designed to quantify the necessary reserve requirements for secondary and tertiary control by considering various stochastic factors that contribute to system imbalances. It allows for the consideration of rare events, such as outages of major generating plants or High-Voltage Direct Current (HVDC) links, as well as the variability and forecast errors associated with renewable energy sources.

The Graf-Haubrich method has become increasingly essential in the context of growing renewable energy penetration due to its ability to effectively dimension control reserves. As the share of variable renewable energy sources (RES) like wind and solar power in the energy mix rises, traditional static reserve dimensioning methods fall short. These conventional approaches often rely on historical data and fixed assumptions about generation and demand, which do not adequately account for the inherent variability and unpredictability associated with RES. In contrast, the Graf-Haubrich method utilizes probabilistic modeling to assess various sources of imbalances—such as load forecast errors and generation outages—by convoluting them into a probability density function. This allows for a more dynamic and responsive reserve sizing that can adapt to the real-time conditions of the power system (Jost et al. 2015).

With the increasing integration of RES, the implications for ancillary services are profound. The need for immediate future requirements in control reserves has shifted towards a philosophy that embraces flexibility and responsiveness. The Graf-Haubrich method facilitates this by enabling grid operators to better anticipate and manage fluctuations in supply and demand, ensuring that sufficient reserves are available to maintain system stability. This dynamic approach not only enhances reliability but also supports the transition towards a more sustainable energy system where variable resources play a significant role. By improving the accuracy of reserve dimensioning, the Graf-Haubrich method helps mitigate risks associated with high RES penetration, thereby fostering a more resilient energy infrastructure capable of meeting future challenges (Hewicker et al. 2020).

The traditional deterministic reserve modeling method typically involves calculating control reserves based on empirical formulas that consider maximum load and fixed parameters, such as constants derived from historical data. This method often uses a one-size-fits-all approach, assessing reserve needs over longer periods without accounting for the variability inherent in renewable energy generation. This limitation is particularly pronounced as the penetration of wind and photovoltaic generation increases, leading to fluctuating energy output that the deterministic models may not adequately address. Consequently, the Graf-Haubrich method is needed as it introduces a probabilistic approach, allowing for a more nuanced calculation of reserve requirements by separating forecast errors related to wind, solar, and load. This method adapts to the unique characteristics of renewable energy sources, making it essential for accurately sizing control reserves in a grid increasingly dominated by such energy types (Jost et al. 2015).

How is the Graf-Haubrich Method different from static reserve modelling methods?

The Graf-Haubrich method and the static method differ significantly in their approach to quantifying reserve requirements for variable generation resources, particularly in the context of increasing renewable energy sources like wind and photovoltaics. Here are the key differences:

1. Forecast Error Treatment:

◇ **Graf-Haubrich Method:** This method uses historical data from the past 12 months to estimate forecast errors for sizing control reserves. It does not separate the forecast errors for different generation sources (wind, photovoltaic, and load) and instead combines them into a single distribution based on historical performance. This aggregation can lead to inaccuracies, especially in future scenarios where the generation mix may differ significantly from the past.

◇ **Static Method:** The static method modifies the Graf-Haubrich approach by separating forecast errors into distinct categories for wind, photovoltaic, and load. This separation allows for a more tailored estimation of reserve requirements based on the specific characteristics of each generation source. However, like the Graf-Haubrich method, it still relies on historical data to size reserves for a longer time frame (e.g., three months).

2. Application to Future Scenarios:

◇ **Graf-Haubrich Method:** It is limited in its applicability to future scenarios with different renewable energy capacities because it bases its error distributions on historical data from the previous year. This means it cannot accurately reflect the changing dynamics of the energy system as renewable penetration increases.

◇ **Static Method:** While it improves upon the Graf-Haubrich method by separating error types, it still sizes control reserves for a longer period, which may not adequately reflect the variability and uncertainty associated with renewable generation.

3. Dynamic Sizing Capability: The static method, while an improvement over the Graf-Haubrich method, does not dynamically adjust to daily or hourly changes in generation forecasts. It sizes reserves based on historical data for a longer duration, which may not capture the immediate variability of renewable generation.

3.2.3.3 DISTRIBUTION ADEQUACY METRICS

The efficiency of the distribution system plays a critical role in delivering reliable electricity to consumers. Low electricity supply discontinuity indicators ensure reliability across the distribution network. Unlike some large customers directly connected to the transmission network, most consumers rely on the distribution system for continuous power supply. Since the distribution network primarily uses radial lines with open endpoints, any damage to a section can cause outages for connected customers until they are switched to a backup feeder (if available) or repairs are completed (Andruszkiewicz, Lorenc, and Weychan 2019).

Distribution Adequacy metrics measure the average interruptions and average duration of such interruptions while serving the customers. Interruptions to the customers and their duration are measured by the following metrics:

- **System Average Interruptions Duration Index (SAIDI):** SAIDI represents the total number of minutes of interruption the average customer experiences. SAIDI is calculated by dividing the sum of all customer interruption minutes within the year by the number of customers served during the year. SAIDI minutes represent how long the average customer experiences an outage and lower SAIDI minutes equate to better electric reliability.

- **System Average Interruptions Frequency Index (SAIFI):** SAIFI represents the average number of times a customer experiences an outage during the year. SAIFI is calculated by dividing the total number of customer interruptions by the total number of customers in the system. Lower SAIFI numbers represent less interruptions and better electric reliability.

- **Customer Average Interruptions Duration Index (CAIDI):** CAIDI is the average time required to restore service. It is calculated as total minutes of customer interruption divided by the total number of interruptions. The lower the number of minutes, the faster the utility restored service to customers.

- **Customer Average Interruptions Frequency Index (CAIFI):** The CAIFI measures the average number of interruptions per customer interrupted per year. It is simply the number of interruptions that occurred divided by the number of customers affected by the interruptions (Michigan Public Service Commission, n.d.).

3.2.3.4 FLEXIBILITY METRICS

Flexibility in the context of power systems can be defined as the ability of the system to cope with variability and uncertainty in generation and demand. This flexibility is crucial for maintaining a reliable supply of electricity, particularly in light of increasing levels of variable renewable energy (VRE) sources such as wind and solar power. Flexibility allows power system operators to manage changes in electricity demand, adjust to fluctuations in energy generation, and thus maintain equilibrium between supply and demand (Cochran et al. 2014).

Flexibility adequacy is a concept used to assess whether a power system has enough operational manoeuvrability to handle future demands. It can be evaluated independently or alongside traditional capacity and energy adequacy studies. Flexibility deficits may not necessarily require additional generation capacity, but rather adjustments to operational practices, like utilising existing reserves more efficiently. Therefore, flexibility metrics need to be interpreted differently from traditional shortfall measures (EPRI, n.d.).

As the integration of renewable energy sources (RES) into power grids accelerates, enhancing grid flexibility becomes increasingly critical. Two key strategies to achieve this flexibility are the incorporation of Battery Energy Storage Systems (BESS) and Demand Response (DR) mechanisms. While the concept of demand response is uncovered in the demand assessment section, these technologies allow for improved management of supply and demand, enabling a more resilient and responsive grid.

Battery Energy Storage Systems (BESS) play a crucial role in enhancing grid flexibility by enabling various essential functions that support the integration of renewable energy sources. One of their primary capabilities is energy shifting, where BESS store excess energy generated during periods of high renewable output—such as sunny or windy days—and release it during peak demand times or when renewable generation is low. This process helps flatten the load curve, ensuring that energy is available when needed and improving overall reliability. Additionally, BESS can respond rapidly to fluctuations in grid frequency, which is vital for maintaining stability. By absorbing excess power when generation exceeds demand and discharging energy when demand surpasses generation, BESS effectively balance the grid (Hosseini et al. 2022).

Moreover, BESS contribute to peak shaving by discharging stored energy during high-demand periods, thereby reducing reliance on fossil-fuel-based peaking power plants that typically have higher emissions. This not only lowers operational costs but also supports broader decarbonisation efforts. In terms of grid resilience, BESS provide backup power during outages or disturbances, enhancing the grid's ability to withstand disruptions caused by natural disasters or other emergencies. Collectively, these functions position BESS as a fundamental component of a flexible and reliable power system in a world increasingly reliant on renewable energy (Hosseini et al. 2022).

Several methods exist to evaluate flexibility, ranging from simple screenings during periods of anticipated stress to comprehensive, minute-by-minute assessments throughout the year. In detailed modelling, flexibility risk metrics like periods of flexibility deficit (PFD) and expected unserved ramping (EUR) are calculated. These metrics consider the net flexibility of the system at each time interval, which is the difference between available flexibility and the flexibility needed to manage anticipated changes based on historical or projected data. Upward and downward flexibility needs are evaluated separately, and multiple time horizons are typically considered, such as short-term ramps (5-60 minutes) and longer-term ramps (3-8 hours) (EPRI, n.d.).

The PFD metric indicates the number of time periods with negative net flexibility, signifying a shortfall in adjusting capabilities. The EUR metric quantifies the total amount of missing flexibility across all studied time horizons. While initially developed for deterministic studies, both PFD and EUR can be adapted for probabilistic applications by averaging results across multiple simulations (EPRI, n.d.).

Flexibility metrics are quantitative measures used to assess the ability of power systems to manage variability and uncertainty in both demand and supply, particularly in the context of integrating Variable Energy Resources (VERs) such as wind and solar power. These metrics help system operators evaluate how well a power system can respond to changes in net-load (the difference between total demand and generation from VERs) and maintain reliability and security (Heggarty et al. 2020).
The existing literature primarily evaluates power system flexibility through various indices, which include:

- **Ramping Capability:** This metric assesses the system's ability to increase or decrease power output within a specific time frame. It is crucial for managing sudden changes in demand or generation, particularly with high penetration of variable energy resources (VERs).

- **Power and Energy Capacity:** These metrics refer to the total amount of power and energy that can be supplied by the system. They do not account for delays in demand response (DR) actions or system contingency responses.

- **Response Time (RT):** This is a new metric introduced to quantify system flexibility. It measures the time taken for the system to respond to changes in demand or generation, capturing the effects of delays in DR actions.

- **Insufficient Ramping Resource Expectation (IRRE):** This index evaluates the power grid's failure to manage variability in demand and supply, providing insights into potential ramping shortages.

- **Lack of Ramp Probability (LORP):** This operational index quantifies inter-temporal ramping flexibility at the real-time despatch time scale, indicating the likelihood of not having sufficient ramping resources available.

- **System Capability Ramp (SCR):** This metric quantifies the accessibility of flexibility by representing the possibility of a ramping capability shortage due to uncertainties such as failure of power plants or forecast errors in VERs.

- **Ramping Capability Shortage Expectation (RCSE):** This index embodies the possibility of ramp shortages when facing uncertainties at specific time intervals.

- **Flexibility Area Index (FAI):** This index combines the flexibility of power system units and reflects the overall system's ability to manage VER curtailment through flexible ramp up (FRU) and ramp down (FRD) components.

- **Building Energy Flexibility Index (BEFI):** This index represents the quantity of available thermal flexibility from thermal storages within buildings, highlighting the role of thermal energy in enhancing overall system flexibility (Hadi et al. 2022).

These metrics provide a comprehensive framework for evaluating the flexibility of power systems, enabling operators to identify potential shortcomings and implement strategies to enhance system performance in the face of increasing variability and uncertainty associated with renewable energy integration.

INERTIA REQUIREMENT

Inertia requirement is a critical concept in modern power systems, particularly as the penetration of distributed generations (DGs) increases. It refers to the minimum amount of rotational inertia required in a power grid to maintain frequency stability during disturbances. As traditional synchronous generators (SGs) are increasingly replaced by inverter-based DGs, the overall rotational inertia of the grid decreases, which can adversely affect frequency dynamics and the performance of frequency control schemes (Golpîra et al. 2022).

Key Aspects of Inertia Requirement

1. **Rotational Inertia and Frequency Stability:**

    - Rotational inertia is the property of a system that resists changes in its rotational speed. In power systems, this inertia is primarily provided by synchronous generators, which store kinetic energy. When there is a disturbance (like a sudden loss of generation or a spike in demand), this inertia helps to dampen the frequency fluctuations that occur.
    - As the share of inverter-based DGs (like solar panels and wind turbines) increases, the grid's overall inertia decreases because these sources do not contribute to rotational inertia in the same way that SGs do. This reduction can lead to faster frequency drops during disturbances, making it more challenging to maintain system stability.

2. **Inertia Requirement Index:**

    - The inertia requirement index quantifies the minimum permissible rotational inertia required to ensure that frequency metrics, such as frequency nadir (the lowest frequency reached after a disturbance) and the rate of change of frequency (RoCoF), remain within acceptable limits.
    - The index is derived based on frequency stability metrics and is formulated to

ensure that the system can respond adequately to disturbances without violating frequency standards.

3. **Mathematical Formulation:**

 - The inertia requirement problem can be mathematically formulated by comparing the inertia of a base system (with conventional generators) to a penetrated system (with high DG penetration). The goal is to calculate the minimum inertia required in the penetrated system to ensure that frequency deviations do not exceed specified thresholds.

 - The formulation considers various factors, including load damping, mechanical input torque, and electrical output torque, which are crucial for understanding how the system responds to imbalances.

4. **Frequency Metrics:**

The inertia requirement index is tied to several frequency stability metrics:

 - **Frequency Nadir:** The lowest frequency reached after a disturbance. The inertia requirement index ensures that this value does not fall below a certain threshold.

 - **Rate of Change of Frequency (RoCoF):** This metric measures how quickly the frequency changes after a disturbance. The inertia requirement formulation includes constraints to ensure that RoCoF remains within acceptable limits.

 - **15-Second Rolling Window:** This metric assesses the system's ability to maintain frequency stability over a specified time interval. The inertia requirement index must ensure that frequency deviations during this period do not exceed acceptable limits.

5. **Coordinated Generation Expansion Planning (GEP) and Transmission Expansion Planning (TEP):**

 - Inertia requirement is integrated into the GEP and TEP processes to ensure that future expansions of generation and transmission capacity consider the impacts of reduced inertia. This involves determining the maximum permissible penetration level of DGs while maintaining system stability.

 - The GEP formulation incorporates the inertia requirement index as a constraint, effectively treating it as a negative load in the optimisation problem. This allows for a more sustainable planning approach that balances economic development with technical requirements.

6. **Practical Implications:**

 - The concept of inertia requirement is essential for ensuring that power systems can reliably integrate high levels of renewable energy while maintaining frequency stability. It requires careful planning and modeling to determine the appropriate mix of generation resources and the necessary infrastructure to support them.

 - The proposed methodologies for assessing inertia requirement can help system operators and planners make informed decisions about future investments in generation and transmission, ensuring that the grid remains resilient in the face of increasing DG penetration.

Inertia requirement is a vital consideration in the transition to modern power systems characterised by high levels of distributed generation. It involves quantifying the minimum inertia required to maintain frequency stability and integrating this concept into generation and transmission planning processes. By addressing inertia requirement, power systems can achieve sustainable economic development while ensuring reliable operation amidst the challenges posed by variable renewable energy sources (Golpîra et al. 2022).

3.2.4 DEMAND ASSESSMENT

Demand assessment is the backbone of a reliable power system since it ensures adequate supply to maintain grid stability. Assessing demand in traditional power systems require operators to plan on a medium to long-term basis considering the commissioning of thermal and hydro power plants that consumed a fair amount of gestation period. Usually, the periodicity for such long-term demand assessments is a minimum of 10 years, estimating the peak demand/load on a monthly or yearly basis while projecting the annual demand growth rates using econometric methods (Mehra and Bharadwaj 2000). Some countries like India also estimate demand in a similar way while also simultaneously assessing sectoral consumption demand.

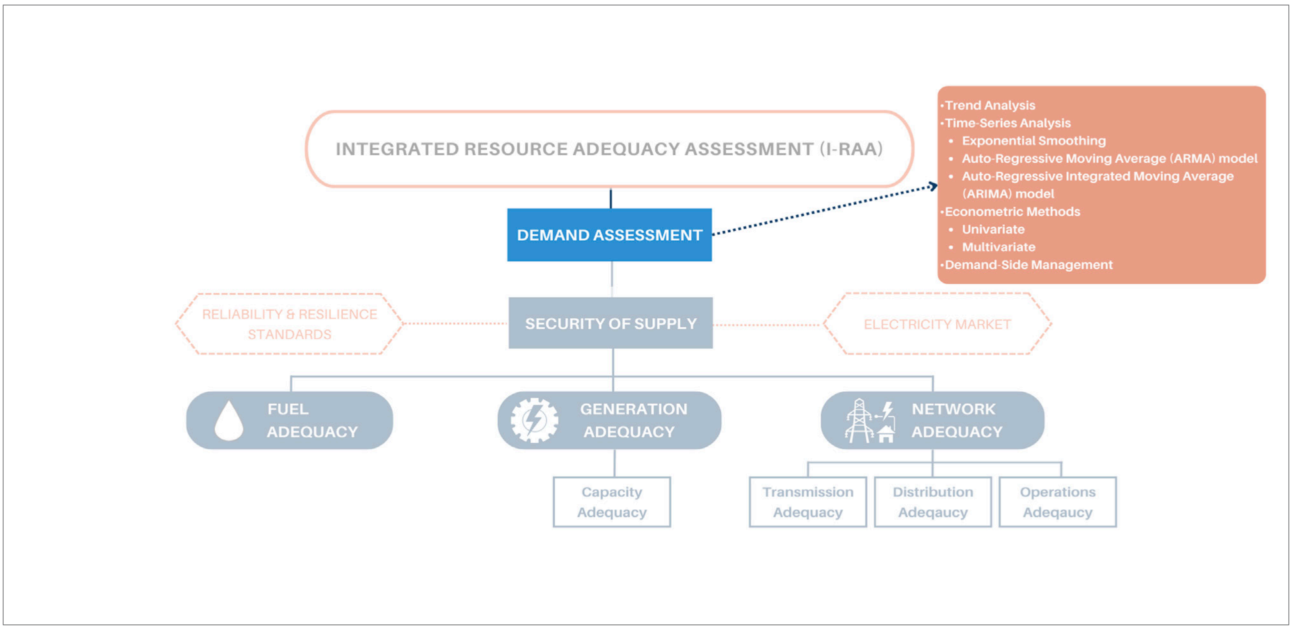


Figure 11: Integrated Resource Adequacy Framework (I-RAA) – Demand Assessment, Source: Authors

Traditional demand assessment techniques have become relatively less synchronous with the evolution in energy-mix. Renewable integration in power systems with growing changes in demand patterns have highlighted two main drawbacks arising out of traditional demand assessment methods: the inability of current metrics to capture the impact of supply variability and the normalisation of the duck curve (Synergy, n.d.), especially in the case of solar generation; and the lack of spatial and temporal granularity in capturing hourly demand changes. Changes in demand assessment primarily requires a pedagogical review of the classification of various demand assessment methods in short and long terms; these changes must also account for the stochastic factors that affect demand in shorter time frames. Eventually, these demand assessment models become capable of predicting low-probability high-impact events that can be averted.

As far as resource adequacy is concerned, demand assessment is primal since it provides insights into consumption and demand estimates that helps understand the load and its allied risk metrics that calculate the capacity to meet the peak or overall demand. Moreover, it is the very first step in any analysis aimed at ensuring sufficient resources to meet electricity needs. This process involves predicting both the peak power requirements (measured in Megawatts or MWs) and the total energy consumption (measured in Megawatt-hours or MWhs) for various timeframes. These forecasts are crucial for planning in three key horizons: short-term, medium-term, and long-term (Forum of Regulators 2023).

Demand assessment is crucial for the following reasons:

- **Reliability:** Demand assessment helps operators and utilities anticipate peak periods, ensuring enough power generation to maintain grid frequency, network stability while effectively meeting demand.
- **Temporal Arbitrage:** Demand assessment is useful to study the peaks and troughs of consumption demand. This aids in utilities to buy electricity at lower prices during troughs and sell it at high prices during peak demand.
- **Informed Planning:** Demand assessment aids in short-term and long-term investment decisions for power plants, transmission, and distribution infrastructure to meet growing needs. These decisions help in understanding the need for investing or retiring traditional generation sources. In a way, demand assessment techniques help in reducing capital costs and improving integration of renewables into the power system.

3.2.4.1 FACTORS THAT AFFECT DEMAND ASSESSMENT

A multitude of economic, environmental, demographic, technological and regulatory factors affect the assessment of electricity demand while much of these directly affect the demand patterns due to their nature of uncertainty (Momani 2013). The main factors that affect demand assessment are:

- **Economic Factors:** The two main economic factors that affect electricity demand are national income and price. Demand is expected to increase with a rise in the GDP while a rise in the price of a unit of electricity reduces consumption.
- **Environmental Factors:** Local climate or geography tends to affect the demand patterns in select sections of any region in the world. Air temperature, relative humidity, rainfall, level of solar irradiance and wind speed are considered factors in demand assessment.
- **Demographic Factors:** A nation's growing population might largely influence a surge in electricity demand. With the population explosion, consumption rises, increasing the total power requirement across the country's sectors.
- **Technological Factors:** Introduction of new technologies to improve productivity, improvements in logistical and raw material processing and technological upgradation to improve communication may largely influence energy demand. Recent developments also include standards that measure the energy efficiency of end-use appliances and equipments to ensure demand response and demand-side management, which are further discussed later in this section.
- **Regulatory Factors:** International and regional policy changes, regulations, taxation, and policy commitments for energy transition such as Green House Gas (GHG) emission, shifting towards renewable and cleaner energy, use of energy efficient equipments might significantly affect electricity demand assessment (Momani 2013).

3.2.4.2 REVIEWING THE EXISTING METHODOLOGIES OF DEMAND ASSESSMENT

Electricity demand assessment methods have come a long way. Early methods simply relied on past trends, but current techniques model various factors to create more accurate forecasts. The choice of method depends on the data available, and the level of detail needed in the forecast. In fact, it is common practice to use multiple methods and compare their results for a more robust prediction. For instance, in India, the 16th Electric Power Survey of India used a combination of trend analysis and end-use method to forecast the consumption pattern of most consumption categories except the high tension (HT) consumer category (Mehra and Bharadwaj 2000). This section explores the commonly used approaches for electricity demand assessment.

TREND ANALYSIS

Trend analysis uses the available/compiled historical data of electricity consumption over the years and expresses the demand for a day purely as a function of time over certain factors with similar characteristics instead of expressing them to be endogenous of other explanatory variables. It is a non-causal model that is widely used due to its ease of use and derivation of trend from the available data. The inherent assumption of this model is that the future values will maintain the current growth rate (WEC India, n.d.).

Similar Day Approach is a commonly used technique under the trend analysis methodology. The Similar Day Approach explores historical data to find a day with similar characteristics to make prediction for a day. Similar characteristics, for instance, include weather conditions like temperature, humidity, season, and dates. Also, they indicate a typical character of demand variation during public holidays or festivals. The demand goes very low for some part of the day and ramps very high by evening, thus posing a challenge for system operators. The load of the preceding day is the forecasted load for the day in analysis. For improved results, instead of considering a single day datum, many like days data are fitted into a linear combination or regression procedures to define a specific trend (Takiyar and Singh 2015).

Trend analysis does not internalise the effects of demography, economic factors, price, and other variables. Moreover, trend analysis also provides preliminary estimate of the forecasted variable value, making it accurate in the short-term. While less prominent in academic research, the trend method remains popular among practitioners due to its simplicity and ease of use. This method leverages historical data, such as sales figures or electricity consumption, to directly calculate growth rates. This provides a quick and clear picture of demand trends, making it a valuable tool for initial assessments (WEC India, n.d.).

TIME-SERIES ANALYSIS

Time series analysis involves a specific type of econometric model. In these models, the variables used to explain and predict the target variable are lagged values of the target variable itself. The underlying assumption is that a variable's future behaviour is related to its past values, both observed and predicted. This includes some built-in adaptation to account for past deviations from expectations. Therefore, a crucial requirement for time series forecasting techniques is access to data for the past 20 to 30 time periods.

The key distinction between econometric models using time series data and pure time series models lies in the explanatory variables. Econometric models incorporate external factors like income, prices, population, GDP, or temperature as causal influences to establish a relationship. In contrast, time series models solely rely on lagged (previous) values of the same variable for prediction purposes (Mehra and Bharadwaj 2000).

These models predict future demand with the assumption that the past trends will continue. While this works well in some situations, it does not account for unexpected events (like economic downturns or new technologies) that can drastically alter demand. However, these models can be adapted to consider such external factors, making them more robust in unpredictable environments (Takiyar and Singh 2015).

The commonly used time-series models for demand assessment are:

a. Exponential Smoothing
b. Auto-Regressive Moving Average (ARMA) model
c. Auto-Regressive Integrated Moving Average (ARIMA) model

Exponential Smoothing

Exponential smoothing is a popular technique for analysing time series data. It can be used for two main purposes: smoothing the data for better visualisation or generating forecasts. Unlike the simple moving average method, which assigns equal weight to all past observations, exponential smoothing prioritises recent data. This means more recent observations have a greater influence on the forecast compared to older ones. This makes it particularly suitable for short-term and medium-term forecasting.

There are several variations of exponential smoothing used for forecasting, each with increasing complexity:

- **Simple exponential smoothing:** This is the most basic method, considering only the actual value from the previous period and the most recent forecast to calculate the next period's forecast. It assigns weights to these values, with a higher weight given to the most recent data. This method assumes no trend or seasonal patterns exist in the data.

  $$V_{t+1} = \alpha\, A_t + (1-\alpha)\, V_t$$

  where,
  V_{t+1} = Forecasted Value for period t+1
  A_t = Actual value for period t
  v_t = Forecasted value for period t
  α refers to the weight assigned to the recent observation, thus controlling the rate of smoothing

- **Brown's double exponential smoothing:** Similar to simple exponential smoothing, but it refines the smoothing weight itself by applying a secondary smoothing process. This method is suitable for data with a linear trend but is limited to short-term forecasts.

- **Holt's non-seasonal trend smoothing:** This method introduces two smoothing constants: alpha (α) and beta (β). Alpha smooths the level (current value), while beta smooths the trend component separately. This allows for more flexibility by assigning different weights to level and trend smoothing. However, it doesn't account for seasonal variations.

- **Holt-Winters' exponential smoothing (multiplicative and additive):** This method builds upon Holt's model by incorporating a third smoothing factor to capture seasonality. It assumes an additive trend and multiplicative seasonal influence. This method offers the most comprehensive approach, modelling trend, seasonality, and randomness, but requires more data compared to other techniques (WEC India, n.d.).

The Auto-Regressive Moving Average (ARMA) model

The ARMA (p,q) comprises of two components- the Auto-Regressive (AR) component and the Moving-Average (MA) component. The AR component part considers the influence of past values of the time series on the current value. Essentially, it captures how much the current value depends on the recent past values. The MA component part focuses on the average of past forecast errors (the difference between predicted and actual values). It helps account for randomness and unexpected fluctuations in the data.

ARMA models are denoted as ARMA(p, q). The AR part involves modelling the current value of the series as a linear combination of previous values (lags). The order p specifies how many previous values are used. The MA part models the current value of the series as a linear combination of past error terms (white noise). The order q specifies how many lagged error terms are included (Vaibhav Rastogi 2023). The ARMA model is suitable for stationary data where past values and past errors influence the current value. Stationary data refers to the type of data whose overall statistical properties like mean (average value) and variance (spread of the data) remain constant throughout the timeframe.

The Auto-Regressive Integrated Moving Averages (ARMA) model

The ARIMA model on the other hand, utilises a difference operator to transform the non-stationary time series into a stationary one. Both ARMA and ARIMA models rely on analysing past patterns to predict future values. If the underlying patterns keep changing (non-stationary data), the models become unreliable for forecasting.

ARIMA accounts for differencing the data to remove trends and seasonality, essentially transforming non-stationary data into a stationary format suitable for ARMA analysis. In addition to the (p,q) components of the ARMA model, ARIMA model is denoted as (p,q,d), where d represents the differencing of raw observations to allow for the time series to become stationary (Vaibhav Rastogi 2023).

ECONOMETRIC METHODS

Econometric modelling is a common quantitative technique used in economic analysis. It establishes a statistical relationship between a dependent variable (the variable being predicted) and chosen independent variables (factors believed to influence the dependent variable) using historical data. This relationship can then be used for forecasting. By considering changes in the independent variables, we can predict their impact on the dependent variable (Mehra and Bharadwaj 2000).

For example, in electricity demand forecasting, electricity consumption is the dependent variable. Potential independent variables might include population, consumer spending indices, electricity tariffs, weather data, and even time itself.

The selection of independent variables is based on experience and a statistical evaluation of their influence. Only statistically significant factors are typically included in the final model used for demand forecasting.

Commonly used econometric methods are of two types:

a. Univariate Econometric Method
b. Multivariate Econometric Method

Univariate Method
As for the univariate method, the electricity demand would be a function of single variable, say population or time. For instance, consider the following relationship

$$Y = f(\mathrm{P})$$

Where Y is the electrical demand and P is the price of electricity.

Univariate models are sometimes used for forecasting. These models focus on just one independent variable and its relationship with the dependent variable. If this single variable explains a significant portion of the dependent variable's behavior, then further testing with additional variables might not be necessary.

In other cases, a more exploratory approach might involve testing the dependent variable against multiple independent variables initially. However, if only one independent variable demonstrates a statistically strong relationship, then the model might be built using just that single variable for simplicity and efficiency (WEC India, n.d.).

Multivariate Method
Multivariate techniques are a powerful tool for forecasting electricity demand. Unlike univariate models, they consider the potential causal relationships between multiple variables and the dependent variable (electricity demand). These variables can be demographic (population), economic (income per capita), or weather-related.

Using time-series or combined data sets, multivariate techniques can establish these relationships and express electricity demand as a function of various factors. For example, a model might include population, income per capita, and weather data as independent variables influencing electricity demand (Y):

$$Y = f(X, W, \eta)$$

Where,
Y = Electricity demand
X = Income per capita
W = Weather-related parameter
η = Population

The process involves trying different functional forms and combinations of variables until the model meets statistical significance. Once established, forecasts of the independent variables can be used in the equation to generate electricity demand projections.

The coefficients and signs of these variables in the final equation indicate the direction and strength of their influence on electricity demand. More specifically, separate single-equation regression models can be built for different categories of electricity consumers. For example, a model for domestic consumption might consider temperature and GDP, while a non-domestic model might focus on per capita income and the number of consumers. This allows for a more nuanced understanding of how different factors impact electricity demand across various sectors (WEC India, n.d.).

A fundamental aspect of statistical modelling is assessing how well the model aligns with observed data. This concept, known as goodness-of-fit, is evaluated by measures that quantify the discrepancies between the observed values and the values predicted by the model. The chi-square test, particularly Pearson's chi-square test, is a widely used method for quantifying this discrepancy.

END-USE METHOD

The end-use approach focuses on understanding how electricity consumption varies across different zones within a region. It predicts demand based on the specific end uses of electricity in each zone, such as residential, commercial, institutional, and industrial sectors (CEA 2022b).

This method employs various strategies to estimate end-use demand. These can include analysing land-use regulations, typical load requirements per area, and the level of development in each zone (Mehra and Bharadwaj 2000).

For instance, the load in a specific zone (dominated by a particular consumer category) can be calculated by considering factors like the total area, occupancy rate, space allocation norms, and Floor Space Index (FSI). These factors help determine the usable area within the zone. Multiplying this usable area by the estimated load per unit area provides an initial load estimate for the zone. Finally, a utilization factor is applied to account for actual usage patterns, giving a more realistic picture of the zone's electricity demand.

The following equation represents a potential methodology for calculating zone load (Lz):

$$L_Z = A \times O \times S \times F \times L_A \times U_F$$

Where,

L_Z = Utilised Load of a zone (MW)
A = Area of the zone (sq. km)
O = Percentage occupancy based on development level
S = Space Coverage Norms for each consumer category (% of occupied area allowed for construction)
F = Floor Space Index for each consumer category
L_A = Load per area (MW per sq. km)
U_F = Utilisation factor for each consumer category

Similar calculations can be performed for different zones within a region, considering data availability. By summing the estimated loads across all zones, the total energy demand for the entire system can be obtained (WEC India, n.d.). The end-use approach is particularly useful for refining forecasts generated by other methods (e.g., time series, trends, or econometrics). It helps account for demands that might not be captured by historical trends or independent variables in other models. The additional demand identified by the end-use method can then be added to the base demand predicted by the primary methods to create a more comprehensive forecast.

This approach is especially valuable when considering the introduction of new technologies or fuels, or when there's limited historical data on consumption trends and other relevant variables. However, it requires a high level of detail on each specific end-use category.

3.2.4.3 TIME HORIZON OF DEMAND ASSESSMENT

As mentioned in Chapter 2, demand assessment methods require constant evolution to capture the effects of technological advancements, price, income, demography, economic, and policy variables and their impact on the overall/ peak demand. Additionally, conventional models will have to eventually account for non-linear relationships between dependent and/or independent variables, a combination of techniques to express latent demand and include other tail risks and seasonal factors that tend to affect the baseline demand. Demand assessment models will have to grow out of forecast periodicity, i.e., a considerable time gap between assessment exercises that affects assumptions, baselines, and other dynamic factors.

Our framework extends the holistic approach onto demand assessment; demand assessment is classified into short-term demand estimation and long-term demand forecasting methods based on temporal granularities.

- **Demand estimation** deals with understanding current or short-term demand patterns. It uses historical data and additional factors like weather, holidays, and present events to get an idea of the amount electricity that is being used at a specific time.

- **Demand forecasting,** on the other hand, with a broader scope, predicts the medium to long-term future demand for electricity. It does use historical data, but also considers some of the anticipated changes in the economy, population growth and demand-side regulatory changes. This is crucial for planning production levels, inventory management and future infrastructural investments.

3.2.4.4 DATA REQUIREMENTS FOR DEMAND ASSESSMENT

Accurate demand forecasting plays a crucial role in utility system planning and operation. This process necessitates a comprehensive dataset encompassing various aspects of electricity and alternative fuel consumption within the service area. Key data categories for effective forecasting include:

- **Sales Records:** Historical data on electricity sales across multiple years provides a foundation for understanding consumption patterns. This data should be disaggregated by geographical area and customer class (residential, commercial, industrial) to capture variations in demand across different sectors and locations. Additionally, the number of customers in each class and area aids in demand projections.

- **Demand Records:** Time-series data on power demand measured in megawatts (MW) across various timeframes (days, weeks, months, years) is essential. Analysing this data helps establish the relationship between electricity sales and the required generation capacity. Disaggregated data, further dividing demand by customer class or sector, offers more granular insights. The shape of the load curve, reflecting peak load variations over time (load profile), informs decisions regarding the most suitable types of generation capacity to meet demand fluctuations.

- **Economic and Demographic Data:** Historical information on economic performance alongside population or household count data provides context for demand forecasts. This data helps understand the impact of economic growth and population changes on energy consumption.

- **Weather Data:** Real-time data points on temperature, humidity, wind and rainfall patterns, season and weather event predictability, among others can help in assessing the demand for different regions.

- **Economic and Demographic Projections:** Utility companies can leverage their own economic and demographic forecasts for their service territory. Alternatively, projections might be obtained from government planning ministries or specialized institutions.

- **Energy End-Use Data:** Ideal data for end-use analysis includes:

    a. The number or proportion of households using specific electric appliances.
    b. The number or proportion of commercial, institutional, or industrial consumers employing different types of electric equipment.
    c. Electricity consumption per customer per specific end-use (e.g., lighting, heating).
    d. This data, often referred to as penetration/saturation (e.g., percentage of electrified households) and energy intensity (e.g., kWh/household/year), should ideally be available for each customer class and major end-use category. However, obtaining historical data with this level of granularity can be challenging.

- **Data Acquisition Strategies:**

    a. National census documents may offer partial data on appliance ownership or use, primarily for the residential sector.
    b. In developing countries, government agencies or Non-Governmental Organisations (NGOs) may have conducted energy end-use studies or participated in data collection initiatives funded by international aid programs. Despite these efforts, data completeness may not always meet forecasting requirements.
    c. Conducting new end-use surveys often becomes necessary to obtain the level of detail required for robust end-use forecasts.

3.2.4.5 DEMAND SIDE MANAGEMENT (DSM)

The power structure mechanisms, along with the power system, has been under constant evolution. The dynamic nature of electricity demand coupled with integration of variable energy resources have necessitated restructuring of operations from vertically integrated mechanisms to open market systems. With the deregulation of the electricity supply chain industry across countries of the world, the traditional approach of balancing supply to unconstrained demand is now slowly getting replaced with consumer-responsive demand side flexibility (Bhattacharya, Bollen, and Daalder 2001).

Maintaining a reliable electricity grid requires a delicate balancing act – perfectly matching supply and demand in real-time. This task is particularly challenging because both sides of this equation can fluctuate rapidly and unexpectedly. Factors like unplanned outages at power plants, transmission lines, or distribution systems, coupled with sudden surges or dips in consumer demand, can disrupt this balance (Albadi and El-Saadany 2008).

Traditionally, grid operators have relied on building more generation capacity to meet peak demand. However, electricity infrastructure is highly capital-intensive – expensive to build and maintain. This is where demand-side management (DSM), particularly demand response (DR), offers a more cost-effective solution. By incentivising consumers to adjust their electricity usage during peak periods, DR programs leverage an existing resource – the ability of consumers to modify their demand – to help maintain grid stability. This approach represents a new philosophy in grid management, focusing on optimising both supply and demand for a more efficient and cost-effective system.

Demand Side Management (DSM). The Electric Power Research Institute (EPRI) has defined DSM as follows: 'DSM is the planning, implementation and monitoring of those utility activities designed to influence customer use of electricity in ways that will produce desired changes in the utility's load shape, i.e., time pattern and magnitude of a utility's load' (Barakat & Chamberlin Inc. 1993). The changes in electricity consumption pattern under DSM are further classified into energy efficiency and demand response.

Energy efficiency refers to long-term changes that permanently reduce overall energy consumption. These reductions are achieved through investments in technologies and practices that require less energy to produce the same level of output. This is in contrast to demand response programs, which focus on targeted load reductions during specific events. Energy efficiency essentially gets more output from each unit of energy used, leading to a general decrease in consumption across all hours of operation, rather than temporary reductions driven by specific events (Morales-España, Martínez-Gordón, and Sijm 2022).

Demand response (DR) can be defined as the changes in electricity usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time. Further, DR can be also defined as the incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardised (Albadi and El-Saadany 2008).

EXPLICIT DEMAND RESPONSE PROGRAMMES

Explicit DR programmes involve direct, contractual agreements between utilities and participating customers. Also known as Incentive Based Programmes (IBP), they incentivise customers to adjust their electricity usage during peak demand periods or upon request from the utility (Bertoldi, n.d.). The key features of explicit DR include

- **Predefined Agreements:** Utilities and customers establish clear terms outlining the specific actions expected from customers and the corresponding rewards they will receive.
- **Financial Incentives:** Customers are compensated for their participation, typically through direct payments or bill credits proportional to the amount of load reduction achieved.

Some of the major explicit DR forms include:

- **Direct Load Control (DLC):** Direct Load Control programs empower utilities to directly manage specific appliances of participating customers during critical peak periods. This control is typically exercised remotely, with the customer's prior consent. Commonly controlled equipment in DLC programs includes air conditioners and water heaters. These programs are particularly attractive for residential and small commercial customers due to the prevalence of suitable appliances in these sectors.
- **Interruptible/Curtailable Programs:** Programs offering interruptible or curtailable service incentivise participation through upfront payments or discounted rates. In return, customers agree to temporarily reduce their electricity usage to predetermined levels when requested. However, failure to comply with these load reduction requests may result in penalties, as outlined in the program's specific terms and conditions.
- **Demand Response Buyouts/Demand Bidding:** Customers are compensated for installing equipment or adopting practices that reduce peak demand, such as smart thermostats or battery storage systems (Albadi and El-Saadany 2008).

IMPLICIT DEMAND RESPONSE PROGRAMMES

Implicit DR programmes, also referred to as Price Based Programmes (PBP) rely on dynamic pricing structures to influence customer behaviour without the need for formal contracts. By reflecting real-time grid conditions in the electricity price, these programs incentivise customers to adjust their consumption patterns to benefit from lower prices during off-peak periods (Bertoldi, n.d.).

Dynamic pricing methods are the commonly used Implicit DR techniques. A dynamic tariff is defined as the "charging of different electricity rates at different times of the day and year to reflect the time-varying cost of supplying electricity" (Ravi Kumar, Ramesh Tunga, and Sinha 2022).

- **Static Time-of-use (TOU)** pricing is a common example of implicit DR. This usually applies to use of electricity for large time blocks of several hours, with the price for every time block specified in advance and remaining constant. Static ToU may use other time blocks, such as simple day and night pricing for off-peak and on-peak hours, or time blocks can be split into further smaller segments or according to seasonal consumption patterns (Ravi Kumar, Ramesh Tunga, and Sinha 2022).

- **Critical peak pricing (CPP)** adds a pre-determined surcharge to the existing Time-of-Use (TOU) rates or flat rates during specific periods. Higher prices are charged during the day or on days when wholesale electricity prices are highest or the grid is unusually constrained (Ravi Kumar, Ramesh Tunga, and Sinha 2022).

- **Extreme day pricing (EDP)** is similar to CPP in terms of having a higher electricity price. However, EDP differs by applying this higher price for the entire 24 hours of a pre-identified "extreme day," which is not known until the day before.

- **Extreme day critical peak pricing (ED-CPP)** combines elements of both CPP and EDP. During pre-identified "extreme days," CPP rates are applied for both peak and off-peak periods. However, on all other days, a flat rate applies (Albadi and El-Saadany 2008).

- **Real-time pricing (RTP)** is a mechanism where prices are set according to real time electricity consumption and are determined according to wholesale electricity prices (Ravi Kumar, Ramesh Tunga, and Sinha 2022). These programmes charge customers hourly electricity prices that fluctuate based on the actual cost of electricity in the wholesale market. Customers enrolled in RTP programs receive price information either a day ahead or even an hour ahead of time. Many economists advocate for RTP as the most direct and efficient form of demand response (DR) program, particularly suited for competitive electricity markets. This is because the dynamic pricing structure directly incentivises customers to adjust their consumption patterns based on real-time electricity costs (Albadi and El-Saadany 2008).

3.2.5 RESILIENCE METRICS

Resilience means the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents (Executive Office of the President 2013). Resilience is different from reliability in the sense that the former focuses on uncertainties whereas reliability assessment methods like resource adequacy assessments focus on risks (Carvallo et al. 2023). In power planning studies, risks are included instead of uncertainties because while the outcome of the risk is unknown, the probabilities surrounding these outcomes can be ascertained. Factoring in uncertainty involves factoring in unknown outcomes and unknown occurrences.

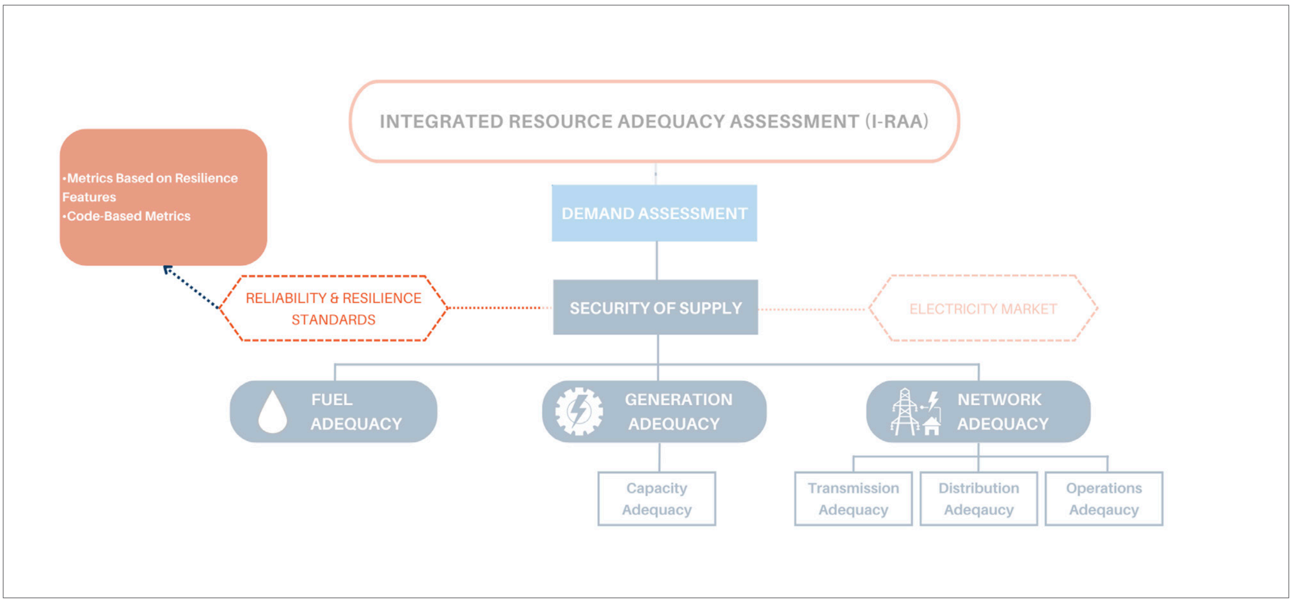


Figure 12: Integrated Resource Adequacy Framework (I-RAA) – Reliability and Resilience Standards, Source: Authors

It is for the same reason that planning processes prioritise repeated modelling of risk events where demand exceed supply over uncertain events that assess the impact of, say, adverse weather events over the power system. This is why, in practice, uncertain events are managed through emergency responses and contingency procedures that operators can use on a short-term basis once the uncertain event and its magnitude of impact are known (Carvallo et al. 2023).

3.2.5.1 CONCEPT OF GRID RESILIENCE: CONTEXTUAL DEFINITIONS

In the context of the North American Transmission Forum (NATF), resilience goes beyond traditional reliability concerns. It focuses on preparing for and responding to severe, infrequent, and often unconventional events. These "high impact, low frequency" (HILF) scenarios, also referred to as "gray sky" and "black sky" days, encompass threats like extreme weather events or coordinated cyber-physical attacks (Galloway Sr 2018).

The NATF's approach acknowledges the possibility, however unlikely, of a major disruption to the Bulk Power System (BPS). Therefore, it emphasizes advanced planning, strategies to "operate through" such events, and comprehensive restoration plans. These plans consider various factors: the type of event (natural disaster vs. ongoing cyberattack), geographic reach, expected duration, affected equipment, and potential impacts on other sectors. In the most severe "gray sky" or "black sky" scenarios, disruptions could last for weeks or even months. This underscores the importance of robust communication, collaboration across sectors, and coordinated restoration efforts based on pre-defined priorities (Galloway Sr 2018).

According to Pacific Northwest National Laboratory (PNNL), resilience is defined as the ability of the electricity system to "prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions," where disruptions include "deliberate attacks, accidents, or naturally occurring threats or incidents" (Kazimierczuk et al. 2023).

The US Department of Energy defines grid resilience as the "The ability of a power system and its components to withstand and adapt to disruptions and rapidly recover from them" (Office of Energy Efficiency & Renewable Energy, n.d.-b).

The Federal Energy Regulatory Commission (FERC) also defines grid resilience in a similar manner as "The ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event" (Vega Penagos et al. 2024).

3.2.5.2 CONCEPT OF POWER SECTOR RESILIENCE

According to the Resilient Energy Platform (REP) of the National Renewable Energy Laboratory (NREL), power sector resilience refers to 'the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions to the power sector through adaptable and holistic planning and technical solutions'.

The REP discusses the need for power system resilience to identify threats that can cause interruptions and chronic undersupply. The power sector might be susceptible to three different types of threats due to vulnerabilities within its infrastructure, systems or operations: natural threats, technological threats and human-caused threats.

Enhancing power sector resilience hinges on a systematic approach. This involves proactively identifying and mitigating vulnerabilities through resilience planning. Resilience planning can be conducted at various geographic scales and should be seamlessly integrated into existing power sector planning processes, such as integrated resource planning or power development planning.

3.2.5.3 RESILIENCE VERSUS RELIABILITY

A critical distinction exists between resilience and reliability in power grids. Resilience is an intrinsic characteristic, reflecting a grid's ability to withstand stress without experiencing outages or service disruptions. A perfectly resilient grid, by definition, would never experience outages. Therefore, traditional reliability metrics, which focus on outage frequency, duration, and impact, are not suitable for quantifying resilience. They essentially measure what happens after resilience has failed. A more accurate definition of grid resilience emphasizes the ability to resist or gracefully degrade under stress, minimising service disruptions (Taft 2017).

Reliability, on the other hand, comes into play after a resilience breakdown (outage) has occurred. Standard reliability metrics fall into two categories: frequency indices (how often outages occur) and duration indices (how long outages last). These metrics provide a picture of how well a grid responds to disruptions, but not how well it avoids them altogether.

The relationship between resilience and reliability is complex. While improving resilience can potentially enhance reliability, it cannot be guaranteed. Reliability metrics depend on specific events causing outages, while resilience aims to prevent such events. Grid stresses may not always intersect with implemented resilience measures, so reliability metrics might not reflect the actual improvement in resilience (Taft 2017).

Both resilience and reliability can be applied at various scales, from the entire power system down to a single device. The chosen scale depends on the specific problem being addressed. It is important to consider both physical extent and time scale when defining the scope of analysis.

3.2.5.4 CHARACTERISTICS OF RESILIENCE

A resilient power grid exhibits several key characteristics: anticipation, resistance, withstanding, absorption, adaptation, recovery, and learning. Let's delve into each of these characteristics:

- **Anticipation:** Proactive measures are taken before disruptions occur. This involves predicting potential events, assessing their severity, and implementing preventive actions to minimize their impact on grid performance.
- **Resistance:** As disruptions unfold, the grid actively resists and mitigates their damaging effects. The goal is to ensure operational continuity despite the challenges.

- **Withstanding:** Even under disruption, the grid maintains a basic level of functionality within acceptable parameters.
- **Absorption:** The system can absorb the blows from disruptions, preventing cascading failures and minimising overall damage.
- **Adaptation:** When disruptions occur, the system adjusts, reorganizes, or modifies its configuration in an attempt to overcome the challenges.
- **Recovery:** Following a disruption, the grid repairs or restores any damage incurred.
- **Learning:** The system continuously learns from past events. These lessons inform improved risk reduction measures and enhance the grid's flexibility to handle future disruptions (Lin and Wu 2024).

3.2.5.5 RESILIENCE METRICS

There are several metrics that capture resilience based on different attributes. Metrics based on power system resilience features capture the impact of resilience attributes –resourcefulness, rapid recovery, robustness, and adaptability. There are code-based metrics that measure the magnitude and duration of an extreme outage event for the use of measuring resilience.

METRICS BASED ON RESILIENCE FEATURES

Pre-Event Evaluation and Post-Event Estimation Metrics: The Resilience Trapezium

The resilience trapezoid offers a visual representation of the relationship between time, system states, and available measures during and after disturbances. The concept of resilience can be visualised through a comparison of system state curves for both resilient and traditional power systems. These curves depict how system performance varies over time. By dividing time into distinct intervals, the curves can illustrate the system's performance and corresponding characteristics at each point. This approach not only captures the system's behaviour at any given moment, but also reveals the spatial and temporal relationships between disruptive events and their impacts on the power grid. This comprehensive view is crucial for understanding how resilient systems navigate disruptions compared to traditional ones.

- **Pre-disturbance resilient state:** This phase involves evaluating potential disturbances and pre-arranging resources needed for post-event recovery.

- **Phase I (disturbance progress):** This phase demonstrates the system's absorption capacity. Smart grid technologies and distributed energy systems play a crucial role here by offering operational flexibility to manage the disruption. The primary goal is to minimise the decline in system performance during this phase.

- **Phase II (post-disturbance degraded state):** This phase showcases the system's ability to adapt. Here, assessments of disturbance-related losses are made, along with the formulation and swift implementation of recovery strategies. The focus here is to shorten the duration of this degraded state.

- **Phase III (restorative state):** This phase highlights the system's recovery capability. Measures like repairing damaged components, restarting units, and re-energising lines are taken to restore system performance and meet electricity demand. The objective is to achieve a swift restoration of load.

- **Post-restoration state:** This final phase involves analysing the impact of the disturbance on the system. Based on this analysis, improvements are implemented to enhance the system's ability to handle similar events in the future (Lin and Wu 2024).

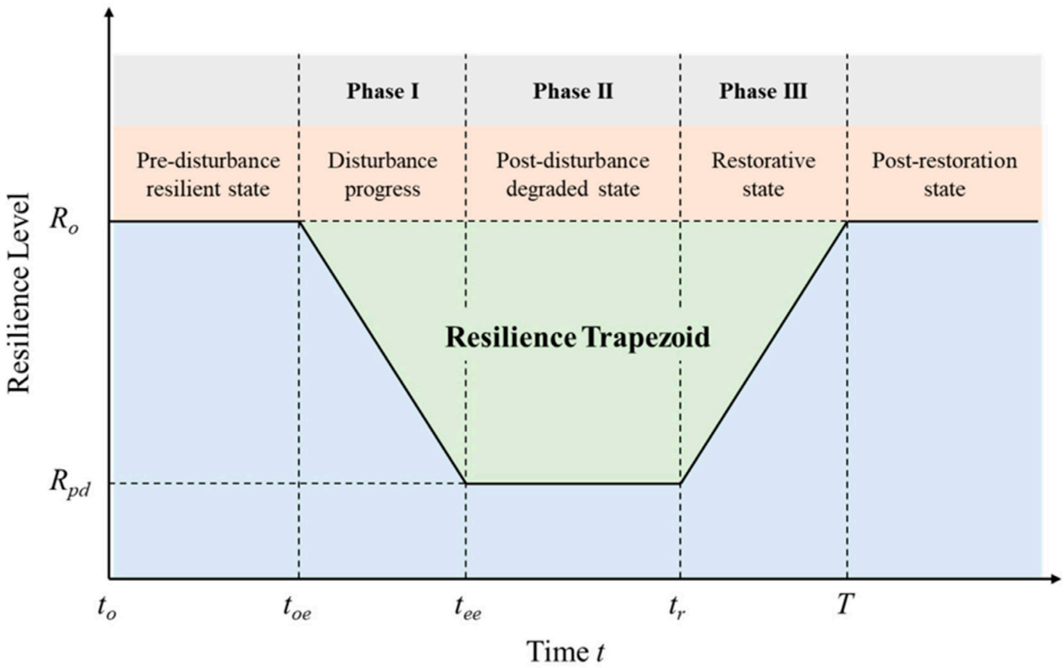


Figure 13: The Resilience Trapezoid, Source: (Lin and Wu 2024)

Pre-Event Evaluation

A general risk evaluation is conducted before the event occurs. D_{event} represents the extent of damage to the electrical power supply caused by the event. P_{event} represents the probability of the event occurring. $I_{RD\ event}$ is the outage risk index for a specific area associated with the event. $I_{Re\ event}$ is the resilience assessment metrics before the event, as shown in the below equation. It is important to note that when calculating D_{event}, all possible emergency supply paths and potential remote-control methods should be taken into consideration to evaluate the number of customers without power (Amicarelli et al. 2018):

$$I_{Re\ event} = \frac{1}{I_{RD\ event}} = \frac{1}{P_{event} \cdot D_{event}}$$

A common tool used for pre-event evaluation is Failure Mode and Effect Analysis (FMEA). FMEA helps identify potential failures in the power grid under various conditions, such as extreme weather events. It considers three factors to calculate a risk priority number (RPN) for different failure modes:

$$RPN = [P \times S \times D]_{m \times n}$$

- **Probability (P):** The likelihood of a failure occurring due to a specific event (e.g., extreme weather).
- **Severity (S):** The seriousness of the consequences of the failure, such as the amount of load lost.
- **Detectability (D):** The ease of identifying the failure mode before it causes a major disruption (Lakshita and Nair 2022).

Post-Event Estimation

Post-event estimation focuses on how a power system's performance changes during and after a disruptive event. The goal is to understand how resilient the system is compared to a traditional system that might experience a larger decline in performance.

One way to measure resilience is by looking at the total load loss over time. A resilient system will have a smaller area of load loss compared to a less resilient system. Mathematically, resilience can be expressed as the reciprocal of load loss (Li et al. 2017).

Resilience = 1/Loss

The load loss can be calculated by integrating the relative deviation over the duration of performance degradation (from time t1 to t4), as shown below:

$$Loss = \int_{t_1}^{t_4} \left[\frac{Q_0 - Q(t)}{Q(t)} \right] dt$$

A shorter performance degradation period (t1 to t2) generally indicates a more robust system that can withstand the initial impact of an event. However, some performance degradation is expected, and a very short degradation period might suggest the event itself was not significant. This initial decline provides time to take corrective measures and mitigate the event's impact, minimising the overall performance decline.

On the other hand, a shorter adaptation and recovery phase (t2 to t4) signifies a more flexible and resilient system. This phase represents the system's ability to adjust and recover from the event to return to normal performance levels. The rate of performance change during this recovery phase should be relatively high compared to the degradation phase (Lin and Wu 2024).

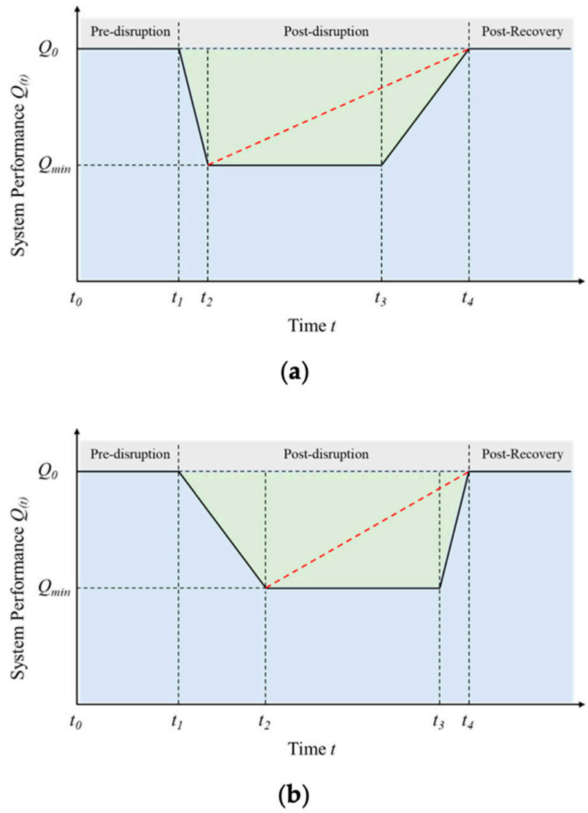


Figure 14: Comparison of two systems with the same load loss under different circumstances- (a) system lacking capabilities of absorption and recovery (b) system with better capabilities of absorption and recovery. Source: (Lin and Wu 2024)

An example is provided in Figure 14, which compares two systems with the same amount of load loss. System 14b is considered more resilient because it has a longer duration for absorbing the event's impact (t1 to t2) and a faster recovery phase (t2 to t4). This indicates better absorption and recovery capabilities.

To account for both the rate of performance degradation and recovery, a coefficient (γ) is

introduced into the resilience metric equation. This coefficient considers the relative lengths of the degradation and recovery phases. A higher coefficient indicates greater resilience.

$$\gamma = \left| \frac{t_2 - t_1}{t_4 - t_2} \right|$$

$$R' = \frac{\gamma}{Loss}$$

where γ is the resilience coefficient and R is the optimised resilience assessment metric (Lin and Wu 2024).

Disturbance and Impact Resilience Evaluation Curve (DIRE)

The Disturbance and Impact Resilience Evaluation Curve (DIRE) illustrates the relationship between time and performance levels for resilient and un-resilient systems. Additionally, several common terms have been presented, including robustness, agility, adaptive capacity, adaptive insufficiency, resiliency, and brittleness. In the DIRE curve, t_i represents the time when the disturbance starts; t_{Bi} indicates the duration during which the system performance is below the resilience threshold (i.e., minimum normal value); t_R is the time when the system reaches the minimum performance level; t_{Bf} signifies the time when the system performance returns to the resilience threshold; t_f represents the end time of the recovery process (Rieger 2014).

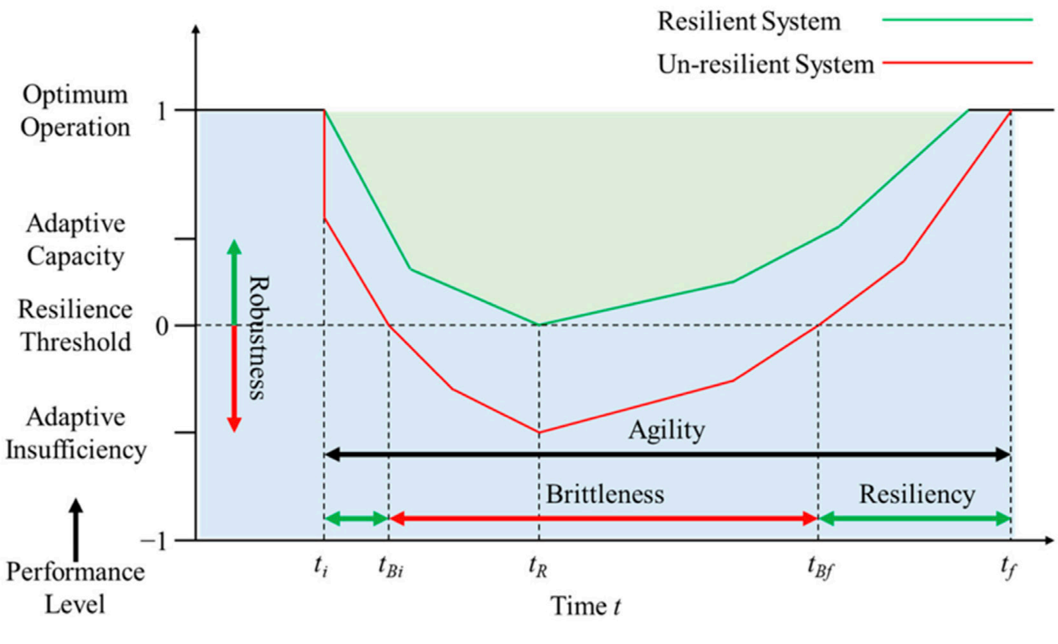


Figure 15: Disturbance and impact resilience evaluation (DIRE) curve, Source: (Rieger 2014)

CODE-BASED METRICS

A code-based metric has been developed to quantify both the severity and duration of power outages. This metric initially calculates unscaled resilience, and then applies a scaling process to transform the values onto a scale from one to nine.

$$m' = c(\alpha + \exp(f))(1+f), \quad (5)$$

$$f = \frac{\text{Load unaffected by PDS events (kW)}}{\text{Total load of PDS (kW)}}, \quad (6)$$

m'	1.00–3.71	3.72–6.42	6.43–9.13	9.14–11.85	11.86–14.56	14.57–17.27	17.28–19.98	19.99–22.70	22.71–25.41
m	1	2	3	4	5	6	7	8	9
	Low Resilience			Moderate Resilience				High Resilience	

m is the scaled resilience value—an integer between 1 and 9

Where:

- m' is the unscaled resilience value
- c is a binary indicator (1 if an event occurred, 0 otherwise)
- α is the outage duration in seconds
- f is the fraction of unaffected load
- 10^6 is a constant representing the assumed maximum repair time in seconds

This metric assumes that repair times can range from 10^0 to 10^6 seconds (Chanda et al. 2018).

Other Resilience Metrics

Grid Recovery Time (GRT): It is a resilience measure to the server for the time taken to restore the grid to pre-attack condition. The assessment of GRT helps in identifying the location of the attack (or cyberattack in case of smart grids).

Resilience to Stress Index

The power system Resilience Stress Index (RSI) is a metric designed to quantify the resilience of power systems under stress conditions. The document outlines a formula for calculating this index, which incorporates various factors related to system performance during disturbances.
The RSI can be expressed as follows:

$$RSI = \frac{L_{Mm}}{L_{max}}$$

Where:

- L_{Mm} represents the maximum level of decline in system performance during a disturbance.
- L_{max} is the total potential loss incurred by the system, which includes the disconnection of all loads and distributed generators (DGs).

This index provides a way to assess how well a power system can withstand and recover from disruptions, with a lower RSI indicating better resilience. The formula emphasises the relationship between the actual performance decline and the maximum possible loss, allowing for a comparative analysis of

resilience across different scenarios or systems (Mohanty et al. 2024).

3.2.5.6 RESILIENCE EVALUATION CRITERIA

The initial step in developing resilience metrics is the identification of appropriate evaluation criteria. Various resilience evaluation criteria have been proposed to assess power system resilience. These criteria encompass interruption of service, duration of outages, cost of recovery, and cost of prevention. Given the lack of universally accepted resilience metrics, resilience has been evaluated using a combination of deterministic and probabilistic criteria, including served/unserved energy, load curtailment and restoration, and outage duration (Bhusal et al. 2020).

Several criteria have been suggested by (Vugrin, Castillo, and Silva-Monroy, n.d.) to capture the consequences of extreme events from different perspectives. These perspectives include:

- **Electric Service:** Total outage hours, unserved energy, and average number of customers experiencing outages.
- **Critical Electric Service:** Cumulative outage hours for critical customers, unserved energy for critical customers, and average number of critical loads experiencing outages.
- **Restoration:** Restoration time, recovery time, and cost of recovery.
- **Monetary:** Loss of revenue, grid damage costs, avoided outage costs, loss of perishables and assets, business interruption costs, and impact on municipal or regional product.
- **Community Function:** Critical services without power, outages exceeding certain hours, and power outages affecting key facilities like military facilities.

Existing resilience evaluation criteria are further explained below:

LOAD CURTAILMENT MINIMISATION

In deterministic approaches, minimising load shedding/curtailment or the cost of lost load is often considered a resilience evaluation criterion. These approaches prioritise critical load curtailments over non-critical ones, implying that a system is more resilient if it avoids or minimises critical load curtailments during disasters. While minimising critical load curtailment is a priority, system constraints (e.g., damaged lines) may prevent power supply to all or part of critical loads. In such cases, extra available power is directed towards non-critical loads. Several studies have considered load shedding or cost of load shedding minimisation as a resilience evaluation criterion. Additionally, they have combined load shedding or cost of load shedding minimisation with service restoration time (Farzin, Fotuhi-Firuzabad, and Moeini-Aghtaie 2016).

RATE OF RECOVERY

Rate of recovery, particularly prioritising critical load restoration over non-critical loads, is a commonly used resilience evaluation criterion. Several studies have focused on maximising critical load restoration after disasters. Other studies have considered both maximising load restoration and minimising restoration time, while some have prioritised minimising recovery time. Additionally, some have emphasised reinforcing physical energy infrastructure and reducing recovery time as resilience evaluation criteria (Mousavizadeh, Haghifam, and Shariatkhah 2018).

SERVED ENERGY

Both deterministic and probabilistic approaches have been used as resilience criteria related to served energy. Deterministic approaches often involve minimising unserved energy or maximising the weighted sum of restored loads over time. Probabilistic approaches may focus on minimising the weighted sum of expected energy not supplied. Maximising energy supplied to critical loads has been considered by some as a resilience evaluation criterion (Gao et al. 2016). Some works have considered minimising expected energy not supplied as a resilience criterion. Other studies have focused on minimising unserved energy, minimising the weighted sum of curtailed loads, or maximising the weighted sum of restored loads over time (Lei et al. 2019).

3.2.5.7 RESILIENCE ENHANCEMENT METHODS

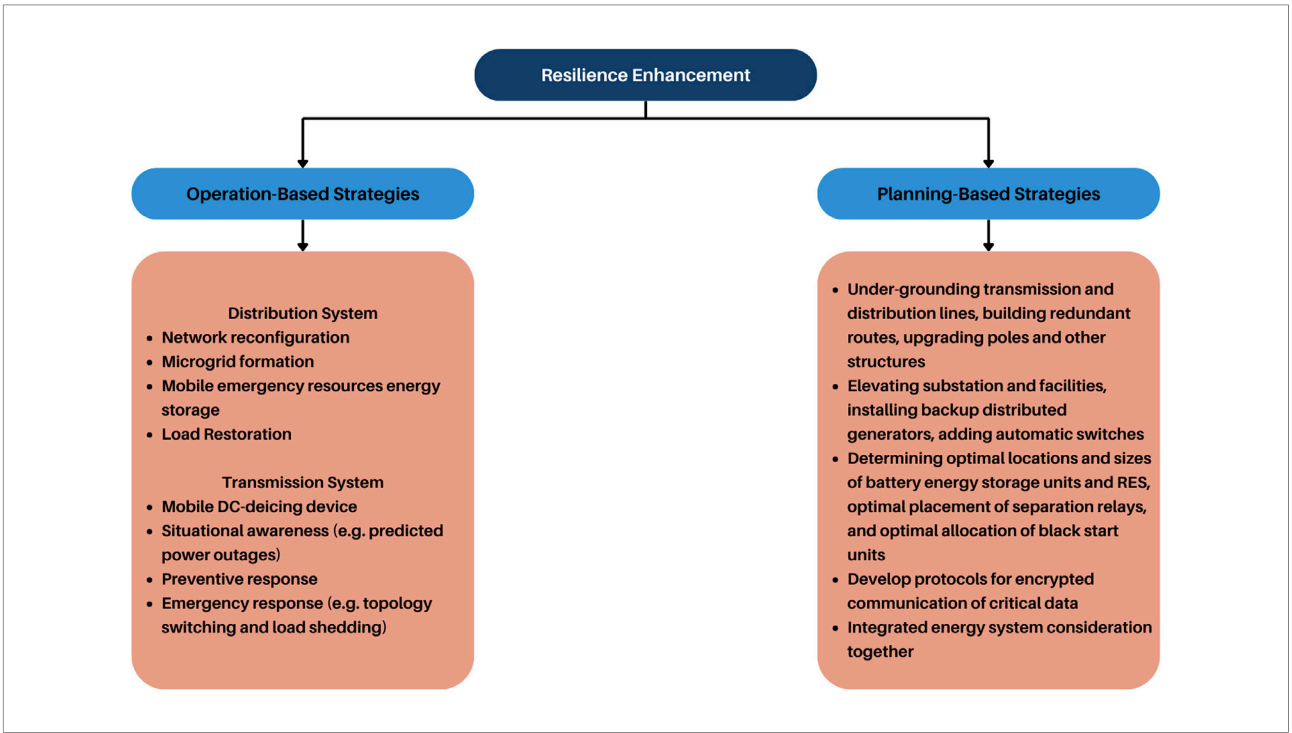


Figure 16: Summary of Resilience Enhancement. Source: (Chanda et al. 2018)

Resilience enhancement strategies for both electric power distribution and transmission systems are becoming increasingly important. While resilience enhancement at the distribution level has garnered significant attention, several methods have also been proposed for the transmission level and for interdependent systems like power and natural gas.

These strategies can generally be categorised into planning-based and operation-based approaches. Planning-based methods focus on developing grid expansion plans to strengthen transmission and distribution systems against future extreme events. Operational-based methods, on the other hand, employ optimisation techniques to utilise existing assets effectively in response to failures and extreme weather conditions (Panteli et al. 2017).

OPERATION-BASED RESILIENCE ENHANCEMENT METHODS

Operational resilience offers immediate solutions to mitigate the impact of adverse events on the power grid. Operation-based strategies for distribution systems can be broadly categorised into network reconfiguration, microgrid islanding, mobile emergency resources and energy storage, and load restoration (Panteli et al. 2017).

- Reconfiguration-based methods have been proposed to enhance distribution system resilience. These methods often involve integrated frameworks combining network reconfiguration, generation rescheduling, conservation voltage reduction, optimal setting of drop-controlled units and demand-side resources, and backup generation utilisation.

- Microgrid formation and splitting the grid into smaller, independent microgrids have also been extensively studied as a resilience enhancement technique. Microgrid islanding and topology reconfiguration have been explored, along with pre-disturbance scheduling and determining feasible island configurations for hybrid microgrids. Defensive islanding strategies have been proposed to prevent cascading events triggered by line damage, and demand response programs have been developed to reduce load curtailments during emergencies (Bajpai, Chanda, and Srivastava 2018).

- Utilising mobile emergency resources and energy storage units has been widely adopted to improve distribution system resilience. Optimal operation of mobile energy resources during both normal and emergency conditions has been studied, and integration of transportable energy storage, generation rescheduling, and network reconfiguration has been explored.

- Load restoration-based approaches have also been investigated. These approaches often focus on despatching repair crews to expedite grid element restoration and leveraging distributed generation to speed up restoration processes. Look-ahead load restoration strategies and distribution service restoration models have been developed to optimise switching sequences and utilise despatchable distributed generation during extreme events (Chanda et al. 2018).

Situational awareness-based integrated resilience response frameworks have been developed to enhance power grid resilience, incorporating predicted power outages, preventive responses like security-constrained optimal power flow, and emergency responses like topology switching and load shedding. Mobile de-icing devices have been proposed for transmission system resilience, and transmission system reconfiguration has been comprehensively studied.

PLANNING-BASED RESILIENCE ENHANCEMENT METHODS

Planning-based resilience enhancement methods have also received significant attention. These methods include undergrounding distribution and transmission lines, building redundant routes, upgrading poles and structures, elevating substations and facilities, adding backup generators, installing remote control switches, enhancing vegetation management, determining optimal locations and sizes of battery energy storage units and renewable energy sources, optimal placement of separation relays and black start resources, developing protocols for encrypted communication of critical data, and integrated electricity and natural gas transportation system planning (Arghandeh et al. 2016).

3.2.5.8 RESILIENCE EVALUATION METHODS

Developing mathematically accurate and computationally efficient resilience evaluation methods is crucial for building resilient power systems. Various approaches have been proposed in the literature, including sequential and non-sequential Monte Carlo simulations, preselected scenario-based methods, contingency-based methods, and machine learning-based methods.

SEQUENTIAL MONTE CARLO SIMULATIONS

Sequential Monte Carlo (SMC) simulations have been used to assess the impact of failure events on both transmission and distribution systems. These simulations generate outage scenarios based on the failure probabilities of system components under extreme weather conditions. Extreme weather events can cause widespread outages, depending on the system's size, type, and the intensity of the weather (Yang et al. 2018).

NON-SEQUENTIAL MONTE CARLO SIMULATIONS

Non-Sequential Monte Carlo (NSMC) simulations can evaluate the spatial impact of extreme events on power systems. They have been used independently and in combination with other methods to assess failure event impacts. Both historical data-based and weather intensity-based failure probabilities have been used to sample outage scenarios (Chanda et al. 2018).

CONTINGENCY-BASED METHODS

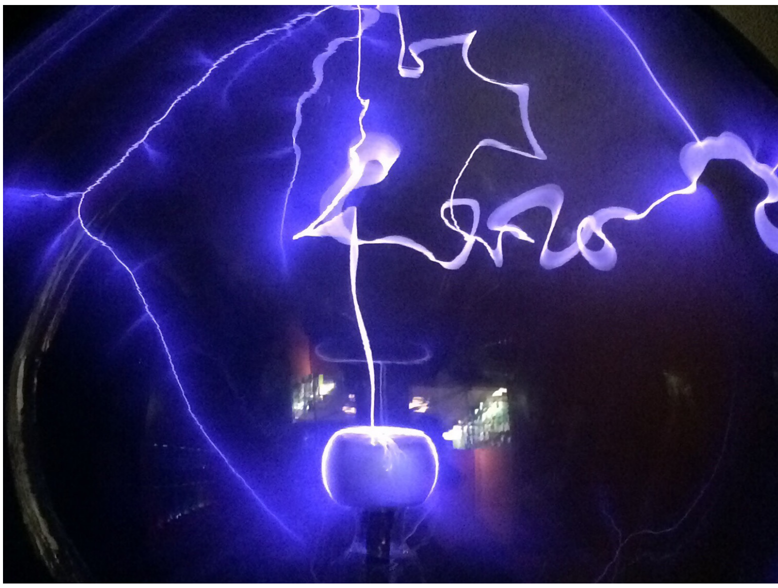
Power system resilience has been evaluated for specific types of contingencies, including vulnerability-based, failure probability-based, arbitrarily selected, microgrid formation probability-based, and cascading failure-based contingencies (Chanda et al. 2018). Vulnerability-based contingencies often consider the intensity and direction of weather events, while failure probability-based contingencies use component failure probabilities. Arbitrarily selected contingencies are used in many studies to validate proposed methods. Microgrid formation probability-based contingencies consider the likelihood of microgrid formation under extreme weather, and cascading failure-based contingencies assess the impact of system-wide cascading failures (Lei et al. 2019).

MACHINE LEARNING-BASED METHOD

A predictive statistical machine learning algorithm has been developed to evaluate power system resilience in terms of outages, outage durations, and interrupted customers. A dataset is created based on hurricane characteristics, service area climate, and network topologies. This dataset is divided into training and validation sets, and a five-fold cross-validation technique is used to optimise the number of samples (Nateghi 2018).

BAYESIAN NETWORK-BASED METHOD

A dynamic Bayesian network-based method has been proposed to evaluate power grid resilience. This method considers structural and maintenance resources as key resilience elements and evaluates failure probabilities with and without external shocks. Power system states are represented by node states, and failure and repair rates of system components are modelled using a dynamic Bayesian network (Cai et al. 2018).



COUNTRY CASE: HAWAIIAN ELECTRIC

Hawaii's unique geographical location and exposure to various natural hazards, including hurricanes, tsunamis, wildfires, lava flows, and earthquakes, pose significant challenges to its power grid. The remoteness of the islands limits evacuation options and hinders rapid response from mainland utilities. The aging infrastructure and overhead power lines, combined with the rugged terrain, further exacerbate the risks. Hawaiian Electric's resilience strategy focuses on reducing the impact of these threats through a comprehensive approach that includes emergency response, generation and transmission resilience, cybersecurity, and business continuity. By addressing these interconnected aspects, the utility aims to safeguard the reliable supply of electricity to the state (Hawaiian Electric 2023).

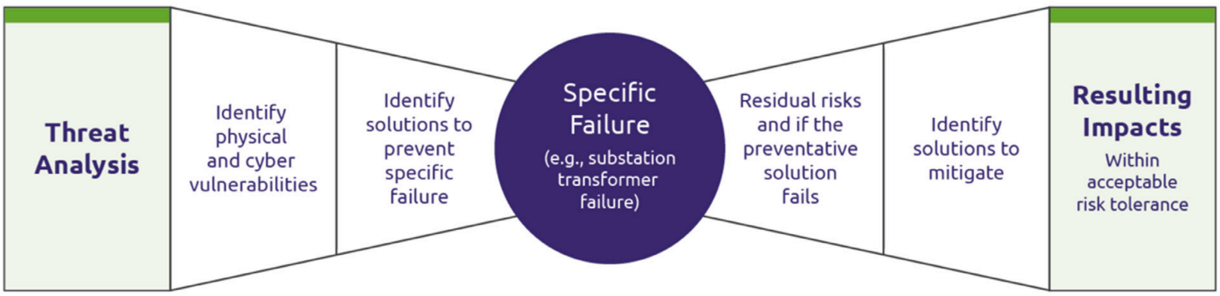


Figure 17: DOE Resilience Bowtie Method. Source: (Hawaiian Electric 2023)

The utility uses a customised resilience standard of the 'bowtie' method, a common tool in the industry that helps translate threat-risk assessments and grid vulnerabilities into specific solutions for preventing and mitigating risks. This approach identifies where and how a portfolio of solutions can have the greatest impact on customers and communities. Hawaiian Electric has developed a comprehensive resilience strategy that focuses on reducing the likelihood and severity of severe event impacts. This strategy encompasses various aspects, including emergency response, generation and transmission resilience, cybersecurity, and business continuity.

1. **Prioritisation of Threats:** The Resilience Working Group (RWG) of the Hawaiian Electric identified hurricanes, floods, and wind as the top threat to address and focused initial resilience efforts on this area.

2. **Performance Targets and Decision-Making:** Developed a framework to baseline grid resilience, identify target levels, and optimize solution portfolios to address the resilience gap cost-effectively.

3. **System Hardening:** Implemented investments to reduce outages and restoration times through damage prevention and reduction.

4. **Residual Risk Mitigation:** Addressed near-term and longer-term risks that hardening investments cannot fully mitigate, including community-driven needs.

4. Electricity Markets

4. ELECTRICITY MARKETS

Electricity markets are crucial in delivering resource adequacy, especially in countries where energy is contracted through exchanges on a large scale. Utilities participating in regional wholesale markets must not only cover their total electric load but also maintain a reserve capacity to handle unexpected outages or demand spikes. This reserve acts as a buffer during emergencies, such as power plant failures or extreme weather conditions.

Regional Transmission Organisations (RTOs) play a significant role by setting resource adequacy requirements that utilities must meet, thereby ensuring that the grid remains stable and reliable. In addition, advancements in market design and the integration of renewable energy sources are reshaping how resource adequacy is assessed, with a focus on probabilistic methods to better account for variable generation and changing demand patterns. This evolving framework helps electricity markets adapt to new challenges while ensuring that consumers have reliable access to power.

This report addresses the role of electricity markets in delivering resource adequacy, shortly after explaining the nature and types of electricity markets across the Energy Supply Chain (ESC) and how markets across the world evolved through liberalisation.

Highlights

- *This chapter provides a comprehensive overview of the role of electricity markets with respect to resource adequacy.*
- *Exploring the various market models, the different market segments, the chapter discusses the market factors that influence resource adequacy. This chapter also discusses the market interaction processes and resource adequacy across the world.*
- *By understanding the intricacies of electricity markets and their interaction with resource adequacy, readers will gain valuable insights into the mechanisms that contribute to a reliable and sustainable power system.*

4.1. PRIMER ON ELECTRICITY MARKET DESIGN

Electricity, unlike large commodities, cannot be stored in large quantities. This characteristic necessitates a complex system for matching supply and demand in real-time. Electricity markets serve as a dynamic platform where various players interact to ensure a reliable and efficient flow of electricity to meet the growing demand. Electricity markets also provide a wide range of purchase and sale options for buyers and sellers while ensuring smooth trading of electricity. Electricity markets are beneficial in the sense that it stabilises price fluctuations and ensures better allocation of risks between buyers and sellers by creating a standardised platform for players to interact (Addepalli 2024).

Since the discovery of electricity, for a significant period, the electricity sector operated under a vertically integrated model where the company owned the plants and facilities where the power was generated, the transmission lines that carry large amounts of high-voltage power across long distances to a transformer/substation and the distribution lines that ultimately deliver electricity directly to the end users—homes, businesses, factories, hospitals, and anyone that needs power (Sarah Krieger 2020).

These traditional utilities were publicly regulated, usually operating as monopolies with little or nil competition. In these markets, utility companies held exclusive control over specific geographic territories, encompassing all aspects of the electricity supply chain from generation and transmission to distribution. This vertical integration eliminated competition, thereby limiting consumer choice. Furthermore, utility companies would directly incorporate the costs of their operations, including power plant construction, into customer bills. While subject to review and approval by state regulatory bodies, this system could still lead to customers ultimately paying for projects exceeding initial cost estimates or those ultimately abandoned (stranded assets) (Glachant and Rossetto 2022).

However, in 1990s, an idea emerged to restructure electricity systems across different parts of the world like the European Union (EU) through various regulatory models. These regulatory models paved way for unbundling the vertically integrated electricity markets via three distinctive models.

4.1.1 WHAT ARE THESE REGULATORY MODELS?

Regulatory models refer to the organisation of the different activities needed to provide end-users with power supply. Traditionally, four main activities have been identified: generation, transmission, distribution and supply. However, other activities such as system operation (independent from transmission) or metering (independent from distribution) can be highlighted and developed independently. Determining the adequate level of unbundling of the monopolistic network companies from the companies performing competitive activities is of major importance when discussing regulatory models. Central to the definition of a regulatory model is the assignment of responsibilities (who makes the key decisions?) and the relevant procedures (how are these key decisions made?).

The electricity sector is a capital-intensive business. Thus, the key decisions conditioning the efficiency of the sector are the ones that

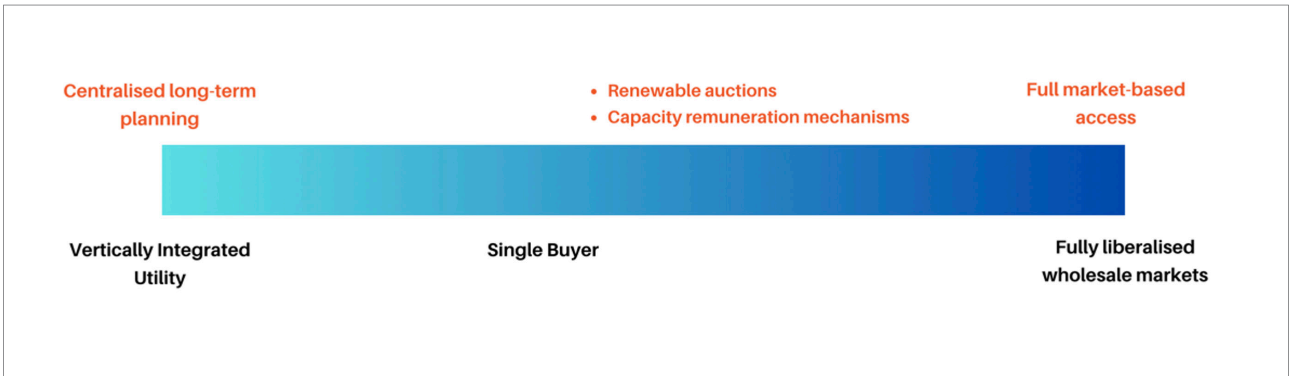


Figure 18: Regulatory Models Scale, Source: (Florence School of Regulation 2020)

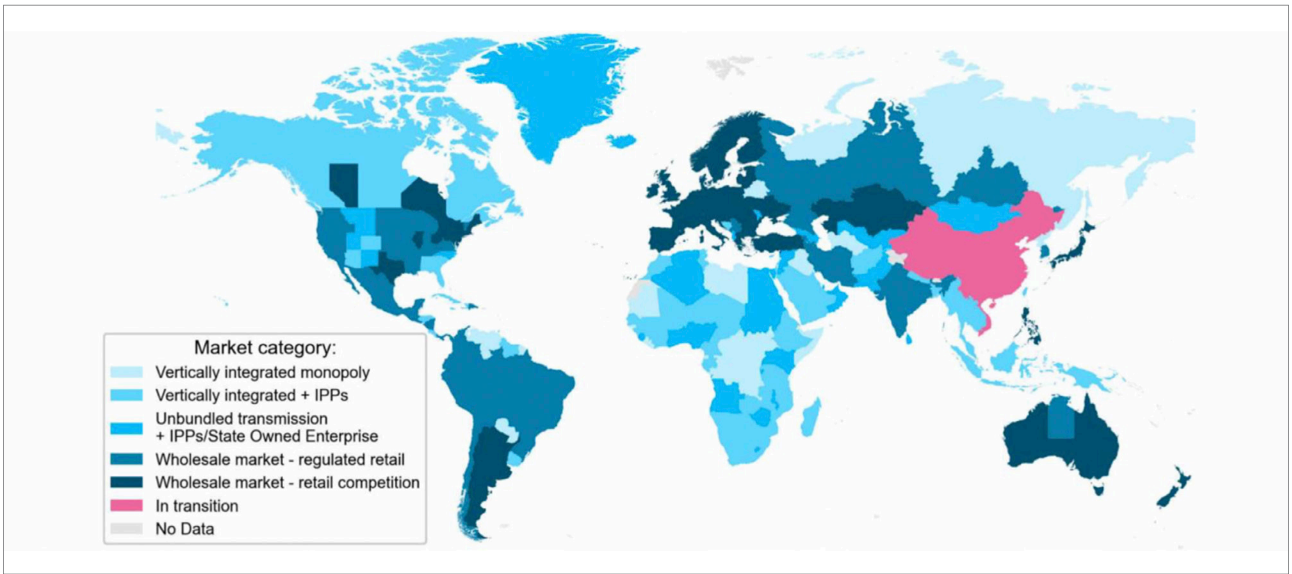


Figure 19: Variety of Market Models Across the World, Source: (Florence School of Regulation 2024)

determine the future mix of resources. On the one hand, we have centralized decision making through publicly controlled or owned institutions and the investments are then developed by a vertically integrated utility. On the other hand, we have investments resulting from fully free decisions made by market parties. However, in between these two extremes, various models exist, which primarily rely on private initiatives, but in practice could also be supported by different support mechanisms in the form of renewable auctions or capacity remuneration mechanisms to drive investments.

4.1.1.1 THE SINGLE BUYER MODEL

The single buyer model is a market structure in the electricity industry where a single entity acts as the sole buyer of electricity from various generators including independent power producers (IPPs). This single entity also performs all other activities of the Energy Supply Chain (ESC) such as the System Operator (SO), the Distributed System Operator (DSO), and the despatcher of the system (who may or may not coincide with the SO). This creates a scenario where the single buyer has monopsonist power, meaning it can influence the prices paid to IPPs. The single buyer model can serve as a transitional step towards a more competitive market. By diversifying generation ownership through mechanisms like ownership unbundling, tolling agreements, and virtual power plants, the single buyer can gradually open up the market for competition. The interactions between the single buyer and generating companies are governed by power purchase agreements (PPAs). These contracts outline the terms of electricity purchase and payment, including pricing, delivery obligations, and dispute resolution mechanisms.

However, the single buyer model is not without its challenges. The monopsonist power of the single buyer can potentially distort market outcomes and reduce competition. Additionally, if the single buyer also owns power plants, conflicts of interest and reduced competition may arise. To address these issues, effective regulation and careful negotiation of PPAs are crucial (Cretì and Fontini 2019).

4.1.1.2 THE WHOLESALE MARKET MODEL

A wholesale market essentially splits the functions of the single buyer into distinctive entities such as the System Operator operates the grid and despatches electricity; one or more Load Serving Entities (LSE), also called Distribution companies (Discoms), which bundle the activities of electricity distribution and monitoring and retailing together. These distribution utilities could be several DISCOMs, one per each distribution network, or simply just one. Wholesale power markets or simply wholesale markets can be defined as 'the marketplace where power flowing from the power plant is remunerated in the place where the needs, expressed by the loads, meet the production possibilities, brought by the power plants'.

The wholesale market offers multiple mechanisms for exchanging electricity, through power pools and power exchanges. **Power pools** are a wholesale power market where all those who exchange power are asked to participate. Thus, the pool involves the compulsory participation of IPPs and the Load Serving Entities (LSE). **Power exchanges**, on the other hand, are wholesale power market platforms where plants and the load can make match between the quantity of power and price before its effective delivery. Thus, a power exchange is voluntary in nature. In the power exchanges market participants communicating their willingness to pay, or be paid, through **bids**. These market bids play a crucial role in price discovery and resource allocation. Offer bids are submitted by IPPs to sell electricity, while bids are submitted by Discoms to purchase electricity. Load-serving entities can also submit self-scheduling bids to express their demand for electricity. Power exchanges facilitate anonymous transactions between buyers and sellers, reducing risk by acting as a counterparty for every trade. These exchanges ensure transparency by publishing all trading volumes and prices on their platforms and play a central role in various markets – day-ahead, intraday, and balancing – by providing continuous trading platforms and, in some cases, even hosting auctions to determine electricity prices (Ravi Kumar, Ramesh Tunga, and Sinha 2022). In the case of power pools, where participation is mandatory, it gets harder to set the terms of exchange between power and the monetary payment, for both the seller and the off taker due to the asymmetry of information between market participants. Both power pools and power exchanges are centralised marketplaces governed by rules that dictate the role and characteristics of market agents and their economic settlements. (Cretì and Fontini 2019).

In addition to the centralised marketplaces, IPPs and Discoms can also engage through over the counter (OTC) **bilateral contracts** for direct electricity transactions. The OTC market operates differently from an exchange or pool. Here, deals are negotiated directly between two parties, fostering a bilateral relationship. Unlike exchanges where anonymity reigns supreme, both parties in an OTC trade know exactly who they are dealing with (Ravi Kumar, Ramesh Tunga, and Sinha 2022).

4.1.1.3 THE WHOLESALE & RETAIL MARKET MODEL

In this regulatory model, in addition to the attributes discussed in the previous section, there is a further degree of unbundling at the distribution level, where in the Discoms split into DSO and entities (retailers) that supply electricity to final consumers. For effective retail competition, there must be at least two suppliers competing within each distribution network.

Various market arrangements can exist at the distribution level. Suppliers can group load and acquire energy from different sources to serve their customers. Consumers may also directly acquire energy, either at the wholesale level or through intermediaries called retailers.

The retail electricity market serves as the final link in the electricity supply chain, directly connecting suppliers and consumers. Unlike the wholesale market where generators and suppliers interact, the retail market focuses on the sale of electricity to end users. Here, consumers, including households, businesses, and communities, are the key participants.

This is the market most familiar to everyday individuals. When consumers pay their electricity bills or choose their electricity provider, they are directly interacting with the retail electricity market. These interactions occur after suppliers have procured electricity from generators in the wholesale market. Having secured the necessary supply to meet customer demand, retailers then deliver this electricity to their contracted customers across a specific region or country.

The retail market acts as a bridge between the complex world of wholesale electricity transactions and the everyday needs of consumers. It ensures that electricity reaches its final destination – powering homes, businesses, and communities (Littlechild 2022).

In a fully liberalised electricity market, the traditional structure of distribution companies (Discoms) is unbundled into two distinct entities:

- **Distribution System Operator (DSO):** The DSO is responsible for operating and maintaining the local electricity distribution network. This includes tasks such as ensuring grid reliability, managing network upgrades, and addressing faults.
- **Retailers:** Retailers are entities that sell electricity directly to final customers. They compete with each other to offer the most attractive tariffs, services, and customer support.

This unbundling of Discoms creates a competitive environment in the retail market, allowing consumers to choose their electricity supplier and tariff plans. This increased competition can lead to (Cretì and Fontini 2019):

- **Lower Prices:** Retailers may compete on price to attract customers, potentially resulting in lower electricity bills for consumers.
- **Improved Customer Service:** Retailers may offer better customer service to differentiate themselves from competitors and retain customers.
- **Innovative Offerings:** A competitive market can foster innovation, leading to new products and services, such as smart grid technologies or renewable energy options.

In some fully liberalised markets, consumers may have the option to directly purchase electricity from the wholesale market, bypassing retailers. This can provide consumers with greater control over their electricity supply and potentially lower costs, but it also requires consumers to have the expertise and resources to manage their own energy procurement (Defeuilley 2009).

As systems have evolved from radial to bi-directional power flows, it is all the more important to account for demand side management (DSM) and distributed energy resources (DER), keeping in mind the evolving nature of consumers also turning into prosumers. We now see the emergence of new innovative models such as:

ELECTRICITY/ENERGY SAVING COMPANIES (ESCOS)

ESCOs are specialised retailers that offer energy-saving services to their customers. They can help customers identify energy-saving opportunities, implement energy-efficient technologies, and share in the cost savings. ESCOs can be particularly valuable in helping consumers reduce their electricity consumption and costs. In a fully liberalised market, an ESCO can acquire power at the wholesale level and sell it to its customers. This model contrasts with a fully vertically integrated industry, as seen in many European countries, which vary in terms of the actual level of competition among suppliers in retail markets. (Defeuilley 2009).

DEMAND AGGREGATORS

Aggregators, acting as intermediaries between distributed energy providers, end-users, and power system participants, can be classified based on the resources they allocate. **Demand aggregators** focus on aggregating the demand response capabilities of end consumers, while load aggregators accumulate the load flexibility of residential consumers. Production aggregators, on the other hand, gather small-scale generators to form virtual power plants. This classification highlights the diverse roles that aggregators can play in the energy landscape.

Aggregators manage various types of resources, including consuming resources, producing resources and bi-directional resources. Consuming resources refers to flexible loads that can be aggregated to provide ancillary

services. Producing resources typically includes renewable and small traditional generation units. Bi-directional resources encompass movable and static energy storage devices.

Aggregators interact with end consumers by analysing their demand response (DR) potential, scheduling interventions, installing control equipment, and providing incentives. Analysing DR potential helps offer customised services and evaluate profitability. Scheduling informs consumers about potential interruptions or demand reduction needs. Control equipment, such as smart meters, enables communication and DR implementation. Economic incentives motivate consumers to participate in DR programs (Puskás-Tompos and Tantau 2021).

VIRTUAL POWER PLANTS

Virtual power plants (VPPs) are contractual arrangements where a power plant owner retains ownership of their facility but grants another entity, typically the buyer, the right to use it for electricity generation. VPP contracts must clearly define two key components:

- **VPP Premium:** The price paid for the right to use the power plant's capacity. This is typically expressed in monetary terms per kilowatt (kW).
- **Energy Price:** The price at which the electricity generated by the plant will be remunerated. This is expressed in monetary terms per kilowatt-hour (kWh).

In addition to these financial terms, VPP contracts should also specify the obligations of both parties. This includes outlining penalties for non-compliance, such as missed energy payments or unavailability of the plant. It's important to note that under a VPP arrangement, the plant owner remains responsible for the day-to-day management and operation of the facility (Cretì and Fontini 2019).

Now, the schedules resulting from power exchange transactions or pool operations, along with the bilateral contracts and innovative retail markets interactions must be communicated to the system operator and/or despatcher (both could be same entity depending on the country). This body is responsible for deciding which energy producers to activate (and must be informed accordingly) and must then consider the proposed despatch schedules that arise from the economic agreements between various market participants. Now the physical delivery of power governed by Kirchhoff's laws, cannot coincide with the economic considerations, and thus economic exchanges close ahead of real time delivery. And hence there are rules in place to specify the roles and responsibilities of the market parties involved whenever the planned economic exchange cannot be respected by the physical flow of power, which is done ex-post (Cretì and Fontini 2019).

4.1.2 TIME SEQUENCE OF ELECTRICITY MARKETS

Electricity markets are characterised by their unique time structure, which distinguishes them from other commodity markets. A fundamental aspect of electricity markets is the temporal separation between the time of trading and the time of physical delivery. This temporal separation gives rise to two primary market segments: forward markets and spot markets.

Forward markets involve the trading of electricity contracts for future delivery. These contracts specify the price, quantity, and delivery date of the electricity. In contrast, spot markets deal with the immediate delivery of electricity. The price of electricity in the spot market is determined by the real-time balance between supply and demand.

Understanding the interaction between forward and spot markets is crucial for comprehending the dynamics of the electricity market. Forward markets provide a platform for participants to manage price risk and ensure long-term supply, while spot markets facilitate the efficient allocation of electricity in real-time.

Energy-only and capacity markets are two primary market designs for the electricity industry. In energy-only markets, capacity investments are incentivised indirectly through price volatility. The price of electricity fluctuates based on supply and demand, and generators must ensure they have sufficient capacity to meet demand during peak periods. This means

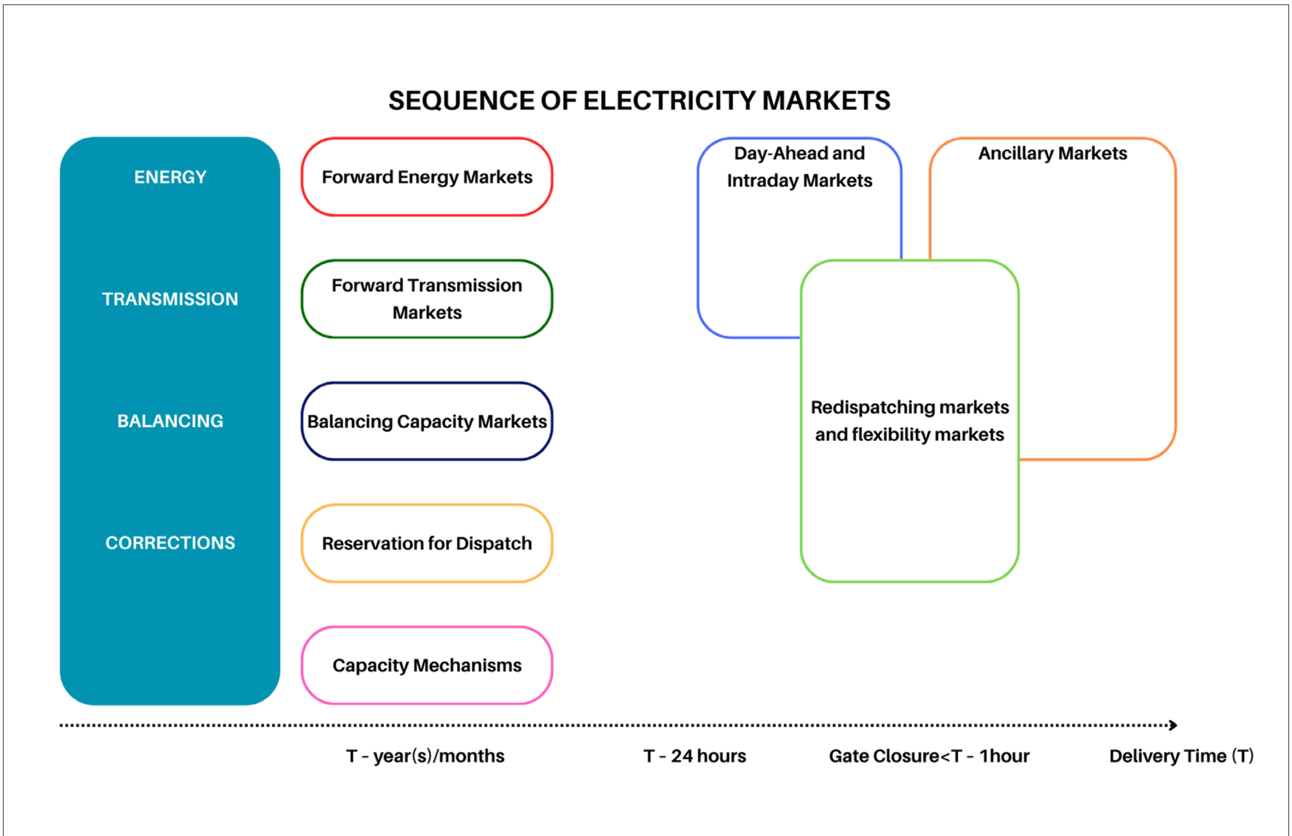


Figure 20: Time Sequence of Electricity Markets, Source: (Ravi Kumar, Ramesh Tunga, and Sinha 2022)

that generators earn higher revenues during peak times, providing an incentive to invest in capacity.

However, some argue that energy-only markets may not always provide sufficient incentives for optimal capacity investment. To address this, capacity markets explicitly remunerate generation capacity. This means that generators receive payments for being available to supply electricity, regardless of whether they actually produce it. This provides a more direct incentive for capacity investment, but it can also lead to higher electricity prices for consumers (Creti and Fabra 2007).

ENERGY-ONLY AND CAPACITY MARKETS

The energy-only market is a form of market design wherein the power producers are compensated for the power that is actually produced. Power producers earn revenues by trading electricity either through power exchanges or over-the-counter (OTC) trades such as spot markets or long-term contracts,

without receiving additional payments to provide capacity for electricity production. This market model is based on the principle that the price of electricity is determined by supply and demand (Bose and Kumar 2015).

The capacity market fundamentally contrasts with the energy-only market. It serves as a regulatory framework designed to guarantee a reliable energy supply by ensuring that adequate power generation capacity is consistently available. Unlike the energy-only market (EOM), where producers receive payment solely for the electricity they deliver, the capacity market financially compensates providers for their readiness to generate electricity (Bose and Kumar 2015).

In this system, power producers commit to supplying a predetermined amount of energy during specific times, especially during peak demand periods. In return, they receive what is known as a capacity payment. These payments are issued regardless of whether the capacity is utilised to produce electricity. They act as financial incentives to maintain sufficient power plant capacity to always meet peak demands, particularly during high-demand situations or when other energy sources may be scarce.

In summary the various functions of the time sequence of the markets are as listed below:

Market	Function
Forward energy markets	Facilitates an agreement to buy or sell electricity as a commodity at a specified price on a defined date in the future.
Forward transmission markets	Securing long-term transmission rights (physical or financial) issued by transmission system operators to transmit power
Day-ahead and intraday market	Electricity traded in day-ahead markets (DAMs), which usually close at noon for next-day delivery and intraday markets (IDMs), to accommodate possible forecast errors (e.g. in demand or renewable energy generation) close to real-time
Balancing markets (energy and capacity)	Balancing is the approach to procuring ancillary services. This includes include balancing energy – which is the energy used by grid operators to maintain frequency – and balancing capacity – which is a flexible capacity made available for a certain period to provide the balancing energy
Redespatch and flexibility markets	There are markets to correct the transmission and distribution network constraints, which may not yet fully be addressed in wholesale and balancing markets. The corrective markets are referred to as redespatching markets in the context of transmission network and flexibility markets in the context of distribution networks
Capacity markets	Corrections are also needed if wholesale and balancing markets do not result in adequate investment in generation capacity, demand-side flexibility or energy storage assets, and these corrections are managed through capacity mechanisms

Table 2: Market types by time sequence. Source: (Ravi Kumar, Ramesh Tunga, and Sinha 2022)

The section below gives more details on the various segments of the electricity market.

4.1.2.1 FORWARD (LONG-TERM) MARKETS

The long-term markets in years or months or weeks in advance are often referred to as forward markets. They ensure the ongoing supply of electricity to clients at the lowest cost by finalising transactions ranging from years in the past to a few weeks in advance before the actual delivery takes place. Forward trading offers a safety net for both energy suppliers and consumers. By locking in prices well in advance of actual energy delivery, these mechanisms shield participants from unexpected price fluctuations. It as a pre-determined price agreement that benefits both sides. Buyers gain peace of mind knowing their energy costs at all times, while sellers secure a guaranteed revenue stream. This form of risk hedging ultimately translates to reduced overall costs for both parties involved (Meeus et al. 2020).

These forward long term bilateral contracts typically include details on price, quantity, delivery obligations, and dispute resolution mechanisms. Over time, various types of contracts have emerges facilitating engagement of various market participants.

POWER PURCHASE AGREEMENTS (PPAS)

One of the major instruments used in forward trading is Power Purchase Agreement (PPA). A Power Purchase Agreement (PPA) is a bilateral contract between an electricity producer (seller) and an off taker (buyer), which can be a consumer or a trader. The agreement outlines the terms of the electricity purchase, including the volume of electricity to be supplied, the negotiated price, risk allocation between parties, accounting procedures, and penalties for non-performance. PPAs offer flexibility to tailor agreements to specific needs and can take various forms (Department of Energy & Climate Change 2013).

Typically, PPAs are long-term contracts spanning 10-25 years depending on the region. Classifications can be based on the buyer type (corporate or merchant) or delivery mode (physical or virtual). **Physical PPAs** encompass on-site or corporate PPAs, where power is delivered directly to the consumer without utilising the public grid. Off-site PPAs deliver power through the public grid with a focus solely on the physical quantity of electricity. Sleeved PPAs utilise the public grid for delivery while focusing on both physical quantity and balancing, often facilitated by an intermediary

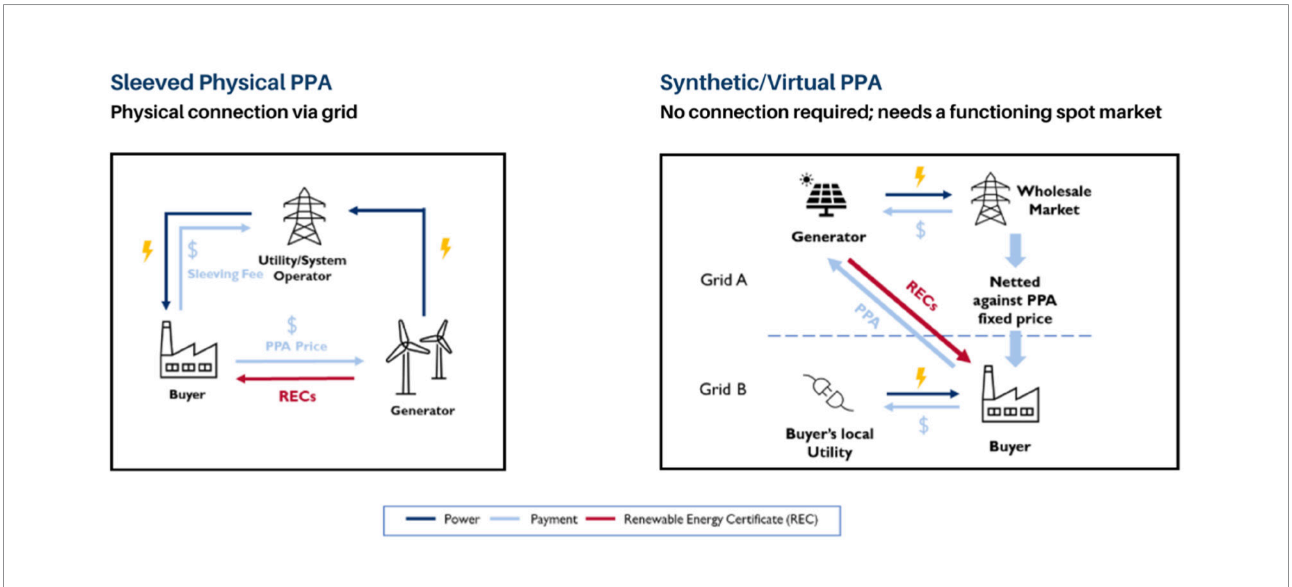


Figure 21: Comparison of Sleeved PPA and Virtual PPA, Source: USAID Southeast Asia Smart Power Program (SPP)

(Ravi Kumar, Ramesh Tunga, and Sinha 2022). **Virtual PPAs (VPPAs)**, also known as synthetic PPAs, decouple physical and financial flows, enabling more flexible contracts. Similar to physical PPAs, they establish a price per kilowatt-hour (kWh) for generated electricity. However, the electricity is not physically delivered but instead traded on the spot market through a power exchange. These VPPAs contracts are structured as **"contracts for differences"** (CfDs), essentially a financial swap electricity derivative agreement (Ravi Kumar, Ramesh Tunga, and Sinha 2022). The figure below presents the interactions between the various market participants.

The United Kingdom (UK) pioneered the use of CfDs to incentivise low-carbon generation investments. An auction determines a guaranteed long-term price for the renewable energy generator, called the "strike price." The PPA is settled at this strike price. If the market price exceeds the strike price, the generator pays the difference. Conversely, if the market price falls below the strike price, the buyer compensates the generator (Grubb and Newbery 2018). By guaranteeing a fixed price for renewable energy, CfDs provide a stable revenue stream, making renewable projects more financially attractive. This support is crucial for overcoming the initial capital costs and competing with traditional energy sources. As the renewable energy sector matures, CfDs can play a vital role in facilitating market integration and building a more sustainable and resilient energy system (Kitzing et al., n.d.).

CfD mechanism not only protects producers from price volatility but also incentivises them to respond to market signals, thereby promoting market integration. The design of CfDs can vary, with options such as hourly reference periods or longer time horizons, each having different implications for market behaviour and investment decisions. Overall, the functioning of CfDs is aimed at balancing the need for stable revenues for renewable energy projects while encouraging participation in the broader electricity market (Department of Energy & Climate Change 2013).

There are different elements to be consideration while designing a CfDs, such as the reference volume, reference price design and implementation options. The table below lists them (Kitzing et al., n.d.):

DIMENSION	Category	Discussed design options
Reference volume	Reference volume	• Generation-based • Capacity-based • Generation-potential-based
Reference price design	Reference market	• Day-ahead only • Mixed price index (e.g. incl. intraday and balancing)
	Reference period	• No aggregation (hourly / half hourly) • Monthly • Quarterly, Seasonal, Annual
	Referencing method	• No averaging • Technology-specific • Technology-uniform RE • Flat average (baseload price)

DIMENSION	Category	Discussed design options
Further design elements	Strike price design	• Cap-and-floor system (rubberband, bufferzone) • Indexation • Add-ons / Deductions
	Market integration safeguards	• Payout limitations at negative prices • Clawback limitations at low prices
	Contract design	• Duration • Administrative payment settlement rules • Timing of referencing and payouts (ex-post, ex-ante) • Exit option(s) for producer

Table 3: Design Dimensions of CfDs, Source: (Kitzing et al., n.d.)

While CfDs offer risk hedging avenues, they also come with certain limitations such as (Kitzing et al., n.d.):

- **Market Distortion Risk:** Guaranteed prices may reduce incentives for producers to engage in market-based hedging or enter into power purchase agreements (PPAs), potentially disconnecting market prices from actual generation costs.
- **Balancing Income Stability and Price Risk:** The design of CfDs must carefully balance providing income stability while exposing producers to some level of price risk to maintain market responsiveness.
- **Complex Implementation:** Implementing CfDs can be complex, requiring careful consideration of various design dimensions and their implications for different market segments.
- **Political Landscape:** Policymakers must navigate existing support schemes and market characteristics, which can influence the effectiveness of CfDs and their acceptance among stakeholders.
- **Caution in Design:** While CfDs are powerful tools for supporting renewable energy, their design and implementation must be approached cautiously to mitigate potential risks.

4.1.2.2 SPOT (SHORT-TERM) MARKETS

The electricity market operates through a two-pronged approach: forward transactions and spot market trading. Spot market (or energy market) transactions occur closer to the actual delivery of electricity, ranging from the day before to mere minutes before use. Here, we delve into the two key segments of the spot market (Cretì and Fontini 2019):

- **Day-Ahead Market:** This market functions like an auction held a day prior to electricity delivery. Buyers and sellers submit bids and offers for specific quantities of energy at their desired prices. The marketplace then uses algorithms to match these bids and offers, ultimately determining the final prices for the day-ahead market. These prices serve as a crucial reference point for the real-time market.
- **Intraday Market:** This market allows for continuous trading throughout the actual delivery day. Unlike the day-ahead market with its day-specific auctions, intraday trading is typically conducted on an hourly or half-hourly basis, with prices determined in real-time based on supply and demand.

DAY-AHEAD MARKET

The day-ahead market is a forward market where electricity is traded for delivery the following day. It is a crucial component of the wholesale electricity market, providing a platform for participants to manage their energy positions and balance supply and demand. These markets are characterised by:

- **Forward Contracts:** Participants trade forward contracts, which are agreements to buy or sell electricity at a specified price and delivery time.
- **Hourly Products:** Electricity is typically traded in hourly increments, allowing for flexibility in matching supply and demand.
- **Centralised Market:** The market is organised by an energy market operator (EMO), which sets rules, facilitates trading, and ensures market integrity.
- **Wholesale Level:** Participants include power producers, distribution companies, and other market players, operating at the wholesale level.

INTRA-DAY MARKET

Intraday markets provide a secondary trading platform for participants to adjust their positions closer to real-time delivery. They offer greater flexibility to address unexpected changes in supply or demand, such as unplanned outages or sudden shifts in consumption. Some of the key features of this market are:

- **Short-Term Trading:** Trades occur within the same day as delivery, allowing for rapid adjustments to market conditions.
- **Continuous or Auction-Based:** Markets can be organised as continuous trading platforms or auctions, each with its own advantages and disadvantages.
- **Gate Closure:** Trading typically ends a few hours before delivery, known as the gate closure time.
- **Participation Requirements:** Some markets may restrict participation to those who have already participated in the day-ahead market, while others may allow open participation.

While day-ahead markets aim to ensure sufficient energy availability to meet anticipated demand, they aren't perfect predictors. Constant fluctuations in energy requirements can cause deviations between day-ahead prices and actual intraday prices (Meeus et al. 2020).

Factors Influencing Intraday Prices:

- **Supply and Demand:** The fundamental principle of any market, supply and demand, dictates intraday electricity prices. This can be influenced by various market conditions such as weather patterns, fuel costs, and the availability of renewable energy sources like solar or wind.
- **Market Conditions:** Beyond supply and demand, broader market conditions can also play a role. For instance, limited transmission capacity can restrict the movement of electricity from generation sources to areas of high demand, potentially driving up prices in those areas. Conversely, the availability of storage facilities to hold excess energy can also affect intraday prices (Nano Energies 2024).

Intraday trading empowers electricity users to adapt their purchases based on real-time market conditions. This flexibility allows them to potentially capitalise on short-term price fluctuations and optimise their energy costs. As a vital component of the overall electricity market, intraday trading plays a critical role in ensuring the efficient and reliable operation of the electricity grid.

4.1.2.3 BALANCING MARKETS – ANCILLARY SERVICES

Balancing relates to a situation closer to real time i.e. after the markets have closed (gate closure), in which system operators need to ensure that supply meets demand in a reliable way. Proper operation of grids does not happen automatically and access to a broad range of services from various providers, including generators and demand response services gives grid operators flexible options to make efficient decisions (Ravi Kumar, Ramesh Tunga, and Sinha 2022).

Efficient balancing markets ensure security of supply at the least cost and can deliver environmental benefits by reducing the need for back-up generation. An important aspect of balancing is the approach to procuring ancillary services (Ravi Kumar, Ramesh Tunga, and Sinha 2022) (ENTSO-E, 2022). “Ancillary services are those functions performed by the equipment and people that generate, control, transmit and distribute electricity to support the basic services of generating capacity, energy supply and power delivery” (Hirst and Kirby 1996). Ancillary services consist of a range of functions such as black start, redespatch, maintaining the load-generation balance (frequency control), maintaining voltage and reactive power support and maintaining generation and transmission reserves (Ravi Kumar, Ramesh Tunga, and Sinha 2022).

Ancillary services are essential support functions in the electricity grid, ensuring its stability and reliability. They can be broadly categorised into (Rebours et al. 2007) (ESO, n.d.):

- **Balancing Services and Reserves:** These services help maintain the balance between electricity supply and demand, ensuring grid **frequency** remains stable. They include:
    - **Spinning Reserves:** Operators procure license obligation to control the grid frequency to the regulated level through frequency response services. This aims to address real-time fluctuations in electricity demand by incentivising generators (and, in some cases, demand-side resources) to adjust their output up or down. This helps maintain a constant balance between supply and demand, mitigating the impact of sudden changes in load. Resources like hydropower plants and energy storage devices are well-suited for providing this fine-tuned regulation.
    - **Supplementary Reserves:** Reserve services are the additional power sources available to the operators. Reserve services focus on securing additional generation capacity that can be rapidly deployed in case of unexpected events that disrupt the grid's balance. While these reserve services contribute to generator revenue, they typically represent a smaller portion of their overall earnings compared to the wholesale market.
- **Voltage Control and Restoration Services:** These services are crucial for maintaining **voltage** levels within acceptable limits and restoring the grid after disturbances. They include:
    - **Reactive Power Support:** Reactive power services also known as network control, ensures voltage levels within the electricity grid remain within a safe range. This is achieved by instructing generators or other grid assets to either absorb or generate reactive power, essentially managing the "background energy movement" within the system to maintain stable voltage levels.
    - **System Restoration Services:** The electricity grid, like any complex system, can experience outages. In the event of a total or partial shutdown of the national electricity transmission system, restoration services, formerly known as black start, come into play. These services focus on restarting the grid and bringing power back online in a controlled and coordinated manner. This process is critical for minimising downtime and ensuring a swift return to normal operations

As markets evolve it is important to note that the design of balancing mechanisms strongly influences trade in short-term spot markets. For instance, high imbalance prices encourage rebalancing by trading on intraday markets and high reserve requirements between balancing markets and other short-term markets may reduce volumes in the short-term markets. The cost of balancing is influenced by two main factors: (i) the volume of reserves – procuring and sharing capacity reserves across borders through intraday markets, improved imbalance settlement and imbalance netting across borders; and (ii) the price of reserves – improved market pricing and increased participation by the demand side acting as balancing service providers (Ravi Kumar, Ramesh Tunga, and Sinha 2022).

4.1.2.4 REDESPATCH AND FLEXIBILITY MARKETS

The wholesale and balancing markets may not yet fully address the constraints of the transmission and distribution networks, and therefore corrections are needed which is addressed in redespatching markets in the context of transmission network and flexibility markets in the context of distribution networks.

The aim of the system operator is to ensure that the system operates under stable conditions, and to ensure reliable supply of electricity to the consumers by averting breakdowns in the grid. All the generating units submit their schedules in advance to the system operator to be able to forecast the grid's available power. If the SO foresees any technical limitations to the usage of the grids, then the SO uses the redespatch mechanisms to alter the despatch from the generators either by curtailment or restricting injection or by reducing the load pattern to change physical flows in the transmission system and relieve physical congestion (Meeus et al. 2020).

Redespatching can be done in two ways:

- **Regulated Approach:** Here the SO centrally plans and mandates the redespatching orders.
- **Market-based Approach:** Here the SO voluntarily asked the market participants to alter either the production or demand at either side of congestion.

On the distribution networks, flexibility could be offered via smart grids through distributed energy resources such as small-scale generation units, energy storage, demand response to adjust their production or consumption directly or through aggregators. Usually redespatch/ flexibility markets are used in areas with high production of renewable generation and kicks in before real time when SO receives the despatch schedule.

4.1.2.5 CAPACITY MARKETS

In an electricity system, capacity means there are adequate resources on the grid to ensure that the demand for electricity can be met at all times. In general terms, capacity markets can be considered as 'generation resource adequacy' needed to ensure supply meets demand at any given point of time. It is a market created in addition to existing electricity markets, where in only capacity is remunerated and traded. A capacity market is designed to ensure sufficient reliable capacity is available by providing payments to encourage investment in new capacity or for existing capacity to remain open. If the wholesale and balancing markets do not result in adequate investment in generation capacity, demand-side flexibility or energy storage assets, then corrections are needed, and these corrections are called capacity mechanisms.

Some electricity markets incorporate capacity markets to supplement the revenue streams of generators. This intervention arises from concerns that the wholesale market alone may not provide sufficient long-term financial viability for generators. Capacity markets address this

issue by offering additional revenue streams to participating generators whose capacity bids are successful. This additional cost is ultimately borne by the final electricity consumers through their electricity bills. However, this cost comes with the benefit of ensuring resource adequacy, meaning there's sufficient generation capacity available to meet peak demand periods. A prerequisite for capacity markets would be the need for a well-functioning wholesale market as well are medium-term forward markets (Wolak 2014).

Some of the key characteristics of capacity markets are (Cretì and Fontini 2019):

- **Capacity Trading:** The primary focus is on trading the capacity of power plants to generate electricity, not the electricity they produce. This means that generators are compensated for their potential to produce electricity, regardless of whether they are actually generating it.
- **Remuneration:** Capacity markets involve mechanisms to remunerate generators for their capacity, providing incentives for investment. These mechanisms, known as Capacity Remuneration Mechanisms (CRMs), can take various forms, as discussed below.
- **Long-Term Gains:** Capacity markets typically operate on a long-term basis, as investments in new capacity can take several years to materialise. This long-term perspective is essential for ensuring that adequate capacity is available to meet future demand.

CAPACITY REMUNERATION MECHANISMS (CRMS)

CRMs refer to all those policies whose aim is explicitly to remunerate capacity (or load) in order to provide the proper level of generation adequacy.

Capacity remuneration can be structured in various ways. One approach involves providing direct financial incentives to generators for their capacity. However, it is also possible to indirectly remunerate capacity by fixing remuneration levels over a sufficiently long period.

The key distinction between CRMs and other support systems lies in their primary objective.

CRMs are specifically designed to address capacity adequacy issues and provide incentives for investment in new generation capacity or load reduction. In contrast, other support systems may focus on environmental, social, or distributional goals, even though they can indirectly influence investment decisions. While these other systems may have significant impacts on the power sector, they are not considered CRMs because their primary purpose is not to directly incentivise capacity investment (Cramton and Ockenfels 2012).

CRMs are the core of capacity markets, providing financial incentives to generators for investing in new capacity. These mechanisms can take various forms, including (Cretì and Fontini 2019) (Ravi Kumar 2024):

- **Capacity Payments:** A fixed payment is provided to generators for their available capacity, regardless of whether they are producing electricity. This provides a stable revenue stream for generators, encouraging investment.
- **Capacity Auctions:** Generators bid for capacity contracts, and the highest bidders are awarded capacity rights. This can promote competition and ensure that capacity is allocated efficiently. It is a centralised approach where capacity is calculated years ahead and auctioned by an independent entity as forward auctions.
- **Capacity Obligations:** Load-serving entities are required to maintain a certain level of capacity. It is a decentralised approach to ensure capacity is contracted by the distribution companies based on their own evaluation of demand.
- **Strategic Reserves:** It is a contingency measure usually used by the system operator, where a certain portion of capacity is set aside and is called upon in case of exceptional circumstances to ensure system security.
- **Reliability Options:** Options contracts that give the system operator the right to call upon capacity when needed. This can provide flexibility and ensure adequate capacity is available during peak demand periods.

The characteristics of the typologies of CRMs are highlighted in the table below:

CRM Type	Mechanism	Key Features	Pros	Cons
Capacity Payments (CPs)	Administratively set price-based	Fixed price, centralised or bilateral allocation, closed system	Simple to implement, predictable revenue	May not incentivise optimal capacity levels, potential for "paying for rust"
Capacity Auctions (CAs)	Quantity-based, centralised market	Predetermined quantity, centralised allocation, open or closed	Can target specific capacity needs, market-based price discovery	Price volatility, potential for market power
Capacity Obligations (COs)	Decentralised, bilateral contracts	Predetermined quantity, bilateral allocation, open or closed	Simple to implement, can incentivise load profiling	Limited time commitment, potential for market power
Strategic Reserves (SRs)	Centralised control, owned by system operators	Predetermined quantity, closed system	Tailored to specific needs, direct control	Limits market liquidity, potential for strategic behaviour
Reliability Options (ROs)	Option contracts, market-based	Option contracts, market-based pricing, open or closed	Flexibility, enhances liquidity, reduces market power	Complex design, requires careful strike price setting

Table 4: Types of CRMs, Source: (Cretì and Fontini 2019)

4.2 FACTORS INFLUENCING ROLE OF MARKETS IN RESOURCE ADEQUACY

Markets play a pivotal role in ensuring resource adequacy by providing (Cretì and Fontini 2019):

- **Price Signals:** Market prices provide real-time signals about supply and demand conditions. When demand outpaces supply, prices rise, incentivising producers to increase generation or curtail load. Conversely, falling prices encourage producers to reduce output or defer maintenance.
- **Investment Incentives:** Market-based pricing mechanisms create attractive investment opportunities for new power plants and renewable energy projects. By offering competitive returns, markets stimulate the development of additional capacity to meet future demand.
- **Efficient Allocation of Resources:** Markets allocate resources efficiently by matching supply and demand at the lowest possible cost. This minimises the need for costly overbuilding and ensures that resources are used optimally.

However, after extensive exploration into resource adequacy planning, regulators and scholars have identified several critical factors that influence the current process (Eckstrom and Shen 2018a).

4.2.1 TRANSMISSION PRICING, CONGESTION MANAGEMENT AND DESPATCH MODELS

Transmission network pricing significantly impacts the efficiency of electricity markets by influencing how resources are allocated, how investments are made, and how market participants behave. Network regulation encompasses two dimensions – access and pricing to ensure non-discriminatory access to incumbents and new entrants, regardless of who owns and operates the grids. Network pricing can be based on two models namely open market model - in which payment made at one point gives access to the entire network and transportation model – in which payment depends on the distance. This intern can be classified into two broad categories of cost-based transmission pricing and value-based transmission pricing (Meeus et al. 2020).

Cost-based pricing aims to recover the costs incurred by the system operator in building, operating, and maintaining the transmission network. It allocates these costs to network users based on their usage. The most common cost-based method is the postage stamp method in which a flat per MW is charged based on total transmission cost. **Value-based** pricing aims to set transmission charges based on the economic value that users derive from the usage of the transmission network. It seeks to maximise the overall economic surplus. The two widely used methods under value-based are zonal pricing - sets a single price for all transactions within a zone based on average costs; and nodal pricing - often synonymous with locational marginal pricing (LMP), determines electricity prices at specific nodes.

Congestion management refers to tactics employed to alleviate situations where demand for electricity exceeds the available transmission capacity, leading to potential outages or inefficiencies in the system. Preventive approaches are implemented before real-time operations, which includes mechanisms such as explicit auctions or implicit auctions that allocate transmission rights based on anticipated demand. Curative approaches are used in real-time to address existing congestion issues, involving actions such as redespatching generation or adjusting load to relieve pressure on congested line.

Both effective transmission pricing and robust congestion management are essential for the efficient operation of electricity markets. While transmission pricing provides the economic signals to guide investment and operational decisions, congestion management ensures reliable power flow within grid capacity constraints.

Furthermore, the way transmission prices are set can significantly influence despatch decisions, which in turn impact market interactions. Despatch models determine how electricity generation resources are utilised to meet demand efficiently, and include methods such as ***Economic Despatch*** – which focuses on minimising generation costs by despatching resources based solely on their marginal costs e.g. merit order despatching; ***Security Constrained Economic Despatch (SCED)*** – which extends the concept of economic despatch to also include reliability of the power system and; ***Optimal Despatching*** – which has a much broader objective of going beyond costs and systems to also include environmental concerns. However, trade-offs between these different methods in terms of optimisation and computational challenges needs to be considered while making methodology choices (Meeus et al. 2020).

Together, decision making across these various elements of transmission pricing and despatch contribute to a more resilient and economically efficient electricity system by influencing how electricity is generated, transmitted, and consumed.

4.2.2 MITIGATING THE MISSING MONEY PROBLEM

The "missing money" problem in electricity markets refers to the situation where prices for energy do not fully reflect the value of investments needed to ensure reliable electric service. This discrepancy can arise from various factors, including regulatory interventions, price controls, and the inherent characteristics of electricity demand. In competitive wholesale electricity markets, the expectation is that energy prices should be determined by the market clearing price, which reflects the balance between supply and demand. However, in practice, these prices often fail to signal the true costs associated with maintaining reliability, particularly as the share of variable renewable energy sources increases (M. Hogan 2017).

As the integration of variable renewable resources like wind and solar grows, the need for flexibility in the power system becomes paramount. Flexibility refers to the ability of various components of the power system - such as demand response, controllable generation, and storage - to adjust supply or demand in real-time to match the fluctuating availability of renewable energy. In modern power systems, energy prices should ideally reflect not only the short-run marginal costs of energy production but also the costs associated with ensuring reliability and balancing supply and demand. This includes the opportunity costs of not having sufficient reserves available during peak demand or low renewable generation periods.

The challenge is that traditional energy pricing mechanisms often do not adequately capture the value of flexibility. Many proposed solutions to the missing money problem, such as capacity remuneration mechanisms (CRMs), operate outside the energy market and can lead to misallocation of resources. They may overcompensate certain resources while undercompensating others, distorting investment signals and undermining the business case for innovative flexible solutions. Therefore, a robust approach to addressing the missing money problem must prioritise improving energy price formation to reflect real-time conditions and the true value of flexibility. This will empower consumers and encourage investment in technologies that enhance demand flexibility, ultimately ensuring reliable electricity supply at the lowest reasonable cost in a low-carbon power system.

4.2.3 TRACKING FRONT OFFICE TRANSACTIONS (FOTS)

Some utilities use short-term market purchases, known as front office transactions (FOTs), to meet their resource adequacy requirements in Integrated Resource Plans (IRPs). When there is excess capacity in the market, relying on FOTs can be a cost-effective and low-risk strategy. Buying electricity in the spot market is often cheaper than building new capacity that would only be used during peak hours. Allowing Load Serving Entities (LSEs) to use FOTs to meet their capacity obligations enables those with surplus capacity to earn more revenue. This approach is cost-effective and has minimal impact on system reliability when there is no double-counting of generation capacity.

However, the reliance on unspecified FOTs can be risky, as many thermal resources are scheduled to retire soon. This could lead to a significant decrease in despatchable generating capacity, reducing the availability of capacity on the market. If many utilities choose to rely on FOTs for their reserve requirements, it could further strain the market. The liquidity of the electricity market may not be sufficient for LSEs to hedge the risk years in advance. Additionally, it is challenging for LSEs to identify key market conditions in real-time and over extended planning horizons, such as market hubs, product types, transmission congestion, and regional resource supply. The lack of coordination and ambiguity in the planning of various LSEs may result in uncertainty in regional reliability and raising concerns among regulators. One way to mitigate this risk could include, organised planning across utilities by undertaking joint analysis of the resource adequacy plans provided by the various LSEs to avoid reliability crisis in the event of a larger-than-expected regional coincident peak event (Eckstrom and Shen 2018a).

4.2.4 UNDERSTANDING CAPACITY CONTRIBUTION

For decades, planners have focused on ensuring resource adequacy and minimising outages, with recent efforts also incorporating carbon emission reductions. As renewables like hydro, wind, and solar become more prevalent, evaluating their contributions to resource adequacy and comparing them with conventional resources becomes increasingly complex.

The variable renewable resources pose challenges due to their intermittency, and hence it is important to take into account the capacity contributions. Their output depends on unpredictable weather patterns, making them non-despatchable and less favoured by planners. Methods to evaluate and incorporate variable resources into planning vary widely, from simple assumptions to complex probabilistic analyses, with no industry standards or best practices established.

Variable resources' capacity cannot be counted at face value, as this overestimates their contribution to meeting peak demand. Adjusting their capacities to match conventional, despatchable resources involves various mechanisms with differing data requirements and calculation methods. Factors like location also play a crucial role in crediting variable resources' generation capacity (Eckstrom and Shen 2018a).

The consequences of inaccurate counting include an imbalanced energy portfolio that may either over-rely on certain types of generation or fail to adequately meet resource adequacy needs. These biases persist in current resource adequacy planning and warrant further attention and standardisation efforts. System planning, especially in terms of assessing system adequacy, must innovate and evolve to ensure power systems can continue to provide secure and affordable electricity supply throughout energy transitions (Milligan 2011).

4.2.5 ADDRESSING VALUE OF LOST LOAD

To comprehend the economic significance of various resource adequacy levels, it is necessary to estimate the value of reliability to customers. One crucial component of this value is the ability to avoid costly load shedding events. The Value of Lost Load (VoLL) is a critical metric in the electricity sector, representing the economic value that consumers place on the continuous availability of electricity. It quantifies the cost incurred by consumers during supply interruptions, thereby serving as a vital input for decision-making regarding investments in generation capacity, grid reliability, and emergency preparedness. The VoLL is particularly relevant in the setting of the reliability standard and also serves as a benchmark for setting electricity prices during periods of scarcity when demand exceeds supply (ACER 2020).

A significant challenge in incorporating economic principles into resource adequacy criteria is establishing assumptions for the Value of Lost Load (VOLL). This is crucial for balancing reliability with cost objectives, but present unique complexities in practical assessment.

VOLL, representing the societal economic damages from lost load, has been a contentious and complex issue. Determining a single VOLL is problematic, as different customers with varying preferences may have significantly different willingness to pay. This raises equity concerns, as socioeconomic factors can influence how outages affect customer well-being. Additionally, the economic impact of power outages varies by customer class, season, and time of day, and is nonlinear, escalating disproportionately with outage duration and magnitude.

Effectively, VOLL is a function of customer type, seasonality, duration, and outage severity, yet it is often reduced to a single number in analysis. It's essential to clarify the perspective from which the cost is measured, whether from the utility's or the customers' standpoint. Both cost functions are calculable and significant, similar to methodologies used in insurance and reinsurance. The key is to avoid treating VOLL as a fixed value, as this oversimplifies the complex nature of outage costs.

However, it's important to note that the system-wide expected VOLL is just one component of the total reliability-related costs for both the system and customers. When evaluating the economic implications of different resource adequacy levels, these costs must be considered holistically (ESIG 2024).

Establishing accurate and representative values for VOLL requires careful consideration of various factors, including customer impacts, the diversity of the resource mix, and the evolving nature of power systems. Despite these challenges, addressing these principles are necessary for developing economically efficient resource adequacy criteria (Pfeifenberger et al. 2013).

4.2.6 LIMITING MARKET POWER AND MANIPULATION

To ensure effective competition, one must ensure that the market has robust regulatory framework to be able to promote efficiency. Electricity markets require robust regulatory frameworks to (Addepalli 2024):

- **Limit Market Power:** Prevent dominant players from artificially inflating prices. This can be achieved through regulations that cap market share or break up monopolies.
- **Monitor Market Behaviour:** Regulatory bodies actively monitor market activity to identify and address potential manipulation attempts. Transparent pricing mechanisms and public access to market data are essential elements of effective monitoring.
- **Consumer Protection:** Ensure fair competition and prevent excessive price hikes. Regulatory bodies might intervene to set price caps or establish consumer safeguards in situations of market volatility.

Effective regulation and monitoring act as essential safeguards within electricity markets, promoting fair competition and preventing market manipulation, ultimately benefiting consumers through stable and reliable electricity.

4.2.7 ROLE OF SMART GRIDS

A smart grid is a modern electricity network that monitors, protects, and optimises the operation of its interconnected elements by leveraging digital and communication technologies; and automation to improve the efficiency, reliability, and sustainability of electricity distribution and consumption. Smart grids will play a pivotal role in enhancing resource adequacy by improving monitoring capabilities, facilitating the integration of renewable energy sources, optimising resource allocation, and empowering consumers through the deployment of suitable technology suits which are guided by robust policy frameworks.

Moreover, resource adequacy assessments should require access and management of diverse data points through data transparency platforms, to be able to model a large population of factors other than historical data, which can also capture the changes in patterns over time.

Data sources and sharing techniques will have to become more legitimate and precise, aiding in production of scientifically ethical models. Data standards like FAIR can help achieve legitimacy and security in data procurement. FAIR Data is a set of principles that guide the management and sharing of data, ensuring it's Findable, Accessible, Interoperable, and Reusable. This framework promotes data transparency, collaboration, and reproducibility in research and other fields.

Key aspects of FAIR data (Wilkinson et al. 2016):

- **Findable:** Data is easily discoverable through clear metadata, persistent identifiers, and indexing in searchable repositories.
- **Accessible:** Data is available to authorised users with appropriate access mechanisms and documentation.
- **Interoperable:** Data follows common standards and formats, allowing it to be integrated with other datasets and tools.
- **Reusable:** Data is well-described and documented, making it suitable for reuse in various contexts and applications.

4.3 RESOURCE ADEQUACY IN GLOBAL MARKETS

4.3.1 THE UNITED STATES OF AMERICA

In the United States, resource adequacy is primarily managed through regional transmission organizations (RTOs) and independent system operators (ISOs), which implement capacity markets to ensure that sufficient resources are available to meet peak demand. A prominent example is the PJM Interconnection, which covers parts of 13 states and the District of Columbia. PJM operates a capacity market known as the Reliability Pricing Model (RPM), conducting annual capacity auctions where generators bid to provide capacity for future years. For instance, the 2021/2022 auction cleared at a price of $50 per MW-day, ensuring that adequate resources were committed to meet projected demand. The importance of this capacity market was underscored during the polar vortex in January 2014, when PJM faced significant demand spikes due to extreme cold. The capacity market allowed PJM to call upon additional resources, including demand response, to maintain reliability during this critical period (W. W. Hogan 2021).

Another significant case is the California ISO (CAISO), which manages the electricity grid for California. CAISO has implemented various mechanisms to ensure resource adequacy, particularly in light of the state's ambitious renewable energy goals (Gish 2012). The Resource Adequacy Program requires load-serving entities (LSEs) to procure enough capacity to meet their peak demand plus a reserve margin. In 2020, CAISO reported a resource adequacy requirement of 23% above peak demand to ensure reliability. As California's energy mix increasingly incorporates renewables, CAISO has introduced flexible resource adequacy requirements to address the variability of solar and wind generation. This adaptability is crucial for maintaining reliability as the state transitions to a cleaner energy portfolio (CPUC 2021).

The New York Independent System Operator (NYISO) also plays a vital role in ensuring resource adequacy in New York State. NYISO operates an Installed Capacity (ICAP) market, which allows for both local and state-wide capacity requirements. In 2021, NYISO implemented a new capacity market design to better account for the increasing penetration of renewable energy and to ensure that sufficient resources are available during peak demand periods. The enhancements in NYISO's resource adequacy measures were particularly influenced by the 2003 blackout that affected large parts of

the Northeast, prompting stricter requirements for capacity resources and improved coordination with neighbouring states to ensure reliability (Kozlova and Overland 2022).

EXTREME EVENTS: ARE MARKETS DELIVERING RESOURCE ADEQUACY IN USA?

In the context of extreme events, the question of whether markets are essential for delivering resource adequacy becomes increasingly pertinent. The contrasting experiences of ERCOT and PJM during extreme weather events highlight the crucial role of market structures in ensuring reliable electricity supply. ERCOT's reliance on a purely energy market model led to significant failures, while PJM's capacity market framework demonstrated a more resilient approach. This emphasises the importance of well-designed market mechanisms in delivering resource adequacy, particularly in the face of extreme events.

TEXAS (ERCOT) MODEL FAILURES

The Texas electricity market, managed by the Electric Reliability Council of Texas (ERCOT), faced significant challenges during the winter crisis of 2021, primarily due to its reliance on a purely energy-only market model. This approach lacked a formal capacity market, which meant that there were insufficient financial incentives for electricity generators to maintain adequate capacity during extreme weather events. Without a capacity market, there was a notable underinvestment in essential infrastructure and winterisation measures, leaving the system vulnerable when demand surged (Baldick et al. 2021).

In addition to the lack of a capacity market, many natural gas facilities and renewable energy sources in Texas were not adequately winterised. This failure to prepare for freezing temperatures resulted in substantial generation losses at a time when electricity demand was at its peak. Consequently, widespread outages occurred, leaving millions of residents without power during one of the coldest periods in the state's history.

The situation was further exacerbated by a delayed emergency response from ERCOT's system operator. Criticism arose regarding the operator's failure to activate emergency protocols in a timely manner. The decision to implement rolling blackouts came too late, prolonging the crisis and compounding the hardships faced by residents. This delay highlighted the inadequacies in the system's emergency management processes.

Moreover, the market-driven approach adopted by ERCOT failed to adequately account for the need for reliability during extreme conditions. The design of the system did not provide sufficient incentives for generators to be available when demand peaked, leading to a critical shortfall in electricity supply during the crisis (Baldick et al. 2021).

Factors Behind ERCOT Failure

- **Market Design Failures:** The Texas power crisis stemmed from flaws in ERCOT's electricity market design, which relies on high wholesale prices to incentivise generation during peak demand. This system failed during the cold snap as many generators were unprepared for extreme weather, leading to significant supply shortages and financial strain on consumers.
- **Supply Chain Vulnerabilities:** Texas's energy supply infrastructure was vulnerable due to freezing natural gas facilities, which hampered electricity generation when demand surged. The lack of weatherisation and insufficient investment in energy efficiency measures further exacerbated the crisis as many businesses continued operations until forced blackouts occurred.
- **Governance Issues:** Governance failures contributed to the crisis as Texas authorities neglected historical cold weather events that should have informed better preparedness. The state's focus on market-driven solutions over regulatory oversight resulted in inadequate infrastructure planning and resilience investments.
- **Extreme Weather Conditions:** The immediate cause of the power failure was an unprecedented winter storm that brought severe cold and snow, placing immense strain on Texas's electricity grid and leading to widespread blackouts. The freezing temperatures disrupted both electricity demand and supply, crippling power generation facilities.
- **Systemic Market Failures:** Fundamental flaws in Texas's deregulated electricity market structure created vulnerabilities during emergencies, with significant outages occurring primarily in natural gas plants rather than wind turbines. The inability of gas pipelines to deliver fuel due to freezing conditions compounded the challenges of meeting electricity demand.
- **Inadequate Infrastructure Planning:** The crisis highlighted a lack of adequate infrastructure planning and investment in resilience, as many power generation facilities remained unprepared for extreme weather despite previous warnings. Reliance on "just-in-time" production left the system without backup resources when supply chains were disrupted by the storm (Stafford 2021).

PJM MODEL MANAGEMENT

In contrast to ERCOT, the PJM Interconnection operates a capacity market that mandates load-serving entities (LSEs) to procure enough capacity to meet peak demand, along with a reserve margin. This design offers several advantages that enhance the reliability of the electricity supply. One of the key features of PJM's capacity market is that it ensures generators are incentivised to maintain availability. By requiring them to commit resources to meet forecasted demand, PJM effectively mitigates the risk of shortages during high-demand periods (W. W. Hogan 2021).

Additionally, PJM effectively utilises demand response programs, which allow consumers to reduce their electricity usage during peak periods. This capability helps alleviate pressure on the grid and ensures that supply can meet demand more effectively. The interconnected nature of PJM's grid also plays a crucial role in its management strategy, as it allows for the import of electricity from neighbouring regions. This interconnectedness provides additional resources during high-demand situations, further enhancing system reliability.

Furthermore, the proactive management of the system operator in PJM enables a more effective response to emergencies. The operator can call upon additional resources and implement emergency measures as needed, as demonstrated during extreme weather events. This proactive approach contrasts sharply with the reactive measures seen in ERCOT, highlighting the importance of a well-structured capacity market in maintaining a reliable electricity supply (W. W. Hogan 2021).

CASE EXAMPLE:
THE RESOURCE ADEQUACY PROGRAM OF CALIFORNIA

The California Public Utilities Commission (CPUC) established the Resource Adequacy (RA) program in 2004 to guarantee reliable electric service. It requires Load Serving Entities (LSEs) to procure enough capacity to meet demand (CPUC 2024).

The Resource Adequacy (RA) program aims to ensure grid reliability by providing sufficient resources where and when needed while also incentivising new resource construction for future grid needs.

Program Overview:

- **Mandated by CPUC:** The RA program was established in 2004 to ensure reliable electric service in California.
- **Applicable to LSEs:** All Load Serving Entities (LSEs) in California, including investor-owned utilities, energy service providers, and community choice aggregators, are subject to RA obligations.

Three Key Requirements:

- **System RA:** Ensuring sufficient capacity for the entire system.
- **Local RA:** Meeting local capacity needs, especially in San Diego.
- **Flexible RA:** Ensuring adequate flexibility to address short-term demand changes.

Filings and Compliance:

- **Annual Filings:** LSEs submit annual filings to demonstrate compliance with System and Flexible RA requirements.
- **Monthly Filings:** LSEs submit monthly filings to demonstrate compliance with monthly System and Flexible RA obligations, as well as local RA obligations in specific areas.
- **Commission Oversight:** The CPUC evaluates LSE filings to ensure accuracy and completeness.

Key Provisions:

- **System RA:** LSEs must procure 90% of their required capacity for the five summer months.
- **Local RA:** LSEs in San Diego must meet 100% of their local requirement for years one and two, and 50% for year three.
- **Flexible RA:** LSEs must demonstrate adequate flexibility to address short-term demand changes.
- **Central Procurement Entity:** The Central Procurement Entity has assumed responsibility for local RA in certain areas, relieving LSEs of this obligation.

4.3.2 THE EUROPEAN UNION (EU)

In the European Union (EU), resource adequacy is approached through a combination of capacity mechanisms and strategic reserves, particularly as countries transition to renewable energy sources. Germany's energy transition, known as Energiewende, exemplifies this approach. While Germany does not have a formal capacity market, it has implemented mechanisms such as strategic reserves to ensure resource adequacy. For example, the country has established a reserve of conventional power plants that can be activated during periods of low renewable generation. The success of Germany's renewable energy policies has led to a significant increase in solar and wind generation, but challenges remain in ensuring reliability during periods of low generation, prompting discussions about the need for additional capacity mechanisms (Hedberg 2017).

The United Kingdom has taken a more structured approach with the implementation of a Capacity Market as part of its Electricity Market Reform (EMR) in 2014. This market conducts annual capacity auctions where generators can bid to provide capacity for future years. In the 2021 auction, the clearing price was £63 per kW/year, securing commitments from various generation sources, including gas, nuclear, and demand response. The Capacity Market has proven instrumental in maintaining reliability during periods of low generation, such as during the "Beast from the East" cold snap in 2018, when demand surged, and renewable generation was low (Department for Energy Security & Net Zero 2022).

France, on the other hand, relies heavily on nuclear power for its electricity generation, which provides a stable and reliable source of energy. The French electricity market, managed by RTE (Réseau de Transport d'Électricité), ensures resource adequacy through a combination of nuclear generation and strategic reserves. France has a capacity mechanism that allows for the activation of backup generation during peak demand. Additionally, France's interconnectedness with neighbouring countries enhances overall system reliability, allowing for the sharing of resources. For instance, during the winter of 2020, France exported electricity to neighbouring countries while maintaining its own resource adequacy, showcasing the benefits of cross-border cooperation in ensuring a reliable electricity supply (RTE 2021).

EXTREME EVENTS: ARE MARKETS DELIVERING RESOURCE ADEQUACY IN THE EU?

The ongoing market changes in Europe, particularly in the wake of the Ukraine crisis, have significantly influenced the energy landscape, especially regarding the integration of renewable energy (RE) sources. The surge in gas prices due to reduced supplies from Russia has been a primary driver of the crisis. In 2022, gas prices soared to unprecedented levels, affecting electricity prices across Europe. The European Commission (EC) noted that the existing market design, which primarily relies on gas-fired generation, was not adequately serving consumers or promoting efficient investment in renewable energy sources. The crisis has also contributed to rising inflation, with energy costs significantly impacting overall economic conditions. It has also underscored the vulnerabilities of European energy systems, particularly their reliance on fossil fuel imports, prompting a renewed focus on energy security and the transition to cleaner energy sources. As a result, there has been a marked increase in the deployment of renewable energy technologies across the continent, driven by both policy initiatives and market dynamics aimed at reducing dependence on external energy supplies (Al-Saidi 2023).

The EU's response to the crisis has been on both short-term and long-term footing. Despite a high share of renewables in energy generation, the merit order principle—where electricity prices are set based on the cost of the most expensive fuel needed to meet demand—led to soaring electricity prices when gas prices surged. In response to these price spikes in summer 2022, EU countries implemented immediate measures such as grants and Value Added Tax (VAT) suspensions to alleviate consumer burdens. However, these were seen as temporary fixes rather than long-term solutions. The reforming of the electricity sector, however, was seen as the start of EU's long-term response to the energy crisis. The reform aims to decouple electricity prices from fossil fuel costs, thereby reducing volatility and protecting consumers from future price shocks. The overarching goals include (European Council of The European Union 2024):

- Better protection for consumers
- More stability for companies
- Increased integration of green electricity

Some of the key reforms proposed by the EC aimed at stabilising electricity prices and enhancing market efficiency in the long-term include (Fabra 2023):

- **Preservation of Short-Term Markets:** The EC plans to maintain short-term electricity markets to ensure productive efficiency to manage the volatility associated with renewable resources by counteracting it with gas-fired generation, storage, demand response and through trade across borders.
- **Promotion of Long-Term Contracts:** Recognising that short-term markets alone are insufficient for long-term investment signals, the EC advocates for long-term Power Purchase Agreements (PPAs) and Contracts-for-Differences (CfDs). These contracts are intended to provide more stable revenue streams for renewable energy investments
- **Retail Price Regulation During Emergencies:** To protect consumers from extreme price volatility, Member States will be allowed to regulate retail prices during crises. However, this measure raises concerns about its implementation and potential unintended consequences for energy suppliers
- **Option for Fixed-Price Contracts:** The EC requires energy retailers to offer fixed-price contracts to consumers along with other pricing contract options, aiming to reduce fluctuations in consumer bills and enhance predictability in pricing.

In conclusion, the reform of the European electricity market not only addresses the immediate challenges posed by the energy crisis but also aims at achieving various long-term goals. By creating a more resilient and efficient market structure, the proposed reforms aim to facilitate smoother transition to renewable energy, ensure fair pricing for consumers, and promote sustainable investment in low-carbon technologies. While EC's proposals reflect its aim towards a more resilient market structure, their success will depend on careful implementation and ongoing adjustments to ensure they meet the needs of the consumers and investors alike. Moreover, reforms will only prove beneficial upon the collaboration and interaction between regulators, market participants, and policymakers. The focus on balancing short-term efficiency with long-term stability is crucial as Europe strives to transition towards a more sustainable energy future.

CASE EXAMPLE:

THE EUROPEAN RESOURCE ADEQUACY ASSESSMENT (E-RAA) FRAMEWORK

The European Resource Adequacy Assessment (ERAA) is a crucial tool for ensuring the security of electricity supply within the European Union (EU) (ACER 2024a). Mandated by the 2019 Clean Energy Package, the ERAA is conducted annually by the European Network of Transmission System Operators for Electricity (ENTSO-E) to assess the EU's ability to meet future electricity demand. (ACER 2023).

Key Objectives and Scope

- **Security of Supply:** The ERAA aims to identify potential risks to the security of electricity supply in the EU, by considering factors such as generation capacity, demand forecasts, and grid infrastructure to provide a holistic view of resource adequacy. This comprehensive analysis plays a significant role in enhancing the stability of energy markets across Europe (ACER 2024b).

- **Long-Term Outlook:** The assessment provides a 10-year outlook, enabling policymakers and market actors to make informed decisions about investments, market design, and regulatory measures (ENTSO-E 2024).

- **Regional Interdependency:** The ERAA offers a comprehensive view of the EU's electricity system, considering interdependencies between Member

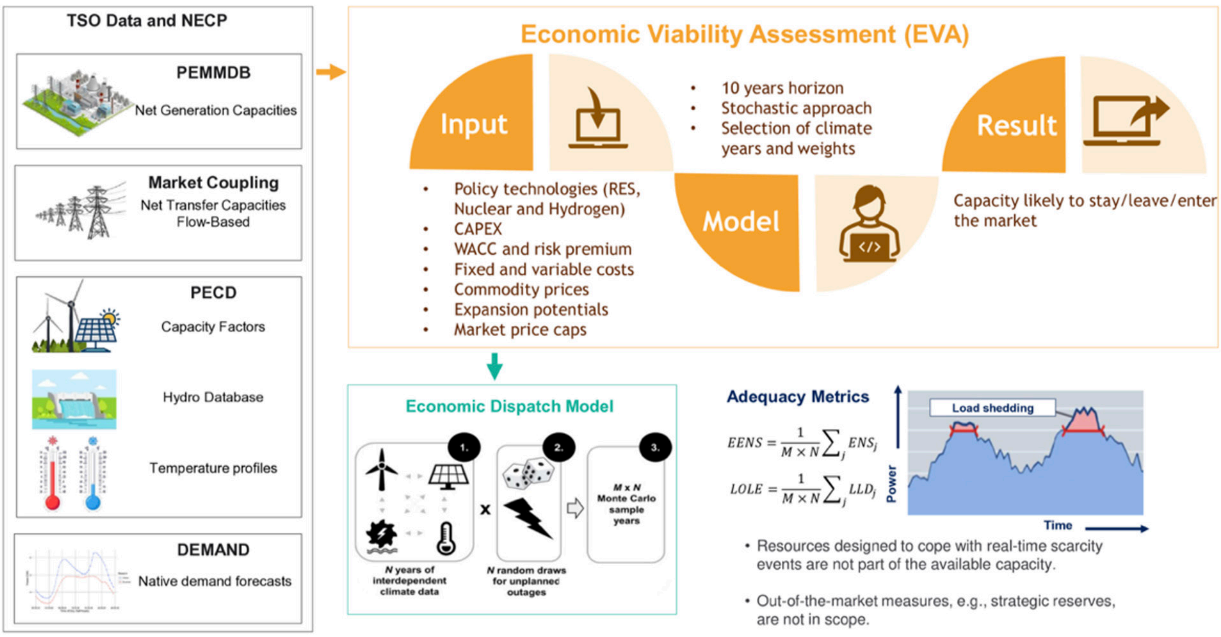


Figure A: The European Resource Adequacy Assessment Process. Source: (Yaser Tohidi 2024)

States and identifying potential regional imbalances (ENTSO-E, n.d.-a).

The E-RAA has three main pillars or elements to address resource adequacy in its framework, each having its own advantages and complexities:

- **Supply:** The E-RAA forecasts the available electricity supply, considering factors such as weather events impacting renewable generation, unforeseen thermal capacity outages, and the increasing influence of new technologies like energy storage.

- **Transmission:** Europe's integrated grid allows energy to flow across the continent through interconnectors. Modelling these electricity flows between generation and demand centres requires accounting for the physical availability of infrastructure and the functioning of energy markets. The ERAA has implemented the application of "Flow Based Market Coupling" analyses at the Continental European scale in future time frames to complement conventional techniques.

- **Demand:** With increased energy integration and bi-directional power flow, the role of demand participants will be of greater importance in electricity trading. Consumers can respond to the electricity market in real-time, adjusting their activities based on price changes and other triggers. The E-RAA models this evolving demand behaviour through time.

THE E-RAA PROCESS ENTAILS (ENTSO-E, n.d.-a):

Data Collection and Analysis

- Collect detailed data on available generation capacity, including power plants, renewable energy sources, and demand-side response capabilities from Transmission System Operators (TSOs) across Europe.
- Gather accurate forecasts of electricity demand based on historical trends, economic indicators, and demographic projections.
- Assess the capacity and condition of transmission and distribution networks.
- Employ a robust quality check process to ensure data accuracy and reliability.

Scenario Development

- Develop central reference scenarios projecting future supply and demand conditions.
- Simulate various scenarios, such as extreme weather events, economic downturns, and security threats, to assess the system's resilience.
- Evaluate the impact of different factors, such as fuel prices, renewable energy penetration, and policy changes, on the system's adequacy.
- Complement reference scenarios with sensitivity analyses to evaluate how changes in key assumptions might impact resource adequacy

Adequacy Indicators

- **Probabilistic Modelling:** The E-RAA employs probabilistic methods to account for uncertainties in both supply and demand, including factors such as weather variability and unexpected outages.
- The assessment uses metrics like Loss of Load Expectation (LOLE) and Expected Energy Not Served (EENS) to quantify reliability and adequacy levels.
- Capacity margin calculation of the difference between available generation capacity and peak demand.

- Load factor assessment of the average utilisation of generation capacity.
- Reserve margin to evaluate the system's ability to cope with unexpected events or sudden changes in demand.
- Contingency analysis simulating various scenarios to assess the system's resilience to equipment failures or grid disturbances through flow-based studies.

Risk Assessment

- Identification of potential risks to security of supply, such as insufficient generation capacity, grid congestion, and cyber threats.
- Quantification of the likelihood and potential impact of identified risks.
- Development of strategies to mitigate identified risks, including investments in additional capacity, grid upgrades, and market-based solutions.

Stakeholder Engagement

- The process involves consultations with various stakeholders, including regulatory authorities, industry participants, and member states, to gather input on scenarios and assumptions used in the assessments.

Reporting and Dissemination

- Results from the E-RAA are compiled into reports that provide insights into resource adequacy across different regions. These reports inform policymakers, regulators, and market participants about potential risks and necessary interventions.

Policy Implications

- The findings from the E-RAA guide national governments in setting resource adequacy targets and designing capacity mechanisms if necessary. They help ensure that interventions are based on transparent assessments rather than reactive measures.

4.3.3 INDIA

Over the past few years, India has emerged as one of the fastest-growing economies globally, projected to become the third-largest economy by 2030. The growing economic needs will have to simultaneously be met by a stable and sufficient electricity supply. In May 2024, India registered a record maximum power demand of 250GW owing to extreme summer temperatures. The National Electricity Plan (NEP) 2024 of the Central Electricity Authority (CEA) has projected an increase in peak demand from 273GW in 2025 to 297GW in 2026, and a 34% rise to 366GW by 2031. Amidst the growing challenges, India has also set an ambitious target of achieving 500GW of installed renewable capacity by 2030, thereby envisioning a RE-heavy power system in the near future.

India's electricity market, on the other hand, operates through a decentralised wholesale structure, enabling generators, large consumers, and captive generators to trade electricity via market mechanisms. Distribution companies (DISCOMs) procure power primarily through long-term Power Purchase Agreements (PPAs), which dominate the market, accounting for approximately 87% of transactions. However, power exchanges such as the Indian Energy Exchange (IEX), Power Exchange of India Ltd. (PXIL), and Hindustan Power Exchange Ltd. (HPX) have emerged as platforms for short-term trading, contributing to 6-7% of electricity trade today. These exchanges promote transparency and flexibility by allowing participants to respond to real-time demand fluctuations. Despite this growth, India's market design faces challenges like suboptimal scheduling by DISCOMs and renewable energy curtailment, necessitating reformation to enhance efficiency, reduce costs, and integrate renewable energy into the grid.

India's increasing vulnerability to extreme weather events, such as cyclones and floods, and the growing supply of renewables have necessitated a re-evaluation and enhancement of power system planning framework in the country. The Central Electricity Authority (CEA) in September 2022 proposed the draft guidelines for the resource adequacy planning in India, a concept and discourse that are relatively new to the power sector. The report highlighted constraints faced by the power system such as - the variability of supply with growing integration of renewable energy sources; the increasing frequency of short-term demand events; the need for power system and network optimisation and the level of temporal granularity in resource planning and the series of error functions causing loss of load. Building on these constraints, the draft guidelines focused on designing parameters for the resource adequacy framework along with integrated resource planning guided by an institutional mechanism for compliance monitoring (CEA 2022a).

- ◇ Frame resource adequacy regulations in accordance with the guidelines and from the model regulations framed by the Forum of Regulators (FoR)
- ◇ Distribution licensees to formulate the resource adequacy plan in accordance with these regulations and seek approval from the regulatory commissions, who will in turn review the plan
- ◇ Empowering the commission to determine non-compliance charges for failure to comply with the resource adequacy target approved by the commission

In addition, the National Load Despatch Centre (NLDC), the Regional Load Despatch Centres (RLDCs) and the State Load Despatch Centres (SLDCs) were all authorised to carry out resource adequacy assessments for operational planning at the national and regional level on an annual basis respectively, in accordance with the guidelines (Ministry of Power 2022).

The Ministry of Power, in consultation with the CEA, released the guidelines for resource adequacy planning framework in June 2023 that outlined the resource adequacy plan, institutional timeline for resource adequacy planning, and the guidelines for procurement of required resources. The guidelines also highlight the key design parameters for the resource adequacy framework and their determination (Ministry of Power 2023).

THE RESOURCE ADEQUACY IMPLEMENTATION PROCESS

The guidelines on the resource adequacy (RA) plan framework include a year-long process to draft resource adequacy plan at different spatial levels. There exist four types of plans that would be implemented under the framework:

LONG-TERM NATIONAL RA PLAN (LT-NRAP)

The CEA will compile and publish the LT-NRAP report for a 10-year period that would be updated on an annual basis. This includes, but not limited to:

- ◇ A national level Planning Reserve Margin (PRM) as a guidance for all the states and Union Territories (UTs) while undertaking their RA exercises.
- ◇ To ensure least cost and system compliance with RA plan, the report shall also publish the optimal generation mix for the next 10 years.
- ◇ To estimate the resource and capacity value of resources at the regional level, the report shall also publish capacity credits for different resource types on a regional basis
- ◇ To better estimate the share of demand on a granular level, the report shall also specify the states/UTs’ contribution towards the national peak demand

SHORT-TERM NATIONAL RA PLAN (ST-NRAP)

Annually, the National Load Despatch Centre (NLDC) shall publish a ST-NRAP report. This report looks ahead at the next year and predicts:

- ◇ Demand forecasts
- ◇ Resource availability based on under construction status of new projects

- Planned maintenance schedules of existing stations
- Station-wise historic forced outage rates
- Decommissioning plans

To create the LT-NRAP and ST-NRAP, State Transmission Utilities (STUs) or SLDCs shall gather information on behalf of the state's electricity distribution companies. This information includes hourly demand forecasts for the next 10 years (covering both peak usage and overall energy needs) and an assessment of the state's existing electricity generation resources. All this data is then submitted to the CEA and NLDC.

LONG-TERM DISTRIBUTION LICENSEE RA PLAN (LT-DRAP)

Distribution licensees across the country are to undertake LT-DRAP for a 10-year period that can be updated on an annual rolling basis to meet their own peak load and power requirement. Based on the share in national peak demand provided in LT-NRAP, each licensee shall plan to contract the capacity that will be computed as:

> RA Requirement (RAR) (Demand Side) = Contribution to forecasted national peak demand* (1+PRM)

The demand side RAR will be matched with the supply side RAR (ascertained as the overall sum of product generation capacities and their respective capacity credits for all type of generation portfolios) to get the sufficient capacity for that area of supply of the licensee.

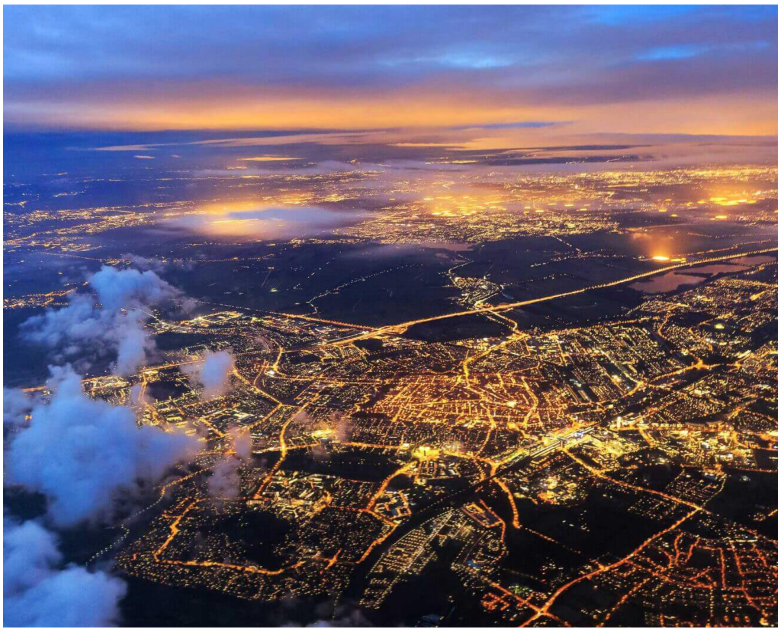
Prepared by the respective distribution licensees, the LT-DRAP shall be vetted or validated by the CEA and subsequently be submitted to SERC/JERC for their approval. The framework considers only resources with long/medium/short-term contracts to contribute to RAR. It will be required to maintain at least 75% of required capacities in LT-DRAP to be met through long-term contracts.

Once the LT-DRAP is approved by the SERC/JERC, electricity distribution companies (DISCOMs) submit details of their contracted capacity to the relevant STU or SLDC. These capacities are then aggregated at the state level by the STU/SLDC and shared with the corresponding RLDC. The RLDC, in turn, aggregates the capacities for its region and shares them with the NLDC.

Finally, the NLDC gathers all the capacity information from the regional levels and combines it to create a national picture. This national capacity is then compared to the ST-NRAP to identify any potential shortfalls in electricity supply for the following year. If a shortfall is identified, the NLDC communicates this to the SERC/JERC. The regulatory commission can then take steps to ensure compliance or facilitate a national-level auction for the remaining capacity. Distribution companies experiencing shortfalls will be eligible to participate in this auction.

SHORT-TERM DISTRIBUTION LICENSEE RA PLAN (ST-DRAP)

The STU/SLDC shall prepare an annual one-year look ahead ST-DRAP based on the LT-DRAP outcomes. The ST-DRAP shall be reviewed by the SLDC on a daily, monthly or quarterly basis based on the actual availability of generation resources (Centre for Energy Regulation 2023).



The figure below illustrates the RA process flow in the case of India:

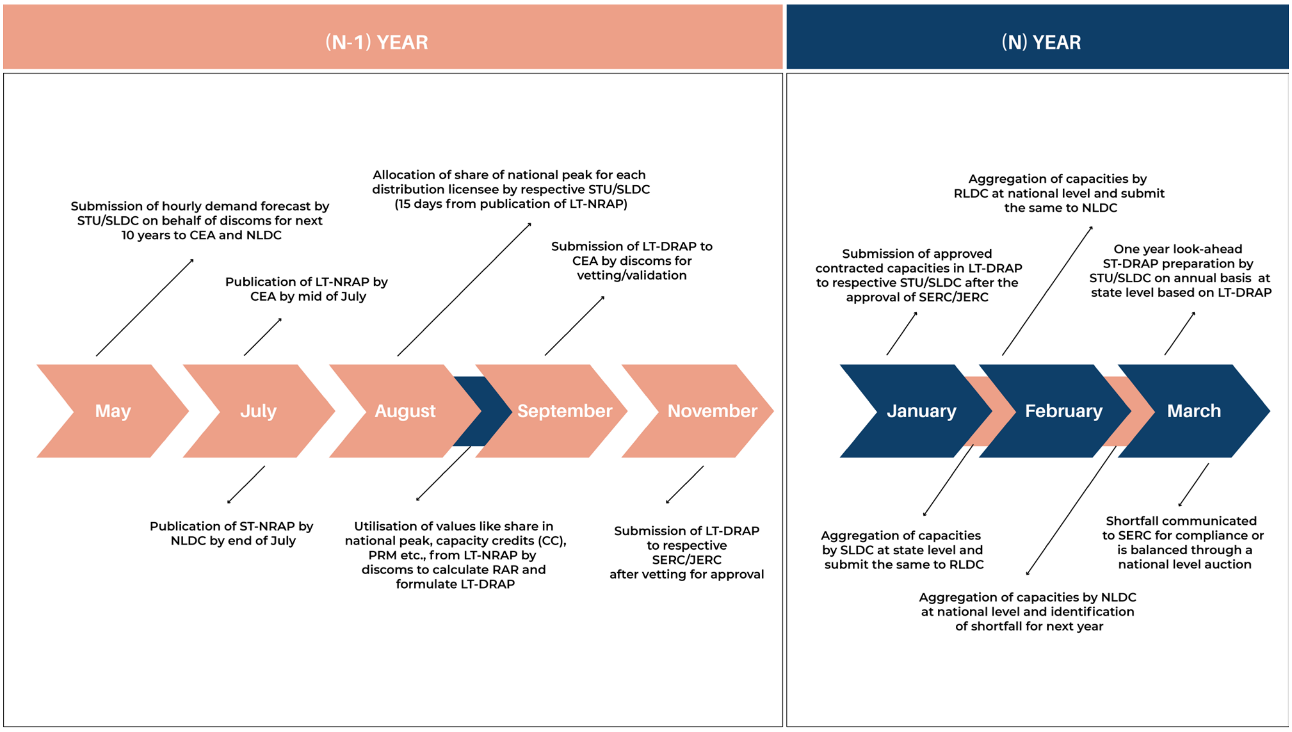


Figure 22: Resource Adequacy Implementation Timeline Source: (Centre for Energy Regulation 2023)

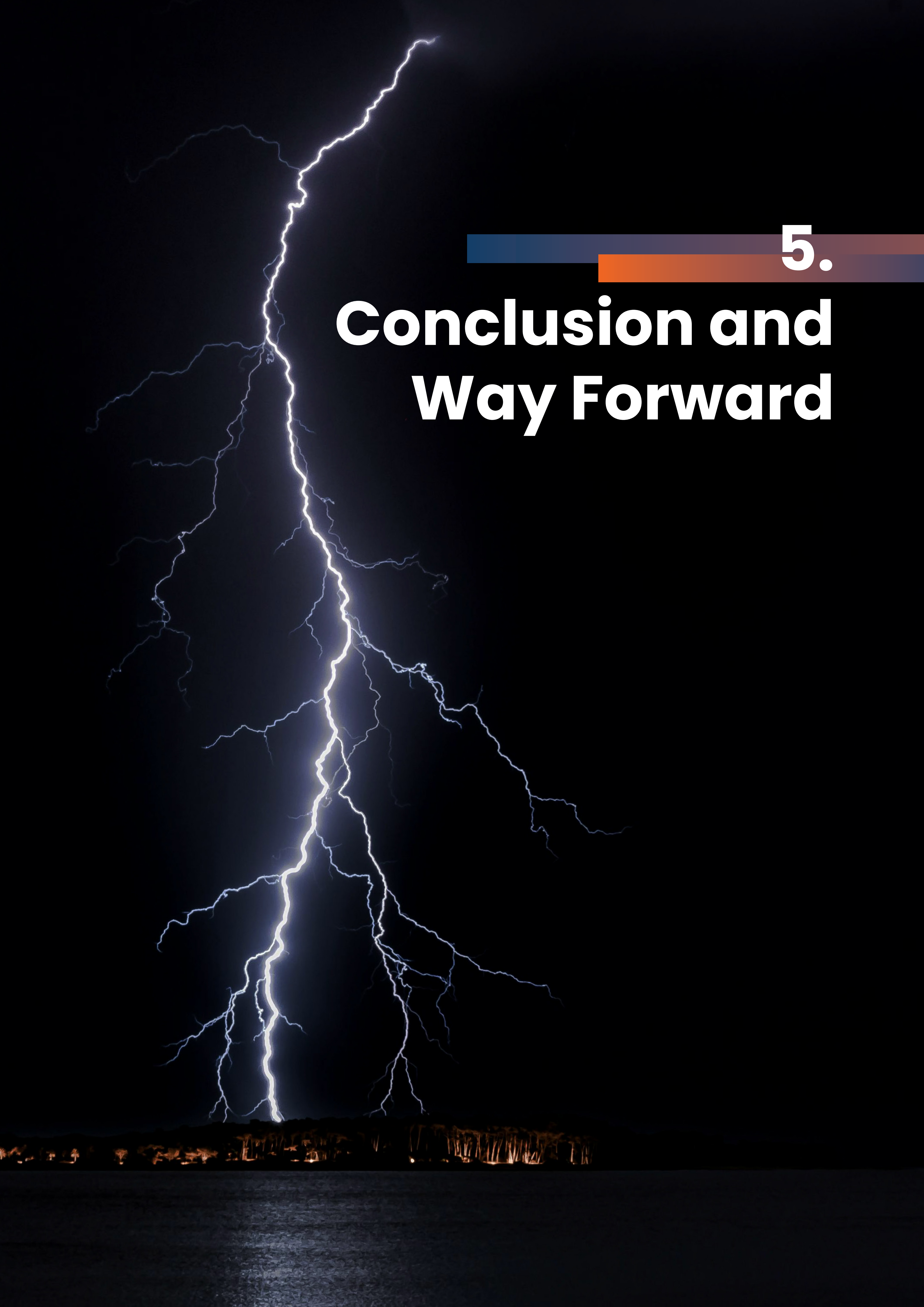
On the other hand, India's electricity markets are undergoing significant reforms to address resource adequacy challenges, but full delivery remains a work in progress.

Progress Through the RA Framework

The RA guidelines mandate states to:

1. Prepare resource adequacy plans to balance demand with generation, storage, and demand-response resources.
2. Shift from voluntary to mandatory planning based on state-specific peak demand and regional resource-sharing.
3. Use statistical metrics like Loss of Load Probability (LOLP) to determine reserve margins and incentivise capacity markets.

5. Conclusion and Way Forward



5. CONCLUSION AND WAY FORWARD

The I-RAA framework is an effort to integrate supply chain planning with a vision of catering to the diversifying energy sources and energy needs that are at the cusp of transition. While the concept of 'keeping lights on' has been prevalent for quite some time, the feasibility of maintaining reliability has become significant with growing energy integration and changing demand patterns.

In this context, the theory of resource adequacy originates from the early 20th century but has been practically contemporary. The report has widely discussed the elements of the framework components that ensure reliability to achieve resource adequacy. Countries are now understanding how to maintain resource adequacy and ensure reliability of their power systems while preparing to exhibit resilience or the ability to endure and recover from unexpected events. The framework expects an ideal power system model to move towards resource adequacy in three levels: the primal being that of resource adequacy of its components, the second being the ability to ensure a consistent balance of demand or supply components (also known as reliability), and the ability to rise from the impact of extreme events (resilience). This is further detailed in table 6 below.

To realise these objectives effectively, an integrated approach to policy decisions is crucial for the successful implementation of the Integrated Resource Adequacy Assessment (I-RAA) framework. To prevent overlapping efforts, it is vital to align the I-RAA with existing energy policies and regulations. This alignment can be achieved through several strategies. First, cross-sector collaboration is essential; engaging stakeholders from various sectors—including renewable energy, coal, and grid management—will help ensure cohesive policy development. By fostering dialogue among these diverse groups, the resulting policies can be more comprehensive and effective.

Additionally, establishing regular review mechanisms will allow for periodic assessments of policies to identify any overlaps and streamline processes. These reviews will help maintain clarity in objectives and enhance the efficiency of resource allocation.

Furthermore, stakeholder engagement should be prioritised to facilitate discussions among state governments, regulatory bodies, and industry players. Such collaboration will harmonise objectives and create a unified approach to energy resource management.

IMPROVED SCOPE FOR DATA AND MODELLING APPROACHES

To support effective resource adequacy planning, advanced modelling and framework optimisation techniques should be implemented at all levels. This includes load forecasting—where accurate and granular load forecasting models are essential for predicting future demand patterns—as well as generation planning, where optimisation models can determine the optimal mix of generation resources based on cost, reliability, and environmental factors. Generation adequacy planning should also include scenario-based modelling techniques understanding the forecast-error associated with variable generation resources. This would make the framework flexible to include renewable resource forecasting into the system, enabling methods like Effective Load Carrying Capability (ELCC) to assess resource addition. Transmission planning can benefit from network optimisation models that help identify bottlenecks and plan for future transmission capacity. Additionally, conducting scenario analysis will assess the impact of different factors—such as climate change, economic growth, and technological advancements—on resource adequacy.

The integration of socio-economic factors and advanced probabilistic modelling techniques is crucial for enhancing resource adequacy assessments. By giving more attention to the variations in reliability preferences among different regions and consumer groups, resource adequacy strategies can be tailored to meet diverse needs, promoting inclusivity and effectiveness. Furthermore, incorporating advanced modelling methods such as recursive convolution and Monte-Carlo simulations can significantly improve the handling of uncertainties inherent in power systems. These techniques allow for a more nuanced understanding of potential risks and enhance the robustness of resource adequacy frameworks. Additionally, a structured approach to resilience metrics, combined with granular socio-economic insights and case studies on international synergies, would not only strengthen the relevance of resource adequacy reports but also provide actionable strategies for addressing the complexities of modern energy demands. Ultimately, such comprehensive assessments are essential for ensuring reliable electricity supply in an increasingly variable climate and evolving energy landscape.

Further, artificial intelligence (AI) and machine learning (ML) hold significant potential to refine resource adequacy metrics such as Loss of Load Probability (LOLP) by leveraging real-time data for enhanced forecasting accuracy. By employing advanced algorithms, AI can analyse vast datasets that include historical consumption patterns, weather forecasts, grid conditions, and even socio-economic factors. This dynamic approach enables the continuous updating of models, allowing for more precise predictions of demand fluctuations and supply constraints. For instance, machine learning techniques can identify patterns and correlations that traditional methods might overlook, improving the reliability of LOLP assessments. Furthermore, integrating real-time data streams allows for adaptive modelling that responds to immediate changes in system conditions, thereby enhancing resilience and operational efficiency. As a result, the incorporation of AI and ML not only sharpens the accuracy of resource adequacy metrics but also empowers grid operators to make informed decisions that optimise resource allocation and ensure a stable energy supply.

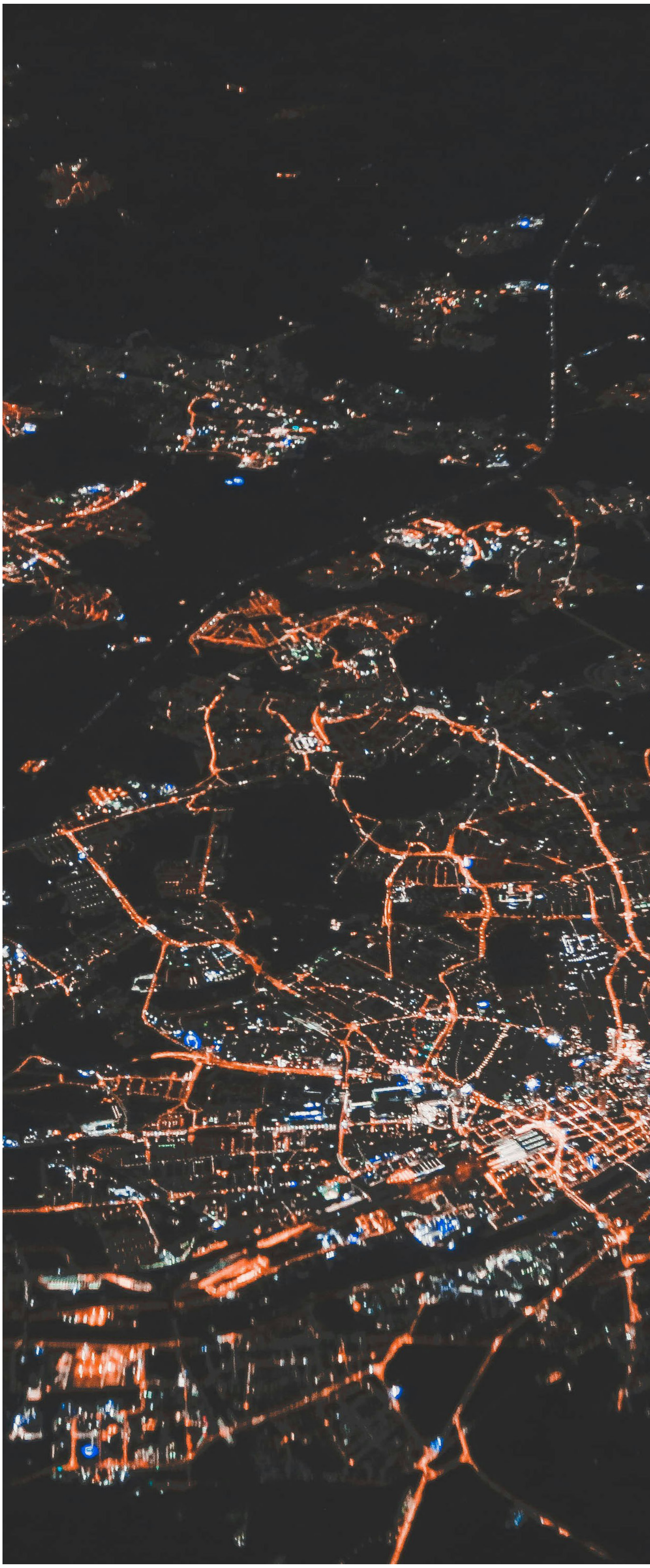
Moreover, resource adequacy assessments should require diverse data points to model a large population of factors beyond historical data. This could be useful in capturing changes in patterns over time-series while also factoring in stochastic changes. Data sources and sharing techniques will have to become more legitimate and precise, aiding in producing scientifically ethical models. Data standards like FAIR can help achieve legitimacy and security in data procurement. FAIR Data is a set of principles that guide the management and sharing of data, ensuring it's Findable, Accessible, Interoperable, and Reusable. This framework promotes data transparency, collaboration, and reproducibility in research and other fields.

Key aspects of FAIR data include being findable—where data is easily discoverable through clear metadata, persistent identifiers, and indexing in searchable repositories; accessible—ensuring data is available to authorised users with appropriate access mechanisms; interoperable—following common standards that allow integration with other datasets; and reusable—where data is well-described for suitability across various contexts (Wilkinson et al. 2016).

Finally, it is important to note that resource adequacy planning is still evolving; developing back-end software and modelling would need to go beyond basic generational scenarios optimising reliability, resilience, and cost. This would require constant effort and planning but is achievable through collaborative strategies that integrate advanced methodologies with robust data management practices.

ACHIEVING AN IDEAL STAGE OF RESOURCE ADEQUACY

We have presented an extensive array of components and metrics across the I-RAA Framework enabling prospective stakeholders who will be provided with the choice of selecting reliability metrics from the wide-range of menu, synchronising system planning across the electricity supply chain. However, different countries are equipped with different degrees of system operations and grid infrastructure that represents unique sets of opportunities and challenges in ensuring resource adequacy. We have carefully considered and curated the framing of the I-RAA Framework in such a way that we do not end up providing a straitjacketed version of the stylised options that would limit users from fully utilising the potential of the framework.



The table below explains the basic and advanced aspects of a resource adequate system upon interaction with markets. Our framework proposes an ideal stage of power system adequacy in meeting demand at all times by establishing the criterion of resource adequacy. An advanced stage of ensuring electricity supply at all times with minimal to nil interruptions would be categorised as a reliable system, whereas the ability of the power system to anticipate and overcome extreme disruptions can be referred to as a resilient power system. All the three aspects are discussed in detail below.

Aspect	Basic	Advanced	
	Resource Adequacy	+ Reliability	+ Resilience
Definition	The ability of the power system to ensure that sufficient generation, transmission, distribution, and storage resources are available to meet electricity demand, at all times, commensurate with stated economic growth assumptions and equity considerations that ensure access and a threshold level of consumption by all.	The ability of the power system to consistently deliver electricity without interruptions during normal operating conditions.	The ability of the power system to anticipate, absorb, adapt to, and recover quickly from disruptions like extreme weather, infrastructure failures, or cyberattacks.
Primary Goal	To plan for and ensure adequate capacity to meet future electricity demand, at all times, commensurate with stated economic growth assumptions and equity considerations that ensure access and a threshold level of consumption by all.	To prevent power interruptions and maintain a stable power supply during regular operations.	To ensure the power system can withstand and recover quickly from unforeseen events or shocks.
Timeframe	Long-term planning to ensure enough capacity and resources for future demand, at all times, commensurate with stated economic growth assumptions and equity considerations that ensure access and a threshold level of consumption by all.	Continuous performance during normal conditions.	Focuses on recovery and adaptability after disturbances.
Key Focus	Ensuring suffcient generation and grid infrastructure to meet demand across various time horizons.	Ensuring uninterrupted power delivery to consumers during standard operational scenarios.	System's ability to recover from events like natural disasters, cyberattacks, or major system failures.

Aspect	Basic	Advanced	
	Resource Adequacy	**+ Reliability**	**+ Resilience**
System Response	Ensures there are enough resources (generation, storage, transmission) to meet both current and future demand under all scenarios.	Ensures a stable, consistent power supply, with minimal disruptions during regular operating conditions.	Ensures that the power system can adapt and recover quickly from major shocks and disruptions.
Flexibility	Flexibility in planning for various energy sources, storage solutions, and demand-side management.	Ensures a reliable, steady performance with minimal variance under standard operating conditions.	Requires operational flexibility to restore power quickly and mitigate damage during extreme events.
Preparedness for Future Risks	Prepares for long-term demand growth, integration of renewable energy, and potential grid expansion.	Focuses on managing current load, maintaining power quality, and reducing interruptions.	Prepares for future shocks such as climate change, extreme weather events, or infrastructure failure.
Technology Role	Involves the integration of advanced forecasting tools, energy storage systems, demand response, and smart grids to balance supply and demand.	Ensures the existing infrastructure operates reliably using redundancy systems and modern grid technologies.	Utilises smart grids, advanced monitoring, and energy storage to enable quick response and recovery from disruptions.
Impact on End Consumers	Ensures power availability even during peak demand periods, minimizing the risk of power shortages.	Reduces the frequency and duration of power outages, providing a stable and reliable electricity supply.	Minimises long-term outages after events like storms, ensuring faster restoration of power supply.
Policy Integration	Linked to national energy policy and long-term planning.	Relies on current regulations for grid operation and service quality standards (e.g., SAIFI, SAIDI targets).	Requires coordination with disaster management, climate adaptation strategies, and infrastructure resilience plans.
Grid Design	Designed to ensure capacity suffciency and future scalability to meet growing demand.	Designed for stability and consistent performance under normal conditions.	Designed for adaptability and recovery to handle emergencies and extreme events.

Table 5: The Aspects of Power System Resource Adequacy in Three Levels. Source: Authors

The resource adequacy assessment is still at its infancy in different countries across the world and is adapting to the changing energy landscape. With growing variability and integration, the need for a standard resource adequacy assessment is imperative. This report provides a step-by-step guide for power stakeholders across the world to undertake an integrated approach towards resource adequacy that would help them in realising productive outcomes:

1. **Establish a National Resource Adequacy Committee (NRAC):** The NRAC will develop an I-RAA Framework for the country while conducting extensive discussions with different stakeholders to better understand the technical feasibility of the exercise at the regional and sub-regional levels. It would initiate and review the progress and impact of framework integration with system planning annually.

2. **Integration into Existing Planning Frameworks:** Integration of the I-RAA framework into existing planning processes present in each country will improve the alignment of resource adequacy assessments with demand forecasts, generation capacity planning and, network planning.

3. **Cross-Sectoral Collaboration:** Encouraging integrated planning across electricity, transportation, and industry sectors to align resource adequacy with broader energy transition goals. Planners to also initiate discussions alongside stakeholder engagement efforts. Implement a holistic integrated planning framework for inter and intra-sectoral collaboration that explores the sectoral linkages and the economic impact.

4. **Localisation of Frameworks at Regional and State Levels:** Development of localised versions of the I-RAA framework at the regional and state levels to initially leverage synergies and ensure optimisation at different levels of decision making and operations. This would result in enhanced relevance of assessments to local conditions that would be ideal to understand the bottlenecks at the decentralised level.

5. **Enhancing Private Sector Engagement:** Based upon its economic interest and infrastructure regulation, a country can encourage private sector engagement or public-private partnership (PPP) in scaling up resource adequacy integration. Private sector participation in the power sector can bring in investments, efficiency, and drive innovation, thereby reducing the financial burden on governments alone to improve service quality. Private sector engagements can further aid in enhancing competition, encourages technological advancements in renewable energy and smart grids, and ensures better management of power generation and distribution, including consumer engagement.

6. **Capacity Building Initiatives:** Development of comprehensive training programs (online and in-person) for utilities, regulators, system operators and, policymakers to enhance understanding of the existing Resource Adequacy Framework in the respective country and the subsequent advancements in the framework according to the policy evolution.

7. **Development of Robust Modelling Tools:** Creation of a robust modelling tool would capture the I-RAA Framework with respect to the regional diversity and energy profiles across states and utilities. This will be supported by standardised and reliable datasets for modelling and analysis that is accessible to relevant stakeholders. Additionally, planners should also explore and leverage on other ongoing policy initiative to be able to feed into the exercise.

8. **Continuous Monitoring and Feedback Mechanisms:** Establishing monitoring processes through a National Resource Adequacy Committee (NRAC) to evaluate the framework's effectiveness. This

committee would play a pivotal role in gathering feedback from various stakeholders, including utilities, regulators, and private sector participants, to evaluate the framework's effectiveness in real-time. Additionally, the committee would be responsible for providing periodic updates to the metrics and frameworks, thereby fostering continuous improvement and adaptability within the power system.

9. **Integration of Resilience Metrics into Policy:** Incorporation of resilience-focused metrics such as recovery times into national and state energy policies will capture the asset sensitivity to geography specific weather or extreme event scenarios. These metrics will be developed in a manner compatible with the I-RAA Framework.

10. **Data Standardisation and Transparency:** Development of standardised data collection protocols for resource adequacy assessments, promoting transparency through publicly accessible dashboards including factoring in data governance principles. Additionally ensuring collection tabs on both demand and supply side components to better understand the end-use approaches of the I-RAA Framework. Moreover, it is also important to develop advanced data collection process of stochastic factors for meta-modelling and scenario testing.

WAY FORWARD

The report on I-RAA Framework can potentially serve as a valuable resource for system stakeholders and planners, synchronising their planning process, thereby eliminating redundancies and inefficiencies from siloed planning. While reiterating the fact that resource adequacy is at its infancy, a seamless channel of techno-policy regulation and economic assessment would enhance supply chain planning and reliability in the long run. The concept of resource adequacy is dynamic in nature. The ongoing integration of renewable energy sources, such as variable renewable energy (VRE), necessitates a flexible and adaptive approach to ensure that power supply meets demand reliably and efficiently.

We believe that this report would facilitate a comprehensive understanding of the challenges and opportunities in integrating different energy sources while ensuring resource adequacy. By leveraging these discussions and frameworks, countries can level through the different stages of resource adequacy as prescribed towards a more robust and resilient power system that supports its economic growth and environmental goals. Ultimately, the successful implementation of a resource adequacy framework depends on how well countries adapt to changes in technology and operations, which will in turn be pivotal in ensuring power sector reliability and efficiency to future changes.

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Annex 1:
DEFINITIONS OF RESOURCE ADEQUACY FROM ACROSS THE WORLD

RESOURCE ADEQUACY

USA (Western Interconnect Regional Electricity Dialogue - WIRED): fundamental to reliability of the electric grid and can be defined as a forward-looking planning framework to identify future resource needs, considering (Colorado State University 2020):

- Transmission deliverability
- Resource capabilities and limitations
- Planning for uncertainties

USA (National Renewable Energy Laboratory - NREL): Resource adequacy is measured by the probability of an outage due to insufficient capacity. It is measured at the system level to capture the overall impact of outages of individual components including generators and transmission (Ibanez and Milligan 2012).

India (Ministry of Power, Government of India): Resource Adequacy means tying up sufficient capacity to reliably serve expected demand of the consumers in the DISCOMs license area in a cost-effective manner. A key aspect of resource adequacy planning is to ensure that adequate generation capacities are available, round-the-clock, to reliably serve demand, under various scenarios. This translates into requirement of an adequate reserve to cater to varying levels of demand and supply conditions prevailing in the grid(Ministry of Power 2023).

Australia (Australian Energy Market Operator): Having a sufficient overall portfolio of energy resources to continuously achieve the real-time balancing of supply and demand (Australian Energy Market Operator 2020).

USA (Electric Power Research Institute - EPRI): Resource adequacy (RA) is an assessment of whether the current or projected resource mix is sufficient to meet capacity and energy needs for a particular power system (EPRI 2020).

Italy (Florence School of Regulation – FSR): Resource adequacy is about complying with an administratively determined margin by ensuring that enough resources are connected to the power grid and available at moments of peak demand (Schittekatte and Meeus 2021b).

USA (Energy Information Administration - EIA): Resource Adequacy defined as the availability of enough generating capacity to meet demand (Energy Information Administration 2020).

USA (The Tellus Institute): Integrated Resource Planning, or IRP, can be thought of as a process of planning to meet users' needs for electricity services in a way that satisfies multiple objectives for resource use (The Tellus Institute, n.d.-b).

SECURITY OF SUPPLY

1. **Switzerland (Bundesamt für Energie - BFE):** Securing the electricity supply is based on the interaction between power plant capacities and the electricity grid (Weigt et al. 2022).

2. **Belgium (KU Leuven Energy Institute):** Security of supply is the ability of the electrical power system to provide electricity to end-users with a specified level of continuity and quality in a sustainable manner (KU Leuven Energy Institute 2013a)

3. **Europe (Intelligent Energy- Europe programme of the Executive Agency for Competitiveness and Innovation):** Ensuring that the generation system is able to cover the peak demand, avoiding loss-of-load events (Intelligent Energy- Europe programme of the Executive Agency for Competitiveness and Innovation, n.d.).

4. **Europe (European Union Agency for the Cooperation of Energy Regulators – ACER):** security of supply means the ability of an electricity system to guarantee the supply of electricity to customers with a clearly established level of performance, as determined by the Member States concerned (Papandreou 2023).

FUEL ADEQUACY

1. **Australia (Institute of Public Affairs, TRUenergy):** Cost of source/fuel is defined as fuel adequacy (Moran and Skinner 2008).

GENERATION ADEQUACY

1. **USA (USDOE Office of Energy Efficiency and Renewable Energy (EERE)):** Loss of interties & generator failure is defined as generation adequacy (Stenclik et al. 2021).

2. **USA (California Independent System Operator - CAISO):** Load-serving entities contract enough capacity to meet the 1-in-2 peak demand forecast, plus an additional planning reserve margin (California ISO 2023).

3. **USA (Lawrence Berkeley National Laboratory):** "Supply-side resources have traditionally... the system would be resource adequate if enough capacity was available to meet projected peak demand plus a reserve margin to hedge against inaccuracies in projected demand, unexpected outages, and other operational deviations." (Carvallo et al. 2023)

SYSTEM ADEQUACY

1. **Ireland (Environmental Research Institute - ERI, University College Cork):** Assessing determination the likelihood of sufficient generation to meet customer demand (Chiodi et al. 2011).

2. **Australia (Australian Energy Market Operator):** Identify low or lack of reserve conditions for a region based on specific threshold triggers (Australian Energy Market Operator 2020).

CAPACITY ADEQUACY

1. **Australia (Australian Energy Market Operator):** Ability of the energy resource mix to achieve balance at a single point in time (Australian Energy Market Operator 2020).

2. **Norway (THEMA Consulting Group):** Defined as the system's ability to establish market equilibrium in the day-ahead market, and at the same time provide adequate balancing resources for real-time operation, even in extreme situations (THEMA consulting group 2015b).

TRANSMISSION ADEQUACY

1. **Europe (Intelligent Energy- Europe programme of the Executive Agency for Competitiveness and Innovation):** The ability of the transmission system to perform, with the flexibility provided by interconnection and import and export flows (Intelligent Energy- Europe programme of the Executive Agency for Competitiveness and Innovation, n.d.).

2. **Europe (Directorate-General for Energy Internal Energy Market, European Commission):** Transmission adequacy of a power system is an assessment of the ability of a power system to manage the flow resulting from the transfer of power from generation to the consumption centre (Directorate-General for Energy Internal Energy Market 2016).

Annex 2:
DETAILED PARAMETER MAPPING

The following section presents the various parameters that may contribute towards the computation of the various metrices discussed in this handbook.

Parameter	Capacity Factor
Component	*Generation Adequacy*
Type	Input
Definition	It is defined as the ratio of the actual output to the potential output of a generation unit; hence it is a measure of the efficiency of the generation unit and the reliability of the system with respect to long-term variations in the demand.
Data Measurement	%
Time Horizon	Hour, Day or Year
Purpose	Capacity Factor is used to measure performance of renewable generators notably solar PV and wind. It is actual output over a year divided by the theoretical maximum output over a year. Capacity factor will never approach 100% since to do so would require the sun to remain directly overhead and for wind to blow at gale strength continuously for the entire year.

Parameter	Reliably Available Capacity
Component	*Generation Adequacy*
Type	Input
Definition	Reliably Available Capacity (RAC) on a power system is the difference between Net Generating Capacity and Unavailable Capacity. Reliably Available Capacity is the part of Net Generating Capacity actually available to cover the load at a reference point.
Data Measurement	MW or GW
Time Horizon	Day, Week, Month or Year
Purpose	The ENTSO-E forecasts annual adequacy entirely based on the reliably available capacity from thermal plant. By ignoring all else, including wind, it underestimates the capacity available to the grid to achieve reliability at least cost

Parameter	Unavailable Capacity
Component	*Generation Adequacy*
Type	Input
Definition	Although a power station can theoretically generate its Net Generating Capacity, this is not actually the case for the several causes that are listed bellow. Unavailable Capacity is the part of Net Generating Capacity that is not reliably available to power plant operators due to limitations of the output power of power plants.

Data Measurement	MW or GW
Time Horizon	Hour, Day, Weeks or Months
Purpose	Unavailable capacity is important for calculating certain resilience risk factors like the mean time between failure and recovery across regions.

Parameter	Annual Run Hour Limitations
Component	*Generation Adequacy*
Type	Input
Definition	Annual limit on the number of hours a unit or stack (exhaust shared by multiple units) can be on load
Data Measurement	Hours/Year
Time Horizon	Hours/Year
Purpose	Run hour limitations will have an impact on security of supply and operational flexibility in modernising the grid.

Parameter	Under frequency load (UFL) shedding
Component	*Generation Adequacy*
Type	Input
Definition	It is triggered when the frequency drops below a threshold.
Data Measurement	Hertz/second
Time Horizon	Seconds
Purpose	Frequency drop due to loss of massive generation is a threat to power system frequency stability. Under-frequency load shedding (UFLS) is the principal measure to prevent successive frequency declination and blackouts.

Parameter	Expected Unserved Ramping Energy (EURE)
Component	*Generation Adequacy*
Type	Input
Definition	This indicator measures the anticipated amount of unserved energy (in MWh) caused by a lack of flexibility in the generating fleet.
Data Measurement	MWh
Time Horizon	Minutes or Hours
Purpose	The expected unserved ramping metric was proposed in, as the flexibility analogue of the expected unserved energy metric

Parameter	Expected Unserved Energy (EUE)
Component	*Generation Adequacy*
Type	Sufficiency Criteria

Definition	The expected unserved energy typically represents the average amount of energy shortages that will be experienced each year. It is calculated by summing all the shortages identified in a simulation and dividing by the number of simulated years. (Probabilistic estimate of the energy shortfall that results from resource failure.)
Data Measurement	MWh or GWh
Time Horizon	Hourly
Purpose	EUE measures the amount of unserved energy, as opposed to the count of shortfalls, it may be a better measure of system risk and capture the implications of energy limitations on storage and demand response

Parameter	Normalised Expected Unserved Energy (EUE)
Component	*Generation Adequacy*
Type	Sufficiency Criteria
Definition	Total expected load shed due to supply shortages (MWh) as a percent (%) of the total system energy, and therefore represents an overall percentage of system load that cannot be served.
Data Measurement	% or parts per million
Time Horizon	Monthly or yearly
Purpose	Normalised expected unserved energy reports the total unserved energy as a percentage of system load. This allows for some level of comparison across different systems of different sizes.

Parameter	Loss of Load Expectation (LOLE)
Component	*Generation Adequacy*
Type	Sufficiency Criteria
Definition	LOLE is the number of hours in a given period (year) in which the available generation plus import cannot cover the load in an area or region.
Data Measurement	Hours/Year or Days/Year
Time Horizon	Hours/Year or Days/Year
Purpose	It provides an assessment of whether currently installed generation capacity is adequate to serve the forecasted load, given a set of random generator outages
Formula	LOLE= (Cost of New Entry/Value of Lost Load)

Parameter	Loss of Load Events
Component	*Generation Adequacy*
Type	Ex-Post
Definition	The number of times in a year that available generation was incapable of meeting demand.
Data Measurement	Hours/Year or Days/Year
Time Horizon	Hours/Year or Days/Year

Purpose	Loss of load events provides information about the frequency of events and is measured in events/year.

Parameter	Loss of Load Probability (LOLP)
Component	*Generation Adequacy*
Type	Sufficiency Criteria
Definition	An LOLP is the probability of encountering lost load over a given period, or the probability of encountering a loss of load event, where an event can take on any number of definitions
Data Measurement	%
Time Horizon	Day, Week, Month or Year
Purpose	In setting an LOLP criterion, the rationale is that a system strong enough to have a low LOLP can probably withstand most foreseeable outages, contingencies, and peak loads. A utility is expected to arrange for resources—generation, purchases, load management, etc.—so the resulting system LOLP will be at or below an acceptable level.

Parameter	Loss of Load Hours (LOLH)
Component	*Generation Adequacy*
Type	Sufficiency Criteria
Definition	The expected number of hours where load cannot be met with available generation resources
Data Measurement	Hours/Year
Time Horizon	Year
Purpose	The LOLH is a special case of an LOLE metric—it is typically expressed as the expected number of hours per year that encounter lost load. The LOLH is often used in studies where it is not possible to count multi-hour events because of the use of a convolution-based model. These studies sometimes adopt an LOLH standard that reinterprets the one-day-in-ten-year standard as 24 hours in 10 years, or an LOLH of 2.4 hours per year.
Formula	LOLH = LOL Probability/hour × 8760hrs/yr

Parameter	Forced Outage Rate
Component	*Generation Adequacy*
Type	Input
Definition	The number of hours that the power unit is on forced outage over a year
Data Measurement	Hours/Year
Time Horizon	Year
Purpose	It measures the reliability of a unit during scheduled operation. In a way, it is sensitive to service time, i.e., reserve shutdowns and scheduled outages influence Forced Outage Rate results. It is best used to compare similar loads: base load versus base load and cycling versus cycling.

Parameter	Installed Capacity
Component	*Generation Adequacy*
Type	Input
Definition	The maximum amount of electricity that a generating station (also known as a power plant) can produce under specific conditions designated by the manufacturer.
Data Measurement	MW or GW
Time Horizon	Year
Purpose	Installations for the generation of electricity are designed and built for a specific capacity. The installed generation capacity specifies the maximum possible Electricity generation that can be produced by the installation and is usually given in megawatts.

Parameter	Unforced Capacity
Component	*Generation Adequacy*
Type	Input
Definition	It represents the percentage of installed capacity available after an unit's forced outage rate is taken into account.
Data Measurement	MW or GW
Time Horizon	Year
Purpose	Certain transmission companies determine the capacity values of generation based on the unforced capacity of a resource.
Formula	Installed capacity *(1- expected forced outages)

Parameter	Declared Capacity
Component	*Generation Adequacy*
Type	Input
Definition	It refers to the capability to deliver ex-bus electricity in MW declared by such generating station in relation to any time-block of the day as defined in the Grid Code or whole of the day, duly taking into account the availability of fuel or water.
Data Measurement	MW or GW
Time Horizon	Year
Purpose	Declared capacity is useful in calculating certain capacity accreditation indices like the capacity index, which measures the ratio of the declared capacity of a plant to its maximum capacity; a key indicator of machine availability.

Parameter	Effective Firm Capacity
Component	*Generation Adequacy*
Type	Input

Definition	Effective Firm Capacity consists of adding a (typically small, that is incremental or marginal) amount of a resource (e.g. storage) to the system and finding the amount of firm capacity which would be required to produce the same improvement in system adequacy. This can be calculated for a single resource, by adding or removing that resource, or a portfolio of the same or similar resources aggregated together
Data Measurement	MW or GW
Time Horizon	Year
Purpose	EFC may depend on the chosen adequacy indicator measuring the improvement in adequacy resulting from adding the resource at hand and the assumed storage operation. This was one of the findings of, which showed up to a twofold difference in EFC for storage between storage operations when LOLE was used as an indicator and insignificant differences when EENS was used. In this paper both the EENS and LOLE based definitions of EFC were investigated

Parameter	Capacity Credit Approximation with Top Demand Hours
Component	*Generation Adequacy*
Type	Input
Definition	It is defined as the average of the historical contribution of a generator/ generator class during peak demand hours
Data Measurement	MWh or GWh
Time Horizon	Week, Month or Year
Purpose	Since energy demand varies daily and seasonally, accurately determining capacity credit is vital for meeting reliability standards and planning for future infrastructure investment.

Parameter	Capacity Credit Approximation with Top Net Load Hours
Component	*Generation Adequacy*
Type	Input
Definition	It is obtained by averaging the contribution of a generator/generator class during top net load hours
Data Measurement	MWh or GWh
Time Horizon	Week, Month or Year
Purpose	Approximation-based methods usually calculate the capacity credit (CC) of a unit based on the capacity factor (CF), which is the percentage output of a plant relative to its nameplate capacity, during a predetermined period. This period generally covers the hours where the system is expected to be under stress, such as hours of peak load or peak net load. These methods use an estimate for when capacity is expected to be the most constrained, but they might miss certain factors such as the impact of incremental resources on shifting the highest risk periods and inter-temporal constraints on energy-limited resources.

Parameter	Capacity Margin
Component	*Generation Adequacy*
Type	Input
Definition	The capacity margin (CM) of a system is the ratio of the difference between available capacity and peak demand to available capacity, over a period.
Data Measurement	%
Time Horizon	Week, Month or Year
Purpose	The electricity capacity margin is maintained to support security of supply on the electricity system. The smaller the capacity margin, the greater the risk that the GB electricity generation system will at some point fail to meet the total demand placed upon it.

Parameter	Remaining Capacity
Component	*Generation Adequacy*
Type	Input
Definition	Remaining Capacity on a power system is the difference between Reliably Available Capacity and Load.
Data Measurement	MW
Time Horizon	Week, Month or Year
Purpose	

Parameter	Remaining Margin
Component	*Generation Adequacy*
Type	Input
Definition	Remaining Margin on a power system is the difference between the Remaining Capacity and the Margin Against Peak Load. Remaining Margin is the part of the Net Generating Capacity left on the system to cover any unexpected load variation and unplanned outages over the period the Margin Against Peak Load is representative of.
Data Measurement	MW
Time Horizon	Week, Month or Year
Purpose	As a large portion of the generation fleet uses long lead times to react to market signals and wind forecasts, the remaining margin left to address supply adequacy (and supply surplus) falls to the rest of the despatchable merit order.

Parameter	Maximum Continuous Rating (MCR)
Component	*Generation Adequacy*
Type	Input
Definition	The maximum continuous output in MW at the generator terminals guaranteed by the manufacturer at rated parameters
Data Measurement	MW or GW

Time Horizon	Hours, Days or Weeks
Purpose	Helps record the maximum output that a generating station is capable of producing continuously under normal conditions over a year. Additionally, under ideal conditions, the actual output could be higher than the MCR.

Parameter	Marginal Cost of Reducing Load Shed (MCRLS)
Component	*Generation Adequacy*
Type	Input
Definition	Effective increase in cost for every unit of load shed reduced; It is calculated as the increase in system costs by the reduction in load shed.
Data Measurement	$/Hour
Time Horizon	Hour
Purpose	Load shedding is critical to cut down the demand charge cost of the consumers by temporarily shutting down non-critical devices or appliances. A reduction in load shed would mean lesser power system stability and ascertaining the MCRLS would minimise the amount of power required to run essential loads while helping in the overall stabilisation of the power generation system.

Parameter	Planning Reserve Margin
Component	*Generation Adequacy*
Type	Sufficiency Criteria
Definition	Planning Reserve Margin in a power system is expressed as a certain % of peak load forecast of the system
Data Measurement	%
Time Horizon	Annual (Seasonal)
Purpose	It is the predominant deterministic metric used to ensure that sufficient resources are available to meet projected load obligations over the course a determined timeframe. Generally, the PRM measures the percentage by which generation capacity exceeds the forecasted peak demand.

Parameter	Active Power
Component	*Generation Adequacy*
Type	Input
Definition	The product of the components of alternating current and voltage that equate to true power which is measured in units of watts and standard multiples
Data Measurement	MW or GW
Time Horizon	Hour, Week, Month or Year
Purpose	The optimal management of AC grids requires the accurate estimation of active power. This is especially true in the case of bidirectional power flows for smart grids where renewable power plants, loads, and storage systems are present at the same time.

Parameter	Active Energy
Component	*Generation Adequacy*
Type	Input
Definition	The electrical energy produced, flowing or supplied by an electric circuit during a time interval, being the integral with respect to time of the instantaneous Active Power, measured in units of Watt-hours or standard multiples
Data Measurement	MWh or GWh
Time Horizon	Hour, Week, Month or Year
Purpose	

Parameter	Planned Outage
Component	*Generation Adequacy*
Type	Input
Definition	These outages are all outages known at the moment of adequacy assessment. These include maintenances, existing outages due to forced outages and any supply unavailability due to other reasons.
Data Measurement	MWh or GWh
Time Horizon	Hour, Week, Month or Year
Purpose	Planned outages have been an integral part of the electricity distribution business since the beginning of the electricity distribution industry. Compared to unplanned outages, which happen suddenly due to equipment malfunction or another type of failure, planned outages are scheduled and announced adequately to affected electricity consumers. These planned outages occur mainly due to grid activities related to necessary work on electrical distribution equipment needing upgrades or exchanges.

Parameter	Reserve Margin
Component	*Generation Adequacy*
Type	Input
Definition	It is defined as the ratio of the difference between the available capacity and the peak demand to the peak demand. Reserve margin measures the level of available reserved capacity to secure the supply, and it is related to the reliability of the system with respect to short-term stochastic variations
Data Measurement	MWh or GWh
Time Horizon	Hour, Week, Month or Year
Purpose	It is calculated for electric systems or regions made up of a number of electric systems
Formula	Reserve Margin = (Capacity – Demand)/Demand where “capacity” is the expected maximum available supply and “demand” is expected peak demand

Parameter	Firm Capacity
Component	*Generation Adequacy*
Type	Input
Definition	Firm capacity represents the amount of power the generator can reliably provide.
Data Measurement	MWh/GWh
Time Horizon	Hour, Week, Month or Year
Purpose	Firm capacity assesses the contribution of a power plant to meeting demand during critical conditions.

Parameter	Capacity Credits
Component	*Generation Adequacy*
Type	Input
Definition	Capacity credit expresses firm capacity as a percentage of the installed nameplate capacity.
Data Measurement	%
Time Horizon	Annual
Purpose	Capacity credit estimates of wind power plants help generating companies, utility planners, and other decision-makers evaluate this intermittent resource in the context of other types of power plants. Capacity credit is the level of conventional generation that can be replaced with wind generation.

Parameter	Effective Load Carrying Capability (ELCC)
Component	*Generation Adequacy*
Type	Input
Definition	If a new generator added into an existing system, the contribution of the new generator to the resource adequacy of the system is known as its capacity value or ELCC
Data Measurement	MW or GW
Time Horizon	Hour, Week, Month or Year
Purpose	Often-used metric to assess capacity credit, not only for wind plants, but for any power plant. A typical power plant has a relatively low forced outage rate, which implies a high availability rate. This translates into an ELCC value that is typically a large percentage of the conventional plant rated capacity

Parameter	Equivalent Firm Capacity (EFC)
Component	*Generation Adequacy*
Type	Input
Definition	The EFC of a resource estimates how much dependable power generation would be needed to replace that resource, if the power system's ability to handle outages stays the same.
Data Measurement	MW or GW

Time Horizon	Hour, Week, Month or Year
Purpose	

Parameter	Equivalent Conventional Power (ECP)
Component	*Generation Adequacy*
Type	Input
Definition	The ECP of a resource estimates the amount of generating capacity from a traditional, controllable power plant (like a natural gas turbine) that would be needed to replace the resource, if the power system's ability to handle outages stays the same.
Data Measurement	MW or GW
Time Horizon	Hour, Week, Month or Year
Purpose	

Parameter	Mean Available Energy Output During Peak Load
Component	*Generation Adequacy*
Type	Input
Definition	The capacity value of a resource is defined as the mean output of its available generation during a specified peak load period. This is useful for instances where certain probabilistic metrics cannot be calculated because of time or data constraints or in systems with a high correlation between periods of peak demand or maximum system risk.
Data Measurement	MWh or GWh
Time Horizon	Hour, Week, Month or Year
Purpose	

Parameter	Exceedance Available Energy Output During Peak Load
Component	*Generation Adequacy*
Type	Input
Definition	Referred to as the percentile method, this metric defines the capacity value of a resource as the minimum available energy output that can be produced in a certain percentage of peak load hours.
Data Measurement	MWh or GWh
Time Horizon	Hour, Week, Month or Year
Purpose	

Parameter	Mean Available Energy Output During Highest LOLP Hours
Component	*Generation Adequacy*
Type	Input

Definition	Under this method, the capacity value of a resource is defined as its mean available energy output during peak LOLP hours. This method is useful in case where two resources that provide identical amount of annual energy to the grid might have different capacity values based on their output during high LOLP hours.
Data Measurement	MWh or GWh
Time Horizon	Hour, Week, Month or Year
Purpose	

Parameter	Operating Spinning Reserve
Component	*Generation Adequacy*
Type	Input
Definition	Operating spinning reserves are the unloaded portion of generators that are online already and can quickly increase their output to their maximum ratings to meet changes in demand.
Data Measurement	%
Time Horizon	Hour, Day, Week, Month or Year
Purpose	In case of power shortfalls, traditional generators can take hours to "heat up" or return to working capacity. The capability of the spinning reserve to remain on "hot standby," synchronised and ready to respond to a signal from the generator, is vital to continued functioning and power generation.

Parameter	Daily Net Load
Component	*Generation Adequacy*
Type	Input
Definition	It is intended to reflect the potential to experience energy and capacity shortages on that day: the average of the daily average net load and the daily maximum net load.
Data Measurement	%
Time Horizon	Hour, Day, Week, Month or Year
Purpose	In the electricity grid, constantly balancing the supply and demand is critical for the network's stability and any expected deviations require balancing efforts. This balancing becomes more challenging in future energy systems characterised by a high proportion of renewable generation due to the increased volatility of these renewables. To know when any balancing efforts are required, it is essential to predict the so-called net load, the difference between forecast energy demand and renewable supply.

Parameter	Portfolio Balance Constraints
Component	*Generation Adequacy*
Type	Sufficiency Criteria

Definition	The portfolio balance constraints ensure that the total generation within a region and the import of power to the region is equal to the sum of the demand, the exports from the region, any energy not served and curtailment, for each hour
Data Measurement	MWh or GWh
Time Horizon	Day, Week, Month or Year
Purpose	

Parameter	Derating Event
Component	*Generation Adequacy*
Type	Input
Definition	Derating is a protective measure which allows the use of power supplies at high temperatures, at high altitudes or in alternative mounting orientations.
Data Measurement	MW or GW
Time Horizon	Hour, Day, Week, Month or Year
Purpose	The reliability of electronic components decreases when they are operated at high stress levels. These stresses are primarily temperature, voltage, current and power dissipation. Heat-generating components such as transistors, resistors, valves and transformers, are susceptible to these stresses which result in degraded performance and accelerated failure. The theoretical justification for derating is discussed as a means of reducing thermal and electrical stress while deriving two mathematical models relating the rate of component failure to stress conditions.
Formula	Magnitude of event= Nameplate capacity of unit - Net Available Capacity of event (If derating does not overlap); Magnitude of event= Net Available Capacity of previous event - Net Available Capacity of event (If derating overlaps)

Parameter	One-day-in-Ten-Years-Loss-of-Load-Standard
Component	*Generation Adequacy*
Type	Sufficiency Criteria
Definition	This standard is interpreted to mean that planning reserve margins need to be high enough that involuntary load shedding due to inadequate supply would occur only once in ten years.
Data Measurement	Hours/Year or Days/Year
Time Horizon	Year
Purpose	This standard is interpreted to mean that planning reserve margins need to be high enough that involuntary load shedding due to inadequate supply would occur only once in ten years
Formula	One event in ten years translates to 0.1 loss of load events (LOLE) per year, regardless of the magnitude or duration of the anticipated individual involuntary load shed events. Alternatively, one day in ten years translates to 2.4 loss of load hours (LOLH) per year, regardless of the magnitude or number of such outages.

Parameter	Capacity Charge
Component	*Generation Adequacy*
Type	Input
Definition	Capacity charges relate to the energy that is allocated and reserved on the network for power supply
Data Measurement	Kilo Volt Amperes (KVA)
Time Horizon	Day
Purpose	Capacity charges reflect the cost of ensuring that the power that businesses need are always available on the network

Parameter	Capacity Constrained
Component	*Generation Adequacy*
Type	Input
Definition	Occurs when the power system infrastructure is insufficient to meet peak demand. These kinds of disruptions can occur because of rapid and unanticipated growth in demand, infrastructure failures, or a combination of both.
Data Measurement	MW or GW
Time Horizon	Day
Purpose	Capacity charges reflect the cost of ensuring that the power that businesses need are always available on the network.

Parameter	Margin Against Peak Load
Component	*Generation Adequacy*
Type	Input
Definition	Margin Against Peak Load is the difference between the Load at the reference point and the peak load over the period the reference point is representative of.
Data Measurement	%
Time Horizon	Hour, Day, Week, Month
Purpose	Margin Against Peak Load is used to extend analysis from a reference point to the seasons to which the reference point is representative of. Margin Against Peak Load and Load in January are representative of Winter. Margin Against Peak Load and Load in July are representative of Summer.

Parameter	Net Generating Capacity
Component	*Generation Adequacy*
Type	Input

Definition	Net Generating Capacity of a generation unit means the maximum net active electrical power it can produce continuously throughout a long period of operation in normal conditions, where net means the difference between, on the one hand, the gross generating capacity of the alternator(s) and, on the other hand, the auxiliary equipment load and the losses in the main transformers of the power station.
Data Measurement	MW or GW
Time Horizon	Hour, Day, Week, Month
Purpose	They indicate the maximum electricity load a generator can support at the point of interconnection with the electricity transmission and distribution system during the respective seasons.

Parameter	Load Factor
Component	*Generation Adequacy*
Type	Input
Definition	It is defined as the power generated (respectively consumed) by a given generation (respectively consumption) unit, divided by the installed capacity of the generation unit (respectively the maximum demand consumed).
Data Measurement	%
Time Horizon	Hour, Day, Week, Month
Purpose	The peak demand is determined by considering the average load factor, load diversity factor, seasonal variation factors and the energy forecasts.

Parameter	Loss of Load
Component	*Generation Adequacy*
Type	Input
Definition	A loss of load occurs whenever the system load exceeds the available Distributed Energy Resource (DER) capacity.
Data Measurement	%
Time Horizon	Hour, Day, Week, Month
Purpose	Loss of load analysis helps quantify the impact of system variability on desired reserve levels and reliability.

Parameter	Storage Constraints
Component	*Generation Adequacy*
Type	Input
Definition	Storage charge and discharge at any instant are constrained by the storage level or the state of charge (SoC) of the storage resource, and the maximum charge / discharge limit
Data Measurement	Volt/MW
Time Horizon	Hours, Days, Weeks, Months or Year

Purpose	Due to the intermittent nature of renewable generation, the need for resources which can store surplus energy and despatch the stored energy during low renewable energy periods becomes vital.

Parameter	Unit Commitment Problem
Component	*Generation Adequacy*
Type	Sufficiency Criteria
Definition	The Unit commitment (UC) is a popular problem in electric power system that aims at minimizing the total cost of power generation in a specific period, by defining an adequate scheduling of the generating units.
Data Measurement	Volt/MW
Time Horizon	Hours, Days, Weeks, Months or Year
Purpose	In typical unit commitment and economic despatch problems the line flow calculation used is a linear approximation of the AC power flow equations. In addition, the production cost model is also referred to as the unit commitment and despatch model.

Parameter	Single Stage Unit Commitment
Component	*Generation Adequacy*
Type	Input
Definition	Builds on “Single-Stage ED” scenarios to include additional UC details such as minimum up and down time constraints for thermal generators in the single-stage simulation
Data Measurement	
Time Horizon	
Purpose	The unit commitment (UC) model aims to find an economically optimal despatch strategy for the generating units operating within the energy system.

Parameter	Multi Stage Unit Commitment
Component	*Generation Adequacy*
Type	Input
Definition	Further considers day-ahead (DA) UC constraints in a two-stage simulation, where the first stage is a DA UC simulation, and the second stage is a real-time (RT) ED simulation
Data Measurement	
Time Horizon	
Purpose	In typical unit commitment and economic despatch problems the line flow calculation used is a linear approximation of the AC power flow equations. In addition, the production cost model is also referred to as the unit commitment and despatch model.

Parameter	Load
Component	*Generation Adequacy*
Type	Input
Definition	Load on a power system is the net consumption corresponding to the hourly average active power absorbed by all installations connected to the transmission grid or to the distribution grid, excluding the pumps of the pumped-storage stations
Data Measurement	MW or GW
Time Horizon	Seconds, Minutes, Hours, Day, Week, Month or Year
Purpose	As generation adequacy is based on the comparison of load and generation, representativeness of load data and generation data should be almost identical to make the generation adequacy assessment reliable.

Parameter	Peak Load
Component	*Generation Adequacy*
Type	Input
Definition	The peak load is generated when the loads having the highest power consumption are simultaneously activated in all the scheduling groups.
Data Measurement	MW or GW
Time Horizon	A select time-frame (seconds, minutes, hours or days) over the time-period under study (hours, days, weeks or years).
OptimaPurpose	The electric utility industry employs a simple concept for maintaining reliability: utilities must ensure they have enough electric supply a vailable to serve their total electric load and then have a required "cushion" of electric supply beyond their peak load.
Formula	Active Load Management Credit x Active Load Management Factor x Forecast Pool Requirement

Parameter	Insufficient Ramping Resource Expectation (IRRE)
Component	*Generation Adequacy*
Type	Input
Definition	This indicator measures the time (in hours) in which the available ramping of the generating units is less than the required ramping of the net system load (system load minus RES generation).
Data Measurement	Net Load: MW or GW Ramping Capability: MW/min or GW/min
Time Horizon	A select time-frame (seconds, minutes, hours or days) over the time-period under study (hours, days, weeks or years).
Purpose	The electric utility industry employs a simple concept for maintaining reliability: utilities must ensure they have enough electric supply available to serve their total electric load and then have a required "cushion" of electric supply beyond their peak load.

Parameter	Energy Not Supplied
Component	*Generation Adequacy*
Type	Input
Definition	It is the energy not supplied by the generating system due to the demand exceeding the available generating and import capacity
Data Measurement	MWh
Time Horizon	Minutes, Hours, Day, Month or Year
Purpose	During the time of system collapse or system failure, the customer is denied energy. The power supplier and customers need to pay attention to the energy not supplied at the time of system failure as it is essential to understand the financial implication and discomfort this would have created.

Parameter	Optimal Level of Reliability
Component	*Resource Adequacy*
Type	Sufficiency Criteria
Definition	Other market imperfections will not be an impediment. In principle, absent any such imperfections, an MPC set at the estimated VOLL for retail customers should deliver a socially optimal level of reliability
Data Measurement	$/kW year
Time Horizon	Annual
Purpose	Whether reliability is determined by "central planning," that is by a regulatory determined capacity margin mandated by the regulator and implemented by the regulated vertical integrated utility, or as a targeted capacity margin used as the key driver for a capacity market, a methodology to determine the optimal level of reliability/capacity is required.
Formula	The optimal level of reliability at supply/demand equilibrium conditions can therefore be calculated as: [Annual Loss of Load of Hours x Value of Lost Load($/MW)]/1000 = Net Cost of New Entry ($/kW yr)

Parameter	Frequency and Duration (FAD)
Component	*Resource Adequacy*
Type	Sufficiency Criteria
Definition	FAD utilises the transition rate parameters of failure rate and repair rate of distributed energy resources (DERs).
Data Measurement	
Time Horizon	

Purpose	Compared with probability information, frequency and duration information can provide more insight into the sequential behavior of random variables. Frequency and duration concepts are generally used in the field of power system reliability evaluation. In these concepts, the term 'frequency' is used to denote the rate of encountering a system state or subset of states, while the term 'duration' is used to denote the mean residence time in a state or subset of states in one cycle.

Parameter	P95
Component	*Resource Adequacy*
Type	Input
Definition	It represents the number of hours during a very cold winter (once every 20 years) during which the load cannot be covered by all means available. It is equal to LOLE, but calculated in a critical scenario.
Data Measurement	Hours/Year
Time Horizon	Hours/Year
Purpose	Simple definition of the likelihood of encountering problems. The severity of the problem is not quantified. Difficulty in drawing a comparison for different countries due to their peculiarities in the definition of severe operating conditions.

Parameter	Loss of Energy Probability (LOEP)
Component	*Resource Adequacy*
Type	Input
Definition	It indicates the impact of capacity outages on customers by means of the expected energy curtailed.
Data Measurement	%
Time Horizon	Minutes, Hours or Year
Purpose	The LOEP method is a variation of the LOLP method in that it uses essentially the same load and capacity models to derive a measure related to the expected fraction of energy sales lost due to capacity shortages. This measure is useful in that it can be related directly to the revenues collected by the utility and by extension to the purchases made by consumers.
Formula	Loss-of-energy probability (LOEP) is the ratio of expected non-served energy to total energy demand over a period of time

Parameter	Value of Lost Load
Component	*Market Adequacy*
Type	Input

Definition	The average opportunity cost of the involuntary curtailment would be the average “value of the lost load” (VOLL) defined by the implicit demand curve, which represents the correct estimate of the cost of curtailment given the limits on control of inflexible load
Data Measurement	$/MWh
Time Horizon	Hours, Years
Purpose	Value of the lost load (VOLL) is a useful quantity in economical evaluations of power systems. The VOLL depends on multiple factors such as type of customer, regional economic conditions and demographics, time and duration of outage, and other specific traits of power interruption.

Parameter	Mandatory Load Hedge
Component	*Market Adequacy*
Type	Input
Definition	An “energy-only” market design could accommodate a mandatory load hedge (MLH) requirement. This would be a regulatory intervention to address the concern that there would be inadequate forward contracting
Data Measurement	% of load, absolute megawatts (MW)
Time Horizon	Months or Years
Purpose	Hedging deals with executing several transactions where the expectation is to substantially offset the risk that is exposed in the project.

Parameter	Scarcity Revenue
Component	*Market Adequacy*
Type	Input
Definition	In an energy market, scarcity revenue is defined as the revenue coming from prices above the strike price of a call option.
Data Measurement	$, $/MWh
Time Horizon	Seconds, Minutes, Hours or Day
Purpose	

Parameter	Fuel Cost
Component	*Fuel Adequacy*
Type	Input
Definition	A fuel charge is the cost for fuel required to provide each kilowatt-hour (kWh) of electricity.
Data Measurement	$
Time Horizon	

Purpose	Fuel cost is a very key important input that is used to measure the Levelised Cost of Electricity (LCOE), which is defined as the price at which the generated electricity should be sold for the system to break even at the end of its lifetime. Calculating LCOE involves cost inputs such as O&M costs, fuel costs, decommissioning costs and financing costs, of other cost factors.

Parameter	Fuel Valve Time Constant
Component	*Fuel Adequacy*
Type	Input
Definition	
Data Measurement	Seconds
Time Horizon	Seconds
Purpose	

Parameter	Fuel Valve Opening Limits (%)
Component	*Fuel Adequacy*
Type	Input
Definition	
Data Measurement	%
Time Horizon	NA
Purpose	

Parameter	Fuel Valve Opening/Closing Rate Limits (%/sec)
Component	*Fuel Adequacy*
Type	Input
Definition	
Data Measurement	%/sec
Time Horizon	%/sec
Purpose	

Parameter	Variable Operation & Maintenance (O&M)
Component	*Fuel Adequacy*
Type	Input
Definition	Electrical power generation system in an energy system model with high levels of variable renewable generation sources; as more variable generation comes online in future power systems the accurate modeling of these resources becomes important;
Data Measurement	
Time Horizon	

Purpose	The benefits of having a geographical spread to a variable resource such as wind are well understood as poorly correlated resources can smoothen out the total net variability (net variability is the demand minus the wind generation) of the aggregated resource

Parameter	Normative Availability (Coal-Based Thermal Power Generation)
Component	*Fuel Adequacy*
Type	Input
Definition	It is the generative ability of the seller that equals to the guaranteed minimum offtake for a certain share of the contracted capacity by the buyer over a given period
Data Measurement	Tonnes/Million Tonnes
Time Horizon	Monthly, Yearly
Purpose	

Parameter	Normative Capacity Index (Hydro-Based Thermal Power Generation)
Component	*Fuel Adequacy*
Type	Input
Definition	It is the capacity index of that power plant whose maximum availability capacity depend on values of purely run-of-the-river hydro stations and/or pondage/storage-type hydro generating stations
Data Measurement	%
Time Horizon	Monthly, Yearly
Purpose	

Parameter	Reasonably Assured Reserves (RAR) (Nuclear Power Generation)
Component	*Fuel Adequacy*
Type	Input
Definition	These 'proved' reserves have a high assurance of existence. These reserves are defined in terms of uranium recoverable from mineable ore, allowing for mining and processing losses. Resource estimates are expressed in terms of tonnes of recoverable uranium
Data Measurement	Metric Tons (MtU)
Time Horizon	Monthly, Yearly
Purpose	

Parameter	Solar Irradiance
Component	*Fuel Adequacy*
Type	Input
Definition	This refers to the amount of solar radiation (light and heat energy) striking a surface per unit area over a specific time.
Data Measurement	Watts per square metre (W/m^2)

Time Horizon	
Purpose	

Parameter	Solar Constant
Component	*Fuel Adequacy*
Type	Input
Definition	This is the average irradiance received on a surface perpendicular to the incoming rays outside the Earth's atmosphere. It is a theoretical value of approximately 1361 W/m² and serves as a reference point for understanding variations in solar irradiance reaching Earth's surface.
Data Measurement	Watts per square metre (W/m²)
Time Horizon	
Purpose	

Parameter	Solar Window
Component	*Fuel Adequacy*
Type	Input
Definition	This is the usable portion of the electromagnetic spectrum from the sun that can be efficiently converted into electricity by solar photovoltaic (PV) cells. It typically ranges from about 300 to 1100 nanometres (nm) and encompasses visible light and some infrared and ultraviolet wavelengths.
Data Measurement	Nanometres (Nm)
Time Horizon	
Purpose	

Parameter	Solar Spectrum
Component	*Fuel Adequacy*
Type	Input
Definition	This refers to the entire distribution of electromagnetic radiation emitted by the sun. It includes a wide range of wavelengths, from ultraviolet to infrared, with varying intensities. Only a portion of this spectrum falls within the solar window and can be effectively utilised for solar power generation.
Data Measurement	By Wavelength: Nanometres (Nm) By Spectral Irradiance (or Spectral Flux Density): Watts per meter squared per nanometer (W/m²/nm)
Time Horizon	
Purpose	

Parameter	Solar Insolation
Component	*Fuel Adequacy*
Type	Input

Definition	This term describes the total amount of solar radiation received over a specific period on a tilted surface at a particular location. It is influenced by factors like solar irradiance, geographical location (latitude), time of day, season, and tilt angle of the solar panels. Solar insolation data is crucial for designing efficient solar power systems.
Data Measurement	Watt-hours per square meter (Wh/m^2), Kilowatt-hours per square meter (kWh/m^2), Megajoules per square meter (MJ/m^2)
Time Horizon	
Purpose	

Parameter	Direct Radiation
Component	*Fuel Adequacy*
Type	Input
Definition	This is the sunlight that reaches the Earth's surface directly from the sun, without being scattered or absorbed by the atmosphere. It typically has the highest intensity and is the most valuable component for solar power generation.
Data Measurement	Watts per square meter (W/m^2)
Time Horizon	
Purpose	

Parameter	Diffuse Radiation
Component	*Fuel Adequacy*
Type	Input
Definition	This is sunlight that has been scattered or reflected by atmospheric components like clouds, dust, and water vapor. It has a lower intensity compared to direct radiation but still contributes to overall solar insolation
Data Measurement	Watts per square meter (W/m^2)
Time Horizon	
Purpose	

Parameter	Time-Based Availability (Wind)
Component	*Fuel Adequacy*
Type	Input
Definition	This approach calculates availability as a ratio of two time durations: the total time the turbine is operational and the total project duration.
Data Measurement	Hours
Time Horizon	Hours
Purpose	While computationally simpler, it overlooks wind speed variations throughout the period. This can lead to underestimating the significance of availability during high-wind periods when energy production is maximised. The readily available data from operational wind projects makes time-based definitions easier to implement.

Formula	Time-based availability = Time available (in hours) / Total time in consideration (in hours)

Parameter	Production-Based Availability (Wind)
Component	*Fuel Adequacy*
Type	Input
Definition	It calculates availability as the ratio of actual energy produced to the ideal energy production based on wind speeds and site conditions.
Data Measurement	Kilowatt Hours (KWh)
Time Horizon	Kilowatt Hours (KWh)
Purpose	Production-based availability acknowledges that turbines may have lower availabilities during high winds due to increased production and loads, potentially leading to more faults and downtime. Additionally, it accounts for strategically scheduled maintenance during low-wind periods, allowing a turbine to generate more energy compared to one experiencing downtime during high-wind times, even if both have the same total down-hours. For this reason, project evaluations often consider production-based or energy-weighted availability.
Formula	Time-based availability = Time available (in hours) / Total time in consideration (in hours)

Parameter	Full-Period Availability (Wind)
Component	*Fuel Adequacy*
Type	Input
Definition	This method calculates availability as the ratio of operational hours to the total period under consideration, typically a month or a year.
Data Measurement	Hours
Time Horizon	Hours
Purpose	
Formula	Full-period availability = Number of hours available / 8,760 hours/year

Parameter	Wind-in-Limits Availability
Component	*Fuel Adequacy*
Type	Input
Definition	The WIL definition considers availability only during periods when wind speed and temperature fall within the turbine's operational limits. Additionally, it factors in grid and Balance of Plant (BoP) availability.
Data Measurement	Hours
Time Horizon	Hours
Purpose	This method provides a more nuanced picture of availability by focusing on periods when the turbine could have realistically generated power. However, it requires additional data points to assess grid and BoP availability, potentially complicating the calculation.

Formula	Wind-in-limits availability = Number of hours generating kW / Number of hours that the wind is between cut-in and cut-out

Parameter	Conversion Efficiency Ratio
Component	*Fuel Adequacy*
Type	Input
Definition	The conversion efficiency is the ratio of net electric power generated (MWe) to the geothermal heat produced/extracted from the reservoir (MWth)
Data Measurement	%
Time Horizon	%
Purpose	
Formula	Net electric power generated (MWe)/Geothermal heat produced/extracted from the reservoir (MWth)

Parameter	Minimum Storage Capacity
Component	*Operation Adequacy*
Type	Sufficiency Criteria
Definition	The minimum amount of Energy that must be produced from the reservoir of a Pumped Storage Generator for a Trading Day
Data Measurement	MW or GW
Time Horizon	Day, Month or Year
Purpose	Pumped storage is suitable for situations where power is desired many hours after it can be produced; for instance, the wind is strong at night for generating electricity but the demand for the generated power is strong during the day. The minimum storage capacity of a reservoir would help the storage to be more responsive to ramp up power or vice versa.

Parameter	N-1 Criterion
Component	*Operation Adequacy*
Type	Sufficiency Criteria
Definition	This criterion is needed to ensure that the system has the ability to withstand single component outage. It gives a performance table containing all severe contingencies to which planners must pay special attention.
Data Measurement	Per unit, MW or Hertz
Time Horizon	Hours, Months or Years

Purpose	A power system can be described as being N-1 secure when it is capable of maintaining normal operations in the event of a single contingency event, such as the unplanned loss of a transmission line, generator or transformer. This standard has been adopted by system operators around the world to inform operational contingency planning, to guide management of system operation, and to guide emergency efforts to return systems to a secure and stable operating condition within a reasonable time following a single contingency event, usually within 15 to 30 minutes.

Parameter	Actual Net Interchange
Component	*Operation Adequacy*
Type	Input
Definition	Actual Net Interchange is the next positive exported energy.
Data Measurement	MW
Time Horizon	seconds
Purpose	It is used in calculating the Area Control Error (ACE) and the associated departure from scheduled net interchange

Parameter	Scheduled Net Interchange
Component	*Operation Adequacy*
Type	Sufficiency Criteria
Definition	Scheduled Net Interchange is the expected positive exported energy.
Data Measurement	MW
Time Horizon	seconds
Purpose	Used as a standard interchange level to ascertain the actual deviation in order to calculate the Area Control Error (ACE)

Parameter	Frequency Bias Coefficient
Component	*Operation Adequacy*
Type	Input
Definition	A number, either fixed or variable, usually expressed in MW/0.1 Hz, included in a Balancing Authority's Area Control Error equation to account for the Balancing Authority's inverse Frequency Response contribution to the Interconnection, and discourage response withdrawal through secondary control systems
Data Measurement	Change in generation- MW Change in frequency- Hertz
Time Horizon	Seconds, Minutes
Purpose	The Frequency Bias Setting predicts how much frequency response a balancing area (BA) will provide for a given change in frequency. An accurate Frequency Bias Setting allows the amount of Actual Net Interchange from a BA's frequency response to be offset in the ACE equation so that its AGC does not try to countermand its governor and load response.

Parameter	Tie-line bias control
Component	*Operation Adequacy*
Type	Input
Definition	It is the mechanism of correcting Area Control Error (ACE) by factoring in deviation of net actual interchange from net scheduled interchange at regional level as well as frequency deviation
Data Measurement	Unitless
Time Horizon	Not-defined; Responsive in nature
Purpose	It is a mode of Automatic Generation Control that allows the Balancing Authority to: 1. maintain its Interchange Schedule and, 2. respond to Interconnection frequency error.

Parameter	Secondary Control Signal
Component	*Operation Adequacy*
Type	Input
Definition	It is an automated signal generated from the Nodal Agency through which injection or drawl or consumption of an SRAS provider is adjusted, and includes AGC signal
Data Measurement	MW
Time Horizon	Seconds, Minutes
Purpose	The function of secondary control is to restore power cross-border exchanges to their (programmed) set-point values and to restore the system frequency to its set-point value at the same time.

Parameter	Frequency Response Characteristics
Component	*Operation Adequacy*
Type	Input
Definition	It is the automatic, sustained change in the power consumption by load or output of the generators that occurs immediately after a change in the load-generation balance of a control area and which is in a direction to oppose a change in frequency.
Data Measurement	Magnitude- Decibels Phase- Degrees or radians
Time Horizon	Frequency response analysis; hence no particular time horizon
Purpose	Frequency Response Characteristic (FRC) is a comprehensive metric for evaluating the frequency response capability accurately and procuring frequency response sources cost-effectively.

Parameter	Flat tie-line control
Component	*Operation Adequacy*

Type	Input
Definition	It is a mechanism of correcting Area Control Error (ACE) by factoring in only the deviation of net actual interchange from net scheduled interchange at regional level, and ignoring frequency deviation
Data Measurement	Unitless
Time Horizon	Not-defined; Responsive in nature
Purpose	The change in load in a particular area is taken care of by the generator in that area thereby the tie-line loading remains constant.

Parameter	Flat frequency control
Component	*Operation Adequacy*
Type	Input
Definition	It is a mechanism of correcting Area Control Error (ACE) by factoring in only the frequency deviation, and ignoring the deviation of net actual interchange from net scheduled interchange at regional level
Data Measurement	Unitless
Time Horizon	Not-defined; Responsive in nature
Purpose	The purpose of primary regulation methods like flat frequency control is to clear the unbalance between generation and loads, in order to take the system to a stable condition.

Parameter	Automatic Load Frequency Control (ALFC)
Component	*Operation Adequacy*
Type	Input
Definition	This system automatically adjusts the power output of generators to correct frequency deviations. It operates by measuring the frequency and adjusting the generation accordingly.
Data Measurement	Power- Megawatts (MW) Frequency- Hertz (Hz)
Time Horizon	Not-defined; Responsive in nature
Purpose	ALFC acts as a continuous balancing mechanism, making small adjustments to generation output in response to changes in load to maintain system equilibrium

Parameter	Spinning Reserve Margin
Component	*Operation Adequacy*
Type	Input
Definition	The amount of generation capacity that can be quickly brought online to meet an unexpected increase in demand.
Data Measurement	Megawatts (MW)
Time Horizon	Seconds, Minutes

Purpose	Spinning reserve margin is a critical component of power system reliability and stability. It represents the extra generation capacity that is online, synchronised to the grid, and ready to respond immediately to frequency deviations or unexpected load changes.

Parameter	Rate of Change of Frequency (RoCoF)
Component	*Operation Adequacy*
Type	Input
Definition	The speed at which grid frequency changes following a disturbance.
Data Measurement	Hertz per second (Hz/s)
Time Horizon	Seconds
Purpose	RoCoF is a critical parameter used to detect and respond to sudden imbalances between power generation and demand in an electrical power system. It helps prevent cascading failures and blackouts.

Parameter	Time Error
Component	*Operation Adequacy*
Type	Input
Definition	The difference between the actual time and the time measured in AC cycles. This metric is important for maintaining long-term grid synchronization.
Data Measurement	Seconds
Time Horizon	hours, days, or weeks
Purpose	Frequency control and system stability

Parameter	Operating Reserve
Component	*Operation Adequacy*
Type	Input
Definition	This metric refers to the additional capacity available to meet demand fluctuations and maintain system reliability.
Data Measurement	Megawatts (MW)
Time Horizon	Seconds, minutes
Purpose	Frequency control, system stability, contingency planning and reliability

Parameter	Nadir Frequency
Component	*Operation Adequacy*
Type	Input
Definition	The minimum frequency after a contingency in case of generation loss and maximum frequency after a contingency in case of load loss;
Data Measurement	Hertz
Time Horizon	Nadir frequency refers to the lowest frequency experienced during a system disturbance event, such as a sudden loss of generation or a large increase in demand. Hence, it does not have a specific time horizon associated with it.

Purpose	Frequency nadir is an important indicator that measures the post-disturbance frequency stability of power systems, which is vital for fast frequency support and control of future power systems penetrated with renewable energy.

Parameter	Area Control Error (ACE)
Component	*Operation Adequacy*
Type	Input
Definition	It means the instantaneous difference between a control area's net actual interchange and net scheduled interchange, taking into account the effects of frequency bias and correction of measurement errors
Data Measurement	MW
Time Horizon	Seconds
Purpose	Area control error basically measures the difference between scheduled and actual electrical generation in a control area on the power grid, while taking frequency bias into account. This is used to regulate the area frequency and achieve load-fequency control by effective adjusting of generation to minimise frequency deviation and regulate tie-line power flows

Parameter	System Constraint
Component	*Transmission Adequacy*
Type	Input
Definition	A limitation on the use of any user system and/or the National Electricity Transmission System due to lack of transmission capacity or other system conditions.
Data Measurement	Unitless
Time Horizon	NA
Purpose	System constraint helps understand the complexity of the problem involved in transmission and the contingencies that arise as a result while it provides an appropriate strategy path in dissolving complex problems into easier problems, ensuring accuracy in solution

Parameter	Available Transfer Capacity
Component	*Transmission Adequacy*
Type	Input
Definition	Transfer capacity remaining available between two interconnected areas for further commercial activity over and above already committed utilisation of the transmission networks.
Data Measurement	MW or GW
Time Horizon	Minutes, Hours or Days

Purpose	In the distribution licensee-level / State-level planning, short-term import is limited to the available transfer capability. However, as there is no visibility about the power generation profile of other States, unpredictability in the availability of tie line power form other utilities and regions must be factored in

Parameter	Congestion
Component	*Transmission Adequacy*
Type	Input
Definition	It is a situation where the demand for transmission capacity or power flow on any transmission corridor exceeds its Available Transfer Capability
Data Measurement	MW
Time Horizon	Day
Purpose	Transmission congestion occurs when there is not enough transmission capability to support all requests for transmission services, and in order to ensure reliability, transmission system operators must re-despatch generation or, in the limit, deny some of these requests to prevent transmission lines from becoming overloaded

Parameter	Drawl Schedule
Component	*Transmission Adequacy*
Type	Input
Definition	It means the ex-power plant net MW and MWh output of a generating station, for a time block, scheduled to be injected to the Grid from time to time
Data Measurement	MW
Time Horizon	
Purpose	In the modern power systems, appropriate power despatch schedule of the online power generating units is essential for reliable and clean power supply and it is desirable to attain this at the lowest possible operating cost.

Parameter	Frequency Stability
Component	*Transmission Adequacy*
Type	Sufficiency Criteria
Definition	It is the ability of the transmission system to maintain stable frequency in the normal state and after being subjected to a disturbance;
Data Measurement	
Time Horizon	

Purpose	A permanent off-normal frequency deviation may affect power system operation, security, reliability and efficiency by damaging equipment, degrading load performance, overloading transmission lines, and triggering the protection devices. Depending on the amplitude and duration of frequency deviation, different frequency control loops may be required to maintain power system frequency stability.

Parameter	Control Area
Component	*Transmission Adequacy*
Type	Input
Definition	It is an electrical system bounded by interconnections (tie lines), metering and telemetry which controls its generation and/or load to maintain its interchange schedule with other control areas and contributes to regulation of frequency as specified in these regulations
Data Measurement	
Time Horizon	
Purpose	All the generators in an area constitute a coherent group so that all the generators speed up and slow down together maintaining their relative power angles.

Parameter	Net Transfer Capacity (NTC)
Component	*Transmission Adequacy*
Type	Input
Definition	The available commercial capacity (=NTC) offered to the market does not equal the physical capacity.
Data Measurement	
Time Horizon	
Purpose	The expected maximum volume of generation that can be wheeled through the interface between the two systems, which does not lead to network constraints in either systems, respecting some technical uncertainties on future network conditions

Parameter	Simultaneous Interconnection Transmission Capacities
Component	*Transmission Adequacy*
Type	Input
Definition	Simultaneous Interconnection Transmission Capacity of a power system is the overall transmission capacity through its peripheral interconnection lines within the Union for the Coordination of Transmission of Electricity (UCTE). SITC are calculated according to the UCTE Transmission Development Plans. The SITC export value is called Export Capacity and may differ from the SITC import value, called Import Capacity.
Data Measurement	
Time Horizon	

Purpose	Due to potential correlation between the transmission capacities on the adjoining borders of a country, it is not always possible to calculate the SITC of a country by simply adding the Net Transfer Capacity (NTC) on all the borders of the country. A dedicated calculation is then performed by the Transmission System Operators (TSO).

Parameter	System Average Interrupted Duration Index (SAIDI)
Component	*Distribution Adequacy*
Type	Input
Definition	SAIDI represents the total number of minutes of interruption the average customer experiences. SAIDI is calculated by dividing the sum of all customer interruption minutes within the year by the number of customers served during the year. SAIDI minutes represent how long the average customer experiences an outage and lower SAIDI minutes equate to better electric reliability.
Data Measurement	Number of interruptions
Time Horizon	Week, Month or Year
Purpose	How often an average customer experiences sustained interruption during a predefined given time period of a year. SAIDI is commonly used as a reliability indicator by electric power utilities and the most often used performance measurement for a sustained interruption
Formula	SAIDI = S (Encountered power interruption minutes x No. of customers with a power supply break) / Total Number of Customers served by the DSO

Parameter	System Average Interrupted Frequency Index (SAIFI)
Component	*Distribution Adequacy*
Type	Input
Definition	SAIFI represents the average number of times a customer experiences an outage during the year. SAIFI is calculated by dividing the total number of customer interruptions by the total number of customers in the system. Lower SAIFI numbers represent less interruptions and better electric reliability.
Data Measurement	Number of interruptions
Time Horizon	Week, Month or Year
Purpose	SAIFI is a measure of how often an average customer loses supply during one year. A SAIFI of 3 means that the average customers connected to the feeder or supply area being measured on average lost supply thrice during the past 12 months
Formula	SAIDI = S (No. of power interruptions encountered) / Total Number of Customers served by the DSO

Parameter	Customer Average Interrupted Duration Index (CAIDI)
Component	*Distribution Adequacy*
Type	Input
Definition	CAIDI is the average time required to restore service. It is calculated as total minutes of customer interruption divided by the total number of interruptions. The lower the number of minutes, the faster the utility restored service to customers.
Data Measurement	Number of interruptions
Time Horizon	Week, Month or Year
Purpose	Once an outage occurs, the average time to restore service is found from the customer average interruption duration index.
Formula	CAIDI = S (Encountered power recovery periods x No. of customers with a power supply break) / S (No. of power interruptions encountered) CAIDI = SAIDI / SAIFI

Parameter	Customer Average Interrupted Frequency Index (CAIFI)
Component	*Distribution Adequacy*
Type	Input
Definition	The CAIFI measures the average number of interruptions per customer interrupted per year. It is simply the number of interruptions that occurred divided by the number of customers affected by the interruptions.
Data Measurement	Number of interruptions
Time Horizon	Week, Month or Year
Purpose	
Formula	CAIDI = S (No. of power interruptions encountered) / S (No. of customers with a power supply break)

Parameter	Equivalent Demand Forced Outage Rate
Component	*Demand Assessment*
Type	Input
Definition	It estimates the conditional probability of a unit being unavailable when needed by the power system.
Data Measurement	%
Time Horizon	Seasonal (Months), Year
Purpose	Measures the probability of experiencing a forced outage or forced derating during demand periods. Designed for units in all operating states. Recommended reliability metric.

Formula	EFOR= (FOH+EFDH) / (SH+FOH) [Where, EFDH= equivalent de-rated outage hours; FOH= Full forced outage hours; SH=service hours]

Parameter	Operating Reserve Demand Curve (ORDC)
Component	*Demand Assessment*
Type	Input
Definition	ORDC is a complement to energy demand for electricity. The probabilistic demand for operating reserves reflects the cost and probability of lost load.
Data Measurement	Capacity (MW), Response (Minutes)
Time Horizon	Minutes, Hour
Purpose	These operating reserves aim to ensure that there is enough capacity online in the system to account for the increased variability and uncertainty occurring at finer temporal resolutions.

Parameter	Load Forecast Error
Component	*Demand Assessment*
Type	Input
Definition	The difference between actual demand and forecasted demand
Data Measurement	Megawatts (MW)
Time Horizon	Minutes, Hours, Days, Weeks, Months and Years
Purpose	

Parameter	Demand Response
Component	*Demand Assessment*
Type	Input
Definition	It means variation in electricity usage by the end consumers or by a control area manually or automatically, on standalone or aggregated basis, in response to the system requirements as identified by the concerned load despatch centre; balancing the demand on power grids by encouraging customers to shift electricity demand to times when electricity is more plentiful or other demand is lower, typically through prices or monetary incentives.
Data Measurement	MWh
Time Horizon	Hour
Purpose	Potential for demand side management such as shifting of load or demand response can be considered while undertaking the IRP. Constraints such as periods when load shifting can occur, the maximum quantum in an hour and the maximum quantum of load which can be shifted would need to be included.

Parameter	Demand
Component	*Demand Assessment*

Type	Input
Definition	It means the demand of active power in MW and reactive power in MVAr
Data Measurement	MW
Time Horizon	Minutes, Hour, Day, Week, Month or Year
Purpose	

Parameter	Implicit Demand-side Response (DSR)
Component	*Demand Assessment*
Type	Input
Definition	It refers to the change of demand by final customers from their normal or current consumption patterns, in response to time-variable electricity prices or incentive payments. Implicit DSR can either be self-directed or directed by an energy management service provider
Data Measurement	
Time Horizon	
Purpose	Fixed-price contracts protect consumers from the volatility of wholesale prices, but also prevent them from being exposed to short-term price signals to which they could respond with implicit demand-side response

Parameter	System Average Interruption Frequency Index (SAIFI)
Component	*Demand Assessment*
Type	Input
Definition	It represents the number of customer interruptions divided by the total customers served.
Data Measurement	Number of interruptions
Time Horizon	Week, Month or Year
Purpose	SAIFI is a measure of how often an average customer loses supply during one year. A SAIFI of 3 means that the average customers connected to the feeder or supply area being measured on average lost supply thrice during the past 12 months

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