STELLAR

Strategic Expansion for Long-Term Load Adequacy and Resilience

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Optimization Model Framework

INPUT DATA

Plant characteristics (including storage)

- Existing generation and storage facilities
- Technology-specific operational parameters:
  - Technical Minimum
  - Ramp-up and ramp-down rates
  - Minimum up and down times
  - Battery specific (ex. DoD, Degradation)
- Commissioning and retirement timelines
- Operating costs:
  - Variable Operation & Maintenance
  - Fixed Operation & Maintenance
- Availability factors
- Emission characteristics

Demand and Peak Load

- Zonal hourly electricity demand
- Regional load factors
- Demand response parameters
- Ancillary service requirements

Reliability Simulations

Accounting uncertainty in:

- Demand forecasts
- Renewable energy generation profiles
- Hydro generation limits
- Thermal plant availability

Emissions

- Carbon costs
- Emission limits

Renewable Energy Data

- Inventory of renewable energy technologies (solar, wind, ROR, etc.)
- Installed RE capacity by zone
- Zonal hourly RE generation profiles
- Zonal RE potential (technical/assessed potential)

Plant and Network Expansion Data

- (CAPEX) requirements for generation, storage and transmission assets
- CAPEX trajectories for technologies
- Weighted Average Cost of Capital (WACC)
- Capital recovery Factor (CRF)

OPTIMIZATION FRAMEWORK

STELLAR

Strategic Expansion for Long-Term Load Adequacy and Resilience

LP formulation

CPLEX Solver

CAPACITY EXPANSION PLANNING AND UNIT COMMITMENT

INTRA & INTER-STATE TRANSMISSION EXPANSION PLANNING

CO-OPTIMIZAITON OF ENERGY AND ANCILLARY SERVICES

INTEGRATED DEMAND RESPONSE

TYPICAL OUTPUTS

Capacity expansion plan

Energy mix projections for future years

Chronological demand-supply curves for future years

Generation dispatch schedules for all plants

Transmission system augmentations

Projected transmission flows

Disaggregated cost components

- Operational costs
- Balancing costs
- Capital investment costs

Projected electricity prices

Projected CUF of fuels and plants

Emission projections

Reliability metrics:

- LOLP
- NENS

USES

Pathways for achieving renewable energy (RE) targets

Resource adequacy evaluation

Profitability analysis for generation and investment options

Cost–benefit analysis of alternative scenarios and technologies

Strategic planning

Support for regulatory and policy decision-making

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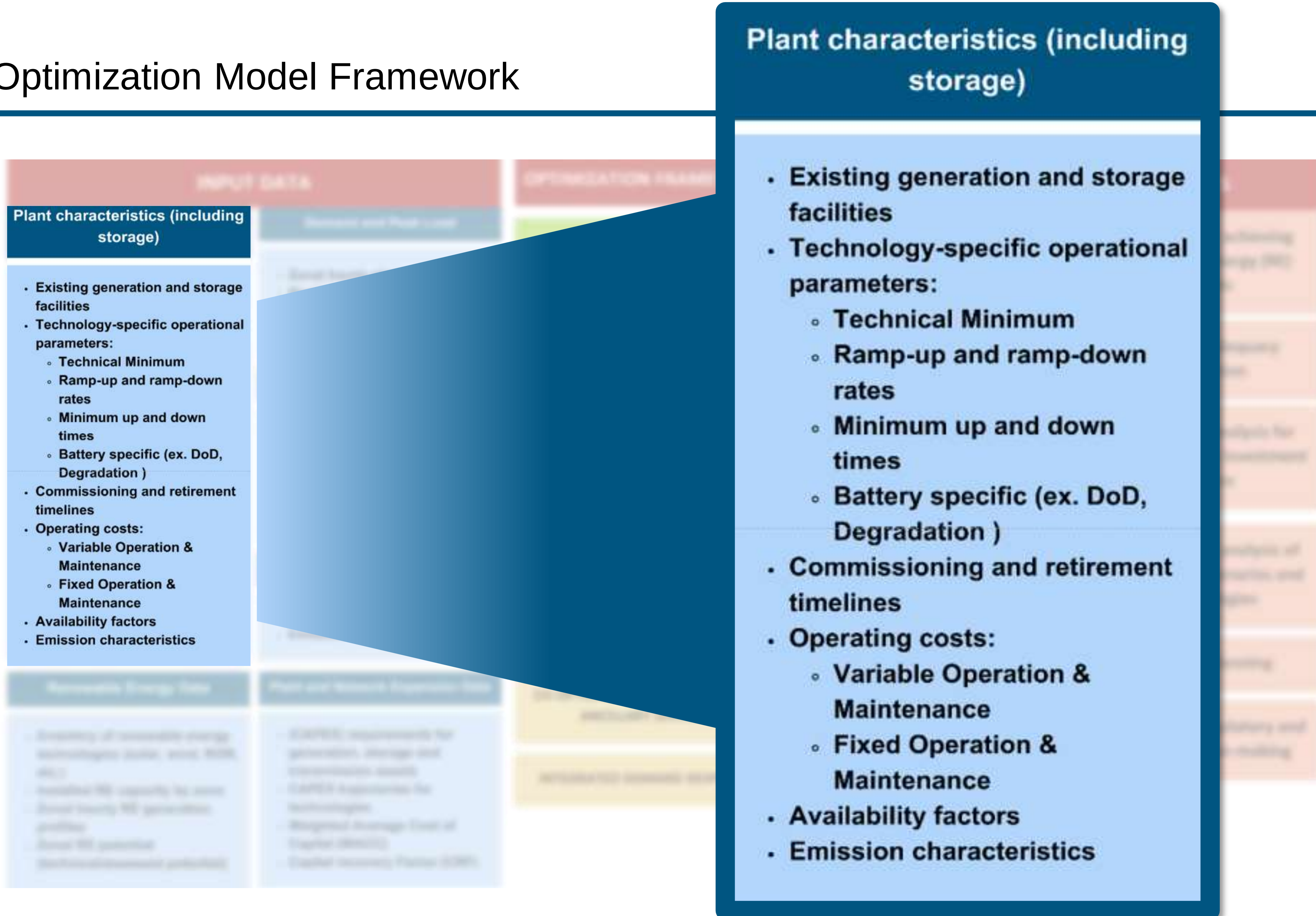
Optimization Model Framework



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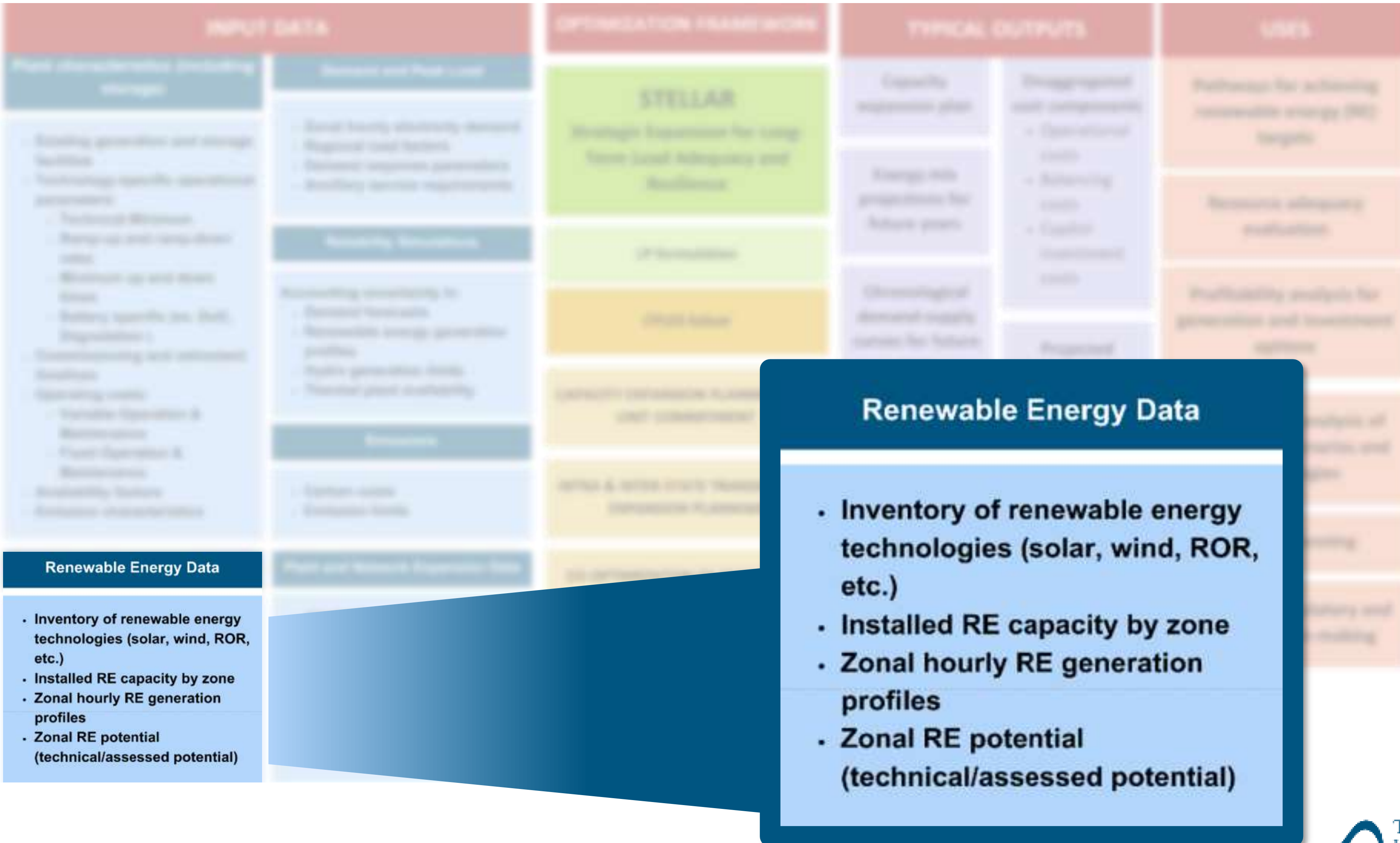

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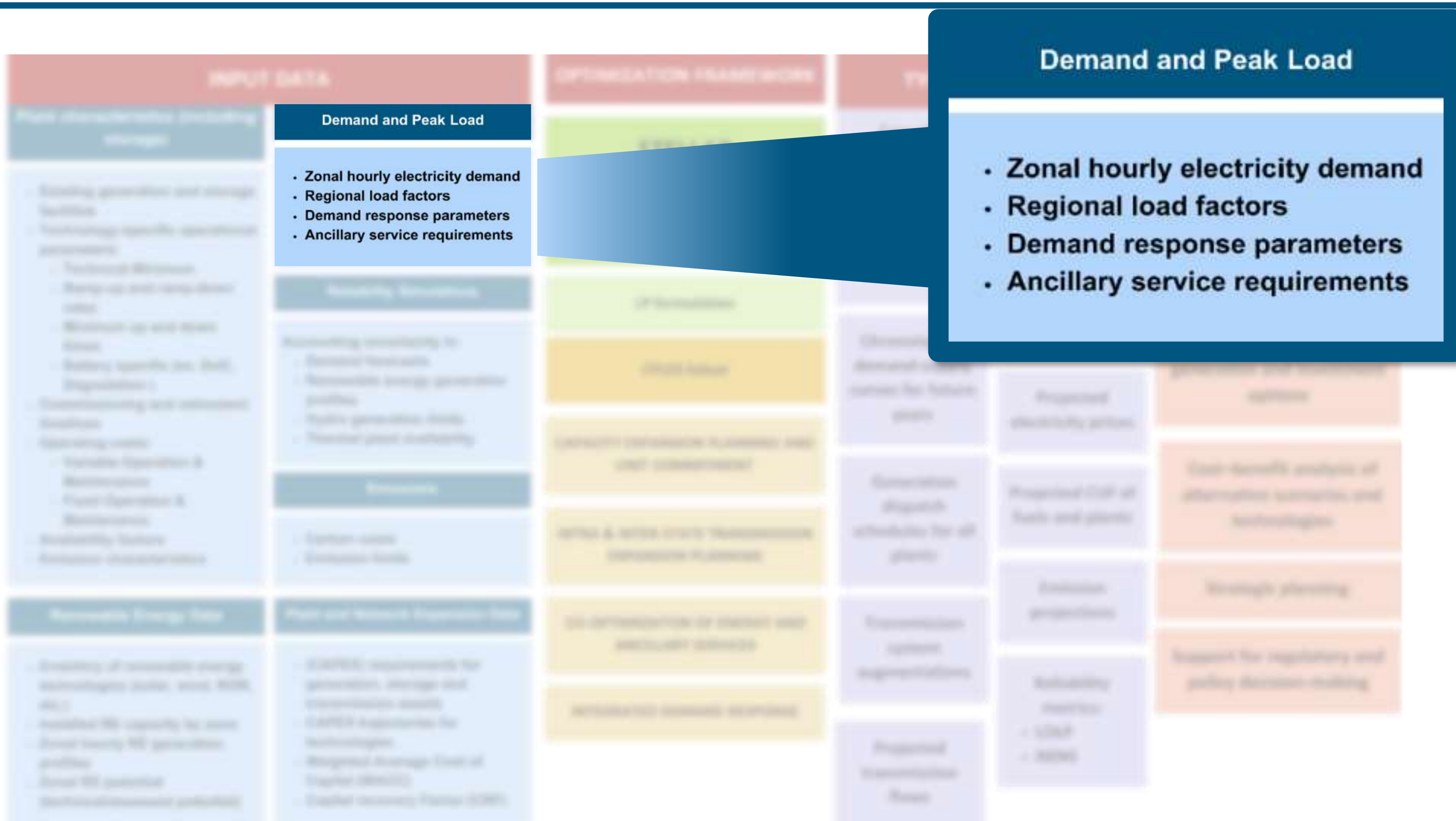

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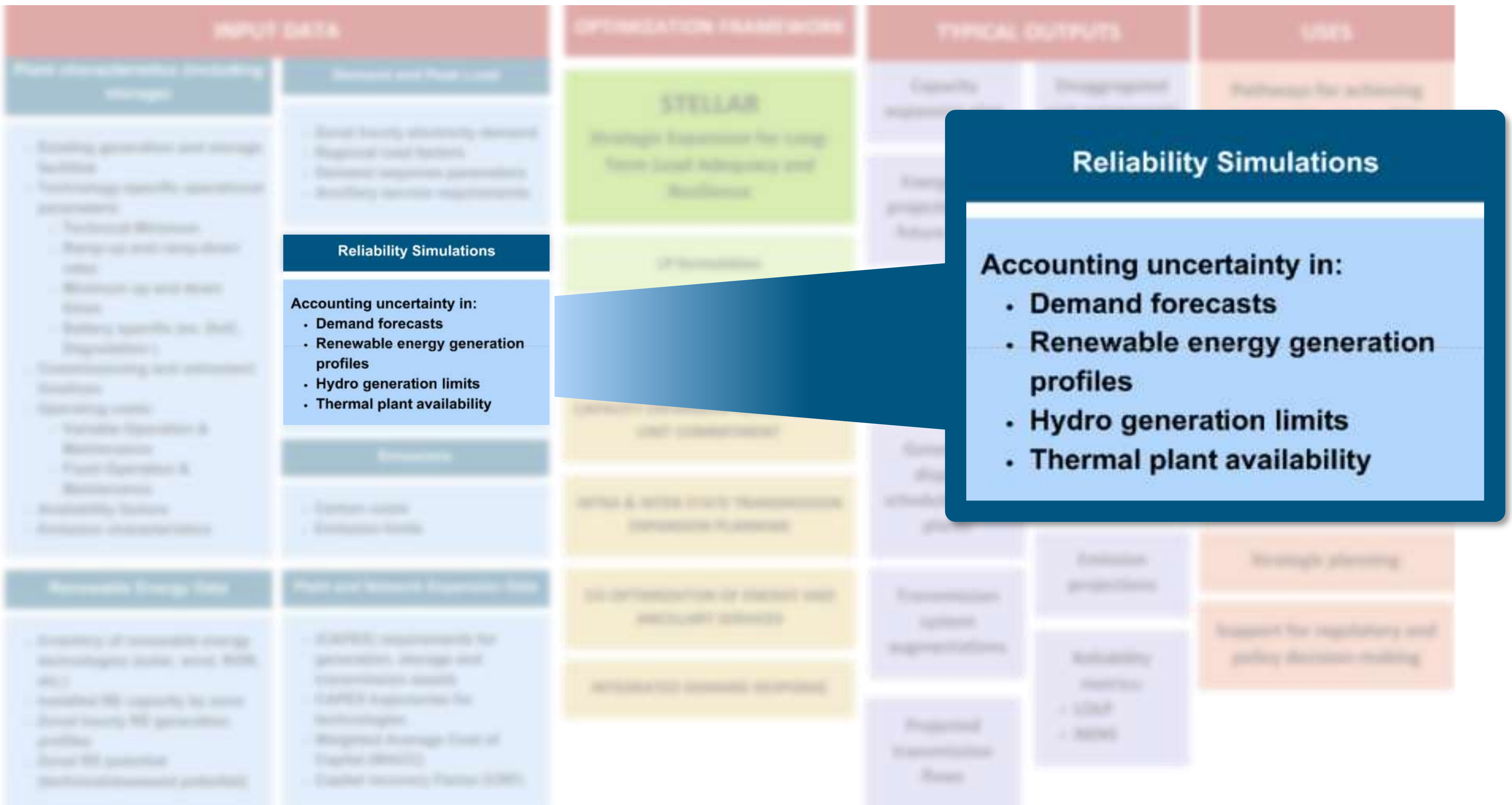

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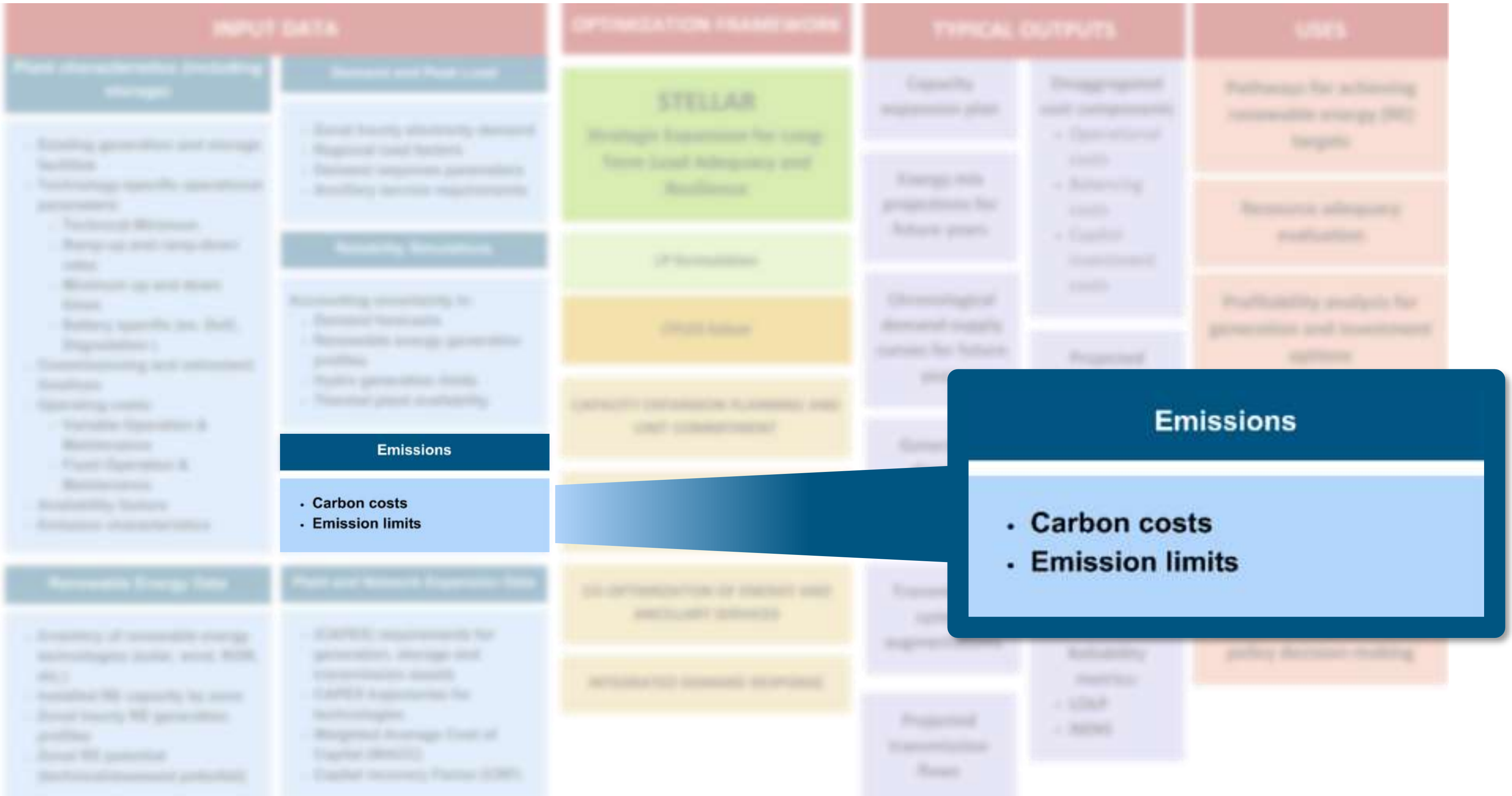

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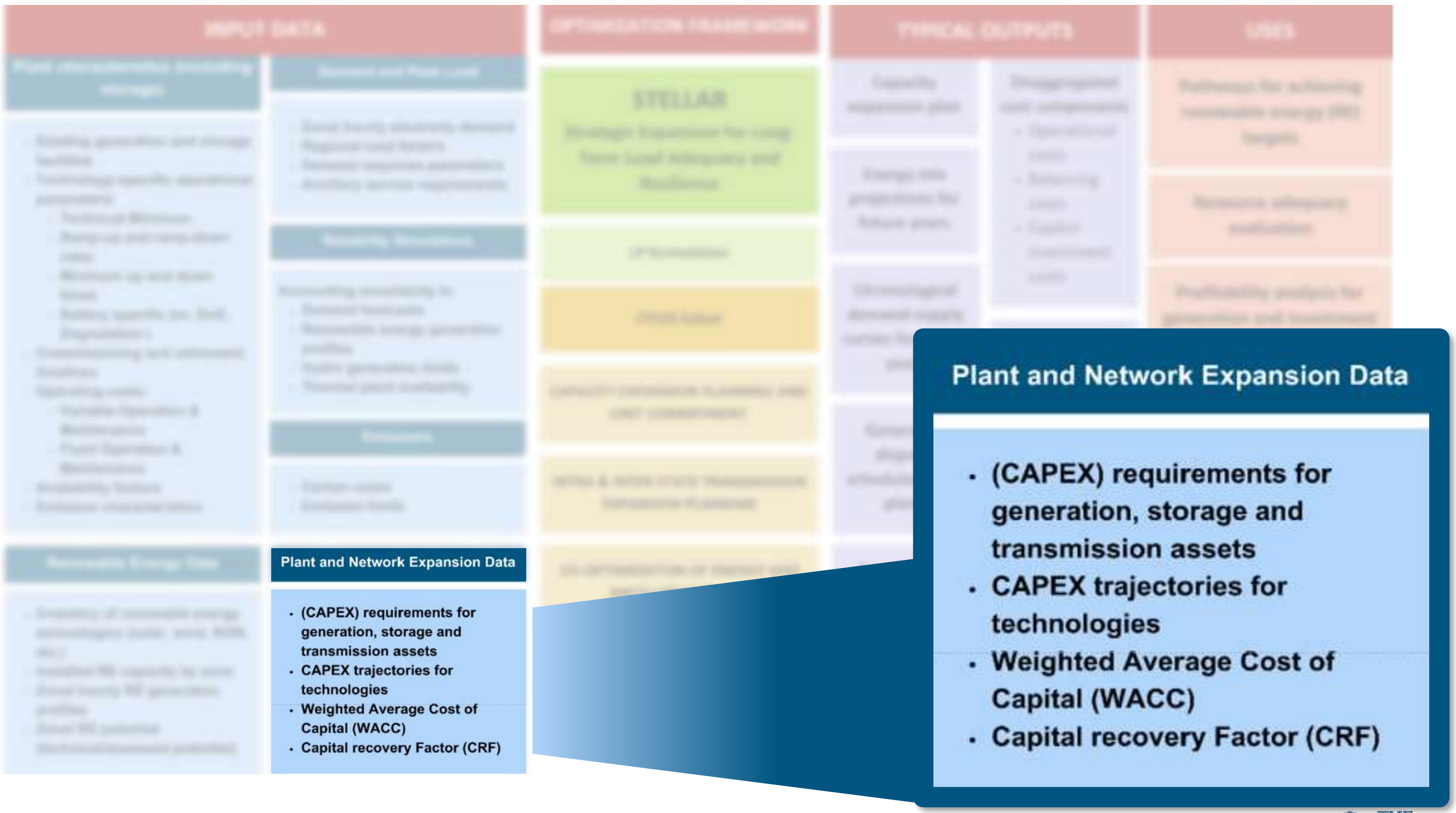

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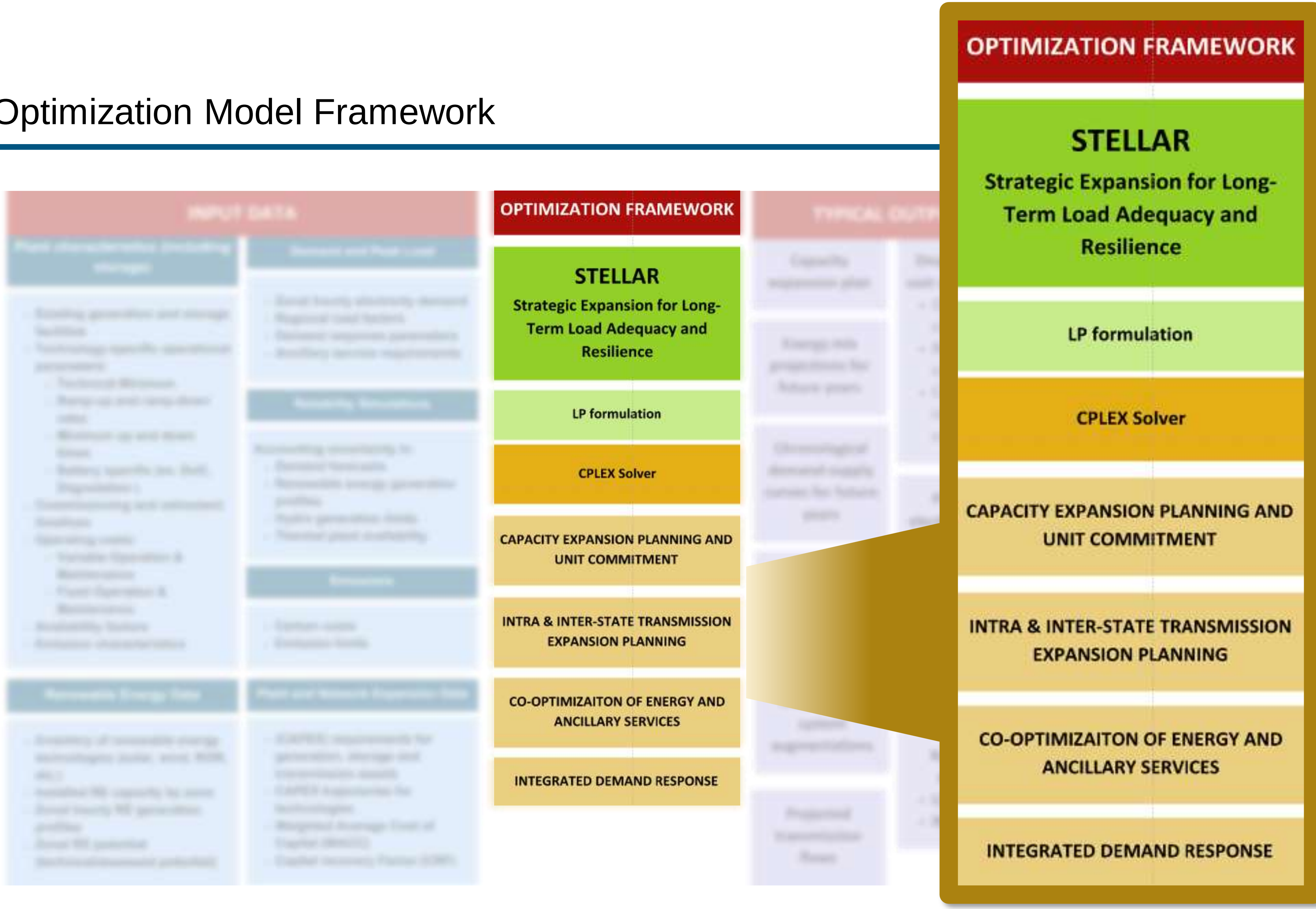
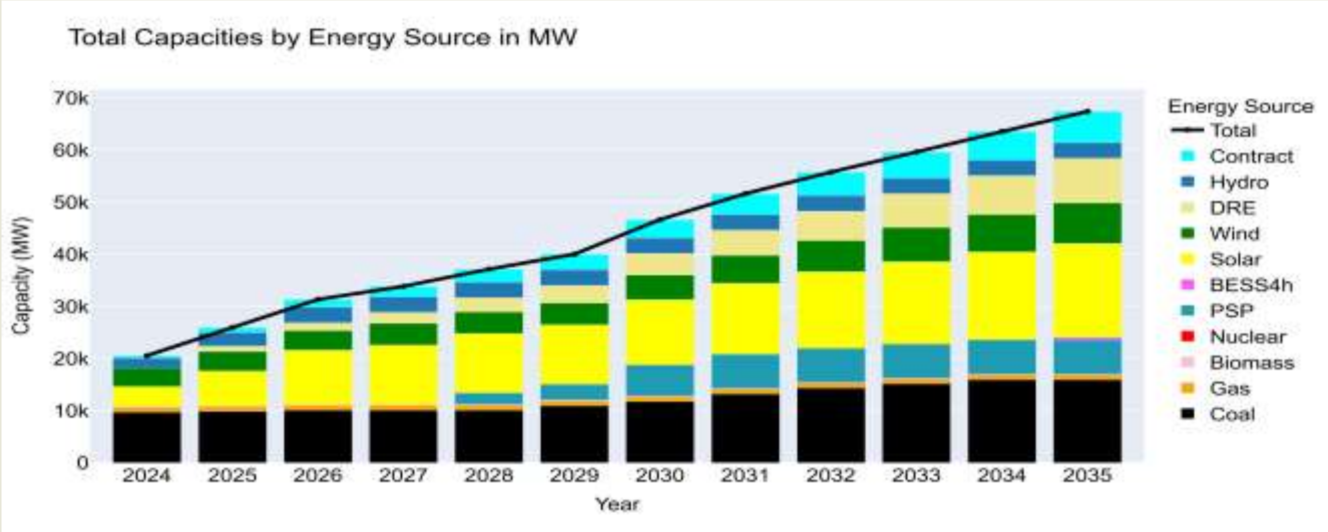
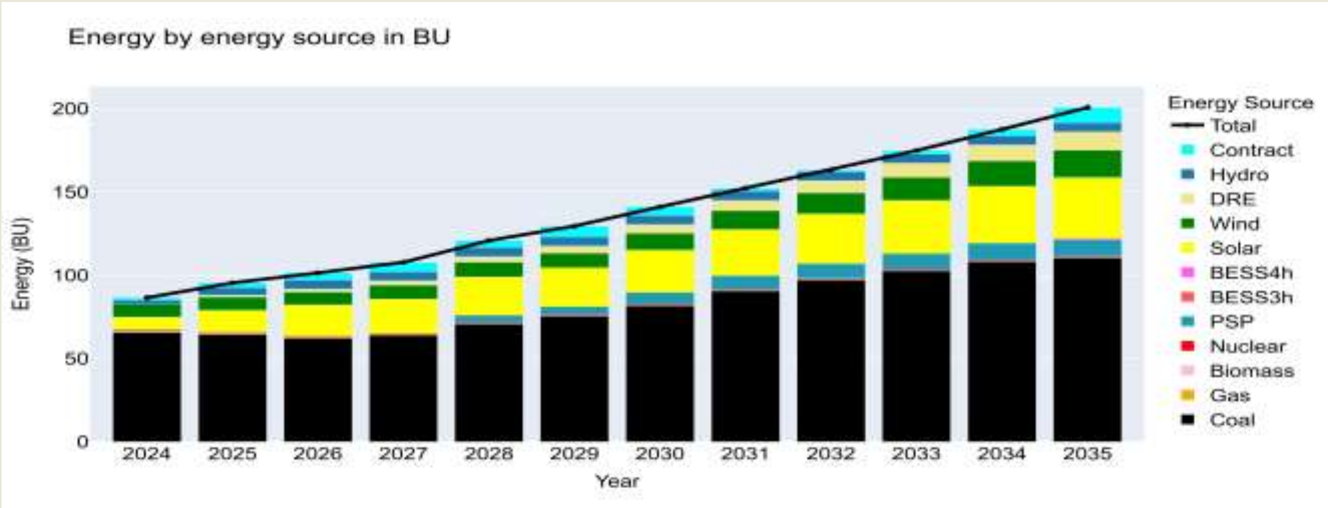


Typical Outputs

- Capacity expansion plan
- Energy mix projections
- Utilization/PLF/CUF
- Chronological demand supply curves
- Generation Dispatch schedules
- Energy Prices
- Emissions and emission factor for future
- Transmission planning and projected flows
- Reliability – LoLP and NENS





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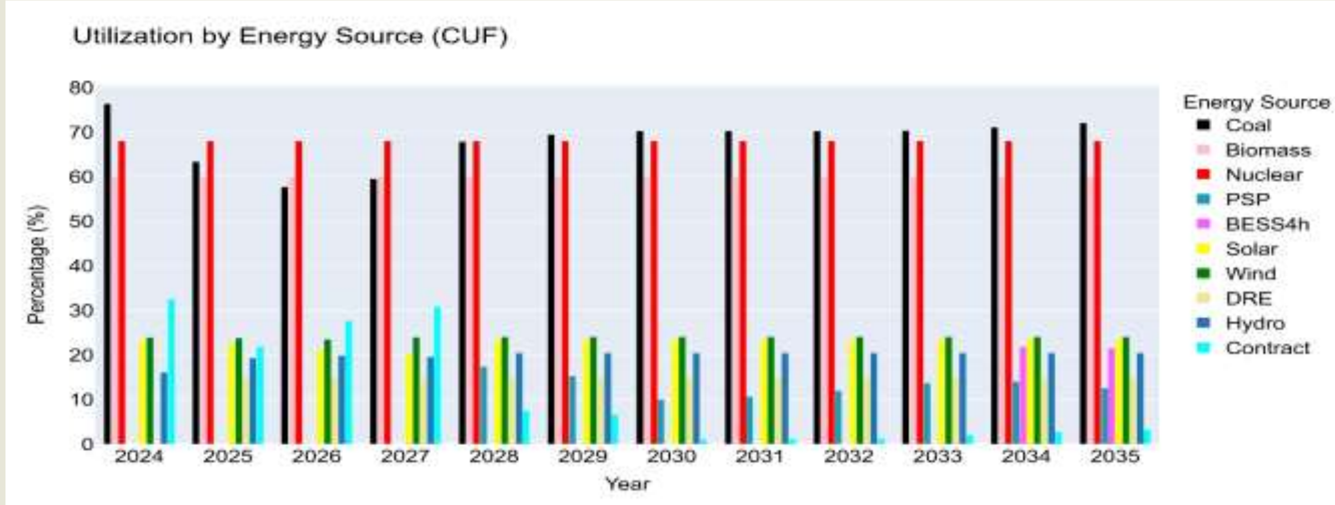

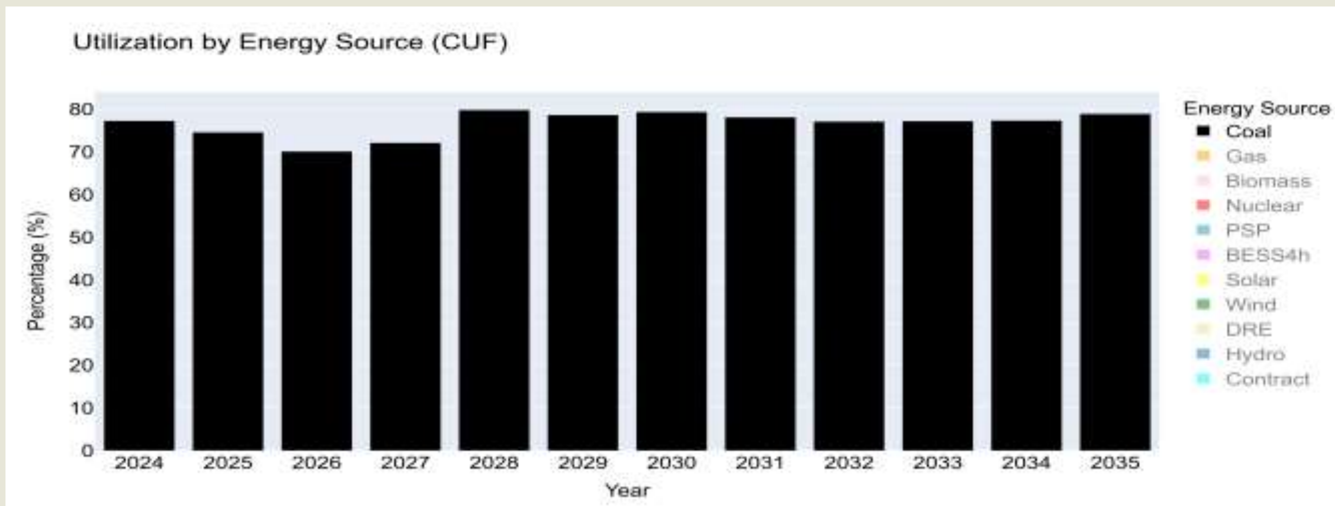

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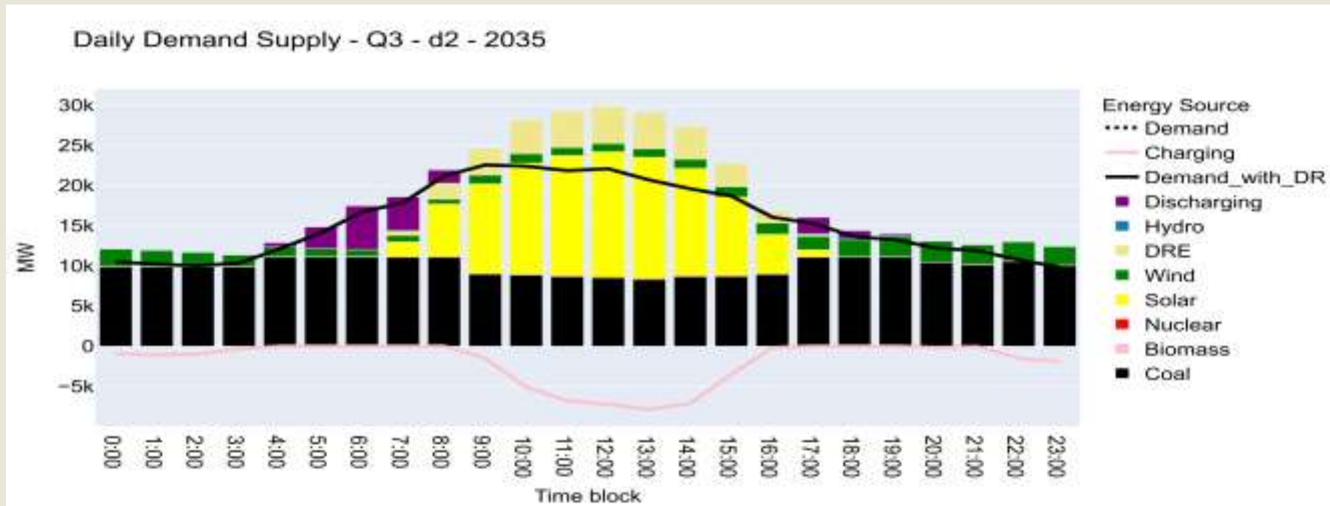

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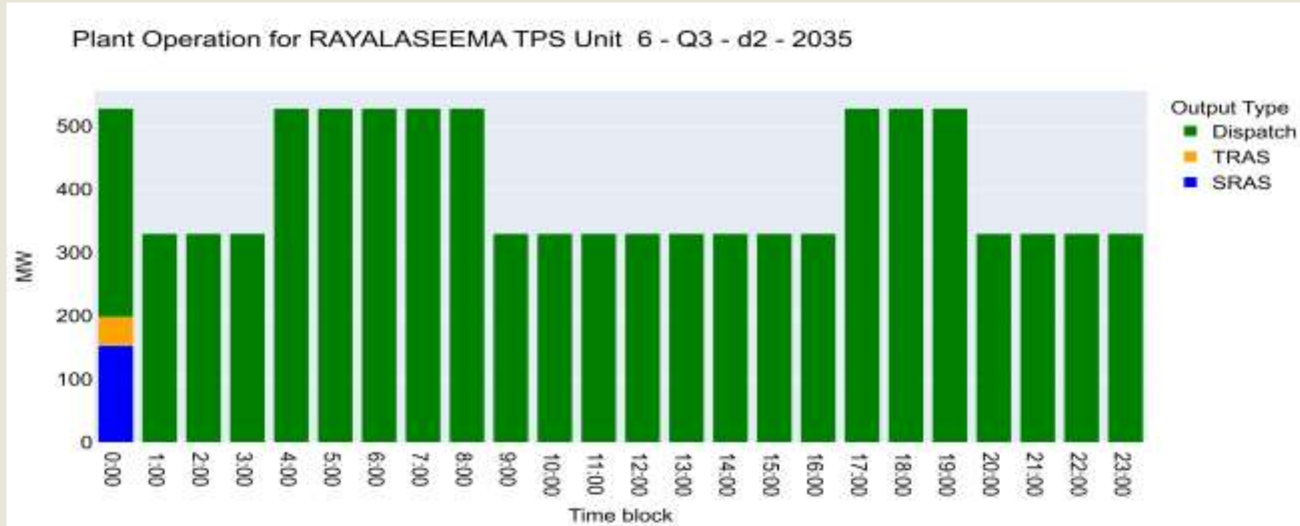

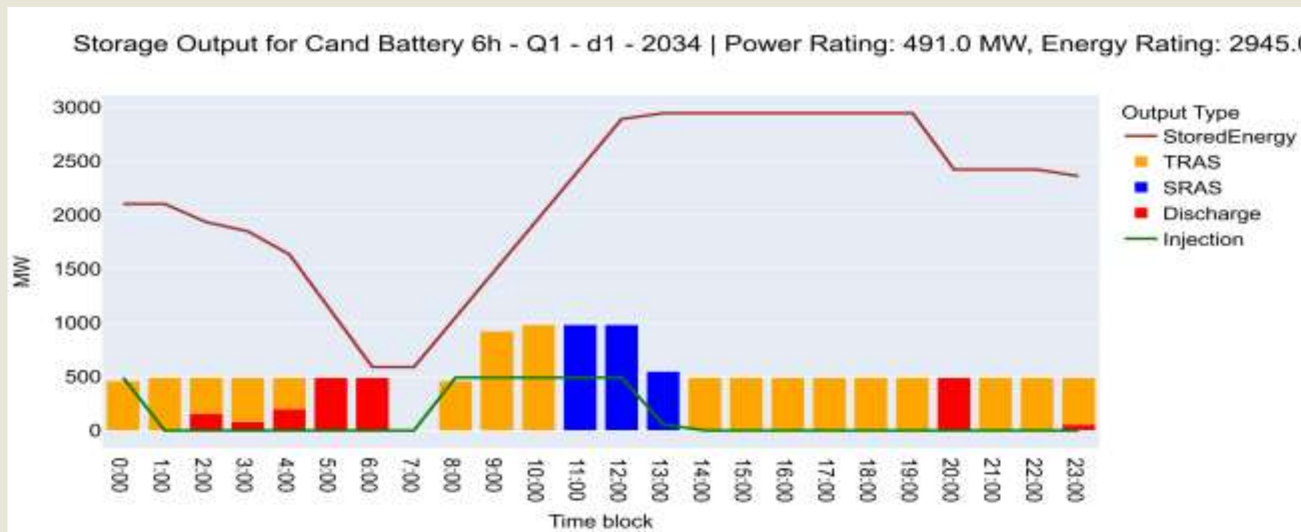

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Capacity expansion plan

Energy mix projections

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Chronological demand supply curves

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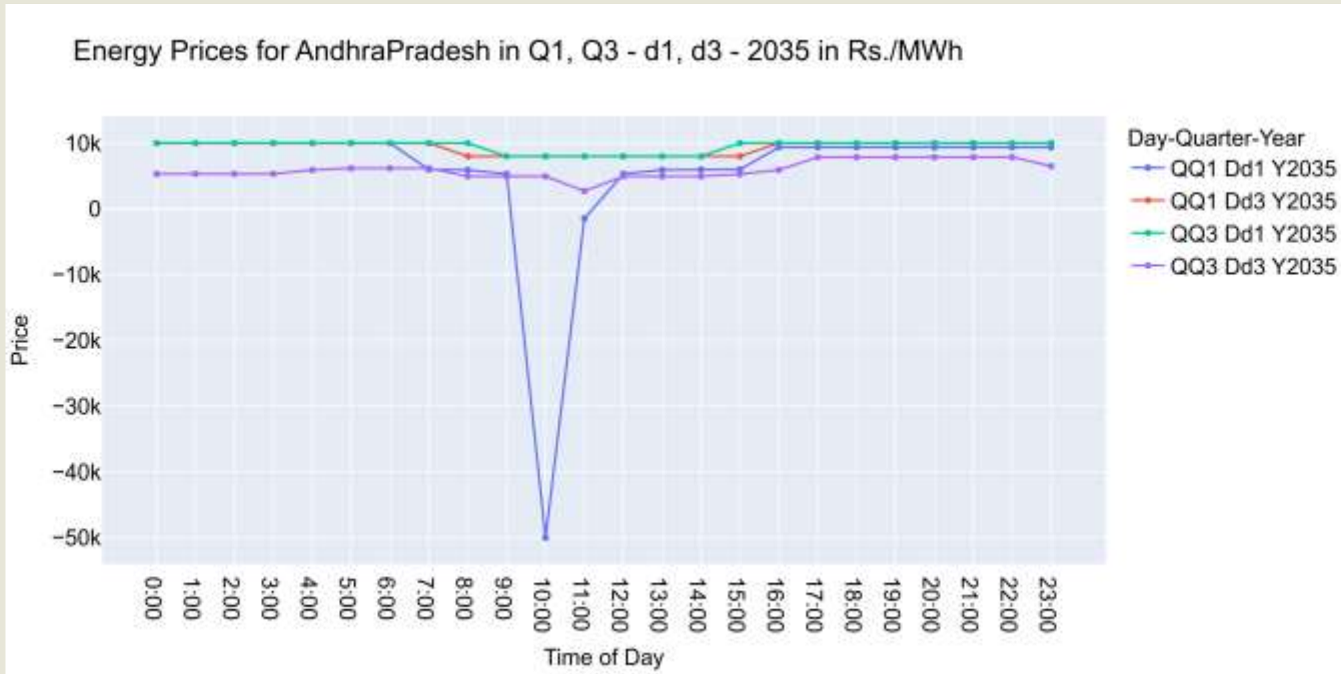

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Optimization Model Framework

Capacity expansion plan

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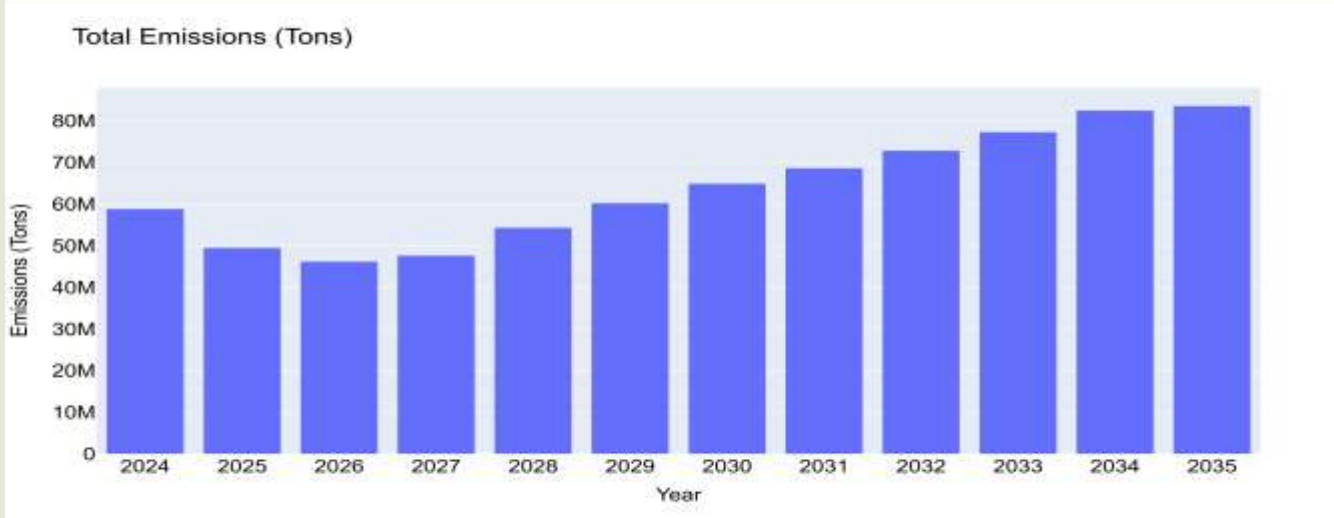

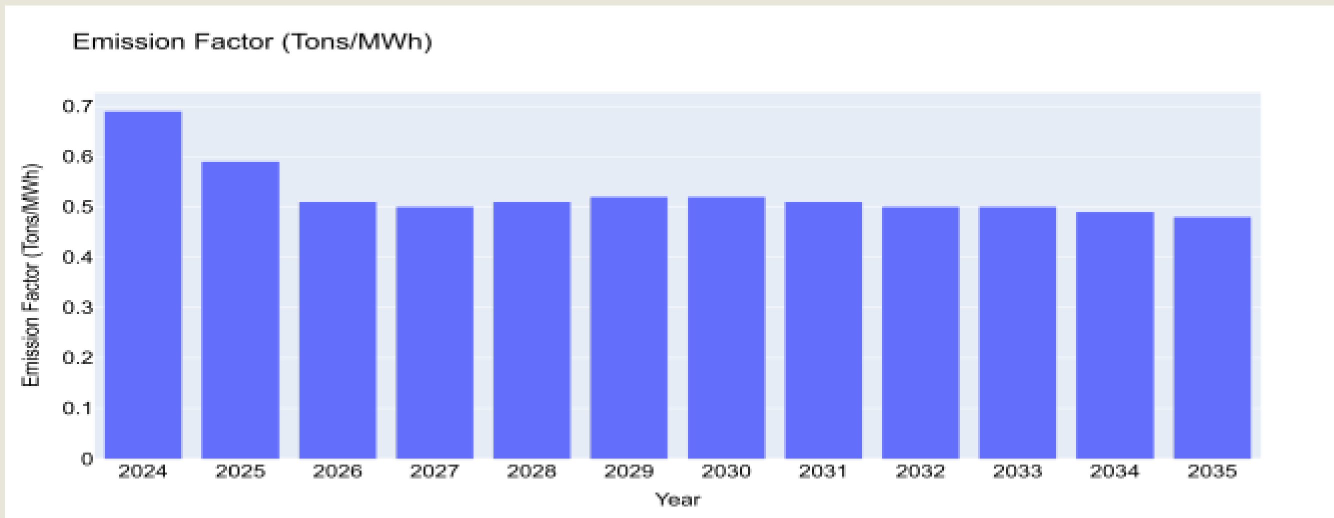

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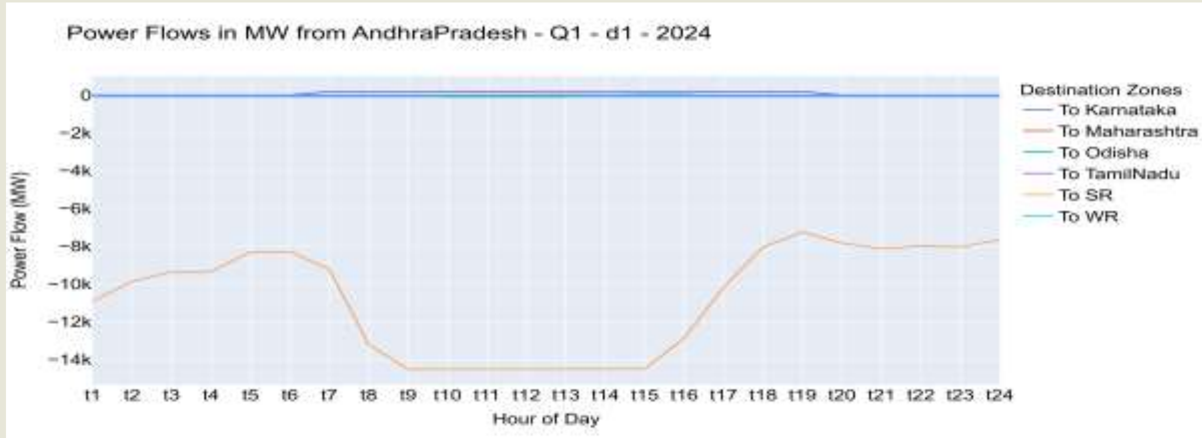

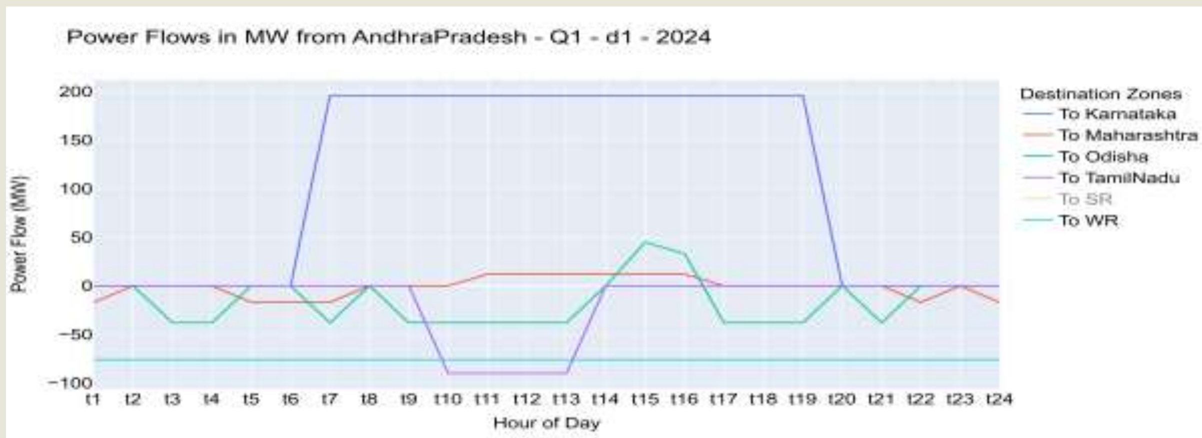

When modelling transmission, the user can view the transmission flows from one zone to another.

Optimization Model Framework

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- **Reliability – LoLP and NENS**

	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
LoLP - (%) - BASE	2.39	0	0	6.56	1.72	0	0	0	0	0	0	0
ENS - MU - BASE	21	0	0	365	70	0	0	0	0	0	0	0
NENS - (%) - BASE	0.03	0	0	0.35	0.06	0	0	0	0	0	0	0
LoLP - Average(%)	6.6	2.5	1.34	6.06	2.3	0.02	0	0	0	0	0	0
ENS - MU - Average	219	88	50	367	129	1	0	0	0	0	0	0
NENS - (%) - Average	0.27	0.1	0.05	0.35	0.12	0	0	0	0	0	0	0
Max LoLP over iterations (% of total hours)	13.5	8.34	5.57	9.73	7.63	0.7	0	0	0	0	0	0
Min LoLP over iterations(% of total hours)	2.72	0	0	0	0	0	0	0	0	0	0	0
Max ENS over iterations - MU	384	298	258	719	475	24	0	0	0	0	0	0
Min ENS over iterations - MU	79	0	0	0	0	0	0	0	0	0	0	0
Max NENS over iterations - %	0.47	0.33	0.27	0.69	0.43	0.02	0	0	0	0	0	0
Min NENS over iterations - %	0.1	0	0	0	0	0	0	0	0	0	0	0

Optimization Model Framework

Capacity expansion plan

Energy mix projections

Utilization/PLF/CUF

Chronological demand supply curves

Generation Dispatch schedules

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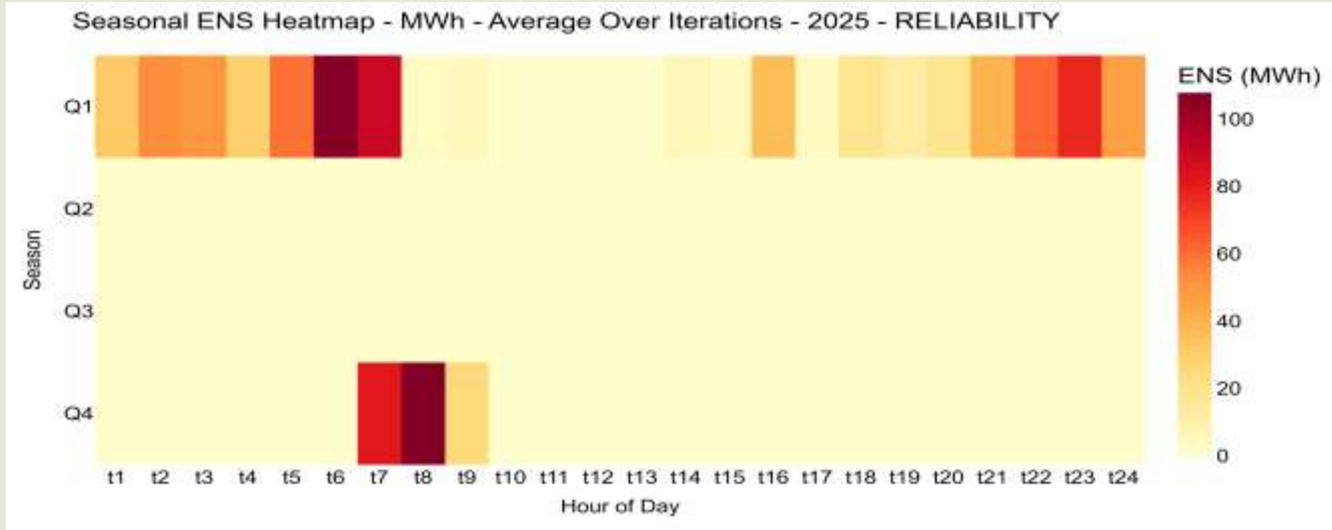

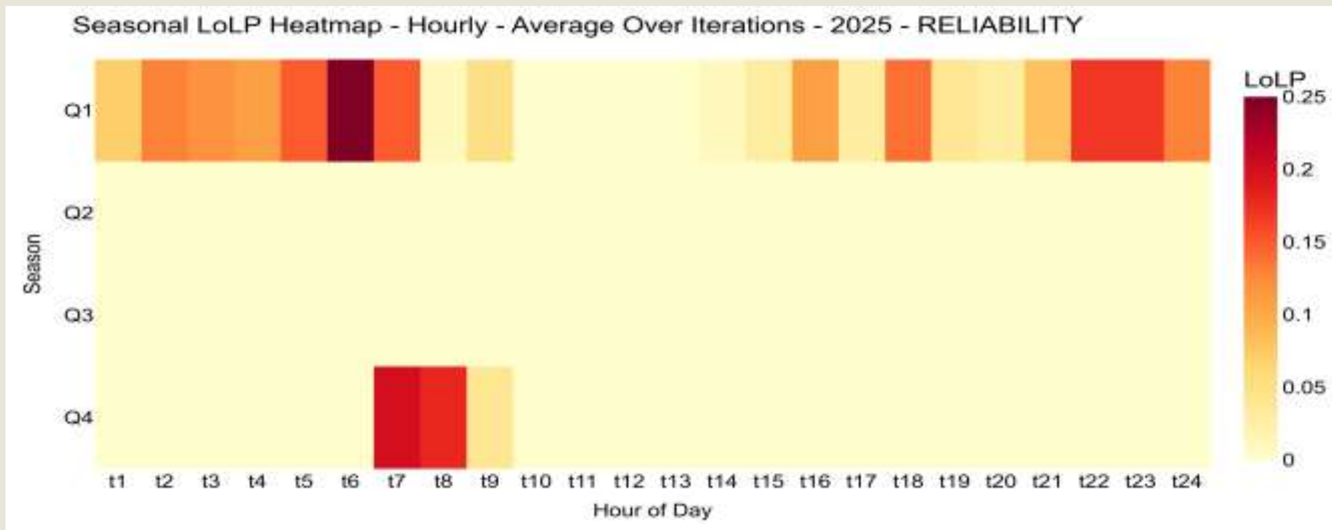

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Defining Features of STELLAR

- Chronological modelling
- Co-optimization of energy and ancillary services
- Unit commitment constraints
- Integrated Demand Response
- Transmission modelling

Defining Features of STELLAR

Chronological modelling

***STELLAR* replaces traditional load duration curves with a chronological model using representative days, better capturing demand and renewable generation patterns.**

Co-optimization of energy and ancillary services

Unit commitment constraints

Integrated Demand Response

Transmission modelling

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Defining Features of STELLAR

Chronological modelling

Co-optimization of energy and ancillary services

The model's integrated framework ensures reserve adequacy while **aligning with real-world power plant constraints, enabling a more reliable and secure energy system.**

Unit commitment constraints

Integrated Demand Response

Transmission modelling

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Defining Features of STELLAR

Chronological modelling

Co-optimization of energy and ancillary services

Unit commitment constraints

This enables:

- ***Modelling actual generator capabilities***
- ***Avoiding overestimation of operational flexibility***
- ***Ensuring reliable, executable energy strategies***

Enables a capacity plan tailored for high renewable system flexibility

Integrated Demand Response

Transmission modelling

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Defining Features of STELLAR

Chronological modelling

Co-optimization of energy and ancillary services

Unit commitment constraints

Integrated Demand Response

The model shifts demand within the day, optimizing both investment and operational costs by reshaping load profiles.

Transmission modelling

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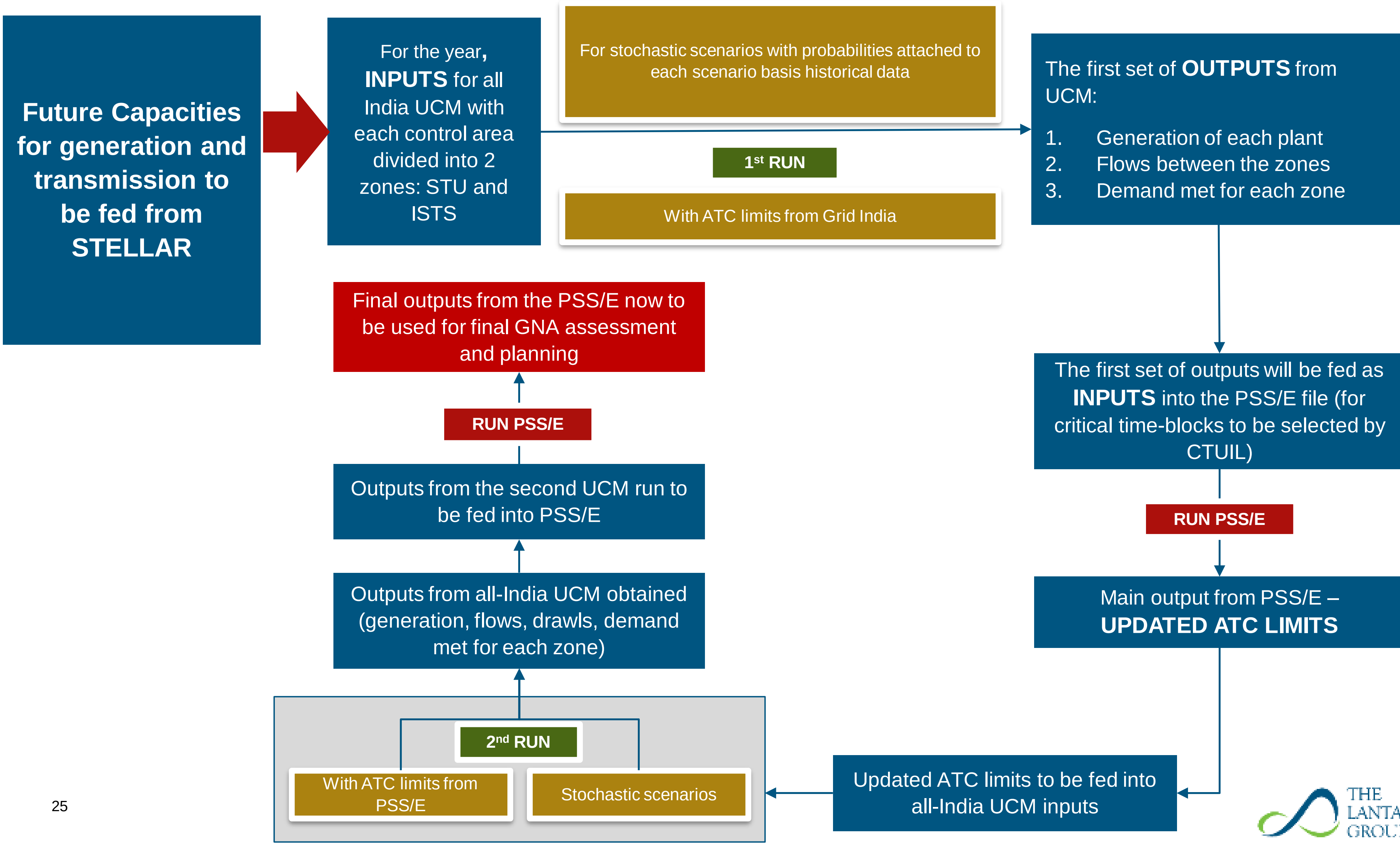
Defining Features of STELLAR

- Chronological modelling
- Co-optimization of energy and ancillary services
- Unit commitment constraints
- Integrated Demand Response
- Transmission modelling

. ***This enables cost-optimal RE integration by***

- ***optimizing power flows and***
- ***substation-level asset planning***
- ***reducing congestion risks.***

Integrated Optimization – A Unified Framework for Generation, Transmission and Storage



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Techniques of scenario generation

	A Sampling based on Multivariate Copula	B Monte Carlo based on independent distributions of random variables
Description	• Model the **correlations** between multiple demand and generation variables • Specialized copulas to **emphasize tail dependencies**, capturing **extreme stress events**	• Generates numerous random samples using historical data assuming uniform probability of occurrence for each sample • Assumes variables are statistically independent, meaning the value of one variable does not affect another
Pros	• Models realistic correlations and complex dependencies e.g. high solar generation in Plant1 would imply a high-solar generation in Plant2 in a nearby location • Provides more reliable results for systems with interdependencies • Especially relevant when simulating extreme scenarios where multiple adverse factors co-occur	• Easy to implement, assuming variables are independent • Linear and does not have any consideration of complex interdependencies • Assumes the same/uniform probability e.g. for 2 variables (gen1,gen2) the probability of occurrence would be same for Event1– {gen1: high, gen2: low} and Event2 – {gen1: high, gen2: high}
Cons	• Data intensive • Computationally more intensive and complex to model joint distributions and dependencies	• Ignores correlations between variables making it inadequate for systems where variables are strongly interconnected

We recommend **Sampling with Multivariate Copula**, as it offers realistic view of interconnected risks and rare extreme events like correlated renewable failures

Demand and solar generation across different grid locations are linked by complex spatial and temporal correlations.

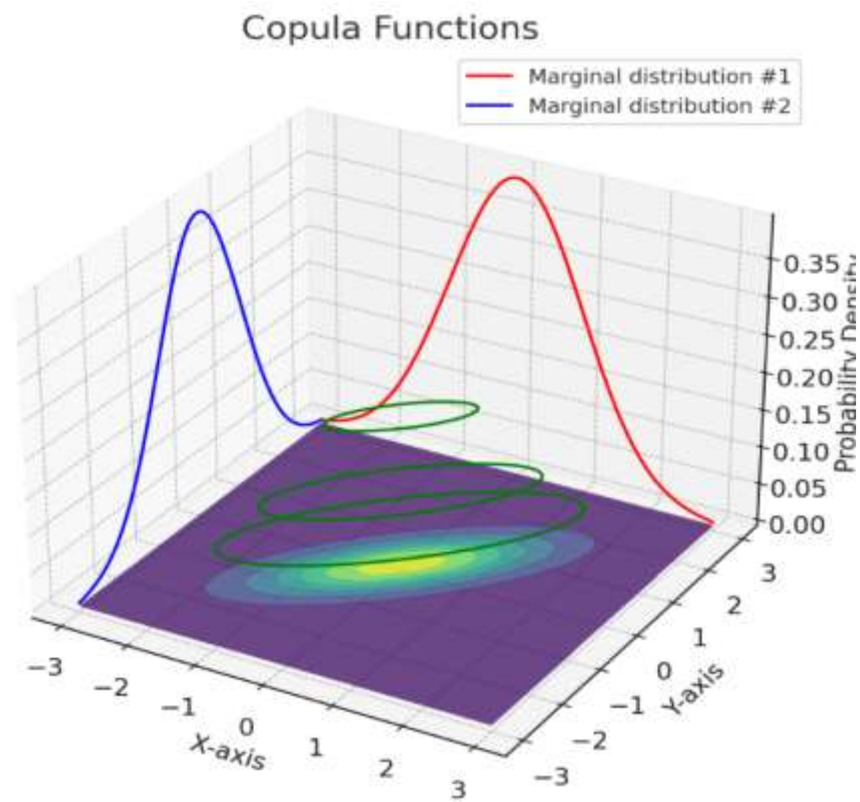
Considering these correlations is essential for effective power system planning and reliability assessment (e.g., LOLP). Aspects like impacts of large balancing areas on planning get captured through this approach to system planning and measuring reliability of such systems.

Copula based scenario generation

Methodology

- Fit copula on month-wise empirical *residual* distributions observed for all solar plant generation profiles and demand profiles. Based on observations, a “normal” distribution was found to be best fit.
- Fit marginal distribution models on individual *residual* distributions.
- Generate residual samples from the fitted multivariate copula-based distribution. These indicate the patterns of co-movements and their probability of occurrence.
- Append the residual samples to fitted distribution. Generate total profiles

Example of Joint Distribution for 2 variables



Copula Methodology

2

1. Time Series Model for Renewable Generation Output

- **Autocorrelation factors** capture the correlations between current generation/demand value with its previous/lag values (e.g. demand at 5:00 PM would be correlated with demand at 4:00 PM, so on..)
- Thus, firstly the distribution of each generation and demand variable is estimated using an appropriate **time series model** capturing *autocorrelation* factors.
- Residuals from fitted model would be calculated testing for stationarity.

2. Copula-based Joint Distribution Modelling and Sampling

- **Spatial-temporal correlations** are appropriately fitted on residuals using copula-based approach which provides a bridge to modelling multi-dimensional distributions (day-wise demand, and generation distributions).
- **Sampling** from this copula-estimation for simulations while estimating the probability of each sample using the fitted copula-model.

3. Clustering

- Clustering techniques for scenarios/simulations to identify **simulations exhibiting similar patterns** to focus analysis on specific scenarios.
- Finalization of scenarios, with associated probabilities of occurrence.

Demand and solar generation across different grid locations are linked by complex autocorrelation, spatial and temporal patterns. Considering these patterns is essential for effectively analyzing possible scenarios for power system planning and reliability assessment (e.g., LOLP).

The framework captures the inter-dependencies in multi-dimension variables (demand, generation) and also, the probability of occurrence for any scenario.

Illustrative process for scenario generation

Selection of representative days for a season through clustering (n days)***, each representative day has a demand, state's own RE generation, RE rich state's RE generation***

Introducing uncertainty through COPULA

By introducing seasonal uncertainty, ***created 3000 days, for each rep. day***

Clustering on individual days to select ***X days for each rep day.***

Clustering on all combinations of representative days, to form ***X^n seasonal scenarios.***

Clustering on seasonal scenarios, to form ***M seasonal scenarios.***

SAME PROCESS IS REPEATED FOR EACH SEASON for "S" seasons

M seasonal scenarios – Season 1

M seasonal scenarios – Season S

Combining all the seasonal scenarios to form ***S^M yearly scenarios***

Clustering to form ***"Y" yearly scenarios, with the respective probabilities of the scenarios***

Expansion planning simulations to carried out on "Y" scenarios

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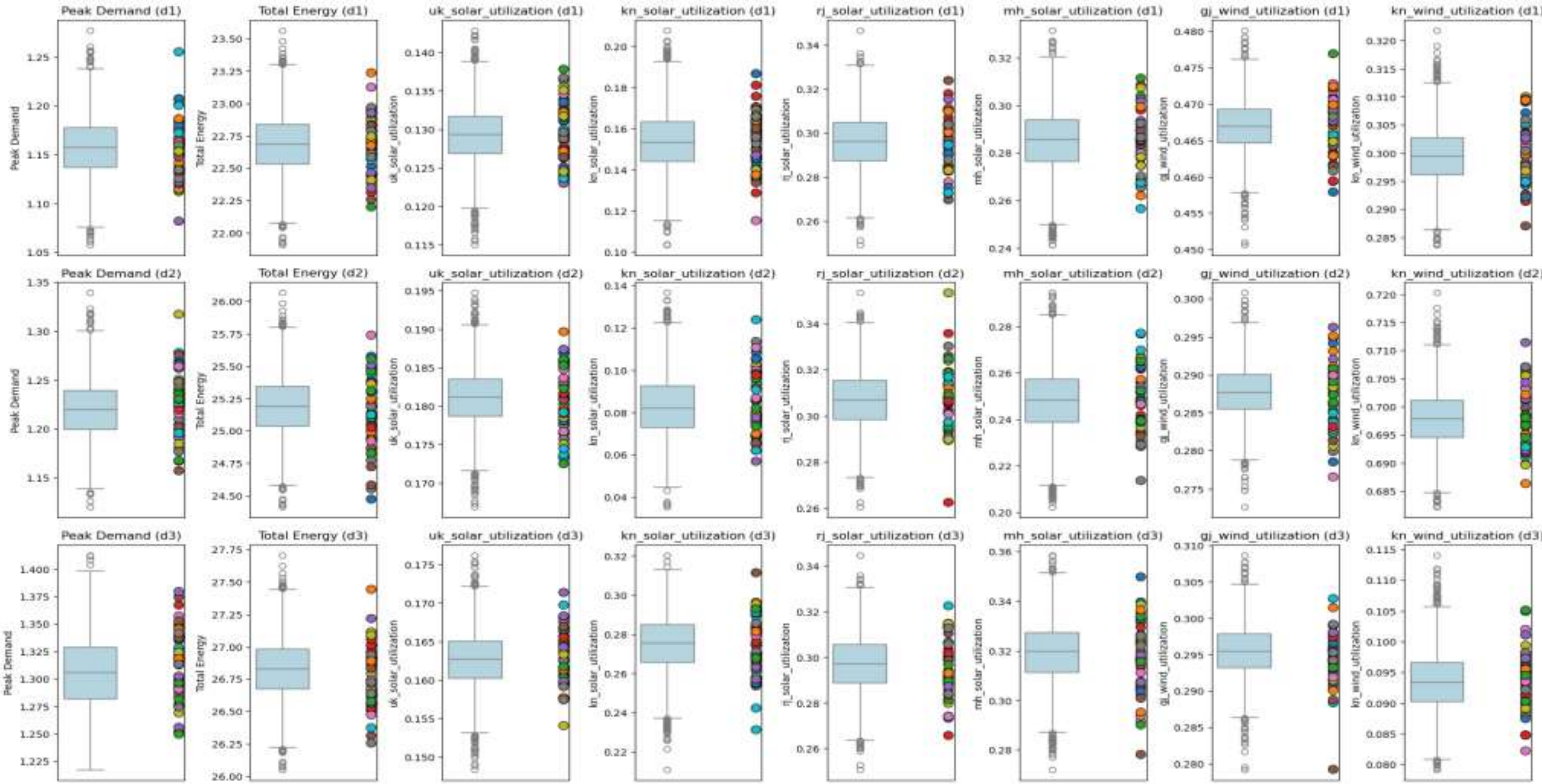
Clustering over 3000 days for each representative days each season



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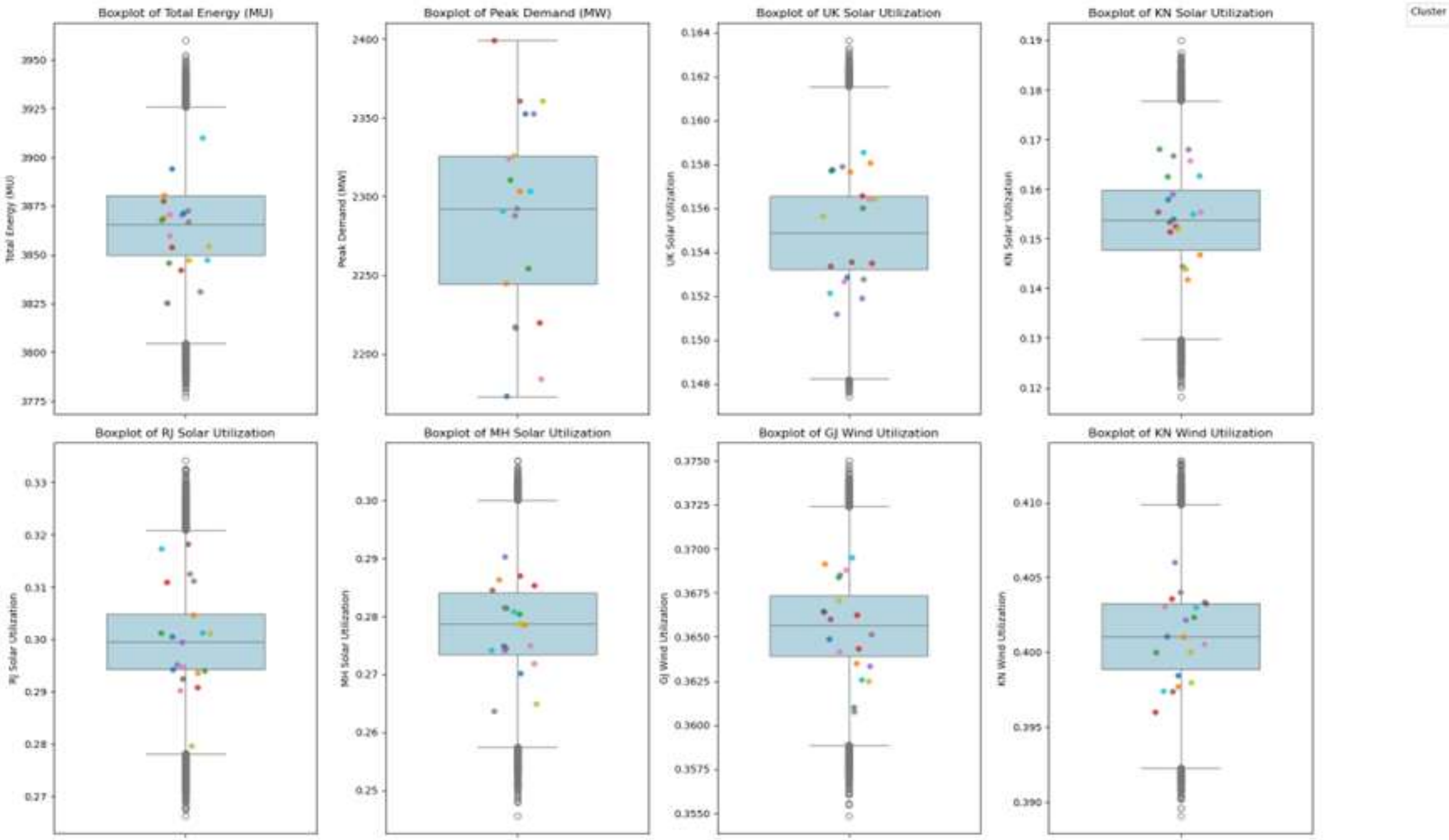
Combining all the representative days to form seasonal scenarios



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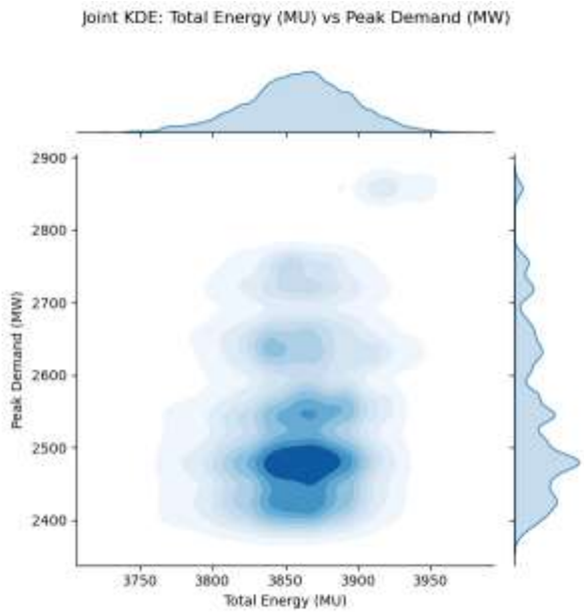

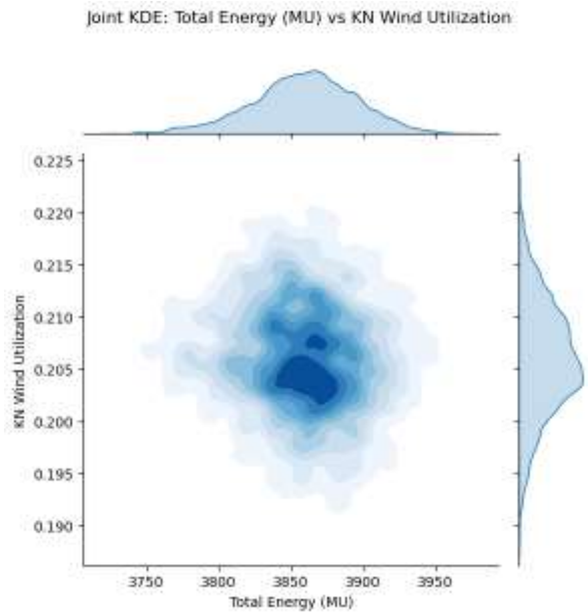

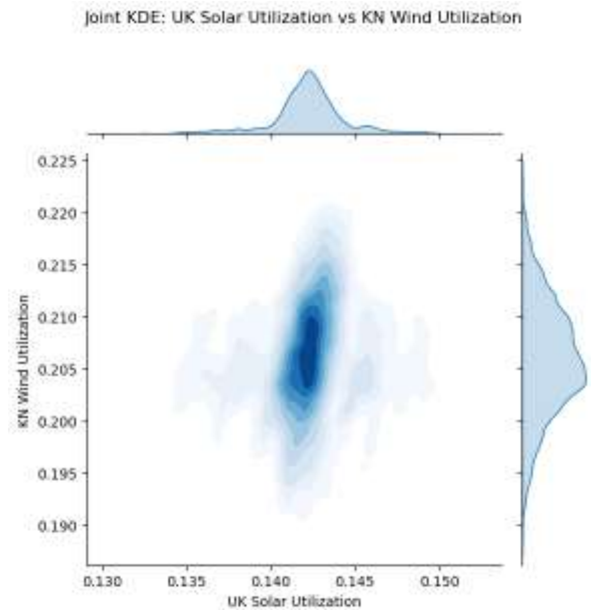

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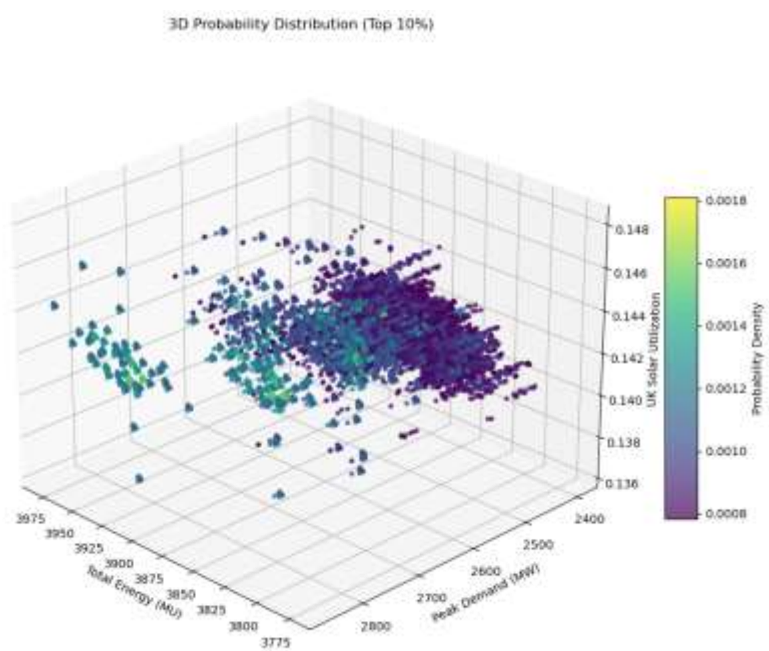

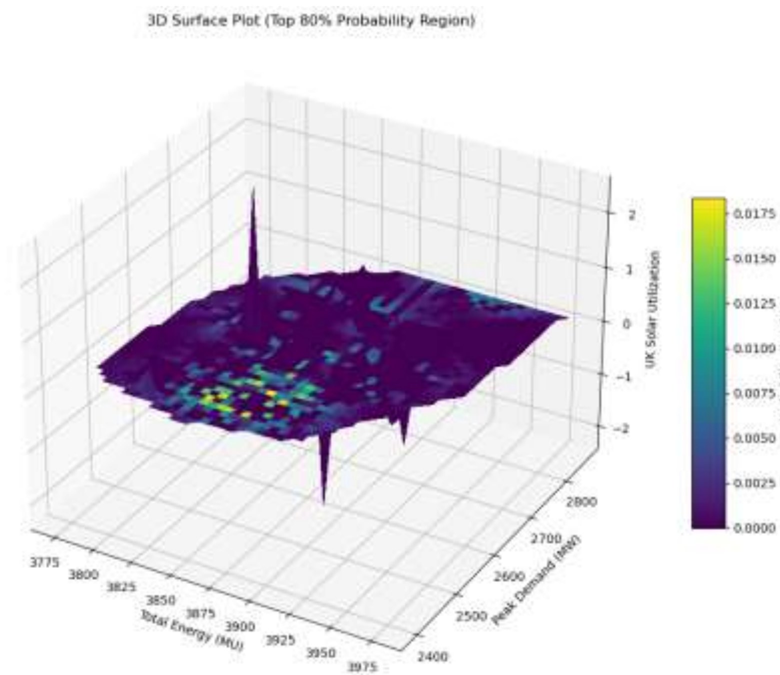

Combining seasonal scenarios to form yearly scenarios