Scenario Results

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Presentation Outline

Goal: To Present the 2016 Economic Study Phase II - Regulation, Ramping, and Reserves: Simulation Results of Performance

(2017 ISO New England System Operational Analysis and Renewable Energy Integration Study)

- Executive Summary
- Simulation Methodology & Scenarios
- Simulated Operating Reserves: Load Following, Ramping and Curtailment Performance
- Simulated Interface & tie-line Performance
- Simulated Regulation Performance
- Simulated Balancing Performance
- Summary of Key Observations

Executive Summary

This executive summary serves as a synopsis of the observations from our simulation results.

Each observation is presented here in a stand alone fashion so as to give the PAC an overview of the study.

The subsequent sections on Methodology, Scenarios, Operating Reserves, Interface Performance, Regulation Performance, and Balancing performance go into how the results were achieved and the associated figures that support these observations.

In the interests of a smooth presentation, we will now highlight these observations.

Executive Summary: Preamble II

As we proceed through the executive summary, if you have questions, please do write them down on your notepads. Then when we come to the body of the presentation, where the observations are supported by the simulation results, we will be able to answer these questions in a methodical fashion.

Executive Summary: Overview I

Taken together, the simulation of the study scenarios show:

1. Beyond the load following and ramping reserves provided by dispatchable resources, curtailment of semi-dispatchable resources becomes an integral part of balancing performance for the study scenarios.
2. Scenarios with greater penetrations of solar and wind generation exhibit systematically higher net load forecast errors. In the absence of immediate improvements in forecasting technology, these imbalances are mitigated by greater quantities of operating reserves.
3. The commitment of dispatchable resources and their associated quantities of committed load following and ramping reserves has a complex, difficult to predict, non-linear dependence on the amount of variable resources and the load profile statistics. High and low levels of variable resources do not necessarily correspond to high or low quantities of operating reserves respectively.

Executive Summary: Overview II

4. Higher quantities of load following and ramping reserves dispatched in real-time improves balancing performance. Curtailment also directly supports the balancing role of load following and ramping reserves.
5. The combination of curtailment of semi-dispatchable resources and the commitment of dispatchable resources within each RSP zone serves to respect interface constraints.

This executive summary highlights the key aspects of the study's methodology and results.

This study uses the ElectricPower Enterprise Control System (EPECS) simulator for assessment.

The EPECS simulator was developed to address the multi-time scale nature of renewable energy integration. It consists of four simulation layers:

- Day-Ahead Resource Scheduling as a Security Constrained Unit Commitment (SCUC) Layer
- Real-Time Resource Scheduling as a Real-Time Unit Commitment (RTUC) Layer
- Real-Time Balancing as a Security Constrained Economic Dispatch (SCED) Layer
- Real-Time Physical Power Flow w/ Integrated Regulation Service Layer

Six scenarios were examined for data sets for two years: 2025 and 2030.

- **Scenario 1 – "RPSs + Gas"**: where the generation fleet meets existing Renewable Portfolio Standards (RPSs), and natural gas combined-cycle (NGCC) units replace retired units.
- **Scenario 2 – "ISO Queue"**: where the generation fleet meets existing RPSs, and new renewable/clean energy resources meet all future needs, including retirements, with the wind resources located mostly in Maine in the same locations indicated in the ISO's Interconnection Queue.
- **Scenario 3 – "Renewables Plus"**: where the generation fleet meets existing RPSs, and the system has additional renewable/clean energy resources.

- **Scenario 4 – "No Retirements beyond FCA #10"**: where the generation fleet has NGCC additions and no retirements after the tenth Forward Capacity Auction (FCA #10) and where local load-serving entitites meet existing RPSs, in part through alternative compliance payments (ACPs).
- **Scenario 5 – "ACPs + Gas"**: where the existing fleet meets existing RPSs in part through ACPs, and NGCC additions replace retired units.
- **Scenario 6 – "RPSs + Geodiverse Renewables**: which is similar to Scenario 2 with the generation fleet meeting existing RPSs and new renewable/clean energy resources meeting all future needs, including retirements, but with more geographically balanced onshore wind, offshore wind, and solar photovoltaic (PV) resources.

By convention, we use the scenario nicknames of the form "2025-2" to reflect Scenario 2 in Year 2025.

Executive Summary: Simulation Scenarios I

- The six scenarios above were examined for data sets for two years: 2025 and 2030. These scenarios were established in the 2016 Economic Study Phase I.
- The 2025 scenario load distributions exhibit the same statistical characteristics except Scenario 3 due to the inclusion of energy efficiency additions and electric vehicle charging loads. The same applies to the 2030 scenario load distributions.

- The scenario net load distributions exhibit significant statistical differences due to differences in solar, wind, and tie-line quantities.
- The net load profiles in all scenarios exhibit excess generation for parts of year.
- The net load profiles in Scenarios 2025-3, 2030-2, 2030-3, and 2030-6 exhibit negative values for parts of the year.

Executive Summary: Simulation Scenarios II

- Load, wind, and solar forecast errors introduce an uncertainty in balancing operations. The state-of-the-art in load forecasting technology is more advanced than solar and wind forecast technology. As more solar and wind generation is introduced, the error introduced by forecasting increases – thereby complicating balancing operations.

- The net load ramping profile shows the greatest ramps when viewed with one minute temporal resolution and generally decreases with coarser temporal resolution.
- Furthermore, ramps up are generally greater in magnitude than ramps down across all scenarios.
- In 2025 and 2030, Scenarios 2, 3 and 6 exhibit the greatest net load ramps – particularly in upward direction – at all temporal resolutions; 1 minute, 10 minute, 1 hour, and 4 hours.

- Even in the absence of load following reserve requirements, the system still has load following reserves (LFR) as a physical quantity.
- Scenario 2025-3 shows a shortage of downward load following reserves reflecting constrained downward dispatch. These occur primarily during low net load conditions in the Spring and Autumn.
- Scenarios 2030-3, 2030-6, and to a lesser extent 2030-2 also demonstrate a shortage of downward load following reserves.
- These shortage of downward load following reserves in these scenarios do coincide with imbalances – suggesting that imbalances can be mitigated with greater LFR quantities.
- Scenarios 2030-1, 2030-2, and 2030-5 entirely exhaust their upward load following reserves; albeit for a fairly short part of the year. Otherwise, the scenarios did not indicate a shortage of upward load following reserves.

Executive Summary: Load Following Reserves (LFR) II

- The commitment of dispatchable resources and their associated quantities of commitment of load following and ramping reserves has a complex, difficult to predict, non-linear dependence on the amount of variable resources and the load profile statistics. Here, despite the similarities between Scenarios 2030-4 and 2030-5, their associated quantities of load following reserves is quite different.
- To varying degrees Scenarios 2025-3, 2030-2, 2030-3, 2030-5 and 2030-6 demonstrated periods that would benefit from additional load following reserves up or down.

- Even in the absence of ramping reserve requirements, the system still has ramping reserves (RampR) as a physical quantity.
- None of the 12 scenarios entirely exhaust ramping reserves.
- Nevertheless, the balancing performance of Scenarios 2025-3 and to a lesser extent 2025-2 and 2025-6 would benefit from an increase in downward ramping reserves.
- Similarly, the balancing performance of Scenarios 2030-2, 2030-3 and 2030-6 would benefit from an increase in downward ramping reserves.
- Finally, the balancing performance of Scenarios 2030-2 and to a lesser extent 2030-3 and 2030-6 would benefit from an increase in upward ramping reserves.

Executive Summary: Curtailment Performance I

- Curtailment becomes an integral part of balancing operations for all scenarios except 2025-4, 2025-5, 2030-4, and 2030-5.
- In all 2025 scenarios except 4 and 5, curtailment forms a significant portion ($\geq$ 1.5%) of the total possible production from semi-dispatchable resources. During these higher wind and PV scenarios, curtailment is used between 32% and 62% of the time.
- In the most pronounced of the 2025 scenarios, Scenario 2025-3, curtailment was used over 60% of the time to a maximum value of 9894MW.
- In all 2030 scenarios except 4 and 5, curtailment forms a significant portion ($\geq$ 8.5%) of the total semi-dispatchable energy resources. During these scenarios it is used between 56% and 88% of the time.
- In the most pronounced of the 2030 Scenarios, Scenario 2030-3, curtailment was used over 88% of the time to a maximum value of 15862MW.

- To varying degrees, the Orrington-South, Surowiec-South, North-South, and SEMA-RI import interfaces exhibit some congestion in Scenarios 2025-1, 2025-2, 2025-3, and 2025-6.
- Similarly, these four interfaces exhibit some congestion in Scenarios 2030-1, 2030-2, 2030-3, and 2030-6.
- In the case of Orrington-South and Surowiec-South interfaces, the 2030 congestion found in Scenarios 1, 2, 3, and 6 is greater than the corresponding scenarios in 2025.
- In the case of the North-South interface, the 2030 congestion found in Scenarios 1, 2, 3, and 6 is similar in magnitude to the corresponding scenarios in 2025.
- In the case of the SEMA-RI import interface, the 2030 congestion found in Scenarios 1, 2, 3, and 6 is less in magnitude to the corresponding scenarios in 2025.

- The other interfaces and tie-lines in their respective scenarios exhibited negligible or no congestion.

Executive Summary: Regulation Performance I

- In both 2025 and 2030, and relative to Scenarios 4 and 5, Scenarios 1,2,3 and 6 exhibit greater regulation reserve mileage and percent time exhausted.
- In 2025, Scenarios 2025-3 and 2025-2 most heavily utilize regulation reserves.
- In 2030, Scenarios 2030-2, 2030-6, and 2030-3 most heavily utilize regulation reserves.

- All scenarios are well-controlled to zero mean. All scenarios except 2025-3, 2030-2, 2030-3, and 2030-6 maintain imbalance variability of less than 100MW.
- Scenarios 2030-2, 2030-3, and 2030-6 significantly increase the degree of imbalance variability (to between 150MW and 300MW) relative to other scenarios.
- Scenario 2030-3 and to a lesser extent 2030-2 and 2030-6 increases the range between the maximum and minimum value of imbalances as a measure of the intensity of improbable/extreme events.

Simulation Methodology

Methodology: Assessment by EPECS Simulation

This study uses the Electric Power Enterprise Control System (EPECS) simulator to assess:

- Simulated Operating Reserves: Load Following, Ramping, and Curtailment Performance
- Simulated Interface & Tie-line Performance
- Simulation Regulation Performance
- Simulated Balancing Performance

EPECS simulation has been published many times and undergone extensive processes of scientific peer-review.

All publications are freely available to the public on the LIINES website.

Methodology: EPECS Simulator Functionality

The EPECS simulator was developed to address the multi-time scale nature of renewable energy integration. It consists of four layers:

- Day-Ahead Resource Scheduling as a Security Constrained Unit Commitment (SCUC) Layer
- Real-Time Resource Scheduling as a Real-Time Unit Commitment (RTUC) Layer
- Real-Time Balancing as a Security Constrained Economic Dispatch (SCED) Layer
- Real-Time Physical Power Flow w/ Integrated Regulation Service Layer

The multiple simulation layers provide deep insight into the need for different types of operating reserves.

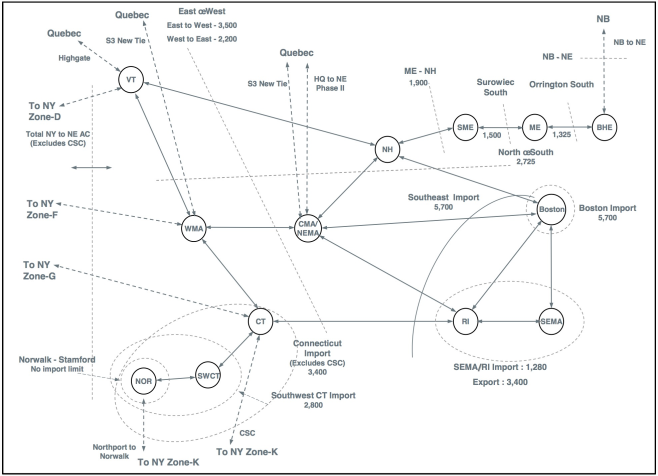
Please see August 3rd PAC presentation for further details on simulation methodology

Methodology: ISO-NE SCUC Characteristics I

Serves to commit generation, commit storage, and schedule reserves.
Implements a security constrained unit commitment (SCUC) algorithm.

- **Objective Function**: Quadratic cost curve based on offer curve & include no load cost & start-up cost
- **Generators**:
  - Minimum up & down time constraints
  - Ramp up & down constraints
  - Initial online hours, self-schedules, maximum # of start ups in a day
- **Pumped and Battery Storage**:
  - Maximum daily energy constraints
  - Maximum and minimum power constraints
- **Operating Reserves**:
  - 10 minute reserves requirements.
- **Topology**:
  - Zonal network (pipe & bubble) model including external transactions

Methodology: ISO-NE SCUC Characteristics II



The zonal network model consists of 13 RSP zones with 21 interfaces and tie-lines.

Serves to commit *fast-start* generation, commit storage, and schedule reserves. Implements a real-time unit commitment (RTUC). Similar to SCUC with several differences:

- **Time Intervals**: 16 fifteen minute intervals spanning 4-hour period
- **Decision Scope**: Commitment On/Off fast-start units
- **Forecast**: Short term system load
- **Reserves**: Imposes system requirements

Definition 1

Fast Start Generation: Dispatchable generation units that can start up from zero and ramp up to maximum output in 30 minutes or less.

Serves to dispatch generation, and schedule storage. Implements a security constrained economic dispatch (SCED). Similar to SCUC with several differences:

- **Objective Function**: Based upon linear cost curve
- **Operating Reserves**:
    - System reserve requirements
- **Time Window**: One 10 minute look-ahead window:
- **Initial Conditions**:
    - Startup/Shut-down instructions from RTUC
- **Regulation Units**: Regulation level is relieved with each SCED run.

Methodology: Real-time Physical Power Flow w/ Regulation

Serves to assess flows of power through the zonal network (Pipe & Bubble) model including external transactions.

- Implements a steady-state “DC” power flow analysis model with one minute time step increments. Closed interface flows were monitored to capture system power flows.
- Includes a regulation service in each RSP zone (bubble) that responds to net load variability and uncertainty.
- Shows power injections in each RSP zone (bubble) and power flows across tie-lines and interfaces.

Simulation Scenarios

- **Load Profiles**
- Net Load Profiles
- Load, Solar, & Wind Forecast Errors in the Net Load
- Net Load Ramping Characteristics

Definition 2

Load Profile: The sum of gross load, charging load from electric vehicles, minus the load saved from energy efficiency measures (i.e. "passive demand resource") all in one minute increments.

Scenarios: Definition of Types of Resources

Definition 3

Semi-Dispatchable Resources: Energy resources that can be dispatched downwards (i.e curtailed) from their uncurtailed power injection value. In this study, wind, solar, run-of-river hydro, and tie-lines are assumed to be semi-dispatchable resources.

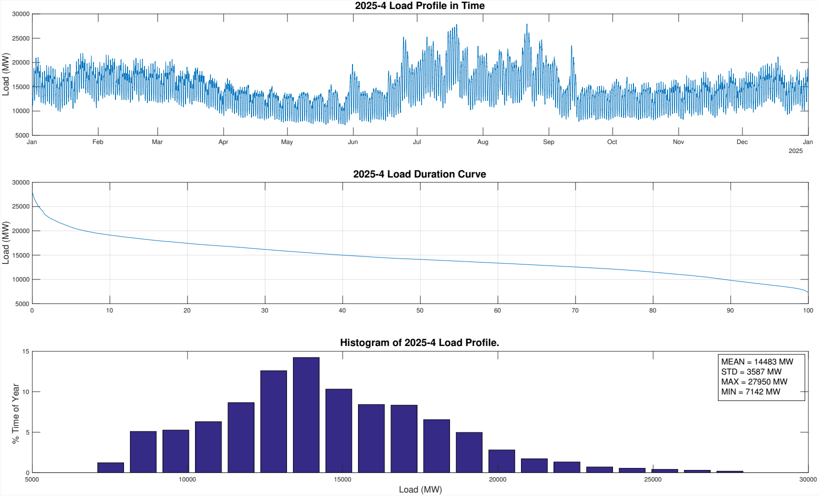
Definition 4

Must-Run Resources: Energy resources that must run all the time at their maximum output. In this study, nuclear generation units (i.e. Seabrook, Millstone 2, and Millstone 3) are assumed to be must run resources.

Definition 5

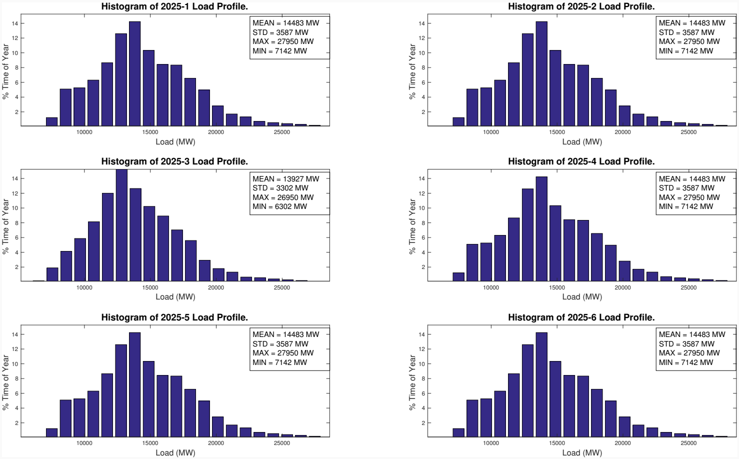
Dispatchable Resources: Energy resources that can be dispatched up **and** down from their current value of power injection. In this study, all other resources are assumed to be dispatchable.

Scenarios: Three Views of a Load Profile



A load profile may be viewed as a function in time, a duration curve, or as a statistical distribution.

Scenarios: The 2025 Load Distributions



2025 Scenario load distributions exhibit the same statistical characteristics except Scenario 3 due to the addition of energy efficiency and electric vehicle charging loads.

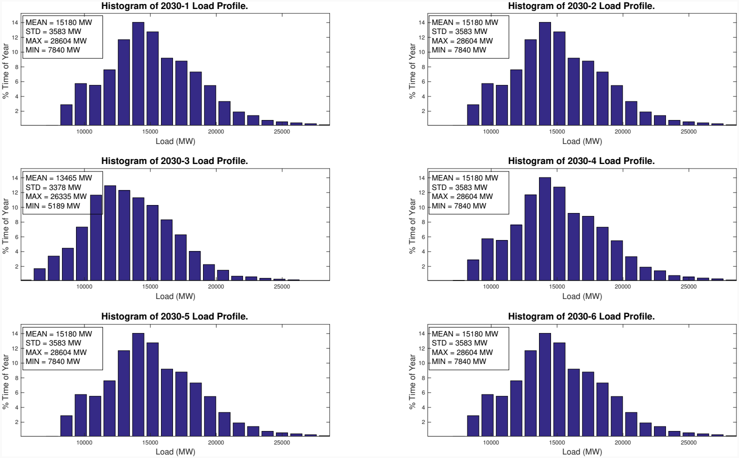
Scenarios: The 2025 Load Distribution Statistics

Table 1: 2025 Load Distribution Statistics

	2025-1	2025-2	2025-3	2025-4	2025-5	2025-6
Max (MW)	27950	27950	26950	27950	27950	27950
Min (MW)	7142	7142	6302	7142	7142	7142
Energy (TWh)	127	127	122	127	127	127
Mean (MW)	14483	14483	13927	14483	14483	14483
STD (MW)	3587	3587	3302	3587	3587	3587

2025 Scenario load distributions exhibit the same statistical characteristics except Scenario 3 due to the addition of energy efficiency and electric vehicle charging loads.

Scenarios: The 2030 Load Distributions



2030 Scenario load distributions exhibit the same statistical characteristics except Scenario 3 due to the addition of energy efficiency and electric vehicles.

Scenarios: The 2030 Load Distribution Statistics

Table 2: 2030 Load Distribution Statistics

	2030-1	2030-2	2030-3	2030-4	2030-5	2030-6
Max (MW)	28604	28604	26335	28604	28604	28604
Min (MW)	7840	7840	5189	7840	7840	7840
Energy (TWh)	133	133	118	133	133	133
Mean (MW)	15180	15180	13465	15180	15180	15180
STD (MW)	3583	3583	3378	3583	3583	3583

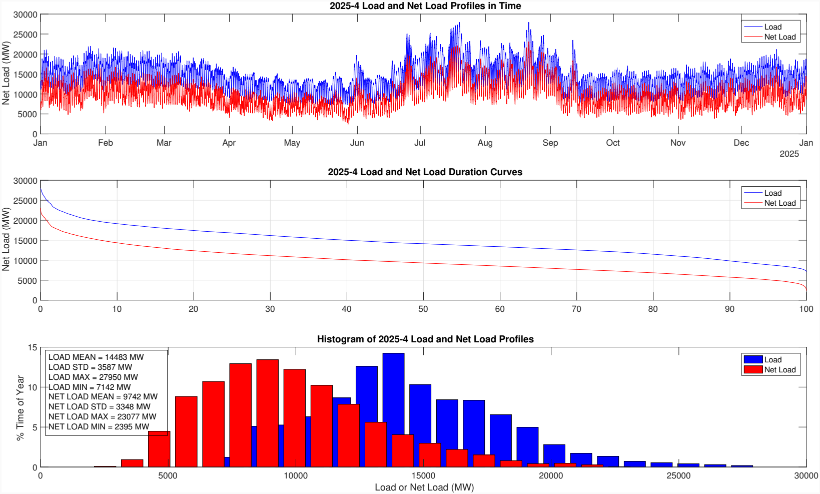
2030 Scenario load distributions exhibit the same statistical characteristics except Scenario 3 due to the addition of energy efficiency and electric vehicle charging loads.

- Load Profiles
- **Net Load Profiles**
- Load, Solar, & Wind Forecast Errors in the Net Load
- Net Load Ramping Characteristics

Definition 6

Net Load Profile: System-wide load minus the unconstrained generation from wind, solar, run-of-river hydro, and tie-line imports all in one minute increments.

Scenarios: Three Views of a Net Load Profile



Variable resources create lower net load curve. Dispatchable resources must meet new variability, min load, & retain peak load capability.

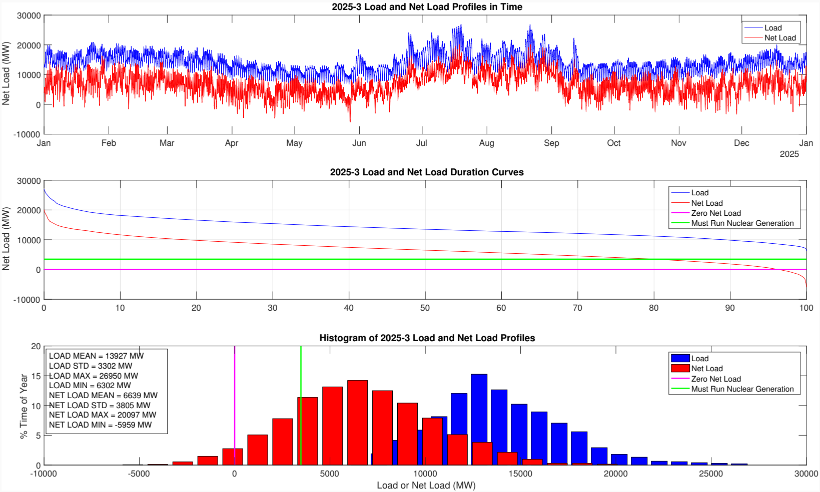
Given the definition of net load, Scenarios 2025-3, 2030-2, 2030-3, 2030-6 exhibit negative net load for parts of the year.

Definition 7

Excess Generation: Given the presence of must-run resources, excess generation at time steps where the net load is less than the power output from must-run resources.

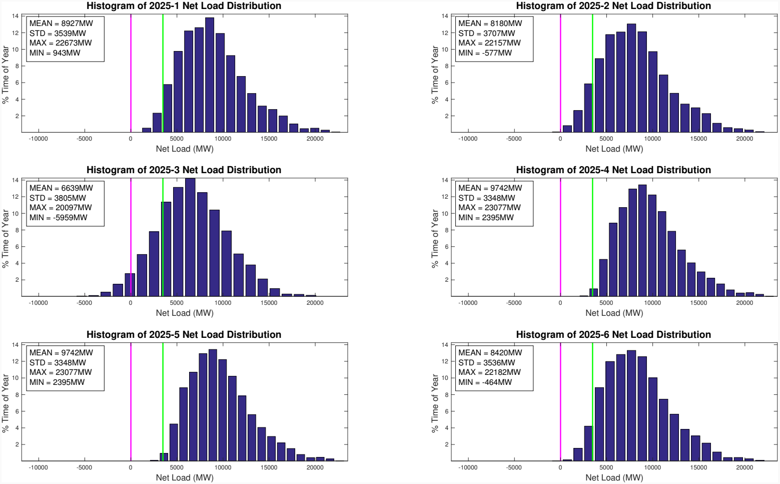
Given the definition of excess generation, all scenarios exhibit excess generation for parts of the year.

Scenarios: Three Views of the 2025-3 Net Load Profile



The 2025-3 scenario exhibits negative net load or excess generation a significant percentage of the time.

Scenarios: The 2025 Net Load Distributions I



Scenarios: The 2025 Net Load Distributions II

2025 Scenario net load distributions exhibit significant statistical differences due to differences in solar, wind, and passive demand resources.

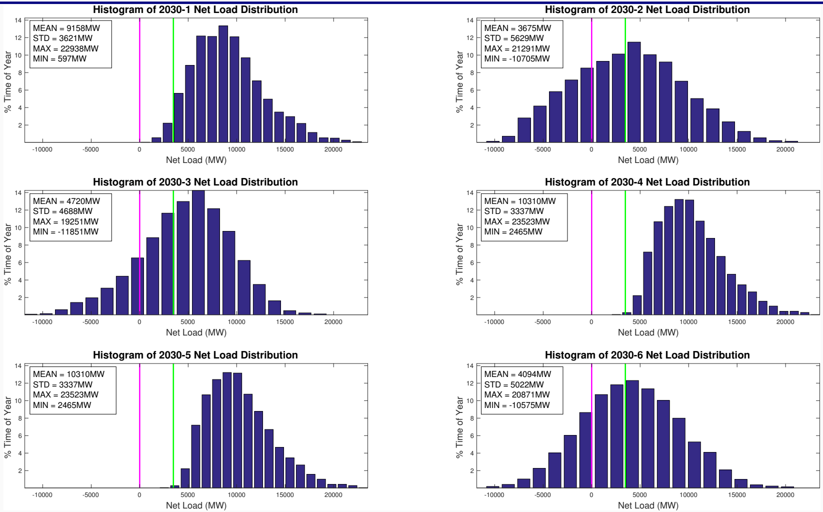
All 2025 Scenarios net loads exhibit excess generation. Scenario 2025-3 net load exhibits negative values indicating the need to curtail some amount of resources.

Table 3: 2025 Net Load Distribution Statistics

	2025-1	**2025-2**	**2025-3**	**2025-4**	**2025-5**	**2025-6**
Max (MW)	22673	22157	20097	23077	23077	22182
Min (MW)	943	-577	-5959	2395	2395	-464
Energy (TWh)	78	72	58	85	85	74
Mean (MW)	8927	8180	6639	9742	9742	8420
STD (MW)	3539	3707	3805	3348	3348	3536
% Time Excess Gen.	3.12	8.33	20.13	0.27	0.27	5.09
% Time Neg Net Load	0.00	0.05	3.68	0.00	0.00	0.03

2025 Scenario net load distributions exhibit significant statistical differences due to differences in solar, wind, and passive demand resources.

Scenarios: The 2030 Net Load Distributions



Scenarios 2030-1, -2, -3, and -6 exhibit negative net load or excess generation a significant percentage of the time.

Scenarios: The 2030 Net Load Distributions

Table 4: 2030 Net Load Distribution Statistics

	2030-1	2030-2	2030-3	2030-4	2030-5	2030-6
Max (MW)	22938	21291	19251	23523	23523	20871
Min (MW)	597	-10705	-11851	2465	2465	-10575
Energy (TWh)	80	32	41	90	90	36
Mean (MW)	9158	3675	4720	10310	10310	4094
STD (MW)	3621	5629	4688	3337	3337	5022
% Time Excess Gen.	2.91	48.11	37.02	0.09	0.09	45.74
% Time Neg. Net Load	0.00	27.49	15.79	0.00	0.00	21.38

2030 Scenario net load distributions exhibit significant statistical differences due to differences in solar, wind, and passive demand resources.

Scenarios: Outline

- Load Profiles
- Net Load Profiles
- **Load, Solar, & Wind Forecast Errors in the Net Load**
- Net Load Ramping Characteristics

The load, wind, and solar resources are stochastic quantities which are used as inputs to three optimization programs:

1. Security Constrained Unit Commitment (SCUC)
2. Real Time Unit Commitment (RTUC)
3. Security Constrained Economic Dispatch (SCED)

Their forecasts introduce error into these optimization programs.

Scenarios: Summary of Net Load Forecast Error Components I

All forecast errors are expressed as mean-absolute-percent-errors (MAPE).

Table 5: Forecast Error Statistics

	Load	**Wind**	**Solar**
SCUC	1.65%	12%	7%
RTUC	1.5%	3%	3%
SCED	0.15%	3%	3%

Definition 8

Load MAPE = Mean of the absolute value of the error between load forecast and actual load normalized by actual load

Definition 9

Solar/Wind MAPE = Mean of the absolute value of the error between solar/wind forecast and actual solar/wind normalized by installed solar/wind nameplate capacity

Scenarios: Summary of Net Load Forecast Error Components II

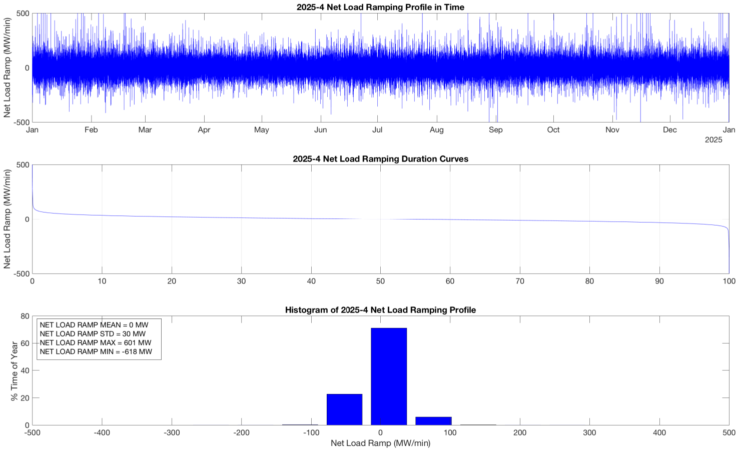
Load, Wind, and Solar forecast errors introduce an uncertainty in balancing operations in the SCUC, RTUC, and SCED.

Load, Wind, and Solar forecast error diminishes as the forecast approaches real time.

The state-of-the-art in load forecasting technology is more advanced than solar and wind forecast technology. As more solar and wind generation is introduced, the error introduced by forecasting increases – thereby complicating balancing operations.

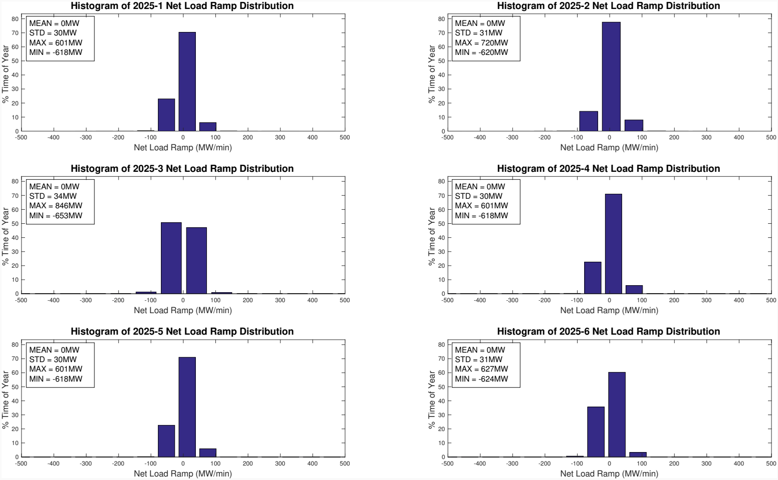
- Qualitative Descriptions
- Load Profiles
- Net Load Profiles
- Load, Solar, & Wind Forecast Errors in the Net Load
- **Net Load Ramping Characteristics**

Scenarios: Three Views of a Net Load Ramping Profile



The net load ramping profile places a ramping requirement on dispatchable resources.

Scenarios: The 2025 Net Load Ramping Distributions



Scenarios 2025-2 and 2025-3 exhibit the greatest net load ramp up at 1-minute resolution.

Scenarios: The 2025 Net Load Ramping Distributions I

Table 6: 2025 Net Load Ramping Distribution Statistics

	2025-1	2025-2	2025-3	2025-4	2025-5	2025-6
Max 1-Min-Up[1] (MW/min)	601	720	846	601	601	627
Max 1-Min-Down[1] (MW/min)	618	620	653	618	618	624
Max 10-Min-Up[2] (MW/min)	184	251	312	126	126	220
Max 10-Min-Down[2] (MW/min)	81	84	78	73	73	78
Max 1h-Up[2] (MW/min)	49	52	73	49	49	57
Max 1h-Down[2] (MW/min)	46	45	60	40	40	44
Max 4h-Up[3] (MW/min)	30	33	49	29	29	37
Max 4h-Down[3] (MW/min)	38	40	42	36	36	38

1. Inter 1-minute ramps are calculated as the difference between consecutive points on the net load profile with 1-minute resolution.
2. Inter 10 minute and Inter 1h ramps are calculated as the difference between consecutive points on the net load profile after it has been averaged into 10 minute or 1h blocks respectively.
3. Intra 4 hour ramps are calculated as the average *sustained* ramp within a four hour window that covers the minimum and maximum net load values of that time period.

The net load ramping profile shows the greatest ramps when viewed with one minute temporal resolution and generally decreases with coarser temporal resolution.

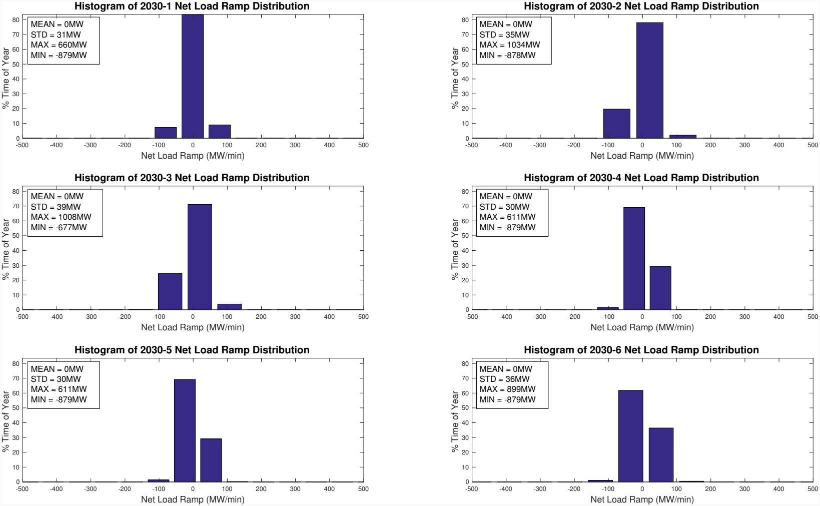
Scenarios 2025-2 and 2025-3 exhibit the greatest net load ramp up at 1-minute, 10 minute and 4 hour resolution.

The maximum 1 minute down ramp and the maximum 10 minute down ramp are similar for all 2025 scenarios.

Scenario 2025-3 exhibits the greatest net load ramp up and down at the 1-hour resolution.

Scenarios 2025-3 and 2025-6 exhibit the largest intra 4-hour ramp in an upward direction.

Scenarios: The 2030 Net Load Ramping Distributions



Scenarios 2030-2, 2030-3, and 2030-6 have greater variability & maximum values in their net load ramping profiles than the other 2030 scenarios.

Table 7: 2030 Net Load Ramping Distribution Statistics

	2030-1	2030-2	2030-3	2030-4	2030-5	2030-6
Max 1-Min-Up[1] (MW/min)	660	1034	1008	611	611	899
Max 1-Min-Down[1] (MW/min)	879	878	677	879	879	879
Max 10-Min-Up[2] (MW/min)	228	748	383	126	126	672
Max 10-Min-Down[2] (MW/min)	109	108	115	109	109	161
Max 1h-Up[2] (MW/min)	53	103	95	52	52	99
Max 1h-Down[2] (MW/min)	45	76	94	40	40	67
Max 4h-Up[3] (MW/min)	33	61	67	32	32	69
Max 4h-Down[3] (MW/min)	39	49	63	36	36	51

The net load ramping profile shows the greatest ramps when viewed with one minute temporal resolution and generally decreases with coarser temporal resolution.

Scenarios 2030-2, 2030-3 and 2030-6 exhibit the greatest net load ramp up at 1-minute, 10 minute, 1 hour and 4 hour resolutions.

The maximum 1 minute down ramp is similar for all 2030 scenarios except for 2030-3.

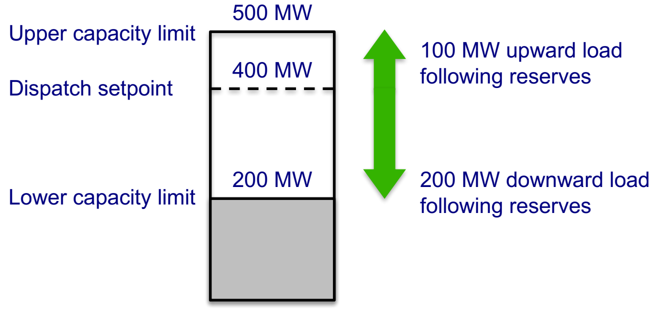
The maximum 10 minute ramps down are similar for all 2030 scenarios.

Scenarios 2030-2, 2030-3, and 2030-6 exhibit the greatest net load ramp down at the 1-hour and 4-hour resolutions.

The Simulated Operating Reserves Performance: Load Following & Ramping

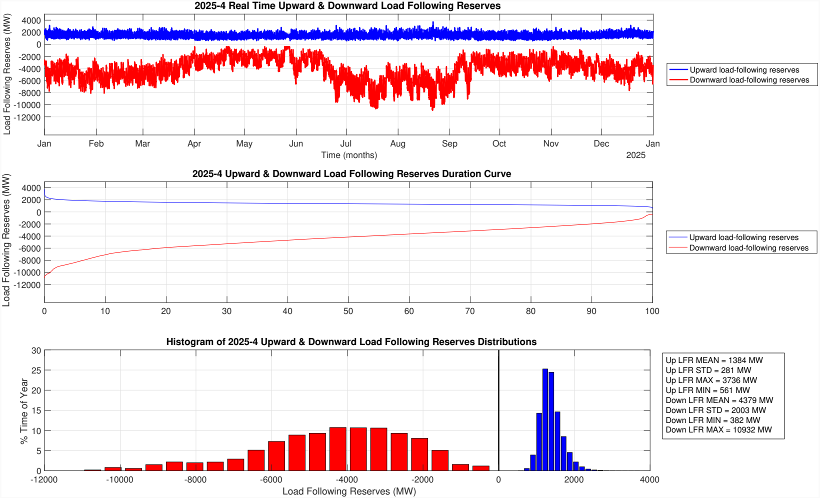
Operating Reserves: Load Following – Physical Quantity vs. Product

- Even in the absence of load following reserve reserve requirements, the system still has load following reserves (LFR) as a physical quantity.
- The quantity of load following reserves is equal to the capacity of the aggregate generation fleet to move up or down (i.e. economic surplus)
- Currently, the ISO does not calculate this type of reserves in its operations.



Load following reserves, as a physical quantity, assists in responding to net load variability and uncertainty.

Operating Reserves: 2025-4 Load Following Reserves Profile I



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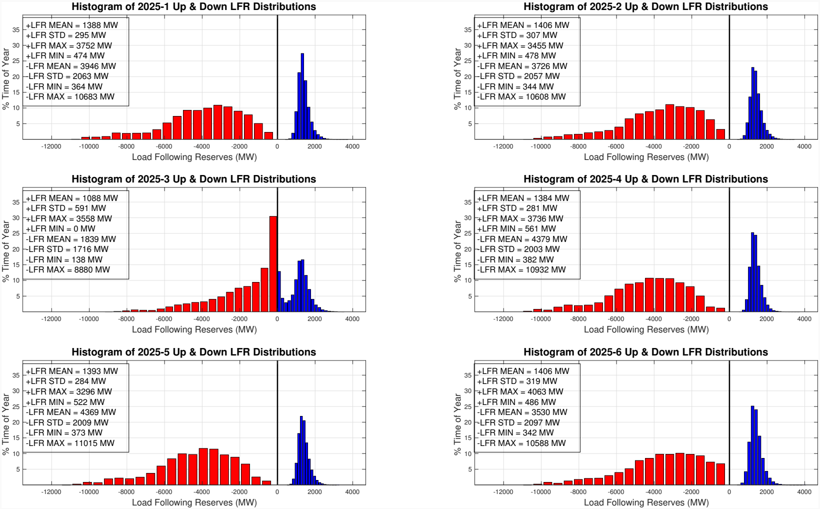
Operating Reserves: 2025-4 Load Following Reserves Profile II

Upward and downward load following reserves are used in time in order to respond to net load variability and uncertainty.

In traditional operation, having sufficient upward load following reserves is of primary concern. Here, both directions are equally important.

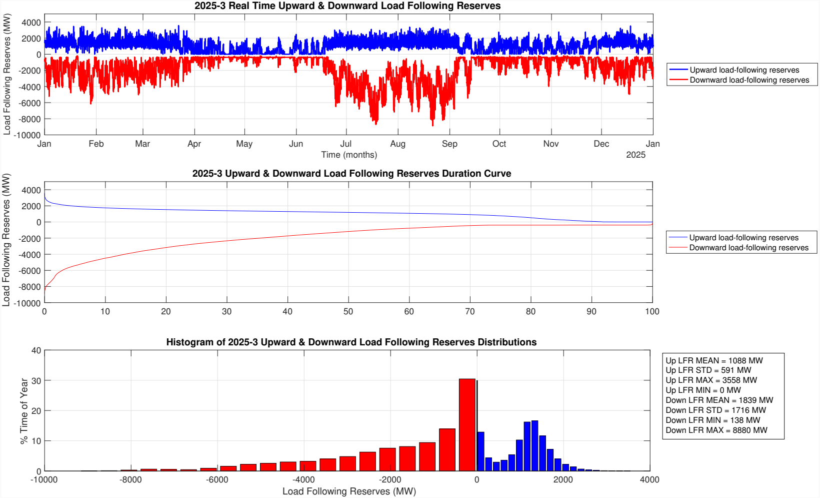
As upward & downward load following reserves are exhausted (approach a the zero black line), the ability to respond to fluctuations in the net load becomes increasingly constrained.

Operating Reserves: 2025 LFR Distributions



Scenario 2025-3 shows a shortage of downward load following reserves reflecting constrained downward dispatch.

Operating Reserves: 2025-3 Load Following Reserves Profile



In Spring & Autumn, the ability to track low net load conditions is particularly constrained.

Table 8: 2025 Upward Load Following Reserves Statistics

	2025-1	2025-2	2025-3	2025-4	2025-5	2025-6
Up LFR Mean (MW)	1376	1385	1160	1377	1380	1392
Up LFR STD (MW)	302	307	558	286	285	321
Up LFR Min (MW)	10	28	0	277	142	81
Up LFR 95 percentile[1] (MW)	958	957	1	977	976	937

All 2025 Scenarios exhibit sufficient upward load following reserves throughout the year.

1. Here, the 95^{th} percentile indicates that the system has more than this quantity of upward load following reserves for 95% of the time.

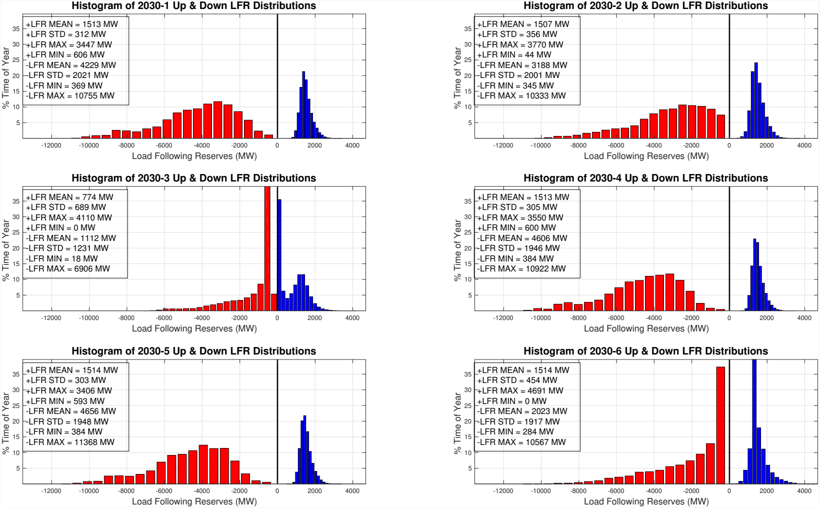
Operating Reserves: 2025 Downward Load Following Reserves Statistics

Table 9: 2025 Downward Load Following Reserves Statistics

	2025-1	**2025-2**	**2025-3**	**2025-4**	**2025-5**	**2025-6**
Down LFR Mean (MW)	4096	3850	1937	4498	4501	3729
Down LFR STD (MW)	1860	1848	1656	1798	1816	1936
Down LFR Min (MW)	339	342	97	383	382	340
Down LFR 95 percentile (MW)	1318	1180	342	1784	1788	786

In the 2025 Scenarios, downward LFR are more constrained than upward LFR. Scenarios 2025-2 and 2025-3 entirely exhaust this reserve.

Operating Reserves: 2030 Load Following Reserves Distributions



Scenarios 2030-3 and 2030-6 demonstrate a shortage of downward load following reserves.

Table 10: 2030 Upward Load Following Reserves Statistics

	2030-1	2030-2	2030-3	2030-4	2030-5	2030-6
Up LFR Mean (MW)	1507	1506	818	1512	1496	1525
Up LFR STD (MW)	324	355	683	304	314	478
Up LFR Min (MW)	0	0	0	356	0	0
Up LFR 95 percentile[1] (MW)	1072	1022	0	1104	1067	935

Scenarios 2030-1, 2030-2, and 2030-5 entirely exhaust their upward load following reserves; albeit for a fairly short part of the year.

The commitment of dispatchable resources and their associated quantities of commitment of load following and ramping reserves has a complex, difficult to predict, non-linear dependence on the amount of variable resources and the load profile statistics. Here, despite the similarities between Scenario 2030-4 and 2030-5, their associated quantities of load following reserves is quite different as a result of the differences in the resource characteristics between the two scenarios.

Operating Reserves: 2025 Downward Load Following Reserves Statistics

Table 11: 2030 Downward Load Following Reserves Statistics

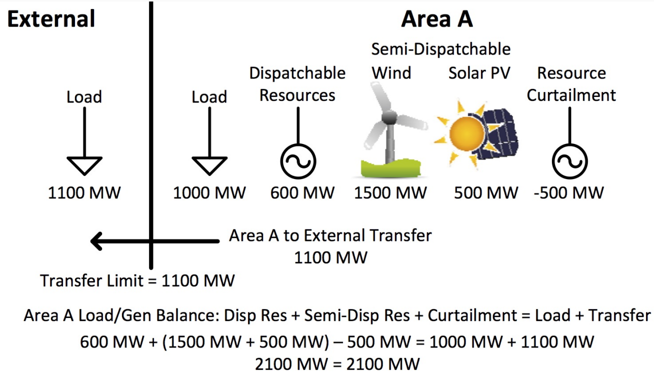
	2030-1	2030-2	2030-3	2030-4	2030-5	2030-6
Down LFR Mean (MW)	4374	3333	1145	4730	4805	2125
Down LFR STD (MW)	1805	1827	1212	1738	1714	1865
Down LFR Min (MW)	351	340	0	425	389	0
Down LFR 95 percentile (MW)	1728	714	335	2167	2285	342

Scenarios 2030-3 and 2030-6 demonstrate a shortage of downward load following reserves.

Definition 10

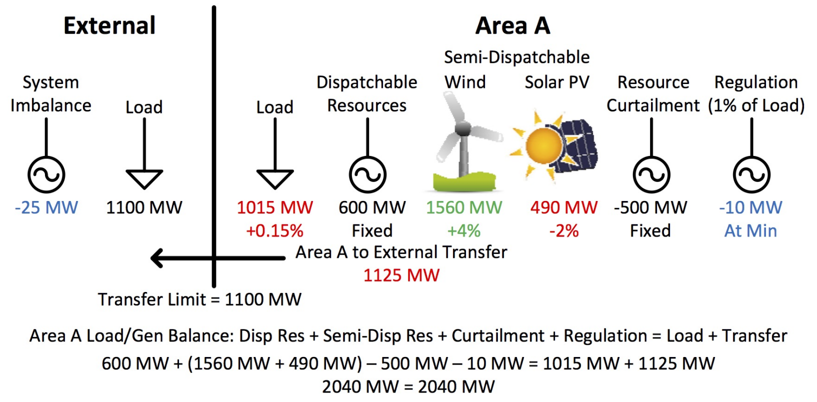
Imbalance Profile: The sum of all dispatchable energy resource power injections minus the net load profile as a function of time.

Consider the case of the power balance constraint in the SCED:



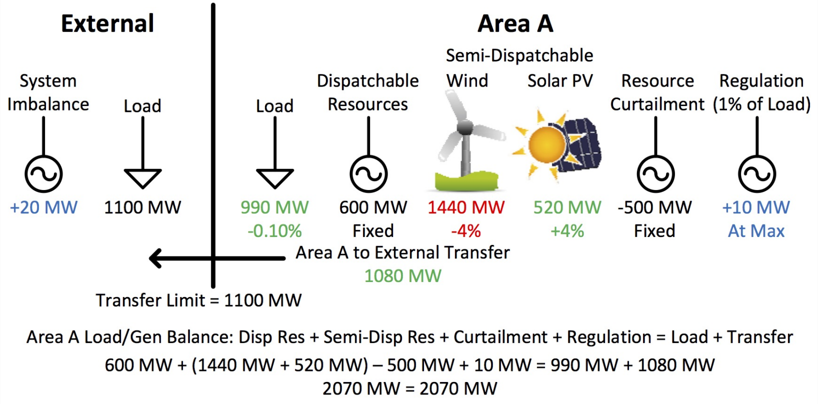
Operating Reserves: An Introduction to Imbalances II

Consider the case of negative imbalances in the real-time physical power flow layer:



Operating Reserves: An Introduction to Imbalances III

Consider the case of positive imbalances in the real-time physical power flow layer:

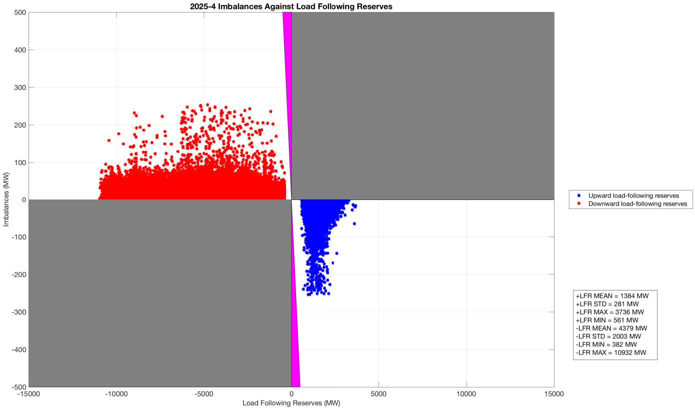


All types of operating reserves serve to reduce imbalances.

When imbalances coincide with a shortage of load following reserves, it indicates that increasing this reserve quantity can serve to improve balancing performance.

The following slides show that Scenarios 2025-3, 2030-2, 2030-3, and 2030-6 have imbalances that occur when there is a shortage of downward load following reserves.

Operating Reserves: 2025-4 Imbalances Against LFR I



Operating Reserves: 2025-4 Imbalances Against LFR II

Imbalances may coincide with a shortage of load following reserves.

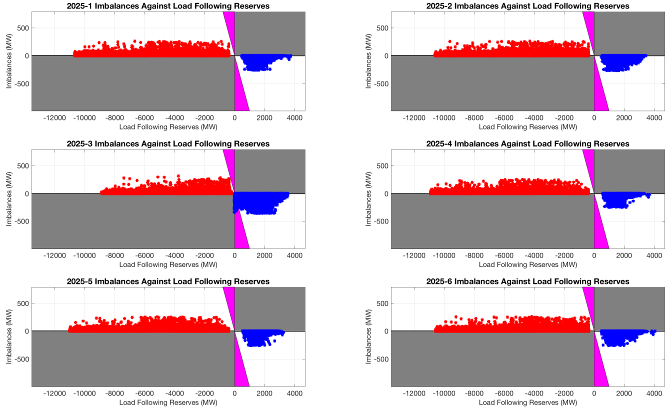
In the grey regions, upward and downward load following reserves do not serve to mitigate positive and negative imbalances respectively.

In the white regions, upward and downward load following reserves serve to mitigate positive and negative imbalances respectively.

In the magenta regions, a 1MW increase of load following reserves leads to a 1MW reduction of imbalances. This region represents when there are insufficient amounts of load following reserves to serve the system imbalance.

In Scenario 2025-4, imbalances do not coincide with low load following reserves – suggesting that imbalances can be mitigated in another way.

Simulated Balancing Performance: 2025 Imbalances Against LFR



Of the 2025 Scenarios, 2025-3 and to a lesser extent 2025-2 and 2025-6 would benefit the most from additional downward load following reserves.

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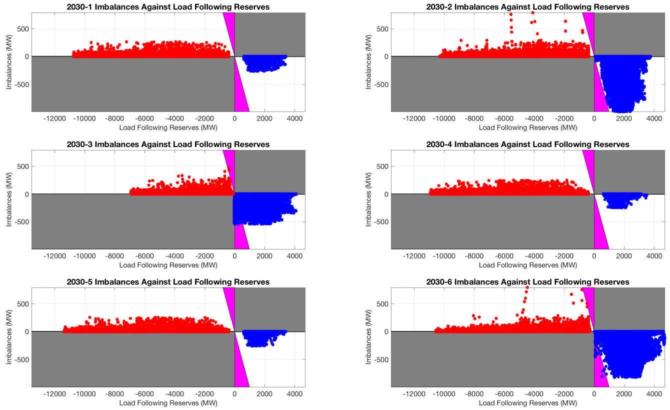
Simulated Balancing Performance: 2030 Imbalances Against LFR



Scenarios 2030-2, 2030-3, and 2030-6 clearly show a strong coincidence of downward load following reserves and positive imbalances – suggesting a need for more of this type of reserve.

Operating Reserves: Load Following Reserves in Magenta Zone

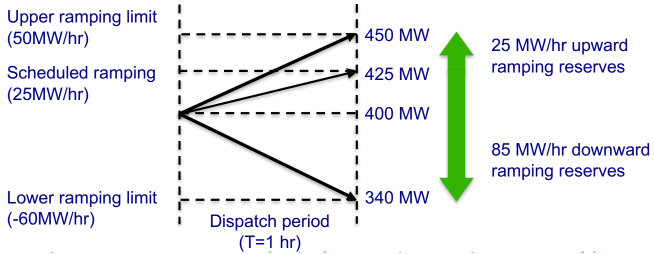
Table 12: Load Following Reserves in Magenta Zone

	2025-1	2025-2	2025-3	2025-4	2025-5	2025-6
% Time +LFR in Magenta Zone	0.00	0.00	5.60	0.00	0.00	0.00
% Time -LFR in Magenta Zone	0.00	0.00	0.00	0.00	0.00	0.00
	2030-1	**2030-2**	**2030-3**	**2030-4**	**2030-5**	**2030-6**
% Time +LFR in Magenta Zone	0.06	0.00	24.25	0.00	0.25	0.02
% Time -LFR in Magenta Zone	0.00	0.00	0.00	0.00	0.00	0.00

To varying degrees, Scenarios 2025-3, 2030-2, 2030-3, 2030-5, and 2030-6 demonstrate periods that would benefit from additional load following reserves.

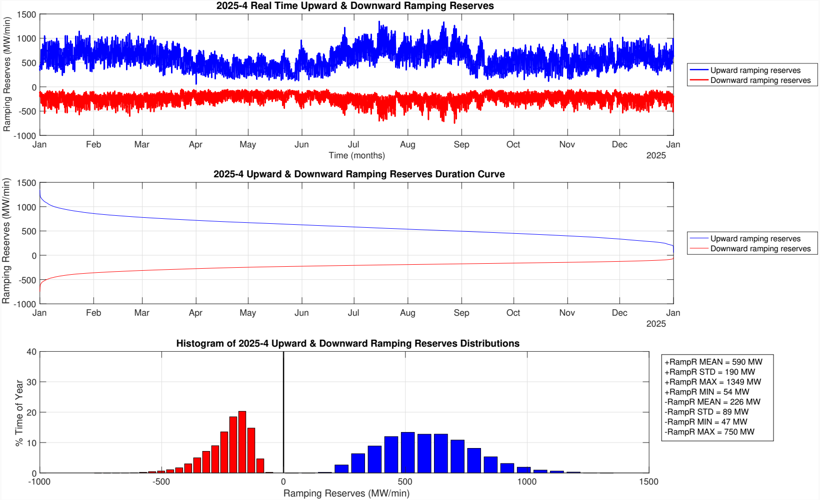
Operating Reserves: Ramping Physical Quantity vs. Product

- Even in the absence of reserve requirements, the system still has ramping reserves (RampR) as a physical quantity.
- The quantity of ramping reserves is equal to the excess ramping capability of the aggregate generation fleet to move up or down in time.
- Currently, the ISO does not calculate this type of reserves in its operations.



Ramping reserves, as a physical quantity, assists in responding to net load variability and uncertainty.

Operating Reserves: 2025-4 Ramping Reserves Profile I

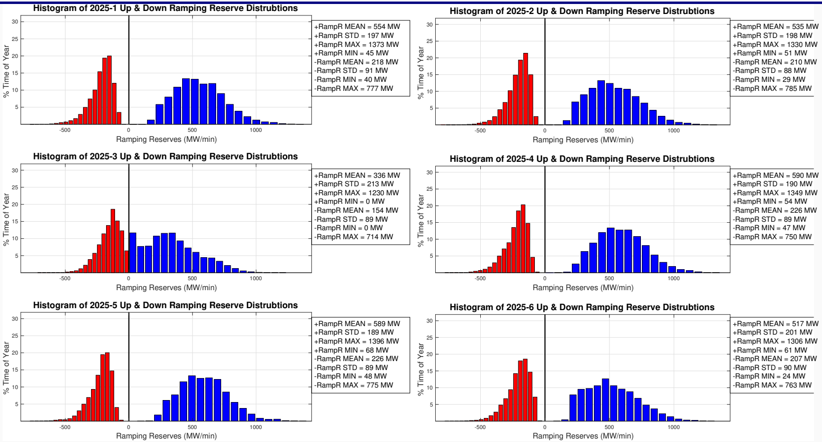


Upward and downward ramping reserves are used in time in order to respond to net load variability and uncertainty.

In traditional operation, having sufficient upward ramping reserves is of primary concern. Here, both directions are equally important.

As upward & downward ramping reserves approach zero, the ability to respond to fluctuations in the net load becomes increasingly constrained.

Operating Reserves: 2025 Ramping Reserve Distributions



The 2025 scenarios exhibit sufficient upward and downward ramping reserves.

Scenarios 2025-2, 2025-3, and 2025-6 low quantities of downward reserves which may impact imbalance levels.

Table 13: 2025 Upward Ramping Reserves Statistics

	2025-1	**2025-2**	**2025-3**	**2025-4**	**2025-5**	**2025-6**
Up RampR Mean (MW/min)	591	571	367	621	623	554
Up RampR STD (MW/min)	204	204	218	194	197	210
Up RampR Max (MW/min)	1412	1390	1291	1420	1433	1362
Up RampR Min (MW/min)	78	85	0	69	38	95
Up RampR 95 percentile (MW/min)	285	267	38	329	326	243

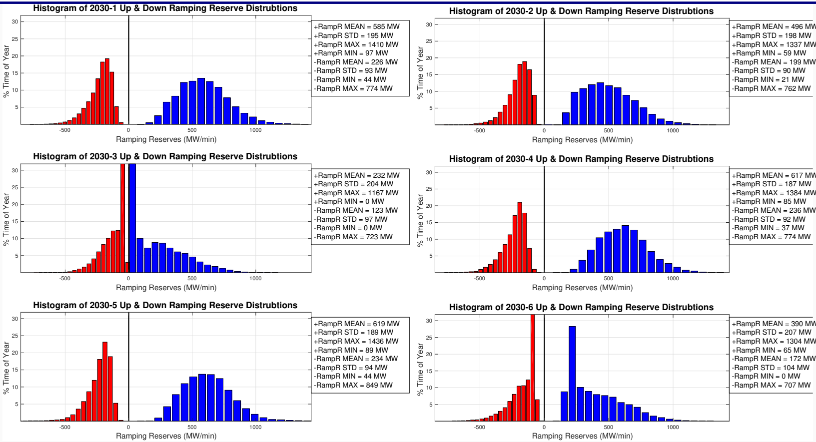
All 2025 Scenarios exhibit sufficient upward ramping reserves throughout the year.

Table 14: 2025 Downward Ramping Reserves Statistics

	2025-1	2025-2	2025-3	2025-4	2025-5	2025-6
Down RampR Mean (MW/min)	235	226	167	238	243	220
Down RampR STD (MW/min)	102	100	94	98	100	100
Down RampR Min (MW/min)	-0	-0	-0	-0	-0	-0
Down RampR Max (MW/min)	805	782	766	802	819	780
Down RampR 95 percentile (MW/min)	112	105	36	120	123	93

All 2025 Scenarios exhibit sufficient downward ramping reserves throughout the year.

Operating Reserves: 2030 Ramping Reserve Distributions



The 2030 scenarios exhibit sufficient upward and downward ramping reserves.

Scenarios 2030-2, 2030-3, and 2030-6 low quantities of downward reserves which may impact imbalance levels.

Table 15: 2030 Upward Ramping Reserves Statistics

	2030-1	**2030-2**	**2030-3**	**2030-4**	**2030-5**	**2030-6**
Up RampR Mean (MW/min)	623	531	254	656	659	414
Up RampR STD (MW/min)	206	209	216	190	200	220
Up RampR Max (MW/min)	1458	1420	1239	1424	1459	1388
Up RampR Min (MW/min)	87	59	0	95	86	52
Up RampR 95 percentile (MW/min)	316	228	33	370	362	177

The 2030 scenarios exhibit sufficient upward ramping reserves.

Operating Reserves: 2030 Downward Ramping Reserves Statistics

Table 16: 2030 Downward Ramping Reserves Statistics

	2030-1	**2030-2**	**2030-3**	**2030-4**	**2030-5**	**2030-6**
Down RampR Mean (MW/min)	242	213	134	251	250	182
Down RampR STD (MW/min)	109	101	105	102	112	111
Down RampR Min (MW/min)	-0	-0	-0	-0	-0	-0
Down RampR Max (MW/min)	850	801	771	845	836	791
Down RampR 95 percentile (MW/min)	118	91	31	129	123	70

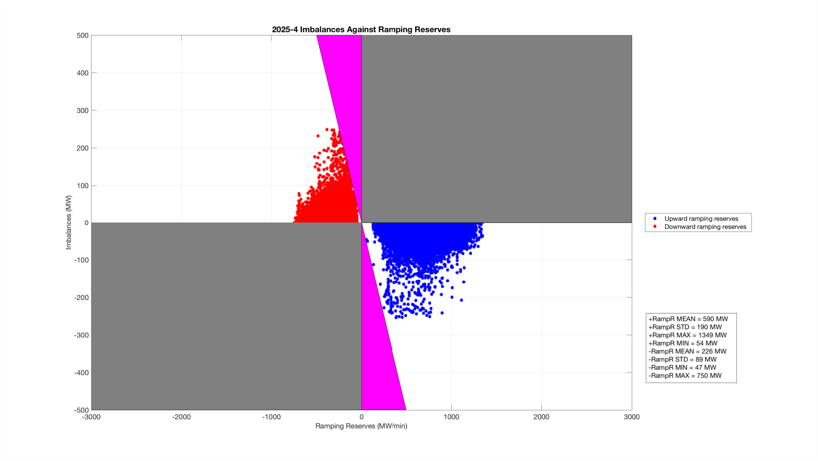
The 2030 scenarios exhibit sufficient downward ramping reserves.

All types of operating reserves serve to reduce imbalances.

When imbalances coincide with a shortage of ramping reserves, it indicates that increasing this reserve quantity can serve to improve balancing performance.

The following slides show that Scenarios 2025-3, 2030-2, 2030-3, and 2030-6 have imbalances that occur when there is a shortage of downward ramping reserves.

Operating Reserves: 2025-4 Imbalances Against Ramping Reserves I



Imbalances may coincide with a shortage of ramping reserves.

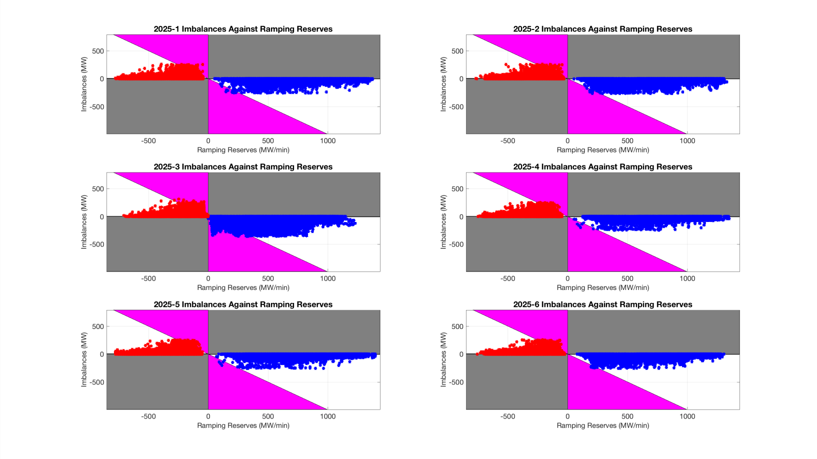
In the grey regions, upward and downward ramping reserves do not serve to mitigate positive and negative imbalances respectively.

In the white regions, upward and downward ramping reserves serve to mitigate positive and negative imbalances respectively.

In the magenta regions, a 1MW/min increase of ramping reserves leads to a 1MW reduction of imbalances. This region represents when there are insufficient amounts of ramping reserves to serve the system imbalance.

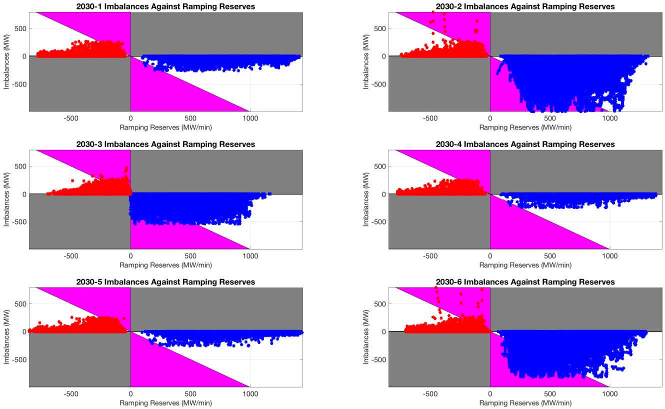
In Scenario 2025-4, imbalances do not coincide with low ramping reserves – suggesting that imbalances can be mitigated in another way.

Operating Reserves: 2025 Imbalances Against Ramping Reserves



Scenario 2025-3 and to a lesser extent 2025-2 and 2025-6 would benefit from an increase in downward ramping reserves.

Operating Reserves: 2030 Imbalances Against Ramping Reserves



Scenarios 2030-2 and to a lesser extent 2030-3 and 2030-6 would benefit from an increase in upward ramping reserves.

Scenario 2030-2, 2030-3, and 2030-6 would benefit from an increase in downward ramping reserves.

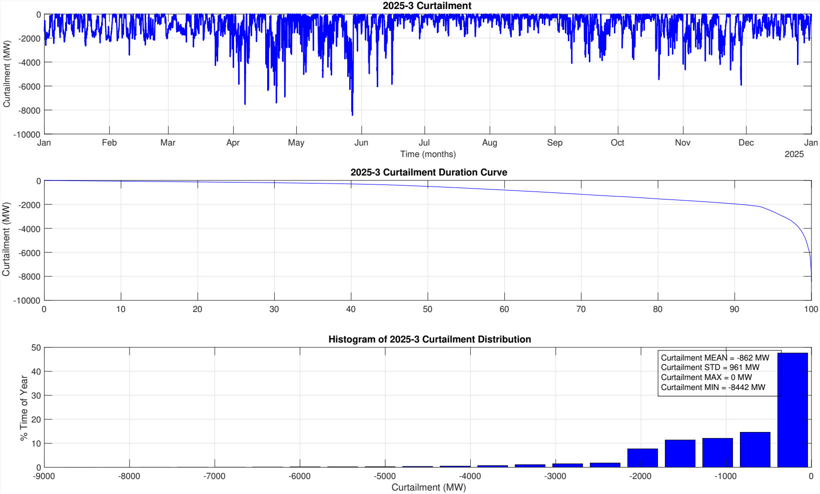
Operating Reserves: Ramping Reserves in Magenta Zone

Table 17: Ramping Reserves in Magenta Zone

	2025-1	2025-2	2025-3	2025-4	2025-5	2025-6
% Time +RampR in Magenta Zone	0.01	0.01	2.10	0.00	0.00	0.01
% Time -RampR in Magenta Zone	0.04	0.04	0.36	0.03	0.03	0.04
	2030-1	**2030-2**	**2030-3**	**2030-4**	**2030-5**	**2030-6**
% Time +RampR in Magenta Zone	0.00	1.71	15.47	0.00	0.01	6.34
% Time -RampR in Magenta Zone	0.03	0.08	2.04	0.02	0.03	0.18

To varying degrees, Scenarios 2025-2, 2025-3, 2025-6, 2030-2, 2030-3, and 2030-6 demonstrate periods that would benefit from additional ramping reserves.

Operating Reserves: 2025-3 Curtailment Profile I

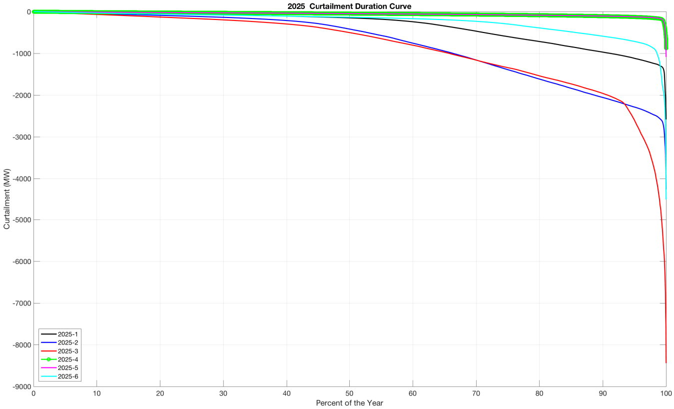


Operating Reserves: 2025-3 Curtailment Profile II

In the absence of load following and ramping reserves, curtailment serves a vital balancing function.

Scenario 2025-3 shows some form of curtailment for 60% of the year.

Operating Reserves: 2025 Curtailment Profiles



Curtailment becomes an integral part of balancing operations for all 2025 Scenarios except 2025-4 and 2025-5.

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Operating Reserves: 2025 Curtailment Statistics

Table 18: 2025 Curtailment Statistics

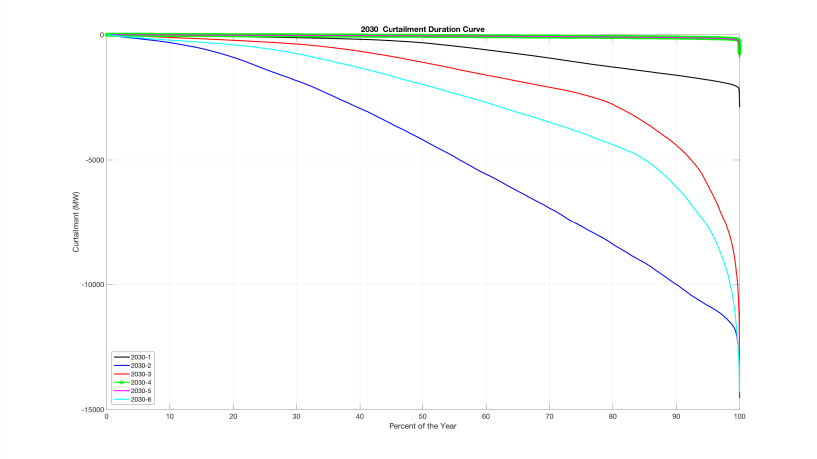
	2025-1	2025-2	2025-3	2025-4	2025-5	2025-6
Tot. Semi-Disp. Res. (GWh)	48674	55215	63850	41532	41532	53118
Tot. Curtailed Semi-Disp. Energy (GWh)	3604	7333	7600	1130	1123	2585
% Semi-Disp. Energy Curtailed	7.41	13.28	11.90	2.72	2.70	4.87
% Time Curtailed	99.61	99.79	99.90	98.89	98.83	99.63
Max Curtailment Level (MW)	2880	4115	8442	1605	1701	4748

In all the 2025 Scenarios except 2025-4 and 2025-5, curtailments form a significant portion ($\geq$1.5%) of the total semi-dispatchable energy resource.

Furthermore, they are used between 32% & 62% of the time in those same scenarios.

In the most pronounced case of Scenario 2025-3, curtailment was used over 60% of the time to a maximum value of 9894MW.

Operating Reserves: 2030 Curtailment Profiles



Curtailment becomes an integral part of balancing operations for all 2030 Scenarios except 2030-4 and 2030-5.

Table 19: 2030 Curtailment Statistics

	2030-1	**2030-2**	**2030-3**	**2030-4**	**2030-5**	**2030-6**
Tot. Semi-Disp. Res. (GWh)	52748	100786	76606	42662	42662	97115
Tot. Curtailed Semi-Disp. Energy (GWh)	5993	41517	14495	1149	1162	22531
% Semi-Disp. Energy Curtailed	11.36	41.19	18.92	2.69	2.72	23.20
% Time Curtailed	99.85	99.95	99.88	98.84	98.91	99.95
Max Curtailment Level (MW)	3378	14534	14468	1640	1637	14234

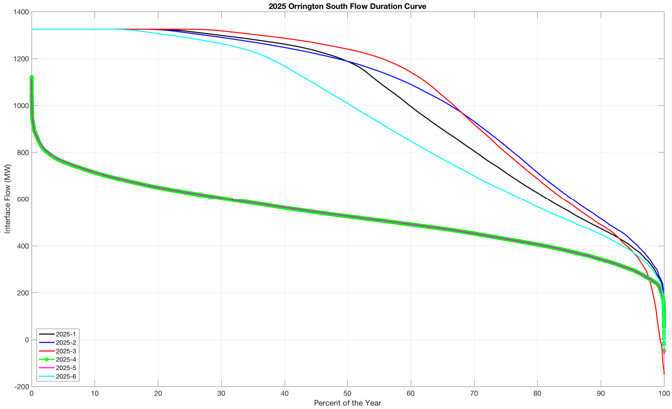
In all the 2030 Scenarios except 2025-4 and 2025-5, curtailments form a significant portion ($\geq$8.5%) of the total semi-dispatchable energy resource.

Furthermore, they are used between 56% & 88% of the time in those same scenarios.

In the most pronounced case of Scenario 2030-2, curtailment was used over 88% of the time to a maximum value of 15862MW.

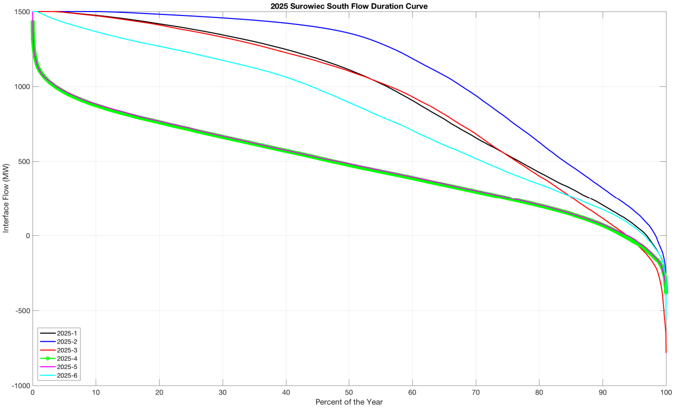
The Simulated Interface & Tie-line Performance

Interface Performance: 2025 Orrington-South Flow Duration Curve



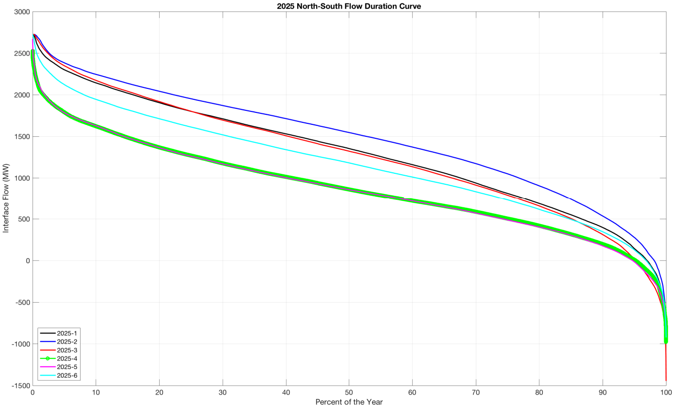
Scenarios 2025-1, 2025-2, 2025-3, and 2025-6 exhibits some congestion on the Orrington-South Interface.

Interface Performance: 2025 Surowiec-South Flow Duration Curve



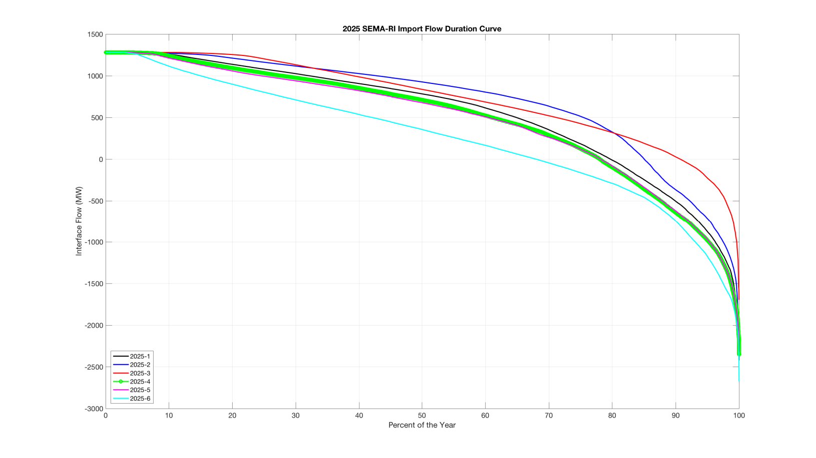
Scenarios 2025-1, 2025-2, 2025-3, and 2025-6 exhibits some congestion on the Surowiec-South Interface.

Interface Performance: 2025 North-South Flow Duration Curve



Similarly, the North-South interface is constrained in rare cases in all 2025 scenarios.

Interface Performance: 2025 SEMA-RI Import Flow Duration Curve



Scenarios 2025-1, 2025-2, 2025-3, and 2025-6 exhibits some congestion on the SEMA-RI Import interfaces.

Interface Performance: 2025 Congestion Statistics

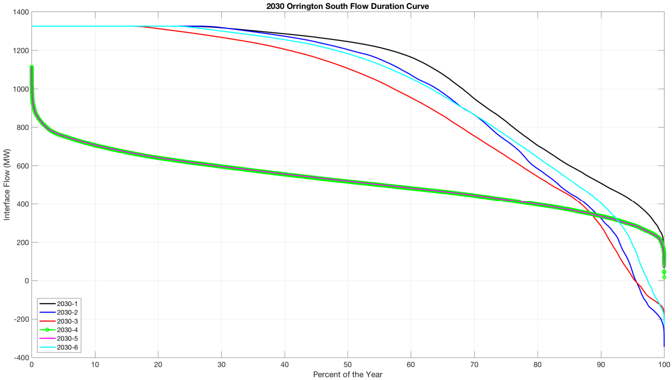
Table 20: 2025 Interface Congestion Statistics

	2025-1	2025-2	2025-3	2025-4	2025-5	2025-6
Orrington South % Time Congested	20.49	19.05	27.06	0.00	0.00	13.91
Surowiec South % Time Congested	4.39	11.82	4.41	0.00	0.00	0.90
North-South % Time Congested	0.15	0.38	0.51	0.00	0.00	0.04
SEMA-RI Import % Time Congested	3.09	3.61	9.88	3.22	3.07	2.00

To varying degrees, the Orrington-South, Surowiec-South, North-South, and SEMA-RI import interfaces exhibit some congestion in all 2025 Scenarios; albeit to a much lesser extent in Scenarios 2025-4 and 2025-5.

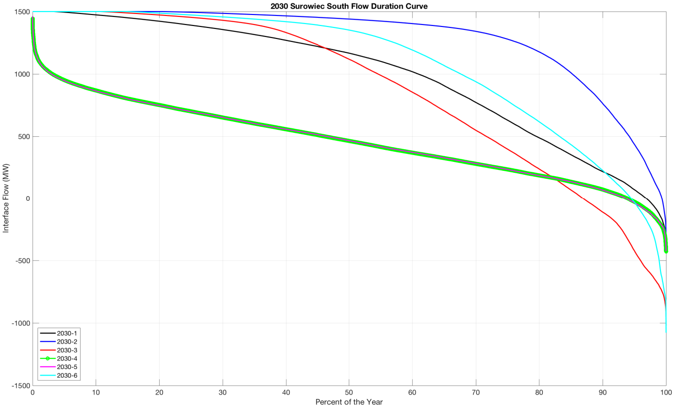
The other interfaces and tie-lines in their respective scenarios exhibit negligible or no congestion.

Interface Performance: 2030 Orrington-South Flow Duration Curve



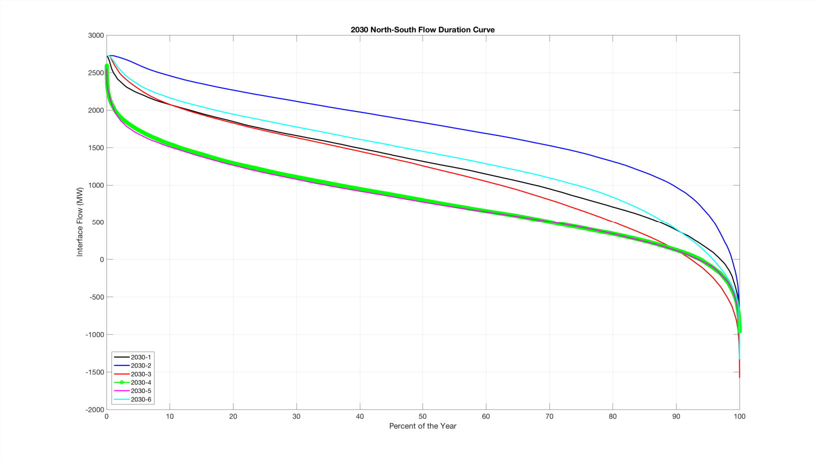
In Scenarios 2030-1, 2030-2, 2030-3, and 2030-6 exhibits exhibit more congestion on the Orrington-South Interface than in the 2025 Scenarios.

Interface Performance: 2030 Surowiec-South Flow Duration Curve



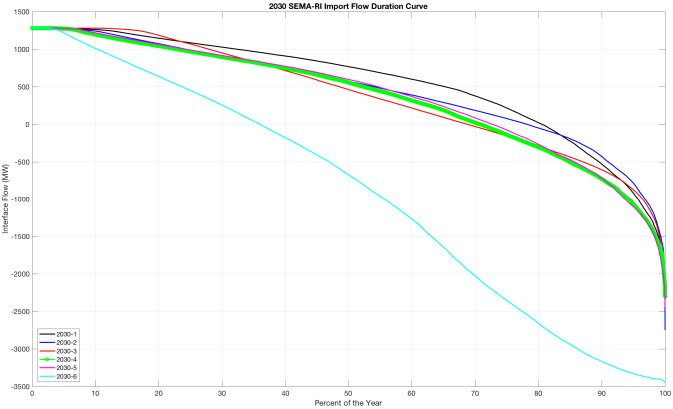
In Scenarios 2030-1, 2030-2, 2030-3, and 2030-6 exhibits more congestion on the Surowiec-South Interface than in the 2030 Scenarios.

Interface Performance: 2030 North-South Flow Duration Curve



Similarly, the North-South interface is constrained in rare cases in all 2030 scenarios.

Interface Performance: 2030 SEMA-RI Import Flow Duration Curve



Scenarios 2030-1, 2030-2, 2030-3, and 2030-6 exhibits some congestion on the SEMA-RI Import interfaces.

Interface Performance: 2030 Congestion Statistics I

Table 21: 2030 Interface Congestion Statistics

	2030-1	2030-2	2030-3	2030-4	2030-5	2030-6
Orrington South % Time Congested	25.80	27.84	17.14	0.00	0.00	24.05
Surowiec South % Time Congested	4.17	21.83	12.00	0.00	0.00	16.30
North-South % Time Congested	0.15	1.13	0.48	0.00	0.00	0.54
SEMA-RI Import % Time Congested	3.45	2.92	9.91	2.65	3.07	1.63

To varying degrees, the Orrington-South, Surowiec-South, North-South, and SEMA-RI import interfaces exhibit some congestion Scenarios 2030-1, 2030-2, 2030-3, and 2030-6.

Interface Performance: 2030 Congestion Statistics II

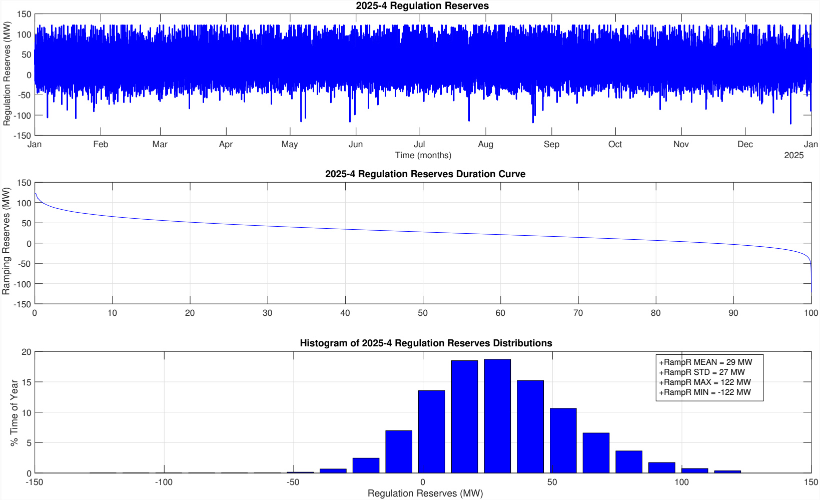
In the case of Orrington-South and Surowiec-South interfaces, this congestion is greater in magnitude to the congestion found in the 2025 Scenarios.

In the case of the North-South interface, this congestion is similar in magnitude to the congestion found in the 2025 Scenarios.

In the case of the SEMA-RI import, this congestion is significantly reduced in magnitude relative to the congestion found in the 2025 Scenarios. The other interfaces and tie-lines in their respective scenarios exhibited negligible or no congestion.

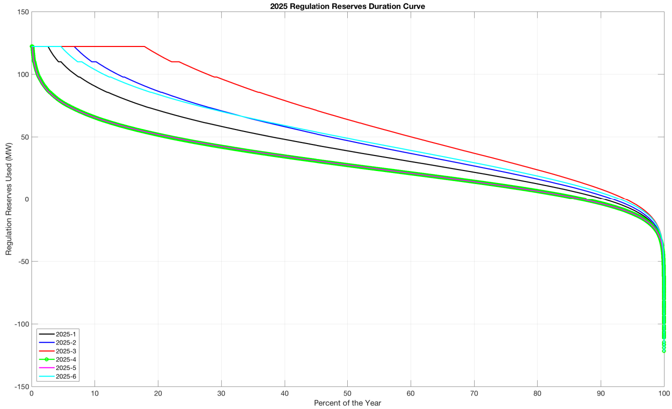
Simulated Regulation Performance

Regulation Performance: 2025-4 Regulation Profile



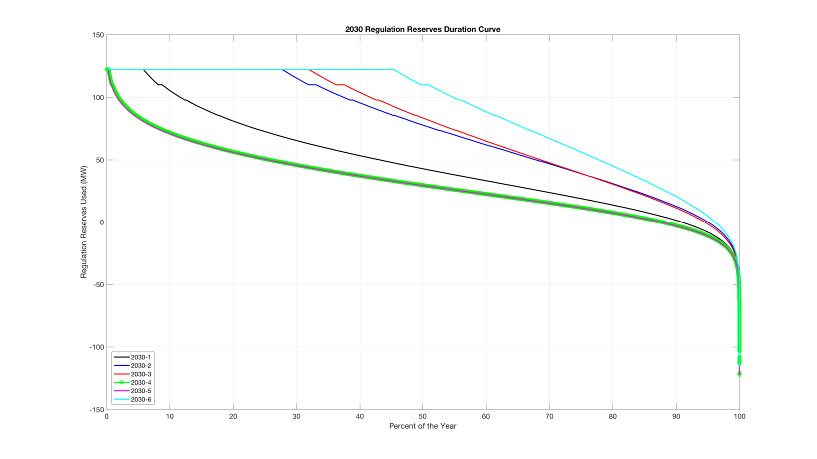
Scenario 2025-4 shows a balanced usage of regulation. Saturation does not appear to occur in any of three figures.

Regulation Performance: 2025 Regulation Duration Curves



Relative to Scenarios 2025-4 and 2025-5, Scenarios 2025-1, 2025-2, 2025-3, 2025-6 all show heavy saturation of regulation reserves.

Regulation Performance: 2030 Regulation Distributions



Relative to Scenarios 2030-4 and 2030-5, Scenarios 2030-1, 2030-2, 2030-3, 2030-6 all show heavy saturation of regulation reserves.

Regulation Performance: Time Exhausted & Mileage I

Table 22: Regulation Reserve Statistics

	2025-1	**2025-2**	**2025-3**	**2025-4**	**2025-5**	**2025-6**
% Time Reg. Res Exhausted	2.74	6.98	18.32	0.17	0.14	4.87
Reg. Res. Mileage (GWh)	389.53	461.72	582.15	283.49	283.73	462.53
	2030-1	**2030-2**	**2030-3**	**2030-4**	**2030-5**	**2030-6**
% Time Reg. Res Exhausted	6.07	28.15	33.03	0.37	0.43	46.20
Reg. Res. Mileage (GWh)	433.23	659.09	684.21	307.50	305.54	778.99

Regulation Performance: Time Exhausted & Mileage II

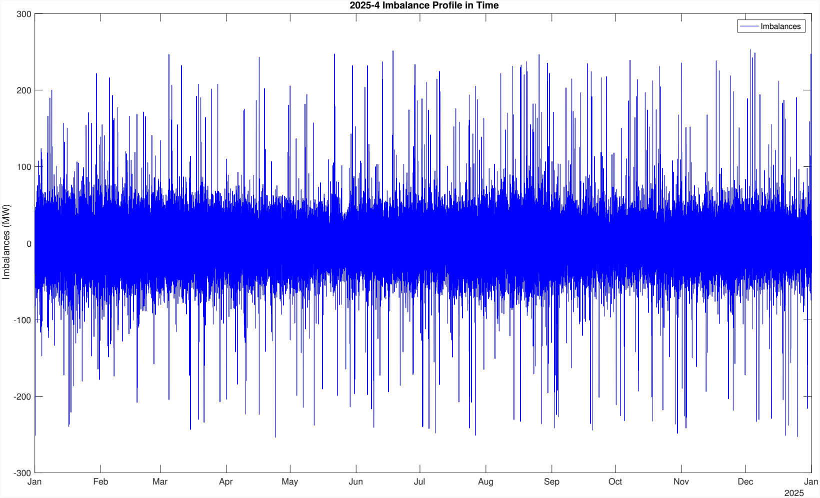
In both 2025 and 2030, and relative to Scenarios 4 and 5, Scenarios 1,2,3 and 6 exhibit greater regulation reserve mileage and percent time constrained.

In 2025, Scenarios 2025-3 and 2025-2 most heavily utilize regulation reserves.

In 2030, Scenarios 2030-2, 2030-6, and 2030-3 most heavily utilize regulation reserves.

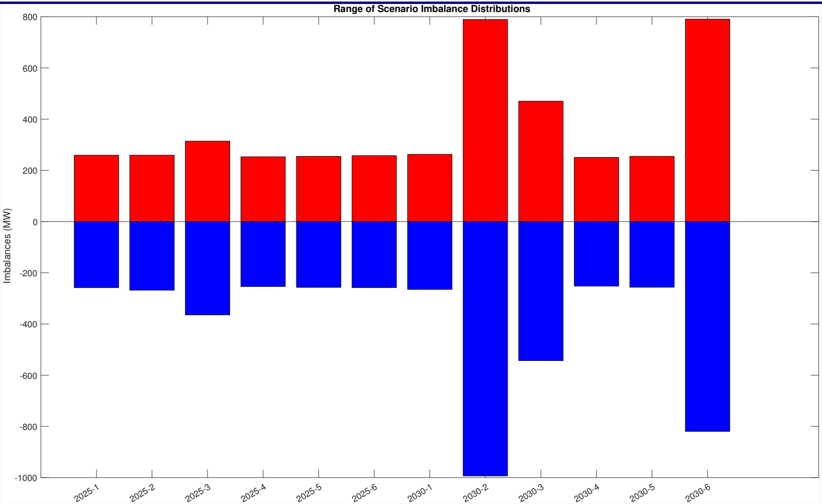
The Simulated Balancing Performance

Simulated Balancing Performance: 2025-4 Imbalance Profile



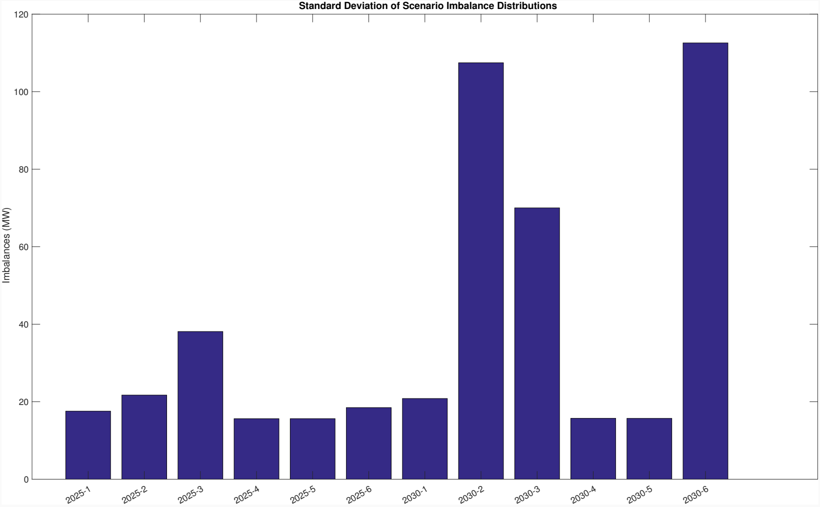
Imbalances are well-controlled to zero mean and moderate variability on the order of 75MW for the overwhelming majority of the year.

Simulated Balancing Performance: Range of Imbalances



Scenario 2030-3 and to a lesser extent 2030-2 and 2030-6 increase the range between the maximum and minimum value of imbalances as a measure of the intensity of improbable/extreme events.

Simulated Balancing Performance: Standard Deviation of Imbalances I



Simulated Balancing Performance: Standard Deviation of Imbalances II

All scenarios except 2025-3, 2030-2, 2030-3, and 2030-6 maintain imbalance variability of less than 100MW.

Scenarios 2030-2, 2030-3, and 2030-6 significantly increase the degree of imbalance variability relative to other scenarios.

Summary of Key Observations

Summary of Key Observations I

Taken together, the simulation of the study scenarios show:

1. Beyond the load following and ramping reserves provided by dispatchable resources, curtailment of semi-dispatchable resources becomes an integral part of balancing performance for the study scenarios.
2. Scenarios with greater penetrations of solar and wind generation exhibit systematically higher net load forecast errors. In the absence of immediate improvements in forecasting technology, these imbalances are mitigated by greater quantities of operating reserves.
3. The commitment of dispatchable resources and their associated quantities of committed load following and ramping reserves has a complex, difficult to predict, non-linear dependence on the amount of variable resources and the load profile statistics. High and low levels of variable resources do not necessarily correspond to high or low quantities of operating reserves respectively.

Summary of Key Observations II

4. Higher quantities of load following and ramping reserves dispatched in real-time improves balancing performance. Curtailment also directly supports the balancing role of load following and ramping reserves.
5. The combination of curtailment of semi-dispatchable resources and the commitment of dispatchable resources within each RSP zone serves to respect interface constraints.

Notes: I