GE
Energy Consulting

PJM Renewable Integration Study

Task 3 Part E

Sub-Hourly Analysis

Prepared for: PJM Interconnection, LLC.

Prepared by: General Electric International, Inc.

March 31, 2014

imagination at work

Legal Notices

Contact Information

This report was prepared by General Electric International, Inc. (GEII); acting through its Energy Consulting group (GE) based in Schenectady, NY, and submitted to PJM Interconnection, LLC. (PJM). Technical and commercial questions and any correspondence concerning this document should be referred to:

Gene Hinkle
Manager, Investment Analysis
GE Energy Management
Energy Consulting
1 River Road
Building 53
Schenectady, NY 12345 USA
Phone: (518) 385 5447
Fax: (518) 385 5703
gene.hinkle@ge.com

Table of Contents

LEGAL NOTICES II

CONTACT INFORMATION III

1 SELECTION OF CHALLENGING DAYS 12

1.1 CRITERIA USED FOR SELECTION OF CHALLENGING DAYS 12

2 SUB-HOURLY ANALYSIS 22

2.1 INTRODUCTION TO SUB-HOURLY PROBE SIMULATION 22

2.2 APPROACH & METHODOLOGY 23

2.3 SUMMARY OF DEFINITIONS AND TERMS 25

2.4 SELECTION OF CHALLENGING DAYS FOR SUB-HOURLY SIMULATIONS 26

2.5 SUB-HOURLY SIMULATION RESULTS AND DISCUSSION 29

2.5.1 Summary of Results: 2% BAU Scenario 29

2.5.2 Summary of Results: 14% RPS Scenario 37

2.5.3 Summary of Results: 20% HSBO Scenario 45

2.5.4 Summary of Results: 20% HOBO Scenario 50

2.5.5 Summary of Results: 20% LOBO Scenario 57

2.5.6 Summary of Results: 20% LODO Scenario 65

2.5.7 Summary of Results: 30% HSBO Scenario 73

2.5.8 Summary of Results: 30% HOBO Scenario 80

2.5.9 Summary of Results: 30% LOBO Scenario 86

2.5.10 Summary of Results: 30% LODO Scenario 95

2.5.11 Comparing One Day across Multiple Scenarios 101

2.6 OBSERVATIONS AND CONCLUSIONS FROM SUB-HOURLY ANALYSIS 105

List of Figures

Figure 2-1: GE MAPS-to-PROBE Simulation Process 24
Figure 2-2: On-line Capacity vs. MW Dispatched for Steam + Combined Cycle (2% BAU, July 15) 30
Figure 2-3: Number of Ramp-constrained Units per 10-minute Interval (2% BAU, July 15) 30
Figure 2-4: Reserve Violation and Price (2% BAU, July 27) 31
Figure 2-5: Reserve Violation and Price (2% BAU, July 28) 33
Figure 2-6: On-line Capacity vs. MW Dispatched for Steam + Combined Cycle (2% BAU, July 28) 34
Figure 2-7: Number of CTs Committed (2% BAU, July 28) 35
Figure 2-8: Number of Ramp-constrained Units per 10-minute Interval (2% BAU, July 28) 36
Figure 2-9: Generation by Type for Each Interval (14% RPS, February 12) 38
Figure 2-10: Number of Ramp-constrained Units per 10-minute Interval (14% RPS, February 12) 39
Figure 2-11: Number of Ramp-constrained Units per 10-minute Interval (14% RPS, March 2) 40
Figure 2-12: Wind Output vs. Demand (14% RPS, March 2) 41
Figure 2-13: Wind Generation Output (14% RPS, May 26) 42
Figure 2-14: Number of Ramp-constrained Units per 10-minute Interval (14% RPS, May 26) 43
Figure 2-15: Headroom - MW Available from Thermal Generation (14% RPS, August 3) 44
Figure 2-16: Generation by Type for Each Interval (14% RPS, August 3) 45
Figure 2-17: Wind Output and Demand (20% HSBO, March 4) 47
Figure 2-18: Number of Ramp-constrained Units per 10-minute Interval (20% HSBO, March 4) 47
Figure 2-19: Demand and LMP (20% HSBO, March 4) 48
Figure 2-20: CT Dispatch by Interval (20% HSBO, July 28) 49
Figure 2-21: Renewable Generation Dispatch for Each Interval (20% HSBO, September 1) 50
Figure 2-22: Number of Ramp-constrained Units per 10-minute Interval (20% HOBO, January 8) 52
Figure 2-23: Wind Dispatch for Each Interval (20% HOBO, May 26) 53
Figure 2-24: Number of Ramp-constrained Units per 10-minute Interval (20% HOBO, May 26) 54
Figure 2-25: Renewable Generation Dispatch for Each Interval 55
Figure 2-26: Load-net-Renewable and CT Dispatch (20% HOBO, July 17) 56
Figure 2-27: Wind Output and Demand (20% LOBO, February 17) 58
Figure 2-28: Headroom - MW Available from Thermal Generation (20% LOBO, February 17) 59
Figure 2-29: CT MW Dispatched (20% LOBO, February 17) 60
Figure 2-30: Headroom - MW Available from Thermal Generation (20% LOBO, March 20) 61
Figure 2-31: Load-net-Renewable and CT Dispatch (20% LOBO, July 17) 63
Figure 2-32: Wind vs. CT Dispatch for Each Interval 64
Figure 2-33: Number of Ramp-constrained Units per 10-minute Interval (20% LODO, March 4) 66
Figure 2-34: Comparison of CT Dispatch for LOBO vs. LODO, May 26 68
Figure 2-35: Renewable Generation Dispatch for Each Interval (20% LODO, June 18) 69
Figure 2-36: Renewable Generation Dispatch for Each Interval (20% LODO, July 17) 70
Figure 2-37: Load-net-Renewable and CT Dispatch (20% LODO, July 17) 71
Figure 2-38: Headroom - MW Available from Thermal Generation (20% LODO, July 17) 72
Figure 2-39: LMP Across Scenarios for July 17 72
Figure 2-40: Demand MW, Solar Dispatch, and Generator Ramp Limitations (20% HSBO, January 5) 74
Figure 2-41: Demand MW, Solar Generation, and Number of CTs Committed in RT (30% HSBO, February 17) 75
Figure 2-42: Renewable Generation Dispatch for Each Interval (30% HSBO, April 12) 77
Figure 2-43: Number of Ramp-constrained Units per 10-minute Interval (30% HSBO, April 12) 77
Figure 2-44: Combined Cycle and CT Dispatch (30% HSBO, April 12) 78
Figure 2-45: Load-net-Renewable with Fuel Generation Dispatch Response (30% HSBO, April 12) 78

Figure 2-46: CT Dispatch vs. Renewable Generation Dispatch (30% HSBO, June 18) 80
Figure 2-47: Thermal Generation MW Offered vs. Dispatched, On-line Units Only (30% HOBO, January 12) 82
Figure 2-48: Number of Ramp-constrained Units per 10-minute Interval (30% HOBO, March 4) 83
Figure 2-49: Renewable Generation Dispatch for Each Interval (30% HOBO, September 21) 84
Figure 2-50: Number of Ramp-constrained Units per 10-minute Interval (30% HOBO, September 21) 85
Figure 2-51: Renewable Generation Dispatch for Each Interval (30% LOBO, January 5) 87
Figure 2-52: Number of Steam Generators On-line During Each Interval (30% LOBO, January 5) 88
Figure 2-53: Demand MW, Renewable Dispatch, and # of CTs Committed in RT (30% LOBO, February 17) 89
Figure 2-54: Renewable Generation Dispatch for Each Interval (30% LOBO, March 11) 91
Figure 2-55: Renewable Generation Dispatch for Each Interval (30% LOBO, March 28) 92
Figure 2-56: CT Dispatch for Each Interval (30% LOBO, March 28) 93
Figure 2-57: CT Dispatch for Each Interval (30% LOBO, December 22) 95
Figure 2-58: Renewable vs. CT Dispatch for Each Interval (30% LODO, March 28) 97
Figure 2-59: Comparison of CT Dispatch LOBO vs. LODO, March 28 98
Figure 2-60: Number of Transmission Constraints for Each Interval LOBO vs. LODO, March 28 99
Figure 2-61: LMP Comparison for March 28 100
Figure 2-62: Number of Ramp-constrained Units per 10-minute Interval (30% LODO, June 18) 101
Figure 2-63: LMP Comparison across June 18 Scenarios 102
Figure 2-64: LMP Comparison for Several 20% and 30% Scenarios (March 4) 104
Figure 2-65: LMP Comparison across February 17 Scenarios 105

List of Tables

Table 1-1: Challenging Days for 14% RPS Scenario 13
Table 1-2: Challenging Days for 20% HOBO Scenario 14
Table 1-3: Challenging Days for 20% HSBO Scenario 15
Table 1-4: Challenging Days for 20% LODO Scenario 16
Table 1-5: Challenging Days for 20% LOBO Scenario 17
Table 1-6: Challenging Days for 30% HOBO Scenario 18
Table 1-7: Challenging Days for 30% HSBO Scenario 19
Table 1-8: Challenging Days for 30% LODO Scenario 20
Table 1-9: Challenging Days for 30% LOBO Scenario 21
Table 2-1: Challenging Day Selections for Study Scenarios 28
Table 2-2: PROBE Analysis Results Summary for 2% BAU Challenging Days 29
Table 2-3: PROBE Analysis Results Summary for 14% RPS Challenging Days 37
Table 2-4: PROBE Analysis Results Summary for 20% HSBO Challenging Days 46
Table 2-5: PROBE Analysis Results Summary for 20% HOBO Challenging Days 51
Table 2-6: PROBE Analysis Results Summary for 20% LOBO Challenging Days 57
Table 2-7: PROBE Analysis Results Summary for 20% LODO Challenging Days 65
Table 2-8: PROBE Analysis Results Summary for 30% HSBO Challenging Days 73
Table 2-9: PROBE Analysis Results Summary for 30% HOBO Challenging Days 81
Table 2-10: PROBE Analysis Results Summary for 30% LOBO Challenging Days 86
Table 2-11: PROBE Analysis Results Summary for 30% LODO Challenging Days 95
Table 2-12: Comparison of June 18 Challenging Days across Four Scenarios 102
Table 2-13: Comparison of Probe analysis for March 4th 103
Table 2-14: Comparison of Probe analysis for February 17 104

Acronyms and Nomenclatures

2% BAU	2% Renewable Penetration – Business-As-Usual Scenario
14% RPS	14% Renewable Penetration – RPS Scenario
20% LOBO	20% Renewable Penetration – Low Offshore Best Onshore Scenario
20% LODO	20% Renewable Penetration – Low Offshore Dispersed Onshore Scenario
20% HOBO	20% Renewable Penetration – High Offshore Best Onshore Scenario
20% HSBO	20% Renewable Penetration – High Solar Best Onshore Scenario
30% LOBO	30% Renewable Penetration – Low Offshore Best Onshore Scenario
30% LODO	30% Renewable Penetration – Low Offshore Dispersed Onshore Scenario
30% HOBO	30% Renewable Penetration – High Offshore Best Onshore Scenario
30% HSBO	30% Renewable Penetration – High Solar Best Onshore Scenario
AEPS	Alternative Energy Portfolio Standard
AGC	Automatic Generation Control
AWS/AWST	AWS Truepower
Bbl.	Barrel
BAA	Balancing Area Authority
BAU	Business as Usual
BTU	British Thermal Unit
CA	Intertek AIM's Cycling⬍Advisor ™ tool
CAISO	California Independent System Operator
CC/CCGT	Combined Cycle Gas Turbine
CEMS	Continuous Emissions Monitoring Systems
CF	Capacity Factor
CO2	Carbon Dioxide
CV	Capacity Value
DA	Day-Ahead
DR	Demand Response
DSM	Demand Side Management
EI	Eastern Interconnection

EIPC	Eastern Interconnection Planning Collaborative
ELCC	Effective Load Carrying Capability
ERCOT	Electricity Reliability Council of Texas
EST	Eastern Standard Time
EUE	Expected Un-served Energy
EWITS	Eastern Wind Integration and Transmission Study
FERC	Federal Energy Regulatory Commission
FLHR	Full Load Heat Rate
FSA	PJM Facilities Study Agreement
GE	General Electric International, Inc. / GE Energy Consulting
GE MAPS	GE's "Multi Area Production Simulation" model
GE MARS	GE's "Multi Area Reliability Simulation" model
GT	Gas Turbine
GW	Gigawatt
GWh	Gigawatt Hour
HA	Hour Ahead
HSBO	High Solar Best Onshore Scenarios
HOBO	High Offshore Best Onshore Scenarios
HR	Heat Rate
HVAC	Heating, Ventilation, and Air Conditioning
IPP	Independent Power Producers
IRP	Integrated Resource Planning
ISA	PJM Interconnection Service Agreement
ISO-NE	Independent System Operator of New England
kV	kilovolt
kW	kilowatt
kWh	kilowatt-hour
lbs	Pounds (British Imperial Mass Unit)
LDC	Load Duration Curve

LM	Intertek AIM's Loads Model ™ tool
LMP	Locational Marginal Prices
LNR	Load Net of Renewable Energy
LOBO	Low Offshore Best Onshore Scenarios
LODO	Low Offshore Dispersed Onshore Scenarios
LOLE	Loss of Load Expectation
MAE	Mean-Absolute Error
MAPP	Mid-Atlantic Power Pathway
MMBtu	Millions of BTU
MVA	Megavolt Ampere
MW	Megawatts
MWh	Megawatt Hour
NERC	North American Electric Reliability Corporation
NOx	Nitrogen Oxides
NREL	National Renewable Energy Laboratory
NWP	"Numerical Weather Prediction" model
O&M	Operational & Maintenance
PATH	Potomac Appalachian Transmission Highline
PJM	PJM Interconnection, LLC.
PPA	Power Purchase Agreement
PRIS	PJM Renewable Integration Study
PRISM	Probabilistic Reliability Index Study Model
PROBE	"Portfolio Ownership & Bid Evaluation Model" of PowerGEM
PSH	Pumped Storage Hydro
PV	Photovoltaic
REC	Renewable Energy Credit
Rest of EI	Rest of Eastern Interconnection
RPS	Renewable Portfolio Standard
RT	Real Time

RTEP	Regional Transmission Expansion Plan
SC/SCGT	Simple Cycle Gas Turbine
SCUC/EC	Security Constrained Unit Commitment / Economic Dispatch
SOx	Sulfur Oxides
ST	Steam Turbine
TARA	"Transmission Adequacy and Reliability Assessment" software of PowerGEM
UCT	Coordinated Universal Time
VOC	Variable Operating Cost
WI	Western Interconnection

1 Selection of Challenging Days

1.1 Criteria Used for Selection of Challenging Days

The following criteria were used to select challenging days for detailed analysis of sub-hourly operation in the Real-Time market.

- Largest 10-minute ramp in net load (LNR)
- Largest daily range in LNR (maximum LNR – minimum LNR for the day)
- Largest 10-minute ramp up or down deviations relative to the ramp capability of committed units
- High volatility day, with largest number of 10-minute periods where the change in net load (LNR) exceeded the range capability of committed units

The following pages of this appendix show the results of the screening process for each study scenario. Tables show the top ranked days for each of the four selection criteria. The bullet lists indicate which days were selected for detailed analysis with sub-hourly simulations of operation and market performance.

Table 1-1: Challenging Days for 14% RPS Scenario

- 2/17/2026
- 3/2/2026
- 8/3/2026
- 5/26/2026 (Day with difference between LNR peak and min, LNR period to period change, and number of ramps that exceed committed resource capability)
- 2/12/2026 (Day with LNR period to period change and day with ramps that exceed committed resource capability)

Top 10 Day's with largest difference between LNR peak and min		
Rank	Date	MW
1	7/27/2026	79,440
2	7/15/2026	79,104
3	5/26/2026	78,706
4	7/28/2026	77,461
5	7/13/2026	76,637
6	6/18/2026	75,380
7	8/3/2026	74,018
8	7/6/2026	73,156
9	7/14/2026	72,819
10	7/23/2026	72,518

Top 10 Day's with largest LNR Period to Period change		
Rank	Date	MW
1	2/17/2026	9,650
2	3/4/2026	9,651
3	2/12/2026	9,652
4	2/11/2026	9,653
5	1/8/2026	9,654
6	1/20/2026	9,655
7	2/19/2026	9,656
8	1/6/2026	9,657
9	3/5/2026	9,658
10	3/3/2026	9,659

Top 10-Days with largest number of ramps that exceed commited resource capability				
Rank	Date	Number	Max 10-min Ramp	MW Exceeded
1	3/2/2026	2	8,051	1
2	1/26/2026	2	8,614	2,858
3	2/5/2026	2	8,471	2,447
4	2/3/2026	2	8,664	2,299
5	2/12/2026	2	9,289	1,923
6	1/19/2026	2	7,787	1,188
7	3/19/2026	2	8,080	560
8	3/20/2026	2	6,656	2,205
9	1/2/2026	1	8,472	2,057
10	1/13/2026	1	7,903	1,251

Top 10 Days with number of periods exceeding committed resource head room				
Rank	Date	Number	Max 10-min Range	MW Exceeded
1	8/3/2026	9	5,808	3,151
2	4/20/2026	9	-4,603	2,048
3	7/17/2026	8	11,064	5,966
4	11/16/2026	8	-6,022	2,249
5	9/2/2026	8	-5,488	1,980
6	5/26/2026	7	-6,185	3,576
7	7/12/2026	7	-6,228	3,390
8	7/15/2026	7	-5,392	1,771
9	4/27/2026	7	-3,933	1,372
10	4/23/2026	7	-5,046	1,253

Table 1-2: Challenging Days for 20% HOBO Scenario

- 5/26/2026
- 3/4/2026
- 3/9/2026 (Day with large number of periods exceeding committed resource ramp capability and large number of periods exceeding committed resource range capability)
- 7/17/2026
- 7/27/2026 (Day with large difference between LNR peak and min and day with large number of periods exceeding committed resource range capability)
- 1/8/2026 (Day with large period to period ramp and large number of periods exceeding committed resource ramp capability)

Top 10 Day's with largest difference between LNR peak and min		
Rank	Date	MW
1	5/26/2026	75,229
2	7/27/2026	73,002
3	7/15/2026	72,971
4	7/28/2026	72,915
5	7/13/2026	71,653
6	7/29/2026	68,687
7	7/20/2026	67,683
8	8/5/2026	67,373
9	7/12/2026	66,754
10	7/22/2026	66,003

Top 10 Day's with largest LNR period to period change		
Rank	Date	MW
1	3/4/2026	9,677
2	2/17/2026	9,479
3	2/12/2026	9,258
4	2/11/2026	9,209
5	1/20/2026	9,090
6	1/23/2026	8,978
7	1/8/2026	8,964
8	3/5/2026	8,871
9	1/6/2026	8,868
10	2/19/2026	8,739

Top 10-Days with largest number of ramps that exceed committed resource capability				
Rank	Date	Number	Max 10-min Ramp	MW Exceeded
1	3/9/2026	5	7,125	1,049
2	12/27/2026	1	18,064	2,912
3	3/3/2026	1	8,664	22
4	3/10/2026	1	6,977	1,220
5	4/12/2026	1	2,488	152
6	1/6/2026	0	8,964	0
7	1/8/2026	0	8,868	0
8	1/5/2026	0	8,551	0
9	1/2/2026	0	8,482	0
10	1/15/2026	0	8,288	0

Top 10 Days with number of periods exceeding committed resource head room				
Rank	Date	Number	Max 10-min Range	MW Exceeded
1	7/17/2026	4	10,151	2,925
2	7/28/2026	3	8,531	700
3	8/3/2026	2	7,699	1,835
4	7/29/2026	2	7,180	2,357
5	7/30/2026	2	7,093	3,912
6	7/27/2026	2	6,821	1,784
7	7/15/2026	2	5,467	984
8	8/4/2026	2	5,205	1,340
9	3/9/2026	2	4,572	1,122
10	10/26/2026	2	3,351	164

Table 1-3: Challenging Days for 20% HSBO Scenario

- 7/28/2026
- 3/4/2026
- 9/1/2026 (Day with large number of periods exceeding committed resource ramp capability and day with large number of periods exceeding committed resource range capability)

Top 10 Day's with largest difference between LNR peak and min		
Rank	Date	MW
1	7/28/2026	46,231
2	5/26/2026	46,168
3	7/27/2026	46,230
4	7/13/2026	46,216
5	7/29/2026	46,232
6	6/18/2026	46,191
7	7/12/2026	46,215
8	7/15/2026	46,218
9	8/13/2026	46,247
10	8/3/2026	46,237

Top 10 Day's with largest LNR period to period change		
Rank	Date	MW
1	3/4/2026	9,696
2	2/17/2026	9,696
3	2/12/2026	9,362
4	2/11/2026	9,200
5	1/20/2026	9,158
6	1/8/2026	9,131
7	3/5/2026	9,131
8	2/19/2026	9,048
9	1/6/2026	8,904
10	9/25/2026	8,891

Top 10-Days with largest number of ramps that exceed committed resource capability				
Rank	Date	Number	Max 10-min Ramp	MW Exceeded
1	9/1/2026	3	2,678	1,726
2	3/2/2026	2	8,083	3,152
3	1/13/2026	1	7,961	651
4	1/23/2026	1	8,667	364
5	1/26/2026	1	8,755	1,952
6	2/2/2026	1	8,356	934
7	2/5/2026	1	8,534	1,320
8	2/9/2026	1	7,441	908
9	3/3/2026	1	8,768	423
10	3/10/2026	1	6,907	112

Top 10 Days with number of periods exceeding committed resource head room				
Rank	Date	Number	Max 10-min Range	MW Exceeded
1	9/1/2026	8	5,205	2,138
2	7/17/2026	7	9,214	5,281
3	8/5/2026	6	9,336	2,556
4	3/19/2026	5	5,341	1,061
5	7/14/2026	5	7,125	2,766
6	8/18/2026	5	6,678	2,167
7	8/19/2026	5	6,943	4,612
8	3/18/2026	4	5,618	2,771
9	4/22/2026	4	5,014	1,383
10	4/23/2026	4	5,158	1,548

Table 1-4: Challenging Days for 20% LODO Scenario

- 6/18/2026
- 3/4/2026
- 3/20/2026
- 7/17/2026
- 5/26/2026 (Day with large difference between LNR peak and min, and day with large number of periods exceeding committed resource range capability)
- 9/1/2026 (Day with large number of periods exceeding committed resource ramp capability and day with large number of periods exceeding committed resource range capability)

Top 10 Day's with largest difference between LNR peak and min		
Rank	Date	MW
1	6/18/2026	76,298
2	5/26/2026	75,606
3	7/15/2026	75,078
4	7/27/2026	74,372
5	7/28/2026	73,546
6	7/14/2026	72,876
7	8/3/2026	72,757
8	7/6/2026	72,124
9	7/23/2026	72,042
10	7/13/2026	69,619

Top 10 Day's with largest LNR period to period change		
Rank	Date	MW
1	3/4/2026	9,930
2	2/17/2026	9,827
3	1/8/2026	9,365
4	2/11/2026	9,343
5	2/12/2026	9,282
6	3/5/2026	9,167
7	1/20/2026	9,163
8	2/19/2026	9,097
9	1/23/2026	8,983
10	1/26/2026	8,936

Top 10-Days with largest number of ramps that exceed committed resource capability				
Rank	Date	Number	Max 10-min Ramp	MW Exceeded
1	3/20/2026	3	6,719	2,091
2	2/3/2026	2	8,806	436
3	2/5/2026	2	8,459	1,095
4	3/2/2026	2	8,133	2,780
5	2/6/2026	2	8,132	1,205
6	3/10/2026	2	6,814	1,000
7	9/1/2026	2	2,726	845
8	3/19/2026	1	25,211	10,584
9	2/4/2026	1	8,936	3,083
10	2/27/2026	1	8,789	1,697

Top 10 Days with number of periods exceeding committed resource head room				
Rank	Date	Number	Max 10-min Range	MW Exceeded
1	7/17/2026	9	10,396	7,015
2	7/28/2026	7	8,422	3,383
3	9/1/2026	6	5,241	908
4	8/5/2026	5	9,559	2,748
5	8/3/2026	4	9,559	2,795
6	5/26/2026	4	7,115	1,330
7	7/27/2026	4	6,530	3,064
8	9/2/2026	4	6,143	3,908
9	12/31/2026	4	5,892	1,161
10	9/3/2026	4	5,864	2,620

Table 1-5: Challenging Days for 20% LOBO Scenario

- 7/15/2026
- 2/17/2026 (Day with large period to period ramp and day with large number of periods exceeding committed resource ramp capability)
- 3/20/2026
- 7/17/2026
- 5/26/2026 (Day with large difference between LNR peak and min, and day with large number of periods exceeding committed resource range capability)
- 9/1/2026 (Day with large number of periods exceeding committed resource ramp capability and day with large number of periods exceeding committed resource range capability)

Top 10 Day's with largest difference between LNR peak and min		
Rank	Date	MW
1	7/15/2026	77,790
2	6/18/2026	76,205
3	5/26/2026	75,717
4	7/27/2026	74,991
5	7/28/2026	74,835
6	7/6/2026	73,364
7	7/23/2026	73,335
8	8/3/2026	71,786
9	7/13/2026	70,192
10	7/21/2026	69,856

Top 10 Day's with largest LNR period to period change		
Rank	Date	MW
1	2/17/2026	10,050
2	3/4/2026	9,927
3	2/12/2026	9,525
4	2/11/2026	9,457
5	2/19/2026	9,301
6	1/8/2026	9,267
7	1/20/2026	9,226
8	3/5/2026	9,173
9	1/26/2026	8,931
10	2/27/2026	8,857

Top 10- Days with largest number of ramps that exceed committed resource capability				
Rank	Date	Number	Max 10-min Ramp	MW Exceeded
1	3/20/2026	3	6,669	794
2	2/5/2026	2	8,591	2,219
3	3/2/2026	2	8,087	2,731
4	3/10/2026	2	6,932	1,447
5	9/1/2026	2	2,774	733
6	2/3/2026	1	10,050	165
7	1/26/2026	1	8,931	1,998
8	2/27/2026	1	8,857	927
9	2/17/2026	1	8,646	293
10	1/23/2026	1	8,643	368

Top 10 Days with number of periods exceeding committed resource head room				
Rank	Date	Number	Max 10-min Range	MW Exceeded
1	7/17/2026	8	10,449	7,345
2	7/28/2026	6	8,280	3,388
3	9/1/2026	6	5,244	754
4	8/3/2026	5	5,965	3,049
5	5/26/2026	4	9,387	2,133
6	9/21/2026	4	9,387	2,210
7	7/27/2026	4	7,053	3,579
8	8/4/2026	4	6,353	2,236
9	8/5/2026	4	5,675	391
10	3/19/2026	4	4,975	1,073

Table 1-6: Challenging Days for 30% HOBO Scenario

- 1/12/2026
- 3/4/2026
- 11/16/2026 (Day with largest number of ramps exceeding resource capability and largest number of periods exceeding committed resource head room)
- 9/21/2026 (Day with largest number of periods exceeding committed resource head room and largest number of ramps exceeding resource capability)
- 11/13/2026 (Day with largest difference between LNR peak and min and day with large number of periods exceeding committed resource head room)

Top 10 Day's with largest difference between LNR peak and min		
Rank	Date	MW
1	1/12/2026	80,187
2	7/29/2026	75,240
3	5/26/2026	74,185
4	1/26/2026	72,784
5	7/27/2026	69,695
6	11/13/2026	69,479
7	7/15/2026	69,105
8	7/13/2026	68,342
9	1/5/2026	68,321
10	7/12/2026	68,311

Top 10 Day's with largest LNR period to period change		
Rank	Date	MW
1	3/4/2026	10,213
2	2/17/2026	9,646
3	2/11/2026	9,608
4	2/12/2026	9,515
5	9/25/2026	9,277
6	3/5/2026	9,238
7	1/8/2026	9,196
8	1/20/2026	9,140
9	1/23/2026	9,002
10	2/19/2026	8,921

Top 10-Days with largest number of ramps that exceed commited resource capability				
Rank	Date	Number	Max 10-min Ramp	MW Exceeded
1	11/16/2026	14	4,020	2,191
2	4/6/2026	12	2,784	1,760
3	9/21/2026	11	3,959	1,781
4	11/18/2026	10	3,034	1,211
5	2/3/2026	7	8,842	7,712
6	3/2/2026	7	8,176	7,457
7	5/1/2026	7	3,047	1,031
8	4/20/2026	7	2,790	1,387
9	3/18/2026	6	7,005	943
10	2/14/2026	6	6,571	1,883

Top 10 Days with number of periods exceeding committed resource head room				
Rank	Date	Number	Max 10-min Range	MW Exceeded
1	9/21/2026	12	6,889	2,982
2	11/13/2026	12	5,921	3,632
3	2/3/2026	11	6,355	2,812
4	8/3/2026	9	8,054	6,297
5	11/16/2026	9	6,902	5,150
6	8/4/2026	8	9,666	3,201
7	10/28/2026	8	6,621	3,291
8	3/19/2026	8	5,061	3,157
9	6/1/2026	8	4,970	3,949
10	8/5/2026	7	9,666	3,500

Table 1-7: Challenging Days for 30% HSBO Scenario

- 6/18/2026
- 2/17/2026
- 4/12/2026
- 4/26/2026
- 1/5/2026 (Day with largest difference between LNR peak and day with largest LNR period to period change)

Top 10 Day's with largest difference between LNR peak and min		
Rank	Date	MW
1	6/18/2026	74,680
2	2/20/2026	72,783
3	5/26/2026	72,007
4	7/28/2026	71,885
5	1/12/2026	71,310
6	7/29/2026	71,225
7	7/24/2026	70,335
8	7/27/2026	70,042
9	1/5/2026	69,816
10	8/21/2026	69,574

Top 10 Day's with largest LNR period to period change		
Rank	Date	MW
1	2/17/2026	10,574
2	3/4/2026	10,372
3	3/5/2026	10,353
4	9/25/2026	10,343
5	2/11/2026	9,983
6	2/12/2026	9,785
7	2/19/2026	9,499
8	1/8/2026	9,316
9	1/20/2026	9,269
10	1/5/2026	9,072

Top 10-Days with largest number of ramps that exceed commited resource capability				
Rank	Date	Number	Max 10-min Ramp	MW Exceeded
1	4/12/2026	4	3,379	701
2	9/1/2026	3	2,758	1,903
3	1/26/2026	2	9,016	2,085
4	3/2/2026	2	8,013	3,172
5	3/10/2026	2	7,062	2,476
6	6/25/2026	2	2,567	451
7	6/26/2026	2	2,810	540
8	1/2/2026	1	8,857	796
9	1/13/2026	1	8,396	2,290
10	1/29/2026	1	8,361	1,019

Top 10 Days with number of periods exceeding committed resource head room				
Rank	Date	Number	Max 10-min Range	MW Exceeded
1	4/26/2026	71	38,816	37,380
2	4/25/2026	65	45,162	39,406
3	4/19/2026	62	37,604	30,348
4	5/16/2026	62	43,670	27,994
5	5/17/2026	62	45,941	35,626
6	3/29/2026	60	43,326	39,978
7	6/6/2026	60	43,978	26,956
8	5/20/2026	59	49,033	35,790
9	4/14/2026	58	46,905	32,192
10	4/5/2026	58	46,123	39,233

Table 1-8: Challenging Days for 30% LODO Scenario

- 6/18/2026
- 3/4/2026
- 3/9/2026 (Day with largest number of ramps exceeding resource capability and largest number of periods exceeding committed resource head room)
- 3/28/2026 (Day with largest number of periods exceeding committed resource head room and largest number of ramps exceeding resource capability)

Top 10 Day's with largest difference between LNR peak and min		
Rank	Date	MW
1	6/18/2026	77,707
2	7/14/2026	76,519
3	1/5/2026	76,228
4	7/6/2026	74,325
5	1/12/2026	74,021
6	7/24/2026	74,013
7	5/26/2026	73,697
8	8/11/2026	73,512
9	7/28/2026	72,003
10	7/15/2026	71,885

Top 10 Day's with largest LNR period to period change		
Rank	Date	MW
1	3/4/2026	10,258
2	2/17/2026	10,144
3	2/11/2026	9,865
4	1/8/2026	9,757
5	9/25/2026	9,520
6	2/12/2026	9,477
7	2/19/2026	9,439
8	3/5/2026	9,395
9	1/26/2026	9,346
10	2/27/2026	9,125

Top 10-Days with largest number of ramps that exceed commited resource capability				
Rank	Date	Number	Max 10-min Ramp	MW Exceeded
1	3/9/2026	13	7,660	3,128
2	4/12/2026	11	2,761	1,182
3	1/14/2026	10	8,091	2,195
4	12/22/2026	10	2,569	362
5	3/10/2026	9	6,882	2,819
6	4/3/2026	8	2,505	511
7	3/28/2026	7	5,298	1,043
8	2/13/2026	6	7,250	1,893
9	12/29/2026	6	2,569	403
10	3/11/2026	5	8,890	1,904

Top 10 Days with number of periods exceeding committed resource head room				
Rank	Date	Number	Max 10-min Range	MW Exceeded
1	3/28/2026	12	5,066	2,544
2	4/27/2026	10	5,231	3,110
3	3/11/2026	8	6,500	4,101
4	4/4/2026	8	5,899	2,437
5	9/1/2026	8	5,203	2,067
6	7/17/2026	7	9,723	3,798
7	3/9/2026	7	5,656	2,970
8	1/18/2026	7	4,662	1,342
9	4/1/2026	6	7,797	2,455
10	12/15/2026	6	7,250	2,569

Table 1-9: Challenging Days for 30% LOBO Scenario

- 6/18/2026
- 2/17/2026
- 12/22/2026
- 3/28/2026
- 1/5/2026 (This day common to all selection criteria)
- 3/11/2026 (This day common to all but day with largest difference between LNR peak and min)

Top 10 Day's with largest difference between LNR peak and min		
Rank	Date	MW
1	6/18/2026	79,071
2	1/12/2026	78,407
3	7/15/2026	78,313
4	1/5/2026	76,990
5	7/6/2026	76,873
6	1/10/2026	74,541
7	7/14/2026	74,356
8	7/24/2026	74,178
9	8/21/2026	74,068
10	7/27/2026	73,852

Top 10 Day's with largest LNR period to period change		
Rank	Date	MW
1	2/17/2026	10,527
2	2/11/2026	10,338
3	9/25/2026	10,045
4	2/12/2026	9,792
5	1/8/2026	9,783
6	1/20/2026	9,558
7	1/5/2026	9,340
8	2/19/2026	9,329
9	3/11/2026	9,227
10	2/27/2026	9,078

Top 10-Days with largest number of ramps that exceed commited resource capability				
Rank	Date	Number	Max 10-min Ramp	MW Exceeded
1	12/22/2026	11	2,709	372
2	3/10/2026	8	7,077	2,785
3	1/5/2026	7	9,340	0
4	3/9/2026	6	7,594	2,871
5	12/29/2026	6	2,709	251
6	1/26/2026	4	9,227	3,128
7	3/11/2026	4	8,797	2,290
8	10/24/2026	4	3,371	72
9	10/26/2026	4	2,850	310
10	1/22/2026	2	8,320	2,524

Top 10 Days with number of periods exceeding committed resource head room				
Rank	Date	Number	Max 10-min Range	MW Exceeded
1	3/28/2026	8	4623.774	2169.1823
2	4/27/2026	8	4755.942	2234.5247
3	7/17/2026	8	9789.47	3213.3832
4	10/25/2026	8	7881.432	4636.7908
5	12/31/2026	8	7469.044	3637.5393
6	1/26/2026	7	6830.604	1458.6304
7	3/6/2026	7	7540.922	3134.365
8	1/5/2026	6	6874.377	657.32436
9	3/11/2026	6	6646.145	4779.026
10	12/15/2026	6	7491.954	3634.9119

2 Sub-Hourly Analysis

2.1 Introduction to Sub-Hourly PROBE Simulation

The impacts of various levels of renewable energy penetration in the PJM service territory have been studied via GE MAPS and other methodologies to illustrate long-term impacts of increased wind and solar resources on PJM grid operations. This section describes sub-hourly simulations to analyze potential short-term operational issues for each integration scenario.

Sub-hourly analysis was performed to augment the hourly production cost simulations, to check if committed resources and reserves could keep up with short-term changes in load and renewables in real-time operations. The analysis explored:

- Adequacy of reserves
- Commitment/dispatch of quick-start CTs to follow rapid changes in net load
- Ramping capability and performance of dispatchable units
- Impact of day-ahead forecast errors and forward-market commitments
- Potential for unserved load
- Ability of the system to respond to fast-moving events

The analysis was performed using PowerGEM's PROBE simulation software, which is presently used by PJM to monitor daily performance of the real-time market. The approach involves identifying several challenging days for each scenario; that is, days with rapid changes in renewable output or other situations that would present difficulties for real-time operations. If the system performs successfully during the challenging days, then other less-challenging days would have acceptable performance as well.

The nature of real-time markets, in general, limits the flexibility to respond to changing conditions, due to the limited set of resources available (i.e., impossible to commit large thermal units on short notice) and generator ramp limitations. Large changes in wind and solar generation will create more variability requiring traditional generation to respond. The sub-hourly analysis examines issues such as:

- ✓ Does economic dispatch of committed units keep up with sub-hourly changes in load and renewable energy output variability?
- ✓ How does CT commitment and dispatch change in response to increased renewable resource variability?
- ✓ Are reserves used to cover shortfalls? If so, how often and under what circumstances?

✓ What are the impacts on short-term markets?

This section describes the analysis methodology, the criteria for selecting "interesting days" for analysis, and the results of sub-hourly simulations of PJM grid operations for the study scenarios.

2.2 Approach & Methodology

The sub-hourly simulations are performed using PowerGEM's PROBE market simulation software. The PROBE software simulates day-ahead and real-time markets at various ISOs. It is used in daily market operations at PJM and as the tool for PJM's Perfect Dispatch initiative.

The inputs and outputs of the GE MAPS simulations for the study cases (2% BAU, 14% RPS, etc.) provide the basis for the sub-hourly simulations. Upon completion of the GE MAPS process, several interesting (or challenging) days were selected for each study scenario based on the criteria discussed later in this section. The simulations were performed, one market day at a time, for three to five interesting days for each of the study scenarios.

A process was developed to translate the GE MAPS data into PROBE formats to enable the sub-hourly simulations using GE MAPS inputs and outputs. This enables the sub-hourly simulations to use the same data and general assumptions as GE MAPS to achieve consistency between models; in other words, the 14% RPS scenario in PROBE uses the same network model, wind, generator profiles, and other data as the 14% RPS scenario in GE MAPS.

Despite a focus on ensuring consistency between MAPS and PROBE models, in some cases it was necessary to use different assumptions in PROBE to model the different rules of sub-hourly markets and to achieve the study objective. For example, additional detailed operating parameters are required in PROBE to most accurately model PJM's real-time markets. This was accomplished by supplementing the GE MAPS data with "real" generator data from PJM (with the advance permission of PJM) for items such as ramp rates and detailed start-up data.

The PROBE sub-hourly simulation also captures other essential rules and realities of real-time markets to ensure accuracy to short-term operations, such as restricting unit commitment to quick start generation only. Further, sub-hourly demand and renewable generation profiles are introduced to capture their intra-hour variability.

An overview of the GE MAPS-to-PROBE, or long-term to short-term, simulation process is illustrated in Figure 2-1:

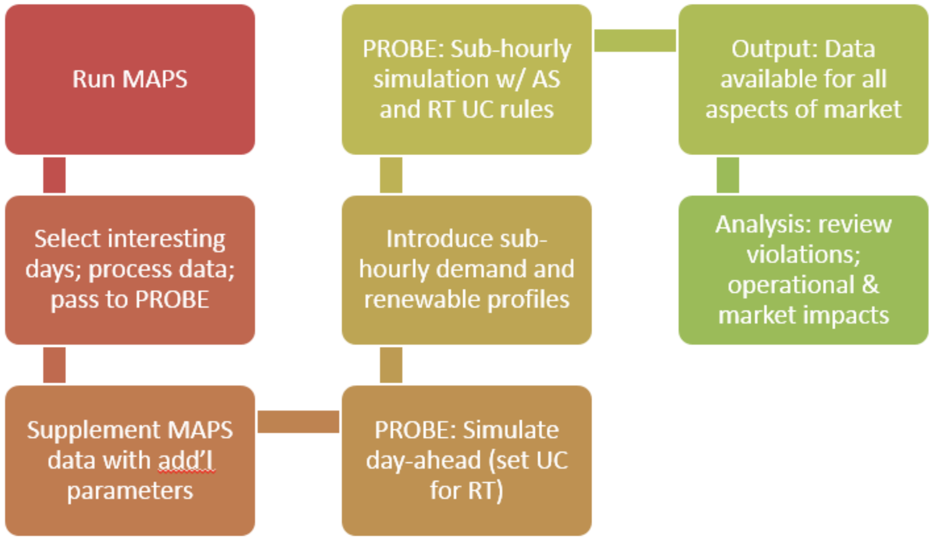

Figure 2-1: GE MAPS-to-PROBE Simulation Process

After data set-up, the PROBE simulation was completed by running each individual market day for each individual scenario separately. The software is capable of producing data on all aspects of the optimization, enabling detailed operational and market analysis.

Finally, analysis was completed for each market day individually. The process of analyzing results and challenging time periods began with identifying obvious concerns first and then drilling down to additional impacts, with the following list providing general analysis guidelines:

- ✓ Are there any instances where load cannot be served?
- ✓ Does economic dispatch of committed units keep up with sub-hourly changes in load?
- ✓ How often are reserves called upon to provide energy?
- ✓ How often is CTs committed intra-day?
- ✓ Constraints: Identify generator ramp limitations. Are there other constraint violations?
- ✓ Market and pricing impacts

One additional approach useful for identifying both operational and market impacts is to "follow the prices." A sub-hourly simulation produces a massive amount of data (hundreds or thousands of outputs times 144 10-minute intervals per day); while explicit major violations are reported and easily identifiable as violations, 'soft violations' and what are sometimes referred to as 'under the surface' constraints may be more visible via general price spikes.

Sub-section 2.5 discusses the results and interpretation of the sub-hourly simulation.

2.3 Summary of Definitions and Terms

The following terms are frequently used throughout the sub-hourly simulations, particularly as they relate to their role in assessing real time operational challenges. Therefore, in addition to providing a general definition, some context regarding their relationship to the sub-hourly simulation discussion is also provided.

Headroom – For the purposes of the sub-hourly simulations, *headroom* is defined as the energy available from on-line thermal generation. Or, for an individual generator:

Headroom = Pmax – Energy Dispatch – Reserve Dispatch

This value is summed across all on-line thermal generation for specific intervals to determine a total headroom value for the system. Low headroom may indicate operational challenges, because online generation alone may not be able to respond to a rapid change in demand and/or renewable energy output. Further, due to transmission constraints and limitations of the transmission system, the availability of headroom does not necessarily mean the specific generators with headroom are in the location where the energy is needed.

Reserve Violation / Borrowing from Reserves – For each interval, a required amount of reserves is identified, and generators are dispatched to fulfill that reserve requirement. A *reserve violation* occurs when there is not enough generation to serve the load, and some amount of the generation identified for reserves is instead used to meet the demand, and as a result leaves the reserve dispatch short of the requirement. In some areas, this is also referred to as *"borrowing from reserves."* Similar to headroom, it may not always be possible to use generation capacity that is set aside for reserves to provide energy, if there are transmission constraints that prevent delivery of that energy to the location in need.

Ramp Constraint / Limitation – When a generator is limited by its physical ramp rate, it is called a *ramp constraint* or *ramp limitation*. For example, a generator may have a ramp rate of 4 MW/minute, meaning a generator's dispatch can move 4MW in either direction each minute. In this example, a generator's dispatch can move up to 40MW in a 10-minute interval, and if the dispatch software is limited by this parameter the generator is considered *ramp limited*. In the context of renewable energy studies, quick changes in renewable energy output in conjunction with changes in demand raises concern that the on-line generator fleet could be limited by ramp constraints when attempting to adjust dispatch for these changes.

Instance - In tables and discussions throughout this report, we often refer to "*instances of ramp-limited generation*". One instance of ramp constrained generation describes one constrained generator for one 10-minute interval. Thus it is possible to see thousands of instances of ramp limited generation per day, if many generators are constrained for up to 144 intervals.

Transmission constraint violation / overload – A transmission line becomes constrained when the power flow on the line reaches the line's physical limit. A *constraint violation* or *overload* occurs when the power flow exceeds the limit. Overloads are typically avoided at all costs in real time operations, though sometimes very small overloads are allowed under emergency conditions, depending on regional operating procedures. In the renewable energy simulations, violations are reported to highlight where there are potential difficulties in real time markets under the various renewable scenarios.

CT commitment – This simply means the process of turning on combustion turbines to serve the demand. CT commitment is not necessarily a negative outcome. CT's are typically committed on peak load days and/or to solve transmission constraints. However, with high penetrations of wind and solar resources, the driving factors that affect CT commitment may change significantly. The sub-hourly simulations track CT commitment to help illustrate how CT utilization changes in the various study scenarios.

In the discussion, a "*unit interval*" of CT commitment describes one CT committed for one interval. Thus it is possible to see hundreds or even thousands of unit intervals per day, if several CTs are committed for up to 144 intervals.

Interval – One 10-minute time step of the simulation. There are 144 intervals in each sub-hourly simulation (24 hours * 6 10-minute intervals per hour).

2.4 Selection of Challenging Days for Sub-Hourly Simulations

The wind/solar profile data and the production simulation results for each scenario were screened to identify specific days which were likely to pose significant challenges to PJM system operations. The screening criteria included:

- Largest 10-minute ramp in net load (LNR)
- Largest daily range in LNR (maximum LNR – minimum LNR for the day)
- Largest 10-minute ramp up or down deviations relative to the ramp capability of committed units
- High volatility day, with largest number of 10-minute periods where the change in net load (LNR) exceeded the range capability of committed units

For each scenario, the days of the year were ranked for each criterion. For each scenario, the days of the year were ranked for each criterion. The Section on "Selection of Challenging Days" lists the top 10 days for each criterion and also includes a list of candidate days that were considered for detailed analysis. Table 2-1 summarize the days that were selected for each scenario. At least one day was selected for each criterion in each scenario. Some days were selected because they met two different criteria. Also, some days were found to be challenging in multiple scenarios, which enabled a level of comparison between scenarios.

Table 2-1: Challenging Day Selections for Study Scenarios

Selection Criteria for Challenging Days				
Scenarios	**Large Difference Between Peak and Minimum LNR in One Day**	**Large 10-Minute Change in LNR**	**10-Minute Ramps in LNR that Exceed Ramp Rate Capability of Committed Units**	**10-Minute Ramps in LNR that Exceed Range Capability of Committed Units**
2% BAU	July 15			
	July 27			
	July 28			
14% RPS		February 12	February 12	
		February 17		
			March 2	
	May 26			May 26
				August 3
20% HSBO	July 28			
		March 4		
			September 1	September 1
20% HOBO	May 26			
		March 4		
			March 9	March 9
				July 17
	July 27			July 27
		January 8		
			January 8	
20% LOBO	July 15			
		February 17	February 17	
			March 20	
				July 17
	May 26			May 26
			September 1	September 1
20% LODO	June 18			
		March 4		
			March 20	
				July 17
	May 26			May 26
			September 1	September 1
30% HSBO	June 18			
		February 17		
			April 12	
				April 26
	January 5	January 5		
30% HOBO	January 12			
		March 4		
			September 21	September 21
	November 13			November 13
			November 16	November 16
30% LOBO	January 5	January 5	January 5	January 5
		February 17		
		March 11	March 11	March 11
				March 28
	June 18			
		December 22		
30% LODO		March 4		
			March 9	March 9
			March 28	March 28
	June 18			

2.5 Sub-Hourly Simulation Results and Discussion

A total of 49 challenging days were simulated for the study scenarios, including three simulations for the 2% BAU Scenario, five for the 14% RPS Scenario, twenty-one for the 20% scenarios, and twenty for the 30% scenarios.

2.5.1 Summary of Results: 2% BAU Scenario

Table 2-2 summarizes high-level results of the sub-hourly simulations for the 2% BAU Scenarios.

Table 2-2: PROBE Analysis Results Summary for 2% BAU Challenging Days

	15-Jul	27-Jul	28-Jul
Instances of Load Shedding	0	0	0
Intervals When Reserves Provide Energy	0	10	48
Average Dispatch Headroom - Online Steam/CC (MW)	5185	3776	1977
Minimum Dispatch Headroom - Online Steam/CC (MW)	0	6	0
Instances of Ramp-Constrained Generation	2420	1640	1850
Total Unit-Intervals of RT CT Commitment	1117	2342	4603
Average RT CT Commitment per Interval	8	16	32
Number of RT CTs Committed - Highest Interval	23	83	151
Average LMP	$115.30	$163.67	$250.08
LMP Spikes	6	13	42
Average Reserve Price	$47.76	$74.14	$102.78

Recall that the sub-hourly simulations are performed for market days that are considered "potentially challenging" based on the criteria described earlier. Each of the 2% BAU Scenario study days were high-demand instances and therefore experienced high LMPs and a large number of thermal units committed entering the real-time market.

Results: 2% BAU - July 15

The July 15 market day was the lowest-load day of the three days selected for sub-hourly analysis in the 2% BAU Scenario, although it was still a high-demand day in general. During several intervals, there was little or no headroom among on-line thermal generators (i.e. all available on-line thermal generation was used to provide energy for load and/or operating reserves), as shown in Figure 2-2. In these instances, additional CTs were committed to serve the demand, but compared to typical peak operating days, the CT usage was not necessarily abnormal.

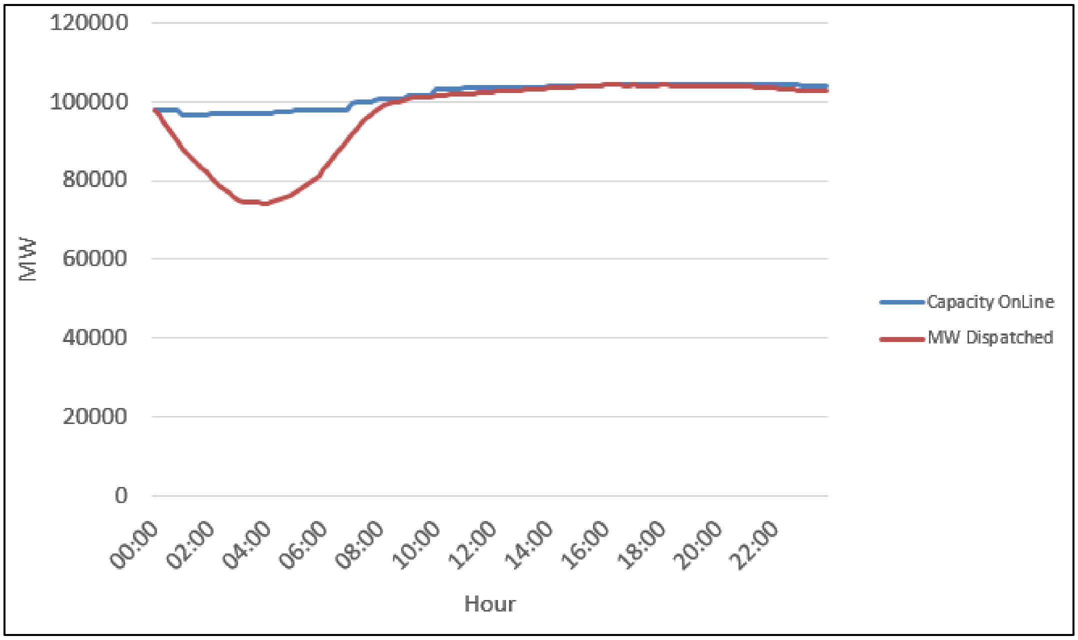

Figure 2-2: On-line Capacity vs. MW Dispatched for Steam + Combined Cycle (2% BAU, July 15)

There were a large number of ramp-constrained generators for the July 15 study day – see Figure 2-3. Ramp rates limit the ability of on-line generation to follow load, and in extreme conditions may cause generation shortages even though there appears to be headroom to meet demand. In this case, CT commitment easily accounted for needed MW, but the ramp limitations were clearly the biggest impediment to lower LMPs and a "less challenging" day.

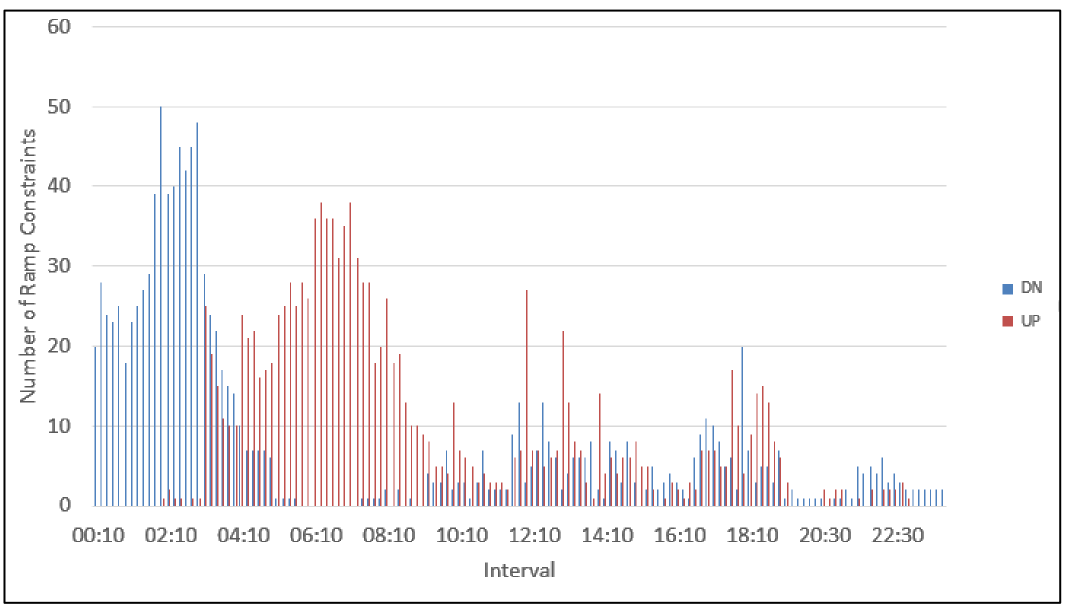

Figure 2-3: Number of Ramp-constrained Units per 10-minute Interval (2% BAU, July 15)

Note that it is possible to have simultaneous ramp up and ramp down constraints for different generators, due to PJM's large footprint and transmission constraints.

Results: 2% BAU - July 27

The July 27 sub-hourly operations proved to have additional issues as compared to July 15. Supply-side resources were more heavily utilized, there were 10 10-minute intervals when on-line reserves were called upon to provide energy, and there were overloads on several transmission lines.

Figure 2-4 shows the intervals with reserves replacing energy: the red line, which correlates to the right axis, shows the reserve violation for each interval of the day. The blue line (left axis) shows the reserve price, noting that a \$200 price indicates a shortage (the reserve penalty price is set at \$200), and other high prices likely indicate near-tradeoffs between energy and reserves.

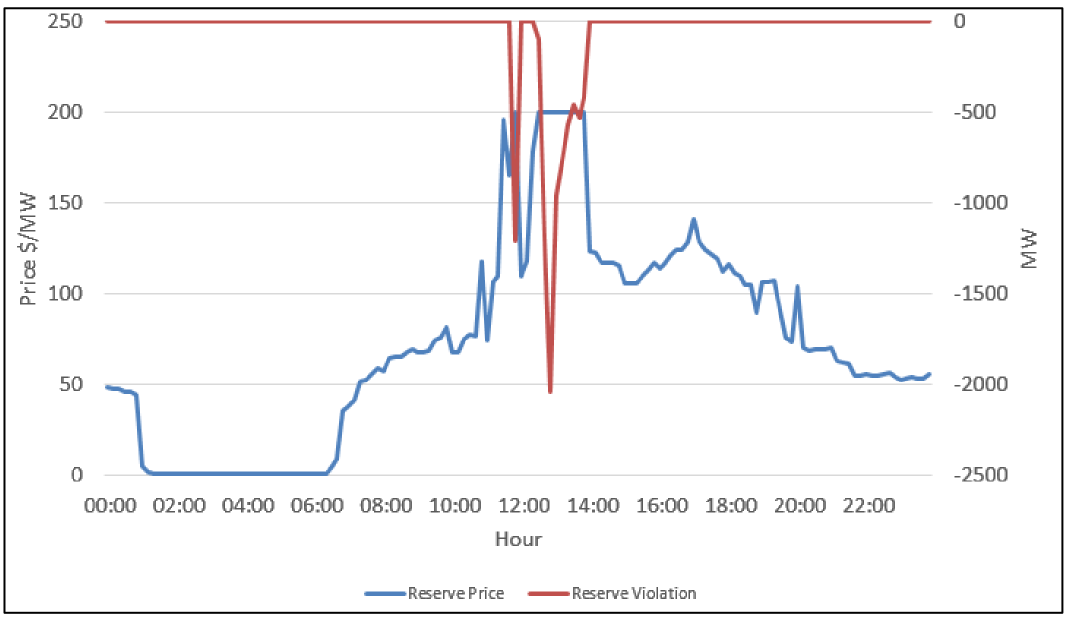

Figure 2-4: Reserve Violation and Price (2% BAU, July 27)

There were more intervals when very little headroom was available from on-line thermal generation, requiring higher CT commitment in addition to the reserves violations. The number of generators limited by ramp capability was lower than July 15, but certainly high enough to add to the challenges presented in real-time operations for the day.

A total of 412 instances of transmission line overloads were also noted in this sub-hourly simulation, across a number of transmission lines. These overloads are typically considered a concern, as it further indicates sufficient resources may not have been available to serve demand in some areas. It should be noted that several of these same transmission lines were also overloaded in the forward market GE MAPS run, and therefore were not a real-time-only concern or phenomena. However, in GE MAPS, a low penalty cost (~$10/MWh) was put on lower voltage lines to prevent the system from making radical changes in dispatch for minor local concerns. Therefore, such constraints are not considered as a major concern.

It was also observed that there was no unserved load. This is also related to the fact that transmission penalty prices in GE MAPS for low voltage lines were sufficiently low so that lines would overload well before dropping load.

Aside from the transmission overloads, it could be argued that the real-time operations performed as designed for a true peak demand day: "dipping into" reserves is acceptable in extreme cases and CTs are installed for the purpose of serving energy almost instantaneously. Nonetheless, the reduced load-following capability – due to the lack of headroom and ramp limitations – from on-line thermal generation is a concern.

Results: 2% BAU - July 28

July 28 displayed particularly difficult challenges for real-time operations. Reserves were called upon to meet energy demand in 48 10-minute intervals, representing one-third of the intervals for the day. Figure 2-5 shows the intervals with reserves replacing energy: the red line, which correlates to the right axis, shows the reserve violation for each interval of the day. The blue line (left axis) shows the reserve price, noting that a $200 price indicates a shortage, and other high prices likely to indicate near-tradeoffs between energy and reserves.

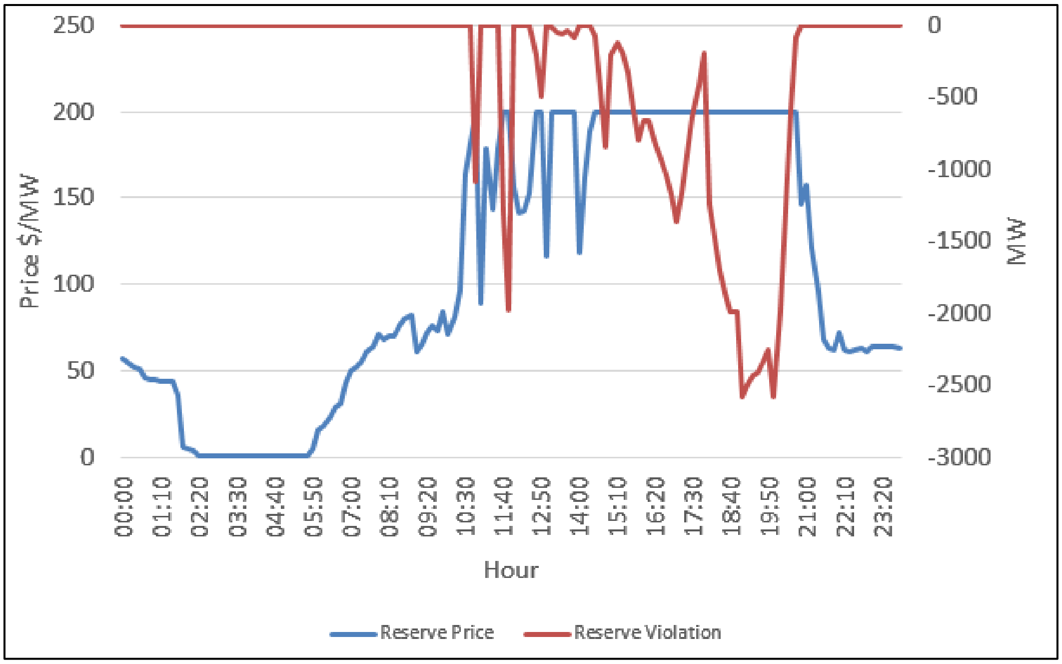

Figure 2-5: Reserve Violation and Price (2% BAU, July 28)

The most concerning factor with the reserves replacing energy in the chart may be the persistence of large sustained energy deficiencies in the peak afternoon hours. For the short-term, "transient" instances earlier in the day, it could be argued that a one-interval usage of reserves for energy is appropriate compared to committing CTs that typically need to remain on for an hour and thus add to costs and LMPs.

A further look at the demand and generation profile for the day demonstrates that this is an extreme peak market day in which generation is heavily utilized; in fact, all but a few of the most expensive and longest start steam generators are initially committed in the GE MAPS (i.e., forward-looking) market run. Still, as shown in Figure 2-6, despite the large thermal unit commitment, their energy available for dispatch (headroom) is minimal or zero for much of the day, which necessitates heavy reliance on CTs.

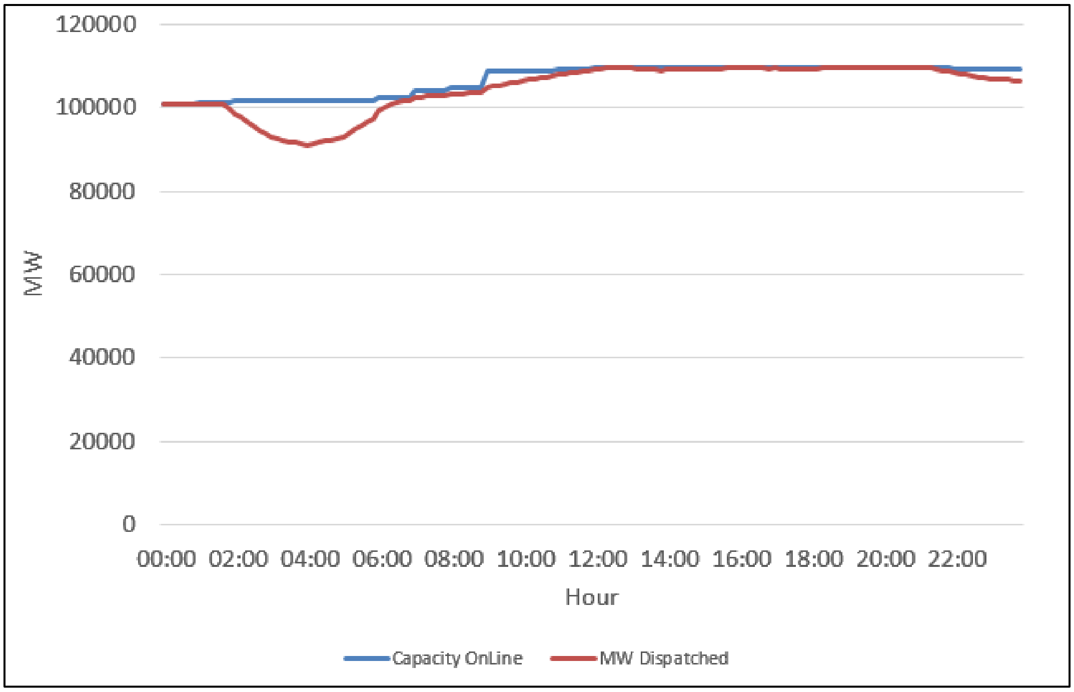

Figure 2-6: On-line Capacity vs. MW Dispatched for Steam + Combined Cycle (2% BAU, July 28)

Higher penetrations of renewable energy (20% and 30%) create operational patterns that are significantly different than what is common today, especially with respect to CT usage. Figure 2-7 shows the CT usage for a summer-peak day in the 2% BAU scenario. It shows that about 56 GWs of CTs were committed in the day-ahead market (blue region) to meet the anticipated peak load during the mid-day hours. About 3 GWs of additional CTs were committed in the real-time market (red region) to make up for relatively minor forecast errors on that day. At the peak, there were still about 1 GWs of CTs available to respond to other unanticipated events.

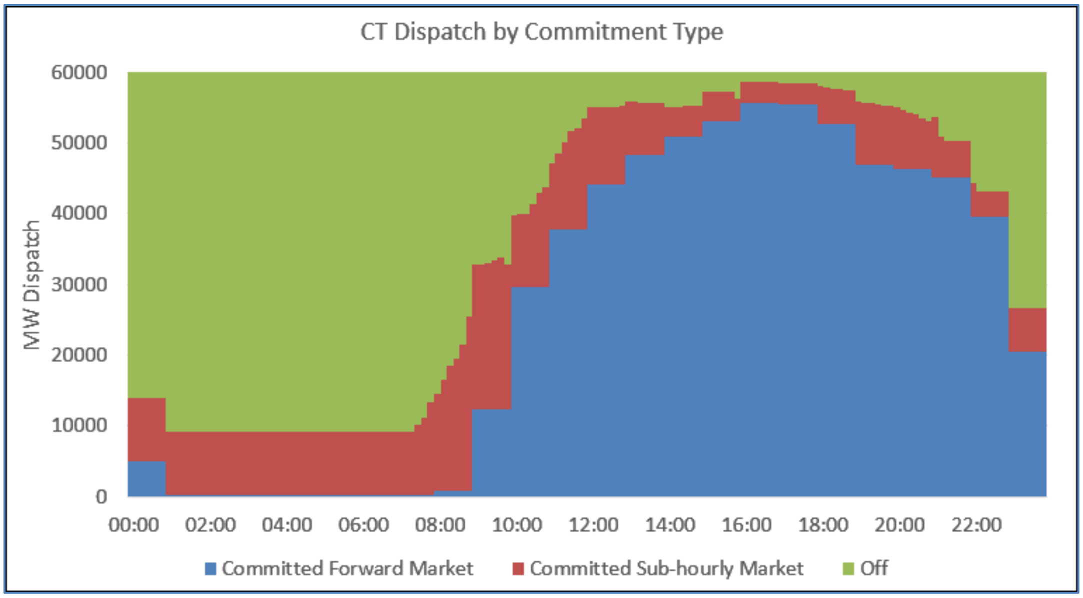

Figure 2-7: Number of CTs Committed (2% BAU, July 28)

It should also be noted in the chart above that, given the level of demand for the day, many CTs were actually identified as required for commitment by the forward-looking simulation commitment process. This leaves fewer additional CTs available for sub-hourly operations commitment.

Thus, there is a relative lack of resources available for commitment and dispatch – both thermal and CT – in the peak afternoon hours on the peak day of the year in the 2% case, necessitating reserves to be used to provide energy.

Further, it is important to understand that while there may appear to be a sliver of headroom available in some peak intervals for thermal dispatch and CTs available, these units may not be in the locations that need the energy. In other words, transmission constraints limit the units that can respond, and therefore committing a CT that appears available at the high level may not serve the demand in a far-away location, ultimately still requiring energy to be served by reserves. There are also a handful of CTs with extremely high bid prices that were not committed due to their costs.

The concerns continue when taking a close look at the transmission system: a total of 690 instances of transmission line overloads were also noted in this sub-hourly simulation, across a number of transmission lines. These overloads are typically considered a major concern, as it further indicates sufficient resources may not have been available to serve demand in some areas. It should be noted that several of these same transmission lines were also overloaded in the forward market, and therefore were not a real-time-only concern or phenomena.

Instances when generators are limited by their ramp rates also are high on this day, but actually play a minimal role in the energy shortages in peak hours. This is due to the fact that nearly all thermal generation is dispatched to the maximum in peak hours, indicating that the ramp limitations occur most often during morning pick-up, and not during peak afternoon load-following. Figure 2-8 shows the number of ramp constrained units per 10-minute interval:

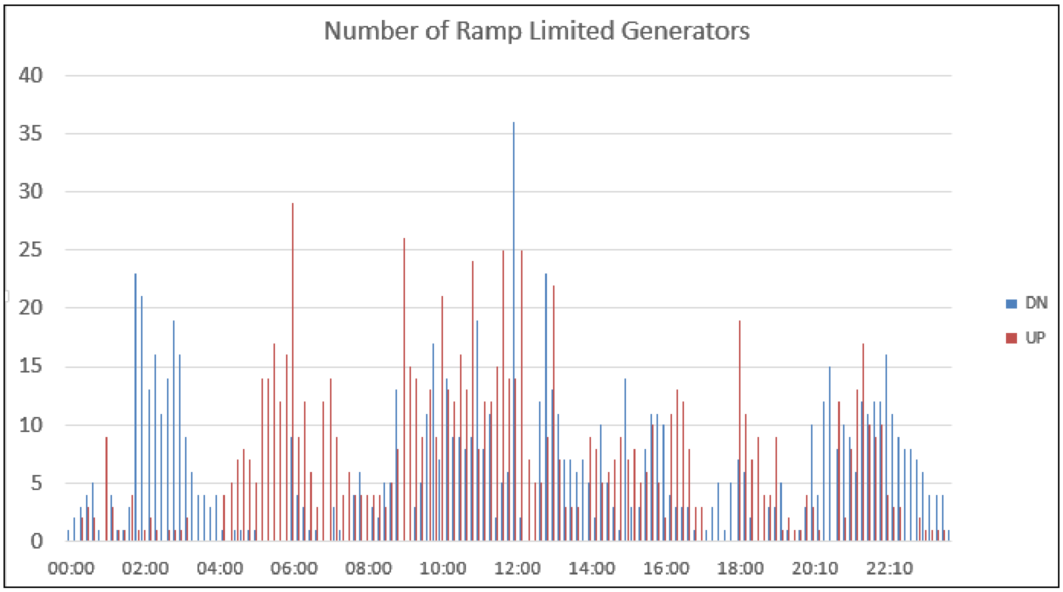

Figure 2-8: Number of Ramp-constrained Units per 10-minute Interval (2% BAU, July 28)

Conclusions: 2% BAU Scenario

As noted in the introduction, the days studied for the 2% sub-hourly analysis were high-load days and were expected to be very challenging. The 2% BAU Scenario has relatively low wind and solar energy, and serves as a benchmark for comparing the scenarios with higher levels of wind and solar resources.

The highest load day, July 28, committed all baseload resources and the majority of all available CTs, proving to be the most challenging day. However, these challenging days did not result in any unserved load in the sub-hourly analysis, though in two out of three simulations, reserves were used to serve load for several hours of the day, creating reserve shortages.

2.5.2 Summary of Results: 14% RPS Scenario

Five sub-hourly simulations were completed for the 14% RPS Scenario. With the addition of renewable generation in the 14% RPS case, there is more total generation available. However, while more generation may help to better meet demand in general, it may also result in additional operational challenges due to the variable nature of renewable generation. Table 2-3 summarizes high-level results of the sub-hourly simulations for the 14% cases.

Table 2-3: PROBE Analysis Results Summary for 14% RPS Challenging Days

	12-Feb	17-Feb	2-Mar	26-May	3-Aug
Instances of Load Shedding	0	0	0	0	0
Intervals When Reserves Provide Energy	0	0	0	0	0
Average Dispatch Headroom - Online Steam/CC (MW)	6950	7359	4048	7563	2931
Minimum Dispatch Headroom - Online Steam/CC (MW)	453	53	36	36	0
Instances of Ramp-Constrained Generation	4074	3174	2904	3929	1955
Total Unit-Intervals of RT CT Commitment	867	472	463	944	1380
Average RT CT Commitment per Interval	6	3	3	7	10
Number of RT CTs Committed - Highest Interval	31	14	7	22	23
Average LMP	$52.32	$59.65	$58.40	$77.29	$96.95
LMP Spikes	0	0	0	0	0
Average Reserve Price	$9.25	$11.75	$10.11	$22.68	$40.46

At the high level, the 14% cases presented some areas for concern, but also lower LMPs and less real-time CT commitment than the 2% cases due to the additional low-cost generation in the model. The February 12 and August 3 study days presented the more interesting results, albeit for very different reasons. Each of the simulations is discussed in more detail below, with a particular focus on February 12 and August 3.

<u>Results: 14% RPS - February 12</u>

Observations / characteristics:

- ✓ Screening criteria met: Large LNR period to period change; large number of ramps that exceeded committed resource capability
- ✓ Above average CT commitment during real-time operations
- ✓ Most ramp constraints among 14% studies

Figure 2-9 illustrates the variation in wind and solar resource output over the day as well as the response of other generation. The wind generation is at its lowest output of the day during the early morning hours, and in fact was decreasing steadily throughout the morning demand increase. The combination of decreasing renewable generation and increasing demand forces load-following generation to respond very aggressively. In fact, some CTs were utilized during part of the morning.

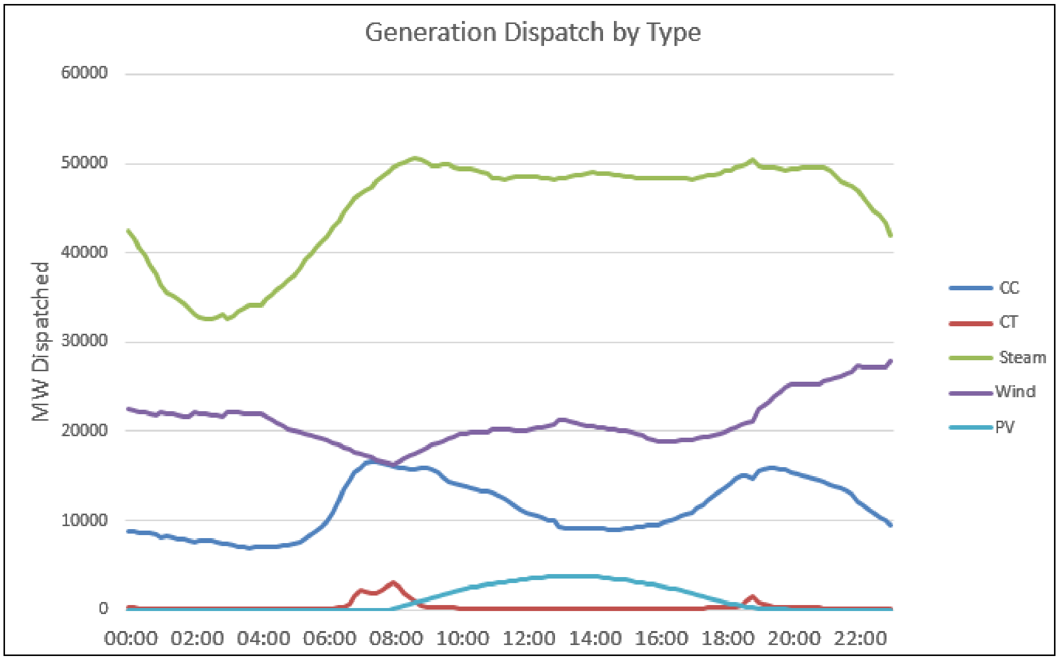

Figure 2-9: Generation by Type for Each Interval (14% RPS, February 12)

Given the conditions, it is not surprising that generator upward ramp constraints are most frequent during the morning demand increase, and are common for the day in general. Note that the frequent ramp constraints at the beginning and end of the day are downward ramp constraints, when wind generation is steady or increasing during periods when demand is decreasing. Figure 2-10 shows ramp constraints per interval.

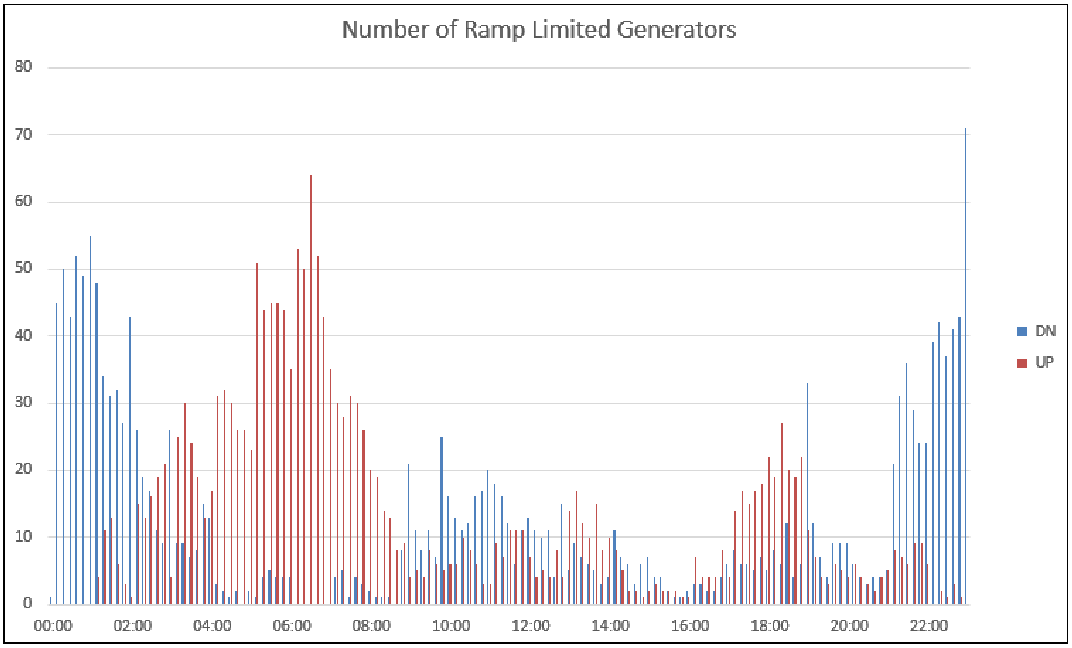

Figure 2-10: Number of Ramp-constrained Units per 10-minute Interval (14% RPS, February 12)

CTs are also committed during the subject morning hours in the sub-hourly analysis that correlates to the factors discussed above. The minimum wind output occurs at the same interval as the morning demand peak; when combined with ramp limitations, CTs must be committed to serve demand.

As noted in the 2% BAU scenario, for short-term "transient" shortages, it could be argued that a one- or two-interval usage of reserves for energy is appropriate compared to committing CTs. However, the limitations are of a long enough duration that CTs are committed instead. Peak reserve prices were observed during the same time period, which may be an indication that the sub-hourly solution was close to using reserves to supply energy.

The February 12 study day provides a good example of how a relatively average demand day can provide operational challenges due to variable resources, particularly if the output of those renewable resources declines as demand is increasing. While there are no significant violations for the day, the wind energy output is a factor causing load following generation to reach ramp limitations and more CT commitment than may typically occur.

<u>Results: 14% RPS - February 17</u>

Observations / characteristics:

- ✓ Screening criteria met: Largest LNR period to period change

- ✓ Several intervals with minimal headroom

The results for the February 17 sub-hourly simulation were similar to those for the February 12 simulation, with less severity and fewer intervals of concern.

It was observed, however, that there were several intervals with minimal headroom, and some real-time CT commitment was required. Overall, this simulation solved with relative ease, but the low headroom at the 14% level proves to be a consistent trend for February 17 in other scenarios with higher penetration levels. It is suggested to review the different February 17 simulations throughout this report for interesting comparison; a summary comparison is also provided in section 2.5.11.

<u>Results: 14% RPS - March 2</u>

Observations / characteristics:

- ✓ Screening criteria met: Largest number of ramps that exceeded committed resource capability
- ✓ High ramp constraints in some intervals

While this simulation did not present as many ramp constraints overall as other simulations, there were indeed a significant number of generator ramp constraints at concentrated intervals throughout the day. Figure 2-11 shows the number of generators with ramp constraints per 10-minute interval.

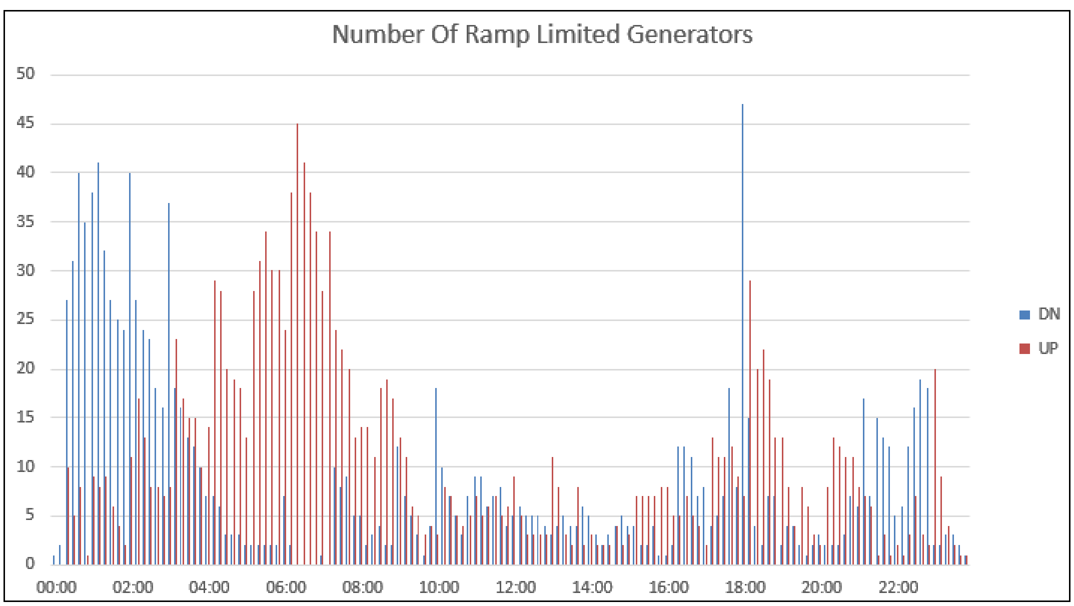

Figure 2-11: Number of Ramp-constrained Units per 10-minute Interval (14% RPS, March 2)

Despite the frequency of ramp limitations, the simulator results showed that there was enough flexibility from the on-line generation mix to meet demand without extensive CT usage or dipping into reserves. This is likely the result of a steadier wind profile that to some extent was similar in profile to the demand. This is opposite from the situation on February 12, where wind generation declined while system demand increased. Figure 2-12 illustrates wind output and demand for March 2:

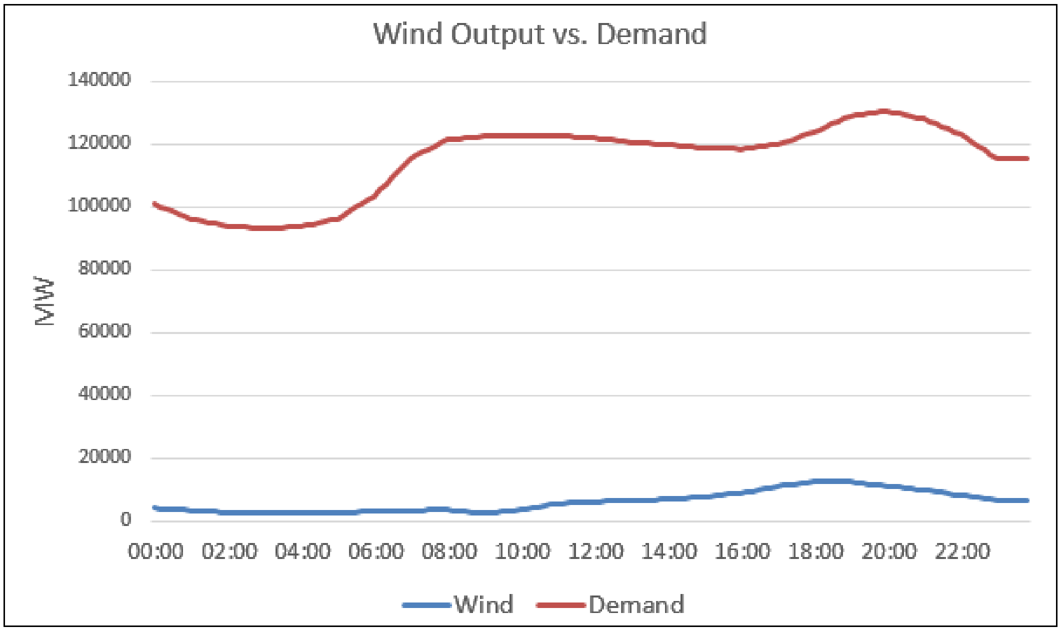

Figure 2-12: Wind Output vs. Demand (14% RPS, March 2)

The March 2 sub-hourly analysis did not present additional operational challenges.

<u>Results: 14% RPS - May 26</u>

Observations / characteristics:

- ✓ Screening criteria met: Large difference between LNR peak and min; large number of periods exceeding committed resource headroom
- ✓ Low headroom during several intervals
- ✓ Large number of ramp constraints; quick change from between generators ramping down and then ramping back up

This day is largely defined by a sharp increase in on-shore wind just after midnight, followed by a sharp decrease in the early morning, with another clear increase in the afternoon, as shown in Figure 2-13.

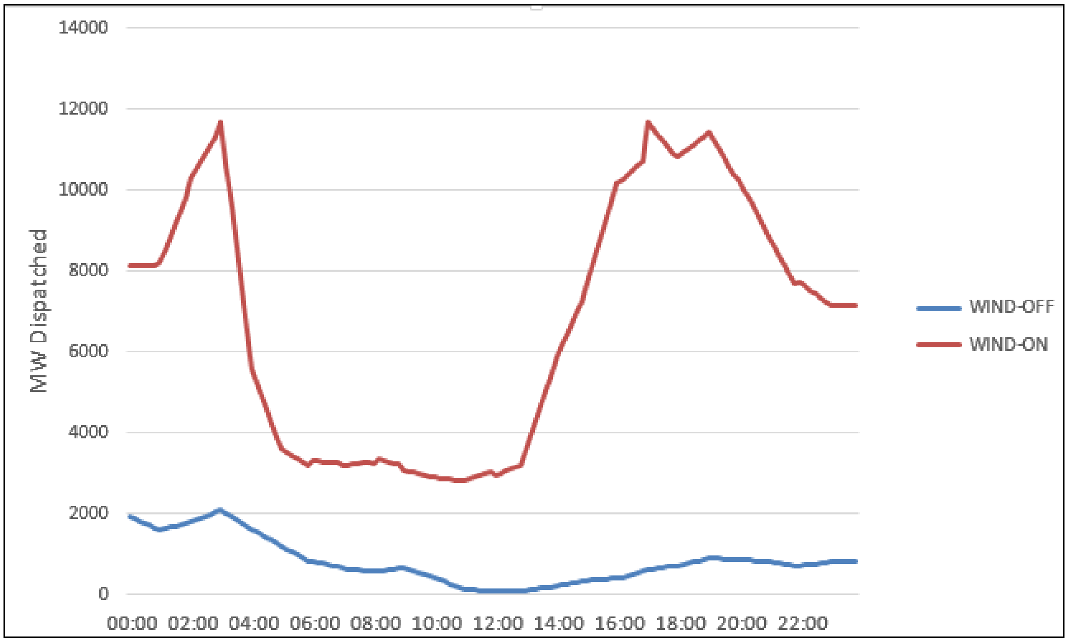

Figure 2-13: Wind Generation Output (14% RPS, May 26)

The combination of wind increase beginning around 1 AM combined with decreasing demand shows one of the highest persistent instances of downward ramp constraints of any study day thus far; in fact, generators simply cannot ramp down fast enough. In Figure 2-14 ramp constraint instances are separated into downward and upward.

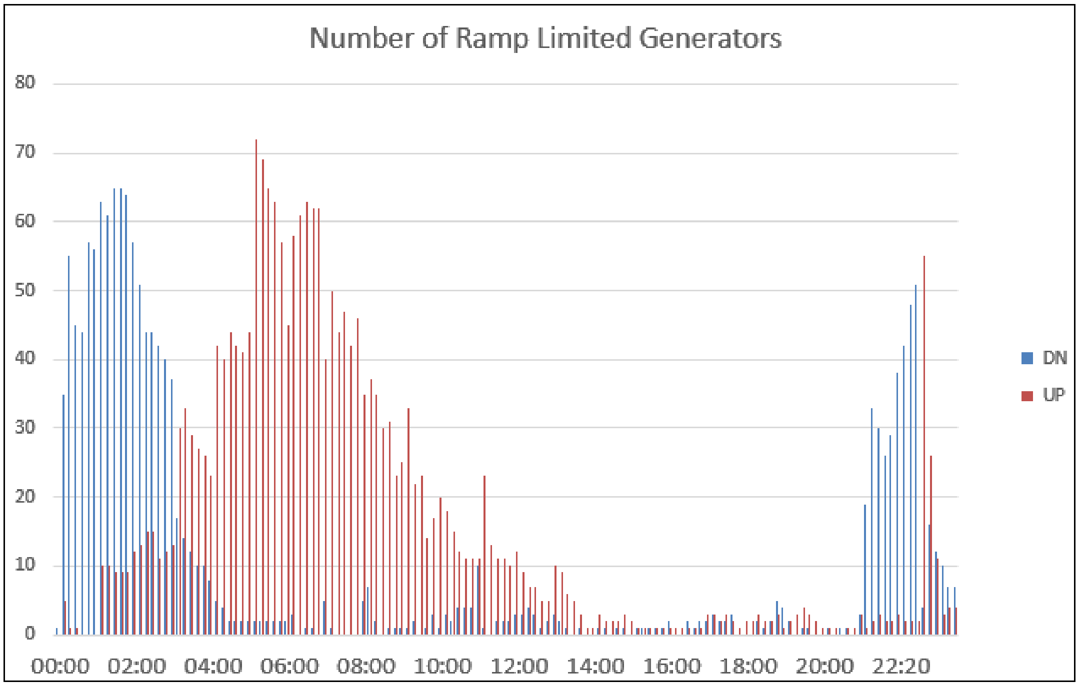

Figure 2-14: Number of Ramp-constrained Units per 10-minute Interval (14% RPS, May 26)

Clearly, thermal generation is ramped down only to be ramped up again shortly afterwards as the wind output drops significantly and load begins to increase. It is also interesting to note that during the afternoon hours, the increased wind generation follows load increase, and in this case <u>reduces</u> the ramp constraints on thermal generation as they are not as active in following load.

<u>Results: 14% RPS - August 3</u>

Observations / characteristics:

- ✓ Screening criteria met: Largest number of periods exceeding committed resource headroom; large difference between LNR peak and min
- ✓ Low headroom
- ✓ Significant CT commitment
- ✓ Summer day with near-peak demand

Figure 2-15 shows available headroom by interval (for Steam and Combined Cycle units). The plot clearly confirms the lack of headroom throughout much of the afternoon and evening hours.

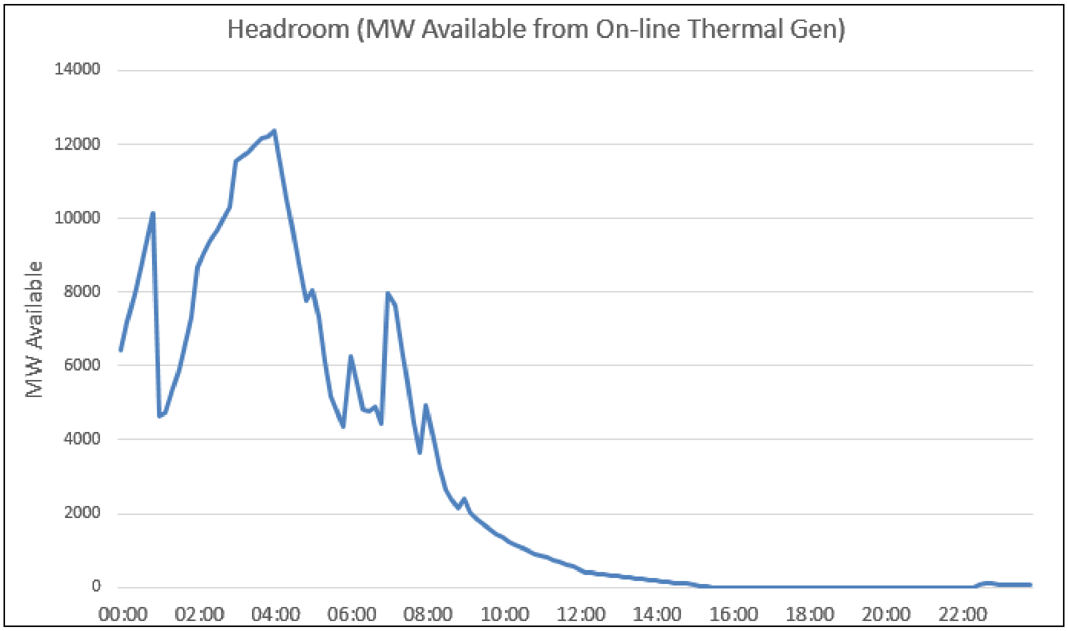

Figure 2-15: Headroom - MW Available from Thermal Generation (14% RPS, August 3)

The result of the low headroom for the study day is a heavy reliance on CT generation. This is another instance where the inability to follow the combined load / renewable variations is far too persistent and prolonged to be met by borrowing from reserves, and opting for CT commitment instead. Figure 2-16 shows the output of the various generation types (note: some types of generation with constant output such as nuclear are not shown). The forward-looking MAPS commitment identified that many CTs would be required, but the PROBE real-time commitment still identified an additional ten to fifteen CTs required for commitment to meet sub-hourly obligations in peak hours.

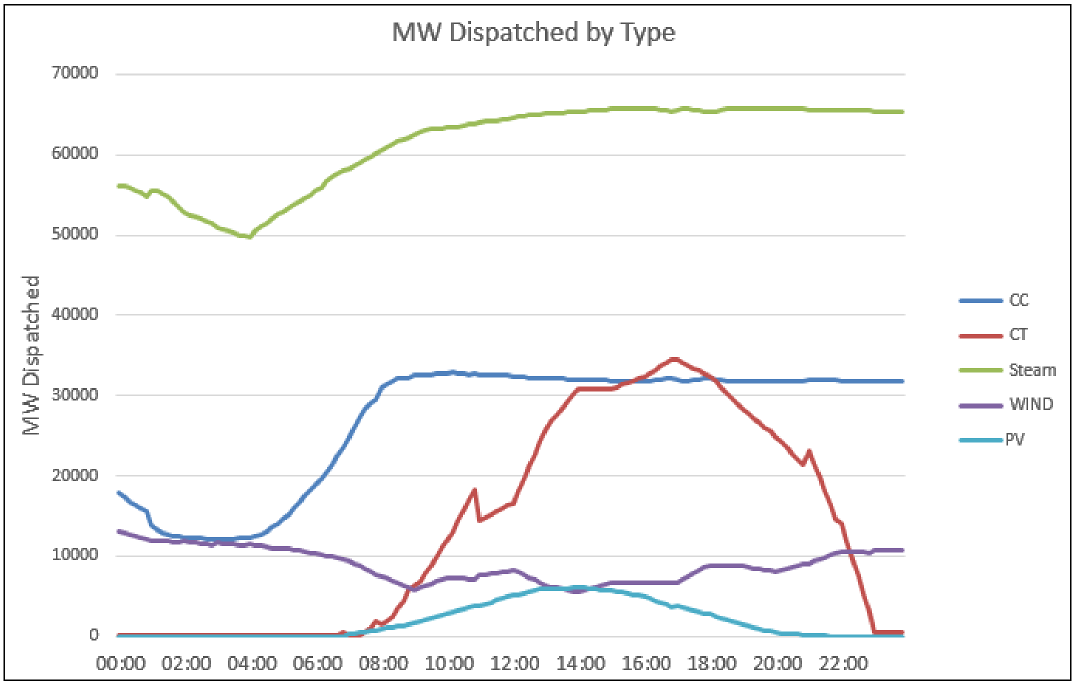

Figure 2-16: Generation by Type for Each Interval (14% RPS, August 3)

Despite the addition of presumably low-cost renewable energy, the high commitment of CTs and lack of availability of thermal generation resulted in above average LMPs and reserves prices throughout the afternoon hours.

Concluding the August 3 discussion, the lack of headroom during high load hours was compensated by plenty of CT availability in the forward and sub-hourly markets – in fact, there were still many CTs available to meet additional challenges. However, there were also many steam units "on the sidelines" that, if they had been committed, could have reduced the need for CTs during real-time operations.

2.5.3 Summary of Results: 20% HSBO Scenario

Three sub-hourly simulations were completed for the 20% high solar case. Similar to the 14% cases, the addition of renewable generation results in more total generation available to meet demand, but may also result in additional operational challenges due to the variable nature of renewable generation. Table 2-4 summarizes high-level results of the sub-hourly simulations for the 20% HSBO simulations.

Table 2-4: PROBE Analysis Results Summary for 20% HSBO Challenging Days

	4-Mar	28-Jul	1-Sep
Instances of Load Shedding	0	0	0
Intervals When Reserves Provide Energy	0	0	0
Average Dispatch Headroom - Online Steam/CC (MW)	10340	5439	6979
Minimum Dispatch Headroom - Online Steam/CC (MW)	1946	36	425
Instances of Ramp-Constrained Generation	4573	2731	3540
Total Unit-Intervals of RT CT Commitment	36	676	18
Average RT CT Commitment per Interval	< 1	4.5	< 1
Number of RT CTs Committed - Highest Interval	2	18	1
Average LMP	$43.21	$110.83	$51.76
LMP Spikes	4	1	2
Average Reserve Price	$4.67	$44.45	$10.87

The data show that high solar generation output correlates reasonably well to changes in demand; this correlation is generally a positive outcome for real-time operations. Each of the simulations is discussed in more detail below, with a particular focus on March 4 and July 28.

Results: 20% HSBO - March 4

Observations / characteristics:

- ✓ Screening criteria met: Largest LNR period to period change
- ✓ Adequate headroom
- ✓ Higher ramp constraints

The most significant concern noted for this operations simulation was a high number of generation ramp constraints. Thermal generators are required to ramp up in the morning hours when demand begins to increase sooner than solar generation, and again in the late afternoon hours when solar generation output is falling faster than demand. Figure 2-17 shows the demand and renewable generation throughout the day.

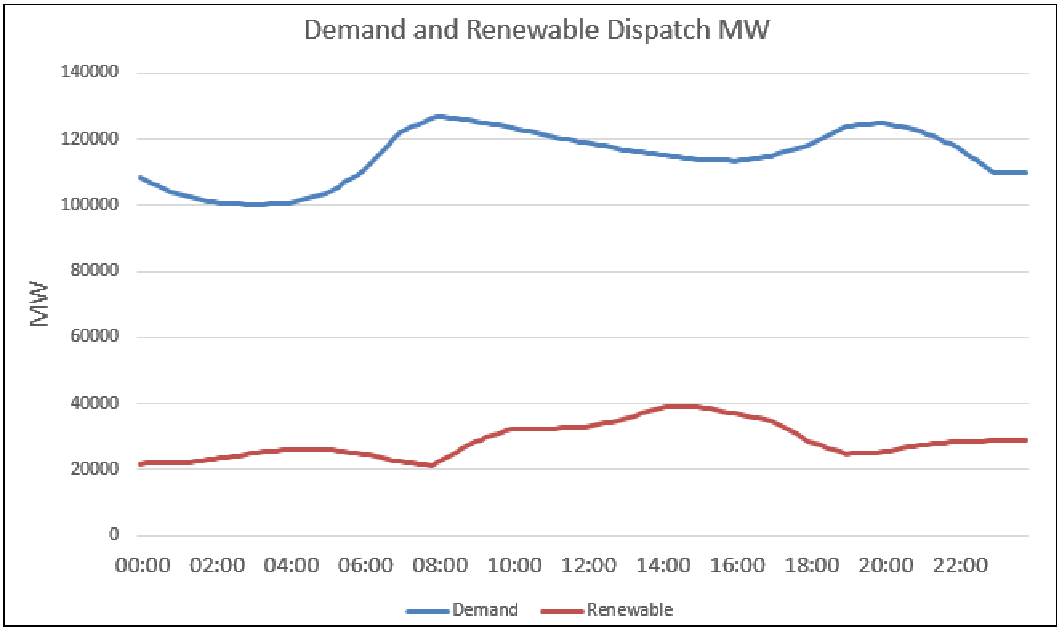

Figure 2-17: Wind Output and Demand (20% HSBO, March 4)

Figure 2-18 shows the number of generators that experience ramp constraints in each 10-minute period of the day.

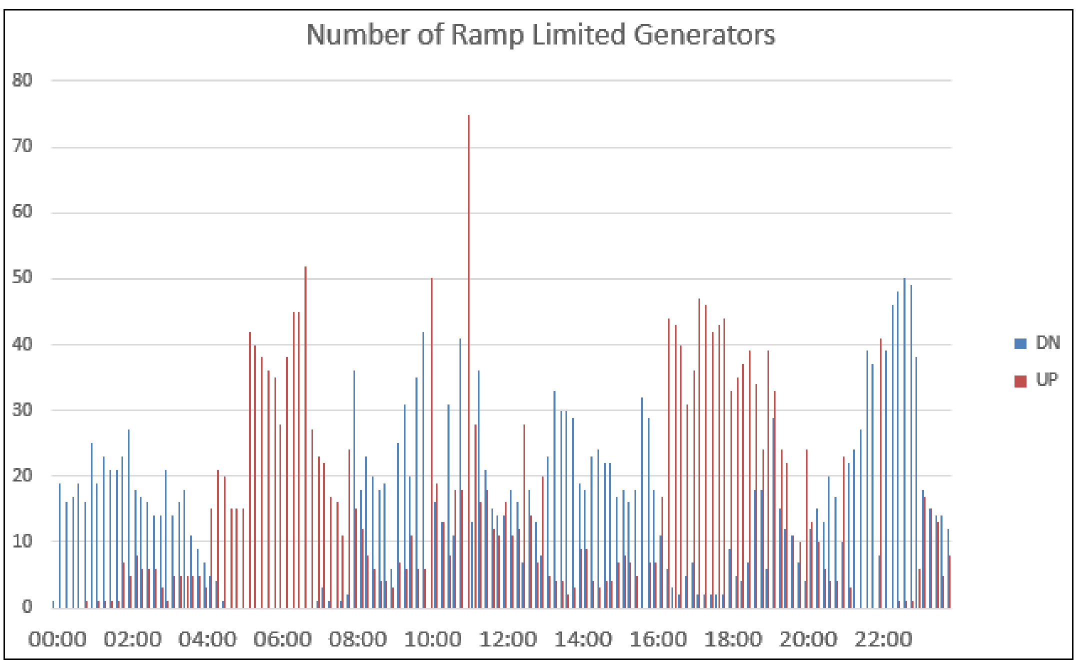

Figure 2-18: Number of Ramp-constrained Units per 10-minute Interval (20% HSBO, March 4)

It was also noted that two modest LMP "price spikes" occurred at intervals 7:00 and 18:50, at the very beginning and end bounds of solar generation output. This correlates to the higher-demand, lower solar, high ramp constraint situation discussed above. See Figure 2-19.

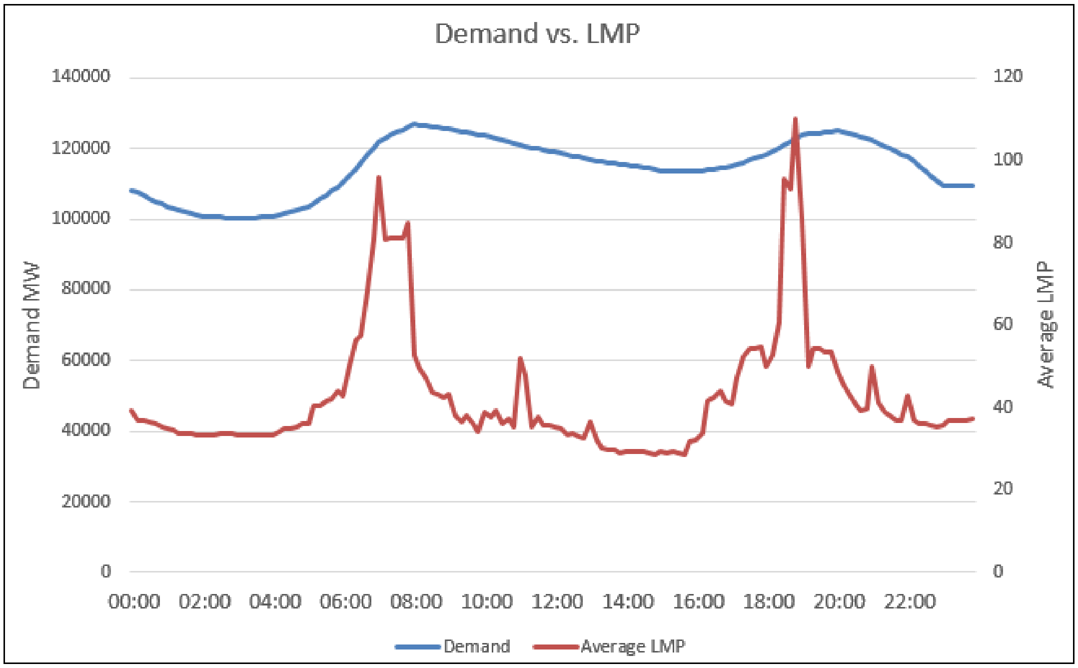

Figure 2-19: Demand and LMP (20% HSBO, March 4)

<u>Results: 20% HSBO - July 28</u>

Recall that the July 28 day was also studied under the 2% scenario, as the most challenging day due to extreme high load conditions. This provides a good basis for comparison with a 20% renewable penetration case.

Observations / characteristics:

- ✓ Screening criteria met: Largest difference between LNR peak and min
- ✓ High LMP – but much lower than the same day from the 2% case
- ✓ Above average CT commitment
- ✓ 416 instances of transmission overload

First, reviewing the 20% HSBO results, the operational simulation found much higher real-time CT commitment – up to 18 CTs for one RT interval – than the other two 20% high-solar sub-hourly simulations (which did not have more than two CTs committed during real-time in any given interval). However, given the peak demand, some CT commitment can be expected and in fact is highest in the intervals immediately following the reduction in solar generation. It was also noted that a portion of the CT commitment was required due to transmission constraints. See Figure 2-20.

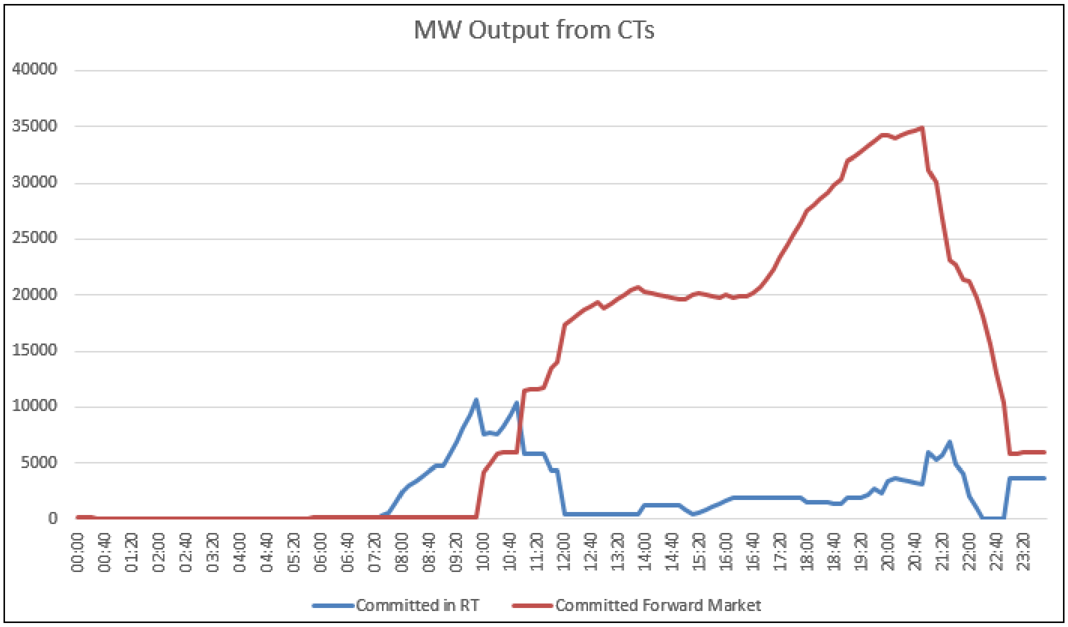

Figure 2-20: CT Dispatch by Interval (20% HSBO, July 28)

A significant price spike occurred in a few intervals after 20:00 hours, corresponding to the high CT commitment during this time.

A total of 416 instances of transmission line overloads were also noted in this sub-hourly simulation, across a number of transmission lines. These overloads are typically considered a major concern, as it indicates sufficient resources may not have been available to serve demand in some areas, or a renewable curtailment may be required (in cases where over-generation caused the overload), or an extremely costly commitment / re-dispatch / reserves shortage event would need to occur to avoid the overload.

Second, it is interesting to compare the July 28 case with 20% renewable energy to the case with 2% renewable energy. While the 20% case presented new challenges, overall, the additional resources provided more operational headroom in terms of MW available during the day. In fact, CT commitment was sharply reduced in the 20% case and instances when reserves were called upon to provide energy were eliminated. The average price for energy was reduced by more than half, and the number of transmission overloads was reduced by 40%.

Results: 20% HSBO - September 1

Observations / characteristics:

- ✓ Screening criteria met: Largest number of ramps exceeding committed resource capability; largest number of periods exceeding committed resource headroom
- ✓ Adequate headroom in the sub-hourly simulations
- ✓ Good operating flexibility

No operational challenges were identified during the September 1 sub-hourly analysis, largely due to non-peak demand and a renewable profile that followed load reasonably well, as shown in Figure 2-21.

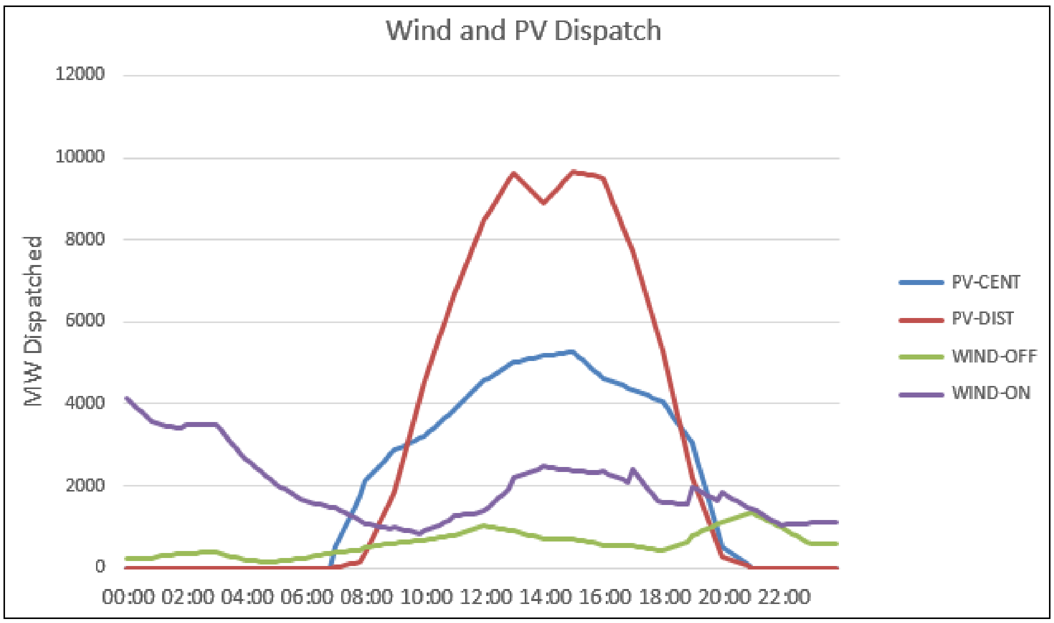

Figure 2-21: Renewable Generation Dispatch for Each Interval (20% HSBO, September 1)

2.5.4 Summary of Results: 20% HOBO Scenario

Six sub-hourly simulations were completed for the 20% HOBO case. Table 2-5 summarizes high-level results of the sub-hourly simulations for these simulations.

Table 2-5: PROBE Analysis Results Summary for 20% HOBO Challenging Days

	8-Jan	4-Mar	9-Mar	26-May	17-Jul	27-Jul
Instances of Load Shedding	0	0	0	0	0	0
Intervals When Reserves Provide Energy	0	0	0	0	0	0
Average Dispatch Headroom - Online Steam/CC (MW)	17766	13445	16516	8989	8379	6396
Minimum Dispatch Headroom - Online Steam/CC (MW)	6981	4634	3818	36	36	53
Instances of Ramp-Constrained Generation	4586	3525	5151	4134	3626	2785
Total Unit-Intervals of RT CT Commitment	0	12	12	58	394	1464
Average RT CT Commitment per Interval	NA	<1	< 1	< 1	2.5	10
Number of RT CTs Committed - Highest Interval	NA	1	1	5	14	29
Average LMP	$38.03	$42.97	$35.25	$68.23	$71.50	$100.68
LMP Spikes	0	1	1	4	0	0
Average Reserve Price	$1.00	$1.89	$1.24	$14.20	$19.32	$40.69

These HOBO sub-hourly simulations generally presented fewer operational challenges than other renewable profiles. The amount and location of the additional generation created a scenario where there was typically plenty of traditional generation available and minimal use for CTs. Each of the simulations is discussed in more detail below.

Results: 20% HOBO - January 8

Observations / characteristics:

- ✓ Screening criteria met: Large LNR period to period change; large number of ramps that exceeded committed resource capability
- ✓ Adequate headroom
- ✓ Good operating flexibility

The only noticeable concern with the January 8 sub-hourly analysis was a high number of generator ramp constraints, limiting the capability of on-line generation to follow changes in demand and renewable generation. However, there was a more than adequate amount of thermal generation committed in the forward market to follow load despite the physical limitations to ramp. No real-time CT commitment was necessary.

Figure 2-22 shows the number of generators that experience ramp constraints in each 10-minute period of the day.

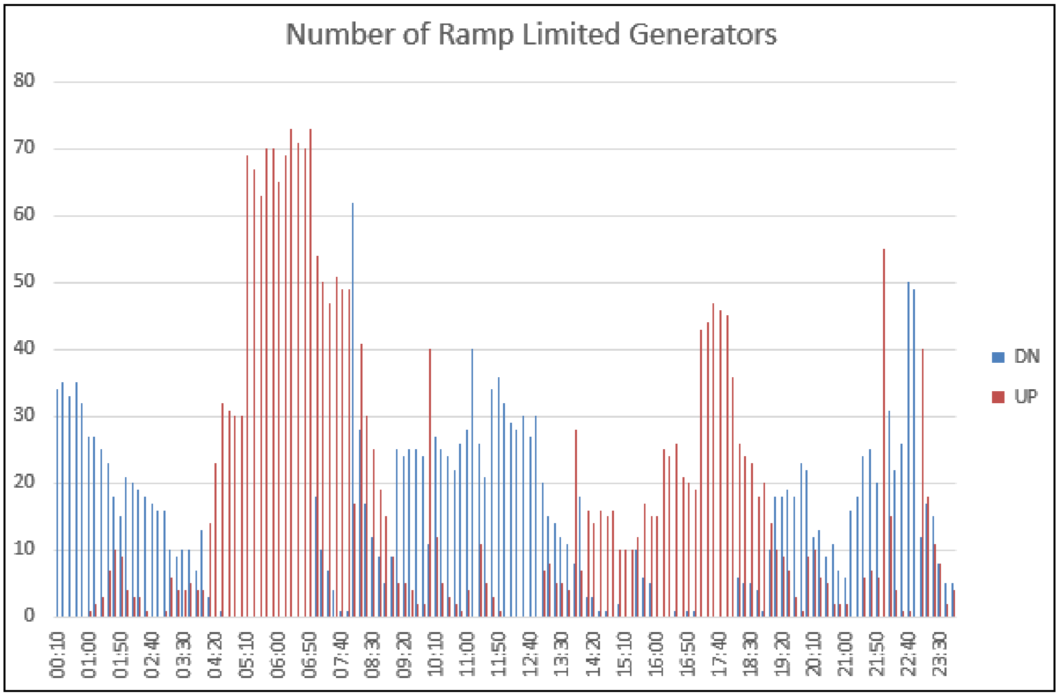

Figure 2-22: Number of Ramp-constrained Units per 10-minute Interval (20% HOBO, January 8)

Results: 20% HOBO - March 4

Observations / characteristics:

- ✓ Screening criteria met: Largest LNR period to period change
- ✓ Adequate headroom
- ✓ Good operating flexibility

Few operational challenges were identified during the March 4 sub-hourly analysis. This day was also studied for the high-solar scenario, and in general, the HOBO renewable profile presented a slightly easier solution than the high solar for the same day (as measured by fewer ramp constraints, fewer price spikes, and more headroom amongst other factors).

Results: 20% HOBO - March 9

Observations / characteristics:

- ✓ Screening criteria met: Largest number of ramps exceeding committed resource capability; large number of periods exceeding committed resource headroom
- ✓ Strong forward-market commitment of thermal generation
- ✓ Plenty of operating flexibility

- ✓ Low LMPs

There were no operational challenges noted during this sub-hourly simulation; there was plenty of thermal generation on-line to meet changes in demand and renewable energy.

Results: 20% HOBO - May 26

Observations / characteristics:

- ✓ Screening criteria met: Largest difference between LNR peak and min
- ✓ Quick increase and decrease in wind output
- ✓ Corresponding generator ramp limitations

May 26 was also studied under the 14% scenario. In both scenarios, the day is largely defined by the sharp increase in on-shore wind – followed by a sharp decrease – in the early morning, with another significant increase in the afternoon. The main difference for the 20% case is a higher amount of off-shore wind. Figure 2-23 shows the high variability of wind power, similar to the 14% scenario.

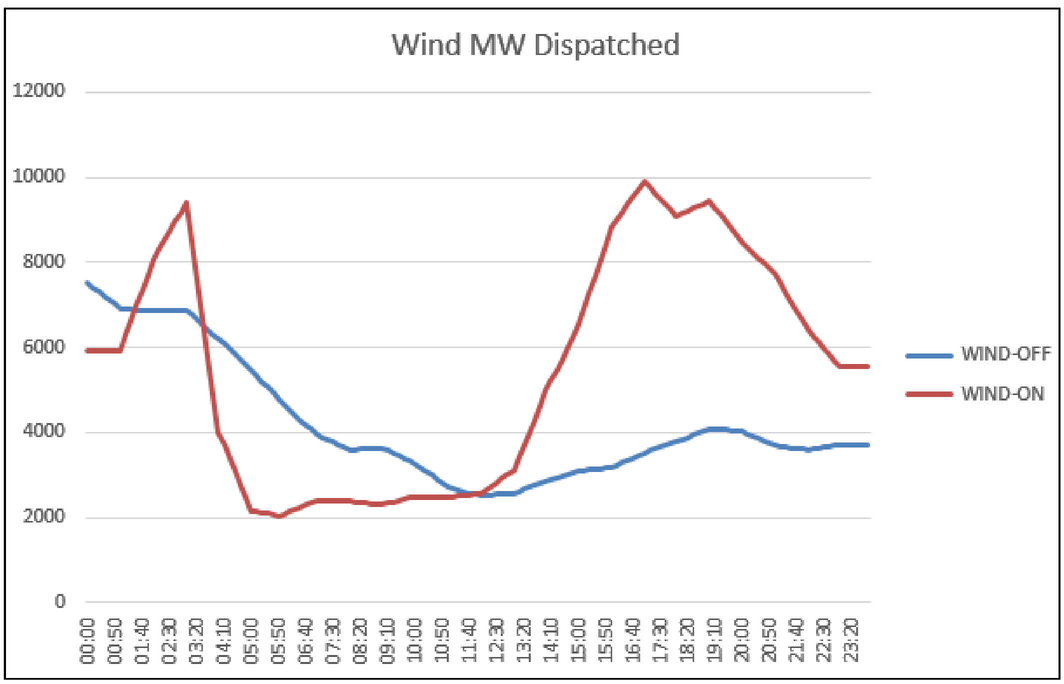

Figure 2-23: Wind Dispatch for Each Interval (20% HOBO, May 26)

The challenges and observations are very similar to the May 26 simulation for the 14% RPS scenario: thermal generation is ramped down only to be ramped up again an hour later as the wind output drops significantly and load begins to increase; ramp constraints are slightly more in the 20% case. Further, during the afternoon hours, the increased wind generation follows load increase, and in this case reduces the ramp constraints on thermal generation as they are not as active in following load. Figure 2-24 shows the extensive ramp up constraints during the early morning, and the lack of ramp constraints when wind increases during toward the afternoon peak demand.

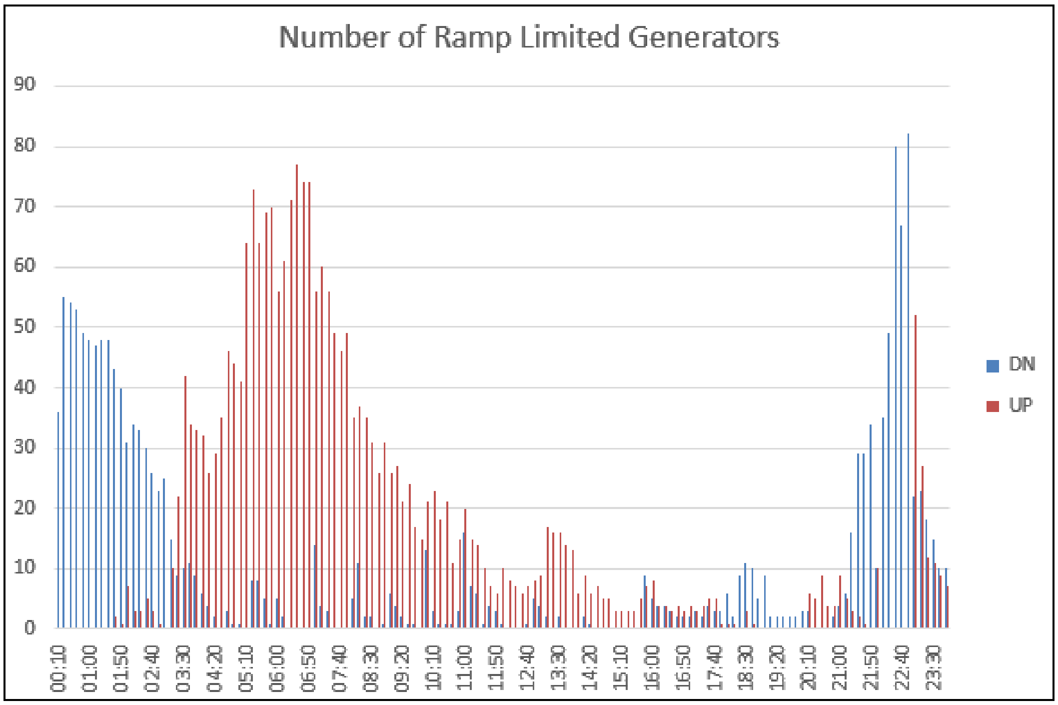

Figure 2-24: Number of Ramp-constrained Units per 10-minute Interval (20% HOBO, May 26)

The additional generation in the 20% case resulted in fewer challenges than the same day in the 14% case, in terms of providing more overall resources and lower costs. However, more price spikes occurred in the 20% HOBO case, which correlates to the morning and evening hours when wind generation is not following load. In other words, during the few times when challenging conditions occur, they are slightly worse in the 20% case, whereas load-following performance is improved by the additional wind and solar resources during the rest of the day.

Results: 20% HOBO - July 17

Observations / characteristics:

- ✓ Screening criteria met: Largest number of periods exceeding committed resource headroom
- ✓ Near peak demand
- ✓ Several intervals with low headroom
- ✓ Some CT commitment required in real-time

The July 17 HOBO case is a higher demand day, with a renewable profile defined by a drop-off in onshore wind in the morning followed by a surge in wind generation during the late afternoon. Figure 2-25 illustrates this effect; note the significant "wind pick-up" beginning around hour 15.

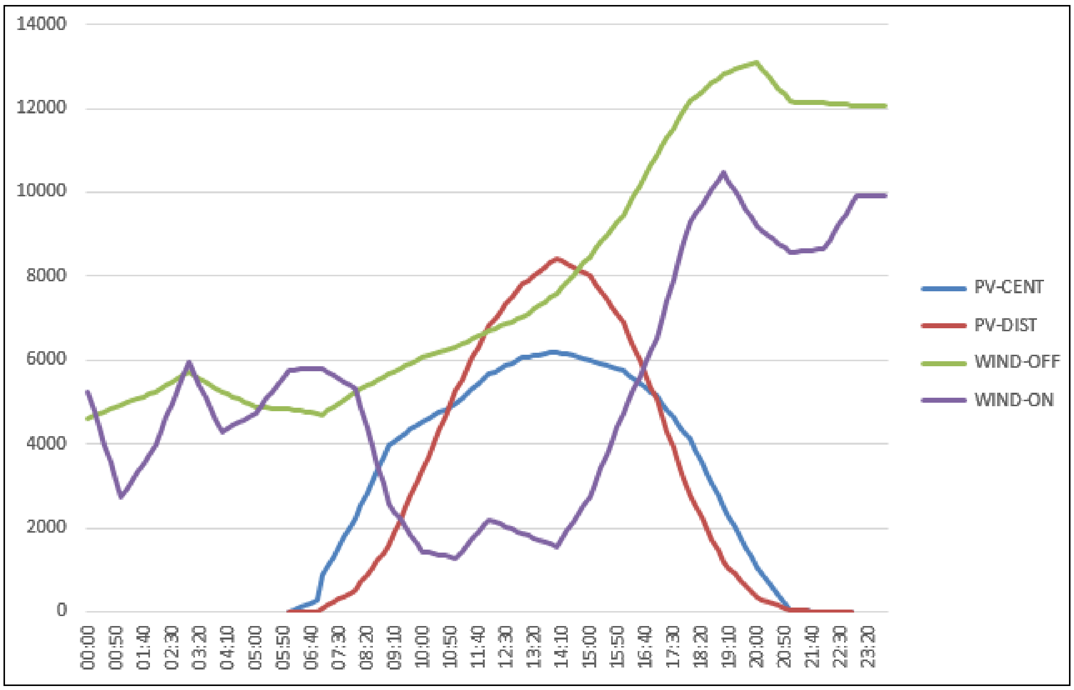

Figure 2-25: Renewable Generation Dispatch for Each Interval

Despite the wind and load profile, the solar energy increase in the morning largely offset the decrease in on-shore wind, and solar plus off-shore wind reasonably followed the load increase. There was an increase in generator ramp-down constraints during the late-afternoon wind surge, but not as significant as other simulations, and also offset to some extent by the natural reduction in solar energy. Figure 2-26 shows the load-net-renewable value and CT dispatch.

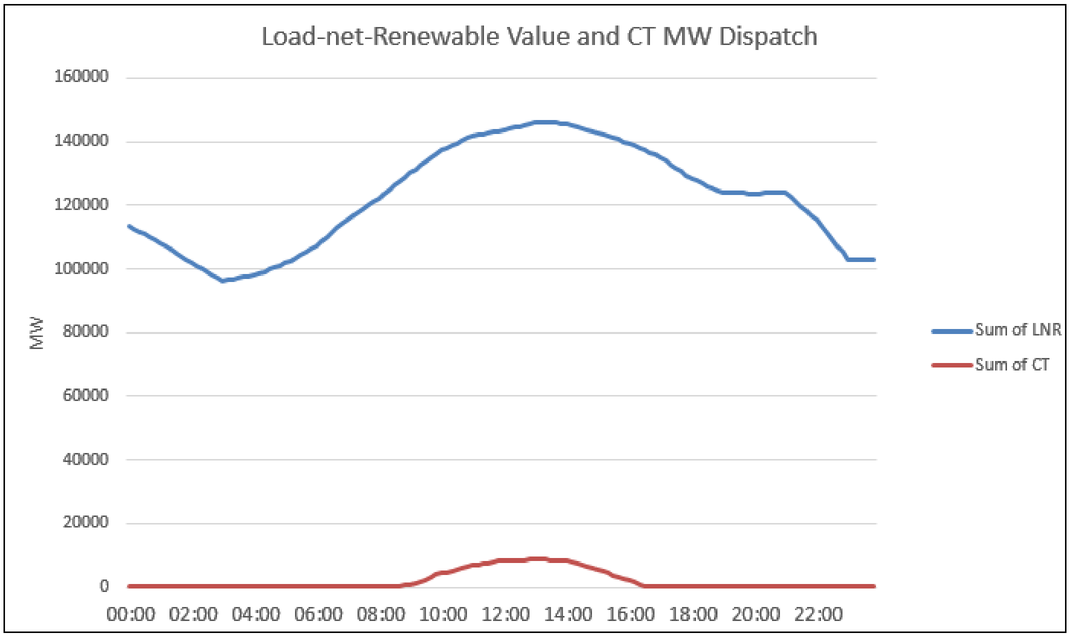

Figure 2-26: Load-net-Renewable and CT Dispatch (20% HOBO, July 17)

<u>Results: 20% HOBO - July 27</u>

Observations / characteristics:

- ✓ Screening criteria met: Largest difference between LNR peak and min; large number of periods exceeding committed resource headroom
- ✓ Near peak demand
- ✓ Several intervals with low headroom
- ✓ High RT CT commitment and high LMPs
- ✓ 182 instances of transmission overloads

The top two operational concerns were the overloaded transmission lines and the CT commitment; turning on CTs in the real-time market is common on peak days, but the pattern of CT commitment may be different than market operators typically experience in current operating days. That is, the renewable studies show CT commitment earlier and later in the day than is typical.

The July 27 HOBO case provides another opportunity to compare a 20% case to one of the extreme 2% BAU cases for which a sub-hourly simulation was performed. The screening criteria identified July 27 for the 20% HOBO scenario as being potentially low on headroom, but in fact it demonstrated the following improvements as compared to the July 27 2% BAU simulation:

- ✓ Elimination of intervals when reserves are called upon to provide energy

- ✓ Additional headroom for on-line thermal generation
- ✓ Less RT CT commitment
- ✓ Lower LMP and elimination of price spikes
- ✓ A 56% decrease in transmission overloads

The instances of ramp constrained generation increased under the 20% scenario, which can be attributed to the renewable variability, but also to the fact that in the 2% BAU case many thermal units were dispatched at full capacity for much of the day.

2.5.5 Summary of Results: 20% LOBO Scenario

Six sub-hourly simulations were completed for the 20% LOBO case. Table 2-6 summarizes high-level results of the sub-hourly simulations for these simulations.

Table 2-6: PROBE Analysis Results Summary for 20% LOBO Challenging Days

	17-Feb	20-Mar	26-May	15-Jul	17-Jul	1-Sep
Instances of Load Shedding	0	0	0	0	0	0
Intervals When Reserves Provide Energy	11	4	0	2	3	0
Average Dispatch Headroom - Online Steam/CC (MW)	592	4716	9040	7034	7011	7521
Minimum Dispatch Headroom - Online Steam/CC (MW)	0	49	116	21	74	1081
Instances of Ramp-Constrained Generation	1946	2722	3915	2892	3065	3236
Total Unit-Intervals of RT CT Commitment	5712	108	74	403	418	128
Average RT CT Commitment per Interval	40	<1	< 1	3	3	5
Number of RT CTs Committed - Highest Interval	108	9	8	14	26	12
Average LMP	$138.40	$60.18	$64.61	$88.43	$87.25	$50.96
LMP Spikes	5	3	3	2	2	3
Average Reserve Price	$94.13	$13.73	$13.60	$29.99	$30.72	$4.15

These sub-hourly simulations demonstrated more challenging intervals as compared to the HOBO cases. While a similar amount of renewable generation was available, the location and profile of the generation in the HOBO scenario created more volatility. Each of the simulations is discussed in more detail below.

Results: 20% LOBO - February 17

Observations / characteristics:

- ✓ Screening criteria met: Largest LNR period to period change; large number of ramps that exceeded committed resource capability
- ✓ Eleven intervals when reserves provide energy
- ✓ Under-commitment of thermal generation in the forward market
- ✓ Highest RT CT commitment of any sub-hourly simulation including all 2%, 14%, 30%, and 20% under other profiles cases
- ✓ High LMPs

February 17 is characterized by the fact that the particular load and renewable profile (average demand with higher renewables) result in minimal commitment of thermal generation in the forward market. This is a formula for concern when entering real-time operations. Further, Figure 2-27 demonstrates an inverse correlation between demand and renewable generation output for the day, resulting in the lowest renewable generation during periods of the highest demand.

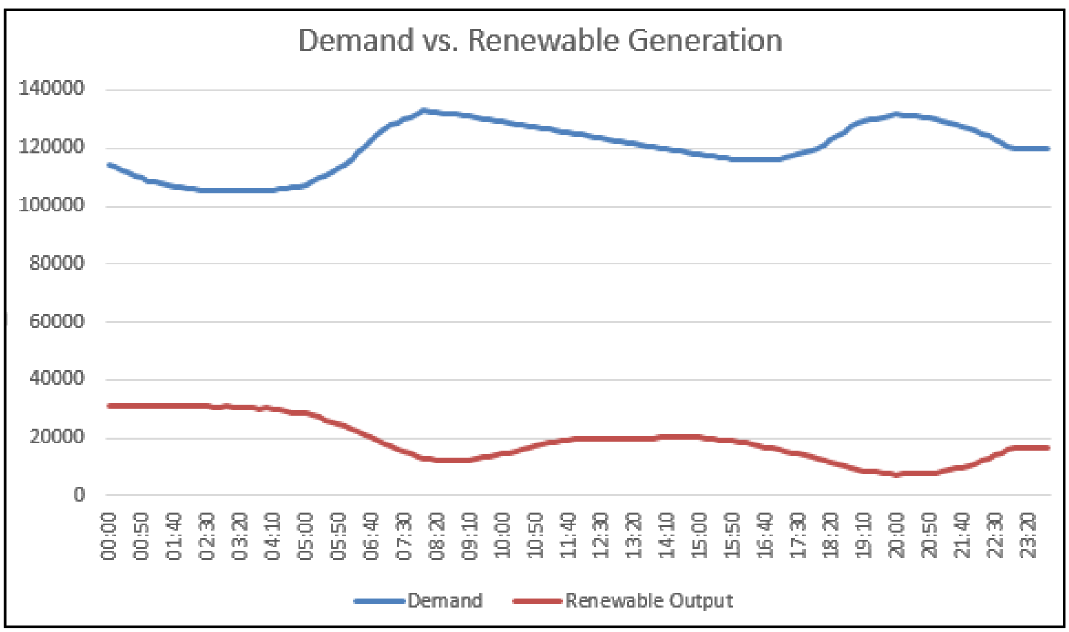

Figure 2-27: Wind Output and Demand (20% LOBO, February 17)

For this simulation, reserves were called upon to provide energy during eleven intervals, most frequently and significantly when the demand and renewable generation go in opposite directions during the early morning hours (6-7) as seen in Figure 2-27.

The ramp constraints are actually slightly less frequent as compared to other sub-hourly simulations, but this is also a result of the fact that fewer thermal units are on-line entering the day. Figure 2-28 shows the headroom available from thermal generation over the course of the day. The spike represents that new generation is committed in the forward market, but needs time to ramp – once it ramps, its capacity is quickly used due to the load increase and wind decrease.

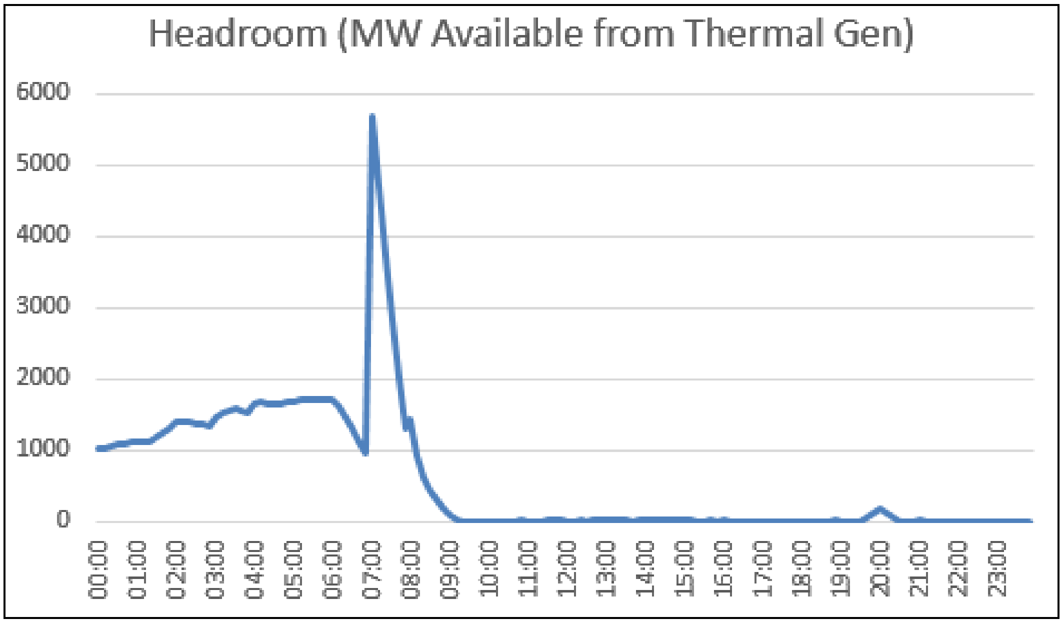

Figure 2-28: Headroom - MW Available from Thermal Generation (20% LOBO, February 17)

The end result of the factors discussed above is an enormous reliance on CTs during the challenging time frames, as shown Figure 2-29.

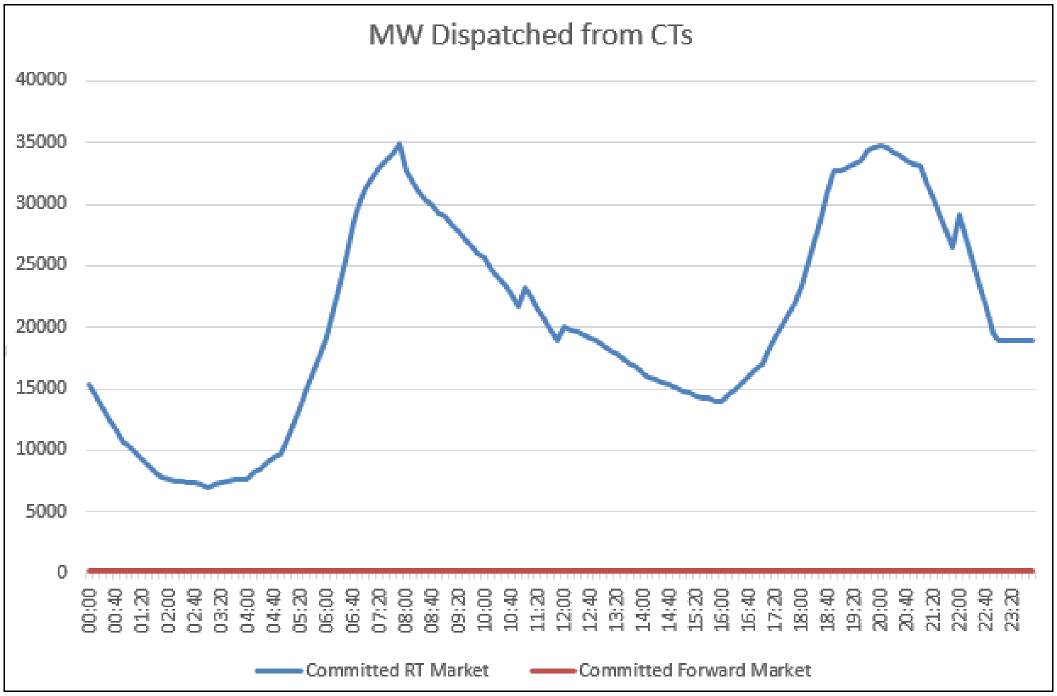

Figure 2-29: CT MW Dispatched (20% LOBO, February 17)

There were also overloads on three transmission lines required to solve this simulation. This is a major concern and depending on exact operational protocols is typically avoided at all costs in real-time operations (i.e. some markets allow very small transient violations or "short-term emergency" violations; the violations reported here are more persistent).

Results: 20% LOBO - March 20

Observations / characteristics:

- ✓ Screening criteria met: Largest number of ramps that exceeded committed resource capability
- ✓ Four intervals when reserves provide energy
- ✓ Several intervals with near-zero headroom
- ✓ Operational challenges during the first two hours of the day

During the March 20 sub-hourly simulation, there were four intervals when reserves were called upon to provide energy; three of these intervals were in the first hour of the day. On this particular day, renewable energy output is lowest shortly after midnight and increases throughout the day.

The result of the renewable energy / demand profile is a generator commitment profile that appears to have an under-commitment of thermal generation at the beginning of the day. The unit commitment software decision from the forward market simulation, however, appears reasonable considering higher thermal generation unit commitment to account for a couple of early morning hours could result in an over-generation situation later in the day (assuming generator parameters such as minimum run times are honored).

Figure 2-30 shows the somewhat unusual pattern of headroom (MW available from thermal generation over the course of the day). The rapid increase around 1am – 2am is a function of both increasing renewable energy and decreasing demand. There were also a couple of large steam turbines that were not committed until the second and third hour of the day in the forward market.

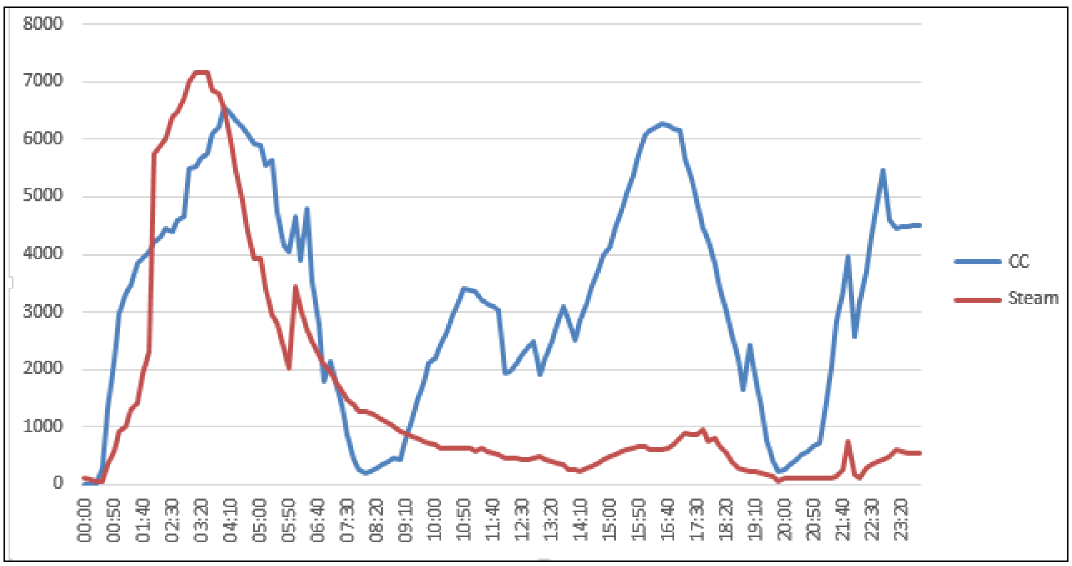

Figure 2-30: Headroom - MW Available from Thermal Generation (20% LOBO, March 20)

In addition to borrowing from reserves, the lack of thermal generation in the first two hours is offset by the use of CTs: all real-time CT commitment found in this study occurs in these two hours. The rest of the day showed no operational concerns.

<u>Results: 20% LOBO - May 26</u>

Observations / characteristics:

- ✓ Screening criteria met: Large difference between LNR peak and min; large number of periods exceeding committed resource headroom
- ✓ Better headroom in the actual simulation and good operational flexibility

The results and conclusions for May 26 20% LOBO are very similar to May 26 20% HOBO. As noted earlier, May 26 is the day characterized by the sharp increase in on-shore wind – followed by a sharp decrease – in the early morning, with another clear increase in the afternoon. The main concern is the generator ramping / load following capability due to the sharp changes.

The price spikes are slightly less severe in this case, but otherwise there is no additional difference between the performance of RT operations in the May 26 HOBO/LOBO cases.

<u>Results: 20% LOBO - July 15</u>

Observations / characteristics:

- ✓ Screening criteria met: Largest difference between LNR peak and min
- ✓ Several intervals with near-zero headroom
- ✓ Two instances of reserve borrowing

There were a couple of transient concerns in this simulation: two completely separate morning intervals where reserves were called upon to provide energy and a couple of late-day intervals when above-average CT commitment was required. A close examination of the CT commitment shows that it is "locational," i.e. solar is decreasing and even though wind is increasing at the same time, the energy replacement is not always where it is needed on the grid due to transmission constraints.

This sub-hourly simulation also provides an opportunity to compare a 20% renewable study to the same day from the 2% BAU case. Despite the short-term operational issues noted above, the additional generation still provided an easier-to-manage real-time market including the following benefits:

- ✓ Additional on-line thermal generation available
- ✓ Much less RT CT commitment
- ✓ Lower LMP and elimination of price spikes
- ✓ Lower ancillary services prices overall

<u>Results: 20% LOBO - July 17</u>

Observations / characteristics:

- ✓ Screening criteria met: Largest number of periods exceeding committed resource headroom
- ✓ High demand

- ✓ Three instances of reserve borrowing
- ✓ Minimal headroom in several intervals

Recall from the July 17 HOBO discussion that this case is a higher demand day, with a renewable profile defined by a drop-off in onshore wind in the middle of the day followed by a surge in wind generation during the late afternoon. In the HOBO simulations, real-time challenges were reduced by solar and wind energy changes offsetting one another. Figure 2-31 below might indicate a similar result in this case, with a load-net-renewable pattern similar to a typical load curve.

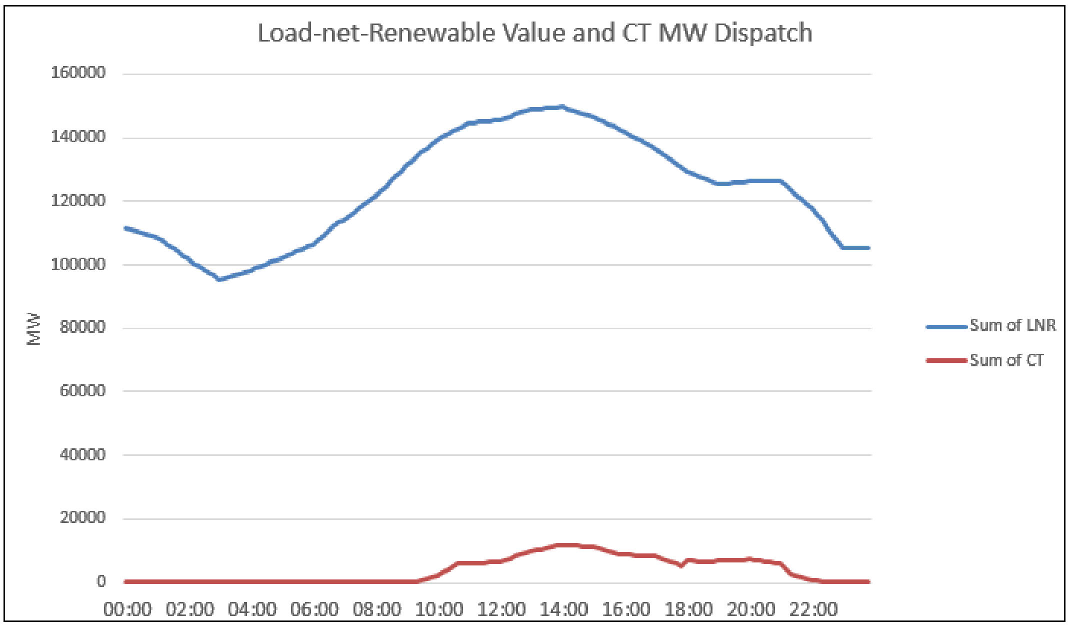

Figure 2-31: Load-net-Renewable and CT Dispatch (20% LOBO, July 17)

However, in this LOBO analysis, hour beginning 10 proved to be much more challenging than in the HOBO. Reserves were used to provide energy, several CTs were committed, and it marked the highest LMPs of the day. This can be attributed to the fact that, around this time, on-shore wind dropped 8000MW in the LOBO case versus 4000MW in the HOBO case, while offshore wind remained approximately the same in both cases. The rapid drop during a time of increasing demand caused an operationally difficult hour with reserve borrowing and significant CT commitment. Figure 2-32 shows these challenges; note the sharp drop in wind and low point in onshore wind around hour 10, and corresponding increase in CT generation.

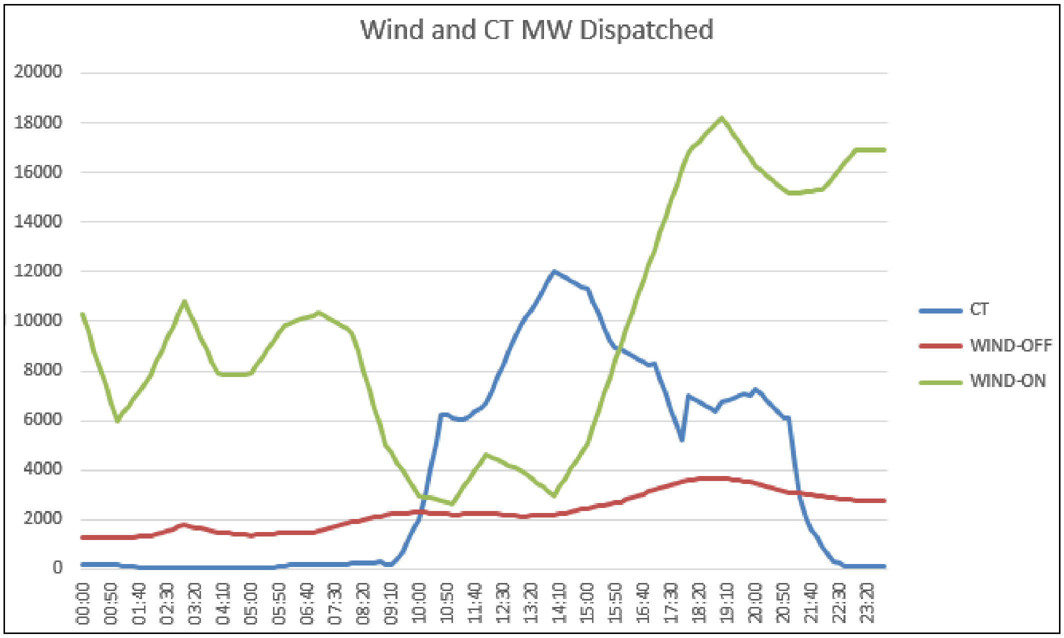

Figure 2-32: Wind vs. CT Dispatch for Each Interval

It should be noted that, unlike the HOBO case, the solar energy could not entirely offset the wind decrease due to the larger reduction in on-shore wind (the LNR increase was 3000MW greater in the LOBO/LODO case than in the HOBO), and the fact that wind and solar generation are not always in the same place. When combined with limitations of the transmission system, i.e. transmission constraints, the challenges noted above were observed.

<u>Results: 20% LOBO - September 1</u>

Observations / characteristics:

- ✓ Screening criteria met: Large number of ramps that exceeded committed resource capability; large number of periods exceeding committed resource headroom
- ✓ Strong forward commitment
- ✓ CT commitment during the first three hours of the day

Real-time CT commitment was required in the first couple of hours of the day in the New Jersey area, due to wind output reduction and fewer thermal units on-line. This is not necessarily a concern; though handling a large, consistent interval-to-interval reduction in generation in the middle of the night is unusual in current operations.

2.5.6 Summary of Results: 20% LODO Scenario

Six sub-hourly simulations were completed for the 20% LODO scenario. Table 2-7 summarizes high-level results of the sub-hourly simulations for these simulations.

Table 2-7: PROBE Analysis Results Summary for 20% LODO Challenging Days

	4-Mar	20-Mar	26-May	18-Jun	17-Jul	1-Sep
Instances of Load Shedding	0	0	0	0	0	0
Intervals When Reserves Provide Energy	0	2	0	0	2	0
Average Dispatch Headroom - Online Steam/CC (MW)	12921	4963	6603	8099	6206	7850
Minimum Dispatch Headroom - Online Steam/CC (MW)	2522	49	0	8	53	1738
Instances of Ramp-Constrained Generation	4824	2727	3621	3890	3421	3632
Total Unit-Intervals of RT CT Commitment	0	121	512	381	461	98
Average RT CT Commitment per Interval	0	1	3.5	3	3	<1
Number of RT CTs Committed - Highest Interval	0	10	19	16	25	5
Average LMP	$41.94	$58.62	$83.13	$73.54	$87.68	$51.71
LMP Spikes	2	2	1	1	2	3
Average Reserve Price	$2.47	$13.53	$27.33	$17.87	$28.70	$5.28

Each of the simulations is discussed in more detail below.

<u>Results: 20% LODO - March 4</u>

Observations / characteristics:

- ✓ Screening criteria met: Largest LNR period to period change
- ✓ Strong forward commitment and good headroom
- ✓ Not a single RT CT commitment required
- ✓ Low LMPs

The March 4 sub-hourly analysis did not present any operational challenges or concerns. This day was also studied for the high-solar scenario and HOBO scenarios. In general, the HOBO/LODO renewable profiles presented a slightly easier solution than the high solar for the same day. However, generators were ramping frequently in this case due to the renewable variability; see Figure 2-33.

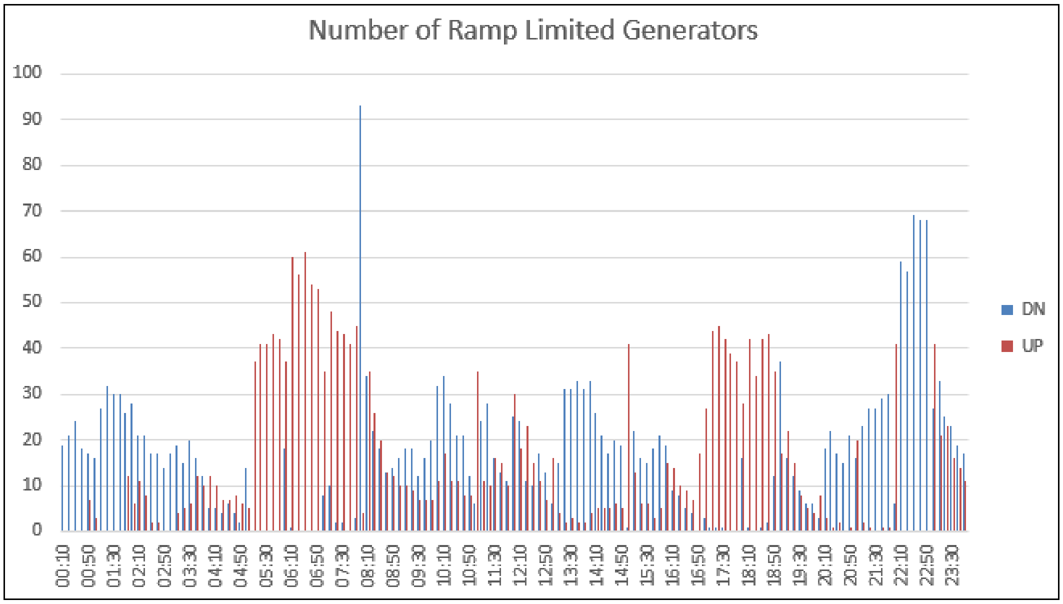

Figure 2-33: Number of Ramp-constrained Units per 10-minute Interval (20% LODO, March 4)

Results: 20% LODO - March 20

Observations / characteristics:

- ✓ Screening criteria met: Largest number of ramps that exceeded committed resource capability
- ✓ Two intervals when reserves provide energy
- ✓ Several intervals with near-zero headroom
- ✓ Operational challenges during the first two hours of the day

Recall from the LOBO discussion that this particular day shows renewable energy output at a low point shortly after midnight and then increasing throughout the day. The generation commitment and concerns were very similar, with the LODO case arguably presenting slightly better operational conditions, as measured by half as many instances where reserves were required to provide energy and slightly more thermal generation on-line. Refer to the March 20 LOBO for further discussion and examples; again, solutions were quite similar.

<u>Results: 20% LODO - May 26</u>

The simulation of May 26 for the LODO scenario was very different and required significantly more real-time CT commitment to meet demand than the HOBO/LOBO sub-hourly simulations for the same day.

Observations / characteristics:

- ✓ Screening criteria met: Largest difference between LNR peak and min; large number of periods exceeding committed resource headroom
- ✓ Several intervals with zero headroom, persistent between hours 18-21
- ✓ Significant transmission constraints and minor overloads
- ✓ CT commitment during challenging intervals

One of the main causes of the greater challenges during hours 18-21 and in the LODO case in general is a less optimal distribution of wind resources; while wind picks up during solar reductions, it is not in the ideal locations. This creates a quick change in "where the power is" and is further aggravated by less MW available from on-line thermal generation, creating (and/or caused by) additional transmission constraints. In some intervals, there were 4-5 additional persistent constraints as compared to other May 26 cases presumably a result of the alternate distribution of the wind resources, i.e. *distributed* onshore as opposed to *best* onshore.

Thus, the majority of additional CT commitment occurred during hours beginning 18 through 21.

Figure 2-34 captures the significant difference in CT dispatch explained above, for the LOBO and LODO cases. To read the chart, compare the red line to the purple line and it shows that the forward market first required significantly more CT commitment in the LODO case. Then, compare the blue line to the green line and note that the real-time market also required significantly more CT commitment in the LODO case. Overall, there were about 50% more transmission constraints in the LODO case that led to higher CT dispatch.

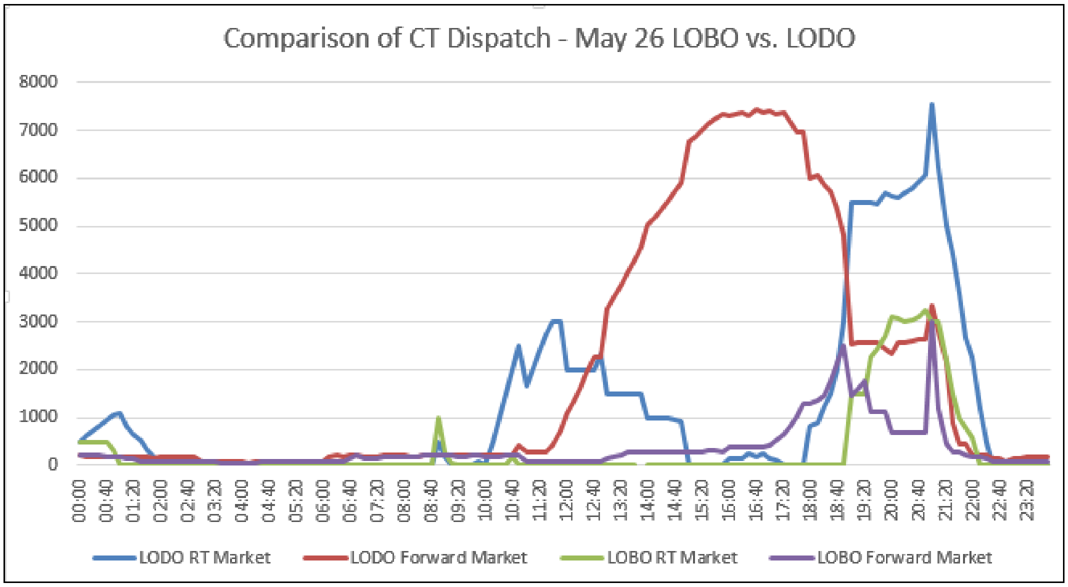

Figure 2-34: Comparison of CT Dispatch for LOBO vs. LODO, May 26

<u>Results: 20% LODO - June 18</u>

Observations / characteristics:

- ✓ Screening criteria met: Largest difference between LNR peak and min
- ✓ Several intervals with near-zero headroom
- ✓ 125 instances of transmission overloads
- ✓ CT commitment during challenging intervals; up to 16 CTs committed in RT during some of these intervals

There were several challenging intervals late in the day where nearly all renewable resources ramped down quickly as shown in Figure 2-35, producing faster renewable generation decrease than demand.

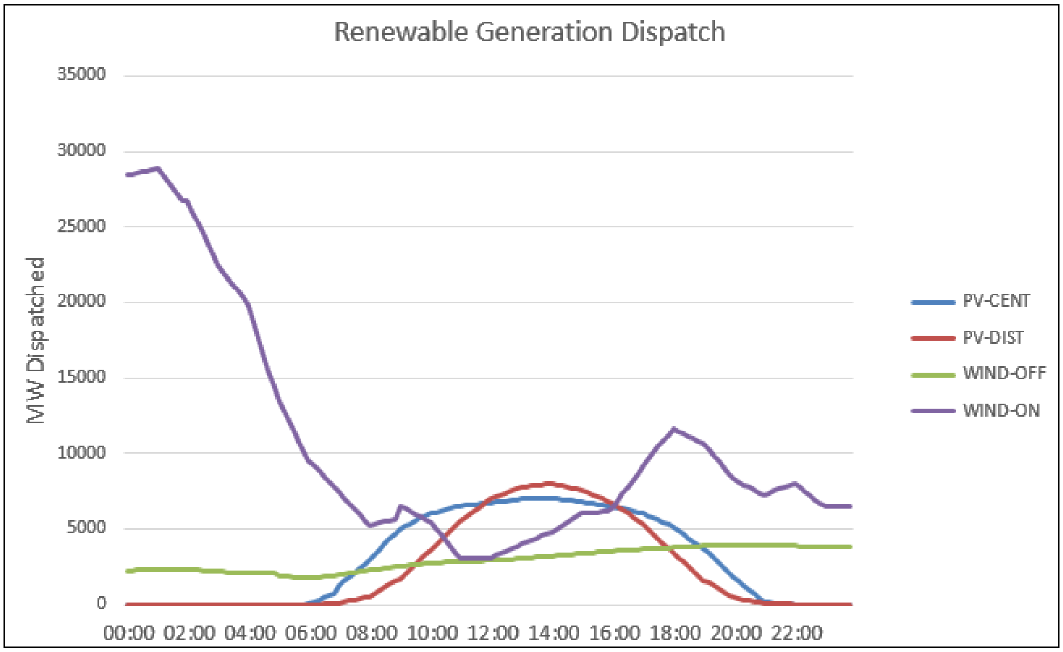

Figure 2-35: Renewable Generation Dispatch for Each Interval (20% LODO, June 18)

Thermal generation ramped up where possible, but quick-start generation commitment was required to fill the gap between demand and changes in renewable generation.

Further, there were several instances of transmission overload during hours beginning 18-21, and additional overloads on two lines in the hours preceding this time frame. Several of these overloads are also present in the forward commitment. This is a cause for concern, and in this particular sub-hourly simulation, it appears that the best solution to the overloads would be to curtail offshore wind.

A pattern has been noted where "distributed" onshore results in more transmission overloads than "best" onshore.

<u>Results: 20% LODO - July 17</u>

Observations / characteristics:

- ✓ Screening criteria met: Largest number of periods exceeding committed resource headroom
- ✓ High demand
- ✓ Two instances of reserve borrowing
- ✓ Minimal headroom in several intervals
- ✓ Some CT commitment and transmission overloads, especially hour 10

Recall from the July 17 HOBO discussion that this case is a higher demand day, with a renewable profile defined by a drop-off in onshore wind in the middle of the day followed by a surge in wind generation during the late afternoon. Figure 2-36 below shows the renewable pattern, which is similar to the HOBO, except that in the LODO case onshore wind replaces offshore.

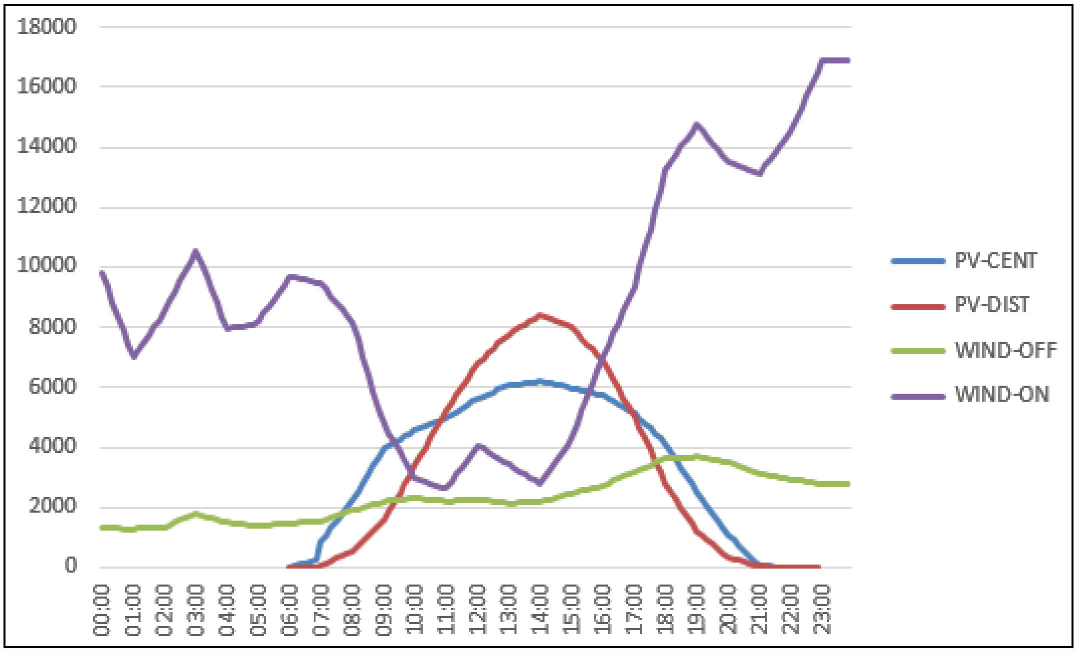

Figure 2-36: Renewable Generation Dispatch for Each Interval (20% LODO, July 17)

In the HOBO case, no significant concerns were identified. However, in this LODO analysis – just like the LOBO analysis – hour beginning 10 proved to be much more challenging than in the HOBO. Reserves were used to provide energy, several CTs were committed, and it marked the highest LMPs of the day. This can be attributed to the fact that, around this time, on-shore wind dropped 8000MW in the LOBO case versus 4000MW in the HOBO case, while offshore wind remained approximately the same in both cases. The rapid drop during a time of increasing demand causes an operationally difficult hour with reserve borrowing and significant CT commitment.

Figure 2-37 demonstrates the correlation between LNR and CT dispatch during the day.

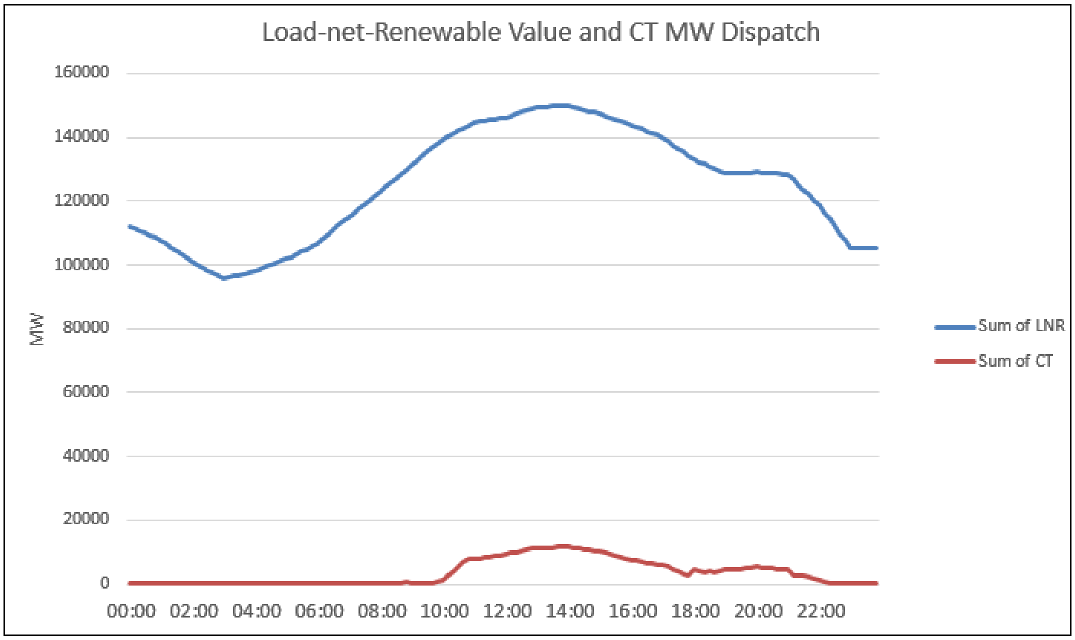

Figure 2-37: Load-net-Renewable and CT Dispatch (20% LODO, July 17)

Also similar to the LOBO, unlike the HOBO case, the solar energy could not entirely offset the wind decrease due to the larger reduction in on-shore wind (the LNR increase was 3000MW greater in the LOBO/LODO case than in the HOBO), and the fact that wind and solar generation are not always in the same place. When combined with limitations of the transmission system, i.e. transmission constraints, the challenges noted above were observed.

Upon close comparison of the July 17 LOBO and LODO cases, while the results are similar, the LODO case has slightly less operational flexibility than the LOBO. The LODO case has less headroom and more ramp-constrained generation, as well as more transmission overloads, and requires a slightly higher CT commitment. Figure 2-38 shows the headroom for the LODO and LOBO cases, and Figure ## shows the LMP across all three scenarios performed for July 17.

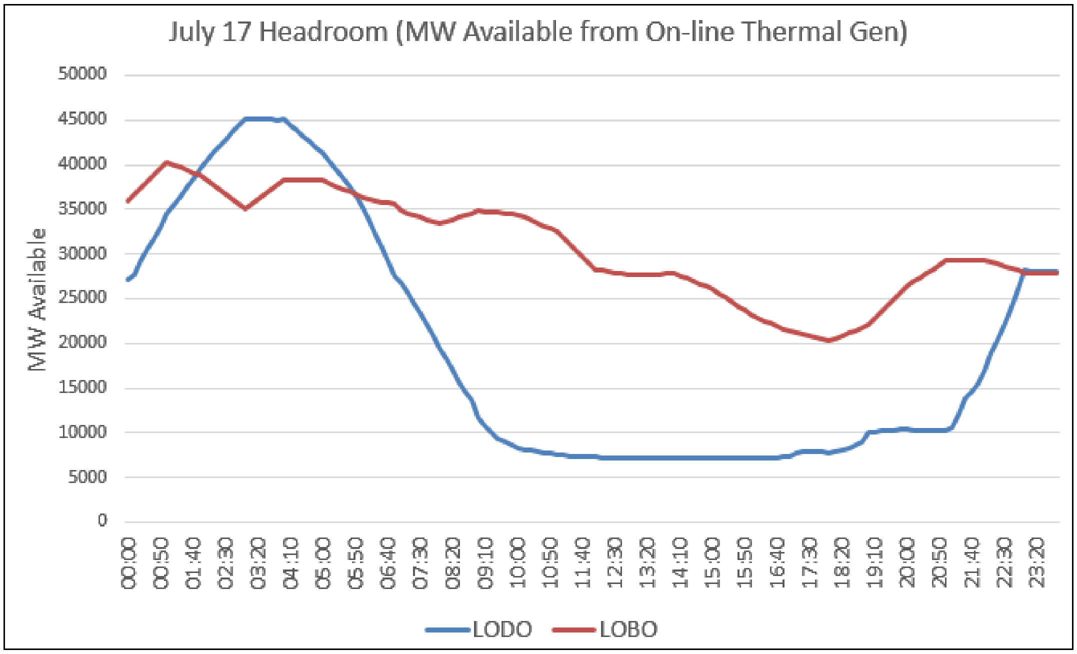

Figure 2-38: Headroom - MW Available from Thermal Generation (20% LODO, July 17)

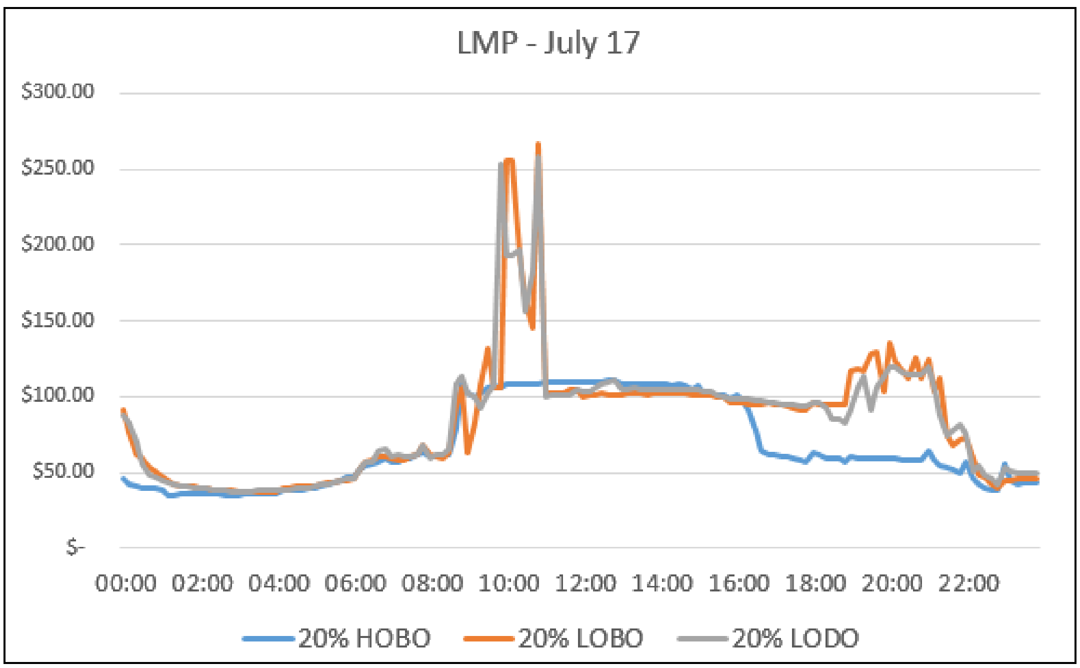

Figure 2-39: LMP Across Scenarios for July 17

<u>Results: 20% LODO - September 1</u>

Observations / characteristics:

- ✓ Screening criteria met: Large number of ramps that exceeded committed resource capability; large number of periods exceeding committed resource headroom
- ✓ CT commitment during the first two hours of the day

The sub-hourly simulation for the September 1 LODO case performed similar to the LOBO: Real-time CT commitment was required in the first couple of hours of the day in the New Jersey area, due to wind output reduction and fewer thermal units on-line. This is not necessarily a concern; though handling a large, consistent interval-to-interval reduction in generation in the middle of the night is unusual in current operations.

2.5.7 Summary of Results: 30% HSBO Scenario

Five sub-hourly simulations were completed for the 30% HSBO scenario. Table 2-8 summarizes high-level results of the sub-hourly simulations for these simulations.

Table 2-8: PROBE Analysis Results Summary for 30% HSBO Challenging Days

	5-Jan	17-Feb	12-Apr	26-Apr	18-Jun
Instances of Load Shedding	0	0	0	0	0
Intervals When Reserves Provide Energy	1	3	1	1	2
Average Dispatch Headroom - Online Steam/CC (MW)	9558	3749	5828	5236	2773
Minimum Dispatch Headroom - Online Steam/CC (MW)	1772	0	0	379	36
Instances of Ramp-Constrained Generation	4578	2226	3558	2687	2138
Total Unit-Intervals of RT CT Commitment	0	745	132	0	1913
Average RT CT Commitment per Interval	0	5	1	0	13
Number of RT CTs Committed - Highest Interval	0	19	7	0	33
Average LMP	$46.68	$80.74	$40.86	$37.16	$103.30
LMP Spikes	1	3	1	4	1
Average Reserve Price	$8.47	$41.74	$15.38	$14.32	$52.04

<u>Results: 30% HSBO - January 5</u>

The January 5 sub-hourly simulation generally presented fewer concerns than other 30% HSBO cases.

Observations / characteristics:

- ✓ Screening criteria met: Large difference between LNR peak and min; large LNR period to period change
- ✓ Many generator ramp constraints in the early morning

- ✓ No real-time CT commitment required

Figure 2-40 demonstrates that demand increases earlier in the day than solar energy output, and demand again increases in the early evening when solar energy is decreasing. As a result, when combined with the fact that solar and other renewable generation reduced overall the thermal commitment as compared to a BAU case, the figure shows that thermal generators are frequently limited by their ramp capability during these times. This reflects the limitation that solar energy does not offer assistance during the morning or evening demand pick-up.

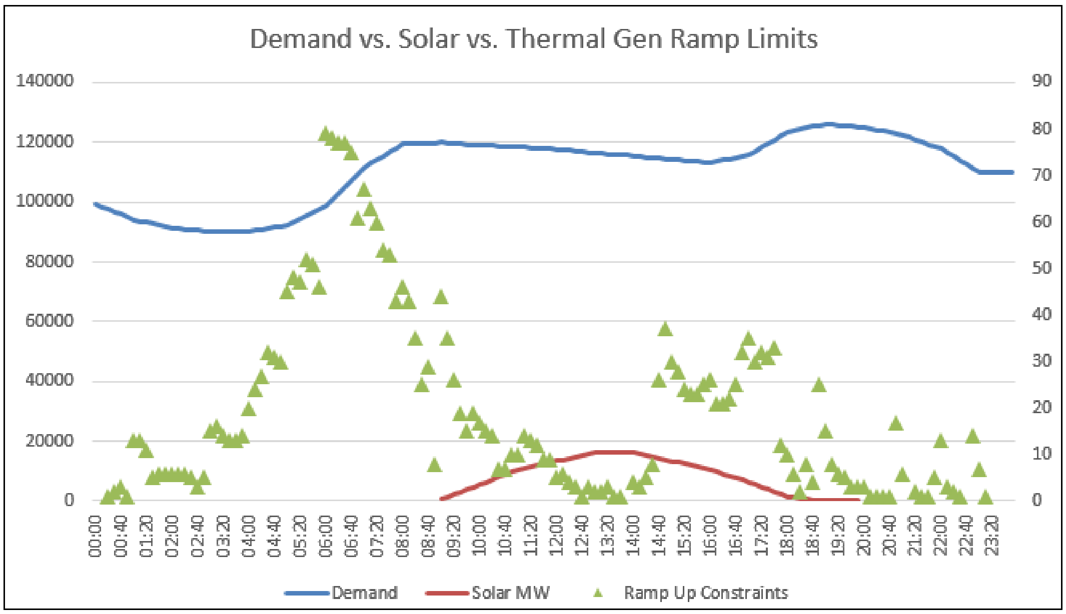

Figure 2-40: Demand MW, Solar Dispatch, and Generator Ramp Limitations (20% HSBO, January 5)

The forward-looking commitment had an appropriate amount and mix of thermal generation on-line entering the day to avoid any negative events despite the fact that many thermal generators were limited by ramp capability.

<u>Results: 30% HSBO - February 17</u>

February 17 has been studied under several different scenarios and has proven to be a challenging day in almost every case.

Observations / characteristics:

- ✓ Screening criteria met: Largest LNR period-to-period change
- ✓ Many sub-hourly intervals with zero headroom

- ✓ Not enough thermal generation committed in the forward market
- ✓ CTs, reserves required to cover energy shortage

Violated line rating on three transmission lines due to high renewable concentration

The particular demand and renewable profile on February 17 appears to under-commit thermal generation in almost all renewable profiles (i.e. HSBO, LOBO, etc.). This results in low headroom, and in this high solar run further results in real-time CT commitment and a couple of instances where reserves are required to provide energy. The maximum CT requirement is in hour 8, when demand is increasing prior to the solar energy increase.

Figure 2-41 shows that without adequate headroom, CTs are required to meet demand when solar energy increases too late or drops off too early to meet demand. This is different than January 5, when plenty of headroom was available to meet the LNR changes and the only concern was ramp constraints (with CTs still available if necessary).

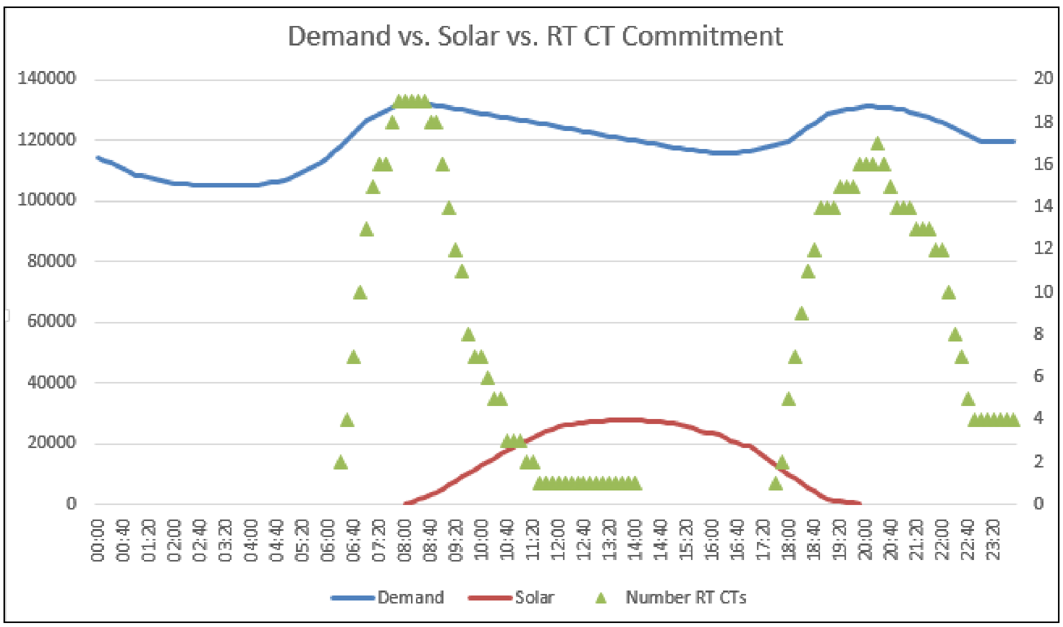

Figure 2-41: Demand MW, Solar Generation, and Number of CTs Committed in RT (30% HSBO, February 17)

Further, the generation shortage and overall pattern of the generation / renewable energy result in constraint violations (i.e. overloads) in some intervals. The overloads are largely related to a "generation pocket" where a large amount of solar energy is concentrated. This could be a major concern and depending on exact operational protocols it would be typically avoided at all costs in real-time operations (i.e. some markets allow very small transient violations or "short-term emergency" violations; the violations reported here are more persistent). In this case, operations would likely have to curtail the solar output.

In some other cases, when penalty prices for transmission overloads are set very low in the GE MAPS simulation, the optimization process would choose transmission overload before curtailment of cheap renewable generation.

Alternatively, the transmission overlay process may not eliminate some local congestion. In the congestion mitigation process used in the GE MAPS iterations to identify the transmission overlays, the price differentials caused by some local congestion may not go above the threshold of $5/MW that would warrant transmission upgrade. High concentration of solar (or wind) generation such local generation pockets would result in a high level of curtailment. Such a possibility could be viewed as a siting issue. Developers typically perform siting and feasibility studies, and would not choose to site solar resources in a known generation pocket.

Results: 30% HSBO - April 12

Observations / characteristics:

- ✓ Screening criteria met: Largest number of ramps that exceed committed resource capability
- ✓ Off-peak hours present more challenges than peak hours
- ✓ Real-time CT commitment required in first two hours of the day

This day's renewable profile, shown in Figure 2-42, does indeed show steep changes in renewable energy; most notably for the distributed PV (the central PV shows a more rounded pattern).

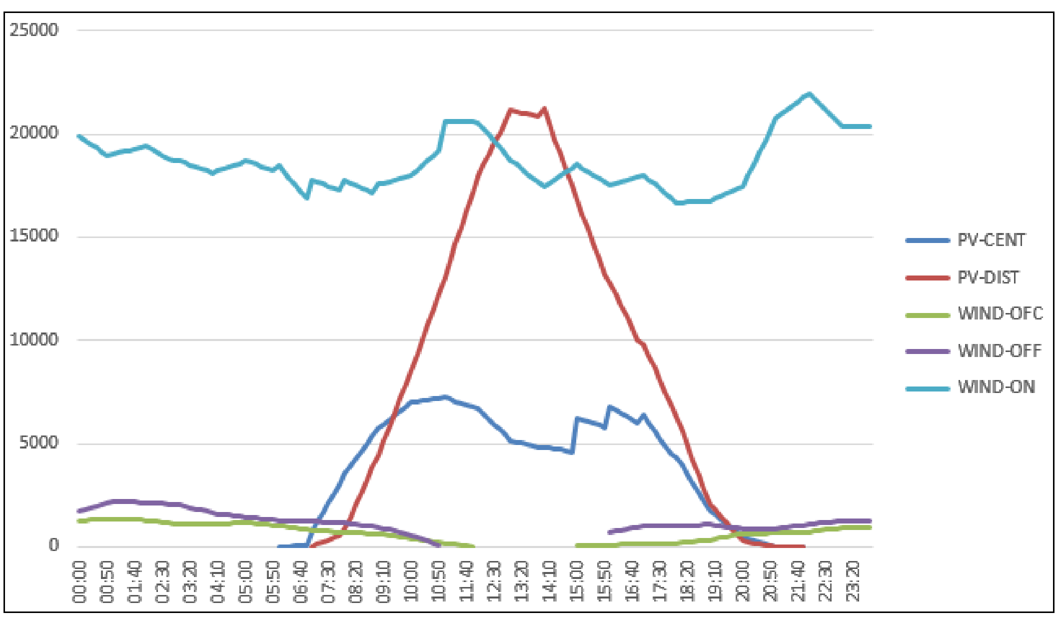

Figure 2-42: Renewable Generation Dispatch for Each Interval (30% HSBO, April 12)

The first result of this variability is above-average ramp limitations, with hour 17 having the most ramp-up constraints as shown in Figure 2-43, which clearly corresponds to the steep reduction in solar energy shown above.

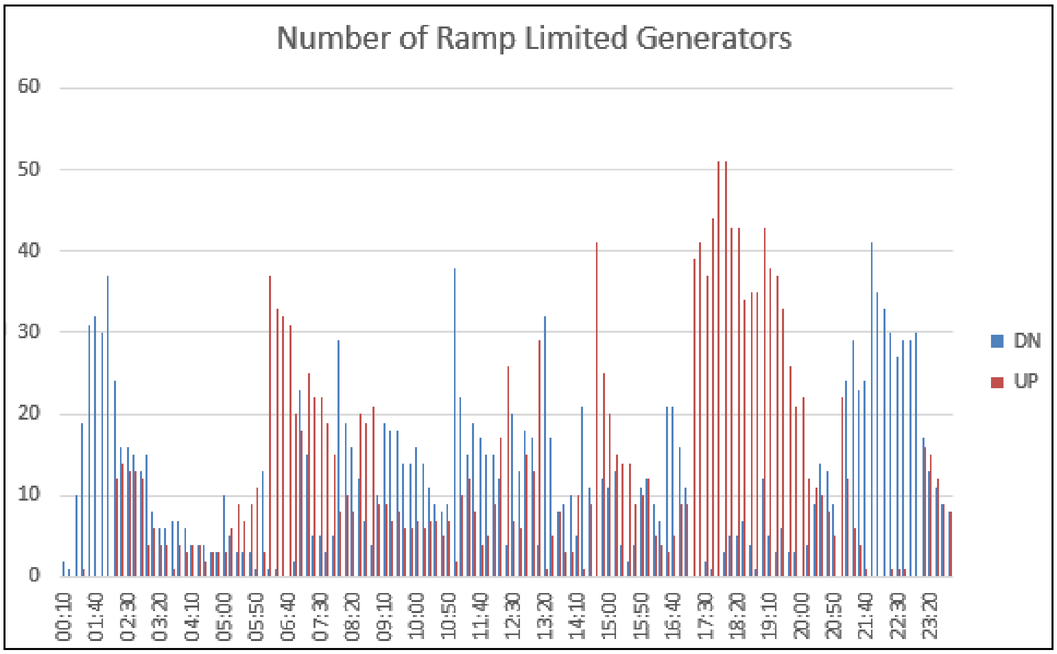

Figure 2-43: Number of Ramp-constrained Units per 10-minute Interval (30% HSBO, April 12)

At the same time, this renewable profile appears to also keep several thermal units offline for the after-midnight hours, presumably to avoid the possibly of an over-generation situation later (considering that thermal generation is typically bound by minimum run times or other parameters).

The result is that CT commitment is required in the first few hours of the day, and combined cycle generation is committed and dispatched much later in the day; this need for a strong combined cycle commitment for late afternoon hours was adequately identified in the forward market. While these are not necessarily a significant problem, the April 12 simulation certainly presents a very different operating scenario for market operators than a business-as-usual day, as measured by the hours when CTs are needed and significant combined cycle ramp-up activity much later in the day. Figure 2-44 illustrates these facts – CT commitment after midnight, and minimal combined cycle dispatch until the massive ramp-up and ramp-down in combined cycle output during the solar reduction.

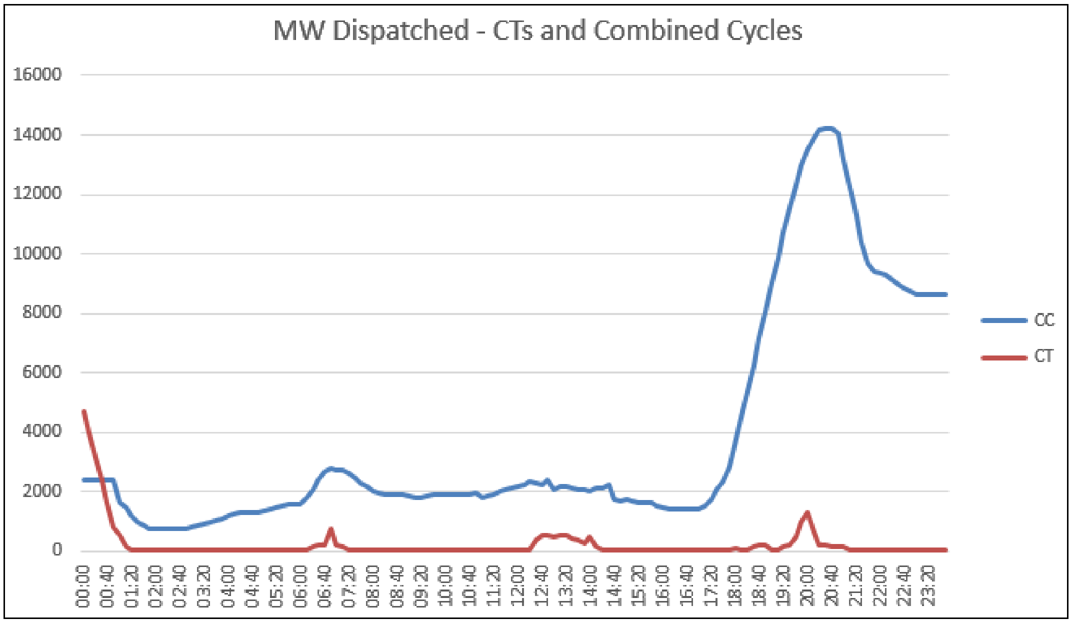

Figure 2-44: Combined Cycle and CT Dispatch (30% HSBO, April 12)

Finally, Figure 2-45 summarizes in one chart the details described above, by showing the total load-net renewable value and the response of CTs, CCs, and Steam generation.

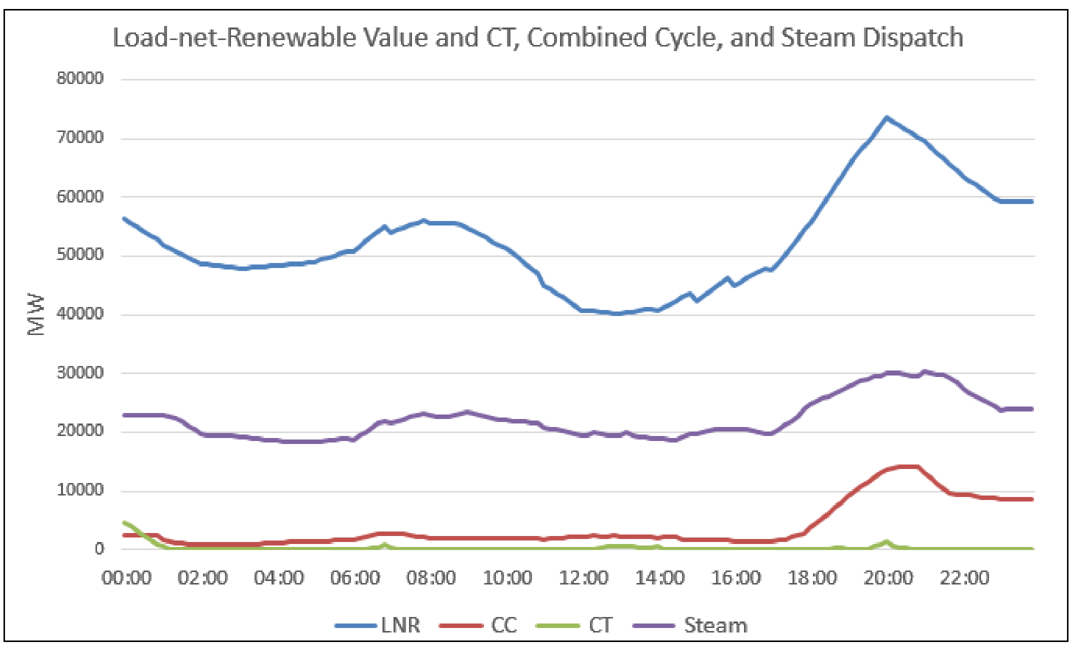

Figure 2-45: Load-net-Renewable with Fuel Generation Dispatch Response (30% HSBO, April 12)

Results: 30% HSBO - April 26

Observations / characteristics:

- ✓ Screening criteria met: Highest number of periods exceeding committed resource headroom
- ✓ During one interval with minimal headroom, reserves were called upon to provide energy

The lack of headroom, while a potential concern, did not produce persistent problems over the course of the day. The reason for this is that the renewable generation profile reasonably followed the demand profile for much of the day.

There were three minor price spikes in the early evening hours as total renewable generation quickly decreased, and thermal generation was ramped up to meet demand.

In summary, there was just enough commitment entering the real-time market, but had the renewable forecast not come in on target, a strong likelihood exists that there would've been much more severe problems.

Results: 30% HSBO - June 18

The high solar study for June 18 proved to present more operational challenges than the June 18 day for other renewable profiles.

Among the observations for this study day:

- ✓ Screening criteria met: Largest difference between LNR peak and min
- ✓ Two intervals where reserves were called upon to provide energy
- ✓ Low headroom for on-line thermal resources
- ✓ High CT commitment in real-time
- ✓ Higher LMPs and reserves prices
- ✓ Above average frequency of transmission constraints
- ✓ Lower number of ramp constrained generators as the solar generation followed load reasonably well

Figure 2-46 shows the MW output of renewable resources along with CTs. The chart shows that CTs (blue line) increase sharply – by nearly 10,000 MW of additional output – in the intervals immediately following a sharp decline in solar output. Note that over half these CTs were identified for commitment in the forward market, with the real-time market committing approximately 33 additional CTs during the challenging evening intervals.

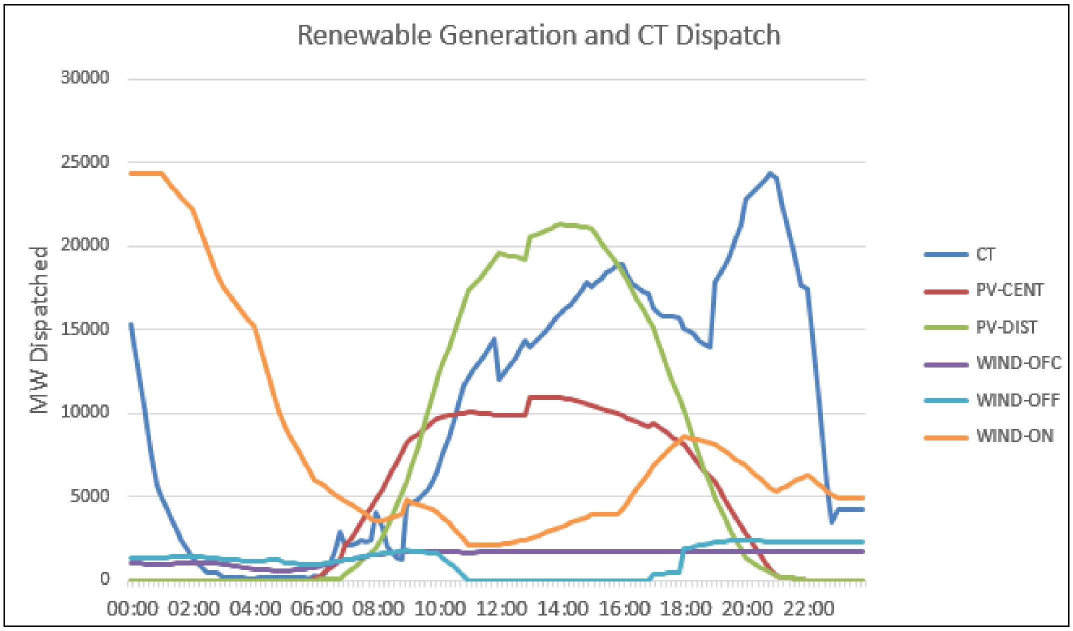

Figure 2-46: CT Dispatch vs. Renewable Generation Dispatch (30% HSBO, June 18)

A stronger forward commitment may have improved real-time operational efficiency on this day; i.e. the combined procurement of 15,000-25,000 MW of CT energy (both in forward and RT) could have been reduced by additional steam commitment.

However, this would require the operator to have advanced knowledge in order to plan. The best the operator can do is to commit in day-ahead according to the renewable forecast. A shorter-term adjustment to the day-ahead commitment - perhaps a 6-hour ahead commitment based on an updated wind and solar forecast may improve the situation.

Similar to April 12, it is also interesting to note that the pattern of commitment for CTs and ramp-up for thermal units (i.e. beginning approximately hour 20) is different than what market operators typically experience today; it would be unusual to need 25,000MW of CT generation at 9pm.

2.5.8 Summary of Results: 30% HOBO Scenario

Five sub-hourly simulations were completed for the 30% HOBO scenario. Table 2-9 summarizes high-level results of the sub-hourly simulations for these simulations.

Table 2-9: PROBE Analysis Results Summary for 30% HOBO Challenging Days

	12-Jan	4-Mar	21-Sep	13-Nov	16-Nov
Instances of Load Shedding	0	0	0	0	0
Intervals When Reserves Provide Energy	0	0	0	0	0
Average Dispatch Headroom - Online Steam/CC (MW)	17689	16762	18426	13716	10802
Minimum Dispatch Headroom - Online Steam/CC (MW)	5154	6221	5326	4670	4141
Instances of Ramp-Constrained Generation	5123	5083	6046	3905	3764
Total Unit-Intervals of RT CT Commitment	6	12	0	36	18
Average RT CT Commitment per Interval	<1	<1	0	<1	<1
Number of RT CTs Committed - Highest Interval	1	1	0	3	1
Average LMP	$36.61	$38.75	$32.44	$37.79	$46.83
LMP Spikes	1	0	1	0	3
Average Reserve Price	$1.00	$1.18	$1.00	$1.46	$4.38

The 30% HOBO cases were clearly and decisively the most problem-free set of sub-hourly simulations as compared to other 20% and 30% scenarios. One reason for this is that the high offshore scenarios result in an onshore forward commitment profile that provides plenty of thermal capacity on-line to counter any renewable variability. In other words, offshore renewable energy displaces less thermal generation commitment than onshore renewable energy. A second reason is that offshore wind is closer to (and east of) the load centers in the eastern portion of PJM and will not create or add to West-to-East transmission congestion. It could also be the case that the forecast for the offshore wind would be more accurate than the forecast for the onshore wind. The offshore wind is not subject to terrain issues and is more a function on-shore to off-shore wind currents which are more predictable.

The pre-screening for 30% HOBO days-to-analyze also did not include any of the days that proved to be challenging during other renewable profiles, nor did it include any extreme peak demand days.

<u>Results: 30% HOBO - January 12</u>

Observations / characteristics:

- ✓ Screening criteria met: Largest difference between LNR peak and min
- ✓ Significant headroom available
- ✓ Plenty of operating flexibility

Figure 2-47 provides a visual (for on-line thermal generation only) demonstrating that the cushion between on-line capacity and actual dispatch is quite significant, resulting in comfortable levels of headroom in these resources.

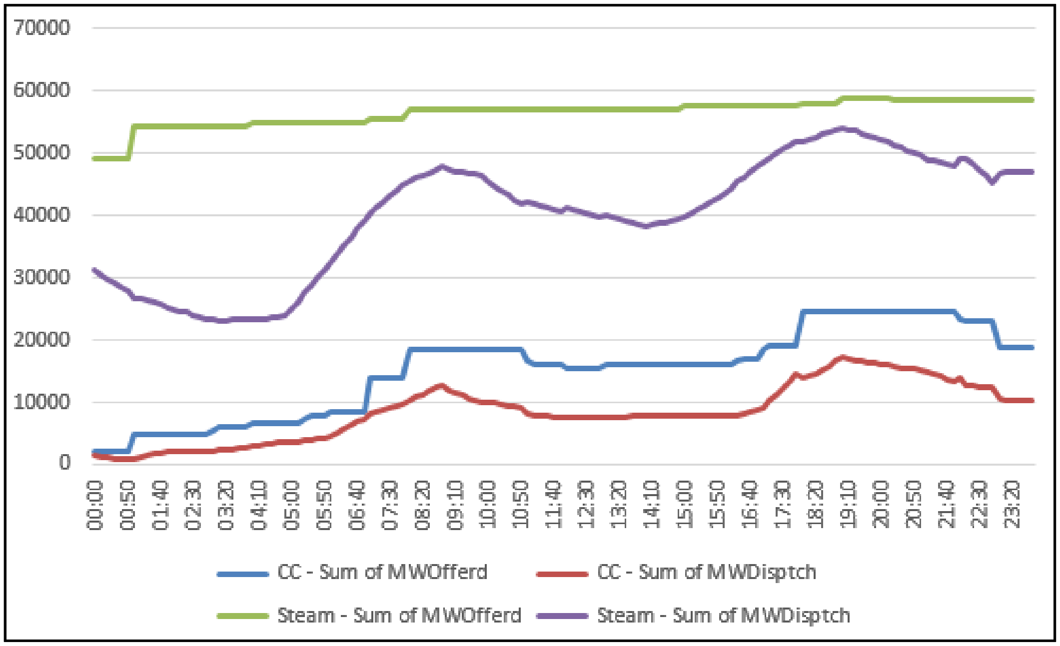

Figure 2-47: Thermal Generation MW Offered vs. Dispatched, On-line Units Only (30% HOBO, January 12)

It could be argued that there is actually over-commitment for this renewable profile. However, there are offshore transmission constraints in several intervals. As noted in the HOBO summary, the high offshore scenarios result in an onshore forward commitment profile that provides plenty of thermal capacity on-line, but that may be necessary since the "load centers" are far away from the renewable generation and subject to transmission limitations and losses. It is also possible that this day starts out with an under-forecast of renewable energy in the day-ahead commitment.

<u>Results: 30% HOBO - March 4</u>

Observations / characteristics:

- ✓ Screening criteria met: Largest LNR period-to-period change
- ✓ Significant headroom available
- ✓ Plenty of operating flexibility

This day has been studied for real-time challenges for many of the scenarios, but typically has not presented problems except for higher-than-average ramp constraints. That trend continued for the 30% HOBO case, with thermal generation ramping in the morning hours when demand begins to increase sooner than solar generation, and again in the late afternoon hours when generation output is falling faster than demand. Downward ramp constraints are also observed when renewable generation increases output. See Figure 2-48.

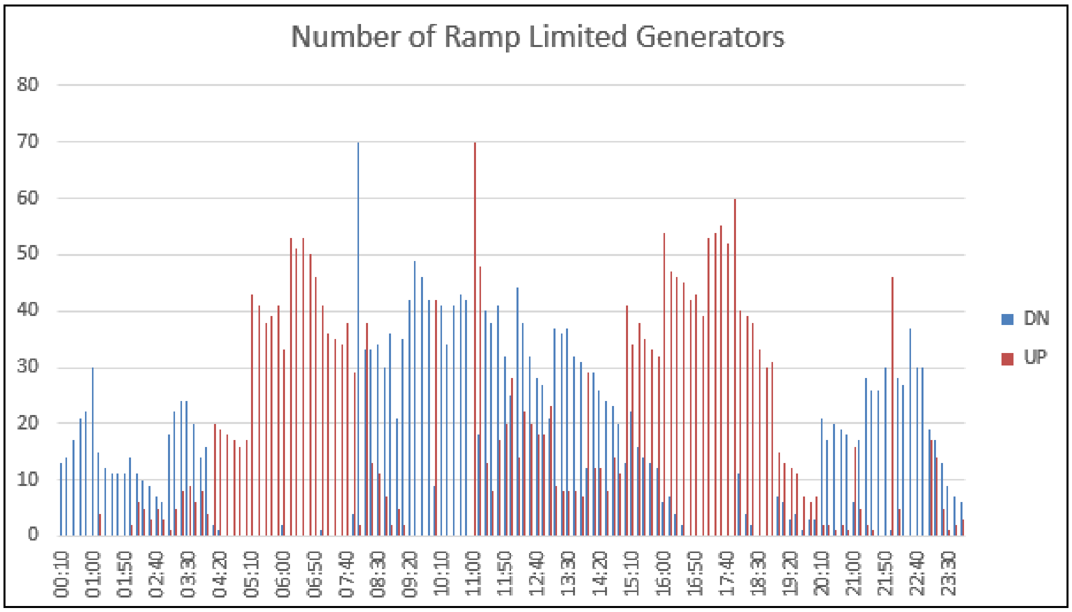

Figure 2-48: Number of Ramp-constrained Units per 10-minute Interval (30% HOBO, March 4)

<u>Results: 30% HOBO - September 21</u>

Observations / characteristics:

- ✓ Renewable selection criteria: Largest number of periods exceeding committed resource headroom
- ✓ Sub-hourly simulations actually found the most headroom of any of the 30% HOBO cases
- ✓ Second lowest average LMP of any sub-hourly simulation
- ✓ Significant generator ramp limitations, though there was enough generation on-line to overcome this
- ✓ Despite no major problems, there are areas for concern, including a couple of transmission overloads

The September 21 sub-hourly simulation, on the surface, seems like one of the "quietest" days with plenty of headroom and low LMPs. However, a closer look at the renewable profile in Figure 2-49 shows considerable variability in output, including a sharp increase in morning and early afternoon.

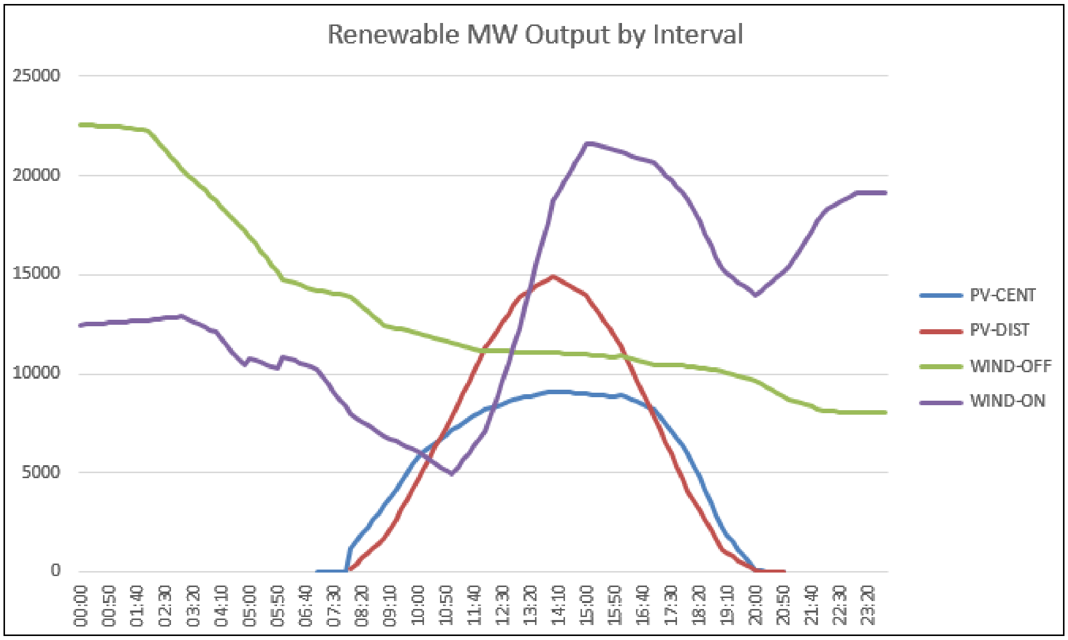

Figure 2-49: Renewable Generation Dispatch for Each Interval (30% HOBO, September 21)

The result of this renewable variability is generators constantly ramping throughout the day, and significant ramp limitations. In a few time periods, generators cannot ramp down quickly enough and there are transmission overloads due to over-generation situations. Figure 2-50 illustrates ramping for the day as measured by ramp constraints: thermal generators ramp up in the morning when wind is decreasing and before solar increases; then generators ramp down during the sharp increase in nearly all renewables; then ramp up again when solar and wind decrease at the same time; and finally, after 9pm, thermal generators ramp down quickly to account for a sudden reversal/increase in wind while the demand is decreasing at the same time.

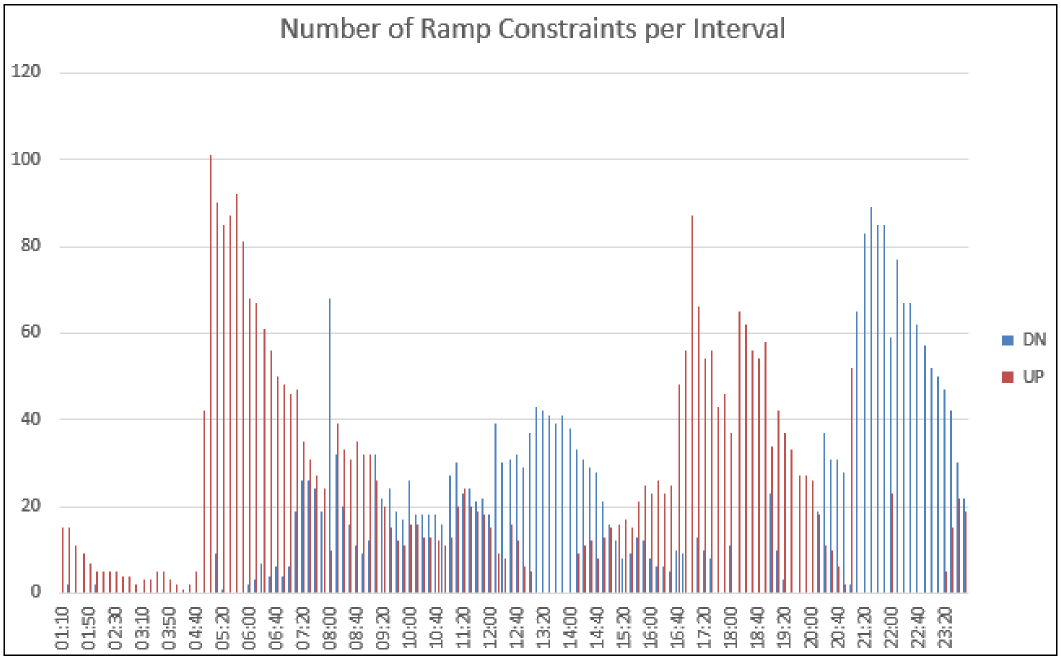

Figure 2-50: Number of Ramp-constrained Units per 10-minute Interval (30% HOBO, September 21)

<u>Results: 30% HOBO - November 13</u>

Observations / characteristics:

- ✓ Renewable selection criteria: Large difference between LNR peak and min; high number of periods exceeding committed resource headroom
- ✓ Ample headroom, although lower than most other HOBO cases
- ✓ A small number of CTs were committed in real-time to meet demand

The November 13 sub-hourly simulation solved without concern and no issues were identified.

<u>Results: 30% HOBO - November 16</u>

Observations / characteristics:

- ✓ Screening criteria met: Largest number of ramps exceeding committed resource capability; high number of periods exceeding committed resource headroom
- ✓ Lowest headroom of 30% HOBO cases, but still adequate and much better than other non-HOBO profiles
- ✓ No concerns

The November 16 sub-hourly simulation solved without concern and no issues were identified.

2.5.9 Summary of Results: 30% LOBO Scenario

Six sub-hourly simulations were completed for the 30% LOBO scenario. Table 2-10 summarizes high-level results of the sub-hourly simulations for these simulations.

Table 2-10: PROBE Analysis Results Summary for 30% LOBO Challenging Days

	5-Jan	17-Feb	11-Mar	28-Mar	18-Jun	22-Dec
Instances of Load Shedding	0	0	0	0	0	0
Intervals When Reserves Provide Energy	2	0	0	6	0	8
Average Dispatch Headroom - Online Steam/CC (MW)	9568	7506	7974	3259	8161	6985
Minimum Dispatch Headroom - Online Steam/CC (MW)	971	0	877	86	1711	1002
Instances of Ramp-Constrained Generation	4228	3468	3363	1704	4331	3881
Total Unit-Intervals of RT CT Commitment	205	1097	434	1084	524	311
Average RT CT Commitment per Interval	1.5	8	3	8	3.5	2
Number of RT CTs Committed - Highest Interval	11	27	19	28	17	18
Average LMP	$51.13	$62.65	$48.99	$56.33	$64.28	$37.84
LMP Spikes	4	1	3	2	2	1
Average Reserve Price	$10.44	$17.16	$16.04	$41.06	$9.06	$27.86

<u>Results: 30% LOBO - January 5</u>

Observations / characteristics:

- ✓ Screening criteria met: Common to all selection criteria
- ✓ Renewable energy is highest during after-midnight off-peak hours
- ✓ Various concerns, or at least interesting observations, over the course of the day

Figure 2-51 below shows the on-shore wind energy at nearly 50,000MW in the early morning hours, and total wind energy over 50,000MW in those same hours.

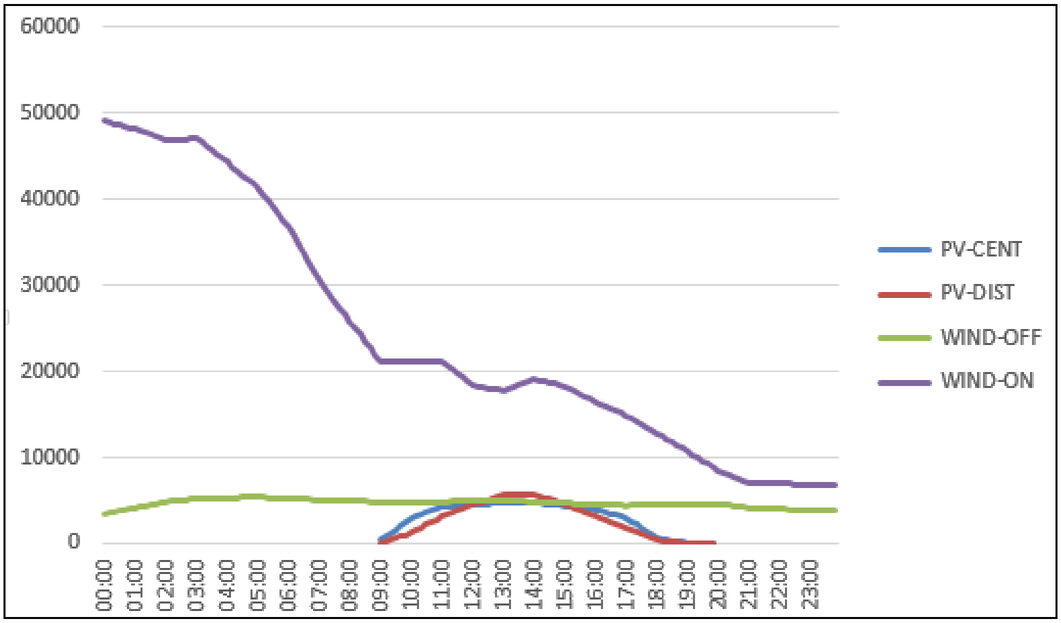

Figure 2-51: Renewable Generation Dispatch for Each Interval (30% LOBO, January 5)

This renewable profile causes some thermal generators to stay offline until the second or third hour of the day, and others aren't committed until 7am, as wind energy continues to taper and demand increases. See Figure 2-52. This further requires commitment of several CTs (totaling over 900MW) shortly after midnight to cover the lack of thermal generation. In current markets, it would be unusual to see significant CT commitment around 1-2am.

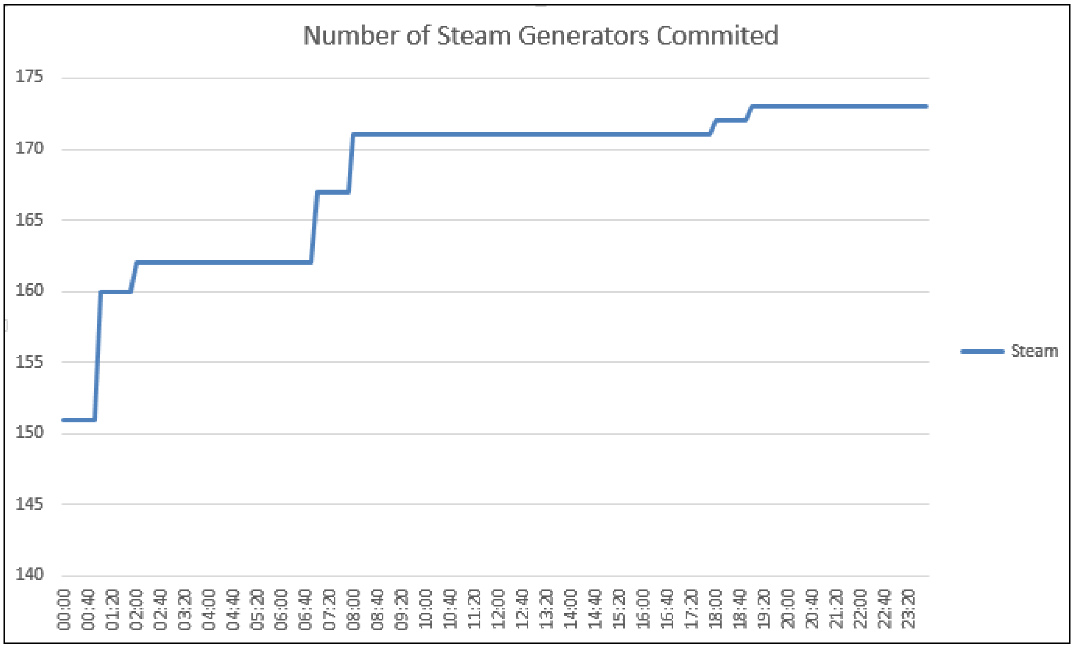

Figure 2-52: Number of Steam Generators On-line During Each Interval (30% LOBO, January 5)

There are also two intervals when a shortage situation occurs and reserves are called upon to provide energy – the first at interval 8:50 and the second at 22:00. As can be seen from Figure 2-52, 8:50 is immediately before solar generation output increases; this was such a "transient" situation the optimal solution was simply to borrow from reserves rather than commit CT(s) which typically need to stay on for a few intervals. The level of violation was only 63MW.

Interval 22:00 also showed reserves borrowed for energy, although further investigation showed the renewable energy profile was not the primary contributor at this moment (though output was still decreasing slightly). Instead, a sharper-than-usual reduction in hydro/pumped storage energy was identified and a couple of thermal generators were de-committed at the same time, causing the short-term reserve borrowing.

Results: 30% LOBO - February 17

February 17 has been studied under several different scenarios and continues to be a challenging day in almost every case.

Observations / characteristics:

- ✓ Screening criteria met: Largest LNR period-to-period change
- ✓ Many sub-hourly intervals with zero headroom
- ✓ Not enough thermal generation committed in the forward market

- ✓ CTs required to cover energy shortages
- ✓ Violated line rating on one transmission line to arrive at a solution
- ✓ The 30% LOBO sub-hourly simulation, while challenging, arguably provided fewer concerns compared to other sub-hourly simulations for the same February 17 day

The particular demand and renewable profile on February 17 appears to under-commit thermal generation in almost all renewable profiles (i.e. HSBO, LOBO, etc.), resulting in low headroom.

Figure 2-53 shows a plot of CT usage for February 17 in the 30% LOBO scenario. The blue trace is total system demand, the red trace is total renewable generation, and the green symbols show the number of committed CTs. The main concern with the renewable energy profile for this day is that renewable energy is at its lowest levels when demand is greatest, and decreases when load increases.

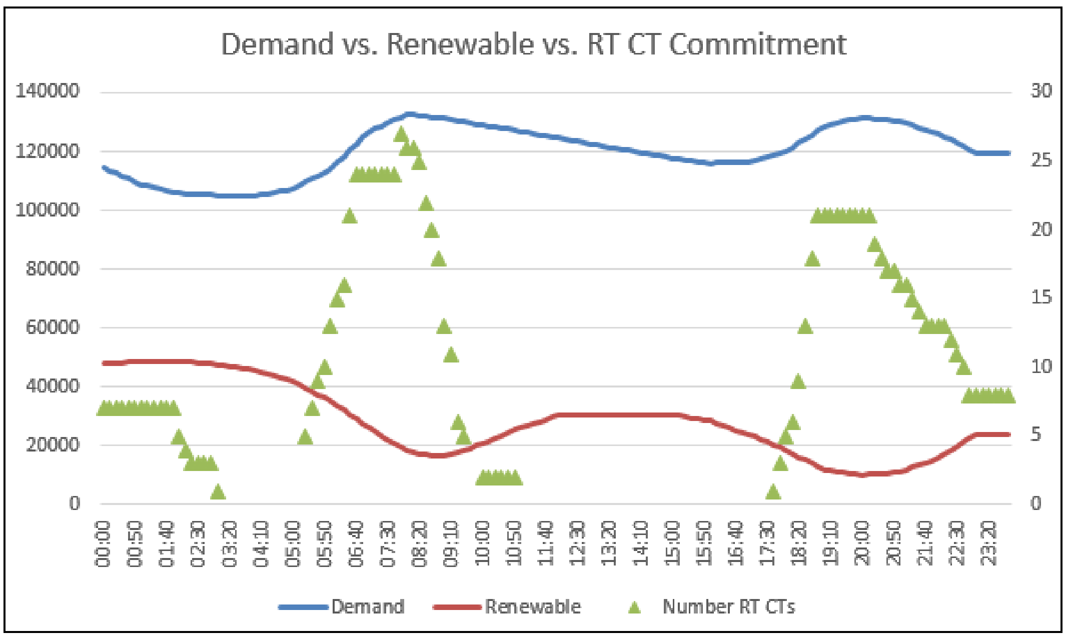

Figure 2-53: Demand MW, Renewable Dispatch, and # of CTs Committed in RT (30% LOBO, February 17)

It is possible that some steam generation is not committed in the forward market to avoid over-generation situations in the off-peak and mid-afternoon hours. Large thermal units often have long minimum run times and cannot be committed and de-committed throughout the day.

The end result is a reliance on CT commitment during the peak demand / lower renewable hours as shown in the same Figure 2-53. Up to twenty-seven CTs representing up to

8464MW of CT generation are committed in some intervals during the real-time market. This also creates higher LMPs.

Further, transmission overloads were experienced in solving this case. This is a major concern and depending on exact operational protocols is typically avoided at all costs in real-time operations (i.e. some markets allow very small transient violations or "short-term emergency" violations; the violations reported here are more persistent).

The number of lines and frequency of overloads were much less in the 30% LOBO than the 30% HSBO.

<u>Results: 30% LOBO - March 11</u>

Observations / characteristics:

- ✓ Screening criteria met: Top 10 for three out of four selection criteria
- ✓ No severe problems but an unusual operating day
- ✓ Significant CT commitment in the first two hours of the day

Figure 2-54 illustrates the renewable profile for the day. While there is a steep reduction in wind during the morning, it stabilizes and increases slightly toward peak hours, and is joined by over 21,000MW of solar energy during peak hours.

The shape, amount, and location of the renewable energy minimized operational problems. However, the amount of wind after midnight kept several thermal units offline and resulted in a significant locational CT commitment in the first two hours of the day.

While the CTs adequately performed to provide required MW to meet demand, it is an unusual operational outcome to require significant CT commitment in the middle of the night, as compared to today's operating practices. But such CT commitment practices are likely to be more common with wind and solar energy penetrations approaching 30%.

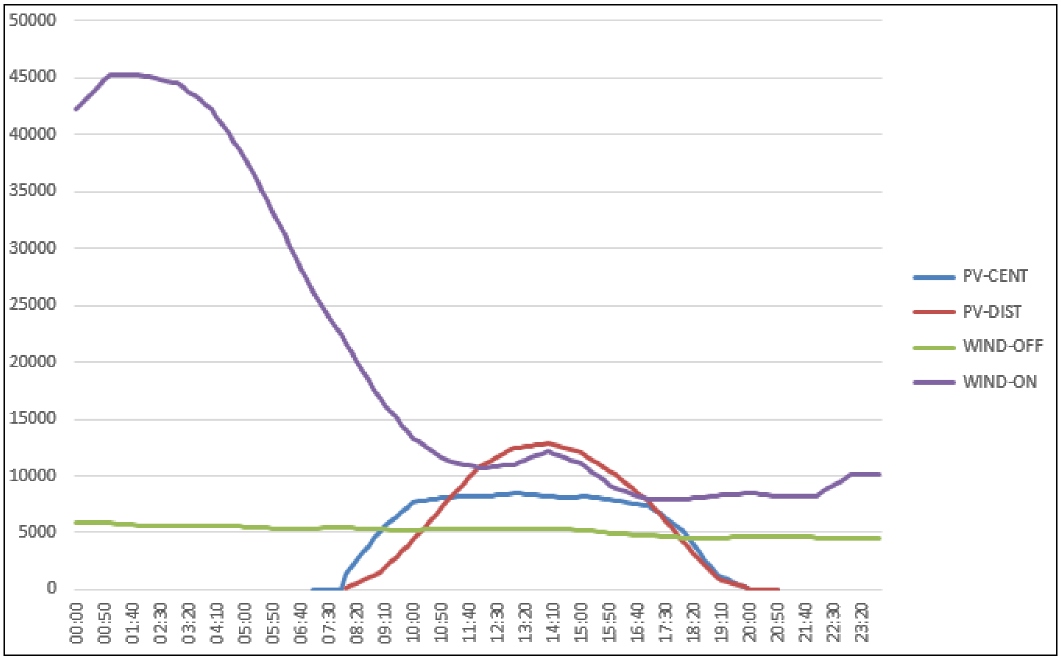

Figure 2-54: Renewable Generation Dispatch for Each Interval (30% LOBO, March 11)

Results: 30% LOBO - March 28

Observations / characteristics:

- ✓ Screening criteria met: Largest number of periods exceeding committed resource headroom
- ✓ Renewable energy decreases throughout most of the day, and is minimal after 8pm
- ✓ Low headroom on thermal generation
- ✓ Reserves provide energy when minimal thermal generation is on-line

Simulating real-time operations for the March 28 LOBO case presented concerns due to the rather unusual profile shown in Figure 2-55 – total renewable resource output decreasing nearly the entire day. Entering the real-time market, thermal generation commitment appeared to be low, likely due to the significant renewable energy available for half the day.

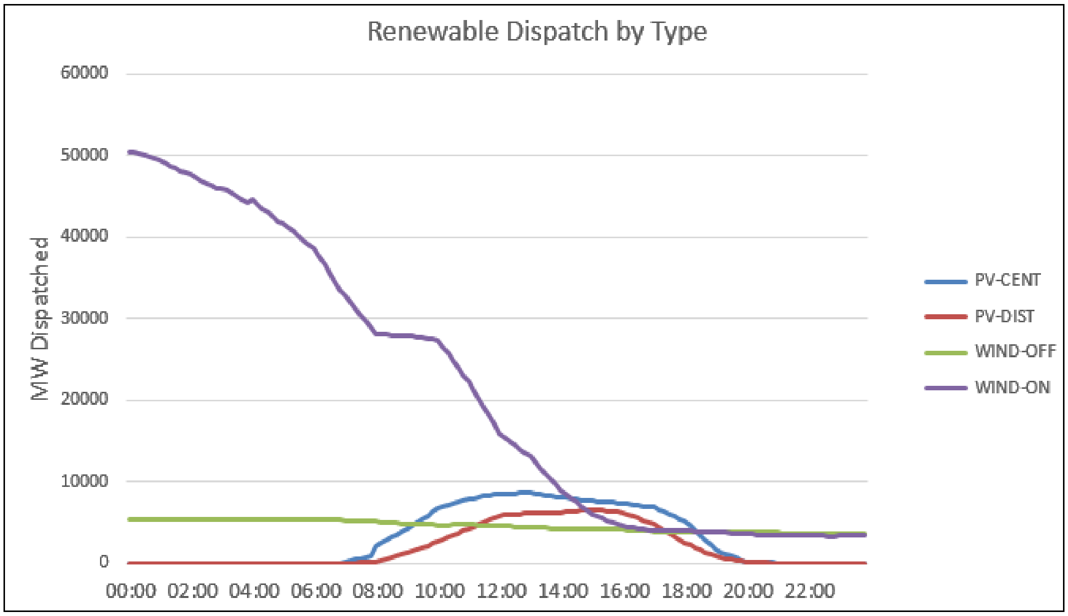

Figure 2-55: Renewable Generation Dispatch for Each Interval (30% LOBO, March 28)

There were six intervals when reserves were called upon to provide energy. These all occurred in the first two hours of the day, when sufficient ancillary services-capable resources were not yet on-line due to the high wind, also further supporting the concept that the high wind output reduced thermal generation commitment especially early in the day.

While eventually more generation is committed to replace renewable generation and serve the demand, this simulation showed more persistent upward ramp constraints than many other days that had shorter durations of ramp constraints, due to the on-going need to increase output.

Finally, CT commitment is high to accommodate the time frames where thermal generation cannot ramp fast enough to serve demand, as well as in transmission constrained areas. CTs are committed later into the evening than other scenarios due to the lower thermal generation online.

Figure 2-56 shows the MW dispatch from CTs, revealing another pattern uncommon in today's market operations, i.e. most of the CT commitment just after midnight and again around 8-9pm.

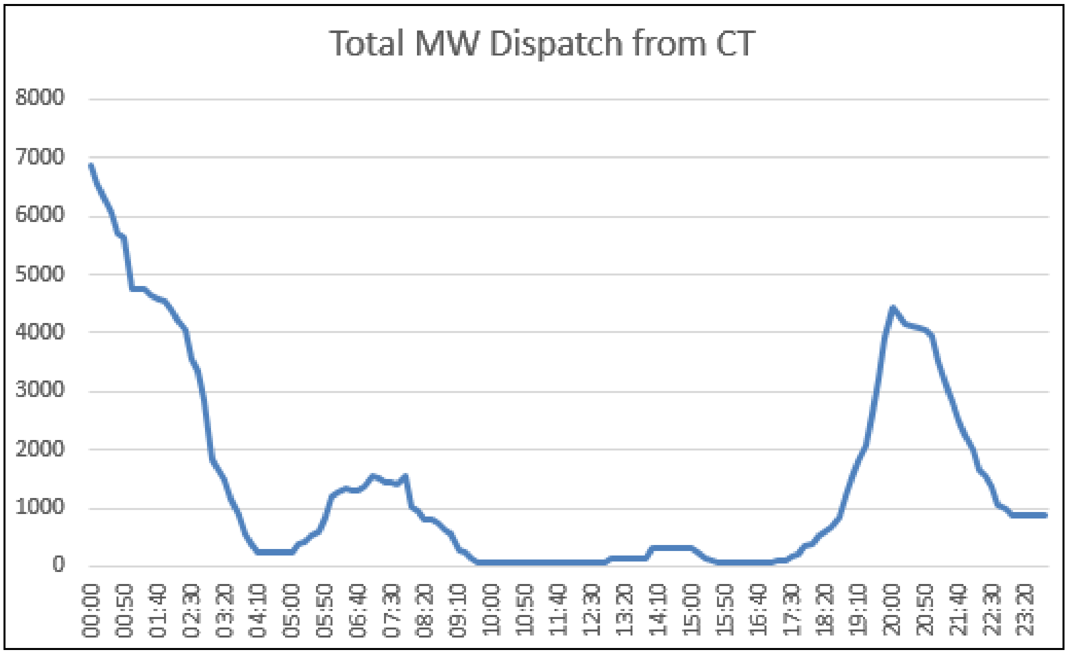

Figure 2-56: CT Dispatch for Each Interval (30% LOBO, March 28)

Results: 30% LOBO - June 18

Observations / characteristics:

- ✓ Screening criteria met: Largest difference between LNR peak and min
- ✓ Strong forward-market commitment of thermal generation
- ✓ No reserve borrowing or overloads; high but manageable ramp limitations

Despite the large difference between LNR peak and minimum, a strong forward commitment combined with renewable energy that followed load reasonably well (the solar output had a longer-than-usual duration due to being one of the longest days of the year) minimized any concerns for this sub-hourly simulation.

Similar to other simulations, there was CT commitment later in the day than may typically be found in current operations, due to rapid reduction in solar generation while demand is still high.

Results: 30% LOBO - December 22

Observations / characteristics:

- ✓ Screening criteria met: Largest number of ramps that exceeded committed resource capability
- ✓ Adequate headroom

- ✓ Low LMPs
- ✓ Instances of reserves borrowing
- ✓ CT commitment in the first two hours of the day; up to 18 CTs committed in RT in some of these early intervals

At first glance, this simulation appeared to be relatively uninteresting – low LMPs, minimal need for real-time CT commitment except for after midnight, and plenty of MW available from on-line thermal generation in most intervals.

However, there were also eight intervals where reserves were called upon to provide energy. Further investigation into these occurrences show that they occur around 2am, when wind generation is very high and demand is lowest, resulting in fewer thermal units on-line to provide reserves. The reserve requirement also increased about 500MW entering this hour, which is the largest hour-to-hour increase for the day, thus making it more difficult for generators to adjust and provide additional reserves. All instances of reserve borrowing were small, with 6 of 8 requiring less than 10 MW of reserves "borrowed" to provide energy during wind dips.

Figure 2-57 shows the high CT dispatch in the first few hours after midnight to account for the lower thermal commitment at this time. There was also a major 230kV transmission constraint for several intervals, also the result of the wind dispatch pattern, which accounted for some of the CT commitment. As noted in other scenarios, extensive CT commitment in the middle of the night only is unusual in today's energy markets.

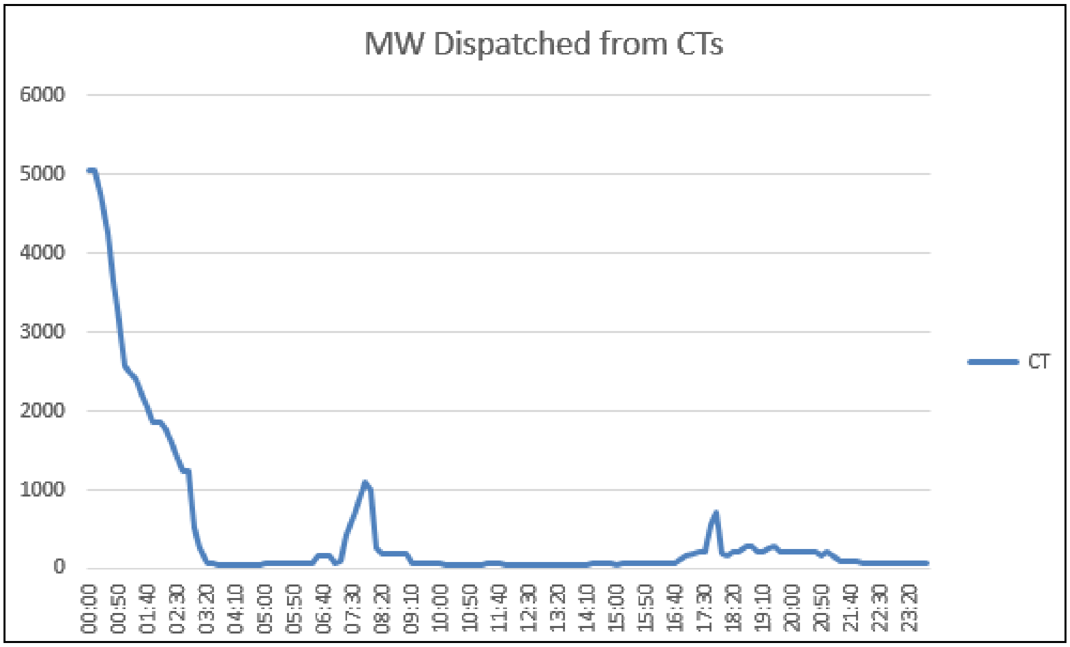

Figure 2-57: CT Dispatch for Each Interval (30% LOBO, December 22)

2.5.10 Summary of Results: 30% LODO Scenario

Four sub-hourly simulations were completed for the 30% LODO scenario. Table 2-11 summarizes high-level results of the sub-hourly simulations for these simulations.

Table 2-11: PROBE Analysis Results Summary for 30% LODO Challenging Days

	4-Mar	9-Mar	28-Mar	18-Jun
Instances of Load Shedding	0	0	0	0
Intervals When Reserves Provide Energy	0	0	2	0
Average Dispatch Headroom - Online Steam/CC (MW)	16717	15159	1474	9337
Minimum Dispatch Headroom - Online Steam/CC (MW)	7258	7576	0	487
Instances of Ramp-Constrained Generation	4311	2736	1761	4387
Total Unit-Intervals of RT CT Commitment	195	264	2537	775
Average RT CT Commitment per Interval	1.5	2	18	5
Number of RT CTs Committed - Highest Interval	7	12	46	20
Average LMP	$38.64	$28.58	$100.61	$67.61
LMP Spikes	2	3	4	3
Average Reserve Price	$1.00	$1.06	$59.24	$8.80

March 28 was clearly the most challenging of these simulations, as indicated by high LMPs and reserve prices, low headroom, and high CT commitment. June 18 provides an opportunity to review a day studied under four different renewable profiles. It is worthwhile to note that 3 of 4 challenging days identified by the screening criteria are in March, as compared to present day operations where March is typically considered to be a less challenging time of year for grid operations.

Results: 30% LODO - March 4

Observations / characteristics:

- ✓ Screening criteria met: Largest LNR period-to-period change
- ✓ Strong forward-market commitment of thermal generation
- ✓ Plenty of operating flexibility

This day has been studied for real-time challenges for many of the scenarios, but typically has not presented problems except for higher-than-average ramp constraints.

The only difference in the March 4 LODO case was a higher real-time CT commitment as compared to other March 4 sub-hourly simulations (but by no means an unusually large CT commitment). Nearly all these CTs were in the same location and were required due to a transmission constraint that did not appear in the other March 4 cases.

Results: 30% LODO - March 9

Observations / characteristics:

- ✓ Screening criteria met: Largest number of ramps that exceeded committed resource capability
- ✓ Strong forward-market commitment of thermal generation
- ✓ Plenty of operating flexibility
- ✓ Lowest LMP of any sub-hourly simulation

There were no operational challenges noted during this sub-hourly simulation; there was plenty of thermal generation on-line to meet changes in demand and renewable energy.

A small number of CTs were committed in the first two hours of the day, due to transmission congestion in the New Jersey area.

Results: 30% LODO - March 28

Recall from analysis of the LOBO scenario for March 28 that there is an unusual renewable energy profile for the day (near-constant decrease throughout the day); the LODO case has essentially the same profile only with a different distribution of wind resources.

Observations / characteristics:

- ✓ Screening criteria met: Largest number of periods exceeding committed resource headroom; seventh highest number of ramps that exceeded committed resource capability
- ✓ Under-commitment of thermal generation in forward market; very low headroom
- ✓ Highest CT commitment of any 30% sub-hourly simulation
- ✓ High LMPs; two intervals when reserves provide energy

Similar to the LOBO case, entering the real-time market thermal generation commitment appeared to be low, likely due to the significant renewable energy available for half the day. Figure 2-58 shows the renewable generation dispatch and the CT dispatch. Late in the day, when the renewable energy drops, it can be seen that CTs are required to offset this reduction and because there is an under-commitment of thermal generation. This is a significant CT commitment – nearly 25,000 MW – representing 40% of total PJM's installed CT capacity and about 24% of PJM load during those intervals.

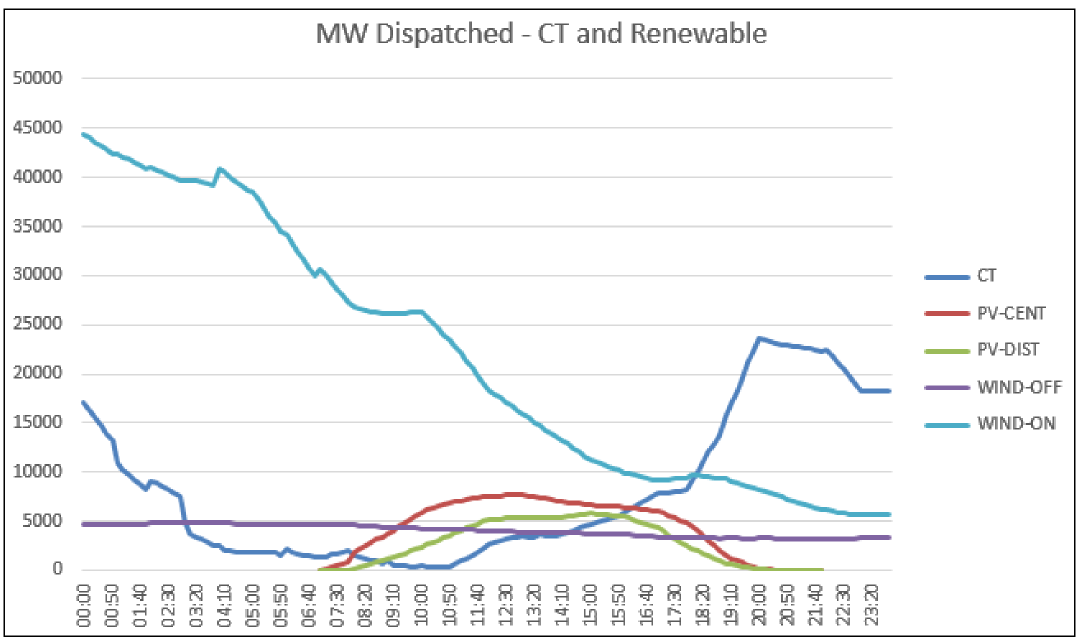

Figure 2-58: Renewable vs. CT Dispatch for Each Interval (30% LODO, March 28)

There were two intervals when reserves were called upon to provide energy, both occurring during first two hours of the day, when sufficient ancillary services-capable resources were not yet on-line due to the high wind.

Comparing to the March 28 LOBO case, there were fewer intervals of reserve shortages in the LODO case, but analyzing details of the operational performance between the two cases shows that this LODO case was more operationally challenging than the LOBO for the same day. For example, this LODO case showed:

- ✓ Far greater reliance on real-time CT commitment than March 28 LOBO
- ✓ Slightly more ramp constraints
- ✓ Lower headroom for thermal generation
- ✓ Higher average LMP and a few additional price spikes

Figure 2-59 demonstrates the difference in CT commitment between the March 28 LODO and LOBO sub-hourly simulations. This includes all CTs, whether identified for commitment in the forward market or real-time market.

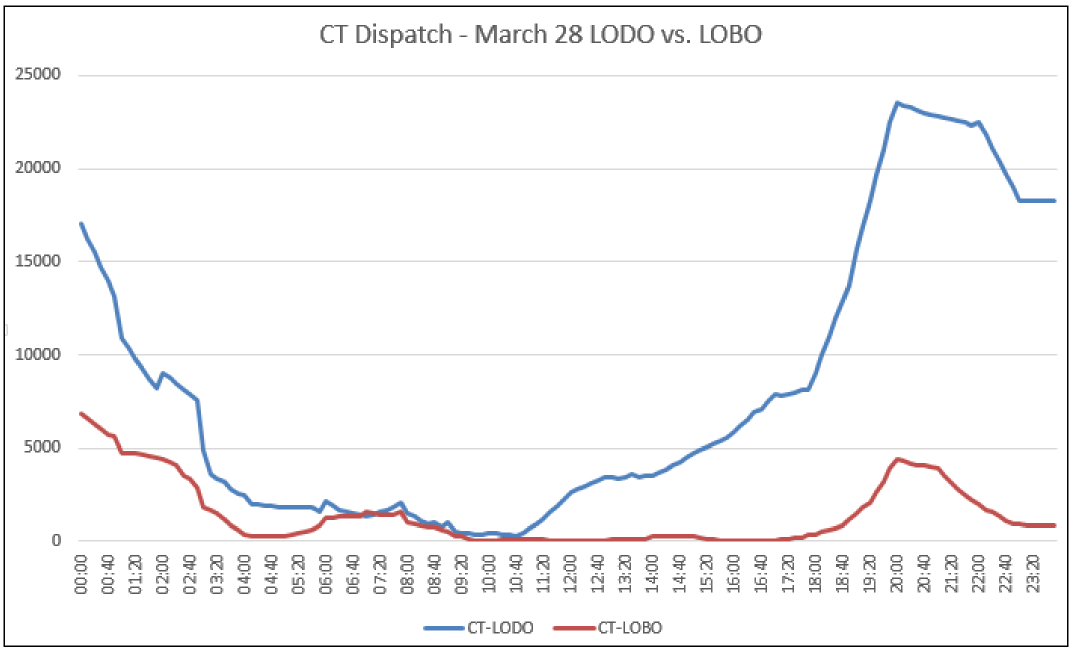

Figure 2-59: Comparison of CT Dispatch LOBO vs. LODO, March 28

There are additional transmission constraints in the LODO case, due to the "distributed" nature of the resources as opposed to the "best location" of the resources, which is the primary reason the LODO scenario is more challenging than the LOBO scenario. Figure 2-60 shows the transmission constraints between the two cases (only internal PJM constraints shown).

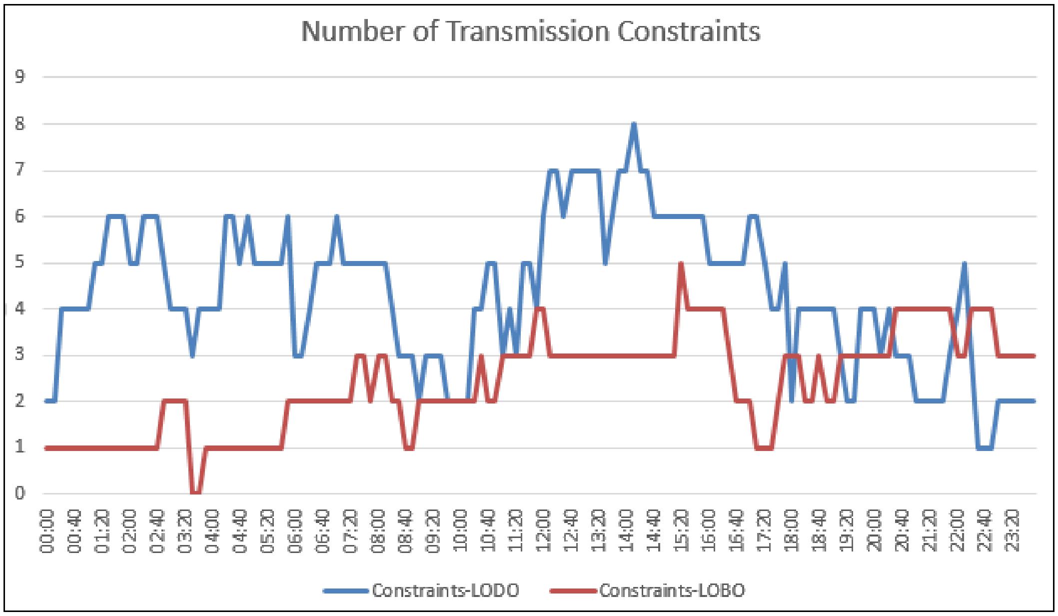

Figure 2-60: Number of Transmission Constraints for Each Interval LOBO vs. LODO, March 28

The following are the transmission constraints that often appeared in the March 28 LODO scenario, but did not appear in the LOBO scenario:

15ELRM 5 138CV - 01MITCHL 13

30 HO_OFBES 69

30 LO_OFBES 334

30 LO_OFDIS 130

30 LO_OFDIS 592

30P HIS PGEM FG 401

FG-445:ClVRDAE_LXNGTN_BLCKOK

Figure 2-61 shows the LMP comparison for the arch 28 LOBO and LODO scenarios.

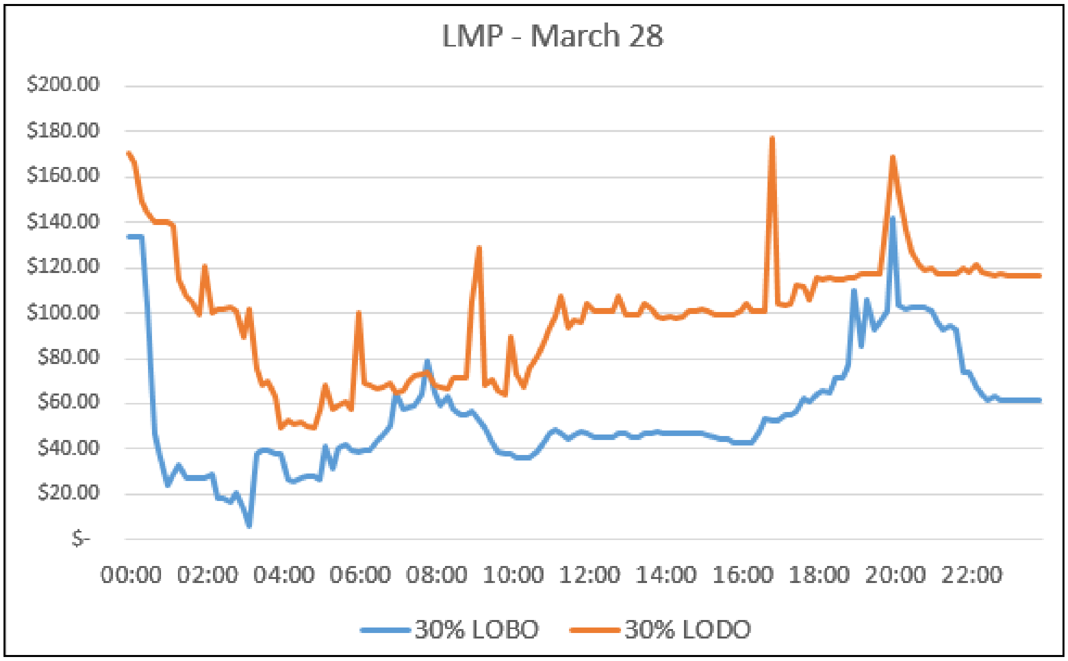

Figure 2-61: LMP Comparison for March 28

Results: 30% LODO - June 18

June 18 is another day that has been studied at the sub-hourly level for several different scenarios providing good basis for comparison.

Observations / characteristics:

- ✓ Screening criteria met: Largest difference between LNR peak and min
- ✓ Higher-than average ramp constraints
- ✓ CT commitment required during challenging hours
- ✓ High LMPs; two intervals when reserves provide energy

First, looking at the 30% LODO case without comparison to others, the operational simulation results do not reveal any particularly challenging conditions. Ramp constraints are high and RT CT commitment occurs but is not too frequent as compared to other scenarios. Figure 2-62 shows the ramp constraints, many of which occur when wind generation drops significantly in the early morning.

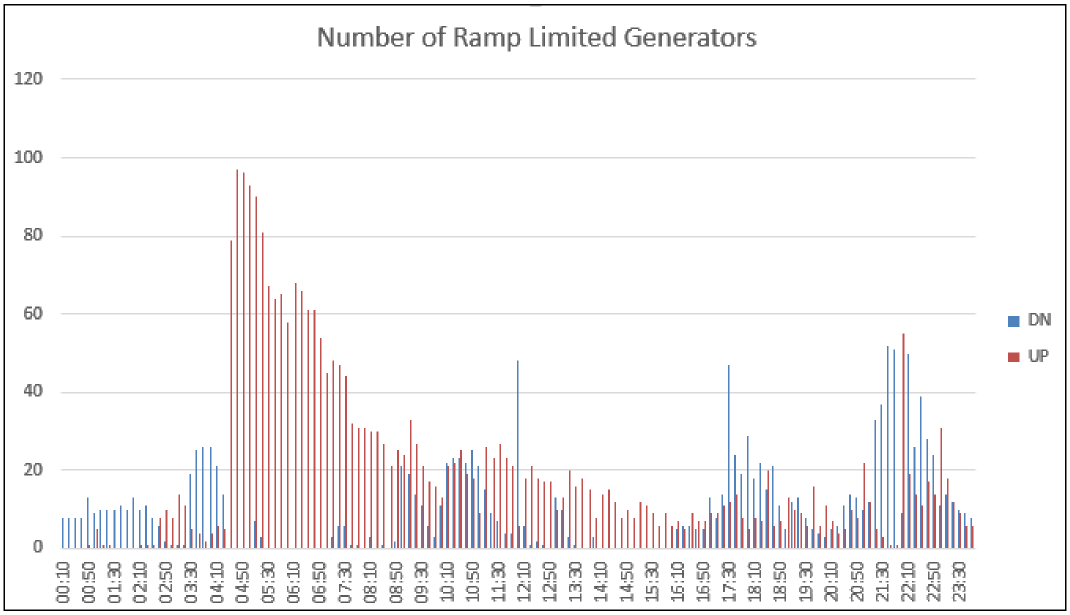

Figure 2-62: Number of Ramp-constrained Units per 10-minute Interval (30% LODO, June 18)

2.5.11 Comparing One Day across Multiple Scenarios

Another interesting analysis is comparing June 18 30% LODO to other sub-hourly simulations for the same day – see Table 2-12 below. For example, on average, the 30% LODO case showed lower prices than the 20% LODO due to the higher penetration renewable resources (with zero fuel cost). However, also due to more renewable energy, the challenging intervals of renewable pick-up/drop-off were "more challenging" in the 30% case: significantly more CTs were committed and ramp constraints were more frequent.

Comparing 30% LODO to 30% HSBO, different outcomes are observed, with the LODO case presenting fewer operational challenges except in the area of ramp constraints because wind generation is less correlated to the demand profile. Refer to the HSBO discussion for further information on those concerns.

Table 2-12: Comparison of June 18 Challenging Days across Four Scenarios

	20% LODO	30% HSBO	30% LOBO	30% LODO
Instances of Load Shedding	0	0	0	0
Intervals When Reserves Provide Energy	0	2	0	0
Average Dispatch Headroom - Online Steam/CC (MW)	8099	2773	8161	9337
Minimum Dispatch Headroom - Online Steam/CC (MW)	8	36	1711	487
Instances of Ramp-Constrained Generation	3890	2138	4331	4387
Total Unit-Intervals of RT CT Commitment	381	1913	524	775
Average RT CT Commitment per Interval	3	13	3.5	5
Number of RT CTs Committed - Highest Interval	16	33	17	20
Average LMP	$73.54	$103.30	$64.28	$67.61
LMP Spikes	1	1	2	3
Average Reserve Price	$17.87	$52.04	$9.06	$8.80

Figure 2-63 shows the LMP chart for the June 18 scenarios.

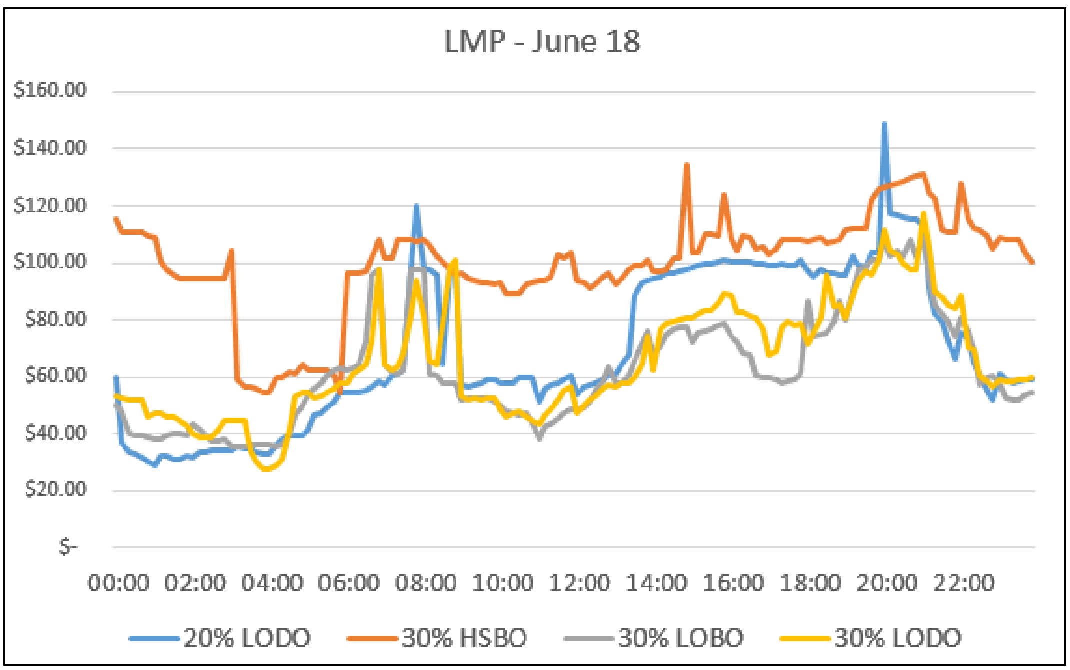

Figure 2-63: LMP Comparison across June 18 Scenarios

Table 2-13 allows direct comparisons across five March 4 scenarios. Two of the Scenarios, HOBO and LODO, can be compared for both the 20% and 30% penetrations. Headroom increases and LMP and Reserve prices drop as renewable penetration is increased.

Table 2-13: Comparison of Probe analysis for March 4th

	20% HSBO	20% HOBO	20% LODO	30% HOBO	30% LODO
Instances of Load Shedding	0	0	0	0	0
Intervals When Reserves Provide Energy	0	0	0	0	0
Average Dispatch Headroom - Online Steam/CC (MW)	10340	13445	12921	16762	16717
Minimum Dispatch Headroom - Online Steam/CC (MW)	1946	4634	2522	6221	7258
Instances of Ramp-Constrained Generation	4573	3525	4824	5083	4311
Total Unit-Intervals of RT CT Commitment	36	12	0	12	195
Average RT CT Commitment per Interval	<1	<1	0	<1	1.5
Number of RT CTs Committed - Highest Interval	2	1	0	1	7
Average LMP	$43.21	$42.97	$41.94	$38.75	$38.64
LMP Spikes	4	1	2	0	2
Average Reserve Price	$4.67	$1.89	$2.47	$1.18	$1.00

Figure 2-64 shows the March 4 PJM average LMP for several 20% and 30% scenarios. The price peaks around 8 am and 6 pm indicate increased commitment of CTs to compensate for short-term changes in load and renewables.

This figure and previous plots (e.g., Figure 2-7 and Figure 2-53) illustrate trends observed in many of the high renewable scenarios, where CT's are used less during peak load periods and more during periods where there are rapid changes in load, wind, and solar (particularly during the beginning and end of the solar day, when solar power output ramps up or down) or to compensate for errors in the day-ahead renewable energy forecast.

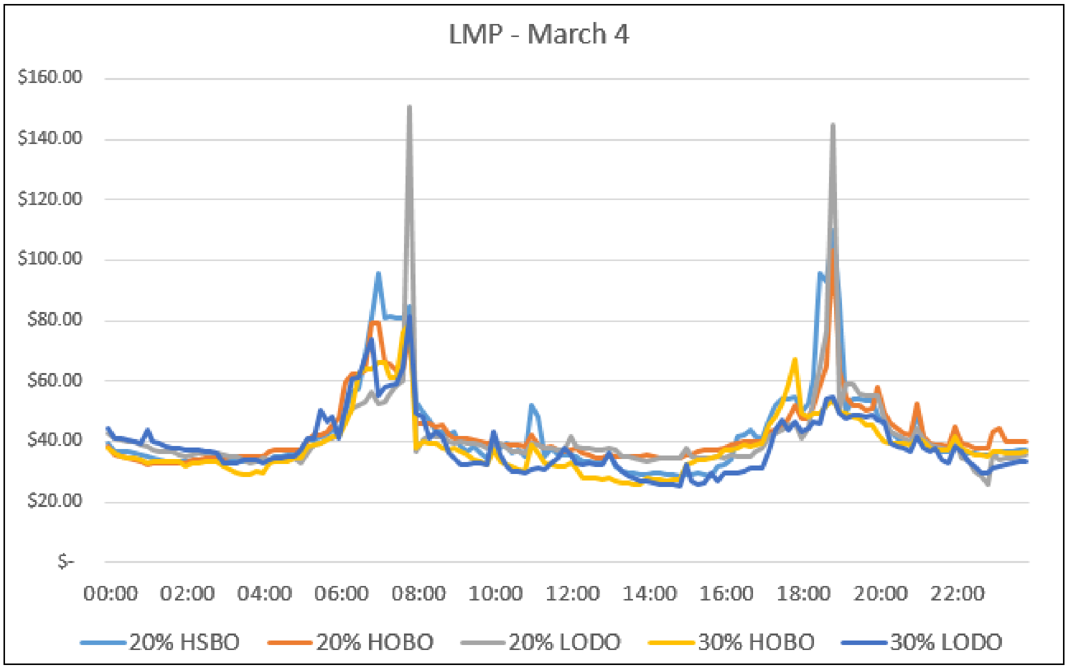

Figure 2-64: LMP Comparison for Several 20% and 30% Scenarios (March 4)

Table 2-14 allows direct comparisons across four February 17 scenarios, which as discussed earlier, proved to be one of the most challenging days studies during the sub-hourly simulations. A trend of low headroom for this day was noted in the 14% case, and the low headroom continued to be more problematic during additional February 17 sub-hourly simulations at higher renewable levels.

Table 2-14: Comparison of Probe analysis for February 17

	14% RPS	20% LOBO	30% HSBO	30% LOBO
Instances of Load Shedding	0	0	0	0
Intervals When Reserves Provide Energy	0	11	3	0
Average Dispatch Headroom - Online Steam/CC (MW)	7359	592	3749	7506
Minimum Dispatch Headroom - Online Steam/CC (MW)	53	0	0	0
Instances of Ramp-Constrained Generation	3174	1946	2226	3468
Total Unit-Intervals of RT CT Commitment	472	5712	745	1097
Average RT CT Commitment per Interval	3	40	5	8
Number of RT CTs Committed - Highest Interval	14	108	19	27
Average LMP	$59.65	$138.40	$80.74	$62.65
LMP Spikes	0	5	3	1
Average Reserve Price	$11.75	$94.13	$41.74	$17.16

Figure 2-65 shows the LMP chart for the February 17 scenarios.

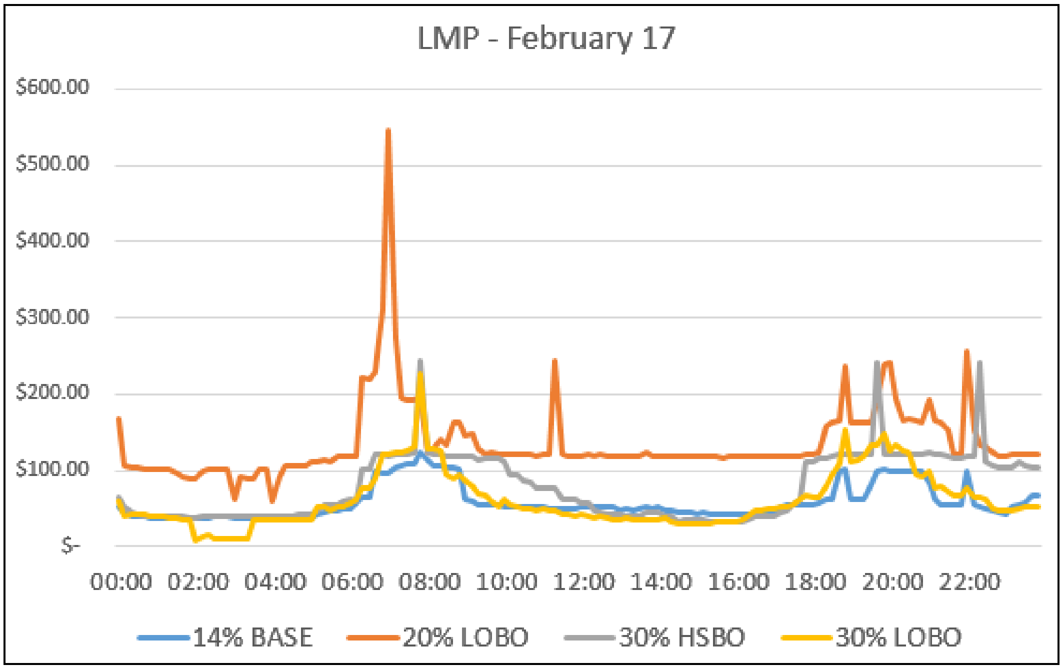

Figure 2-65: LMP Comparison across February 17 Scenarios

2.6 Observations and Conclusions from Sub-Hourly Analysis

A total of 49 sub-hourly simulations were performed for the 2%, 14%, 20%, and 30% scenarios, based on selected days from the screening criteria. In several instances, the same day was studied across more than one renewable profile, providing an opportunity to compare the results of the same day for different scenarios.

The following conclusions are drawn from the individual sub-hourly simulations, comparison of overall performance between scenarios (e.g. HOBO vs. LOBO), and comparison of individual days where the same day was studied under different profiles.

1. In general, all the simulations of challenging days revealed successful operation of the PJM real-time market. Although there were occasionally periods of reserve shortfalls and new patterns of CT usage, there were no instances of unserved load.
    a. CTs contributed significantly to this outcome. The PJM generation portfolio includes 569 CT units with an aggregated capacity of 64,000 MW (which includes the "existing" 29 GW of CTs in PJM, the "new" ISA/FSA qualified plants in the PJM queue, and the additional "generic" CTs added to the PJM system to meet the pool reserve margin targets in 2026 consistent with the assumed load growth). The sub-hourly simulation results show that commitment of CTs in the real-time market was a major factor in addressing operational issues on

challenging days. The CT fleet will be a valuable asset to PJM as wind and solar penetration increases.

b. Another factor affecting this outcome is the study assumption for installed capacity reserve margin in the scenarios. The 2% BAU scenario was designed to have an installed capacity reserve margin of 16.1%, and that same thermal fleet was retained in all other scenarios with higher wind and solar penetration. Therefore, if the capacity values of wind and solar resources are considered, the higher penetration scenarios have higher installed capacity reserve margins than the lower penetration scenarios.

2. The level of difficulty for real-time operations largely depends on the day-ahead unit commitment, which in turn depends on the day-ahead forecast for load, wind and solar. The impact of forecast error is investigated in the section on Sensitivity Analysis. The role of geographic diversity of renewable energy on smoothing the renewable variability is discussed in the section on Reserve Analysis. The following are observations based on the sub-hourly PROBE analysis of operations based on the unit commitment outpour of GE MAPS.

   a. A strong forward commitment, i.e. adequate thermal resources, greatly reduces real time operational challenges.

   b. This is an accurate statement for any current energy markets as well. However, in most of the renewable profiles, having adequate thermal resources committed in the forward market is even more critical due to the additional variability of potentially increased renewal energy output.

   c. Certain days and renewable energy profiles showed a tendency to result in a weaker forward commitment; i.e. some profiles suppress forward commitment more than others and therefore have higher potential for real time operational challenges; which could be due to over-forecasting of renewable energy.

   d. There may be concerns with over-commitment as well, which could be due to under-forecasting of renewable energy.

   e. Renewable dispatch that is not well correlated with load causes bigger challenges in the real-time market, due to greater need for load-following by dispatchable thermal resources. The solar energy may be decreasing the need for thermal generation during the peak of the day and the models decide to just use CTs for hours when the solar is not available.

   f. In summary, on days when the day-ahead commitment was significantly lower than the actual net load to be served in the real-time market - most commonly due to an over-forecast of wind and solar energy - additional CT generation resources were committed in real-time. PJM' large fleet of CTs in

2026 (consisting of existing, in queue, and generic additions), were able to compensate for forecast errors and fast-moving events even on the most challenging days investigated in this study.

3. Higher penetrations of renewable energy (20% and 30%) create operational patterns that are significantly different than what is common today, especially with respect to CT usage.
    a. Some simulations did not necessarily present operational challenges, but instead presented circumstances that are largely unfamiliar in today's energy markets. For example, CTs are committed at very different times for very different reasons in the real-time markets than is commonly seen in today's market. This is true for the forward market too.
    b. Combined cycle generation is also used differently, often committed and ramped to high output levels at unusual times, for example very late in the day; (see April 12, 30% HSBO).
    c. In general, market optimization software, with an objective to minimize production cost, may also find it more "economic" to use CTs for a short duration than commit a large thermal generator for a longer duration. This appears to be a partial explanation for some early morning and late night CT commitment.
4. The LODO scenarios typically presented more challenges than others.
    a. There are usually more transmission constraints
    b. There appears to be more complexity in the wind generation pattern, possibly making unit commitment more difficult, which could be due to distribution of transmission constraints in the LODO scenarios.
5. The HOBO scenarios, on average, provided the fewest operational challenges.
    a. Offshore wind appears to displace less onshore commitment of thermal generation in the forward market. In turn, the real-time market has more thermal resources on-line to respond to renewable variability.
    b. Offshore wind better supports the load centers in the East.
6. The HSBO scenarios offered varying results:
    a. When demand increases earlier than solar generation (or decreases later than solar generation), significant CT commitment occurs and thermal generation may ramp up and down quickly.
    b. However, high solar often resulted in fewer generator ramp constraints _overall_ as solar energy better follows peak demand.

7. RT challenges also occur in specific locations that do not show up when analyzing high-level results for the entire PJM grid.
    a. For example, if renewable energy quickly decreases where there is not sufficient thermal generation on-line and a transmission constraint appears, then mitigating actions are needed (e.g., additional CT commitment, borrowing from reserves to provide energy, and temporary transmission overloads (where/when possible).
    b. Likewise, in the reverse situation where wind quickly increases, transmission overloads were observed if thermal generation could not ramp down fast enough. A possible mitigation for these overloads is to temporarily curtail wind generation via electronic dispatch base-points.