GE
Energy Management

PJM Renewable Integration Study (PRIS)

Project Review (Task 3a)

Revision 07

Stakeholder Meeting of
October 28, 2013

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Meeting Agenda

Time	Topic	Discussion Leader	Minutes
1:00 – 1:15	Team Introductions and Project Overview	PJM + GE	15
1:15 – 1:30	Study Scenarios & Key Findings	GE	15
1:30 – 1:45	Hourly GE MAPS Analysis	GE	15
1:45 – 2:00	Renewable Capacity Valuation	GE	15
2:00 – 2:15	Transmission Overlays Analysis	PowerGEM	15
2:15 – 2:30	Break		15
2:30 – 2:45	Statistical Analysis + Reserve Analysis	EnerNex	15
2:45 – 2:55	Challenging Day Selections	EnerNex	10
2:55 – 3:15	Sub-Hourly PROBE Analysis	PowerGEM	20
3:15 – 3:30	Power Plant Cycling Cost Analysis	Intertek-AIM	15
3:30 – 3:45	Power Plant Emissions Analysis	Intertek-AIM	15
3:45 – 4:00	Next Steps & Q/A		15

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Team Introductions and Project Overview
PJM + GE
[15 Minutes]

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Project Team

PJM
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Manos Obessis
Jim Mitsche

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Study Objective

- Perform a comprehensive renewable power integration study to:
  - Determine, for the PJM balancing area, the operational, planning, and market effects of large-scale integration of wind power as well as mitigation/facilitation measures available to PJM.
  - Make recommendations for the implementation of such mitigation/facilitation measures.
- This study was initiated at the request of PJM stakeholders.
- Disclaimer: The purpose of the study is to assess impacts to the grid if additional wind and solar is connected. It is not an analysis of the economics of those resources, therefore quantifying the capital investment required to construct additional wind and solar is beyond the scope of this study.

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Perspective . . .

- Focus of the Study:
  - This study investigates operational, planning, and market effects of large-scale wind/solar integration, and makes recommendations for possible facilitation/mitigation measures.
    - Study looks at a broad range of issues for long-term future (year 2026)
    - It is not a detailed near-term planning study for any specific issue or mitigation
    - It does not examine the impacts to the Capacity Market
- Data Sources:
  - Renewables integration studies commonly use a combination of confidential ISO-specific data and public non-proprietary data.
    - It is desirable to use as much ISO-specific data as possible
      - Study results are more consistent with PJM planning/operations studies
      - Higher confidence from stakeholders
    - It is also necessary to use some non-proprietary public data to better protect sensitive confidential data
    - Challenge for today is to select the appropriate balance of PJM's data and non-proprietary public data for this study

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Analytical Approach & Tools

- GE MAPS based Hourly Production Simulation (PJM + Rest of EI) - Year of the Study: 2026
- Transmission Overlay Analysis
- PROBE based Sub-Hourly Simulation of Interesting Days
- GE MARS based Wind Capacity Valuation
- Statistical Analysis of Load and Renewable Data
- Reserve Analysis
- Power Plant Cycling Cost Analysis
- Power Plant Cycling Emissions Analysis

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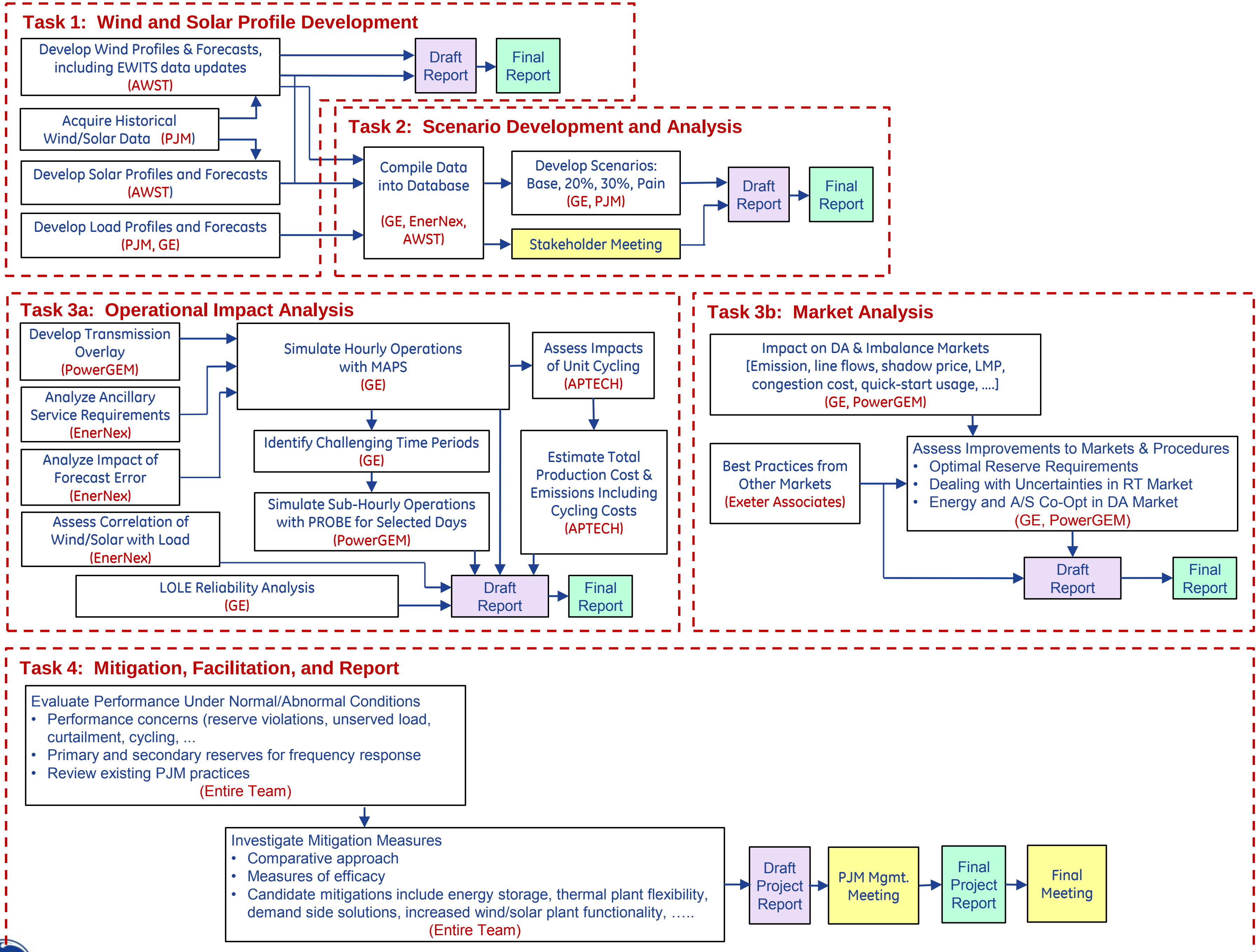

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Study Scenarios & Key Findings (GE) [15 Minutes]

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Study Scenarios

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Study Scenarios

Scenario	Renewable Penetration in PJM	Wind/Solar (GWh)	Wind + Solar Siting	Years Simulated	Comments
2% BAU	Reference	Existing wind + solar	Existing Plants (Business as Usual)	3 years	Benchmark Case for Comparing Scenarios
14% RPS	Base Case 14%	109 / 11	Per PJM Queue & RPS Mandates	3 years	Siting based on PJM generation queue and existing state mandates
20% LOBO	20%	150 / 29	Low Offshore + Best Onshore	3 years	Onshore wind selected as best sites within all of PJM
20% LODO	20%	150 / 29	Low Offshore + Dispersed Onshore	1 year	Onshore wind selected as best sites by state or region
20% HOBO	20%	150 / 29	High Offshore + Best Onshore	1 year	High offshore wing with best onshore wind
20% HSBO	20%	121 / 58	High Solar + Best Onshore	1 year	High solar with best onshore wind
30% LOBO	30%	228 / 48	Low Offshore + Best Onshore	3 years	Onshore wind selected as best sites within all of PJM
30% LODO	30%	228 / 48	Low Offshore + Dispersed Onshore	1 year	Onshore wind selected as best sites by state or region
30% HOBO	30%	228 / 48	High Offshore + Best Onshore	1 year	High offshore wing with best onshore wind
30% HSBO	30%	179 / 97	High Solar + Best Onshore	1 year	High solar with best onshore wind

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The Total Capacity By Wind/Solar For Each Scenario

Scenario	Onshore Wind (MW)	Offshore Wind (MW)	Centralized Solar (MW)	Distributed Solar (MW)	Total (MW)
2% BAU	5,122	0	72	0	5,194
14% RPS	28,834	4,000	3,254	4,102	40,190
20% LOBO	39,452	4,851	8,078	10,111	62,492
20% LODO	40,942	4,851	8,078	10,111	63,982
20% HOBO	21,632	22,581	8,078	10,111	62,402
20% HSBO	32,228	4,026	16,198	20,294	72,746
30% LOBO	59,866	6,846	18,190	16,907	101,809
30% LODO	63,321	6,846	18,190	16,907	105,264
30% HOBO	33,805	34,489	18,190	16,907	103,391
30% HSBO	47,127	5,430	27,270	33,823	113,650

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Renewable Mix

- 14% RPS Scenario meets RPS targets for states within PJM footprint
- Wind/Solar Split
  - Distributed solar is mix of residential (20%) and commercial (80%)
- Transmission system is built out for each scenario based on wind/solar generation ratings and locations

Scenario	Onshore Wind	Offshore Wind	Centralized Solar	Distributed Solar
14% RPS	86%	14%	50%	50%
Low Offshore	90%	10%	50%	50%
High Offshore	50%	50%	50%	50%
High Solar	90%	10%	50%	50%

Scenario	PJM % RE	EI % RE
14 RPS	14%	10%
Low Offshore	20%	15%
High Offshore	20%	15%
High Solar	20%	15%
Low Offshore	30%	20%
High Offshore	30%	20%
High Solar	30%	20%

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Key Assumptions

- Eastern Interconnect system was simulated
- Renewable plants were connected to higher voltage busses
- Remaining PJM coal plants were assumed to have emissions control technology
- Renewable resources were curtailed when dispatch will impact nuclear operation
- Only primary fuel was modeled
- Existing operating reserve practice was used for 2P BAU scenario, statistical analysis was used to modify reserves for others
- 2026 run year used 2006 load and renewable hourly shapes.
- 2026 data was updated based on PJM input on coal retirements, gas repowers, and new builds

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Key Findings

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Key Findings

Scenario	Total RE Delivered (GWh)	Production Cost Delta ($M)	Wholesale Load Payments ($M)	Gas (GWh)	Coal (GWh)	Imports (GWh)	Value of RE ($/MWh)	Transmission Cost ($/MWh)	Value of RE with Transmission Cost ($/MWh)	Gas Displace-ment (% of Total)	Coal Displace-ment (% of Total)	Imports Displace-ment (% of Total)
2% BAU	17,217	36,915	71,773	192,025	421,618	47,390						
		Delta Relative to 2% BAU										
14% RPS	122,858	(5,675)	(4,165)	(49,590)	(32,866)	(21,397)	53.7	3.7	49.2	-47%	-31%	-22%
20% HOBO	174,769	(8,641)	(21,464)	(90,194)	(34,604)	(31,302)	54.9	4.4	51.1	-57%	-22%	-21%
20% LOBO	177,706	(8,507)	(10,138)	(56,854)	(66,940)	(32,267)	53.0	4.1	49.6	-35%	-42%	-23%
20% LODO	178,759	(8,102)	(8,553)	(58,322)	(59,647)	(41,085)	50.2	3.8	47.0	-36%	-37%	-27%
20% HSBO	181,470	(8,575)	(12,686)	(66,682)	(42,505)	(53,696)	52.2	3.9	49.0	-41%	-26%	-34%
30% HOBO	273,617	(13,101)	(21,464)	(118,876)	(58,453)	(77,631)	51.1	10.9	45.1	-46%	-23%	-31%
30% LOBO	276,645	(14,408)	(10,138)	(68,192)	(170,920)	(19,134)	55.5	13.7	48.1	-26%	-66%	-8%
30% LODO	276,562	(12,581)	(8,553)	(68,013)	(119,526)	(68,653)	48.5	5.0	45.8	-26%	-46%	-28%
30% HSBO	271,135	(13,201)	(15,255)	(84,511)	(88,847)	(78,382)	52.0	8.0	47.6	-33%	-35%	-32%
									Average	-39%	-36%	-25%

Note: This study did not evaluate potential impacts on PJM Capacity Market results due to reduced generator revenues from the wholesale energy market, nor did it evaluate the impact of renewables to rate payers. It is conceivable that lower energy prices would be at least partially offset by higher capacity prices.

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Key Findings (Continued)

- The PJM system, with additional reserves and transmission build-out, could handle renewable penetration levels up to 30%.
- The principal impacts of higher penetration of renewable energy into the grid include:
    - Lower Coal and CCGT generation under all scenarios
    - Lower emissions of criteria pollutants and greenhouse gases
    - No loss of load and minimal renewable energy curtailment
    - Lower system-wide production costs
    - Lower generator gross revenues
    - Lower average LMP and zonal prices

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Key Findings (Continued)

- On average for all scenarios, ~36% displacement from coal-based Generation and ~39% displacement from gas-based generation (of the total displacement caused by the renewable generation) as compared to the 2% BAU Scenario.
- The value of the renewable energy was ~$50/MWh (incremental production cost savings / incremental renewable energy MWhs produced).
- Emission Reduction is observed in all scenarios.
- In general, all the simulations of challenging days revealed successful operation of the PJM real-time market.

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Key Findings (Continued)

Effective Load Carrying Capability (not to be confused with Capacity Factor) of Different Renewable Resources in 20% and 30% scenarios:

- Residential PV: 57% - 58%
- Commercial PV: 55% - 56%
- Central PV: 62% - 66%
- Off-shore Wind: 21% - 29%
- Onshore Wind: 14% - 18%

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Key Findings (Continued)

- Although there were occasionally periods of reserve shortfalls and new patterns of CT usage, there were no instances of un-served load.
- The level of difficulty for real-time operations largely depends on the day-ahead unit commitment.
- Higher penetrations of renewable energy (20% and 30%) create operational patterns that are significantly different than what is common today.
- Maximum Regulation increased from 2,000 MW for load only to ~3,000 to 4,000 MW in the 30% scenarios when ~100,000 MW of new renewable capacity was added.
- Cycling Analysis showed slightly reduced emissions and economic values from the hourly analysis, but not significant enough to change the overall conclusions.

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Hourly GE MAPS Analysis
(GE)
[15 Minutes]

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Operational Performance

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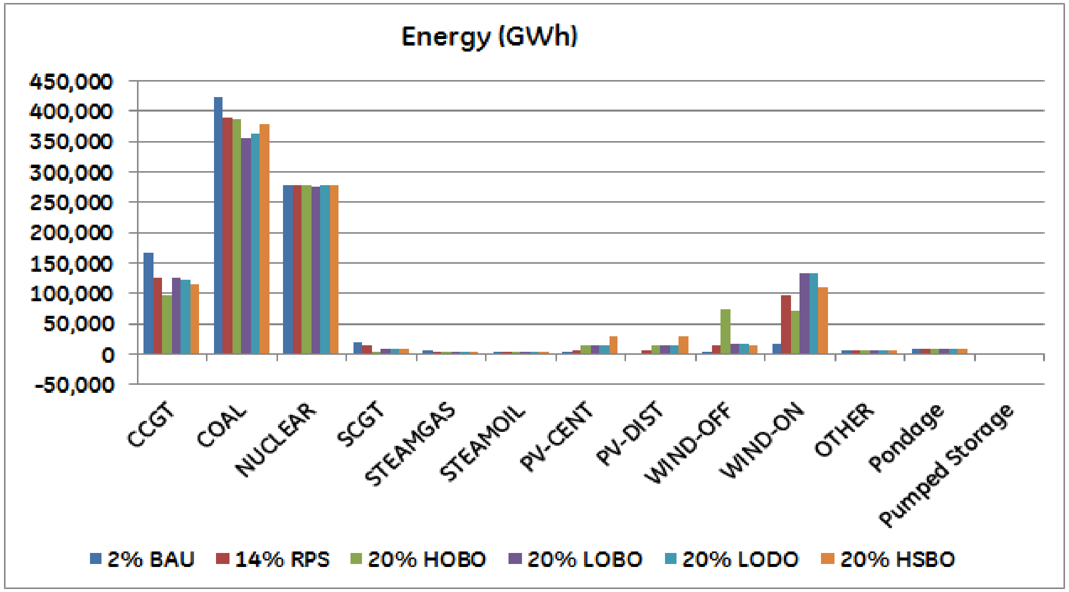
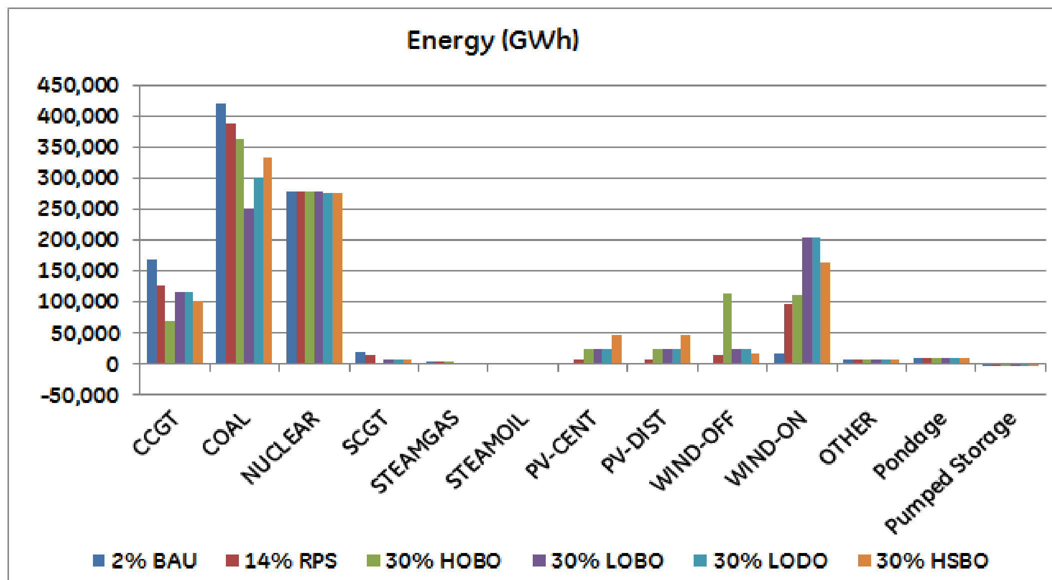
Energy Generation by Unit Type (GWh)



- CCGT & Coal generation decreases as renewable penetration increases



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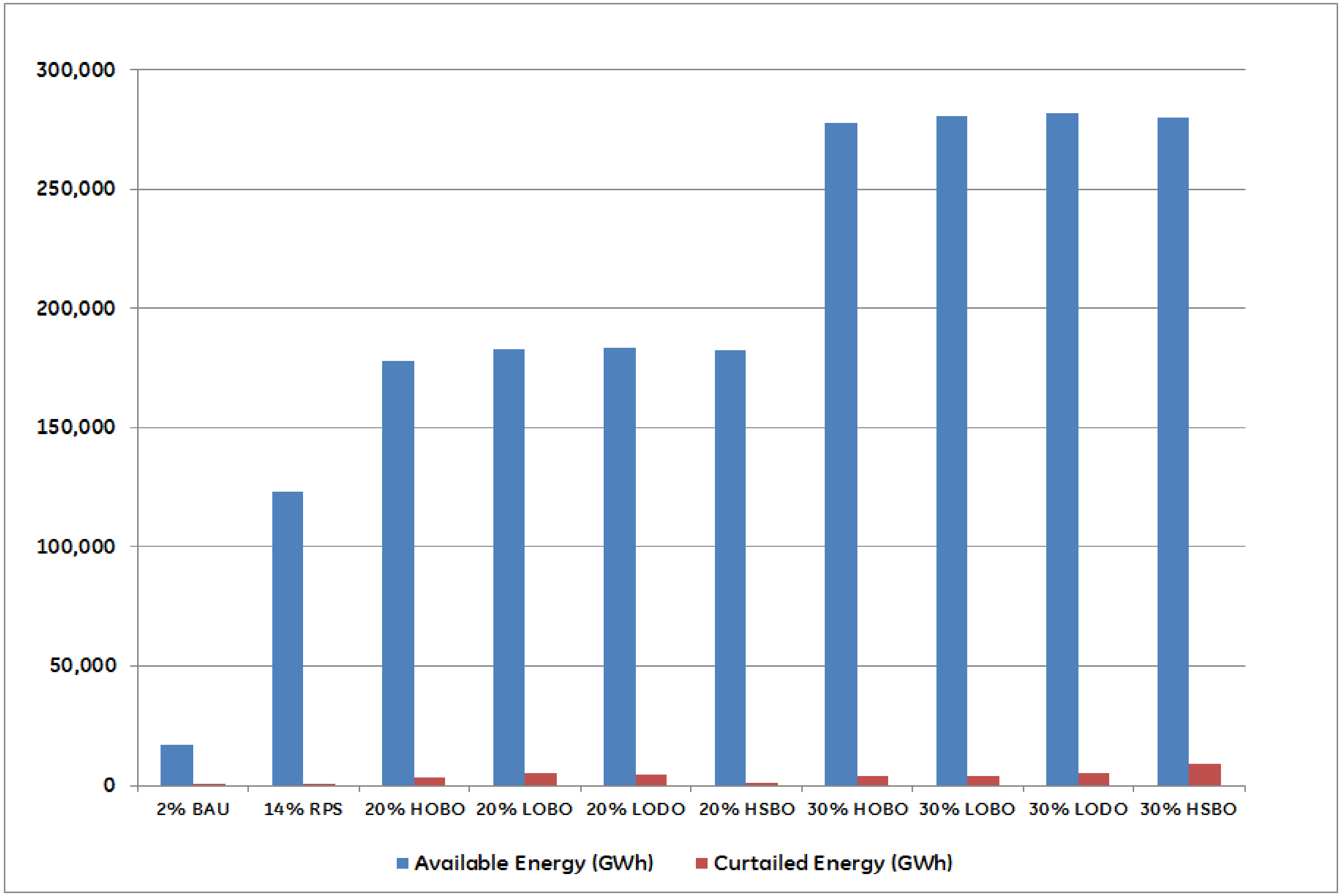
Delivered and Curtailed Renewable Energy



- Overall, very little curtailment
- Highest curtailment seen in the 30P HSBO scenario (some local congestion still exist)

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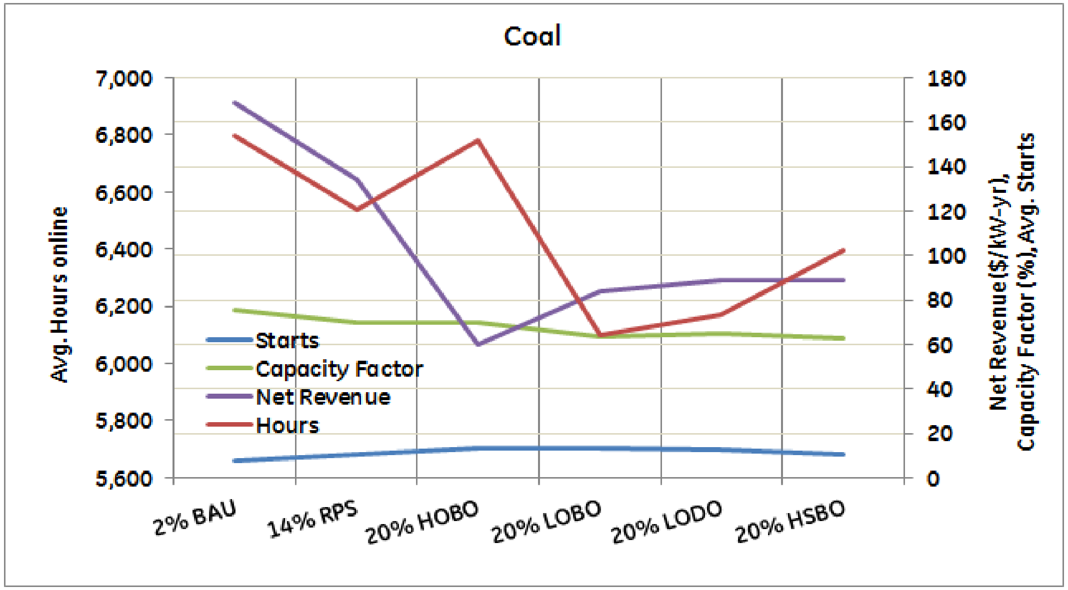
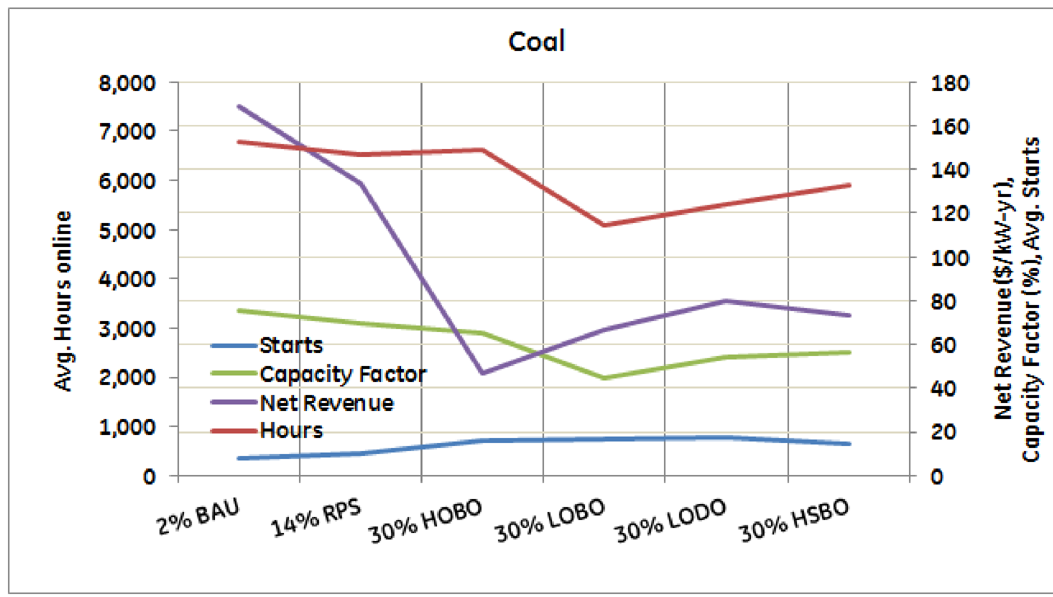
Performance of Coal Units



- Coal generation starts increase and hours online decrease, indicating increased cycling due to increased renewable penetration
- Net Revenue decreases significantly



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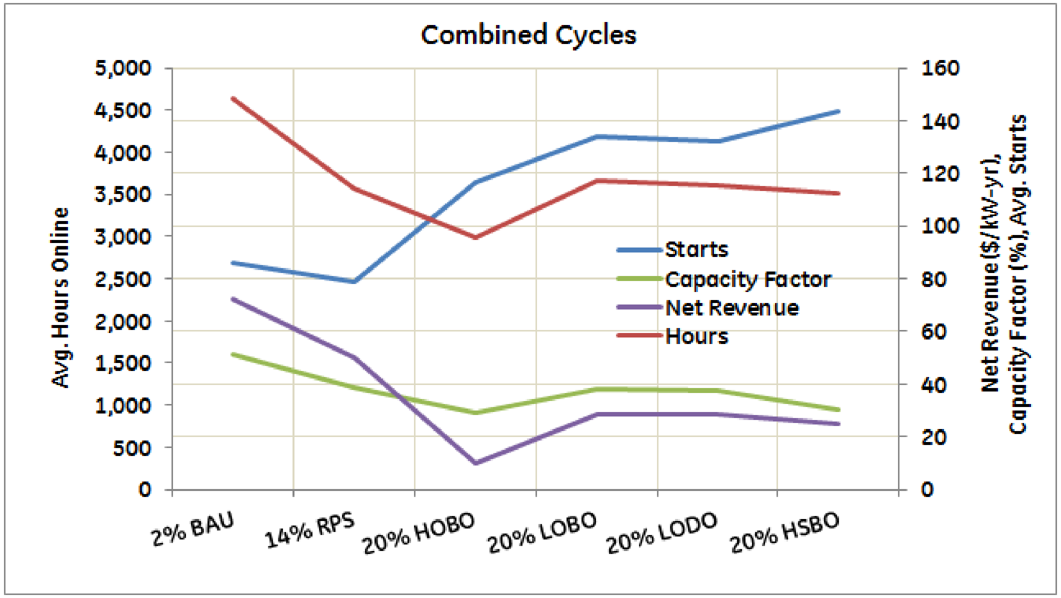
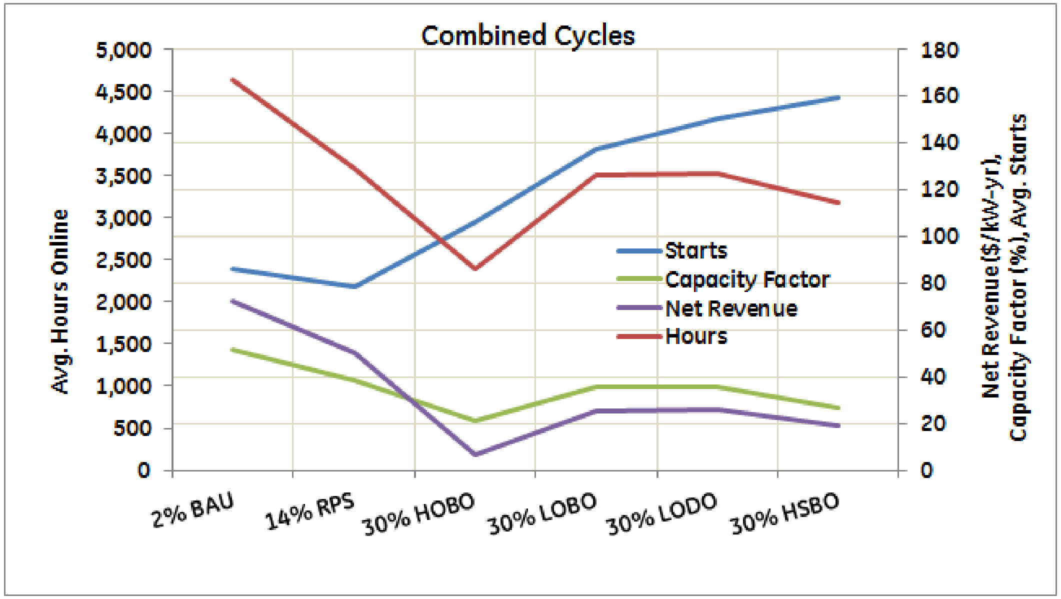
Performance of Combined Cycle Units



- Similar to Coal generation, CCGT starts increase and hours online decrease, indicating increased cycling due to increased renewable penetration
- Net Revenue decreases significantly



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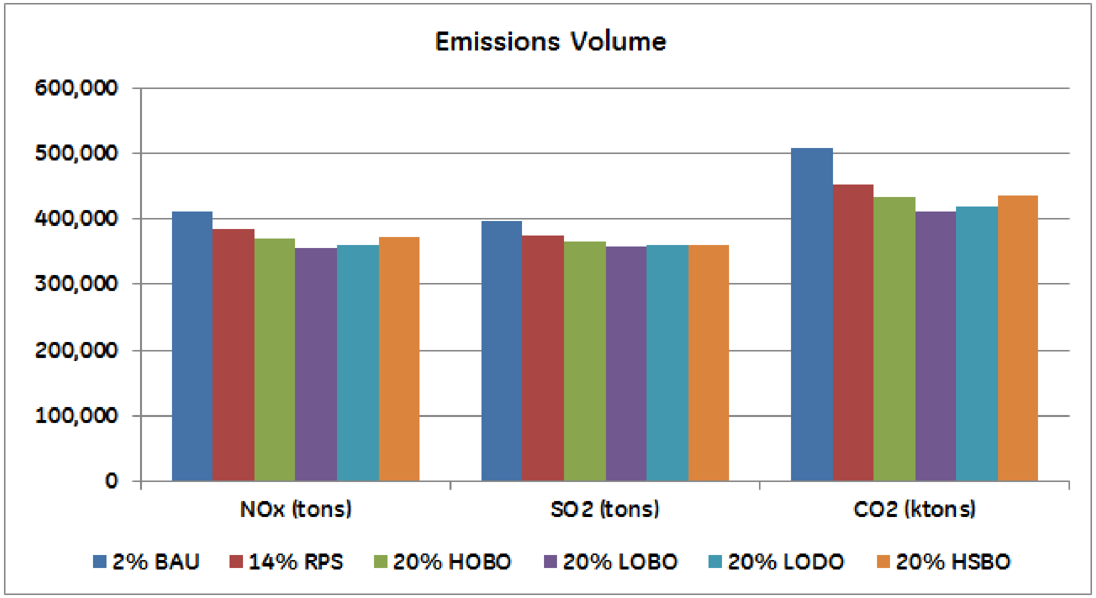
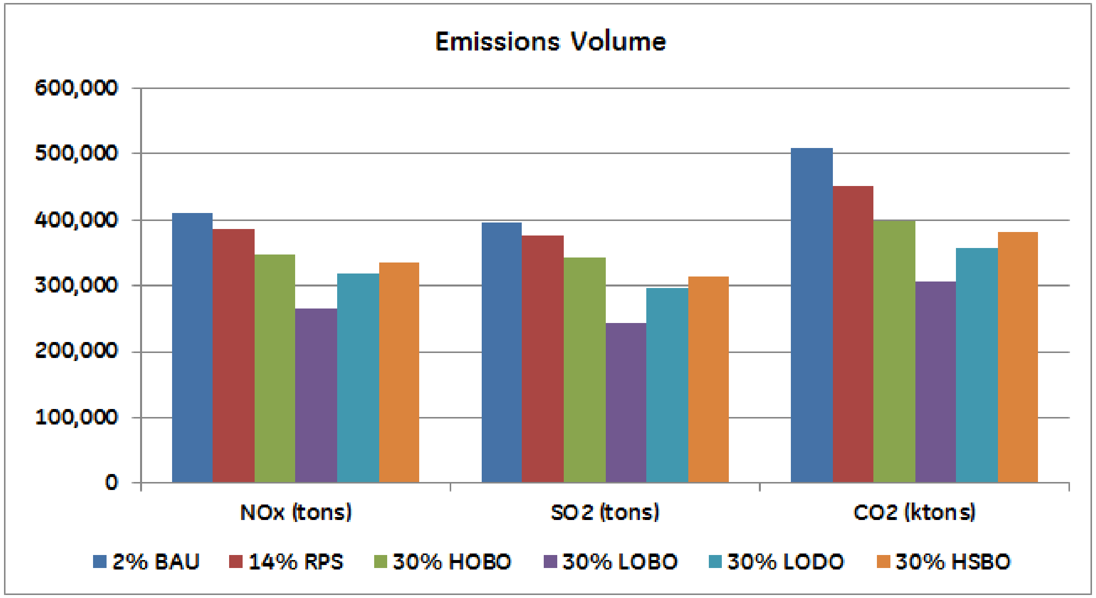
Environmental Emissions



- Emission are reduced with increased renewable penetration



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Economic Performance

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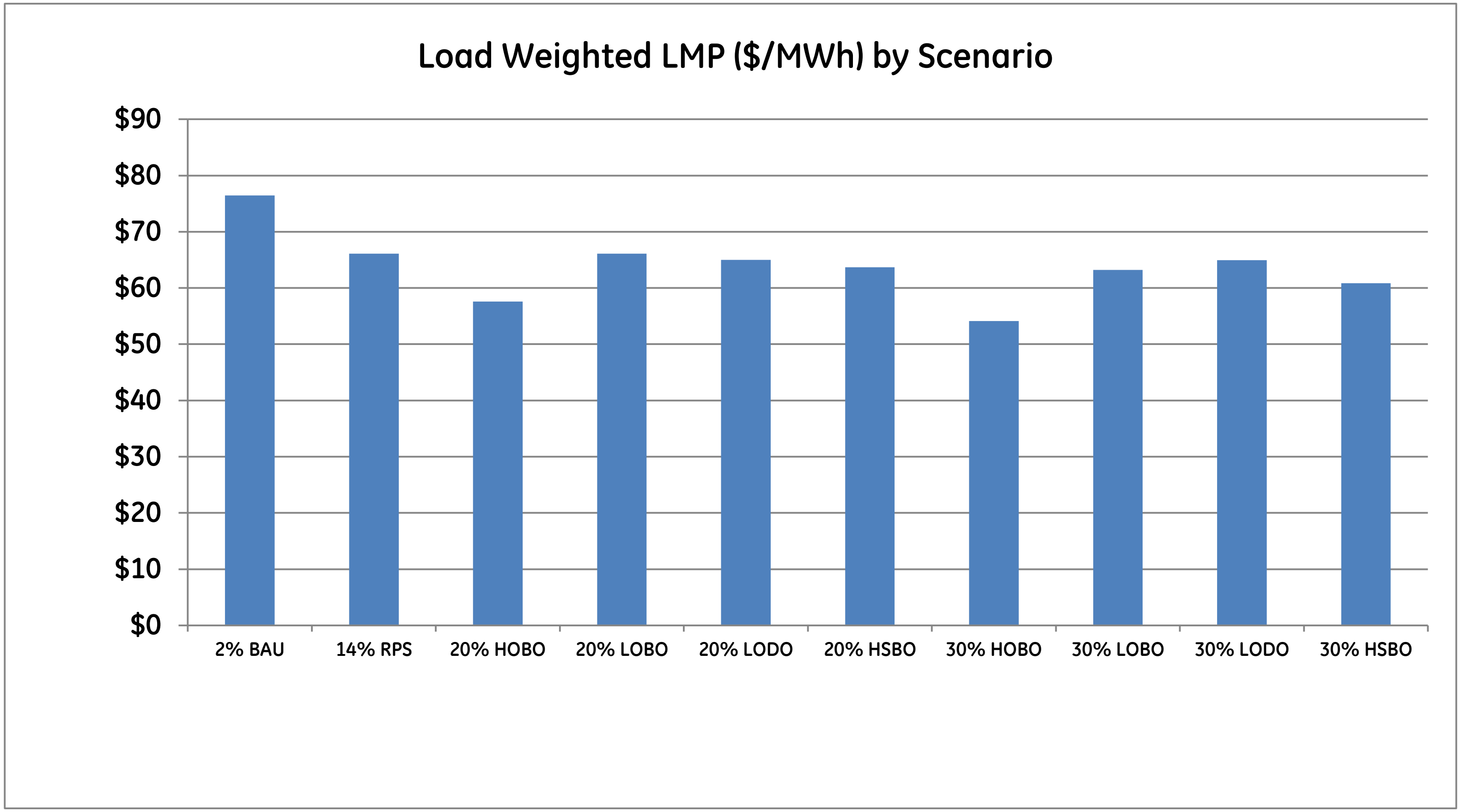
Load Weighted LMP



Geographic variation still exist in all scenarios

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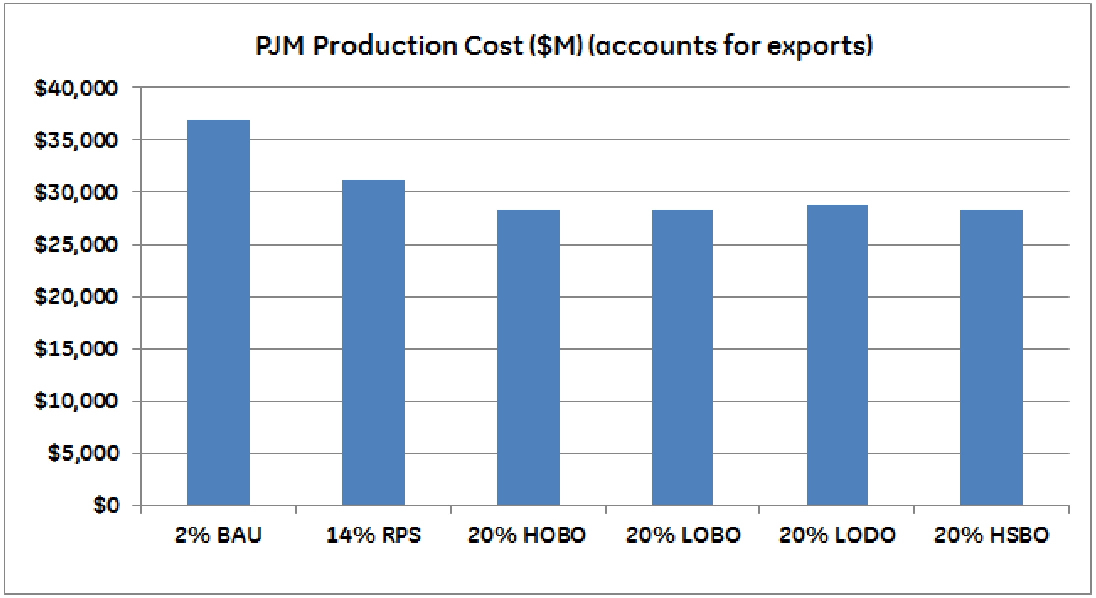
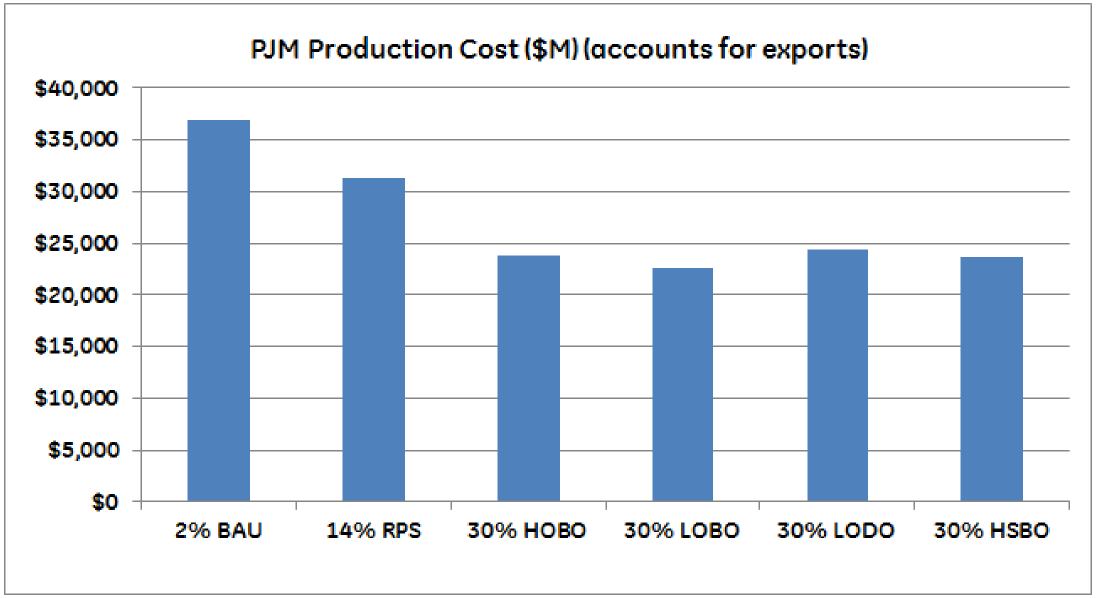
PJM Production Cost ($M) (accounts for exports)



- Production Cost decreases with increased renewable penetration



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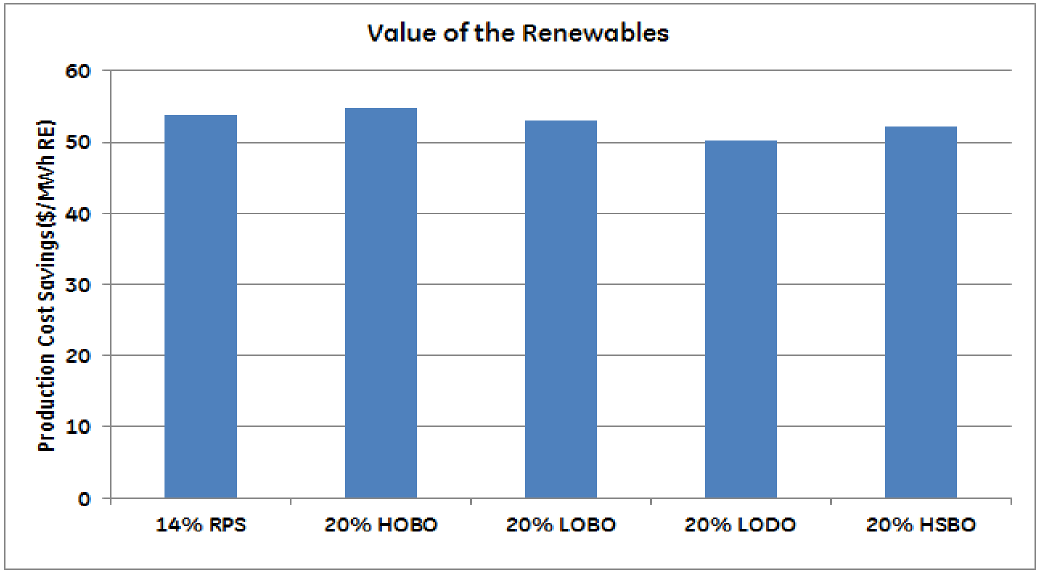
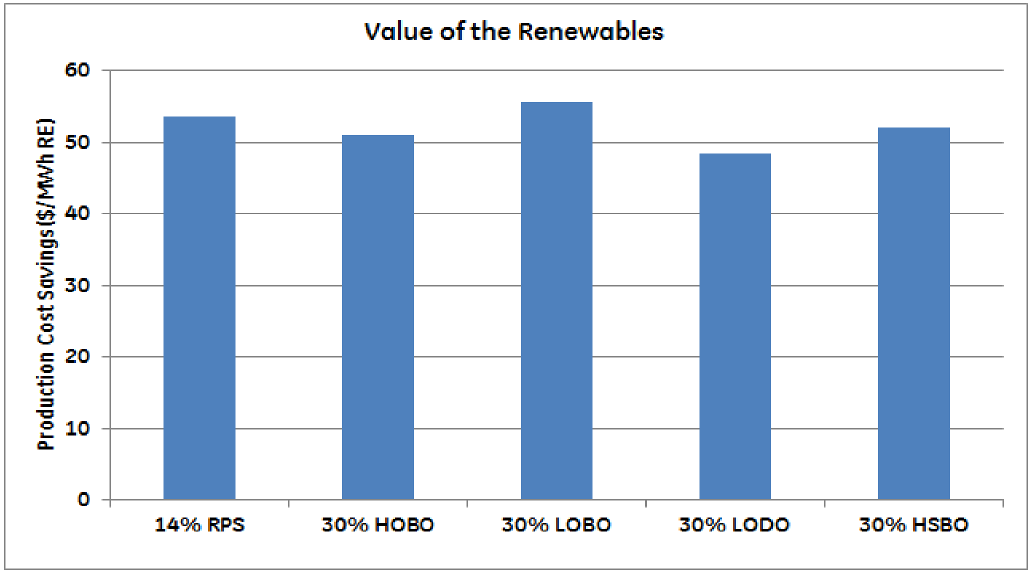
Value of the Renewables ($/MWh Renewable)



- Renewable value calculated by dividing scenario savings compared to 2P BAU case by incremental delivered renewable energy



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Value of the Renewables Accounting for the Transmission Cost for Each Scenario Relative to 2% BAU

Scenario	Transmission Cost ($M/Year)	Delivered Renewable (RE) Energy (GWh)	Transmission Cost per MWh of Delivered Renewables ($/MWh RE)	Value of Renewables ($/MWh RE)	Value of Renewables adjusted for Transmission Cost ($/MWh RE)
14% RPS	555	122,858	4.52	53.72	49.20
20% HOBO	660	174,769	3.78	54.85	51.07
20% LOBO	615	177,706	3.46	53.01	49.55
20% LODO	570	178,759	3.19	50.16	46.97
20% HSBO	585	181,470	3.22	52.20	48.98
30% HOBO	1635	273,617	5.98	51.10	45.12
30% LOBO	2055	276,645	7.43	55.54	48.11
30% LODO	750	276,562	2.71	48.51	45.80
30% HSBO	1200	271,135	4.43	51.99	47.56

Note: A carrying charge of 15% was used to calculate the annual transmission cost. Transmission cost refers to the capital cost of additional transmission.

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Incremental Value of the Renewables in 30% Scenarios over the 20% Scenarios

Scenario	Production Cost ($M)	Transmission Cost ($M/Year)	Incremental Production Cost Savings ($M)	Incremental Transmission Cost ($M/Year)	Net Savings including Transmission Cost ($M/Year)	Incremental Renewable Energy Delivered (GWh)	Incremental Value of Renewables adjusted for Transmission Cost ($/MWh RE)
20% HOBO	28,274	660					
20% LOBO	28,408	615					
20% LODO	28,813	570					
20% HSBO	28,341	585					
30% HOBO	23,814	1,635	4,460	975	3,485	98,848	35.25
30% LOBO	22,508	2,055	5,900	1,440	4,460	98,938	45.08
30% LODO	24,334	750	4,478	180	4,298	97,803	43.95
30% HSBO	23,714	1,200	4,626	615	4,011	89,666	44.74

Note: A carrying charge of 15% was used to calculate the annual transmission cost. Transmission cost refers to the capital cost of additional transmission. Production costs are for the study year.

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Hourly Analysis Key Findings

- Even at 30% penetration, results indicate that the PJM system can handle the additional renewable integration with sufficient reserves and transmission build out.
- The principal impacts of higher penetration of renewable energy into the grid include:
  - Lower Coal and CCGT generation under all scenarios
  - Lower emissions of criteria pollutants and greenhouse gases
  - No loss of load and minimal renewable energy curtailment
  - Lower system-wide production costs
  - Lower generator gross revenues
  - Lower average LMP and zonal prices

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Hourly Analysis Key Findings (Continued)

- On average for all scenarios, ~36% displacement from coal-based Generation and ~39% displacement from gas-based generation (of the total displacement caused by the renewable generation) as compared to the 2% BAU Scenario.
- The value of the renewable energy was ~$50/MWh (incremental production cost savings / incremental renewable energy MWhs produced).
- Emission Reduction is seen in all scenarios.

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Hourly Analysis Key Findings (Continued)

Using Different Load and Wind Profile Years:

- To test impact of different profile years, in addition to the 2006 profile year, the load and wind profiles from years 2004 and 2005 were used in 2% BAU, 14% RPS, 20% LOBO, and 30% LOBO Scenarios.
- Although there was observable difference in operational and economic performance across the profile years, the overall differences were relatively small.

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Sensitivity Analysis

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Sensitivity List

- (LL): Low Load Growth: 6.1% reduction in demand energy compared to the base case
- (LG): Low Natural Gas Price: AEO forecast of $6.50/mmBtu compared to $8.02/mmBtu in the base case
- (LL, LG): Low Load Growth & Low Natural Gas Price
- (LG, C): Low Natural Gas Price & High Carbon Cost: Carbon Cost $40/Ton compared to $0/Ton in the base case
- (PF): Perfect Wind & Solar forecast: Perfect knowledge of the wind and solar for commitment and dispatch

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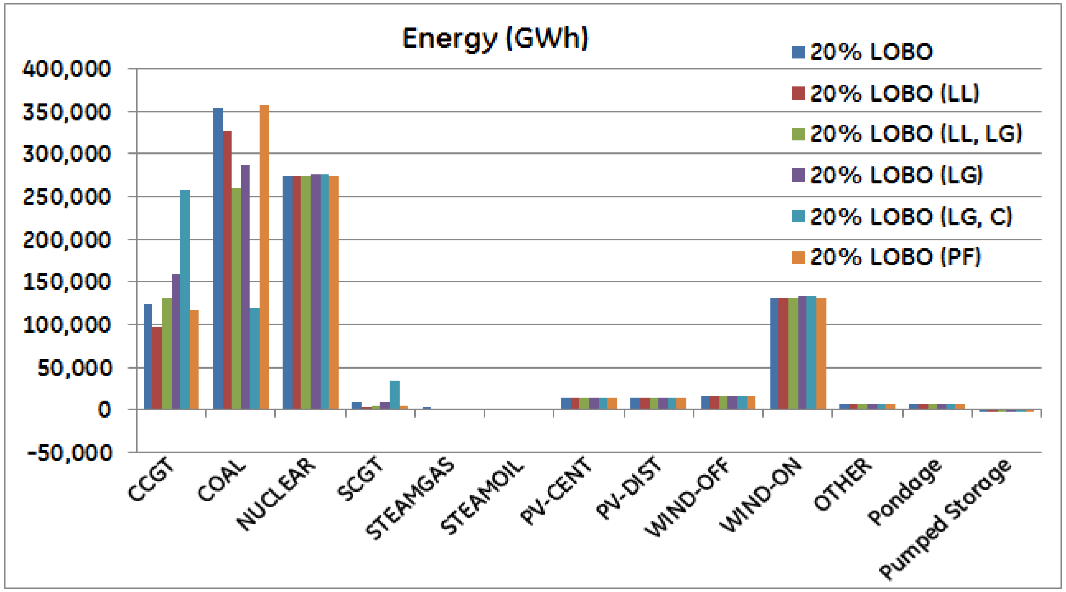
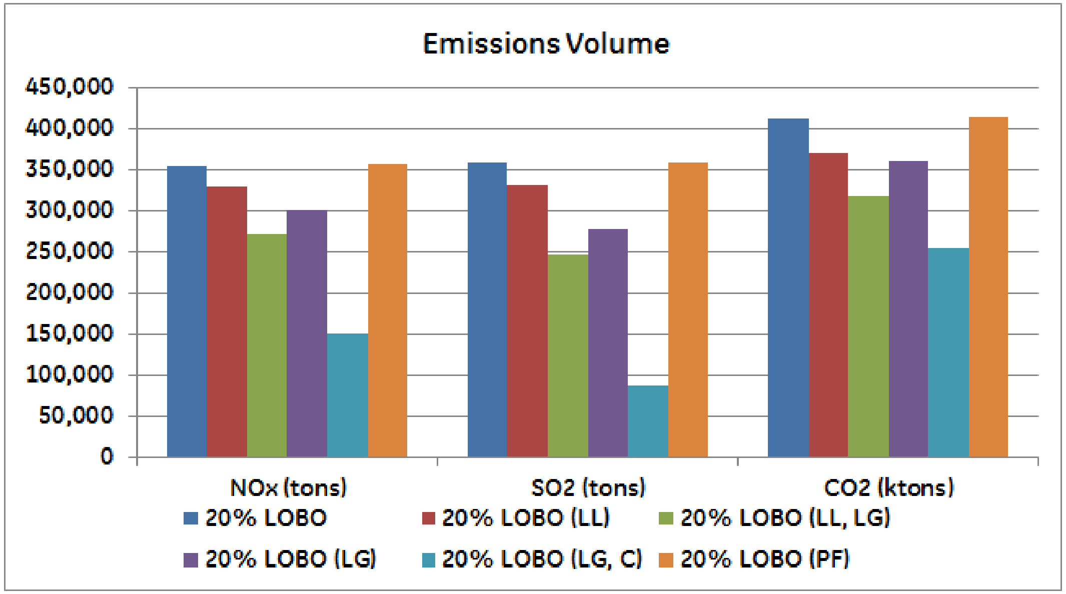
Sensitivity Operational Impacts (20% LOBO)



- Low Gas/Carbon has the largest coal displacement
- In Perfect Forecast case, SCGT operation decreases.
- Impact may be greater in operational (PROBE) analysis



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Sensitivity Economic Impacts (20% LOBO)

PJM Sensitivities	20% LOBO	20% LOBO (LL)	20% LOBO (LL, LG)	20% LOBO (LG)	20% LOBO (LG, C)	20% LOBO (PF)
Production Costs ($M)	28,835	24,961	20,388	23,463	28,607	28,218
Change from Base	0	-3,874	-8,447	-5,373	-228	-617
Relative Change	0.00%	-15.52%	-41.43%	-22.90%	-0.80%	-2.19%
Generator Revenue ($M)	59,178	52,141	45,549	51,916	82,857	57,458
Change from Base	0	-7,037	-13,629	-7,262	23,679	-1,720
Relative Change	0.00%	-13.50%	-29.92%	-13.99%	28.58%	-2.99%
Costs to Load ($M)	61,341	52,551	47,541	54,528	90,294	59,197
Change from Base	0	-8,790	-13,800	-6,814	28,952	-2,144
Relative Change	0.00%	-16.73%	-29.03%	-12.50%	32.06%	-3.62%
Load Wtd LMP ($/MWh)	66.13	60.51	54.74	58.78	97.34	63.82
Change from Base	0.00	-5.62	-11.39	-7.35	31.21	-2.31
Relative Change	0.00%	-9.29%	-20.81%	-12.50%	32.06%	-3.63%

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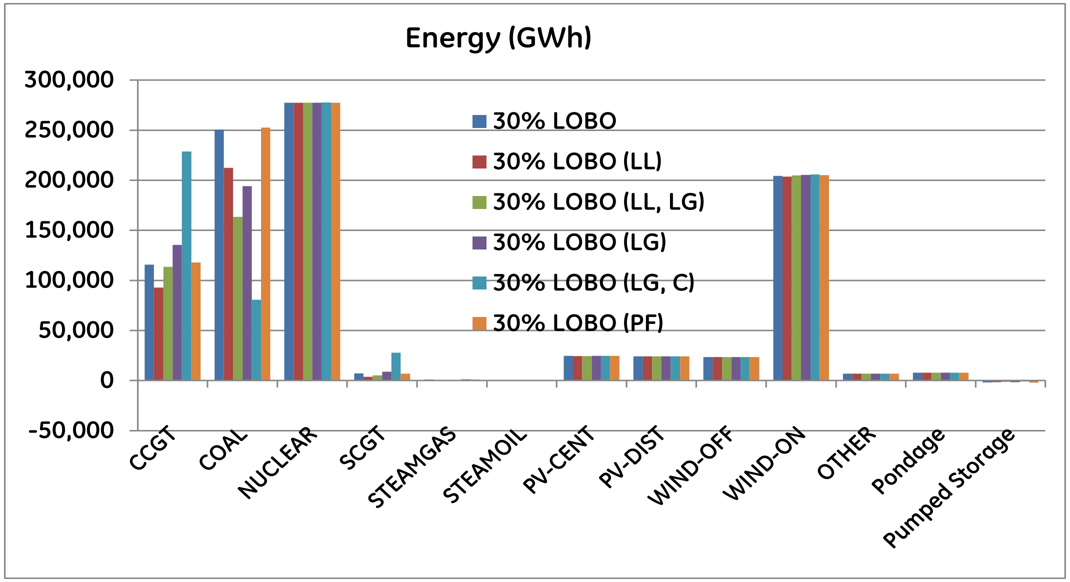
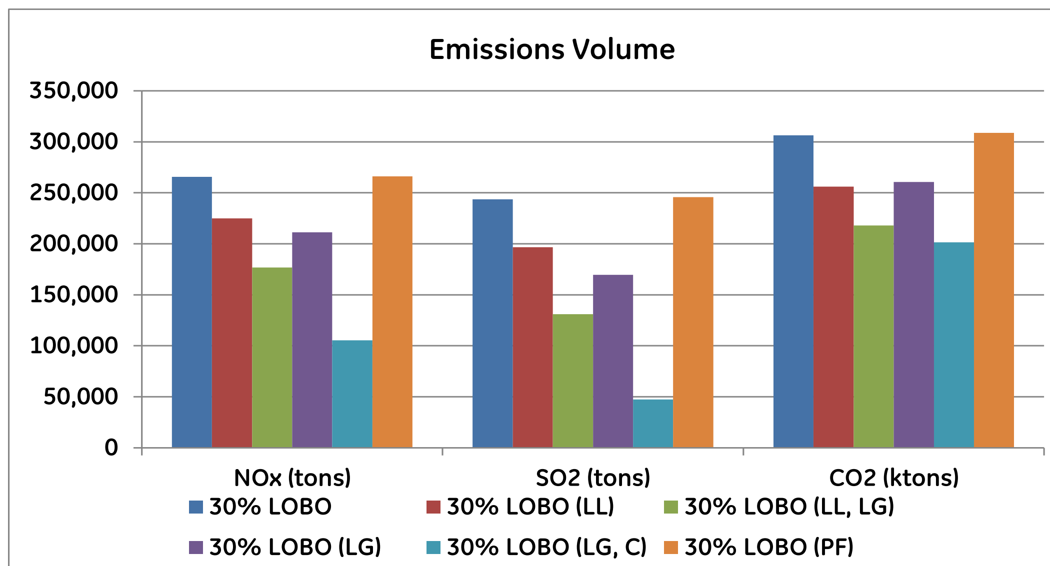
Sensitivity Operational Impacts (30% LOBO)





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Sensitivity Economic Impacts (30% LOBO)

PJM Sensitivities	30% LOBO	30% LOBO (LL)	30% LOBO (LL, LG)	30% LOBO (LG)	30% LOBO (LG, C)	30% LOBO (PF)
Production Costs ($M)	21,854	17,565	13,935	16,880	24,540	22,526
Change from Base	0	-4,289	-7,918	-4,974	2,686	672
Relative Change	0.00%	-24.42%	-56.82%	-29.47%	10.95%	2.98%
Generator Revenue ($M)	56,860	49,648	43,001	48,969	79,940	55,769
Change from Base	0	-7,212	-13,859	-7,891	23,079	-1,091
Relative Change	0.00%	-14.53%	-32.23%	-16.11%	28.87%	-1.96%
Load Cost ($M)	61,635	54,289	48,345	55,156	89,008	59,735
Change from Base	0	-7,346	-13,291	-6,479	27,372	-1,900
Relative Change	0.00%	-13.53%	-27.49%	-11.75%	30.75%	-3.18%
Load Wtd LMP ($/MWh)	63.22	59.28	52.79	56.57	91.29	61.27
Change from Base	0.00	-3.94	-10.43	-6.65	28.07	-1.95
Relative Change	0.00%	-6.65%	-19.76%	-11.75%	30.75%	-3.19%

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Sensitivity Analysis Key Findings

- Sensitivity analysis key findings are:
  - Low Load caused generation displacement of both Coal and Gas generation
  - Low gas caused an increase in Gas generation and a decrease in Coal generation
  - Low gas & Carbon caused a significant increase in CCGT operation and a decrease in Coal
  - Low Load & Low Gas had minimal impact on CCGT operation , because of offsetting impacts and Coal had an additive impact
  - Economic (Price) Impacts such as production cost savings and average LMP's will vary significantly depending on assumptions about fuel price, load growth, and environmental (carbon) policy.
    - For example, the figures reported in this study reflect a natural gas price of $8.02/mmBTU. For the sensitivity analysis with lower loads and a gas price of $6.50/mmBTU, production cost savings in the 14% RPS case were reduced from $6B to less than $2B, and in the 20% LOBO scenario they are reduced from $9B to less than $4B.

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Capacity Valuation Analysis
(GE)
[15 Minutes]

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Capacity Valuation Analysis Approach

- Wind Capacity Valuation involved loss of load expectation (LOLE) calculations for the study footprint using the GE's Multi-Area Reliability Simulation (GE MARS) model.
  - The LOLE analysis determined the Effective Load Carrying Capability (ELCC) of the incremental wind and solar generation additions.
  - The analysis quantified the impact of wind generation on overall reliability measures, as well as the capacity values of the wind generation resources based on the ELCC methodology
  - Three year load and resource (wind/solar) data is used (2004, 2005, and 2006)
  - Artificial variability is introduced in each year's resource data by allowing GE MARS to select the current day profile from +/- 7 day window
    - This is being used as a substitute in absence of having many years of synchronized load/resource data
  - The ELCC of a resource is the average ELCC across the three years (in a particular scenario)

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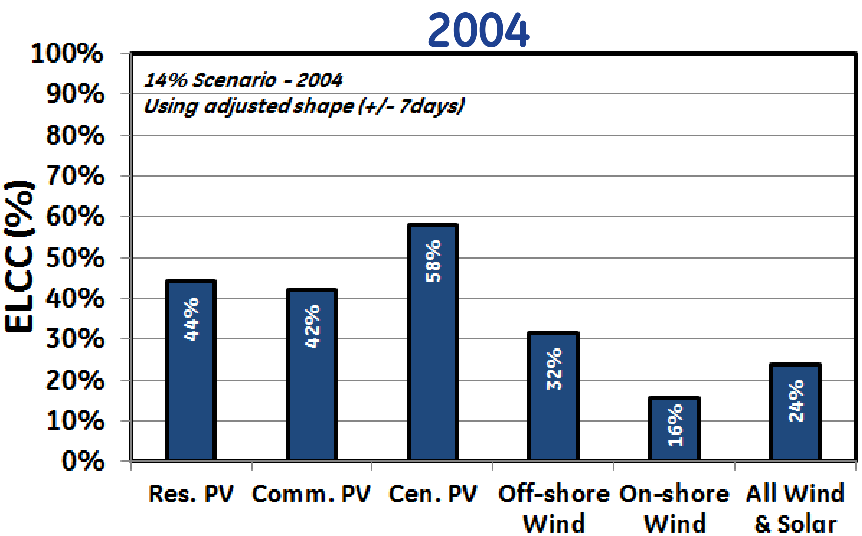
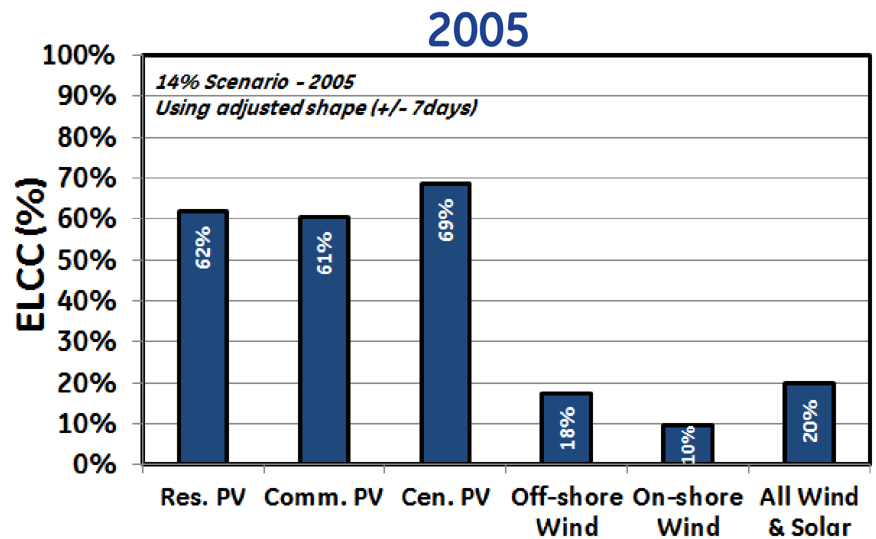
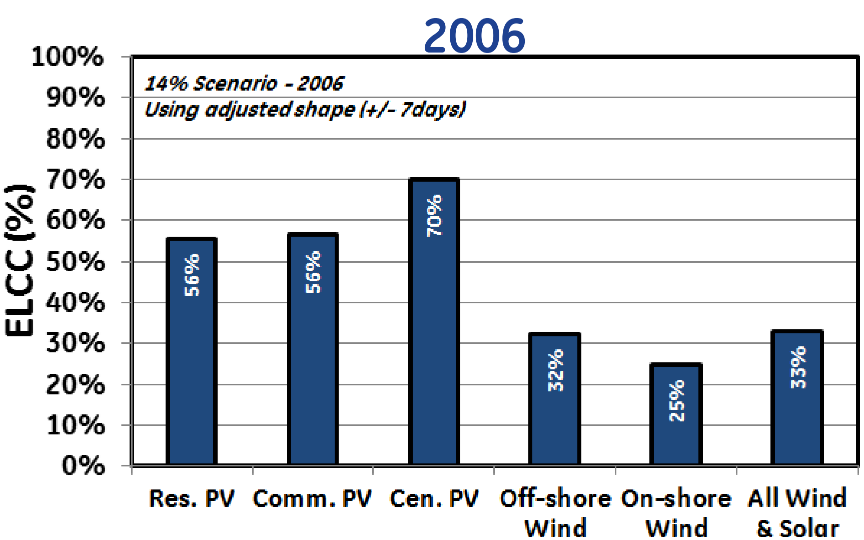
RPS 14% Scenario







- ELCC of a resource is the average of the three years → shown on next slide

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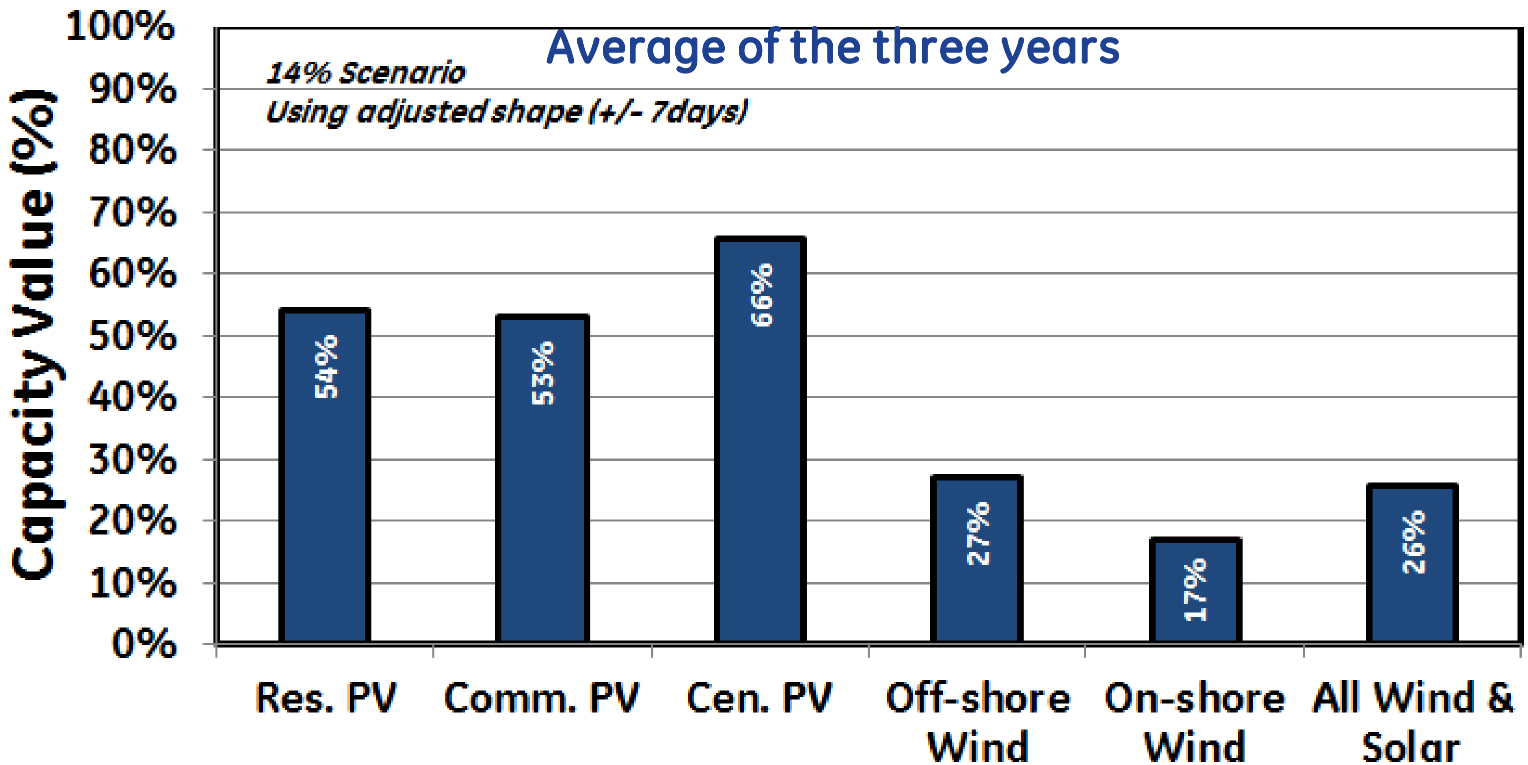
RPS 14% Scenario



The average ELCC takes into account the year-to-year variation in load/resource data, and provides a more stable result

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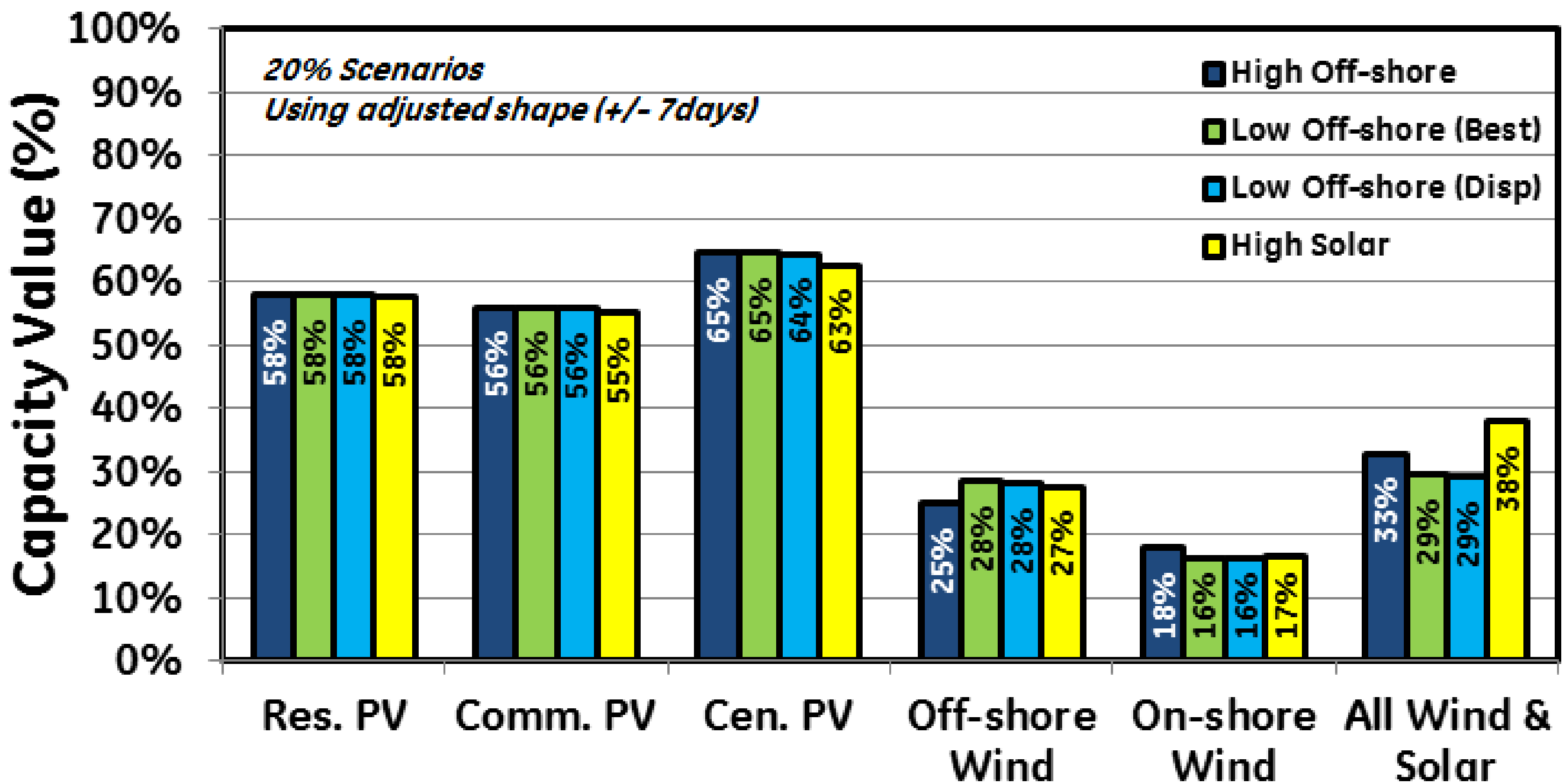
20% Scenarios



- ELCC of distribution-connected Solar PV is between 55-58%
- ELCC of Central PV is between 63-65%
    - ELCC drops in the "High Solar" scenario due to saturation
- ELCC of Off-shore Wind is between 25-28%
    - ELCC in "High Off-shore" scenario is low due to saturation
- ELCC of On-shore Wind is between 16-18%

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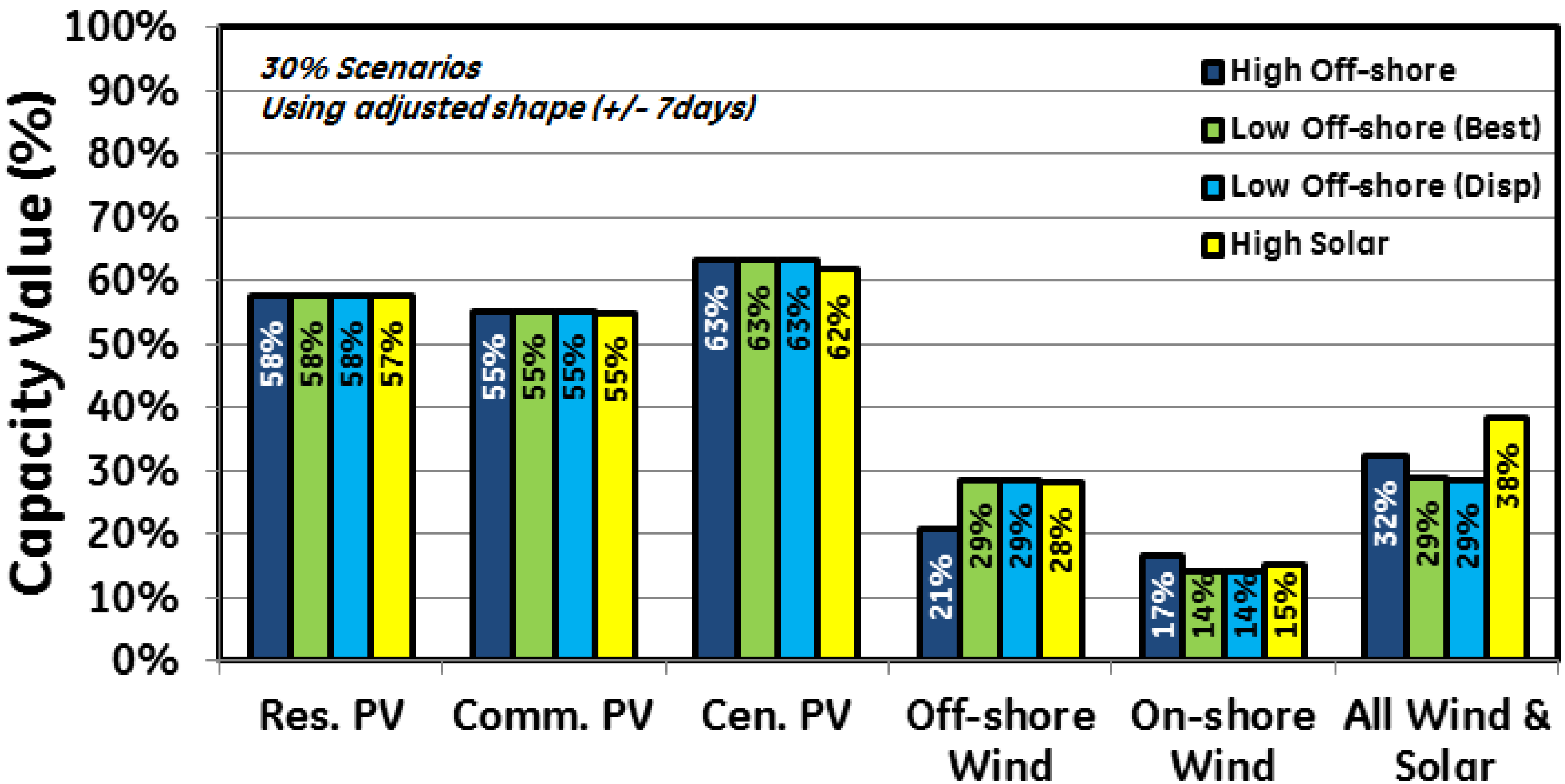
30% Scenarios



- ELCC of the resources is similar to the 20% scenarios
- Drop in ELCC values in some sub-scenarios is mainly due to saturation effect
    - e.g., ELCC of Off-shore Wind drops to 21% from 25% in the “High Off-shore” scenario

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Key Findings: Range of ELCC Values of Different Resources in 20% and 30% Scenarios

Resource	ELCC (%)
Residential PV	57% - 58%
Commercial PV	55% - 56%
Central PV	62% - 66%
Off-shore Wind	21% - 29%
Onshore Wind	14% - 18%

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Transmission Overlay Analysis (PowerGEM) [15 Minutes]

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Transmission Analysis Objective & Approach

- The purpose of this phase of the study was for PowerGEM to create a transmission overlay that resolved the most significant reliability and congestion issues for each renewable scenario.
- The overlay was developed based on two separate drivers.
  - First a transmission overlay was created to resolve any reliability issues caused by the addition of the renewable resources.
  - A congestion study was then performed using this overlay to determine if any areas of the PJM system had significant congestion.
  - An additional transmission overlay was then created to address any flowgates resulting in congestion greater than a certain threshold.
  - The final transmission overlay was the combination of the reliability driven and congestion driven overlays for each scenario.

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Transmission Perspective …

- While the transmission overlays that identified in this task resolved the most significant reliability and congestion issues for each scenario, some potentially significant transmission costs were not within the scope of this study. For example:
  - Generator interconnection costs (wind and solar units were located at nearest EHV bus).
  - Upgrades to resolve overloads at voltage levels below 230kV
  - Upgrades needed to resolve voltage violations.
- Note also there is still significant congestion remaining in some scenarios (up to $6.3B/year).

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Transmission Overlay Process
Example of 20% LOBO Scenario

Transmission Constraints

Dresden – Elwood 345 kV
Brokaw - Pontiac 345 kV
Quad - Sub 91 345 kV
Plano 765/345 kV
Quad - Rock Cities 345 kV
Kanawha River – Matt Funk 345 kV
E. Frankfort – Crete 345 kV

Transmission Overlay for 20% LOBO

Transmission Overlay Due to Reliability
2nd Dresden – Elwood 345 kV
2nd Brokaw - Pontiac 345 kV
Transmission Overlay Due to Congestion
2nd Quad - Sub 91 345 kV
2nd Quad - Rock Cities 345 kV
Reconductor Kanawha R. – M. Funk 345 kV
2nd E. Frankfort – Crete 345 kV
New Plano 765/345 kV

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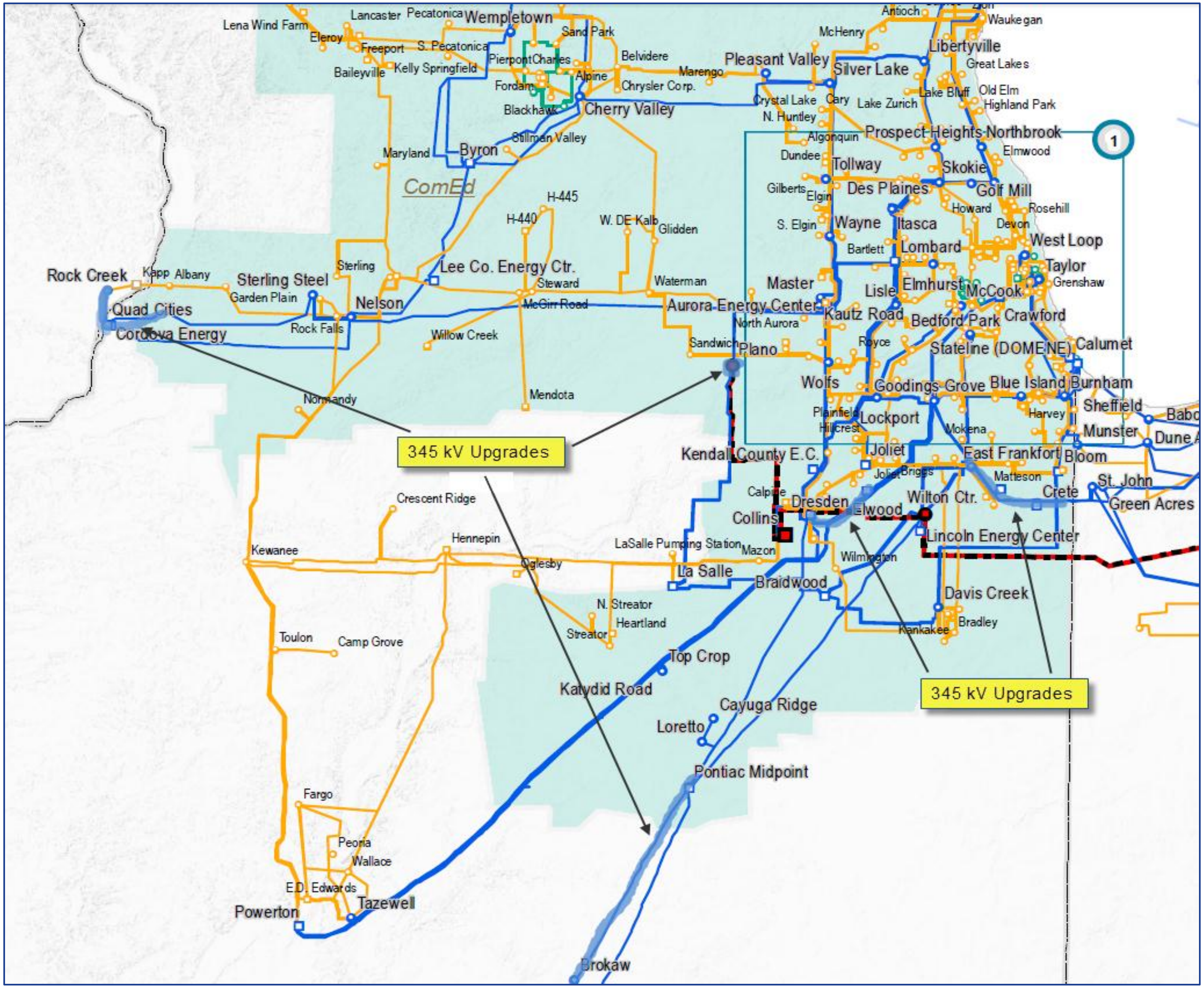
20% LOBO Transmission Overlay - ComED



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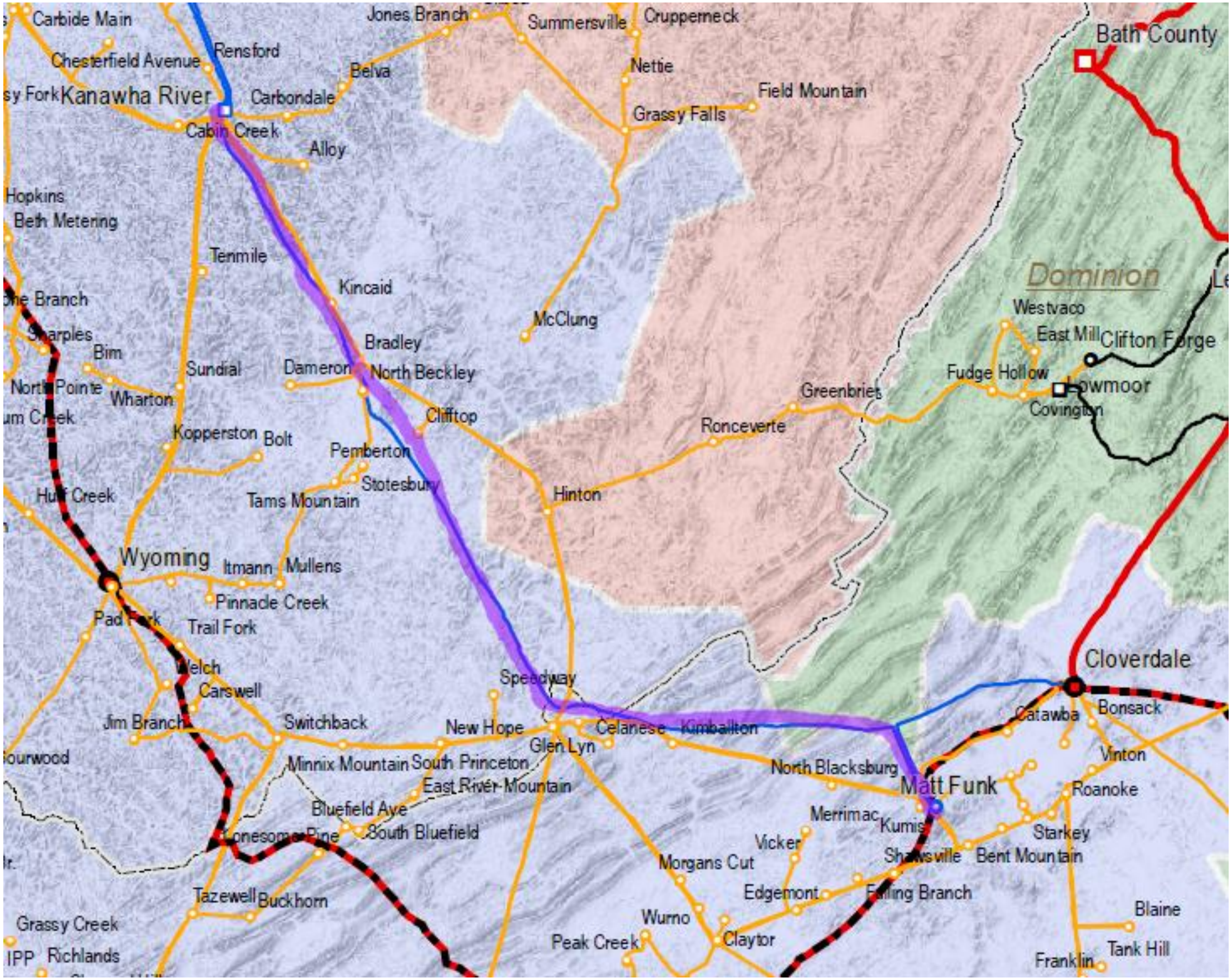
20% LOBO Transmission Constraints - AEP



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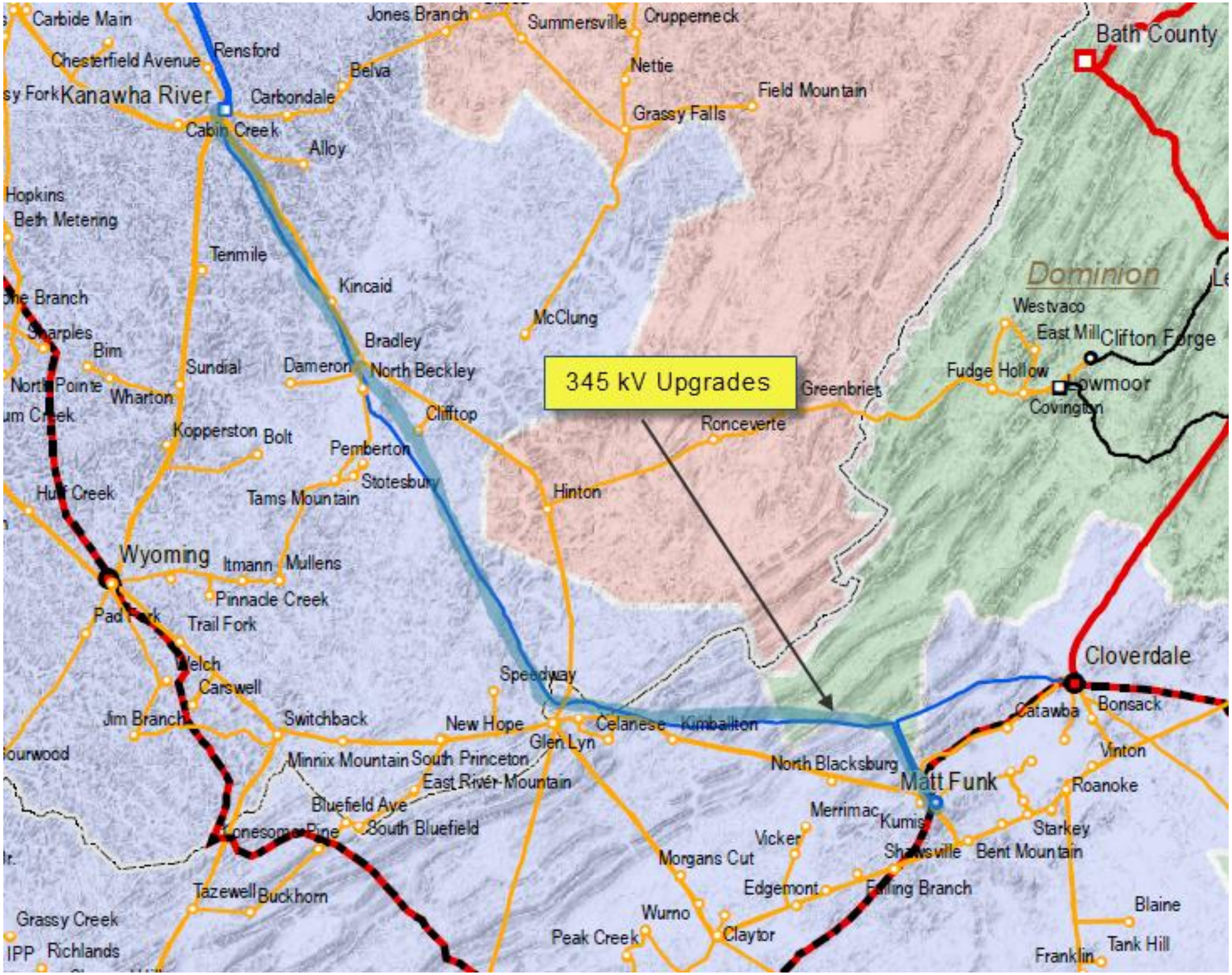
20% LOBO Transmission Overlay - AEP



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Summary of New Transmission Lines and Upgrades for the Study

Scenario	765 kV New Lines (Miles)	765 kV Upgrades (Miles)	500 kV New Lines (Miles)	500 kV Upgrades (Miles)	345 kV New Lines (Miles)	345 kV Upgrades (Miles)	230 kV New Lines (Miles)	230 kV Upgrades (Miles)	Total (Miles)	Total Cost (Billion)	Total Congestion Cost (Billion)
2% BAU	0	0	0	0	0	0	0	0	0	$0	$1.9
14% RPS	260	0	42	61	352	35	0	4	754	$3.7	$4.0
20% Low Offshore Best Onshore	260	0	42	61	416	122	0	4	905	$4.1	$4.0
20% Low Offshore Dispersed Onshore	260	0	42	61	373	35	0	49	820	$3.8	$4.9
20% High Offshore Best Onshore	260	0	112	61	363	122	17	4	939	$4.4	$4.3
20% High Solar Best Onshore	260	0	42	61	365	122	0	4	854	$3.9	$3.3
30% Low Offshore Best Onshore	1800	0	42	61	796	129	44	74	2946	$13.7	$5.2
30% Low Offshore Dispersed Onshore	430	0	42	61	384	166	44	55	1182	$5.0	$6.3
30% High Offshore Best Onshore	1220	0	223	105	424	35	14	29	2050	$10.9	$5.3
30% High Solar Best Onshore	1090	0	42	61	386	122	4	4	1709	$8	$5.6

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Statistical Analysis – Reserve Analysis (EnerNex) [15 Minutes]

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Statistical Analysis Objective

- Statistical Analysis was performed in order to characterize the PJM system load data and renewable resource data.
  - The statistical analysis and characterization of the renewable resources examine the aggregate production i.e. the total generation of all wind and PV sites in each study scenario.
  - PJM provided 5-minute resolution load for the same calendar years as the renewable production data, since system load can be affected by weather conditions and renewable generation is also weather related.
  - The load data was escalated with PJM guidance to make the data sets representative of the future study year.

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Summary Statistics for PJM 2026 Load and Renewable Energy Production by Scenario

Scenario	Abbreviation	Maximum (MW)	Minimum (MW)	Average (MW)	Std. Deviation (MW)	Average Annual Energy (GWh)
Load	Load	200,278	66,583	110,684	19,762	969,596
2% Business as Usual	2%BAU	4,894	29	1,956	1,139	17,132
14% Renewable Portfolio Standard	14%RPS	34,444	802	13,864	6,991	121,445
20% High Offshore Best Onshore Wind	20%HOBO	51,705	685	20,456	8,632	179,199
20% Low Offshore Distributed Onshore Wind	20%LODO	53,203	1,198	20,579	9,673	180,273
20% Low Offshore Best Onshore Wind	20%LOBO	52,095	1,042	20,432	10,025	178,984
20% High Solar Best Onshore Wind	20%HSBO	60,598	883	20,574	10,659	180,230
30% High Offshore Best Onshore Wind	30%HOBO	85,643	1,026	32,634	13,933	285,878
30% Low Offshore Distributed Onshore Wind	30%LODO	87,687	1,728	32,558	15,314	285,204
30% Low Offshore Best Onshore Wind	30%LOBO	85,706	1,473	32,539	16,209	285,039
30% High Solar Best Onshore Wind	30%HSBO	91,152	1,218	30,715	16,278	269,061

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Load and LNR Statistics over all 3 Years of Data

Scenario	Abbreviation	Maximum (MW)	Minimum (MW)	Average (MW)	Std. Deviation (MW)	Net Average Annual Energy (GWh)
Load	Load	200,278	66,583	110,684	19,762	969,596
2% Business as Usual	2%BAU	198,082	65,183	108,729	19,967	952,464
14% Renewable Portfolio Standard	14%RPS	182,294	47,251	96,821	21,200	848,151
20% High Offshore Best Onshore Wind	20%HOBO	170,399	37,322	90,228	20,783	790,397
20% Low Offshore Distributed Onshore Wind	20%LODO	169,571	36,202	90,105	21,575	789,323
20% Low Offshore Best Onshore Wind	20%LOBO	169,504	37,548	90,252	21,758	790,612
20% High Solar Best Onshore Wind	20%HSBO	171,033	30,876	90,110	20,075	789,366
30% High Offshore Best Onshore Wind	30%HOBO	160,917	9,117	78,050	22,421	683,718
30% Low Offshore Distributed Onshore Wind	30%LODO	156,136	9,387	78,127	23,690	684,392
30% Low Offshore Best Onshore Wind	30%LOBO	159,229	7,010	78,146	24,368	684,557
30% High Solar Best Onshore Wind	30%HSBO	164,967	1,927	79,970	22,319	700,535

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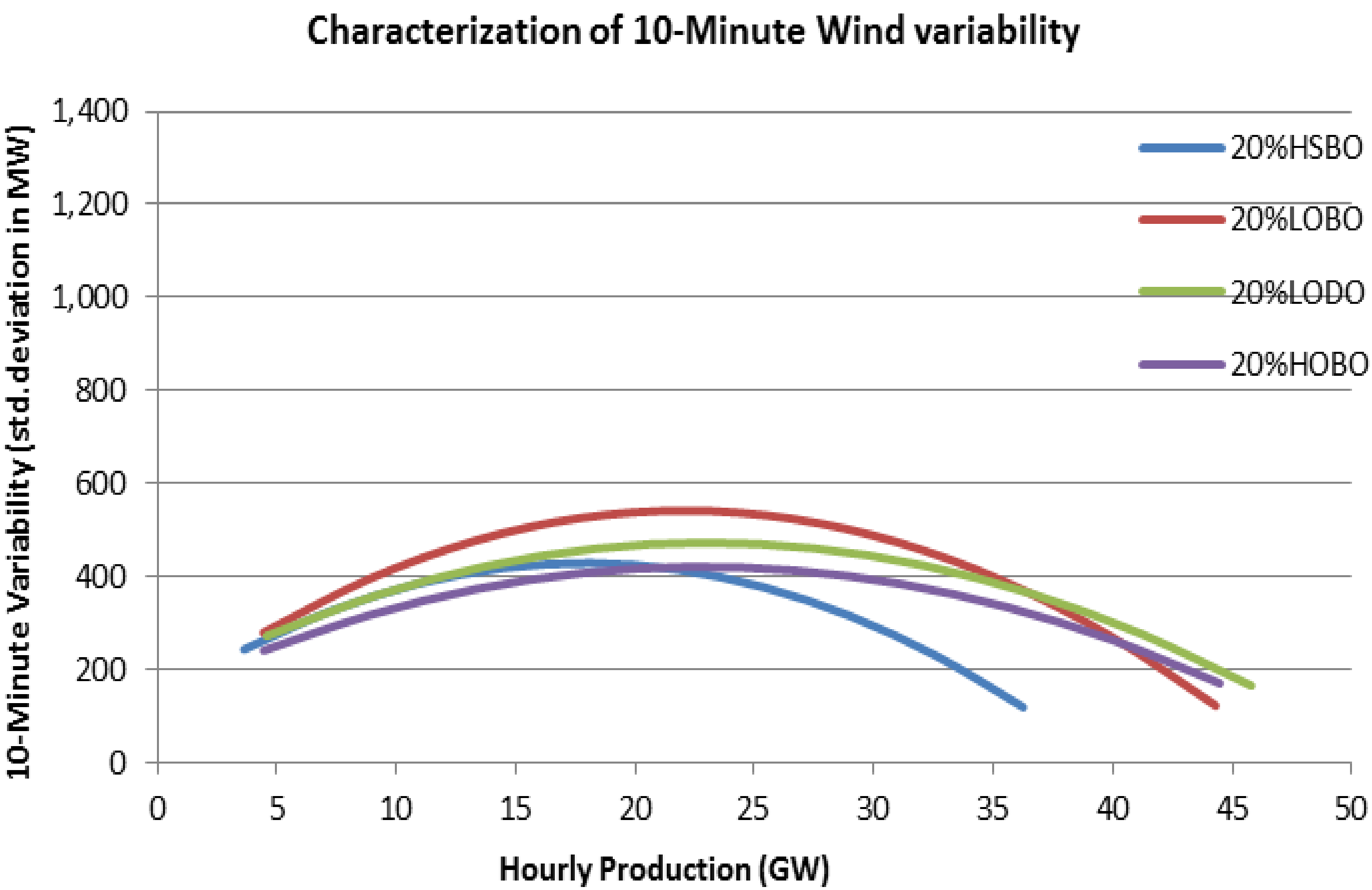
Example of 10-Minute Wind Variability for 20% Scenarios



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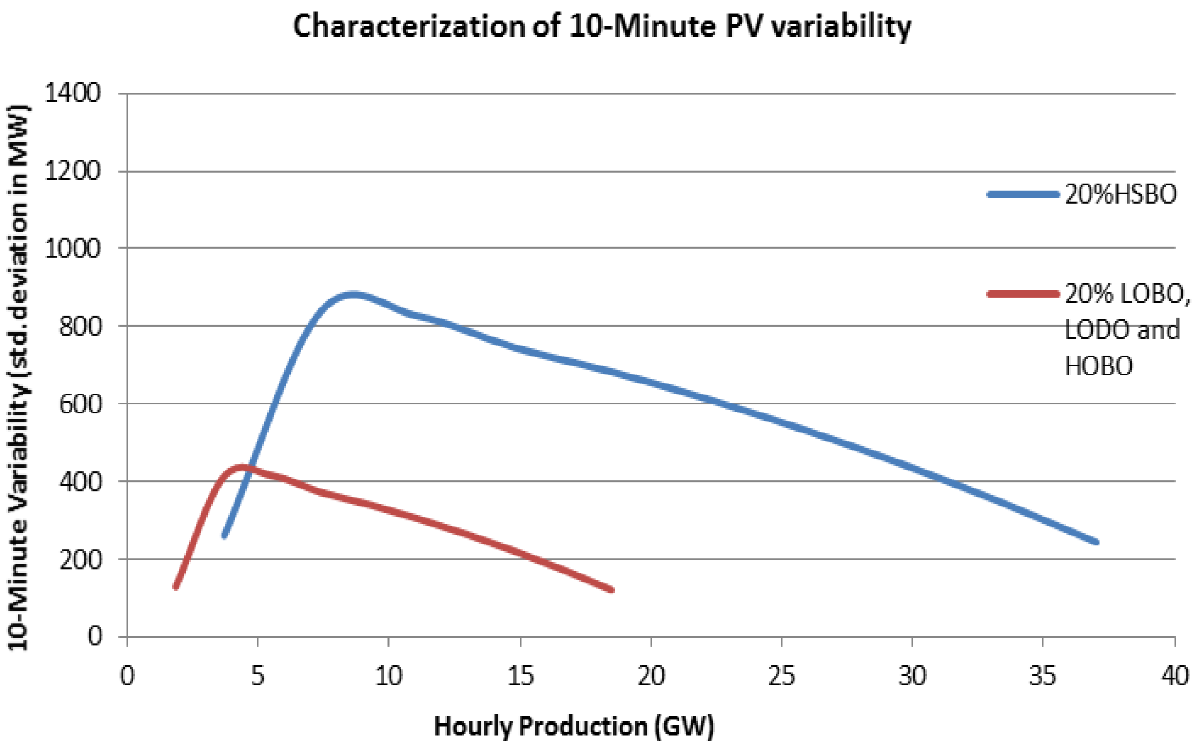
Example of 10-Minute Solar Variability for 20% Scenarios



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Statistical Analysis Key Observations & Conclusions

Statistical analysis was performed to characterize the PJM System load data and renewable resource data.

- Chronological production data at 10-minute intervals over the calendar years of 2004, 2005 and 2006 were extracted and aggregated by generation type for this analysis.
- The statistical analysis and characterization of the renewable resources examine the aggregate production i.e. the total generation of all wind and PV sites in each scenario.
- The various statistical characterizations developed to portray the variability and short-term uncertainties of the aggregate wind and PV generation in each scenario are also critical inputs to the analysis of operating reserve impacts.

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Reserve Analysis

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Reserve Analysis Objective

The objective of this task was to evaluate how various levels of wind and PV generation might impact PJM policies and practices for operating reserves.

- The wind variability adds to the short-term variability of net load (load minus wind), which requires following with synchronized reserve.
- This additional synchronous reserve requirement is above and beyond the synchronized contingency reserves or Regulation Up and Regulation Down since most variations should not impinge on the contingency reserves.

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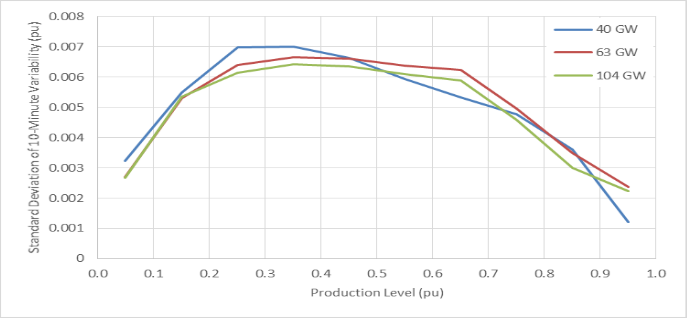
Statistical Analysis for Estimation of Additional Regulation Requirement

- Statistical analysis of wind, PV and load data was employed to determine how much additional regulation capacity would be required to manage renewable variability in each of the study scenarios.
  - Previous studies have established that a statistically high level of confidence for reserve is achieved at about 3 standard of deviation (or σ in industry parlance) of 10-minute renewable variability.
    - In other words, with a reserve margin of 3σ, the chances of a 10-minute wind level drop being greater than 3σ, is highly unlikely.
    - Hence, the appropriate required regulation is 3 times the standard deviation, which would encompass 99.7% of all variations.



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Estimated Regulation Requirements for Each Scenario (All Hours)

- The amount of additional regulation calculated for each hour depends on
  - The amount of regulation carried for load alone.
    - When more regulation is available, the incremental impact of wind and PV generation is reduced due to the statistical independence of the variations in the wind and PV generation and load.
  - The aggregate wind and PV generation production level.
    - The statistics show that wind production varies more when production from 40% to 60% of maximum and PV production varies more when production is from 10% to 20% of maximum.

Regulation	Load Only	2% BAU	14% RPS	20% HOBO	20% LOBO	20% LODO	20% HSBO	30% HOBO	30% LOBO	30% LODO	30% HSBO
Maximum (MW)	2,003	2,018	2,351	2,507	2,721	2,591	2,984	3,044	3,552	3,191	4,111
Minimum (MW)	745	766	919	966	1,031	1,052	976	1,188	1,103	1,299	1,069
Average (MW)	1,204	1,222	1,566	1,715	1,894	1,784	1,958	2,169	2,504	2,286	2,737
% Increase Compared to Load		1.5%	30.1%	42.4%	57.3%	48.2%	62.6%	80.2%	108.0%	89.8%	127.4%

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Reserve Analysis Key Observations & Conclusions

- Significant penetration of renewable energy will increase the regulation capacity requirement and will increase the frequency of utilization of these resources.
  - The study identified a need for an increase in the regulation requirement even in the lower wind penetration scenario (2% BAU), and the requirement would have noticeable increases for higher penetration levels.
  - The average regulation requirement for the load only (i.e. no wind or PV) case was 1,204 MW.
  - This requirement increases to about 1,600 MW for the 14% RPS scenario, to a high of 1,958 MW in the 20% scenarios and then 2,737 MW in the 30% scenarios.

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Challenging Days Selections (EnerNex) [5 Minutes]

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Criteria Used for Selection of Challenging Days

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

- Largest 10-minute ramp in Load Net of Renewable (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

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Example of Challenging Days Selected

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

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Sub-Hourly PROBE Analysis
(PowerGEM)
[20 Minutes]

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PROBE Sub-hourly Simulations

- Large changes in wind and solar generation will create more variability than the past, and the grid's flexibility to manage the variability are constrained due to the limited set of resources available and generator ramp limitations.
- 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?
- A number of interesting or challenging data were selected and examined in more detail through sub-hourly modeling in PROBE.
  - Fifty simulations completed across the various 2%, 14%, 20%, and 30% profiles

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A Sub-Hourly Run Example

May 26 – 20% HOBO/LOBO/LODO

- Renewable profile characterized by:
  - Sharp increase in on-shore wind – followed by a sharp decrease – in the early morning
  - Another clear increase in the afternoon
- Corresponding ramp limitations
- Thermal generation is ramped down only to be quickly ramped back up an hour later
- LODO has more challenges than HOBO/LOBO
  - More transmission constraints

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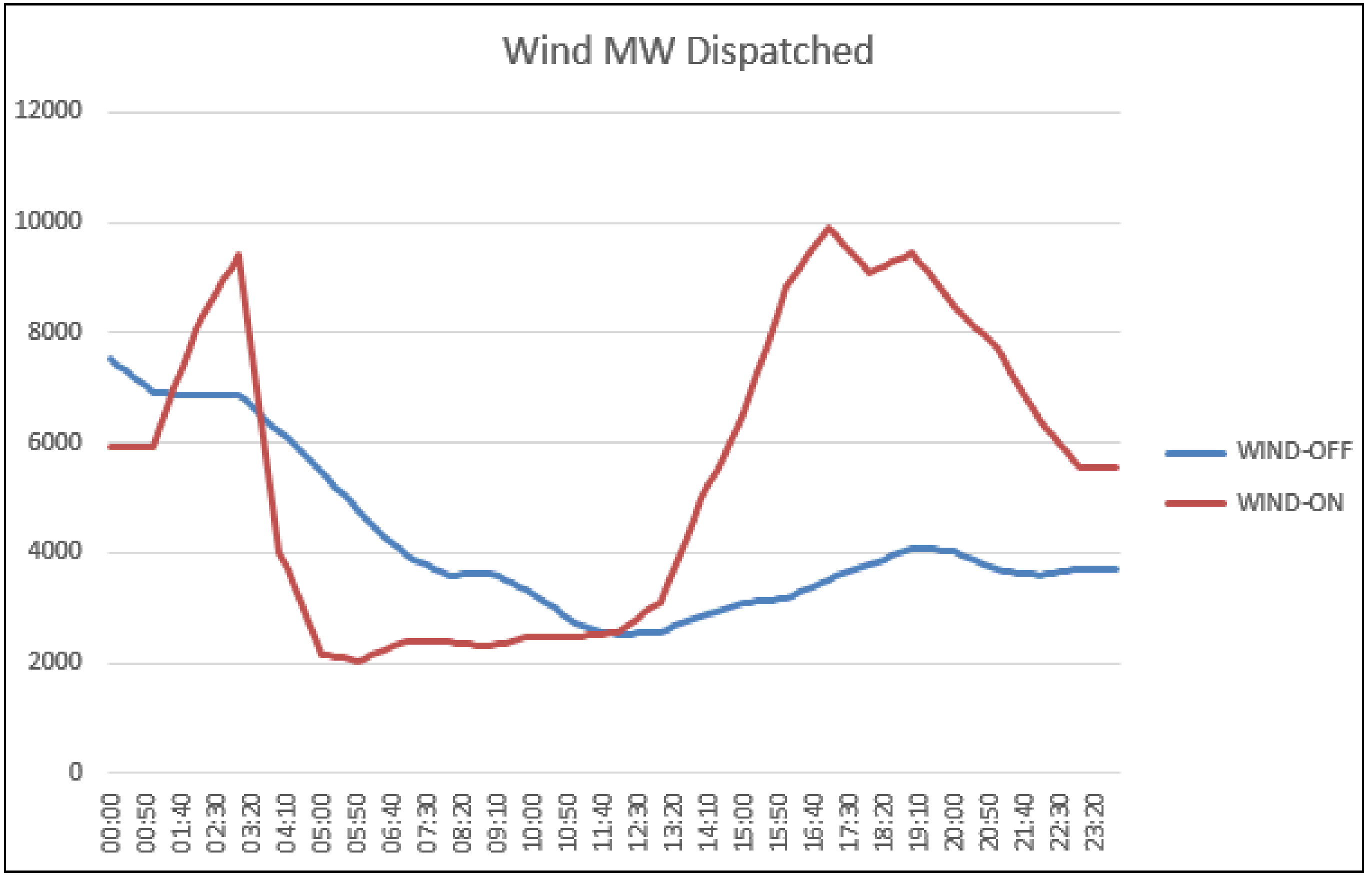
May 26 – 20% HOBO Wind



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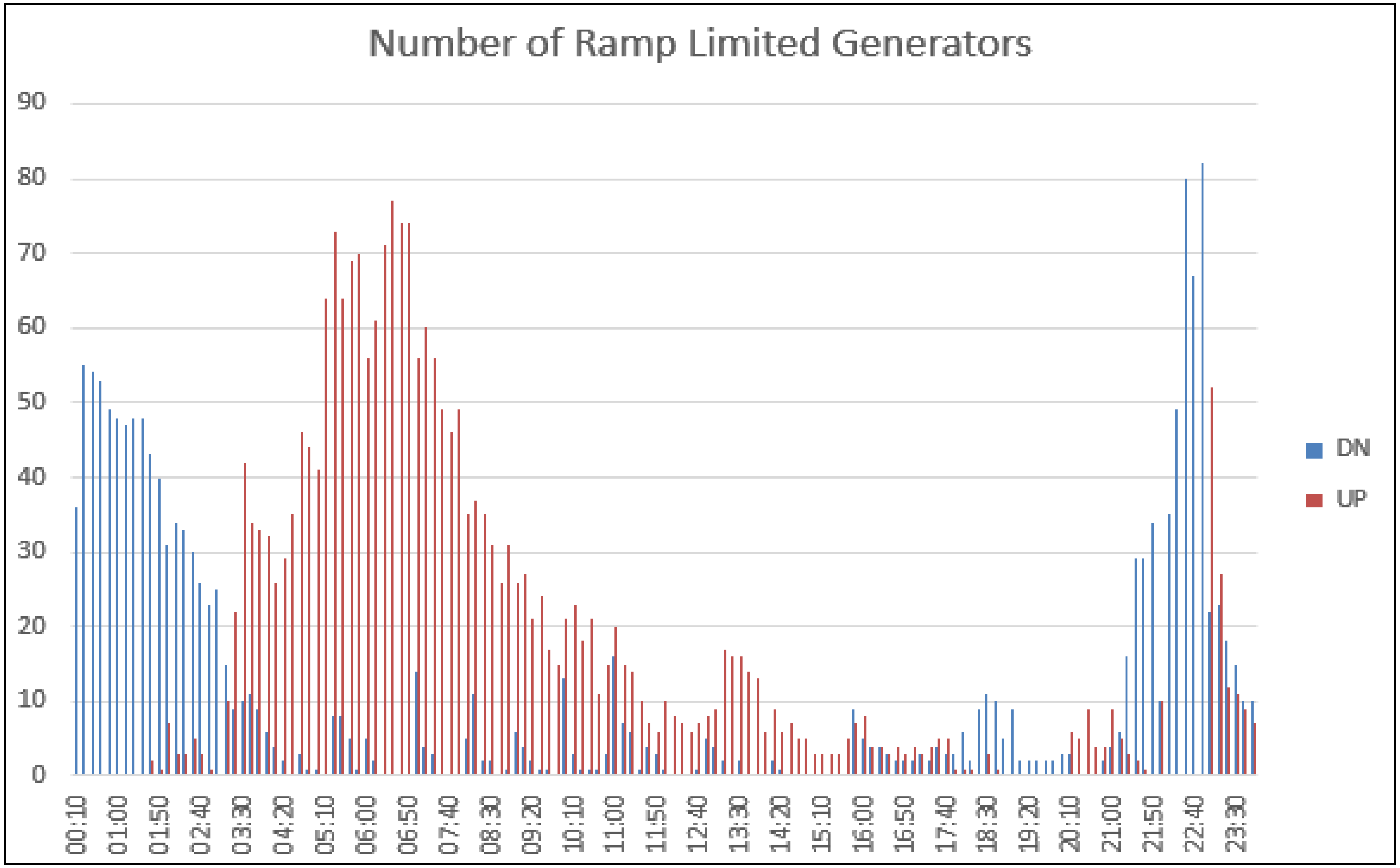
May 26 – 20% HOBO



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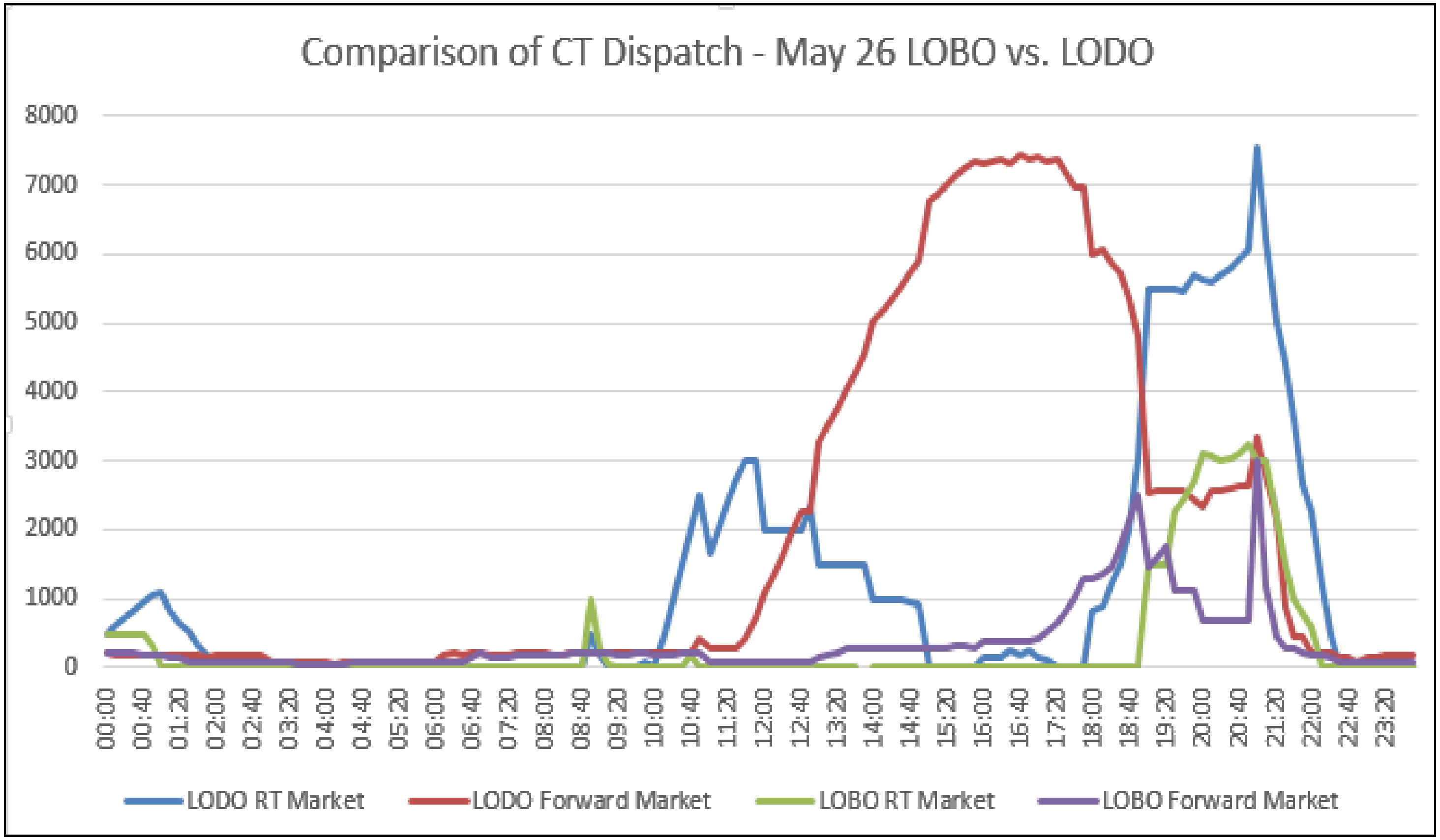
May 26 – LOBO vs. LODO (CTs)



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General Observations and Conclusions from Sub-Hourly Analysis

- 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.
- The level of difficulty for real-time operations largely depends on the day-ahead unit commitment.
- Higher penetrations of renewable energy (20% and 30%) create operational patterns that are significantly different than what is common today.

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Power Plant Cycling Costs (Intertek AIM) [15 Minutes]

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Cycling Cost Analysis Objective and Approach

Further integration of renewable resources into the grid are expected to drive higher cycling by thermal power plants. The objective of this task was to provide estimates of cycling related wear-and-tear costs and variable O&M costs.

- The Intertek AIM's unit commitment model – Cycling ⬍ Advisor ™ (CA) and Loads Model™ (LM) was utilized to evaluate the damage and damage cost to assess impacts of unit cycling.
- The models were used to derive the incremental variable O&M costs of power plant operation by utilizing the models' ability to model unit cycling damage.
- Intertek's work for NREL on the WWSIS Phase II Study was leveraged to determine the incremental cost of cycling. The estimates in the WWSIS Study were based on historical cycling. This study extends the cost estimates to include the cycling from increased renewable penetration.

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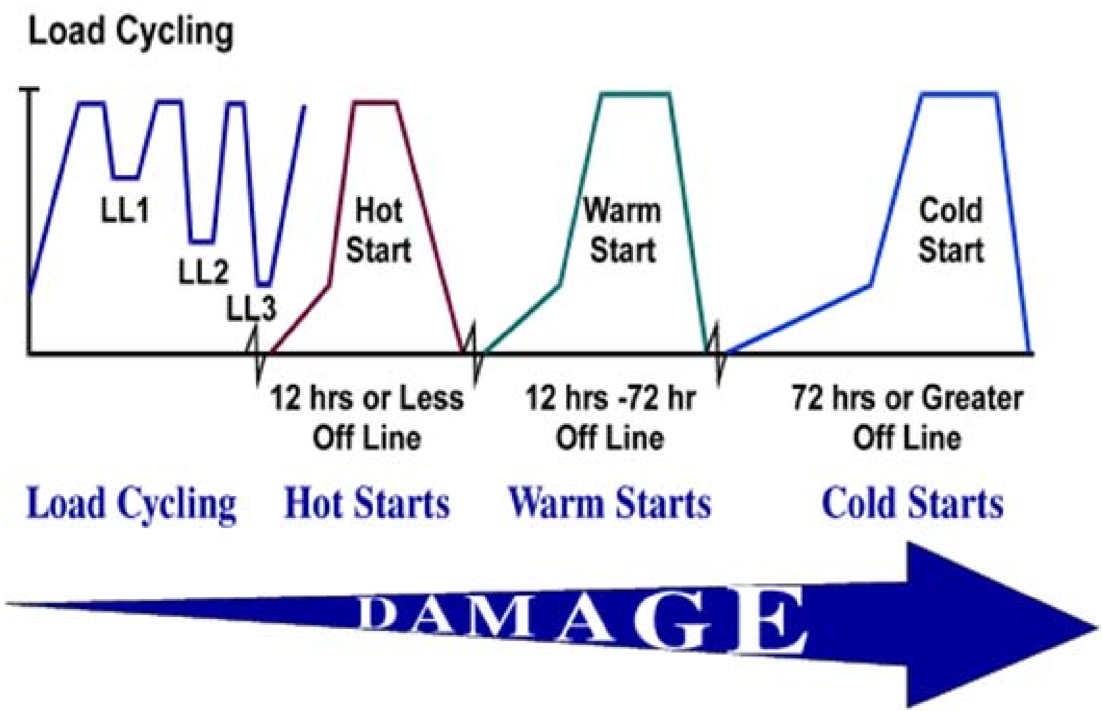
Unit Cycling Definition, Start Types, and Load Follow Cycling



Load Cycling

- LL1: Lowest Load at which design SH/RH temperatures can be maintained
- LL2: Current "Advertised" Low Load
- LL3: Lowest Load at which the unit can remain On-Line

*Offline Hours are only for representation. Different generation types and units will have different offline hours to represent cycle types

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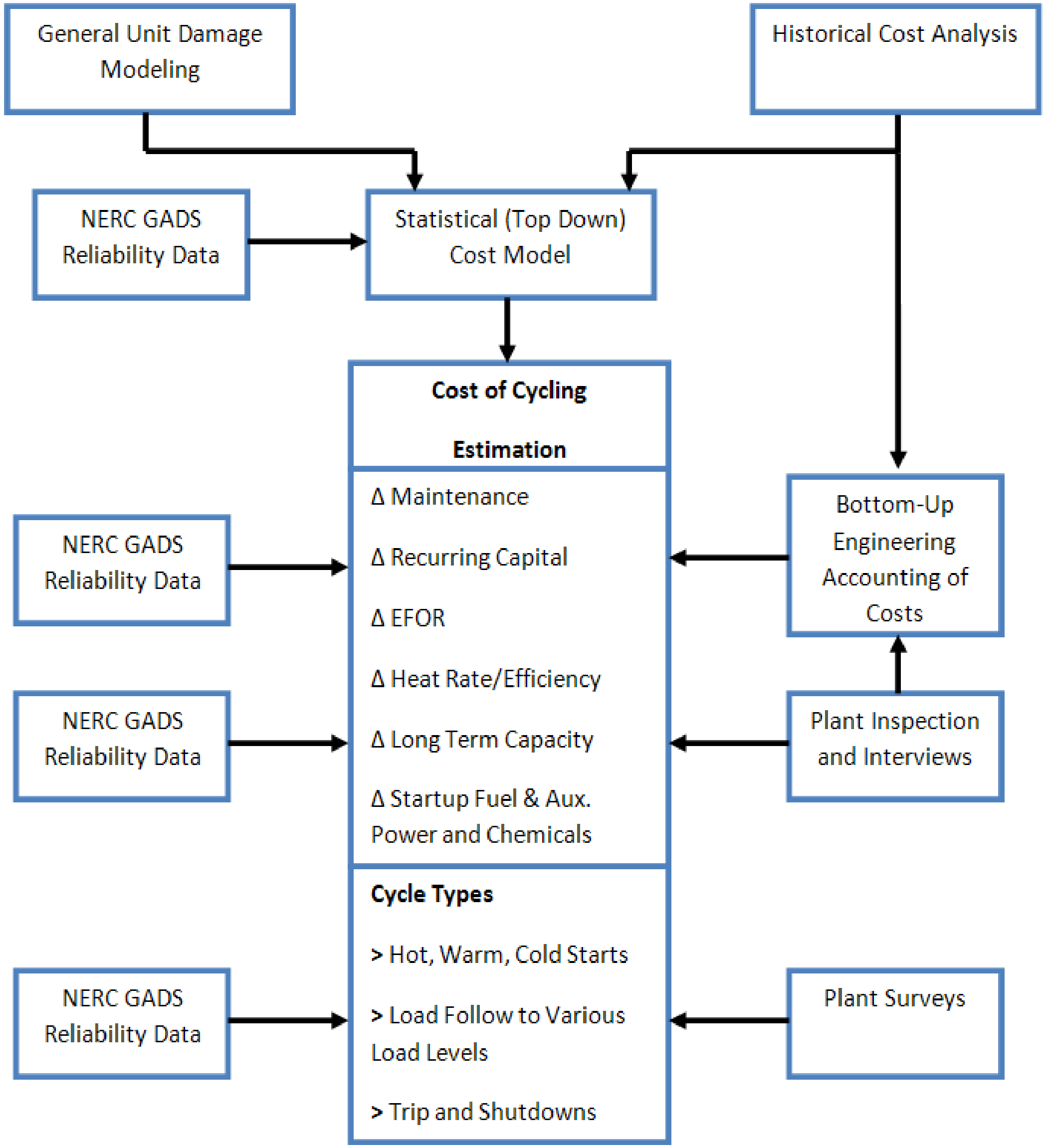
Cost of Cycling Estimation Procedure



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Project Methodology – Baseline Criteria

- Baseline = Historical Operation from 2000-2012 [Hourly MW data of actual plant operations]
- Added 1 additional year of Hourly MW generation (from GE MAPS) for every unit (150 total units) to historical operation.

Up to 12 Year Actual Operating Profile

[CY 2000-2012]

Assume instantaneous addition of renewable

Actual Operating Profile

+ 1 Additional Scenario Year

[CY 2000-2012 + Scenario Year]

Analysis Methodology

- Use Loads Model ™ Cycling Damage Algorithm to determine cycling profile (**for each unit type**) and generate damage parameter
- Cost Regression Model to fit baseline operation to baseline 2012 costs

Baseline Damage (EHS) for operating profile

Hourly MW 2000-12

- *Ignores operating profile between now and future.*
- *Power plants will accumulate cycles and therefore damage (cost) from now until future scenario date*
- *Recommend running intermediary scenarios to capture this.*

Analysis Methodology

- Use Loads Model ™ Cycling Damage Algorithm to determine cycling profile and generate damage parameter <u>with additional scenario operating profile</u>
- Cost Regression Model to fit baseline cost to scenario operating profile

Scenario Damage (EHS) for operating profile

Scenario MW Profile

Hourly MW 2000-12 + Scenario

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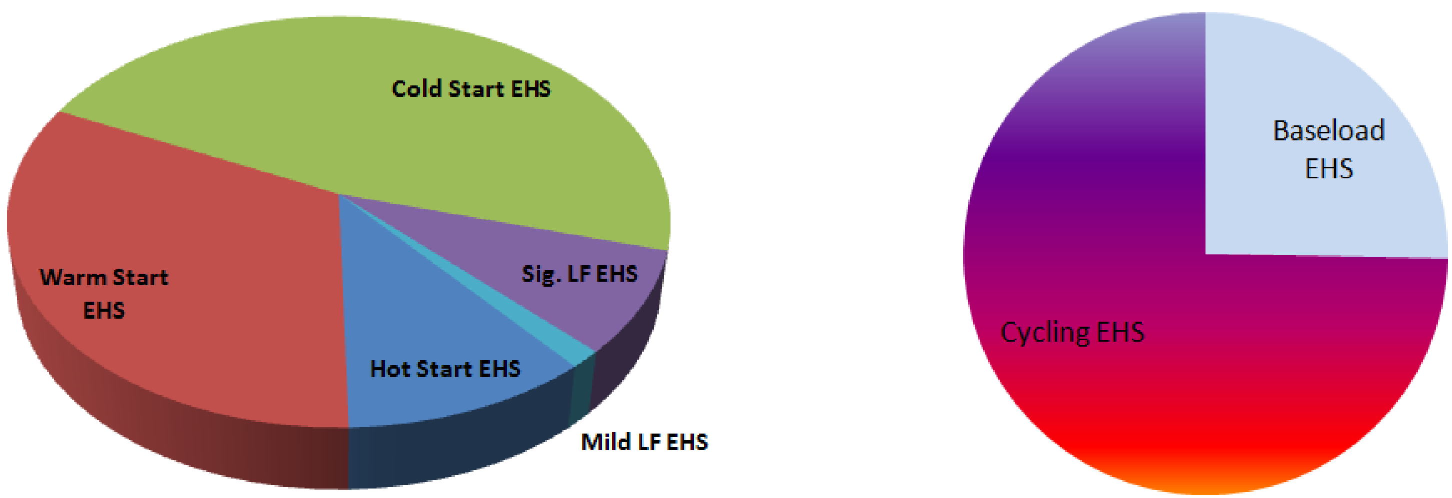
Characterizing Damage and Costs

- Plant cycling characteristics can be classified in terms of Baseload and Cyclic Equivalent Hot Starts (EHS).
- Within the cyclic EHS, there are different operating patterns that contribute towards cost and damage (chart on left).
- Publicly available data on Variable O&M does not include majority of cyclic costs.

Characterizing Damage Parameter (EHS) for different operating profiles.



EHS = Damage per Cycle {Hot, Warm, Cold, Sig. Load Follow, Mild Load Follow}
OR
EHS = Baseload EHS + Cycling EHS

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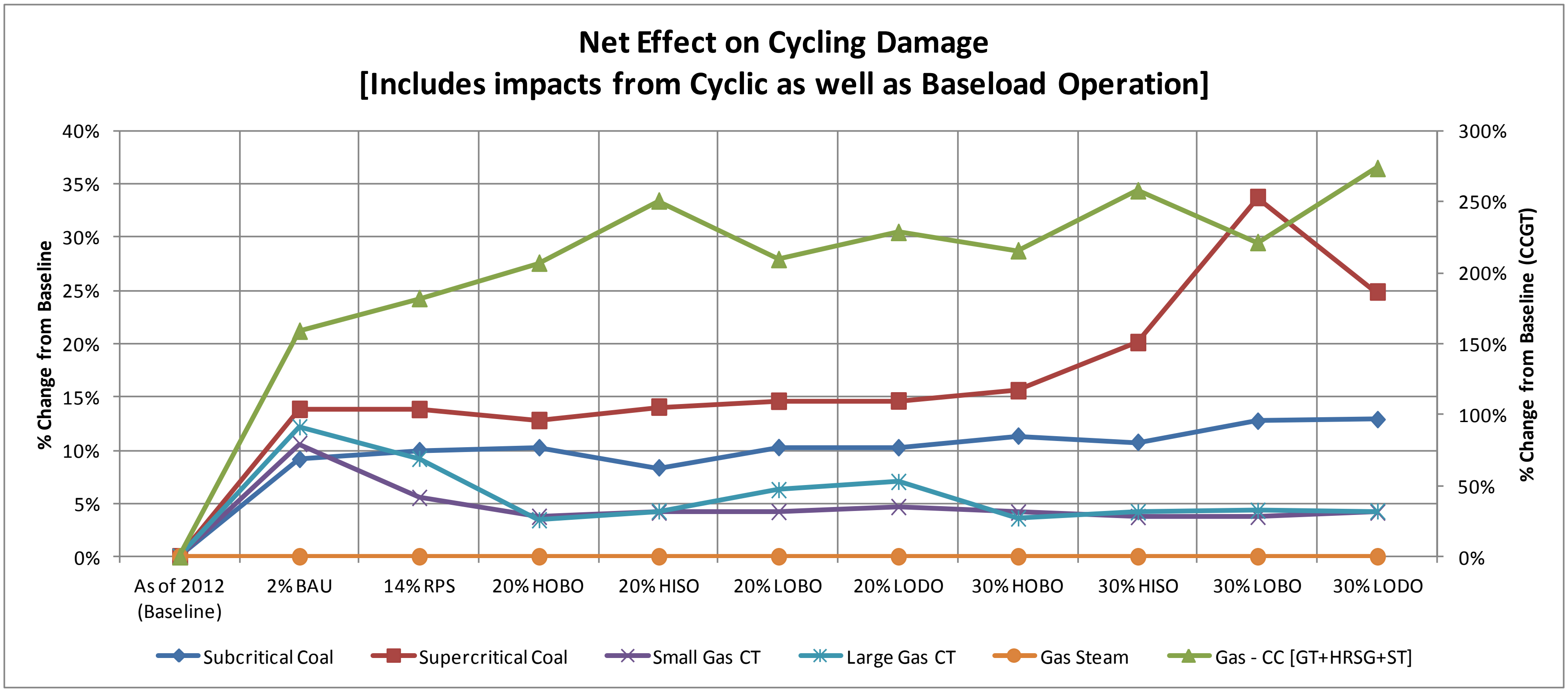
Bottom Line Result – Damage by Unit Type

- Baseline = Historical Operation from 2000-2012
- Biggest change in operations on CCGT units followed by Supercritical Coal



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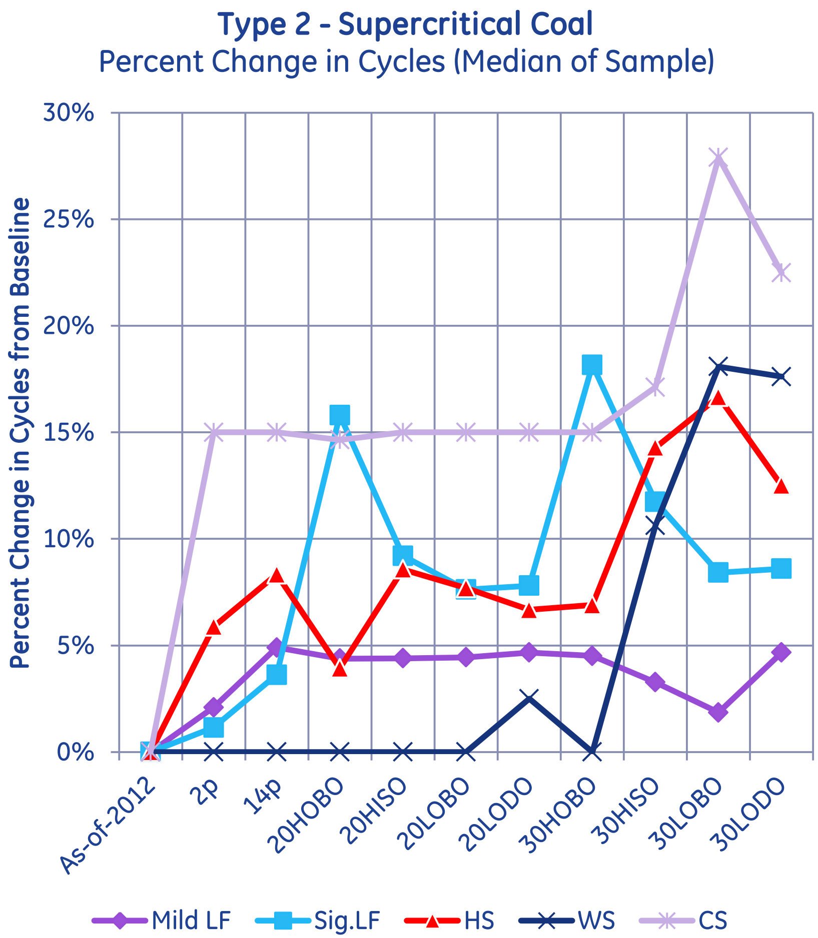
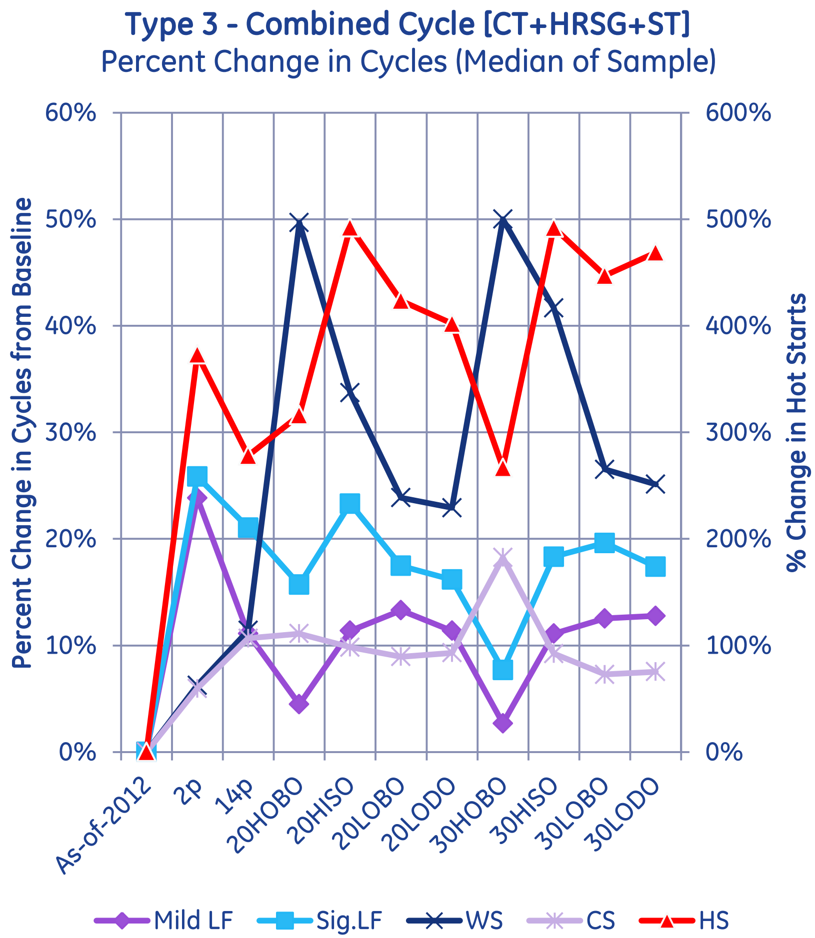
Flexible Operation Trends over Scenarios





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Cycling Costs of 20% HOBO Scenario

Unit Type	Hot Start - C&M cost ($/MW cap.)			Warm Start - C&M cost ($/MW cap.)			Cold Start - C&M cost ($/MW cap.)			**Hot, Warm, Cold Start Defn.**
	Baseline*	20HOBO**	%Change	Baseline*	20HOBO**	%Change	Baseline*	20HOBO**	%Change	Typical WS Hours Offline
Subcritical Coal	78.7	82.0	4.1%	114.2	118.0	3.3%	129.7	145.2	12.0%	8 to 48 Hours
Supercritical Coal	55.6	55.6	0.0%	65.9	65.9	0.0%	107.0	136.8	27.8%	24 to 120 Hours
Combined Cycle [GT+HRSG+ST]	36.0	41.3	14.7%	56.6	77.1	36.2%	81.3	91.1	12.1%	12 to 72 Hours
Small Gas CT	19.6	20.1	2.6%	24.7	25.4	2.7%	32.9	33.8	2.8%	4 to 5 Hours
Large Gas CT	32.9	33.7	2.2%	56.0	57.2	2.2%	92.2	95.1	3.1%	5 to 40 Hours
Gas Steam	37.0	-	-	59.7	-	-	77.2	-	-	4 to 48 Hours
Unit Type				**Sig. Load Follow Cost ($/MW cap.)**			**Baseload VOM Cost ($/MWh)**			
				Baseline*	20HOBO**	%Change	Baseline*	20HOBO**	%Change	
Subcritical Coal				3.0	3.5	16.0%	2.70	2.61	-3%	
Supercritical Coal				2.0	3.8	88.9%	2.96	2.84	-4%	
Combined Cycle [GT+HRSG+ST]				0.7	0.7	0.0%	1.02	0.39	-62%	
Small Gas CT				0.6	0.7	2.9%	0.64	0.62	-4%	
Large Gas CT				1.6	1.7	1.7%	0.66	0.64	-3%	
Gas Steam				2.0	2.0	0.0%	0.92	0.92		

*Source - Kumar, Besuner, Agan, Lefton - http://www.nrel.gov/docs/fy12osti/55433.pdf

** - Change in operating profiles to achieve 20% High Offshore Best Sites Onshore were not included.

Cycling damage and costs accumulate and increase with increasing cycles, therefore the future costs are path dependant e. g. increasing cycles in the future years will increase the future cycling costs

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Cycling Costs of 20% LOBO Scenario

Unit Type	Hot Start - C&M cost ($/MW cap.)			Warm Start - C&M cost ($/MW cap.)			Cold Start - C&M cost ($/MW cap.)			Hot, Warm, Cold Start Defn.
	Baseline*	20LOBO**	%Change	Baseline*	20LOBO**	%Change	Baseline*	20LOBO**	%Change	Typical WS Hours Offline
Subcritical Coal	78.7	82.7	5.0%	114.2	119.6	4.7%	129.7	148.3	14.3%	8 to 48 Hours
Supercritical Coal	55.6	55.6	0.0%	65.9	65.9	0.0%	107.0	154.8	44.6%	24 to 120 Hours
Combined Cycle [GT+HRSG+ST]	36.0	46.5	29.2%	56.6	74.5	31.5%	81.3	89.5	10.1%	12 to 72 Hours
Small Gas CT	19.6	20.0	2.2%	24.7	25.5	3.4%	32.9	33.8	2.8%	4 to 5 Hours
Large Gas CT	32.9	33.5	1.9%	56.0	57.1	1.9%	92.2	95.3	3.4%	5 to 40 Hours
Gas Steam	37.0	-	-	59.7	-	-	77.2	-	-	4 to 48 Hours
Unit Type				**Sig. Load Follow Cost ($/MW cap.)**			**Baseload VOM Cost ($/MWh)**			
				Baseline*	20LOBO**	%Change	Baseline*	20LOBO**	%Change	
Subcritical Coal				3.0	3.2	7.4%	2.70	2.61	-3%	
Supercritical Coal				2.0	2.6	30.8%	2.96	2.80	-5%	
Combined Cycle [GT+HRSG+ST]				0.7	0.7	0.0%	1.02	0.36	-65%	
Small Gas CT				0.6	0.7	2.0%	0.64	0.61	-4%	
Large Gas CT				1.6	1.7	1.3%	0.66	0.64	-3%	
Gas Steam				2.0	2.0	0.0%	0.92	0.92		

*Source - Kumar, Besuner, Agan, Lefton - http://www.nrel.gov/docs/fy12osti/55433.pdf

** - Change in operating profiles to achieve 20% Low Offshore Best Sites Onshore were not included.

Cycling damage and costs accumulate and increase with increasing cycles, therefore the future costs are path dependant e. g. increasing cycles in the future years will increase the future cycling costs

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Cycling Costs of 20% LODO Scenario

Unit Type	Hot Start - C&M cost ($/MW cap.)			Warm Start - C&M cost ($/MW cap.)			Cold Start - C&M cost ($/MW cap.)			Hot, Warm, Cold Start Defn.
	Baseline*	20LODO**	%Change	Baseline*	20LODO**	%Change	Baseline*	20LODO**	%Change	Typical WS Hours Offline
Subcritical Coal	78.7	82.6	5.0%	114.2	122.2	7.0%	129.7	148.8	14.8%	8 to 48 Hours
Supercritical Coal	55.6	55.6	0.0%	65.9	65.9	0.0%	107.0	152.6	42.6%	24 to 120 Hours
Combined Cycle [GT+HRSG+ST]	36.0	45.4	26.0%	56.6	75.8	33.9%	81.3	89.3	9.9%	12 to 72 Hours
Small Gas CT	19.6	20.0	2.2%	24.7	25.5	3.4%	32.9	33.9	2.8%	4 to 5 Hours
Large Gas CT	32.9	33.3	1.2%	56.0	57.2	2.1%	92.2	95.3	3.4%	5 to 40 Hours
Gas Steam	37.0	-	-	59.7	-	-	77.2	-	-	4 to 48 Hours
Unit Type				**Sig. Load Follow Cost ($/MW cap.)**			**Baseload VOM Cost ($/MWh)**			
				Baseline*	20LODO**	%Change	Baseline*	20LODO**	%Change	
Subcritical Coal				3.0	3.2	7.4%	2.70	2.61	-3%	
Supercritical Coal				2.0	2.6	26.9%	2.96	2.82	-5%	
Combined Cycle [GT+HRSG+ST]				0.7	0.7	0.0%	1.02	0.34	-67%	
Small Gas CT				0.6	0.7	2.0%	0.64	0.61	-4%	
Large Gas CT				1.6	1.7	1.2%	0.66	0.64	-4%	
Gas Steam				2.0	2.0	0.0%	0.92	0.92		

*Source - Kumar, Besuner, Agan, Lefton - http://www.nrel.gov/docs/fy12osti/55433.pdf

** - Change in operating profiles to achieve 20% Low Offshore Distributed Sites Onshore were not included.

Cycling damage and costs accumulate and increase with increasing cycles, therefore the future costs are path dependant e. g. increasing cycles in the future years will increase the future cycling costs

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Cycling Costs of 20% HSBO Scenario

Unit Type	Hot Start - C&M cost ($/MW cap.)			Warm Start - C&M cost ($/MW cap.)			Cold Start - C&M cost ($/MW cap.)			**Hot, Warm, Cold Start Defn.**
	Baseline*	20HISO**	%Change	Baseline*	20HISO**	%Change	Baseline*	20HISO**	%Change	Typical WS Hours Offline
Subcritical Coal	78.7	82.2	4.4%	114.2	118.7	3.9%	129.7	146.8	13.2%	8 to 48 Hours
Supercritical Coal	55.6	55.6	0.0%	65.9	65.9	0.0%	107.0	153.1	43.0%	24 to 120 Hours
Combined Cycle [GT+HRSG+ST]	36.0	43.9	21.9%	56.6	73.0	28.9%	81.3	85.7	5.4%	12 to 72 Hours
Small Gas CT	19.6	20.0	2.5%	24.7	25.3	2.5%	32.9	33.9	2.8%	4 to 5 Hours
Large Gas CT	32.9	33.5	1.6%	56.0	57.2	2.2%	92.2	95.1	3.1%	5 to 40 Hours
Gas Steam	37.0	-	-	59.7	-	-	77.2	-	-	4 to 48 Hours
Unit Type				**Sig. Load Follow Cost ($/MW cap.)**			**Baseload VOM Cost ($/MWh)**			
				Baseline*	20HISO**	%Change	Baseline*	20HISO**	%Change	
Subcritical Coal				3.0	3.2	7.1%	2.70	2.62	-3%	
Supercritical Coal				2.0	2.9	45.5%	2.96	2.82	-5%	
Combined Cycle [GT+HRSG+ST]				0.7	0.7	0.0%	1.02	0.35	-66%	
Small Gas CT				0.6	0.7	2.1%	0.64	0.61	-4%	
Large Gas CT				1.6	1.7	1.7%	0.66	0.64	-3%	
Gas Steam				2.0	2.0	0.0%	0.92	0.92		

*Source - Kumar, Besuner, Agan, Lefton - http://www.nrel.gov/docs/fy12osti/55433.pdf

** - Change in operating profiles to achieve 20% High Solar were not included.

Cycling damage and costs accumulate and increase with increasing cycles, therefore the future costs are path dependant e. g. increasing cycles in the future years will increase the future cycling costs

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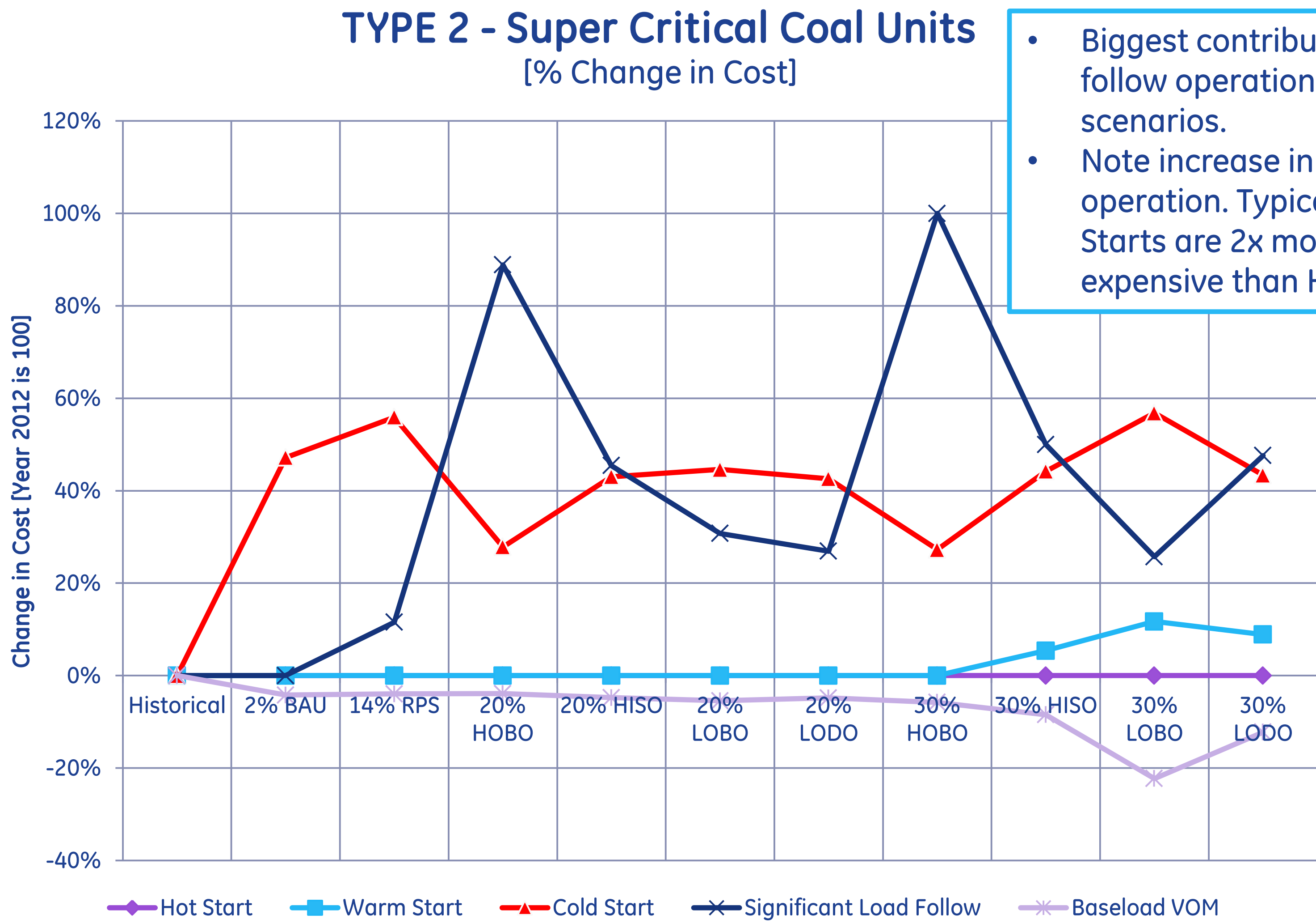
Cost Summary - Supercritical Coal Units



- Biggest contributor to load follow operation in all scenarios.
- Note increase in cold start operation. Typically Cold Starts are 2x more expensive than Hot Starts.

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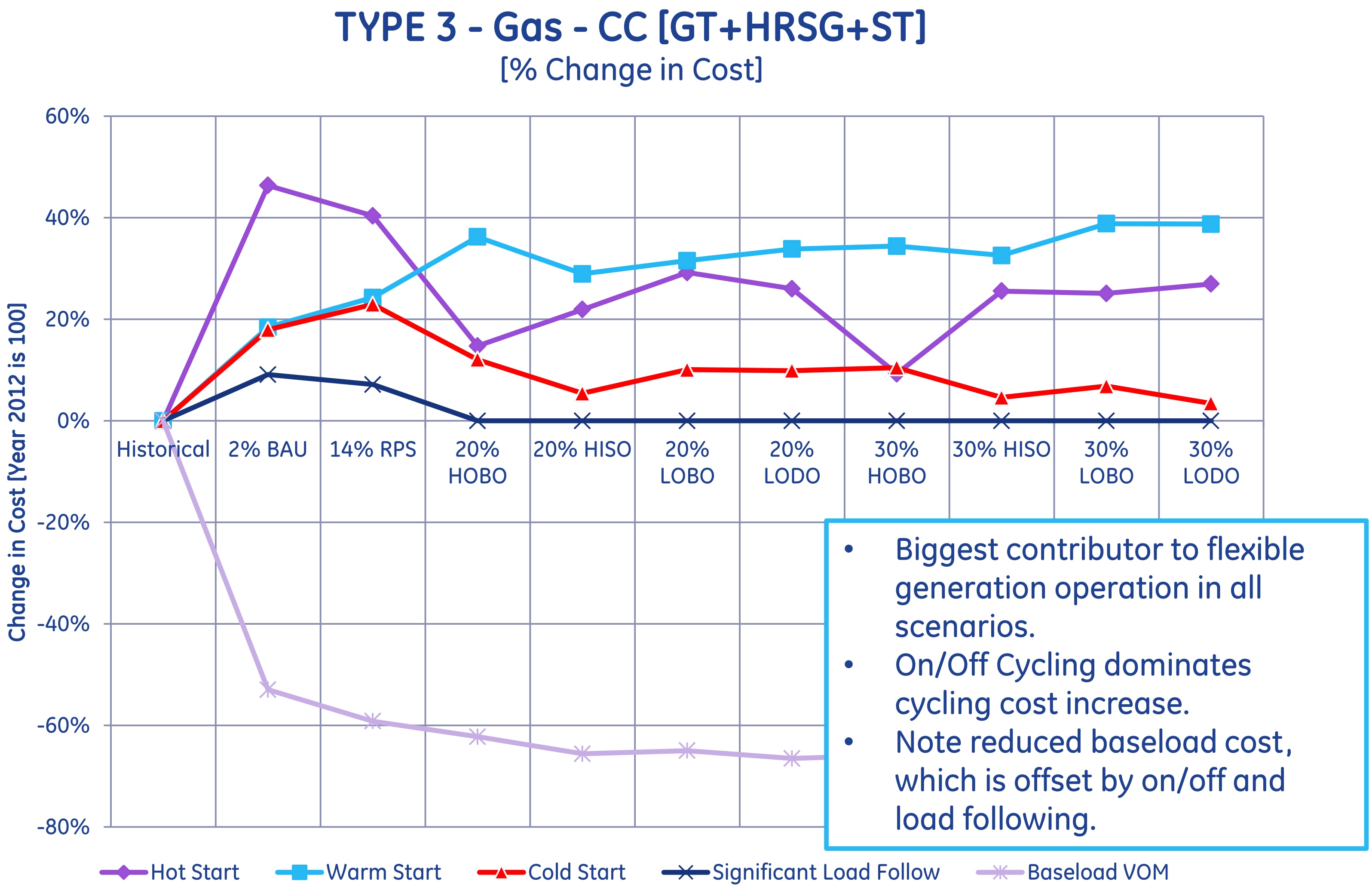
Cost Summary – Combined Cycle (CT+ST+HRSG)



- Biggest contributor to flexible generation operation in all scenarios.
- On/Off Cycling dominates cycling cost increase.
- Note reduced baseload cost, which is offset by on/off and load following.

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Examples of Cycling Costs in $/MWh

	Cycling Cost $/MWh	
	14% RPS	30% LOBO
Subcritical Coal	0.61	1.09
Supercritical Coal	0.66	2.22
Combined Cycle [GT+HRSG+ST]	3.05	6.21
Small Gas CT	7.10	12.48
Large Gas CT	15.62	21.90
Gas Steam	0.00	0.00

Note: Cycling Costs = [Start/Stop + Significant Load Follow]
Note: Costs are related to lower MWh generation on different unit types.

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Cycling Cost Analysis Conclusions

- Increased renewable integration results in increased cycling on existing fossil generation.
  - CCGT Units perform majority of the On/Off cycling in the scenarios, with the coal units performing the load follow cycling.
  - On an absolute scale, the cost of On/Off and Significant Load Follow increases the most on Supercritical and Combined Cycle Units.
- Increased cycling damage does not have a linear relation with cost alone.
  - Increased cycling results in increase in forced outage rates (reliability impacts), which should be included.
- In almost each of the scenarios, the coal and combined cycle units perform increasing amounts of cycling; resulting in higher cycling related VOM cost and reduced Baseload VOM Cost, where:
  - Total Variable O&M (VOM) Cost = Baseload VOM + Cycling VOM.

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Power Plant Cycling Emissions (Intertek AIM) [15 Minutes]

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Emissions Analysis Objective and Approach

- Variability of renewable energy resources requires the coal and gas fired generation resources to adapt with less efficient ramping and cycling operations, which in turn impacts their environmental emissions.
- This study examines the changes in emissions amounts and rates for the PJM portfolio for each of the study scenarios which differ in the level of cycling operations of the units.
  - Actual historical power plant emissions were analyzed to derive the impact of plant cycling on each type of power plant.
  - The output from GE MAPS presents the steady state "without cycling" emission amounts, which are then updated using Intertek's regression outputs to generate the "with cycling" emissions estimates.
- The system-wide emissions of high renewable penetration scenarios were compared to the 2% BAU scenario
  - Total Emissions = Steady State (from GE MAPS) + Extra Cycling-Related Emissions (from Interek AIM Regression Model)

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Regression Variables and Type of Plants Studied

- A period of hourly emissions for 3 years was evaluated (initially 12 years, but emissions control was installed on most units mid decade).
  - The regression of the historical measured emissions data for each of the six unit types uses several independent variables:
    - load,
    - time period,
    - months of year,
    - individual unit,
    - start/shutdown cycles,
    - weekend-holiday vs. work day,
    - emission control, and
    - load follows greater than 20% of the unit's full capacity.
  - The system-wide incremental changes in air emission were estimated for the following six conventional plant generation types:
    - Sub-Critical Coal (35-900 MW)
    - Large Supercritical Coal (500-1300 MW)
    - Combined Cycle Units based on LF CT Cost
    - Small Gas CT (< 50 MW)
    - Large Gas CT (50-200 MW)
    - Gas Fired Steam Plants (50 MW-700 MW)

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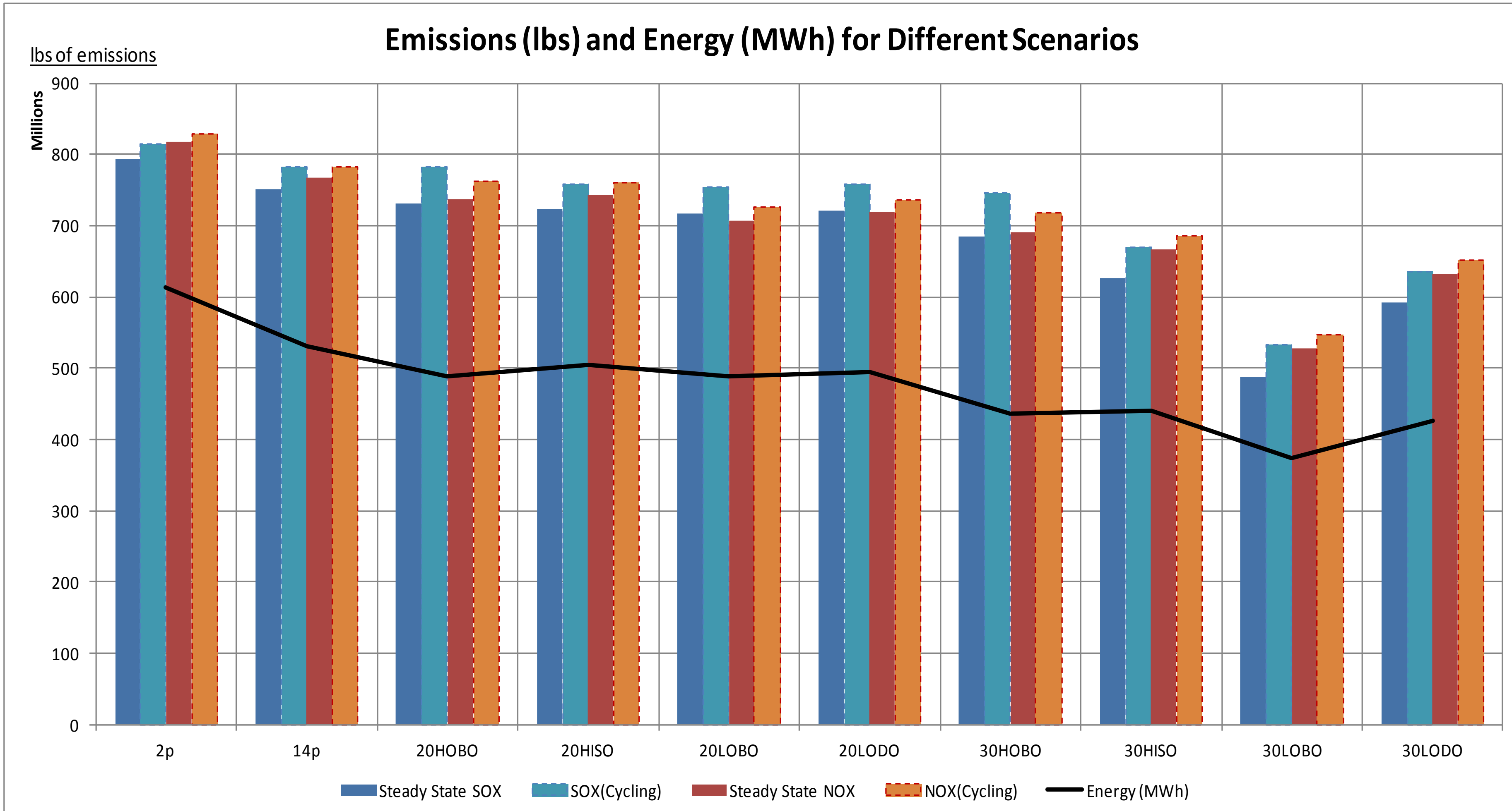
Steady State and Cycling Emissions for All Scenarios



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Cycling Impacts for NOx and SOx Emissions Relative to the 2% BAU Scenario

Compared to 2% BAU Scenario	SOX Expected Steady State Reduction in Emissions	SOX Expected Emissions Reduction with Cycling Impacts
14% RPS	5%	4%
20% HOBO	8%	4%
20% HSBO	9%	7%
20% LOBO	10%	7%
20% LODO	9%	7%
30% HOBO	14%	9%
30% HSBO	21%	18%
30% LOBO	39%	35%
30% LODO	25%	23%

Compared to 2% BAU Scenario	NOX Expected Steady State Reduction in Emissions	NOX Expected Emissions Reduction with Cycling Impacts
14% RPS	6%	6%
20% HOBO	10%	8%
20% HSBO	9%	9%
20% LOBO	14%	13%
20% LODO	12%	12%
30% HOBO	16%	14%
30% HSBO	19%	18%
30% LOBO	36%	36%
30% LODO	23%	22%

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Total MWh, Heat Input, and CO2 Emissions Relative to the 2% BAU Scenario

Compared to 2% BAU Scenario	Reduction in MWh Energy Output from Coal and Gas plants	Reduction in Heat Input (Fuel)	Reduction in CO2 Emissions
14% RPS	15%	14%	12%
20% HOBO	20%	18%	14%
20% HSBO	18%	16%	15%
20% LOBO	19%	19%	18%
20% LODO	18%	18%	17%
30% HOBO	35%	32%	27%
30% HSBO	31%	29%	28%
30% LOBO	40%	40%	41%
30% LODO	30%	29%	29%

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Relative Contribution of On/Off Cycling and Load-Follow Cycling to Total Emissions

	SOX Impact From		NOX Impact From	
	On/Off	Load Follow	On/Off	Load Follow
2% BAU	0.3%	2%	0%	1%
14% RPS	0.4%	3%	1%	2%
20% HOBO	0.3%	6%	0%	3%
20% HSBO	0.4%	4%	0%	2%
20% LOBO	0.6%	4%	1%	2%
20% LODO	0.6%	4%	1%	2%
30% HOBO	0.5%	7%	1%	4%
30% HSBO	0.7%	5%	1%	2%
30% LOBO	1.2%	6%	1%	2%
30% LODO	1.0%	5%	1%	2%

- This is the contribution of cycling transients to the total emissions (steady + cyclic).
- Load follow results are dominated by Supercritical Coal

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Cycling Emissions Analysis Conclusions

- The main observations and conclusions from this analysis are:
  - Emissions from coal plants comprise 97% of the NOx and 99% of the SOx emissions
  - For scenarios that experience increased cycling, the results are dominated by supercritical coal emissions.
  - NOx and SOx rates (lbs/mmBtu) increase at low loads for coal plants and decrease for CTs
  - Load follow cycling is the primary contributor of cycling related emissions.
  - Including the effects of cycling in emissions calculations does not dramatically change the level of emissions for scenarios with higher levels of renewable generation. However, on/off cycling and load-following ramps do increase emissions over steady state levels. This analysis has provided quantified data on the magnitudes of those impacts.

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Next Steps & Q/A
(GE + PJM)
[15 Minutes]

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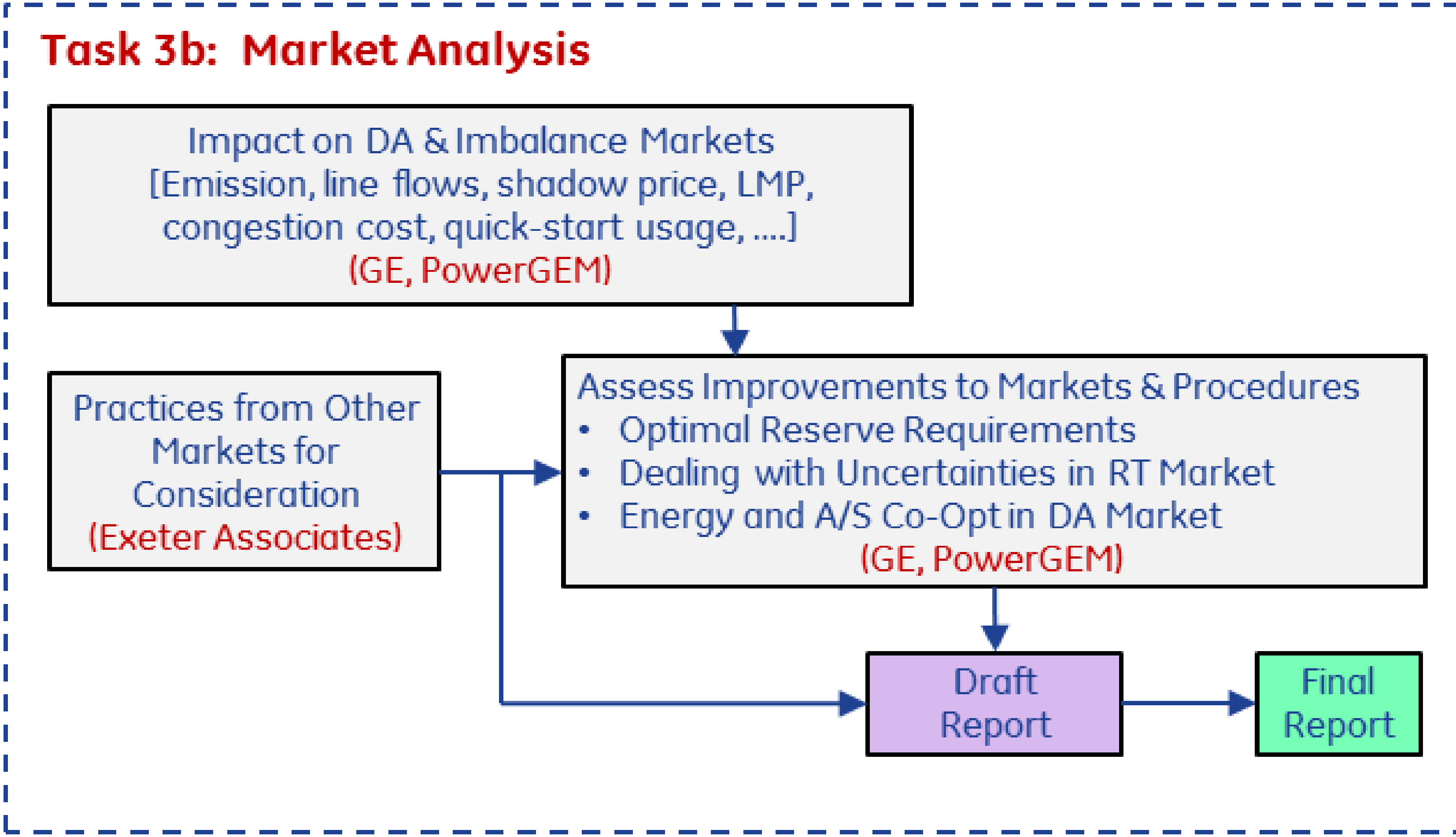
Currently Working on Task 3b



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And Task 4

Task 4: Mitigation, Facilitation, and Report

Evaluate Performance Under Normal/Abnormal Conditions

- Performance concerns (reserve violations, un-served load, curtailment, cycling, ...
- Primary and secondary reserves for frequency response
- Review existing PJM practices

(Entire Team)

Investigate Mitigation Measures

- Comparative approach
- Measures of efficacy
- Candidate mitigations include energy storage, thermal plant flexibility, demand side solutions, increased wind/solar plant functionality, ...

(Entire Team)

Draft Project Report → Interim PJM Meeting → Final Project Report → Final PJM Meeting

Final PJM PRIS Meeting

In-Person Meeting at PJM Offices

Thursday, December 5, 2013

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Thank You!

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Appendix A: Database Assumptions

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Key Assumptions

- Entire Eastern Interconnect system is simulated
- Renewable plants are connected to higher voltage busses
- Remaining PJM coal plants are assumed to have emissions control technology
- Renewable resources are curtailed when dispatch will impact nuclear operation
- Only primary fuel is modeled
- Existing operating reserve practice is used for reference case, statistical analysis is used to modify reserves for others
- 2026 run year uses 2006 load and renewable hourly shapes.
- 2026 data are updated based on PJM input on coal retirement / gas repower and new builds

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Renewable Energy Penetration in the rest of the Eastern Interconnection

- Rest of EI does not grow its overall renewable penetration as quickly as PJM
- Eastern Wind Integration and Transmission Study (EWITS) Scenario 2 (20% Hybrid with Offshore) used as guide to determine allocations to other NERC Regions

EWITS Executive Summary and Project Overview Table 1

TABLE 1. TOTAL AND OFFSHORE WIND IN THE SCENARIOS

Region	Scenario 1 20% High Capacity Factor, Onshore		Scenario 2 20% Hybrid with Offshore		Scenario 3 20% Local, Aggressive Offshore		Scenario 4 30% Aggressive On- and Offshore	
	TOTAL (MW)	Offshore (MW)	Total (MW)	Offshore (MW)	Total (MW)	Offshore (MW)	Total (MW)	Offshore (MW)
MISO/ MAPP[a]	94,808		69,444		46,255		95,046	
SPP	91,843		86,666		50,958		94,576	
TVA	1,247		1,247		1,247		1,247	
SERC	1,009		5,009	4,000	5,009	4,000	5,009	4,000
PJM	22,669		33,192	5,000	78,736	39,780	93,736	54,780
NYISO	7,742		16,507	2,620	23,167	9,280	23,167	9.280
ISO-NE	4,291		13,837	5,000	24,927	11,040	24,927	11,040
TOTAL	223,609	0	225,902	16,620	230,299	64,100	337,708	79,100

[a] MAPP stands for Mid-Continent Area Power Pool.

PJM and EI Renewable Energy Penetration for Each Scenario

Scenario	PJM % RE	EI % RE
Base	14%	10%
Low Offshore	20%	15%
High Offshore	20%	15%
High Solar	20%	15%
Low Offshore	30%	20%
High Offshore	30%	20%
High Solar	30%	20%

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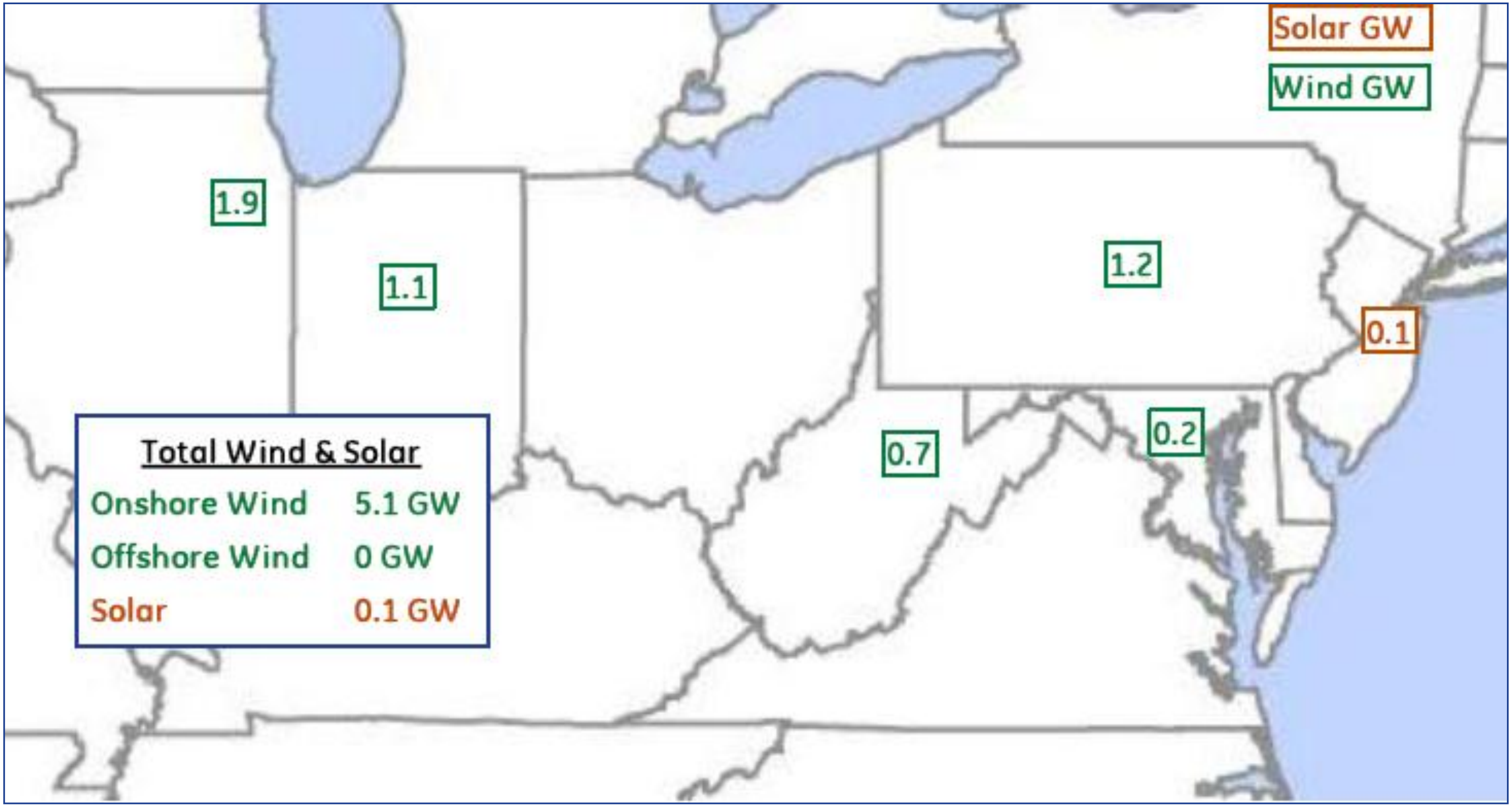
2% BAU Scenario



Note: Dots indicate wind plant sites; Solar resources are not shown.

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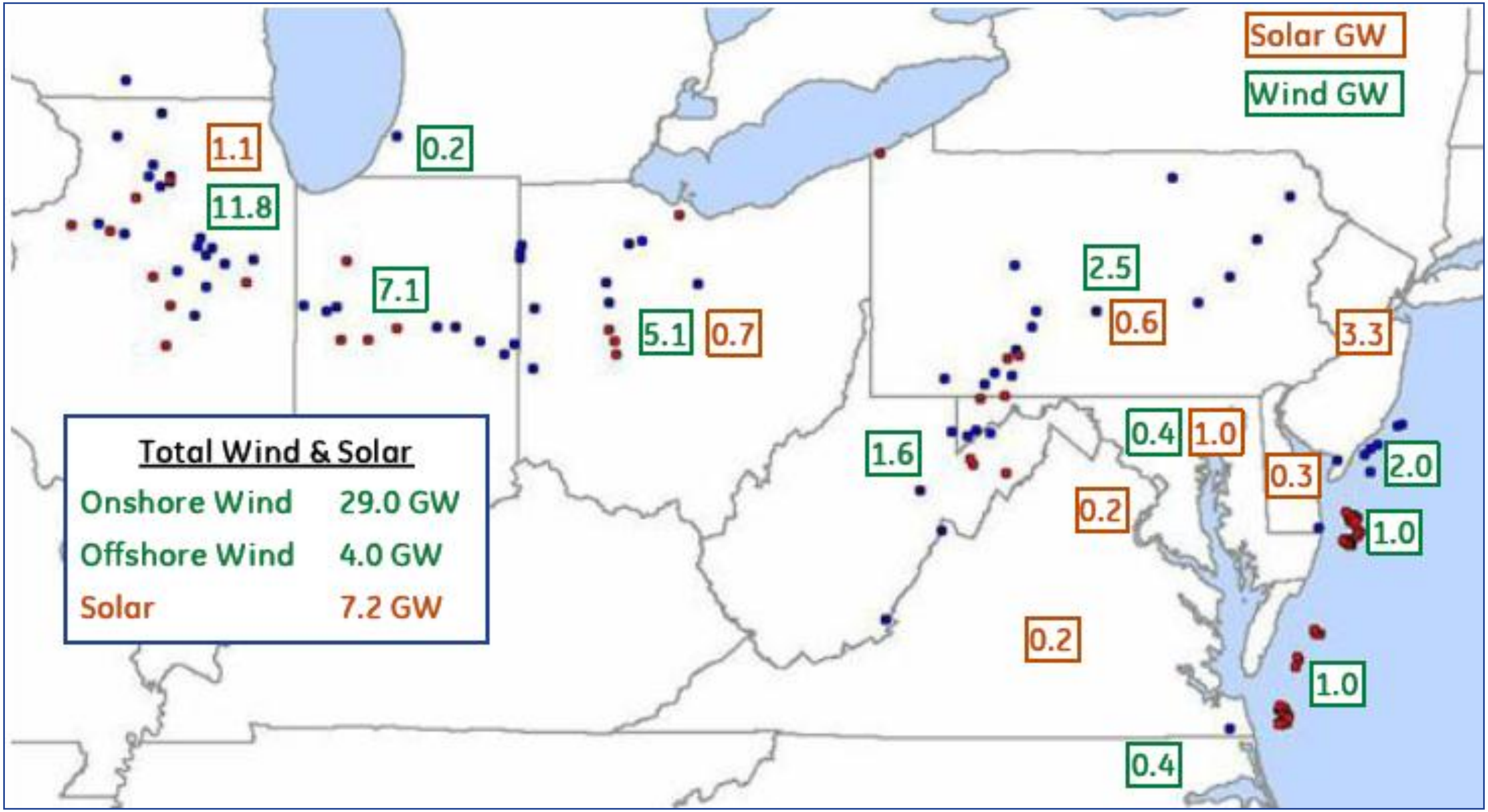
14% RPS Scenario



Note: Dots indicate wind plant sites; Solar resources are not shown.

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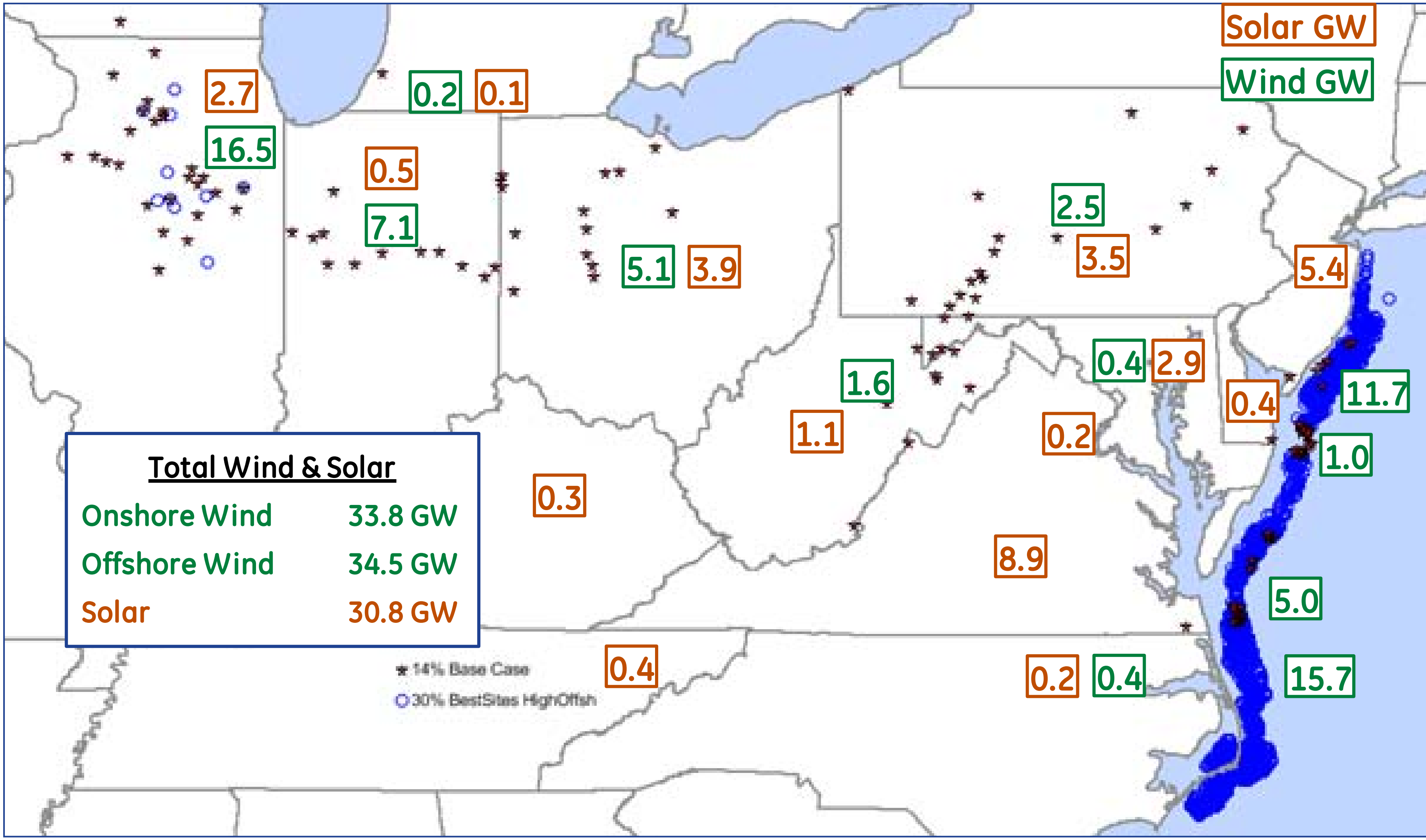
30% High Offshore with Best Onshore Wind



Total Wind & Solar	
Onshore Wind	33.8 GW
Offshore Wind	34.5 GW
Solar	30.8 GW

Note: Dots indicate wind plant sites; Solar resources are not shown.

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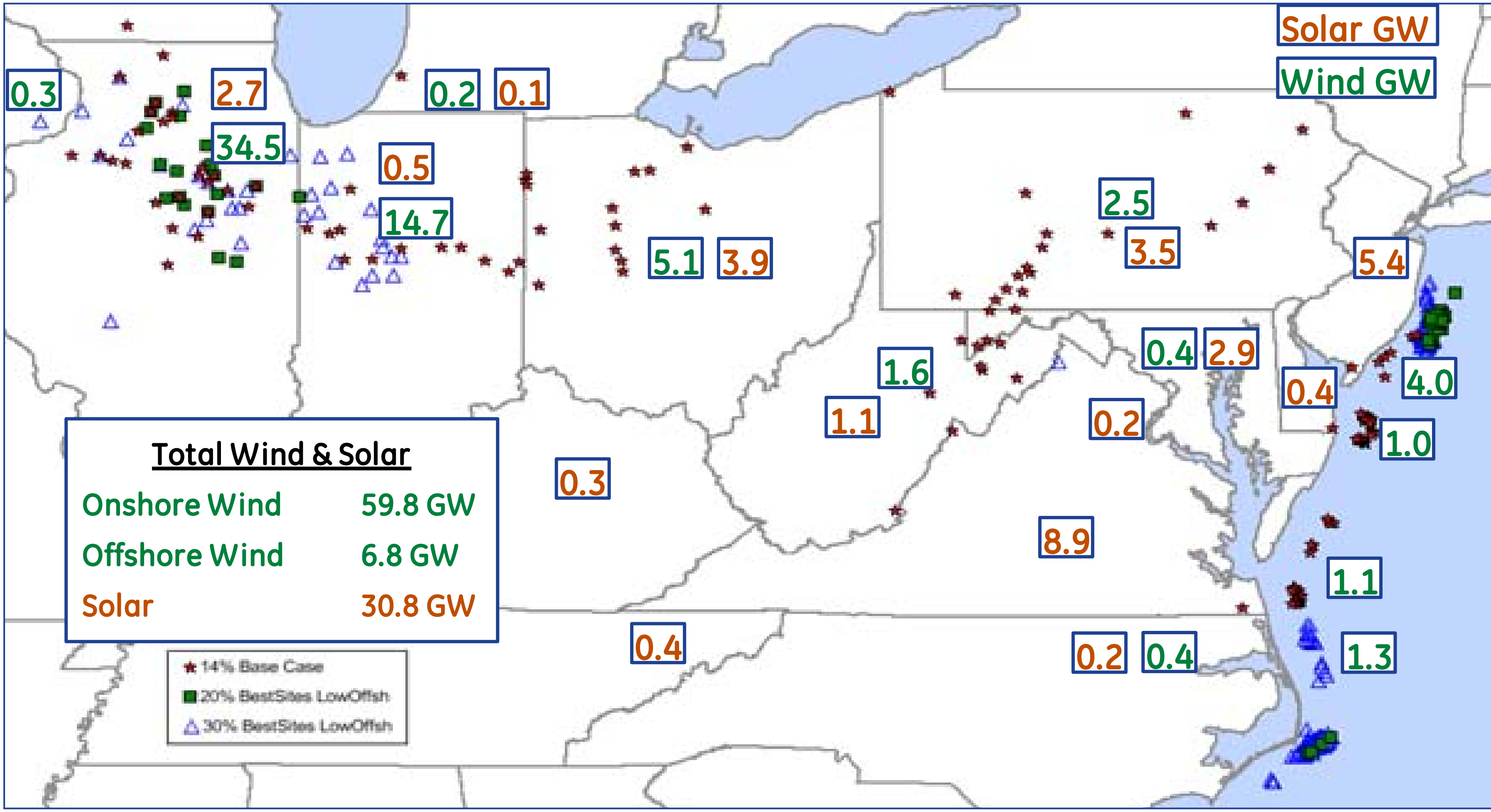
30% Low Offshore with Best Sites Onshore



Note: Dots indicate wind plant sites; Solar resources are not shown.

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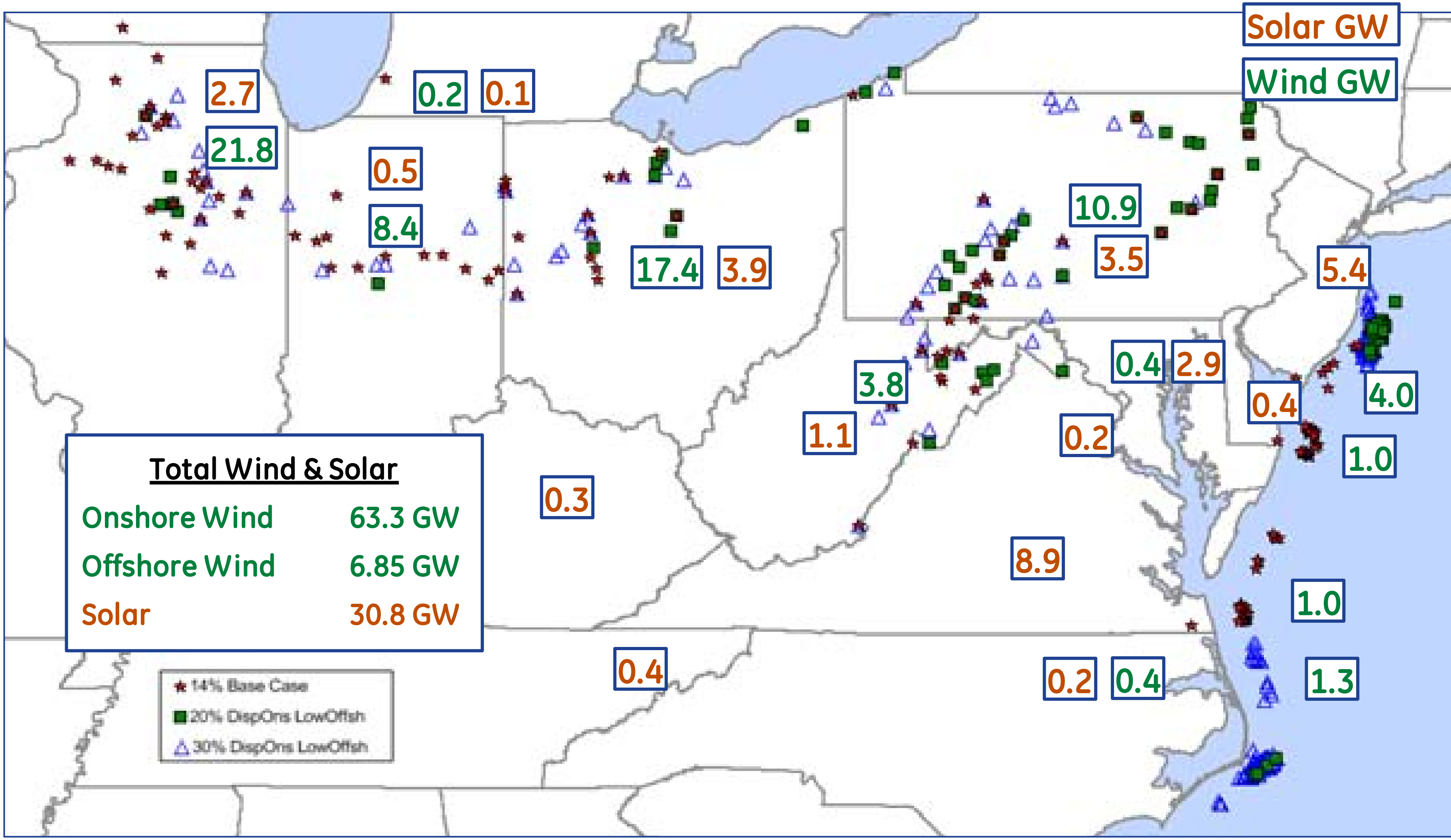
30% Low Offshore, Dispersed Sites Onshore



Note: Dots indicate wind plant sites; Solar resources are not shown.

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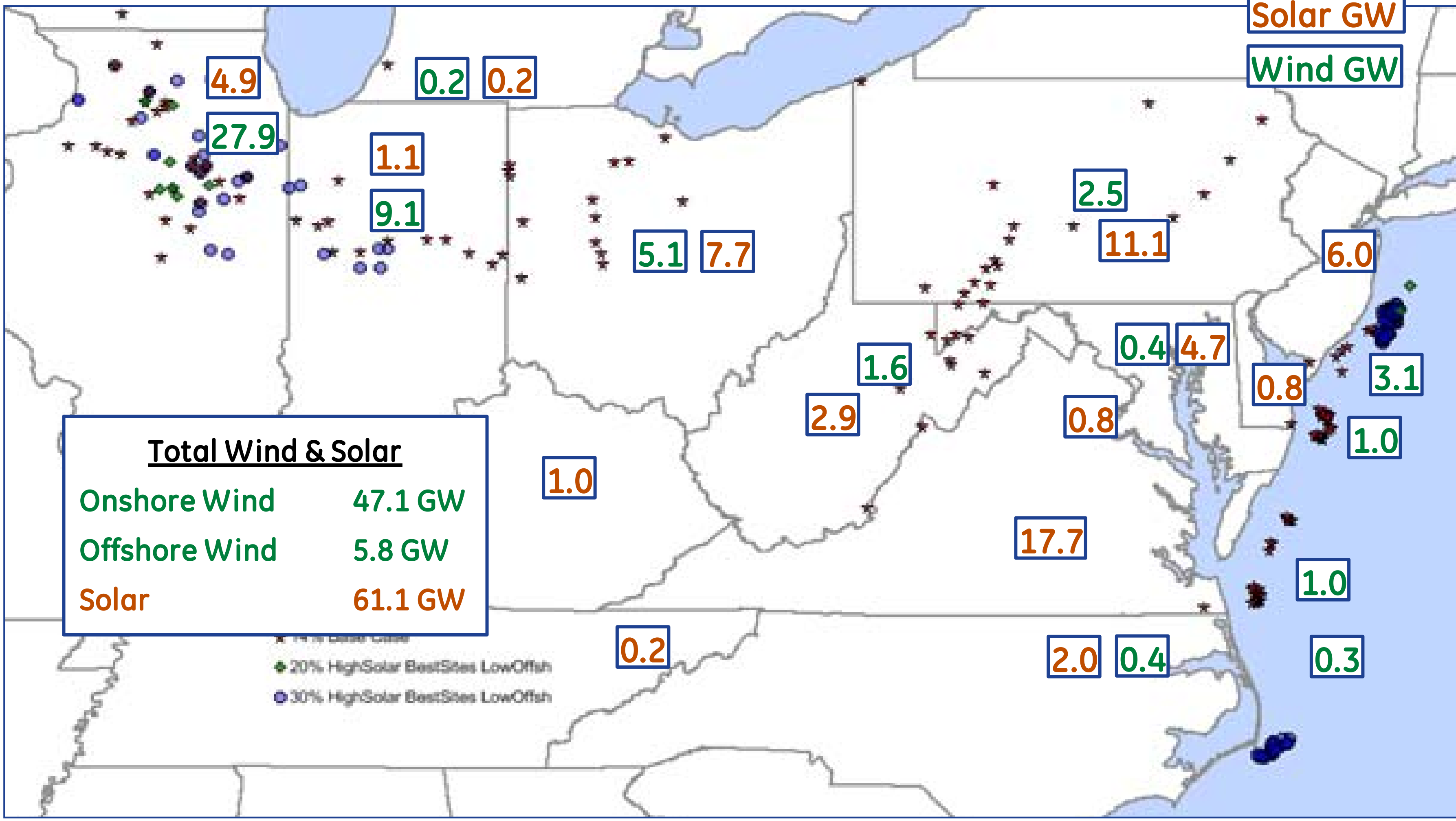
30% High Solar with Best Wind Sites Onshore



Total Wind & Solar	
Onshore Wind	47.1 GW
Offshore Wind	5.8 GW
Solar	61.1 GW

Note: Dots indicate wind plant sites; Solar resources are not shown.

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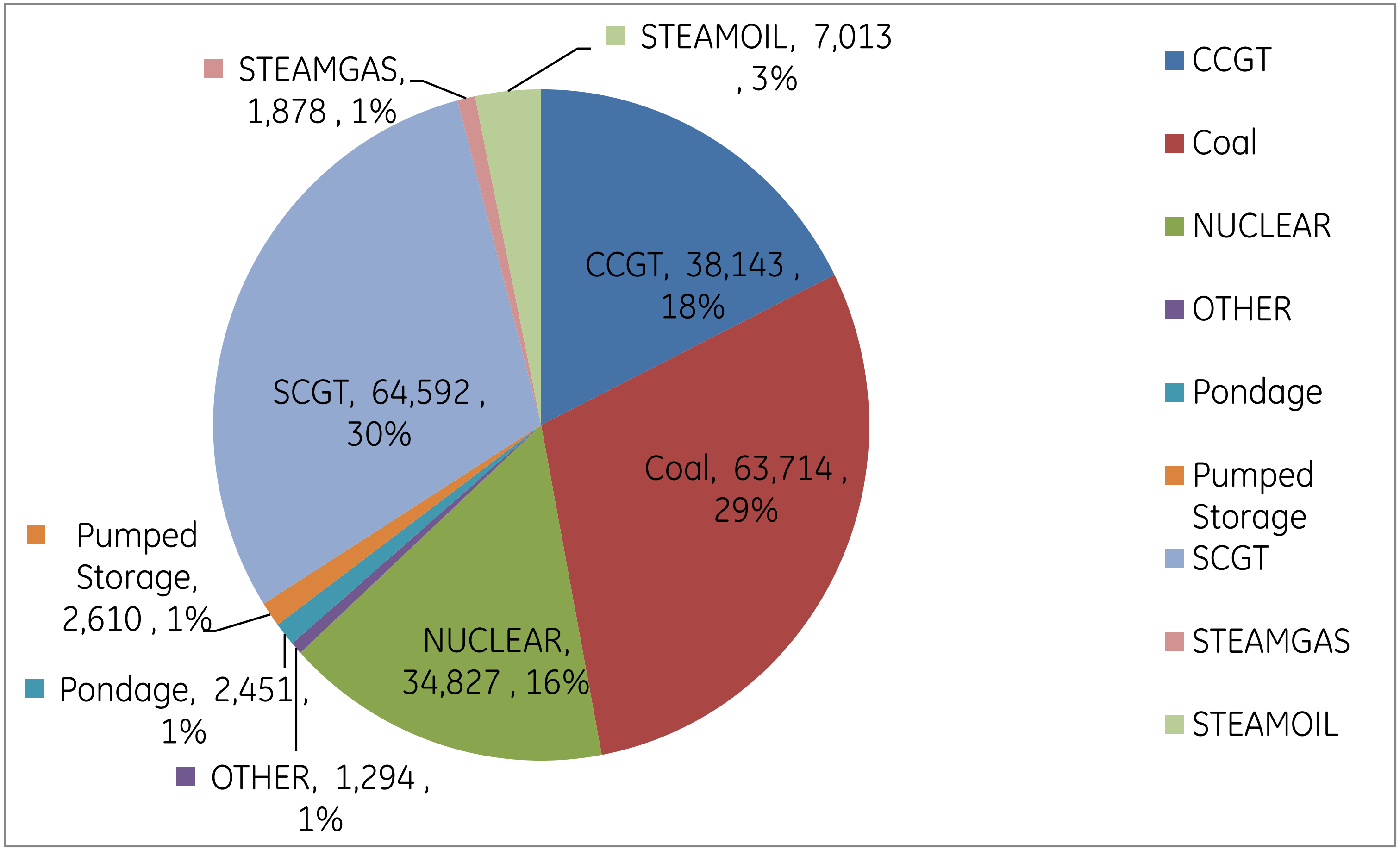
Installed Capacity in 2% BAU Excluding Wind and Hydro



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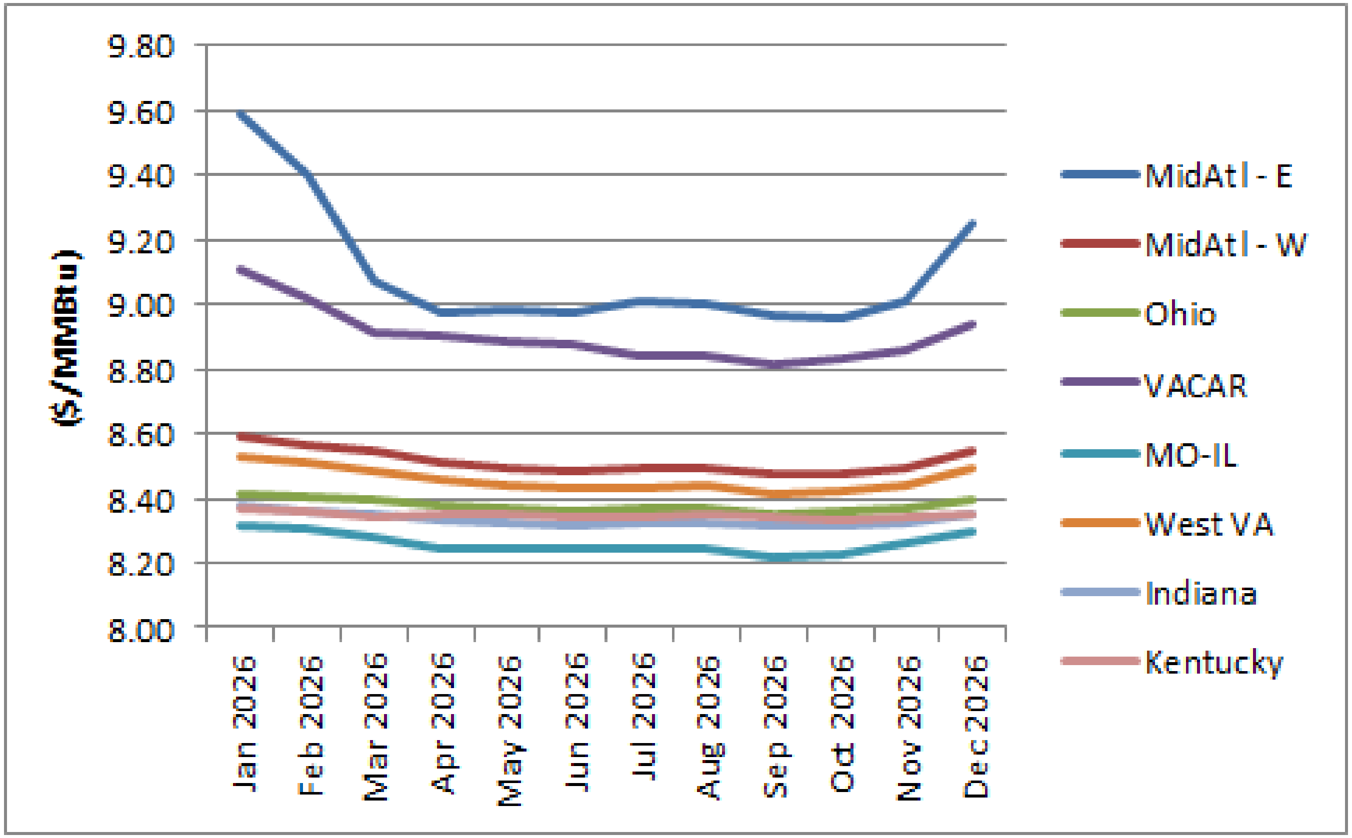
Monthly PJM Natural Gas Prices - Nominal Dollars

- EIA Annual Energy Outlook 2012 Report Henry Hub ($8.02/mmBtu)
- Basis Differentials provided by PJM from Ventyx



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Coal Prices

- EIA Annual Energy Outlook 2012 Report
  - 2026 average US delivered price is $3.51/mmBtu (nominal)
  - Blended plant prices develop from Ventyx average historic coal usage (2009 – 2011)

Coal Region	2026 Price ($/mmBtu)
Central Appalachia	4.79
Central Interior	2.54
Gulf Lignite	6.08
Illinois Basin	2.12
Indonesia	2.20
Lignite	4.32
Northern Appalachia	1.55
Powder River Basin	3.31
Rocky Mountain	4.05
Southern Appalachia	1.15

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Oil & Nuclear Prices

Oil
(Energy Velocity NYMEX Forecast)

Date	WTI	Gulf Coast Resid (No. 6 Oil) $/bbl	Gulf Coast LS Diesel (No.2 Distillate Oil) $/bbl	Gulf Coast Resid (No. 6 Oil) $/mmBtu	Gulf Coast LS Diesel (No.2 Distillate Oil) $/mmBtu
1/1/2026	112.52	93.89	130.43	14.93	22.39
2/1/2026	112.48	93.86	130.38	14.93	22.38
3/1/2026	112.43	93.81	130.32	14.92	22.37
4/1/2026	112.74	94.07	130.68	14.96	22.43
5/1/2026	113.65	94.83	131.73	15.08	22.61
6/1/2026	113.58	94.77	131.65	15.07	22.60
7/1/2026	113.51	94.71	131.57	15.06	22.59
8/1/2026	113.43	94.65	131.48	15.05	22.57
9/1/2026	113.34	94.57	131.38	15.04	22.55
10/1/2026	113.66	94.84	131.74	15.08	22.62
11/1/2026	114.54	95.57	132.76	15.20	22.79
12/1/2026	114.53	95.56	132.75	15.20	22.79

Nuclear
(Energy Velocity)

2026 Price ($/mmBtu)
$0.75

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Emissions Prices

- Compliance by all plants
  - Emission cost assumed to be $0/ton
- All operating plants will have appropriate control technology

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Load Projections

- PJM – Based on PJM's 2011 load forecast report, historical load shapes (2004, 2005, 2006) will be energy scaled to 2026 energy by zone. Methodology discussed in Task 1 report.
- Rest of EI – Based on Ventyx "Historical and Forecast Demand by Zone", aggregated to the MAPS Pool (~NERC sub region) level. Individual control area historical load shapes will then be energy scaled using a pool level scaling factor.

MAPS Pool	Ventyx 2026 Forecasted Energy GWh	2010 Energy GWh	Average Annual Growth Rate
PJM	969,596	810,811	1.1%
MISO	605,177	531,156	0.8%
Southern	305,497	250,284	1.3%
FRCC	279,147	229,783	1.2%
SPP	275,816	236,717	1.0%
VACAR	261,710	226,514	0.9%
Central / TVA	255,532	229,162	0.7%
Delta / Entergy	180,012	156,808	0.9%
NYISO	174,383	163,505	0.4%
ISONE	157,208	128,660	1.3%
IESO	142,080	141,897	0.0%
OVEC	231	495	-4.6%
EI	3,606,390	3,105,792	0.9%

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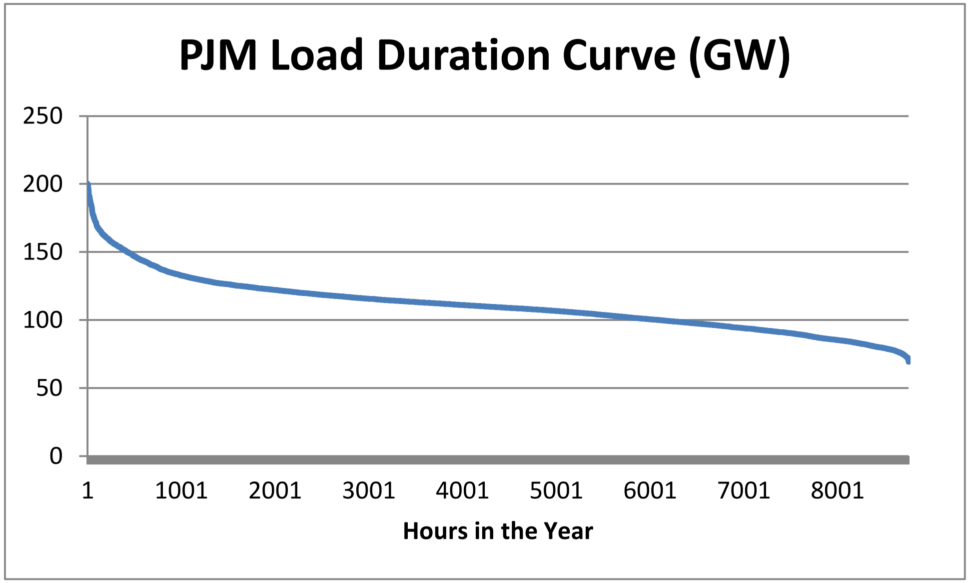
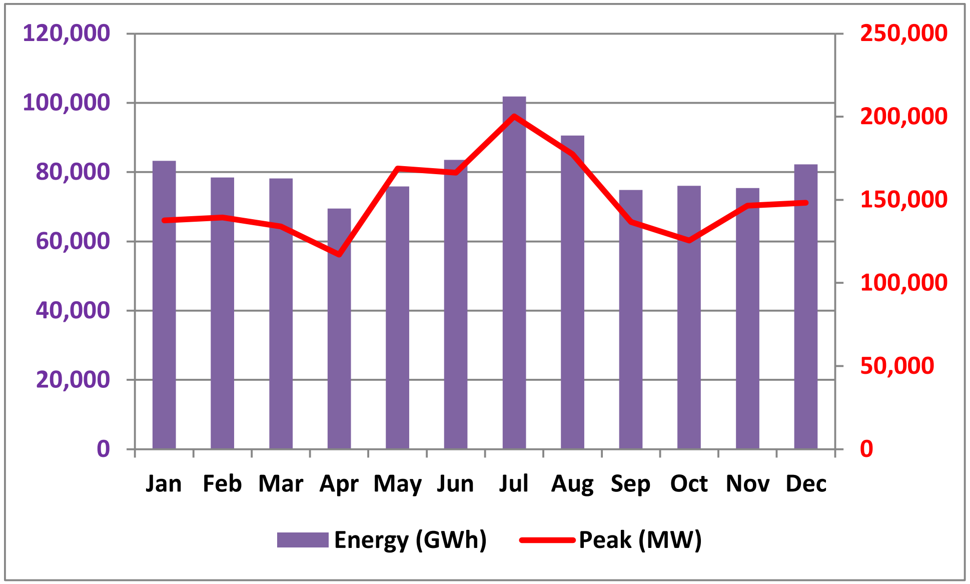
PJM Load





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Thermal Generator Additions

- PJM – queue (with FAC or ISA) plus generics to maintain reserve margin. Generic additions will be added if base case falls below PJM reserve margin target.
  - PJM Queue has 31.5 GW of FSA/ISA qualified
- Rest of EI – under construction per Ventyx plus generic additions to maintain reserve margins at the MAPS pool level. Generic additions will be split between SCGTs and CCGTs depending on regional needs.
- Existing wind and solar - will be given some capacity credit in base case
  - PJM - 13%
  - Sensitivity cases can be run to remove thermal capacity based on MARS analysis for the higher penetration scenarios

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Thermal Generator Parameters

- Start Cost – Based on GE engineering; by size, by type
- Economic Max/Min – Set to operating min/max
- Ramp Rate – Only applied in production cost simulation when looking at spinning reserve capability
- Min Down Time – Based on CEMS data analysis; by type, by size
- Min Run Time – not currently specified
- Heat Rates – GE review of multiple sources including CEMS
- Emissions/Effluent Removal Rates – Net emission rates based on CEMS data analysis from Ventyx
- OM Cost – Ventyx

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Generator Retirements

- PJM – Coal plant retirement forecast provided by PJM, Other types announced from Ventyx

- Rest of EI - Announced from Ventyx

- Assume all nuclear plants continue to operate

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Hurdle Rates

Based on Eastern Interconnect Planning Collaborative (EIPC) study

From	To	Total Hurdle 2010$/MWh
PJM	MIS	
MISO	PJI	
PJM	NY	
NY	PJI	
PJM	Nor Mid	
PJM	TV/	
PJM	VA(	
VACAR	PJI	
TVA	PJI	

From	To	Total Hurdle 2010 $/MWh
PJM	MISO	2
MISO	PJM	2
PJM	NY	6
NY	PJM	8
PJM	Non RTO Midwest	6
PJM	TVA	6
PJM	VACAR	6
VCAR	PJM	7
TVA	PJM	9

Source:
Future 1 Modeling Assumptions
http://www.eipconline.com/uploads/Future_1_Modeling_Assumptions_Master_9-24-11.xls

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Appendix B: Weekly Generation Charts

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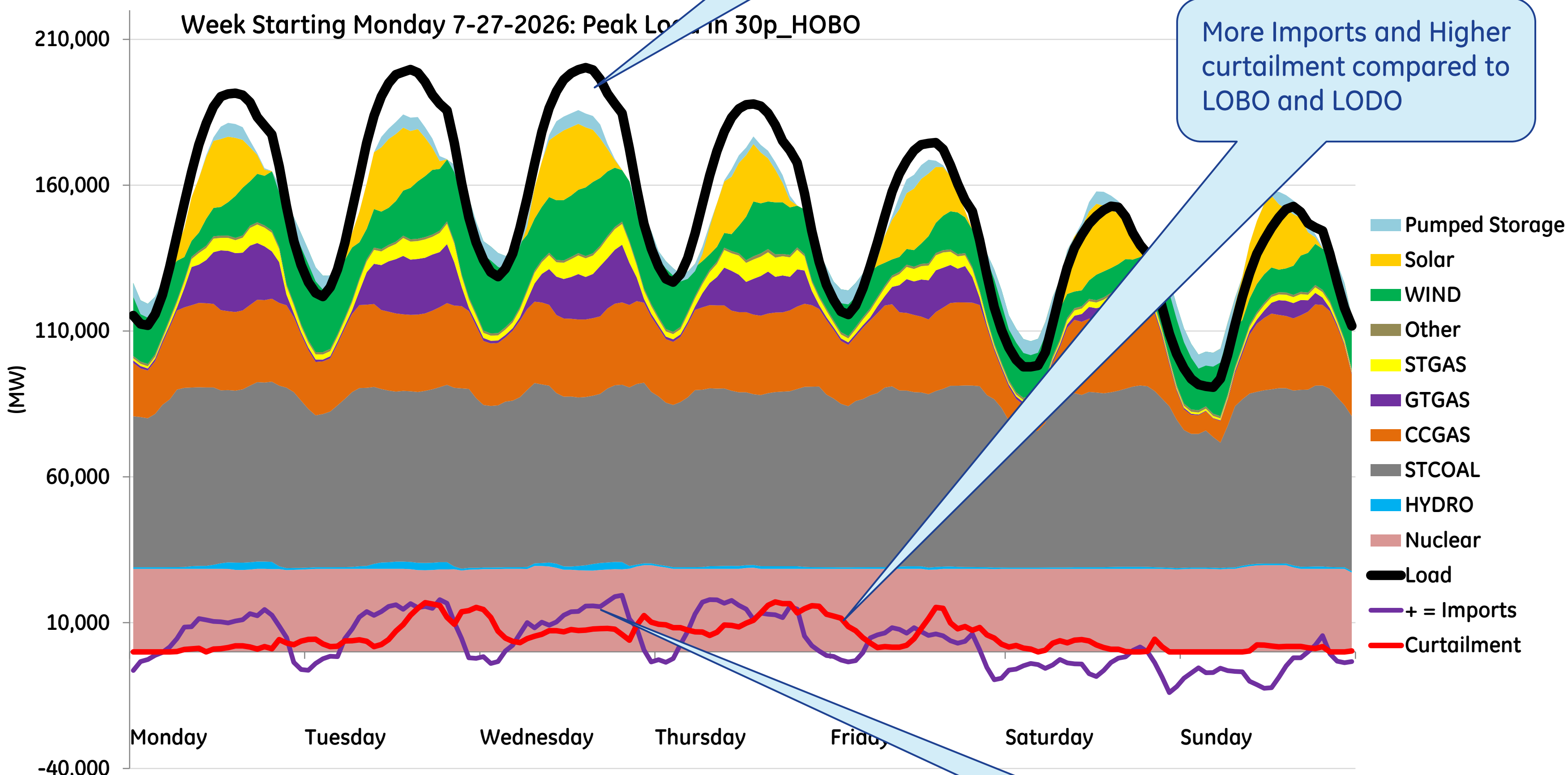
Week of Highest Load

More supply shortage compared to LOBO and LODO

More Imports and Higher curtailment compared to LOBO and LODO



Imports make up for supply shortage

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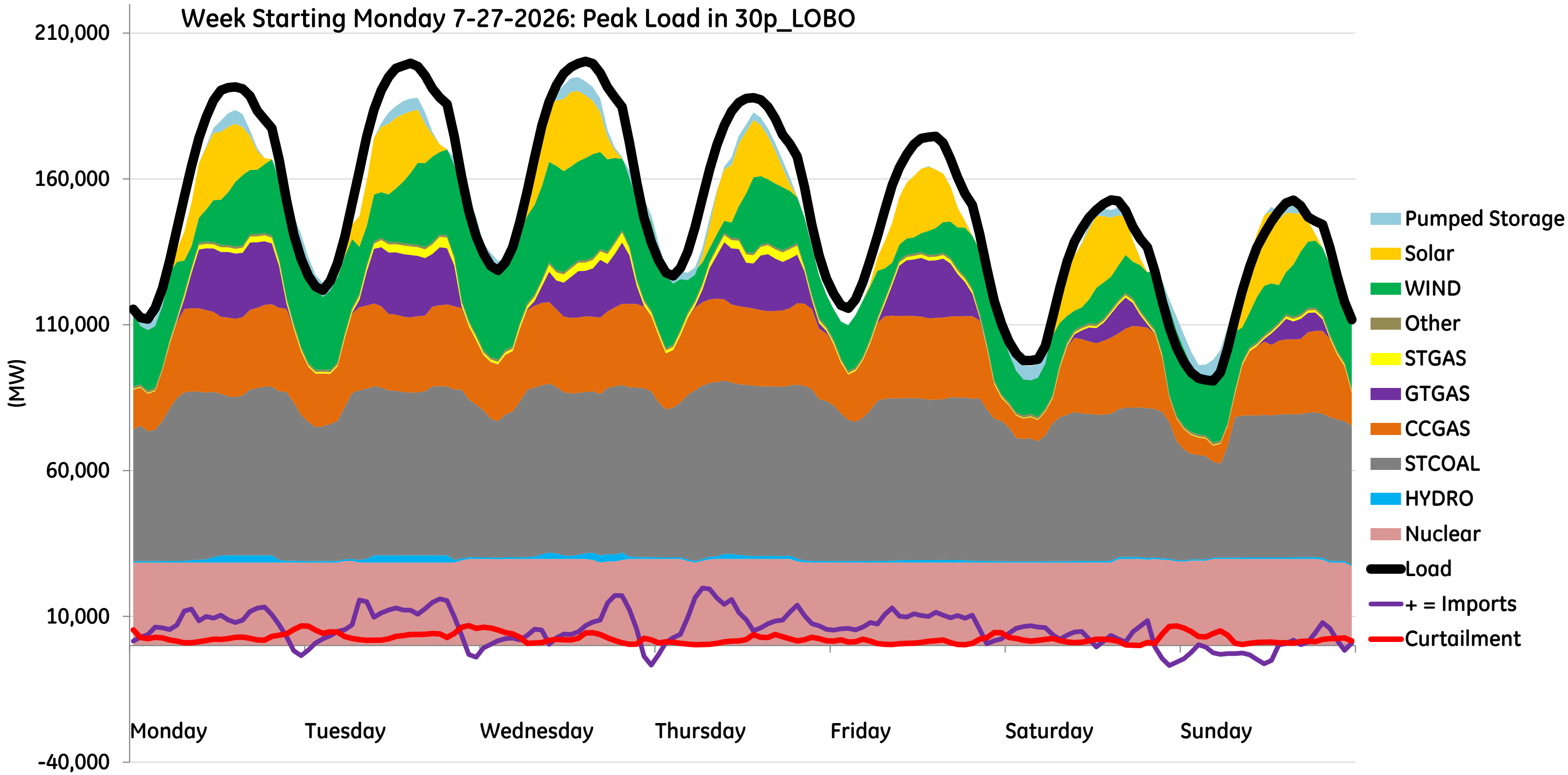
Week of Highest Load



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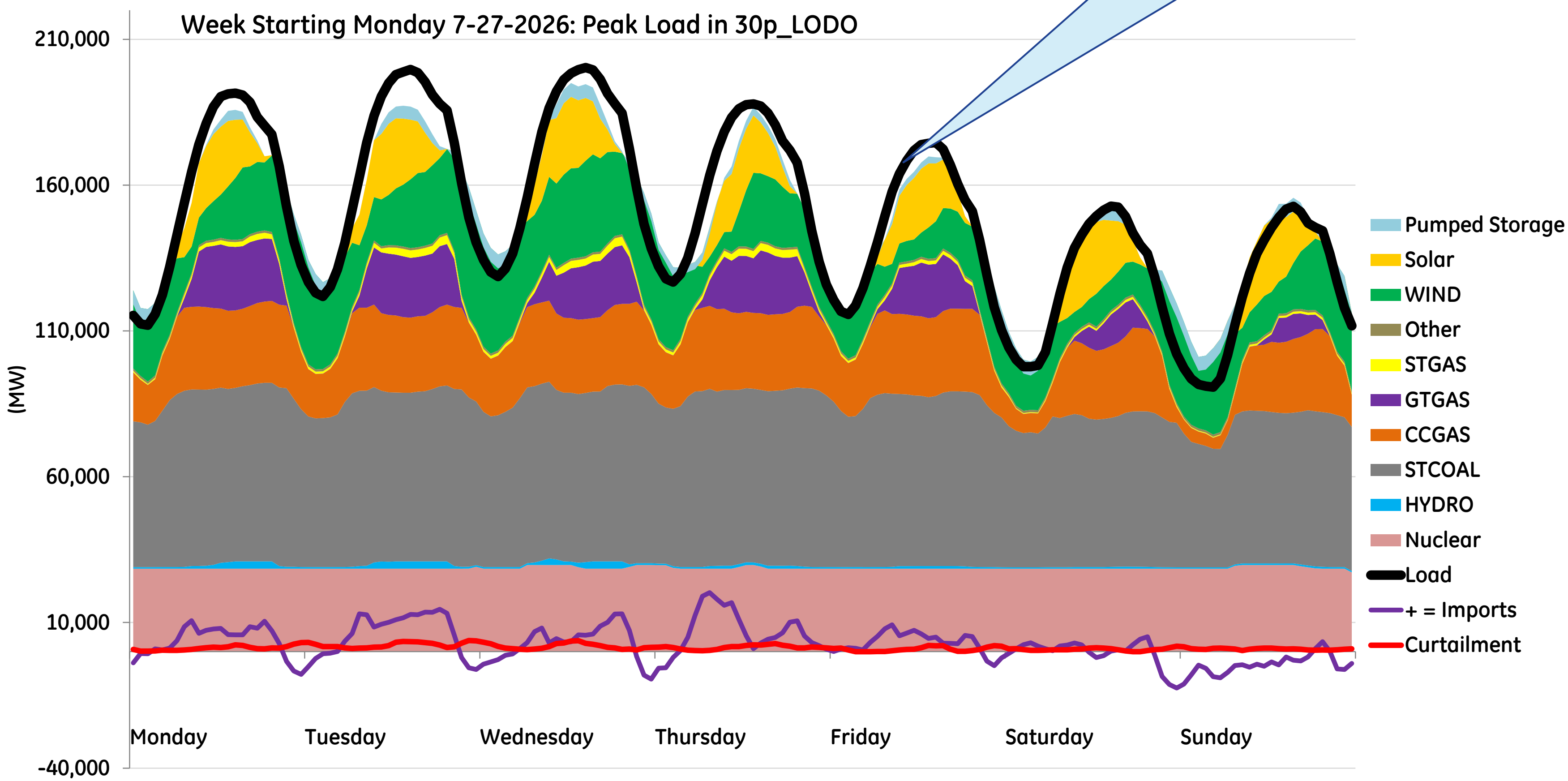
Week of Highest Load

LODO does a better job of meeting load compared to either HOBO and LOBO



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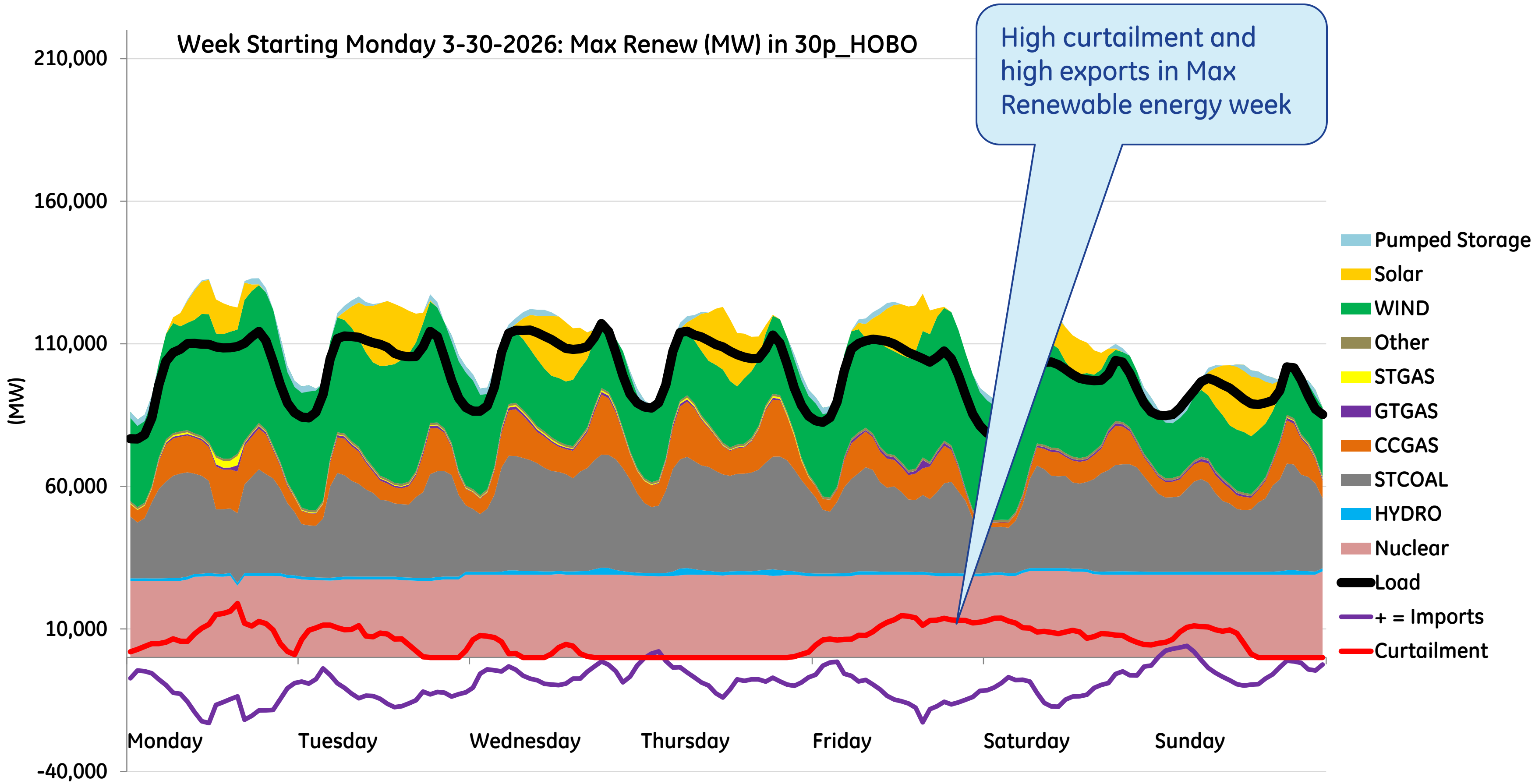
Week of Maximum MW Renewable Energy



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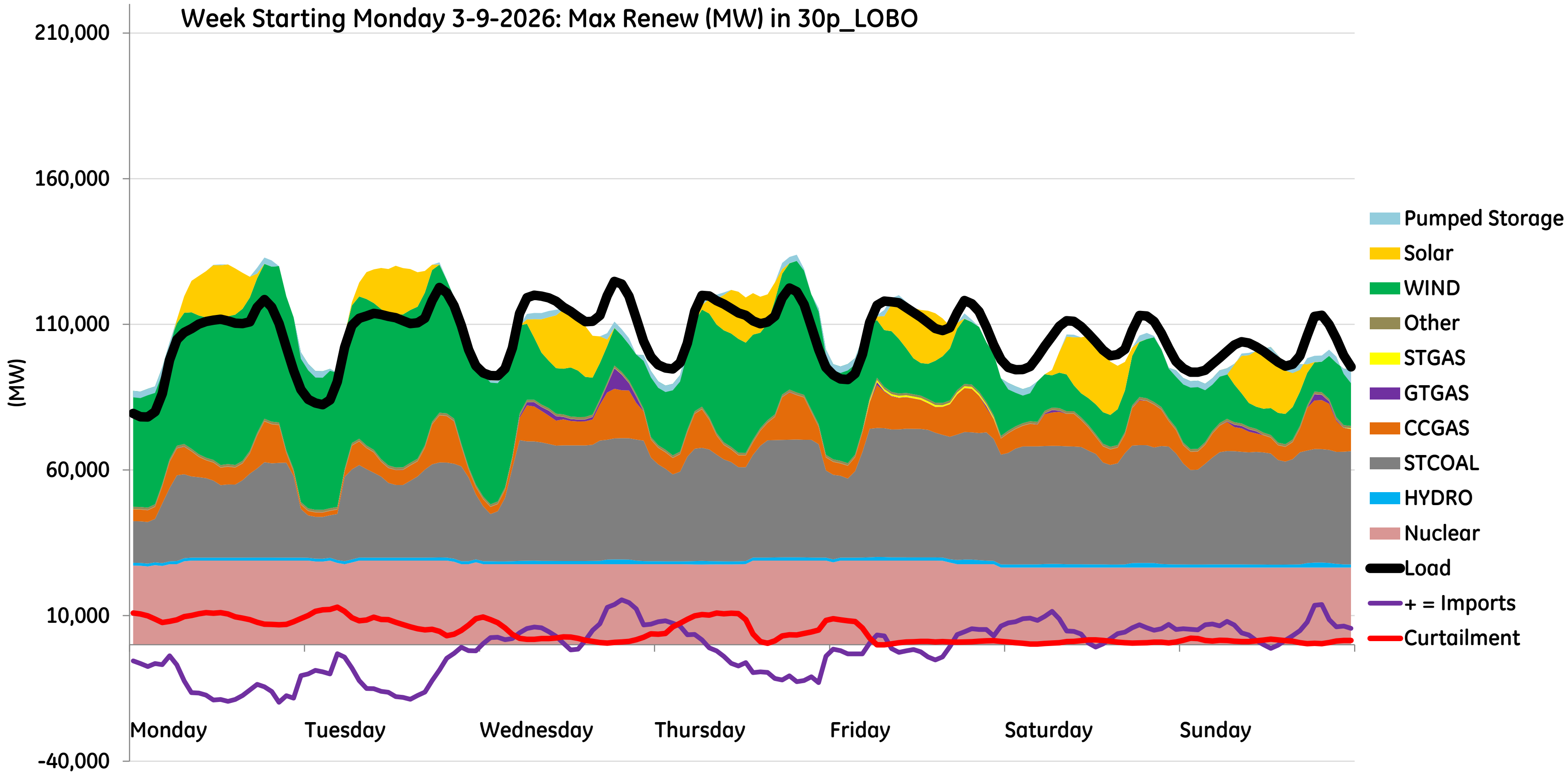
Week of Maximum MW Renewable Energy



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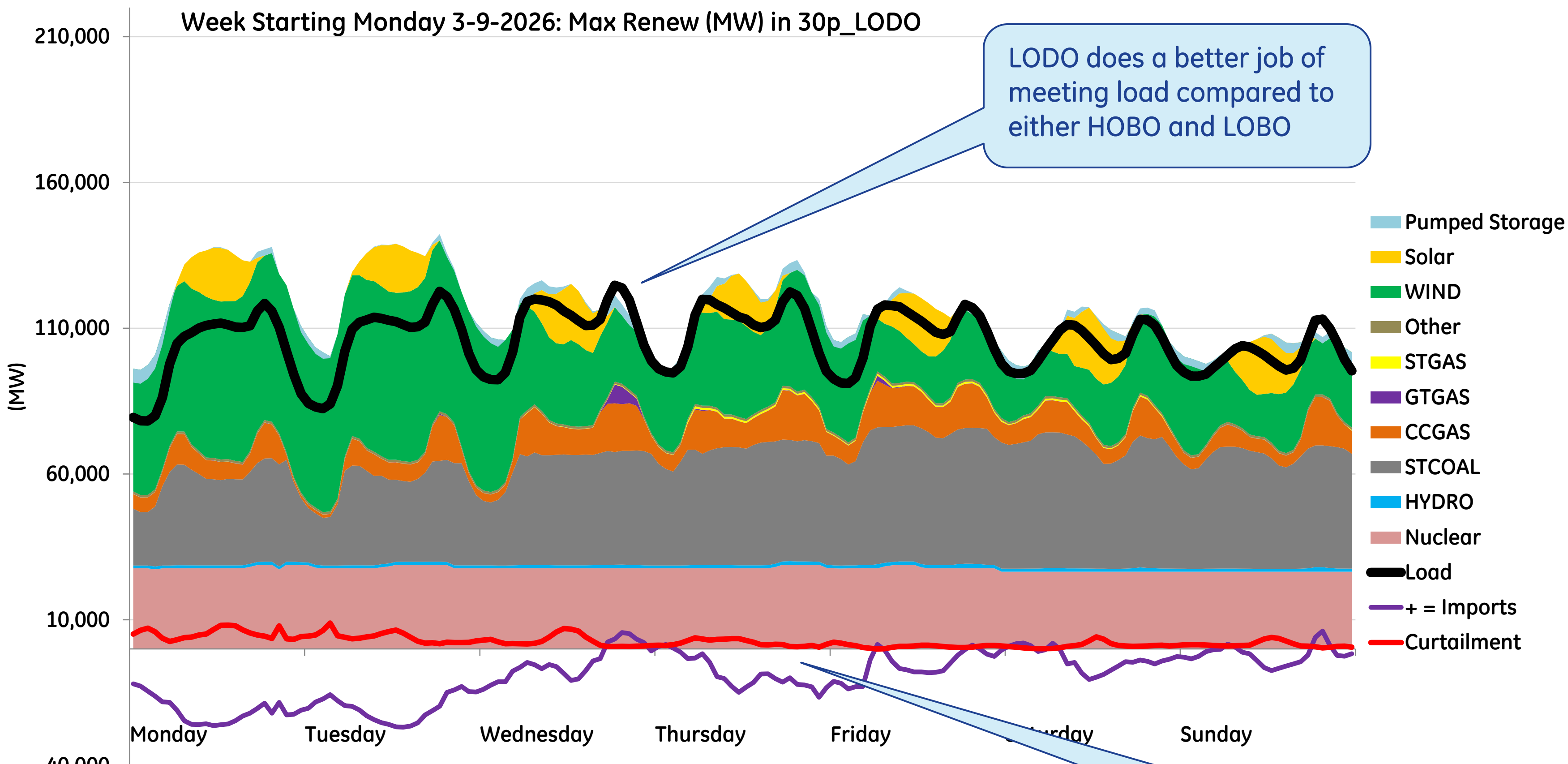
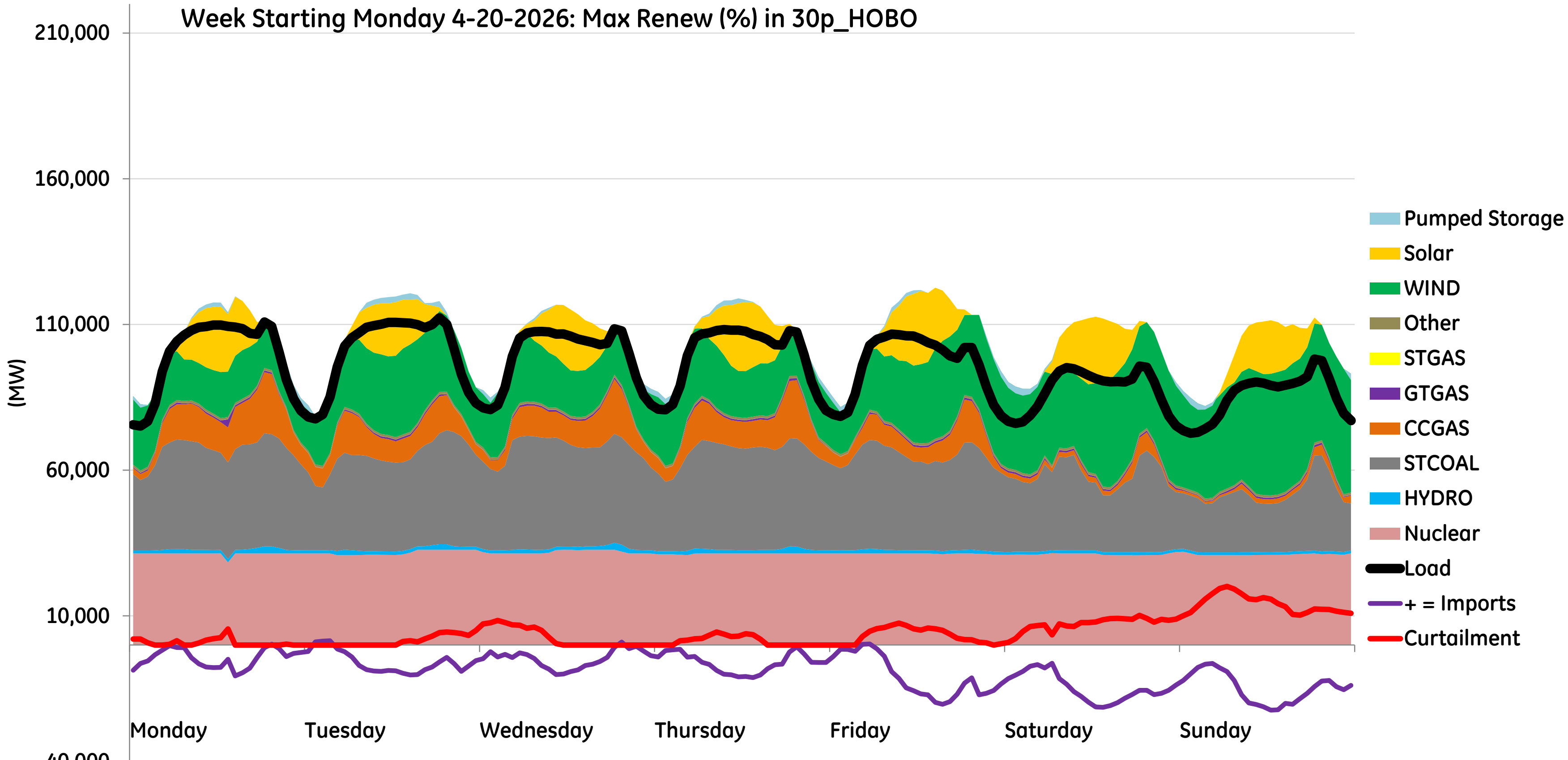
Week of Maximum MW Renewable Energy



LODO does a better job of meeting load compared to either HOBO and LOBO

More exports and lower curtailment compared to LOBO and LODO

Week of Maximum % Renewable Energy



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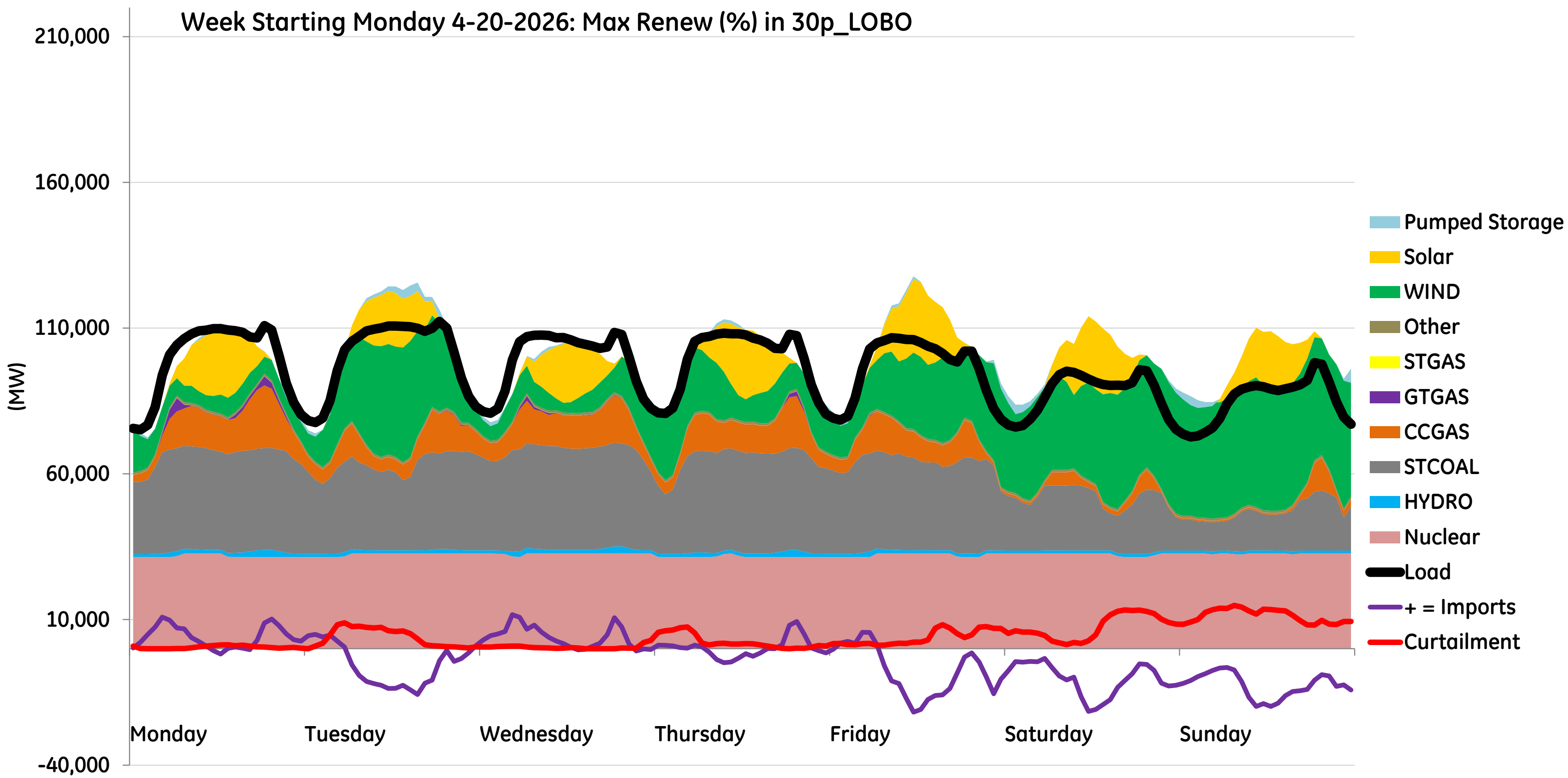
Week of Maximum % Renewable Energy



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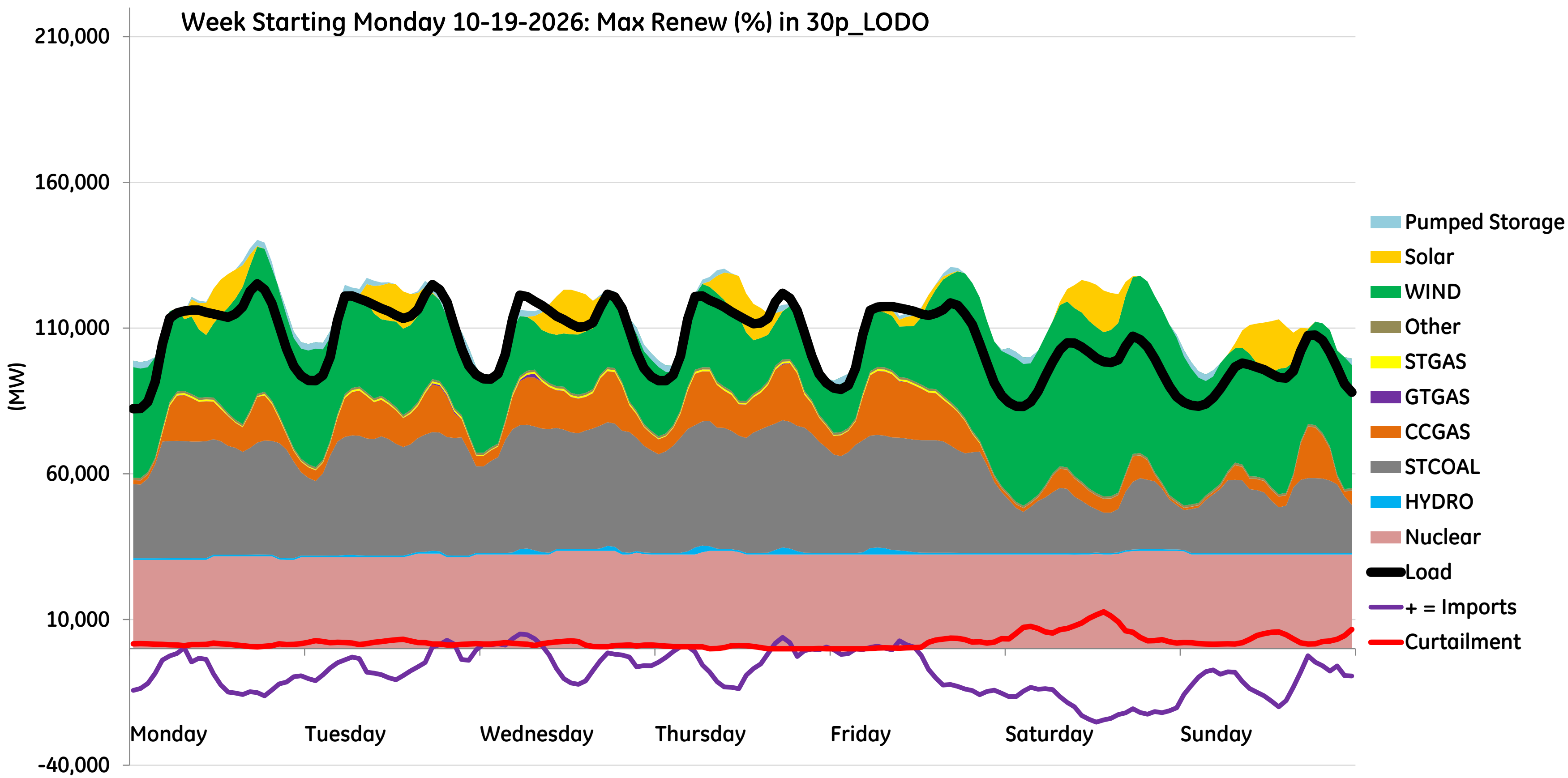
Week of Maximum % Renewable Energy



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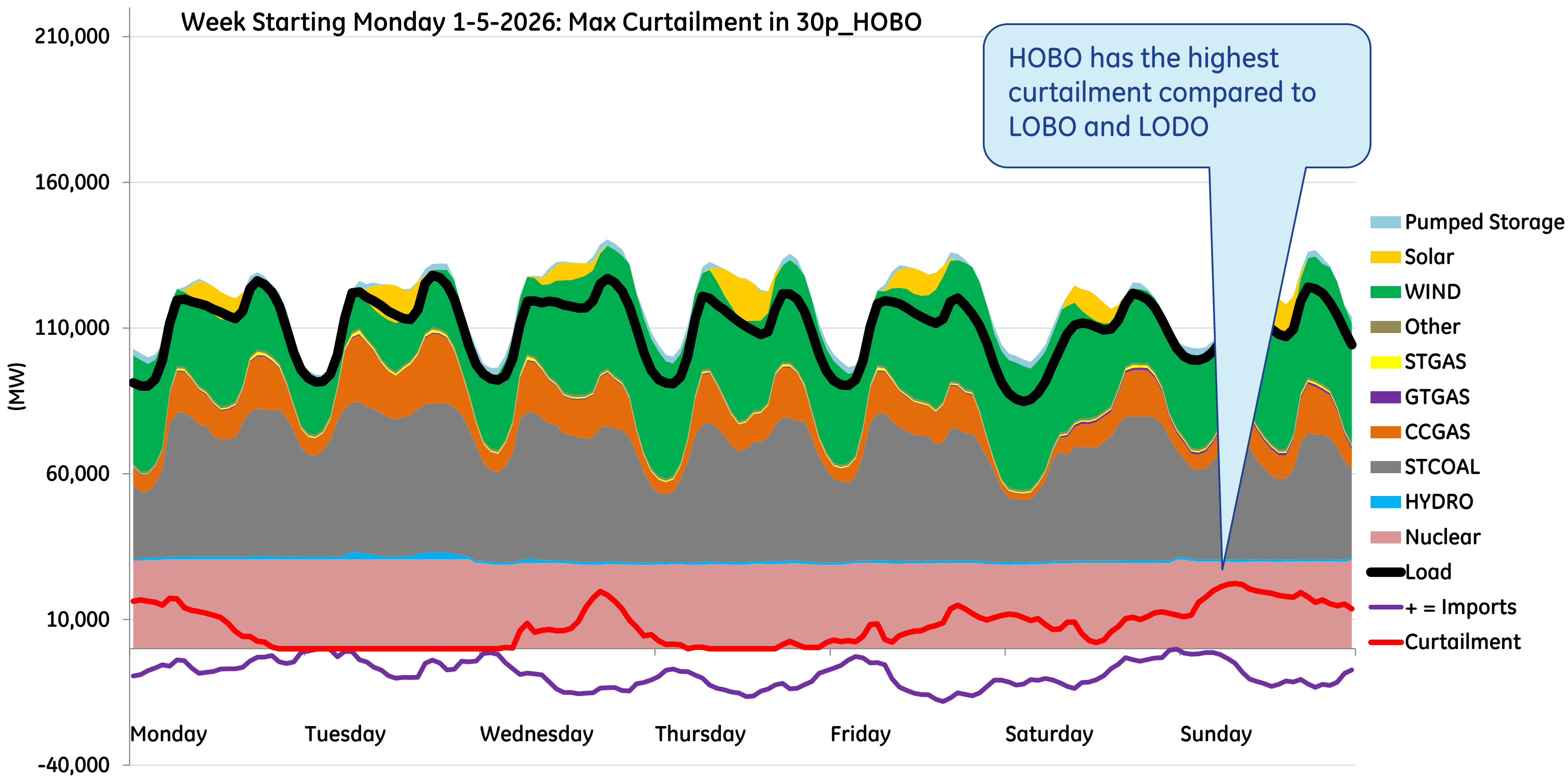
Week of Maximum Curtailment



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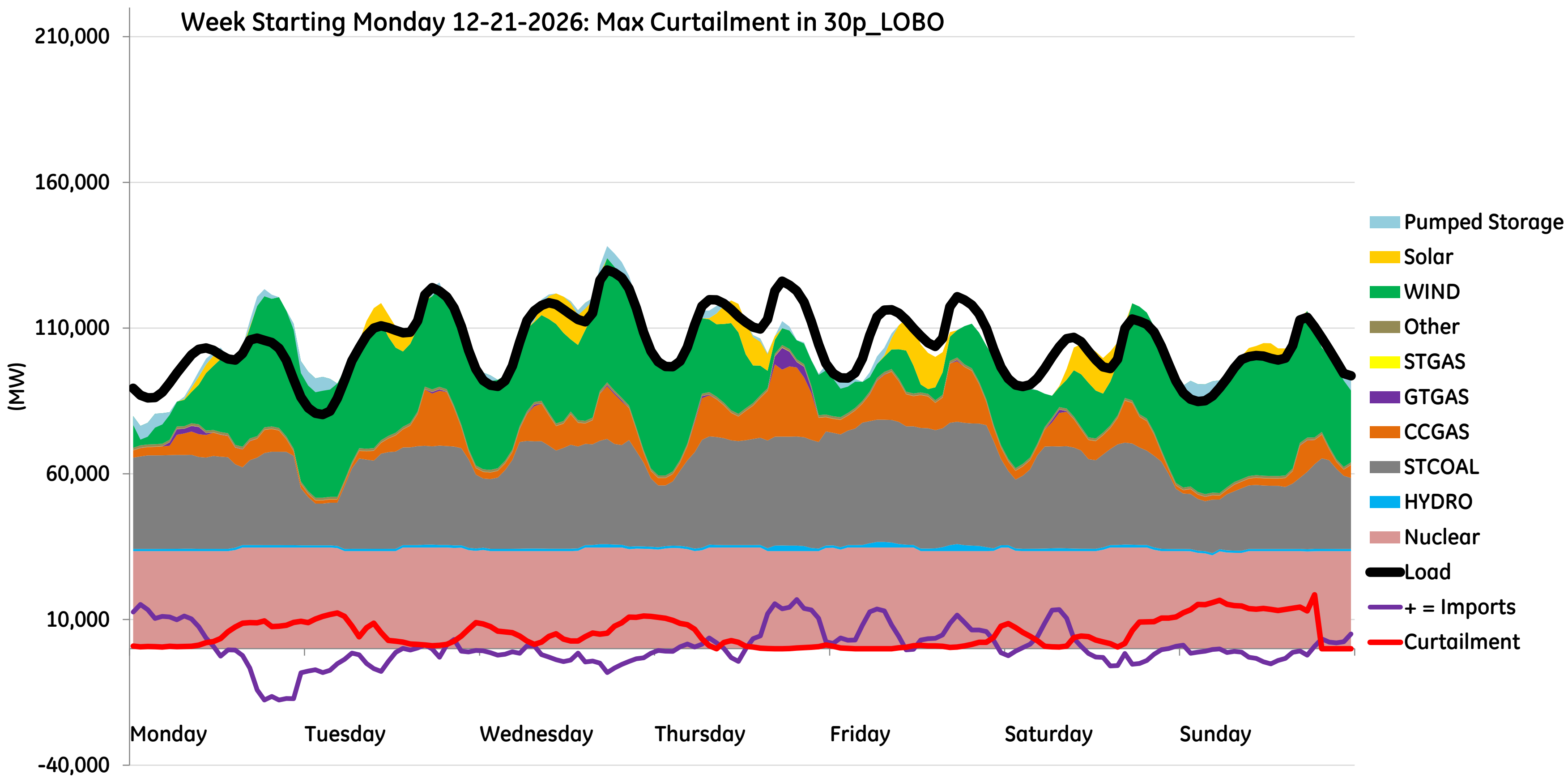
Week of Maximum Curtailment



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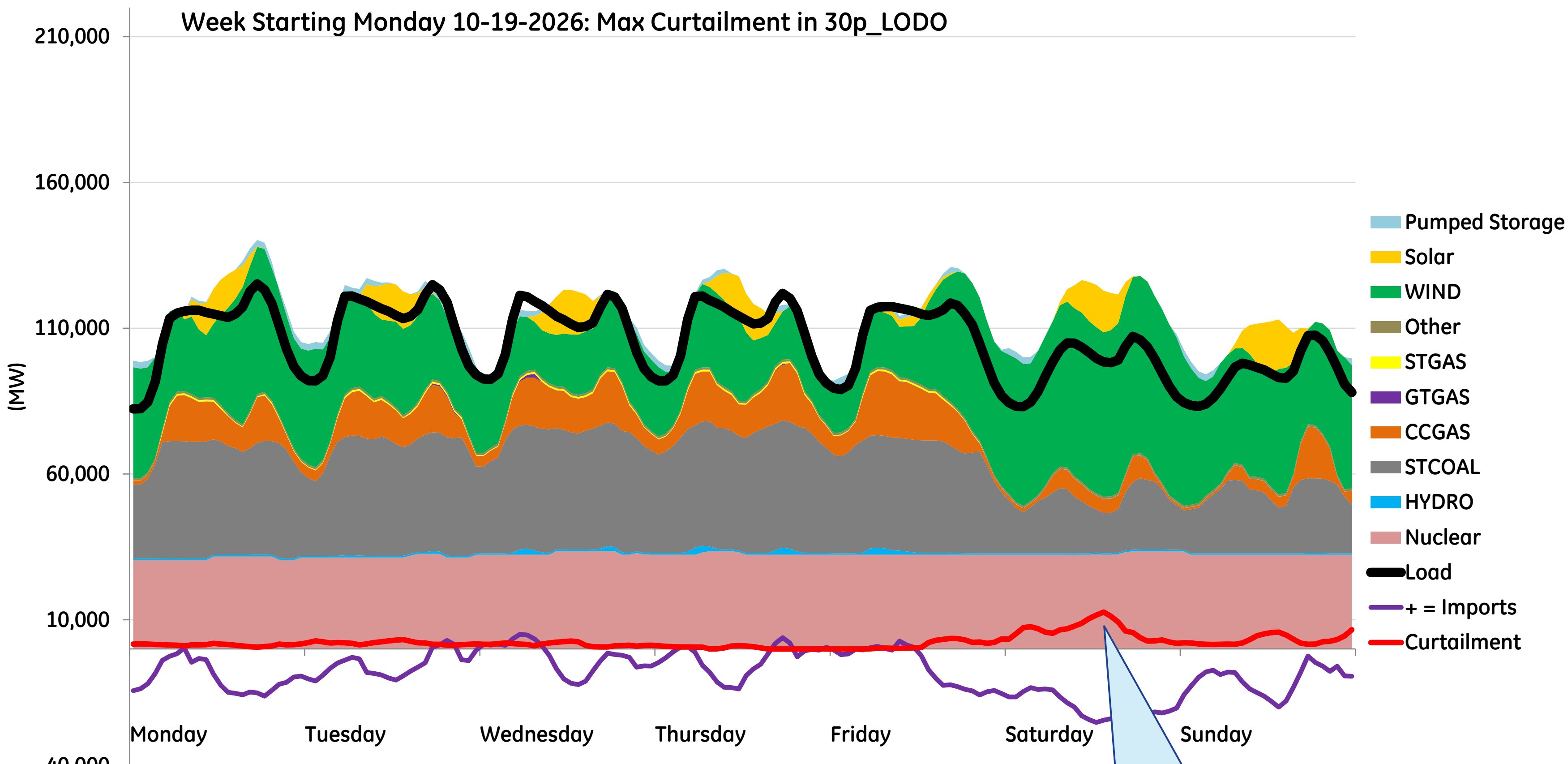
Week of Maximum Curtailment



LODO's highest curtailment is less than either of HOBO and LOBO

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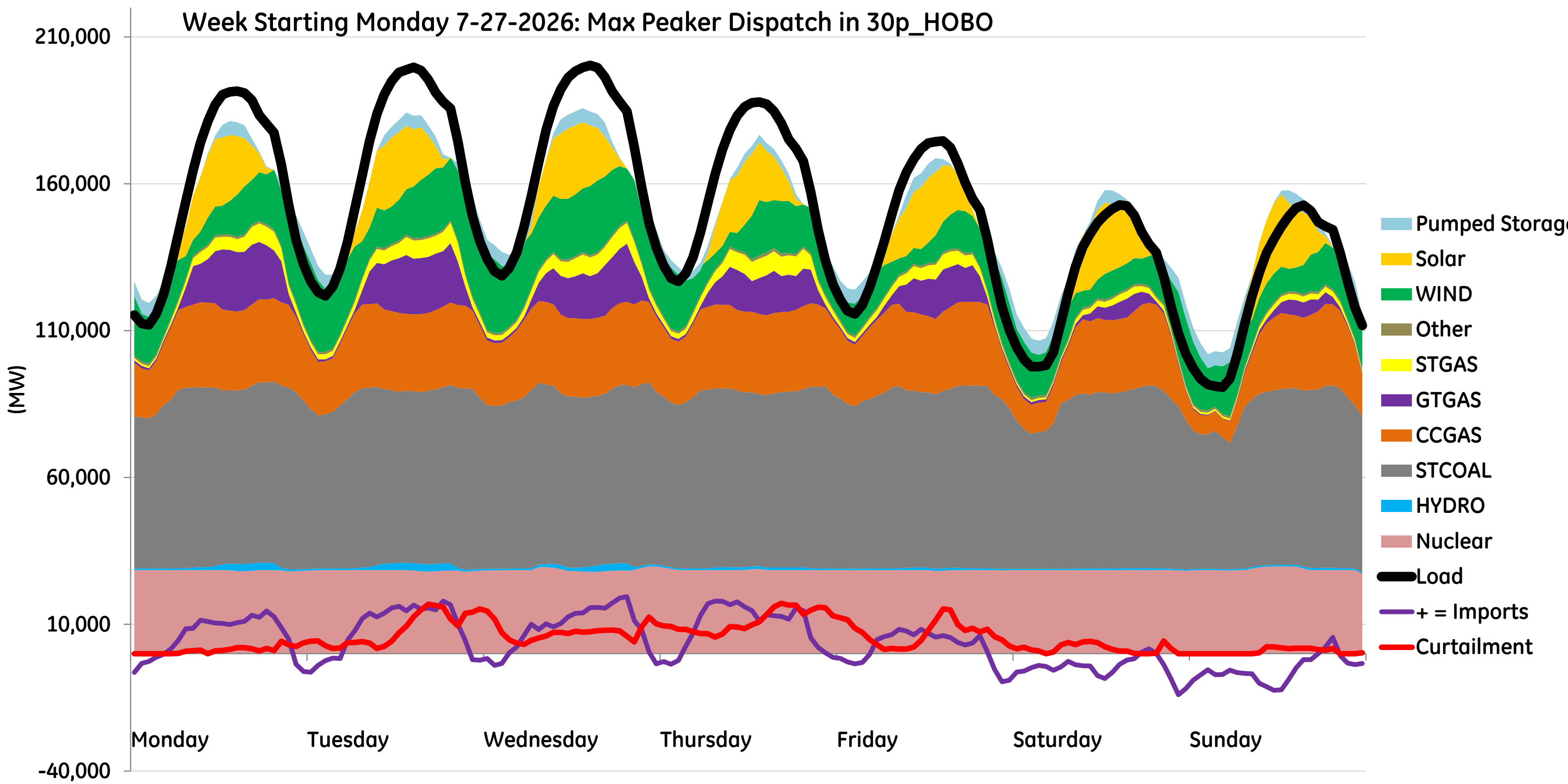
Week of Maximum Peaker Dispatch



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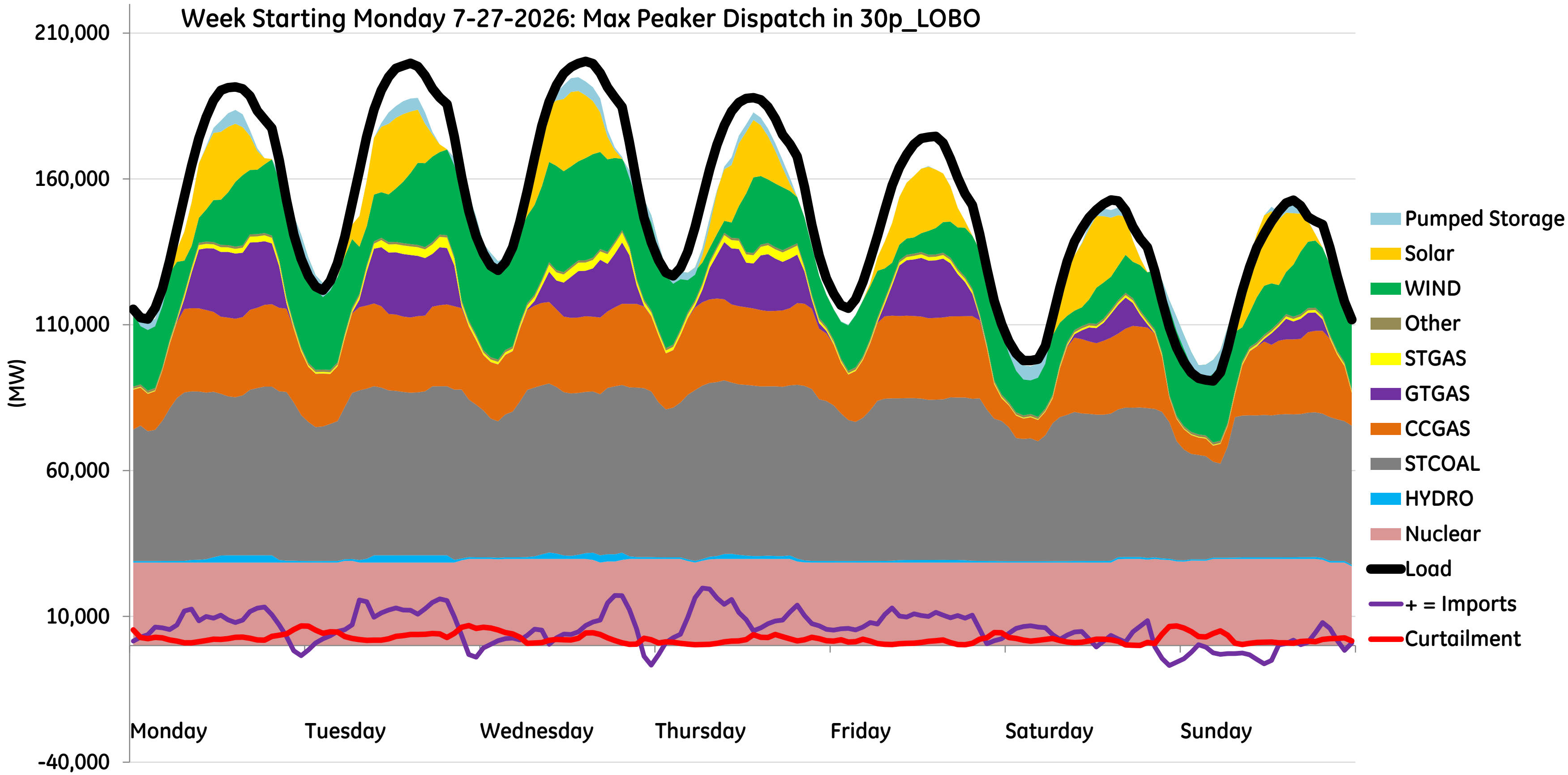
Week of Maximum Peaker Dispatch



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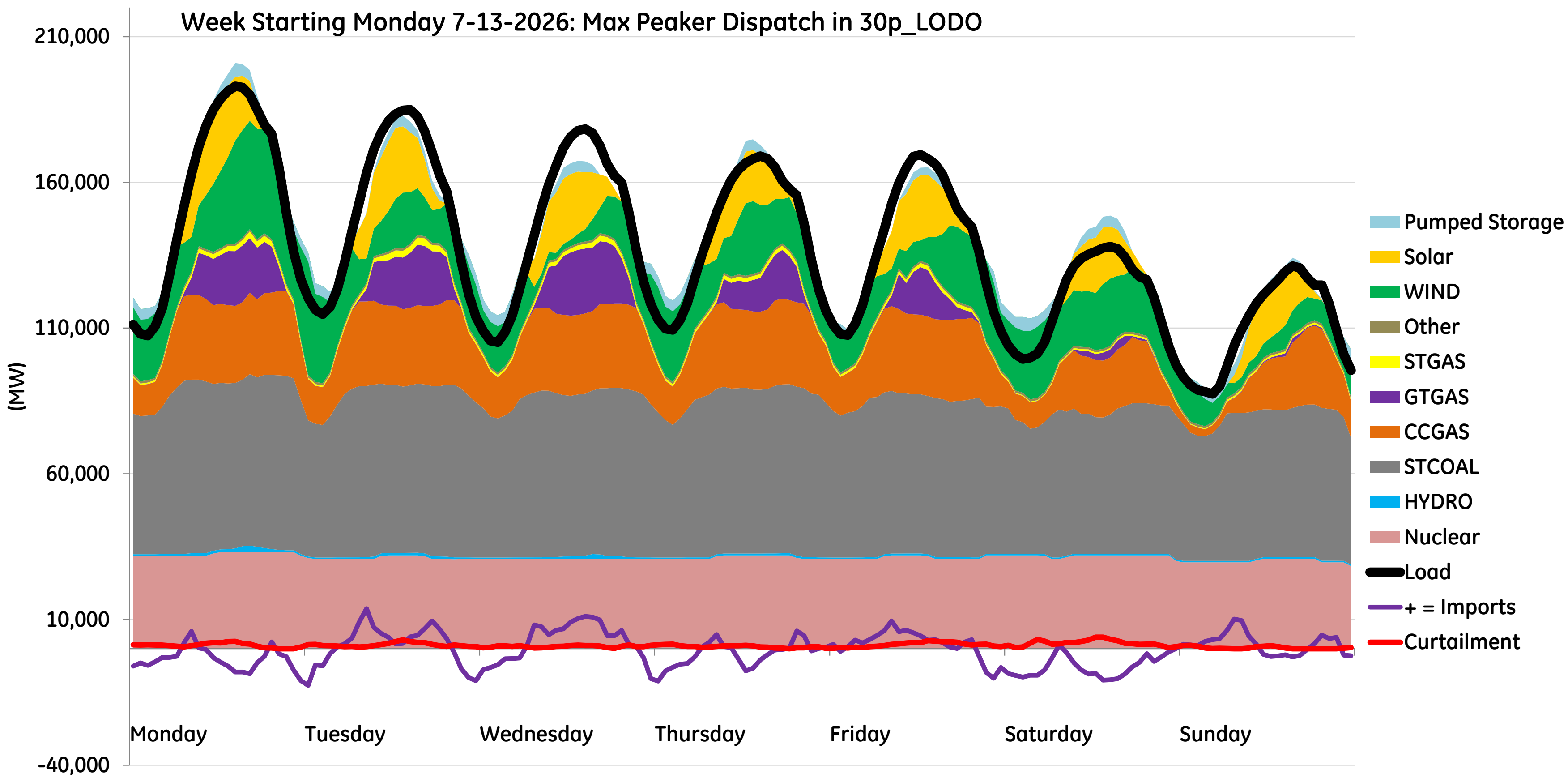
Week of Maximum Peaker Dispatch



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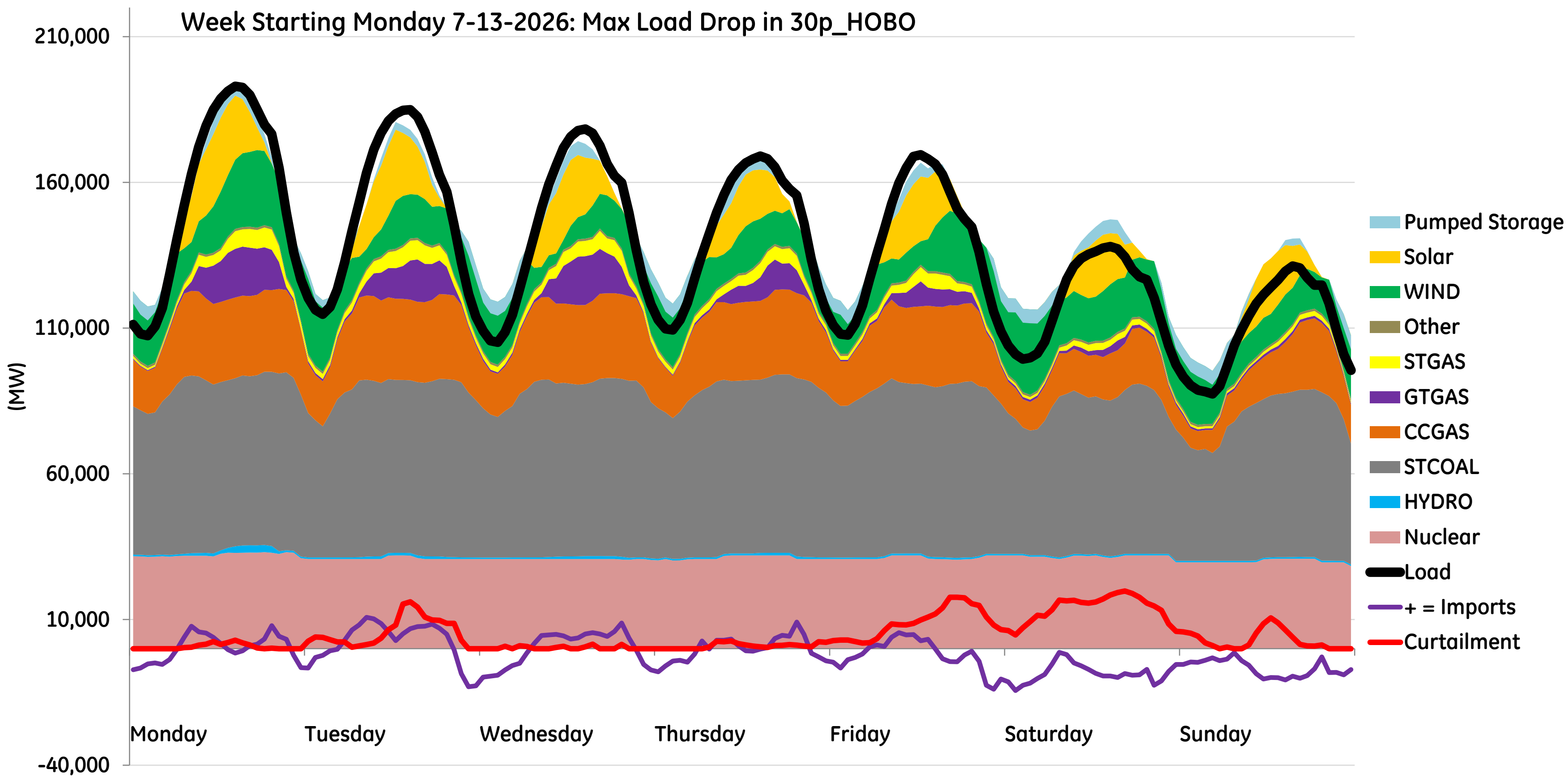
Week of Maximum Load Drop



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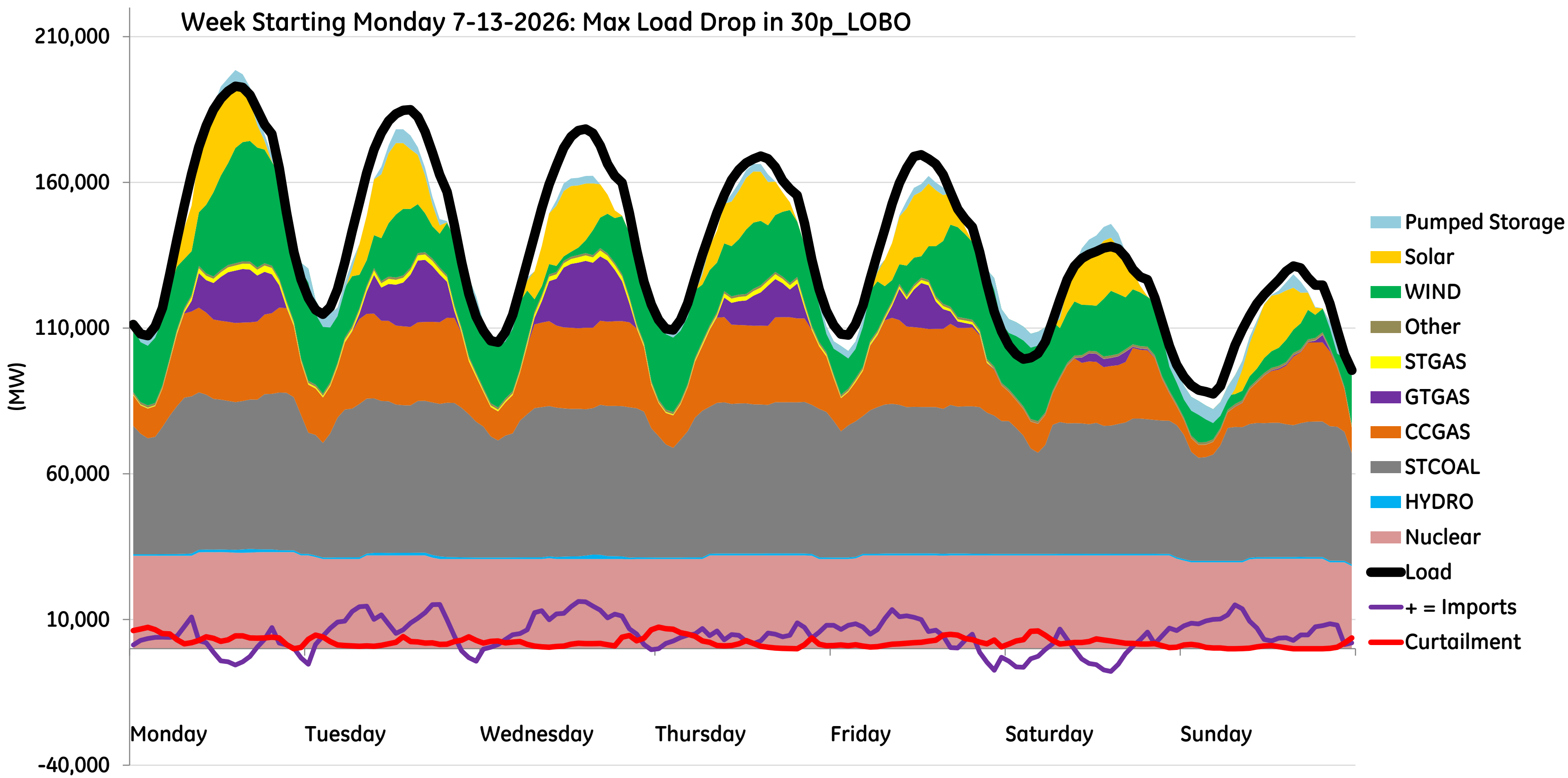
Week of Maximum Load Drop



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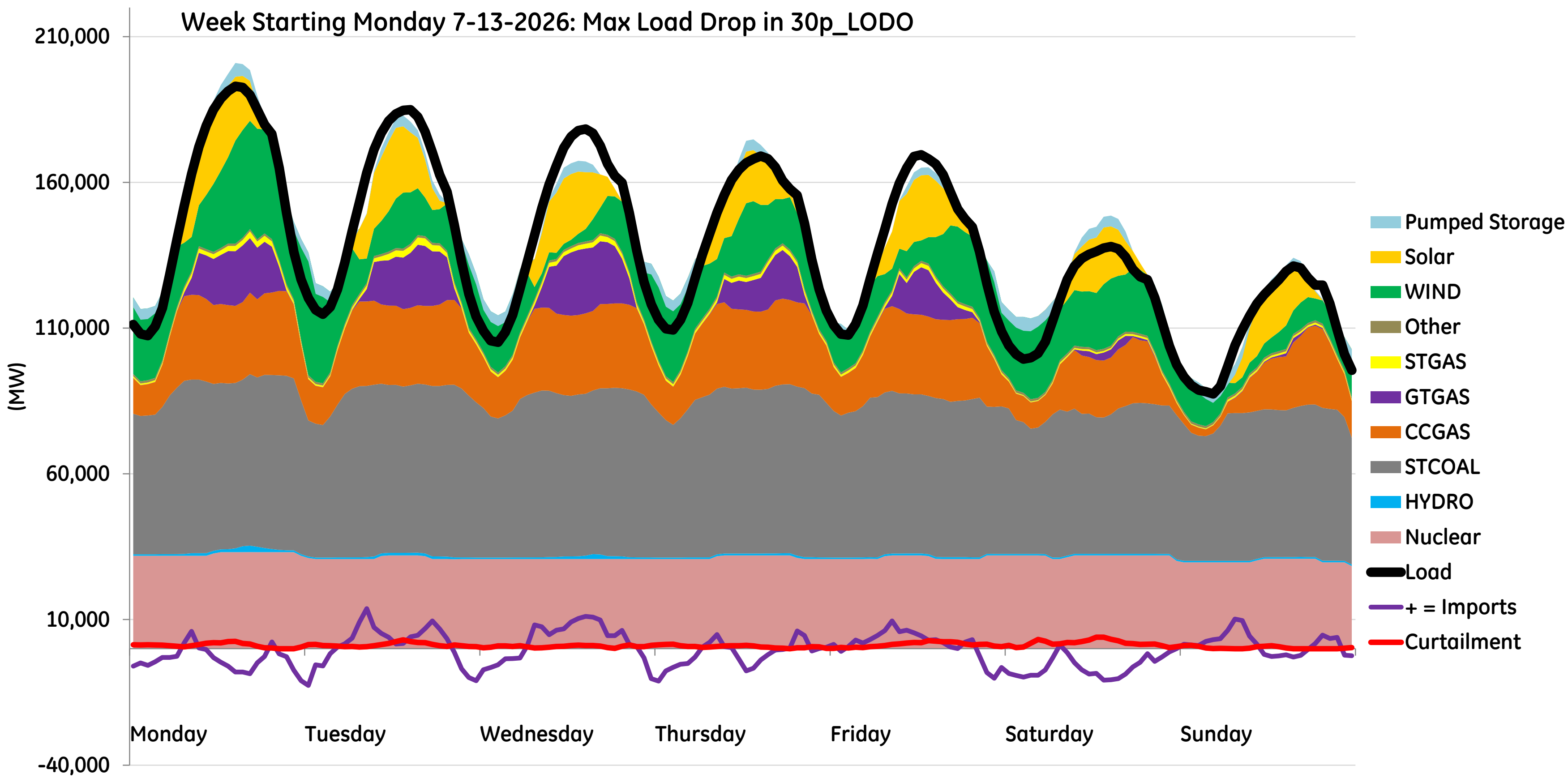
Week of Maximum Load Drop



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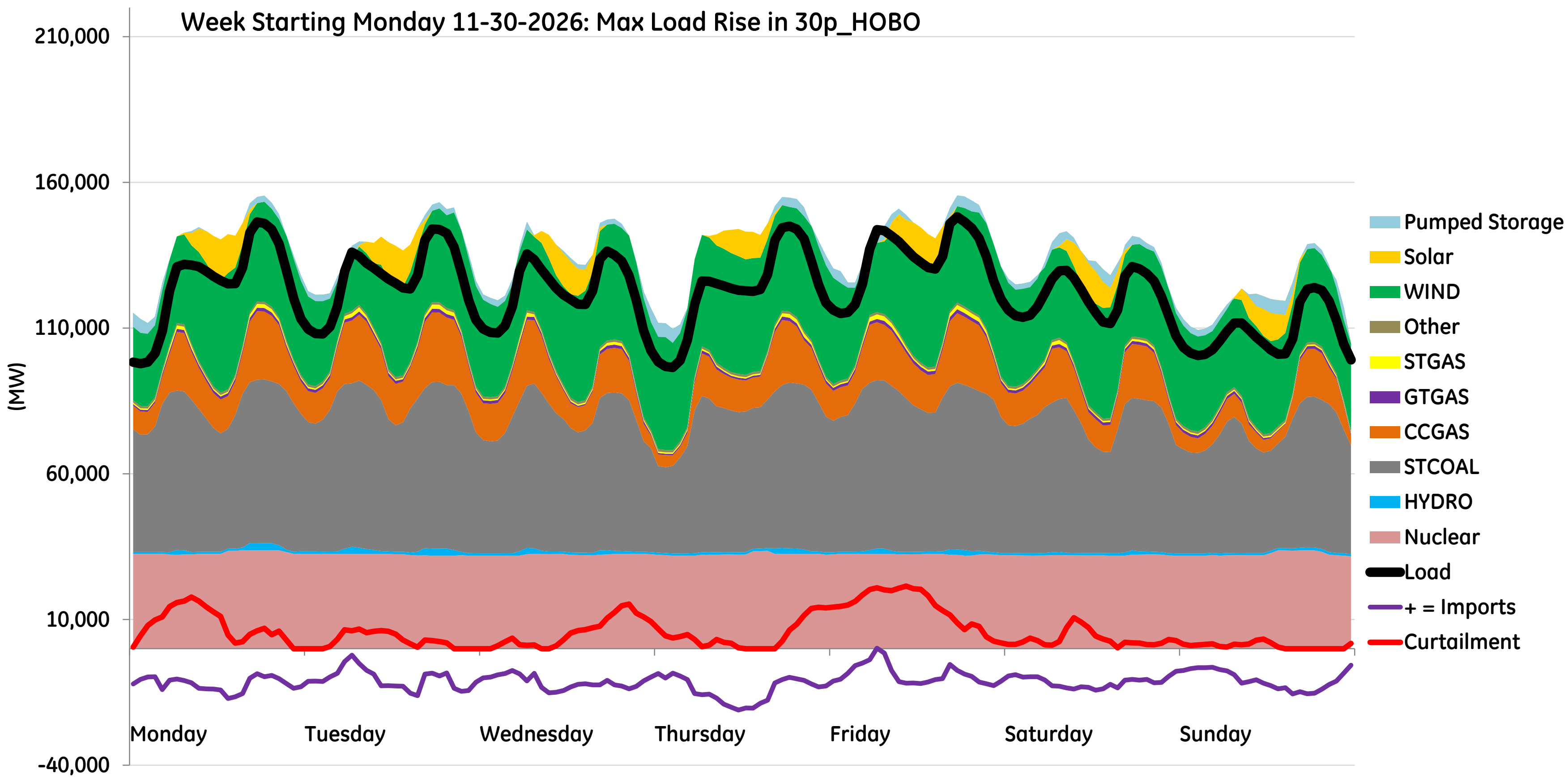
Week of Maximum Load Rise



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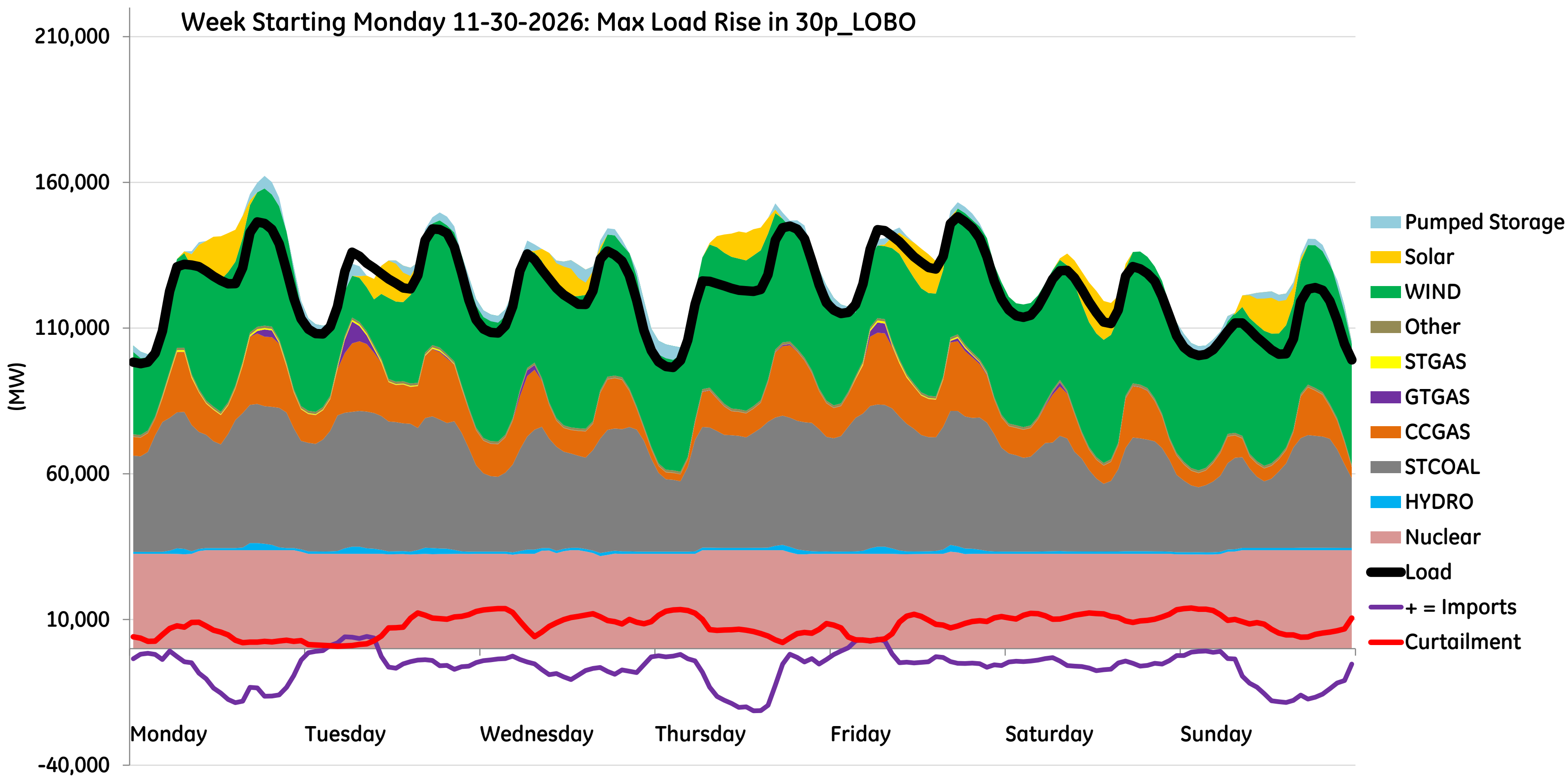
Week of Maximum Load Rise



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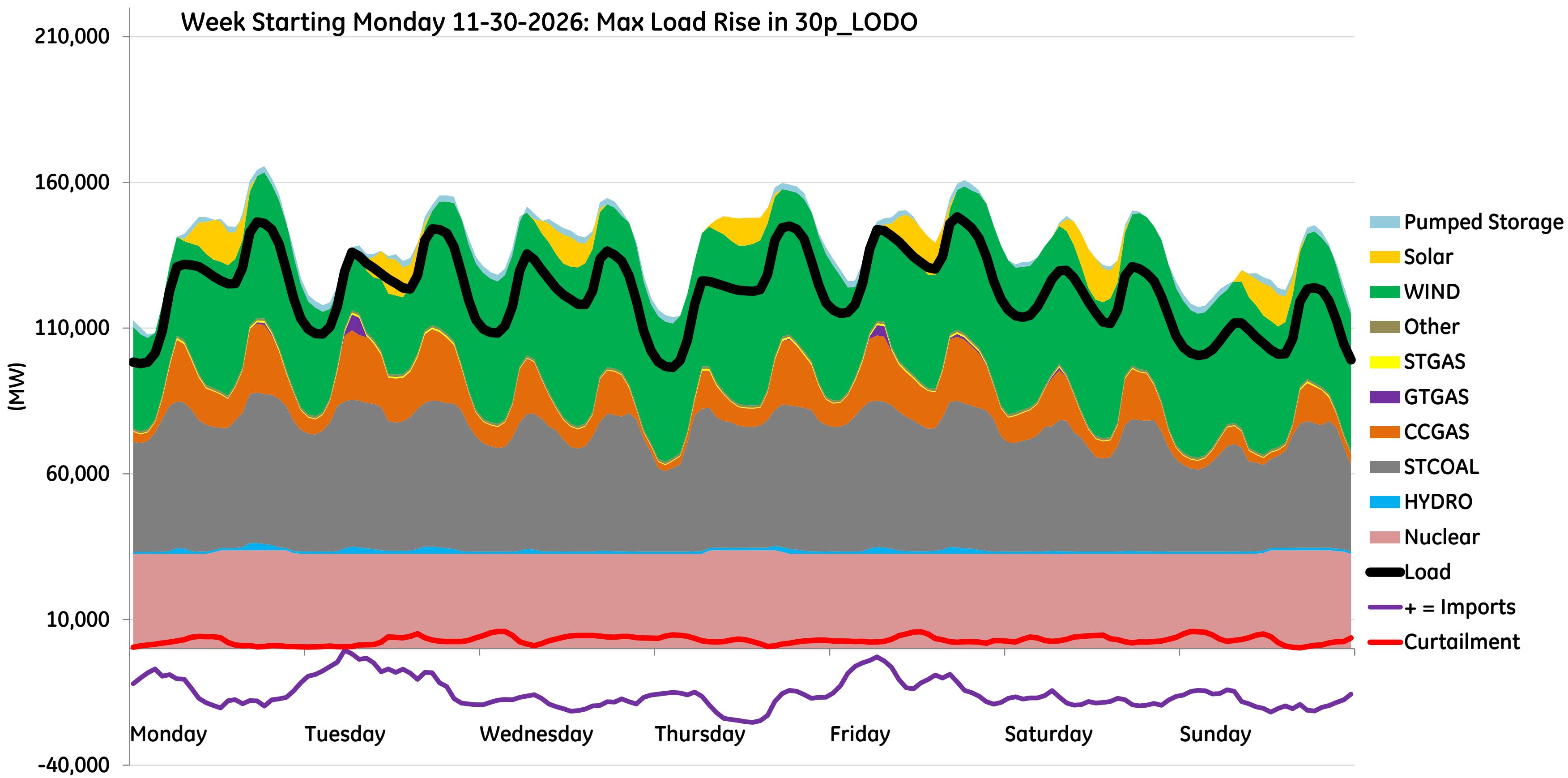
Week of Maximum Load Rise



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