Solar Integration into the PJM Grid

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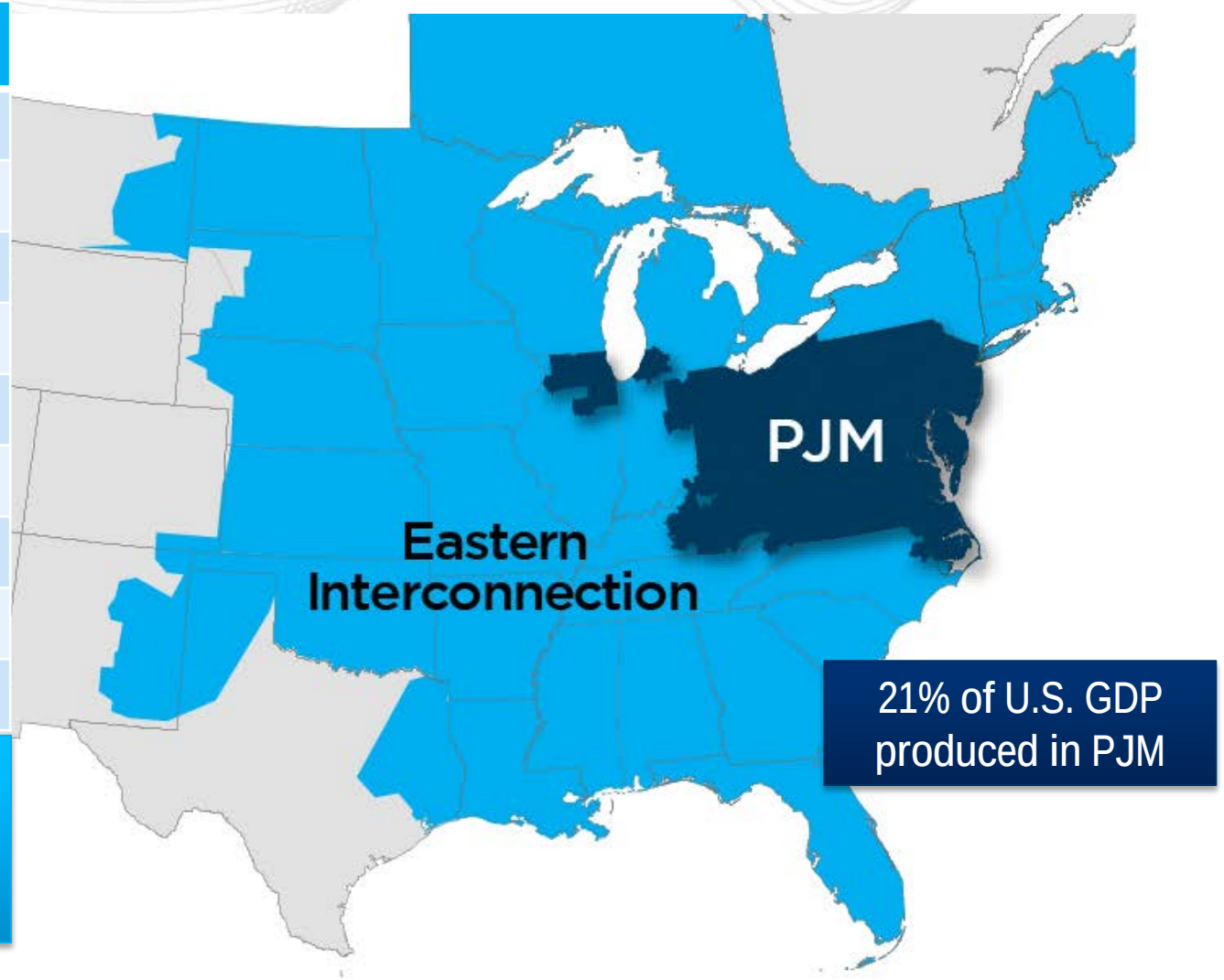
- PJM Background
- PJM Initiatives to Address Impacts
- Analysis of Impacts of Increasing Solar
  - PJM Renewable Integration Study
  - Long Term Forecast of Solar PV
- Evolving Solar Grid Interconnection Standards
- Solar Eclipse – Lessons Learned

PJM as Part of the Eastern Interconnection

Key Statistics

Member companies	1,000+
Millions of people served	65
Peak load in megawatts	165,492
MW of generating capacity	176,569
Miles of transmission lines	82,546
2016 GWh of annual energy	792,314
Generation sources	1,304
Square miles of territory	243,417
States served	13 + DC

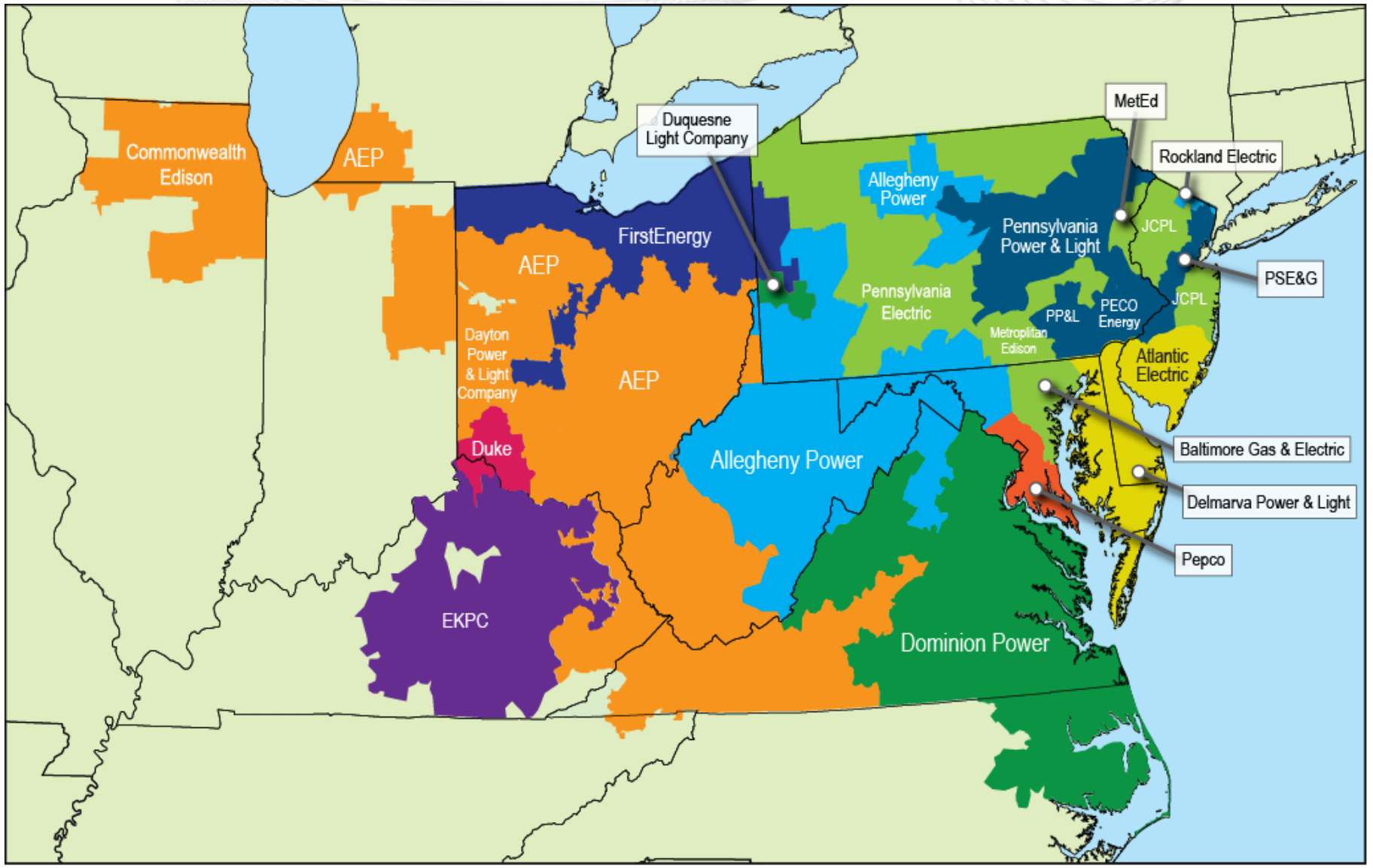
- 27% of generation in Eastern Interconnection
- 28% of load in Eastern Interconnection
- 20% of transmission assets in Eastern Interconnection



As of 2/2017

PJM Evolution

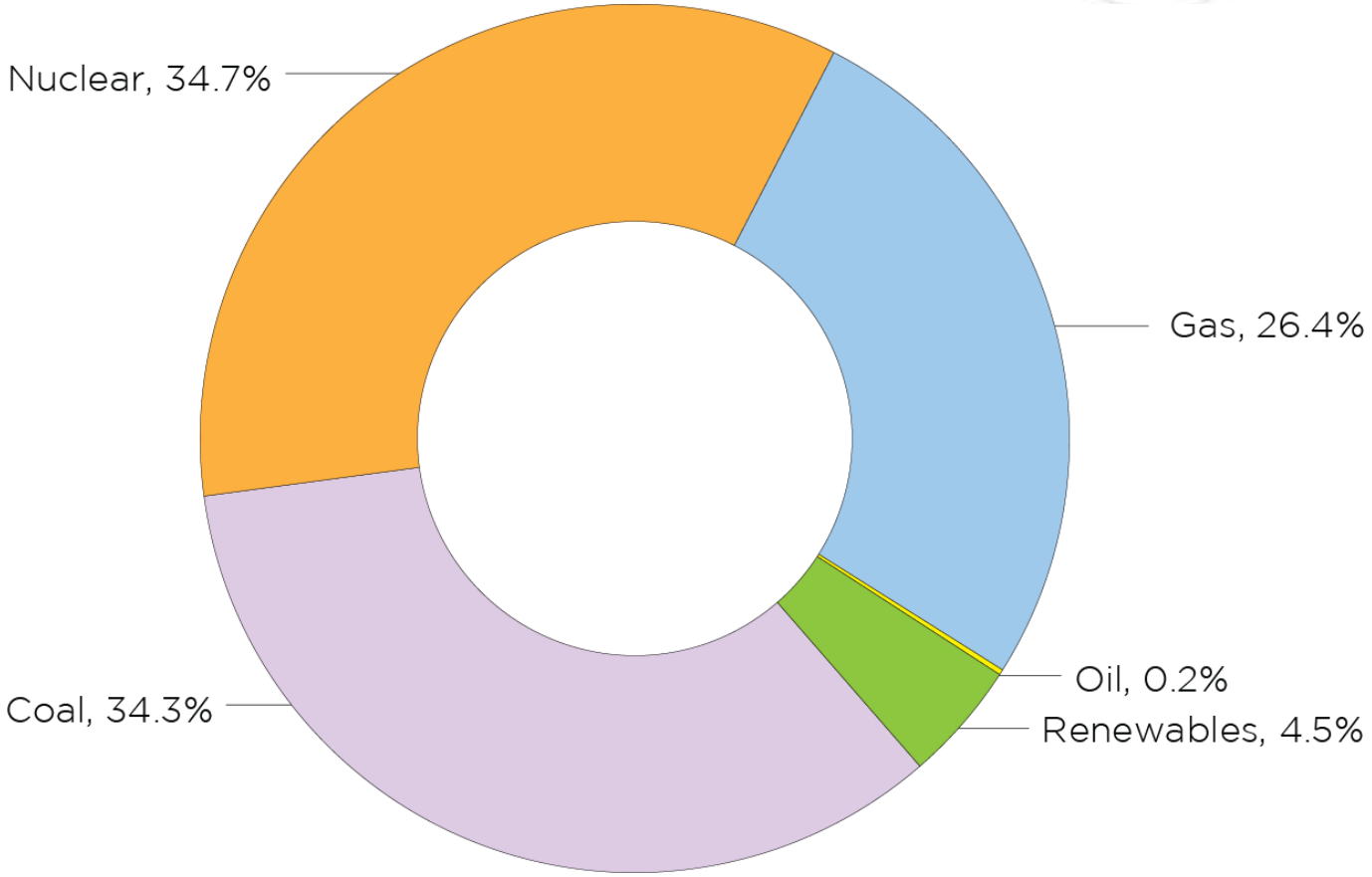
- Joined in 1927
- Joined in 1956
- Joined in 1965
- Joined in 1981
- Joined in 2002
- Joined in 2004
- Joined in 2005
- Joined in 2011
- Joined in 2012
- Joined in 2013

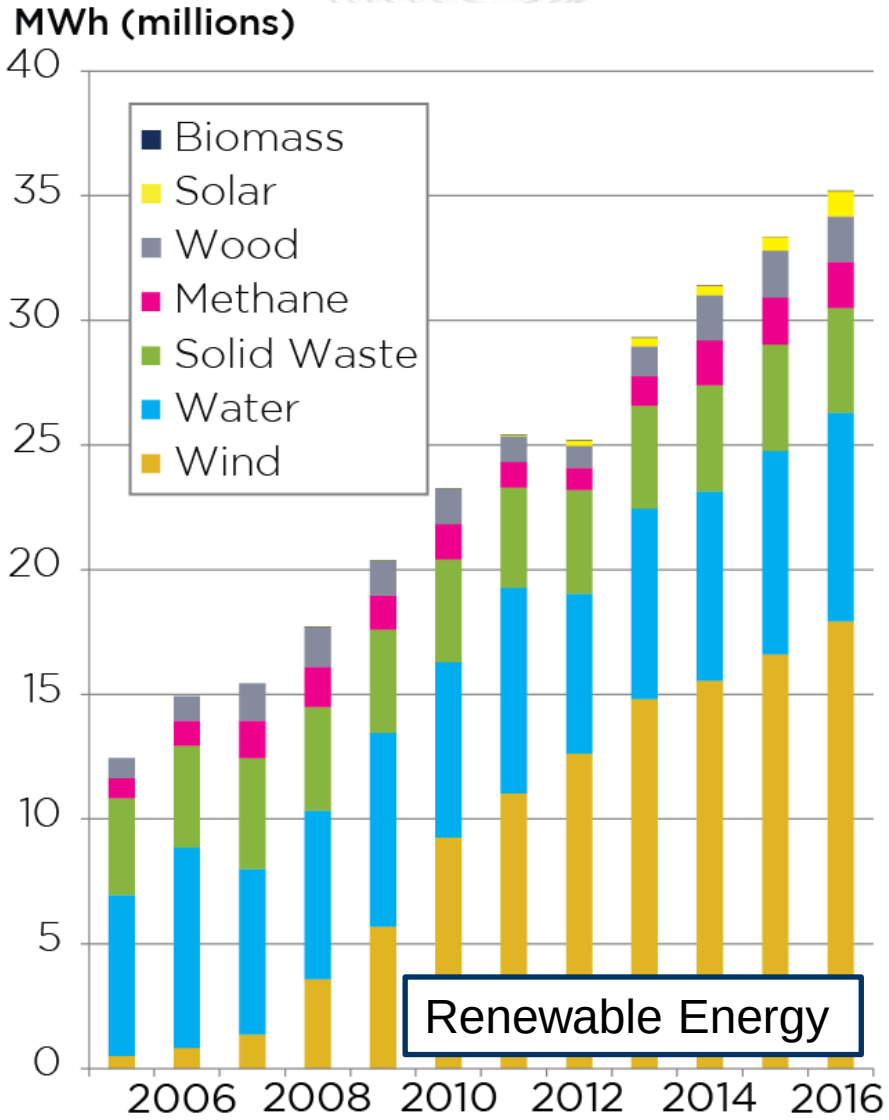


PJM – Focus on Just 3 Things

Percentage of Renewable Energy is Small but Growing

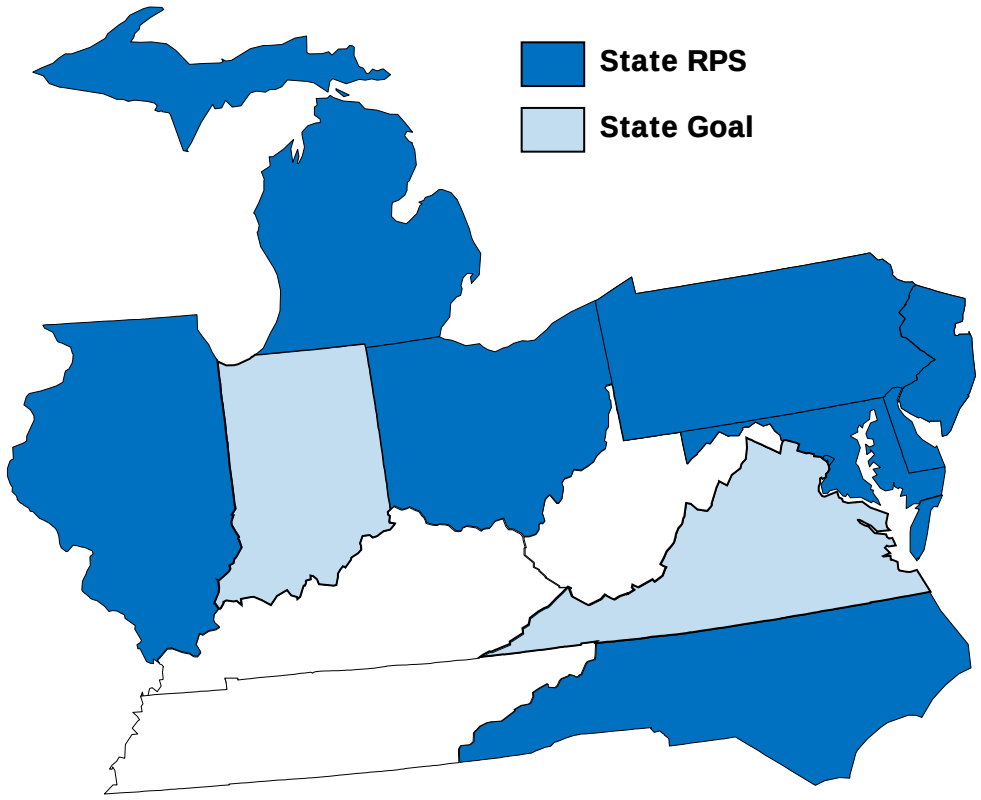
PJM Generation Mix – 2016 Annual Energy





PJM States with RPS

State Renewable Portfolio Standards (RPS) require suppliers to utilize wind and other renewable resources to serve an increasing percentage of total demand.



DSIRE: www.dsireusa.org August 2017

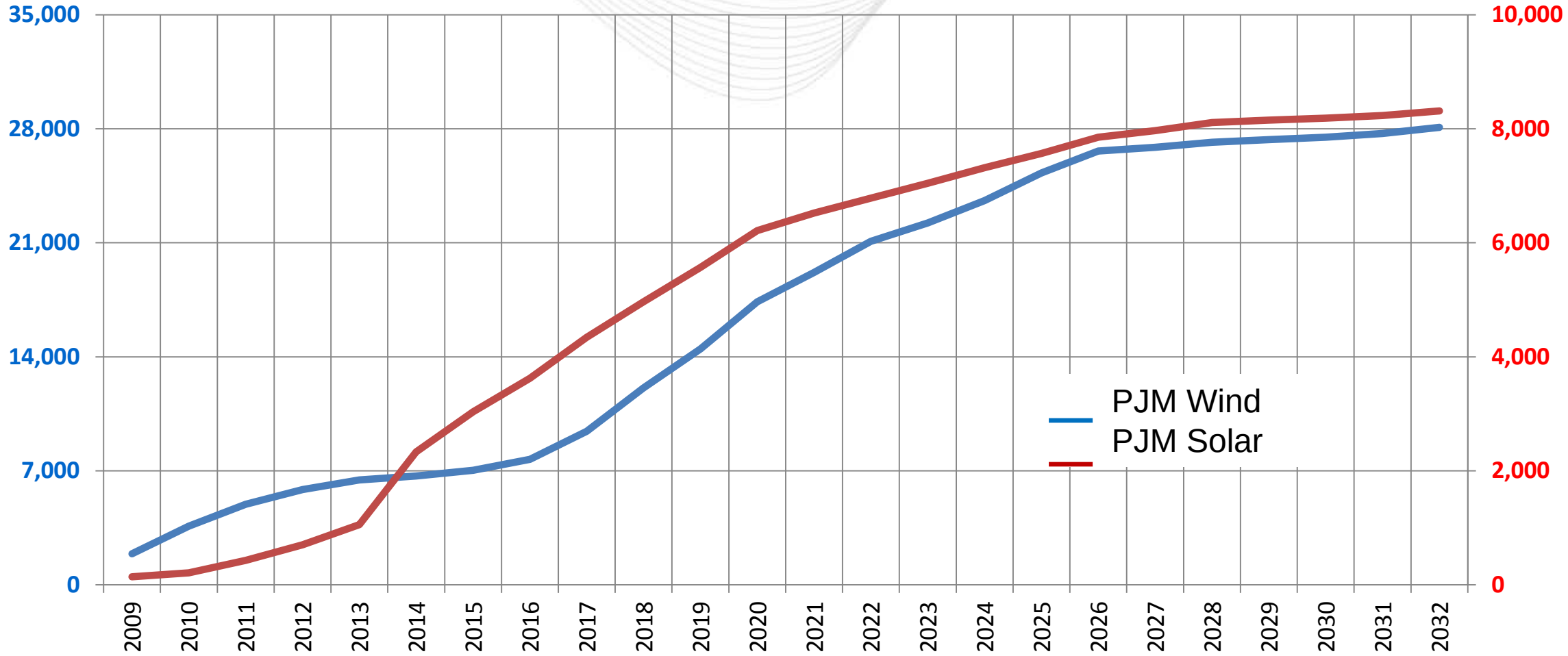
State RPS Targets

- ☼ NJ: 20.38% by 2021
- ☼ MD: 25% by 2020
- ☼ DE: 25% by 2026
- ☼ DC: 50% by 2032
- ☼ PA: 18%** by 2020
- ☼ IL: 25% by 2026
- ☼ OH: 12.5% by 2026
- ☼ NC: 12.5% by 2021 (IOUs)
- MI: 10% + 1,100 MW by 2015
- VA: 15% by 2025
- IN: 10%** by 2025

☼ Minimum solar requirement
** Includes non-renewable “alternative” energy resources

Projected Renewable Energy Requirements

117 GWhs of Energy (**13.8%** of PJM load) by 2032; **28 GW** of Wind, **8 GW** of Solar



Impacts due to **variability** and **uncertainty**:

- **Minute-to-Minute**
  - Additional generation needed to provide regulation
- **Intra-Hour**
  - Conventional generators must adjust output
- **Day Ahead**
  - Forecast errors cause over- or under-scheduling

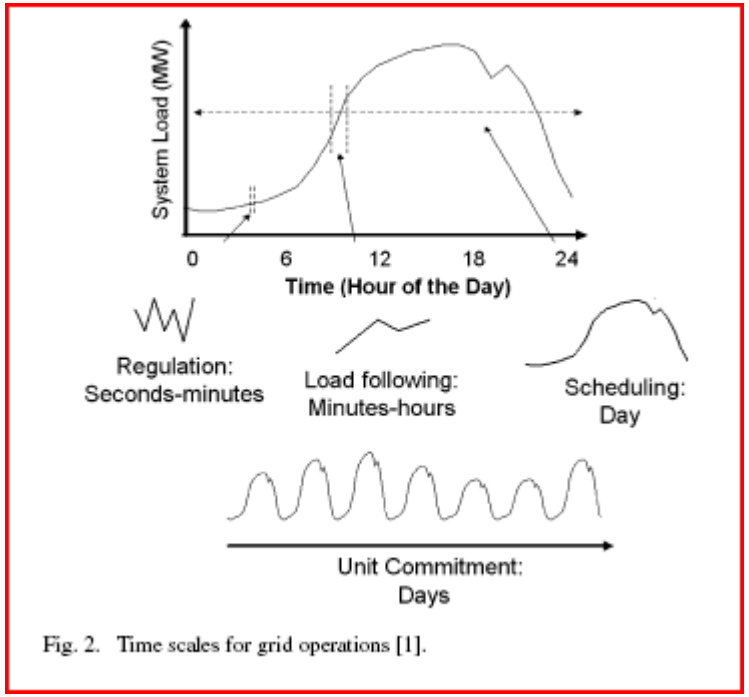


Fig. 2. Time scales for grid operations [1].

Regional markets reduce Variable Energy Resource integration costs

Characteristic	Impact to Integration Cost
Larger balancing areas	• Reduces overall increase in variability • Less regulation and ramping service required
Faster markets, i.e., shorter scheduling intervals (5-15 minutes)	• Less regulation required to accommodate intra-hour variations
Larger geographic area	• Increases weather diversity and reduces overall variability
Centralized wind and solar power forecasting	• Cost-effective approach to reduce scheduling impacts
Regional / Interregional Transmission Planning	• Cost-effective upgrades to ensure grid reliability and mitigate congestion

PJM Initiatives to Address Impacts

Energy Markets / Operations

- Implemented a centralized wind power forecast service
- Solar power forecast is in progress
- Implemented changes to improve wind resource dispatch / control
- Demand Response / Price Responsive Demand improves operational flexibility
- Frequency Regulation – “pay for performance” rewards better performing resources (like storage)
- Interchange Scheduling – compliant with FERC Order 764 (15-minute intervals)

Transmission Planning

- Light load criteria implemented to improve grid reliability
- Expansion planning considers public policy impacts (i.e., RPS)
- Grid interconnection – enhanced standards for new inverter-based resources (wind and solar)

Evaluating Potential Grid Impacts

- PJM Renewable Integration Study (PRIS) - assessed grid impacts

Advanced Technology Research Program (ATRP)

- Pilot programs to evaluate new technologies and remove barriers to participation in PJM markets and operations.

PJM Renewable Integration Study

PJM Renewable Integration Study (PRIS) Project Team

- GE Energy Consulting – overall project leadership, production cost and capacity value analysis
- AWS Truepower – development of wind and solar power profile data
- EnerNex – statistical analysis of wind and solar power, reserve requirement analysis
- Exeter Associates – review of industry practice/experience with integration of wind/solar resources
- Intertek Asset Integrity Management (Intertek AIM), formerly APTECH – impacts of increased cycling on thermal plant O&M costs and emissions
- PowerGEM – transmission expansion analysis, simulation of sub-hourly operations and real-time market performance

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

Hourly Analysis Key Findings

- 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

* 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.

Renewables and the Regulation Requirement

PJM Renewable Integration Study shows a need for regulation reserves to increase under all scenarios, especially under High Solar scenarios.

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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Primary Study Recommendations

- **Adjustments to Regulation Requirements**
  - *Develop a method to determine regulation requirements based on forecasted levels of wind and solar production. Day-ahead and shorter term forecasts could be used for this purpose.*
- **Renewable Energy Capacity Valuation**
  - *Consider an annual or bi-annual application of ELCC methodology in order to calibrate PJM's renewable capacity valuation methodology in order to occasionally adjust the applicable capacity valuation of different classes of renewable energy resources in PJM.*
- **Mid-Term Commitment & Better Wind and Solar Forecast**
  - *Consider using a mid-range wind and solar forecast in real-time operations to update the commitment of intermediate units (such as combined cycle units that could start in a few hours). This would result in less reliance on higher cost peaking generation.*
- **Exploring Improvements to Ramp Rate Performance**
  - *Explore the reasons for ramping constraints on specific units, determine whether the limitation are technical, contractual, or otherwise, and investigate possible methods for improving ramp rate performance.*

Incorporating Solar in PJM Long-Term Load Forecast

RPS and NEM Policy Assumptions by State

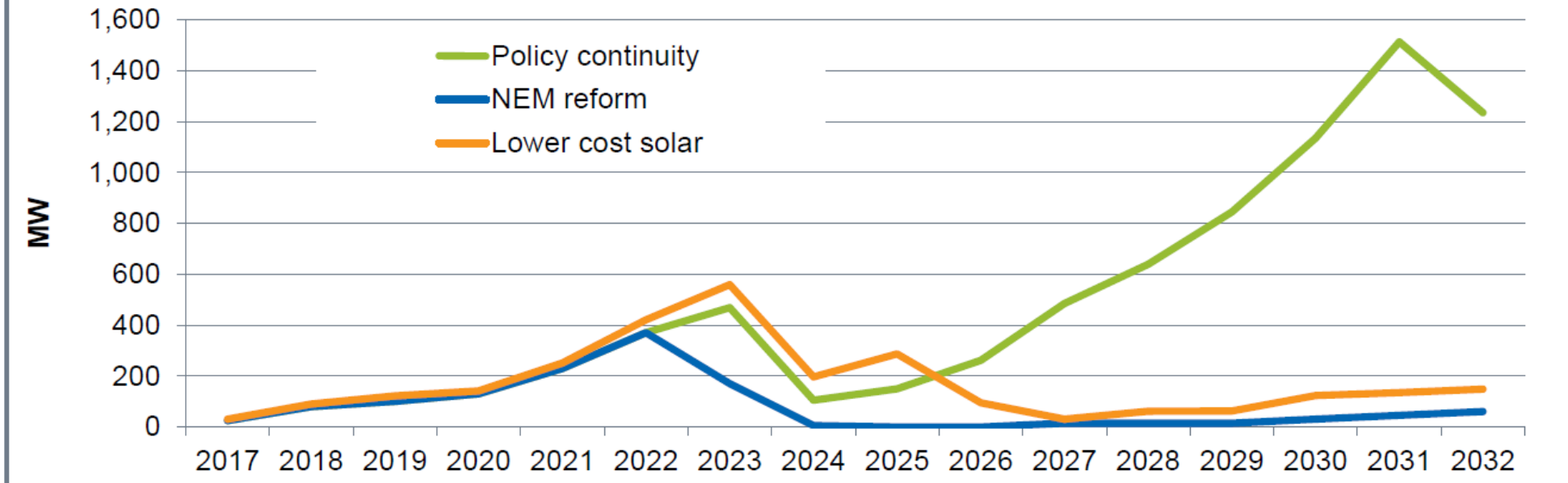
Current RPS and NEM policy by state

State	RPS target (% of retail sales)*	Solar carve-out (% of retail sales)	NEM Cap (% or capacity)	NEM System Size Limits by Segment (MW)	NEM Remuneration	NEG Remuneration
DE	24% by 2026	3.5% by 2026	5% of aggregated customer peak demand	Residential: 0.025 MW Non-residential (Delmarva): 2 MW, Non-residential: (DEC): 0.5 MW	Full retail rate	Full retail rate
DC	50% by 2032	5% by 2032	N/A	1.00	Full retail rate	Full retail rate
MD	25% by 2020	2.5% by 2020	1500 MW	2.00	Full retail rate	Full retail rate
NJ	22% by 2028; state Senate has passed an increase to 83% by 2050	4.1% by 2028	2.9% of retail sales	100% of customer load	Full retail rate	Full retail rate
OH	13% by 2026	0.5% by 2026	N/A	Not specified, must be sized to fit customer load	Full retail rate	Less than retail
PA	8% by 2021	0.5% by 2021	N/A	Residential: .050 MW Non-Residential: 3 MW	Full retail rate	Full retail rate
WV	-	-	3% of peak demand during previous year	Residential: 0.025 MW, Industrial (for large IUOs): 2 MW Commercial (for large IUOs): 0.5 MW, C&I (for small IOUs): 0.5 MW	Full retail rate	Full retail rate
IN	-	-	1% of utility's summer peak load	1.00	Less than retail after 2022	Full retail rate
IL	25% by 2026	1.5% by 2026	5% of utility's peak load in prior year	2.00	Full retail rate	Full retail rate
KY	-	-	1% of utility peak load in prior year	0.03	Full retail rate	Full retail rate
MI	10% by 2015	-	0.75% of prior year peak load	0.15	Full retail rate	Full retail rate
NC	12% by 2021	0.2% by 2020	N/A	1.00	Full retail rate	Full retail rate
VA	15% by 2025 (voluntary target)	-	1% of state's peak load for prior year	Residential: .020 MW Non-residential: 1 MW	Full retail rate	Full retail rate
TN	-	-	N/A	N/A	N/A	N/A

Source: IHS Markit

Pennsylvania solar PV capacity additions by scenario and segment

Annual additions by scenario



Source: IHS

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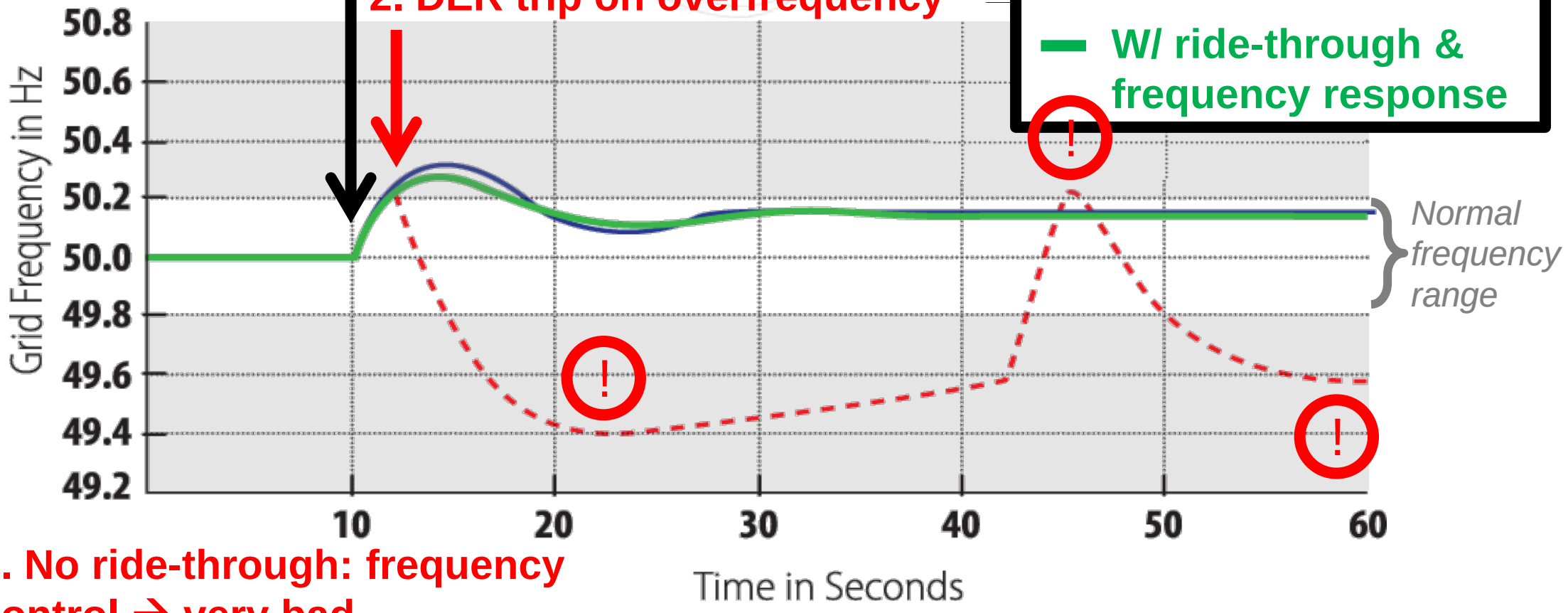
Evolving Grid Interconnection Standards

After contingencies: it is bad if generators trip offline. Germany case.

1. Bad fault→lots of load shed→frequency rise

2. DER trip on overfrequency



3. No ride-through: frequency control → very bad.

Current PJM "Enhanced Inverter" Requirements

- **Applicability**: "non-synchronous" generators that entered the New Service Queue on or after May 1, 2015 (AB1 queue or later) that sign an Interconnection Services Agreement
  - Distribution-connected units that sign "WMPAs" are not subject to PJM's requirements for interconnection.
- **Required functionality**:
  - **Ride through** (mandatory) of abnormal voltage and frequency according to NERC PRC-024
  - **Voltage regulation** (capability) 0.95 leading/lagging measured at high side of facility substation transformers (or measured at the generator's terminals if entered queue prior to Nov 1, 2016 as per FERC Order 827).
  - **Ramp limit** (capability)
  - **Frequency response** (capability) (underfrequency: if available)

Requirements of 1547 revision

- **Applicability:** future: possibly certain state-jurisdictional and FERC-jurisdictional DER.
- **Requirements**
  - **Ride-through** (mandatory) of voltage & frequency
  - **Voltage regulation** (capability): fixed power factor, volt-var, watt-var, fixed reactive power, volt-watt
  - **Frequency response** (capability) (underfrequency: if available)
  - **Communications interface** (capability): SEP2, DNP3, or SunSpec Modbus
  - Enter service **ramp limit** (mandatory)

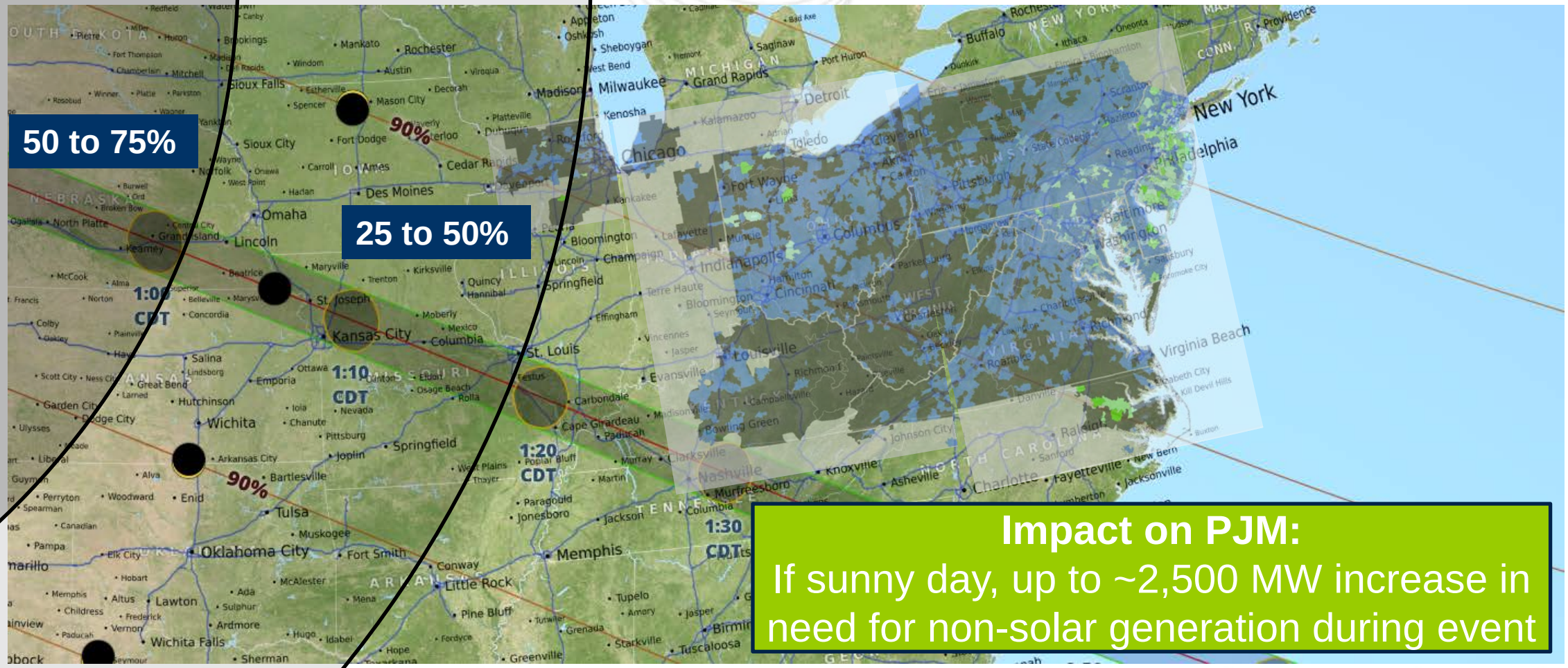
- 1547 revision: expected out in 2018.
- Test procedures (revised “1547.1”) published ~2019+. UL1741 after.
- Regulators or utilities together with NERC Reliability Coordinators (e.g., PJM) to specify 1547 categories and adjustments. Some time required.
- Where PJM cites to 1547 today (e.g., manual 14a), PJM may revise language in response to 1547 revision.

PJM Smart Inverter Technical Demonstrations

- Goal: refine recommended settings for PJM “enhanced inverter” requirements and for coordinating possible state-level ride-through requirements.
- Partnerships with several utilities in two states and one state commission.
- One or more smart inverter installations for testing of actual behavior to refine input for large-scale models. Test plan with most of the functions described in the 1547 revision.
- Large scale modeling in PSS/E of regional reliability impact/benefit of significant deployment of DER with vs. without ride through and voltage regulation.
- Documented results expected early next year.

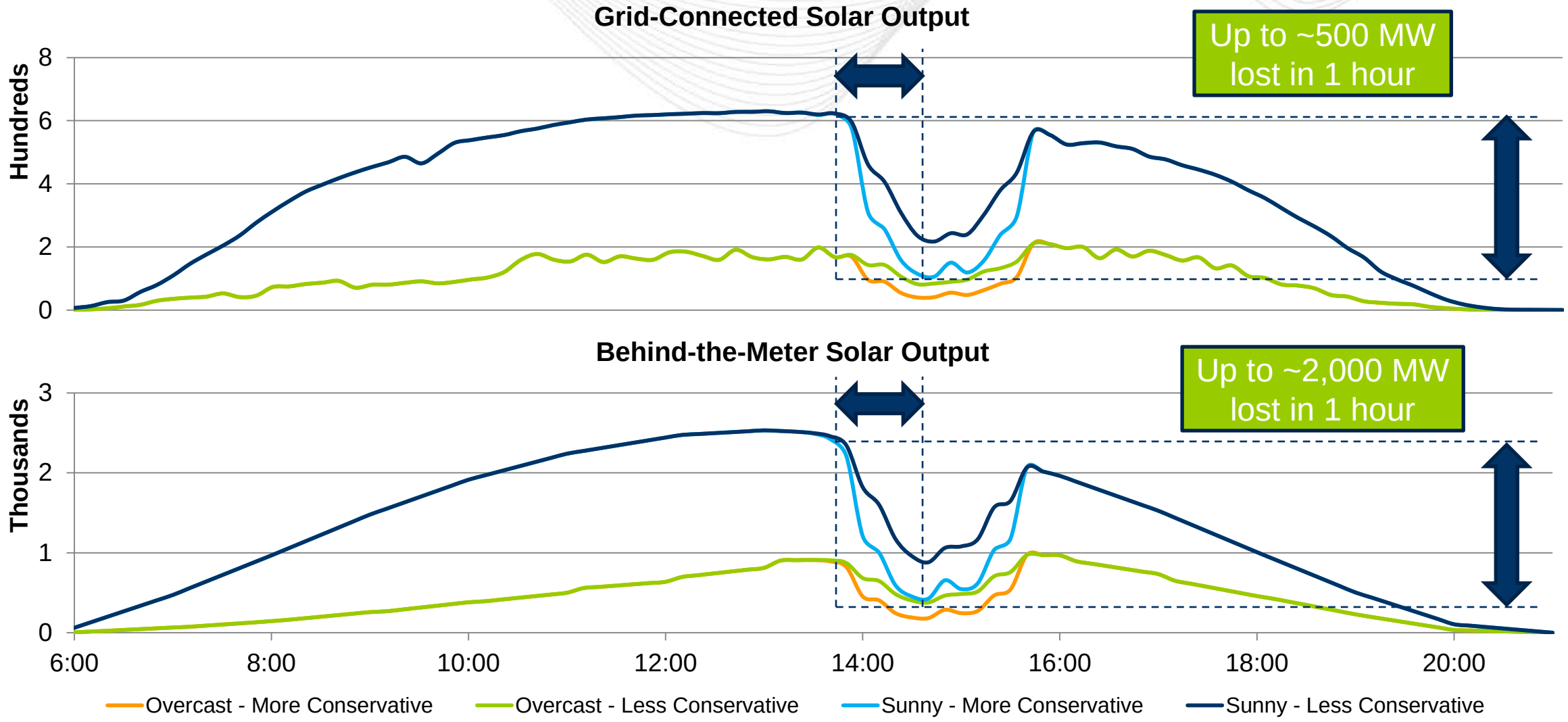
Solar Output During August 21, 2017 Total Solar Eclipse

13:30	13:40	13:50	14:00	14:10	14:20	14:30
14:40	14:50	15:00	15:10	15:20	15:30	15:40

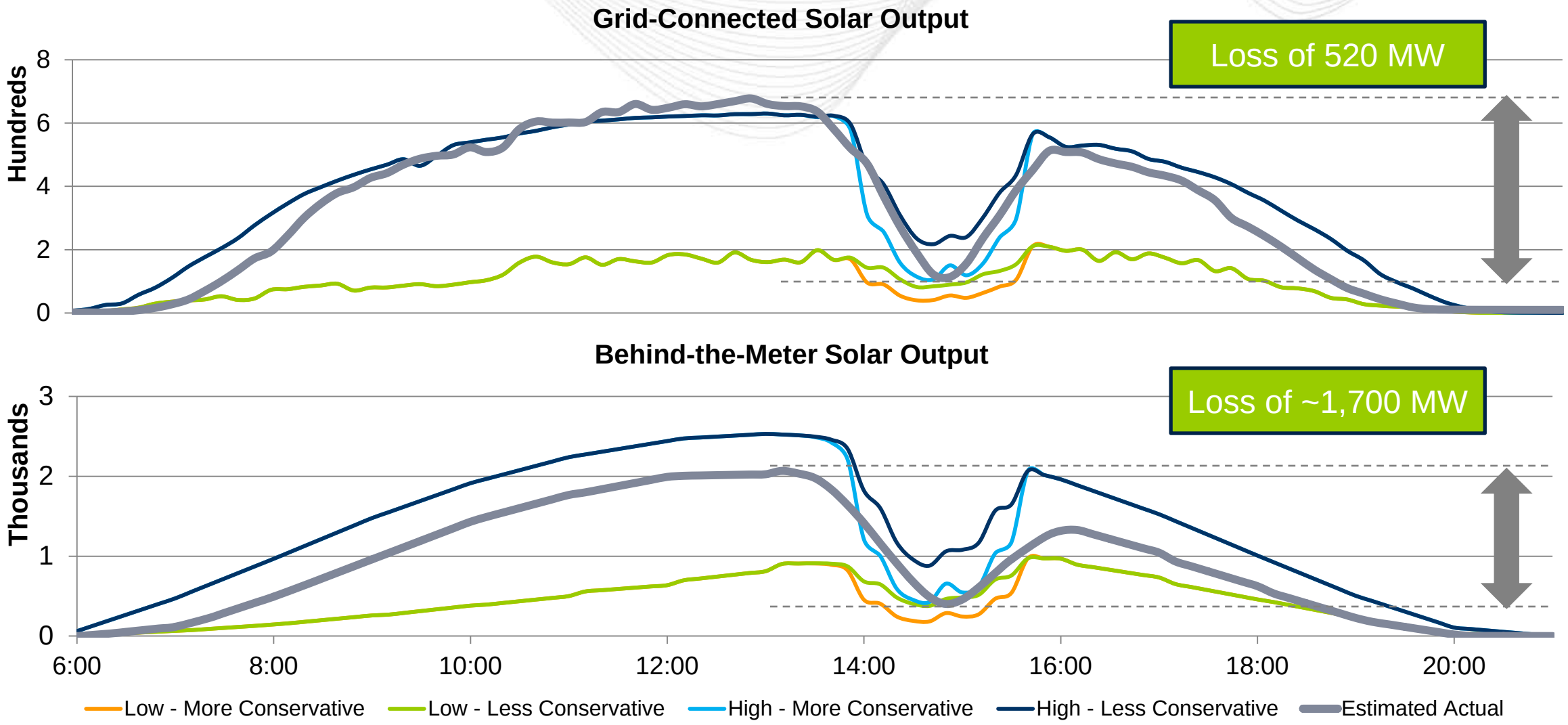


Source of eclipse map: NASA | Source of PJM solar map: PJM Environmental Information Services

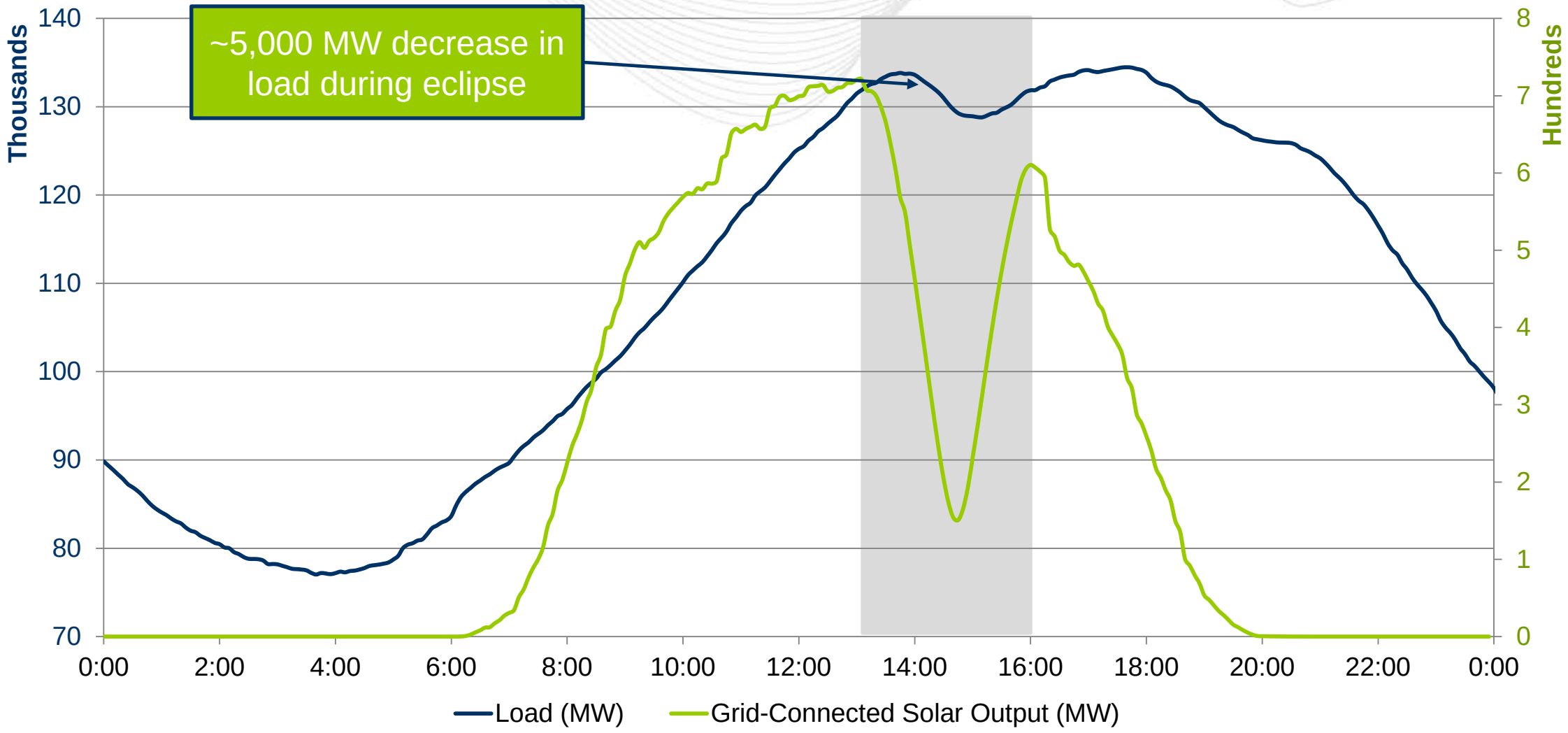
Estimated Solar Output on August 21, 2017



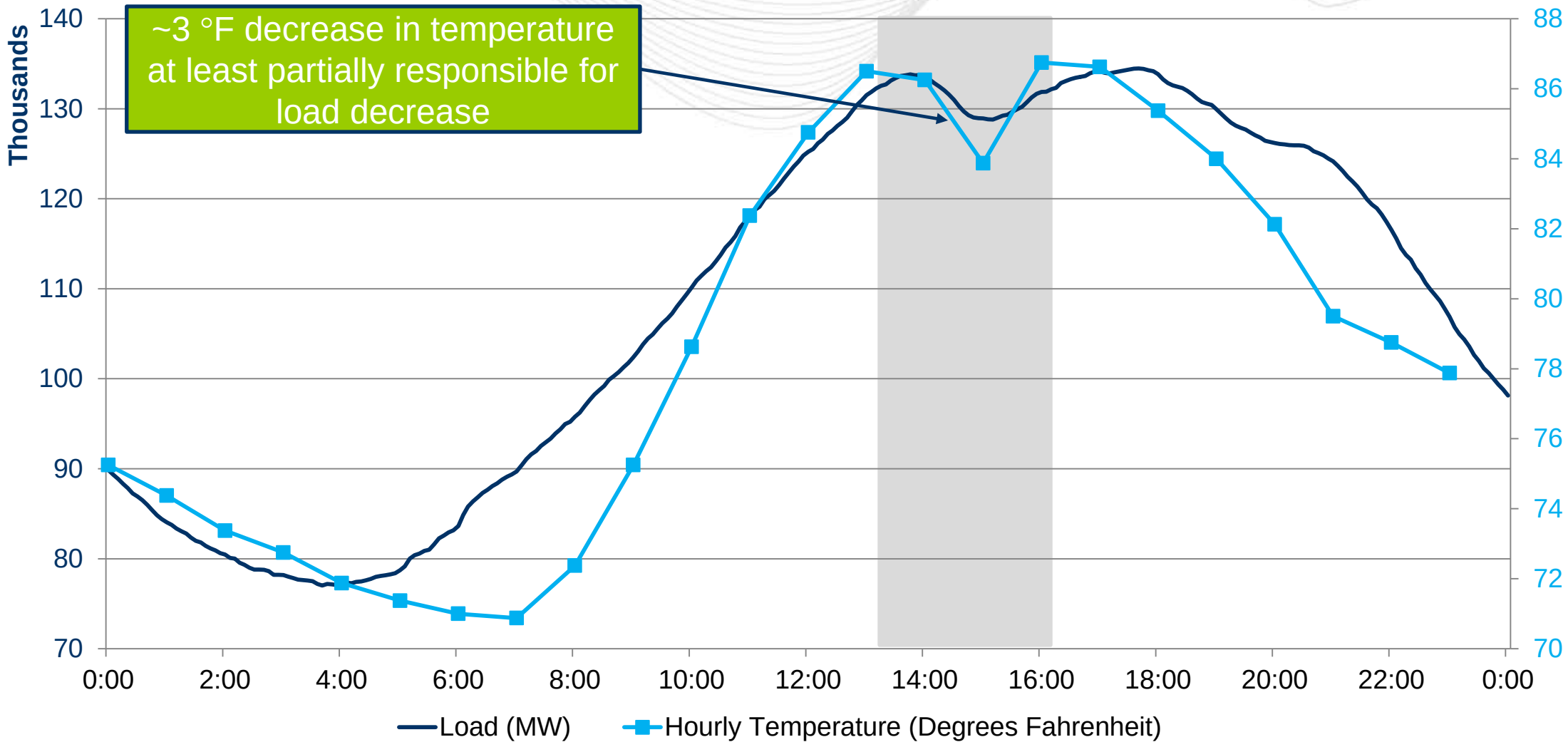
Estimated and Actual Solar Output on August 21, 2017



RTO Load and Solar Output on August 21, 2017



RTO Load and Temperature on August 21, 2017



Example of Load Impacted by Temperature Reduction

ComEd Load vs. Temperature During August 1 Thunderstorms

18000 17000 16000 15000 14000 13000 12000 11000 10000 9000

85 83 81 79 77 75 73 71 69 67

0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000 2100 2200 2300 0

Five-Minute Load Hourly Temperature

Similar changes in temperature have had immediate impacts on load, but not as drastic as those observed during eclipse

Factors Contributing to Load Changes

Factor that Impacted Load	Direction of Impact	Expected Amount of Impact
Reduced behind-the-meter solar	+	~1,700 MW
Increased lighting load	+	Low
Human behavior	–	Inconclusive – not quantifiable
Decreased temperature	–	Inconclusive – forecast models not trained on intra-hour values

Lessons Learned

- Projections of solar output during eclipse were largely accurate
- Load decreased by twice amount that solar output decreased
  - May be different in 2024 with additional installed solar
  - Human behavior is important factor that is not well understood
  - Behind-the-meter assumptions will be difficult to verify
- Current load forecast models are not trained to reflect significant intra-hour temperature changes
- Additional coordination needed for accurate weather forecasts

- PJM Initiatives:
  - PJM Learning Center: Alternative & Renewable Generation
    - » http://learn.pjm.com/energy-innovations/alternative-renewable-gen.aspx
  - PJM Renewable Integration Study (PRIS) Reports
    - » http://www.pjm.com/committees-and-groups/subcommittees/irs/pris.aspx
  - PJM 2017 Load Forecast Report
    - » http://www.pjm.com/-/media/library/reports-notices/load-forecast/2017-load-forecast-report.ashx
  - PJM's Evolving Resource Mix & System Reliability Report
    - » http://www.pjm.com/-/media/library/reports-notices/special-reports/20170330-pjms-evolving-resource-mix-and-system-reliability.ashx