



Overview of PJM Real-Time Co-optimization

Presentation to ERCOT

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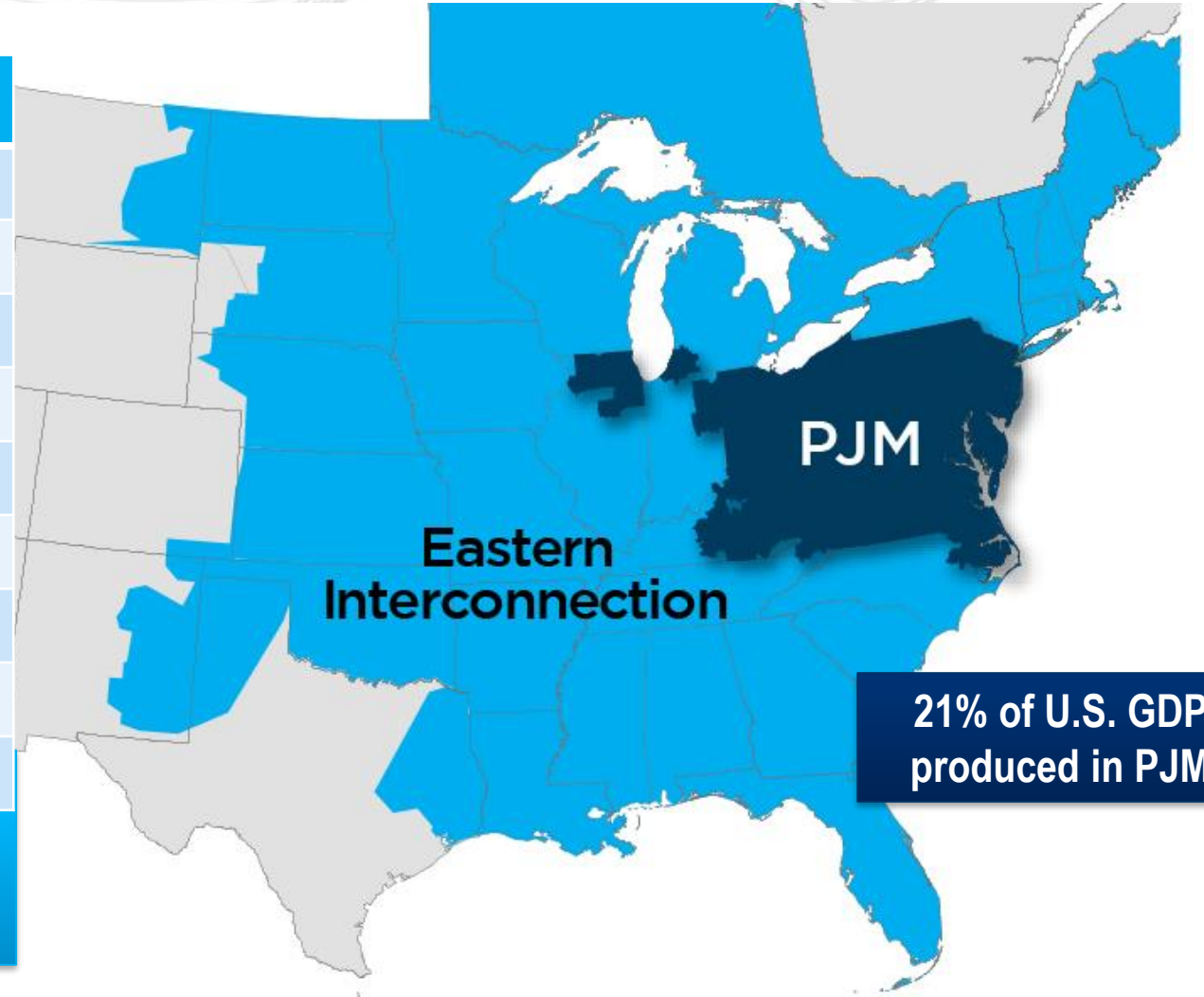
PJM

1. PJM RTO – key statistics
2. A/S Markets Overview
3. Co-optimization
 - Real-time market applications
 - ORDC and Shortage Pricing
4. Co-optimization Implementation & Lessons Learned
5. Major Design Changes in Discussion
6. References
7. Appendix

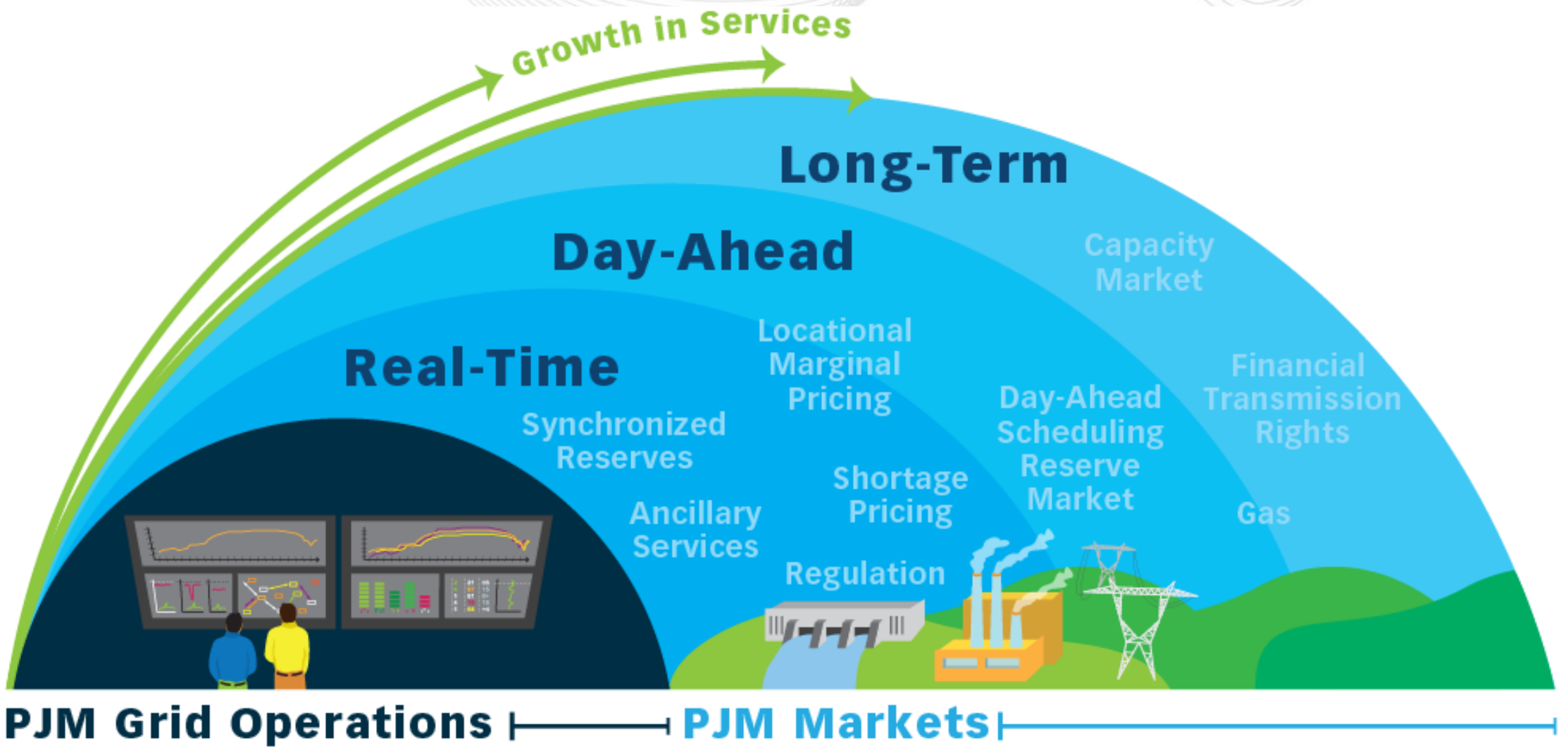
Key Statistics

Member companies	1,010+
Millions of people served	65
Peak load in megawatts	165,492
MW of generating capacity	180,086
Miles of transmission lines	84,236
2018 GWh of annual energy	806,546
Generation sources	1,379
Square miles of territory	369,089
States served	13 + DC

- 26% of load in Eastern Interconnection
- 20% of transmission assets in Eastern Interconnection



As of 1/2019



Scheduling and Operating Reserves

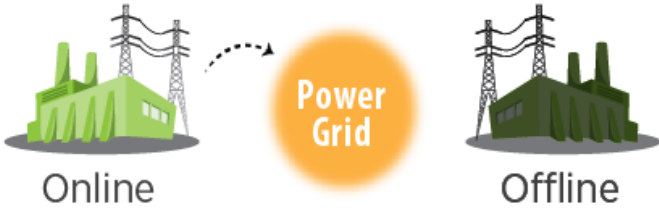
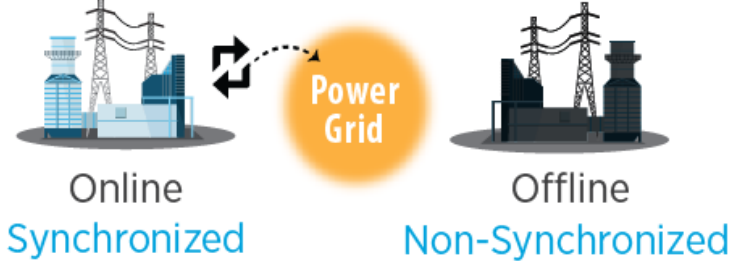
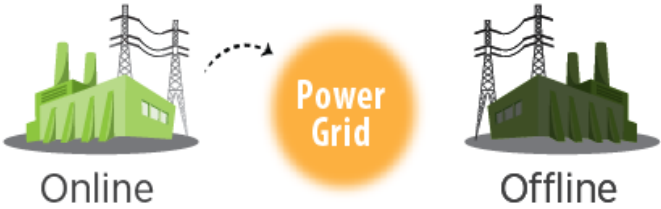
DAY-AHEAD SCHEDULING RESERVES
 Power received within 30 minutes



PRIMARY
 Power received within 10 minutes



SUPPLEMENTAL
 Power received within 10 to 30 minutes

Co-optimized with Energy in Day-Ahead Market

Co-optimized with Energy in Real-Time

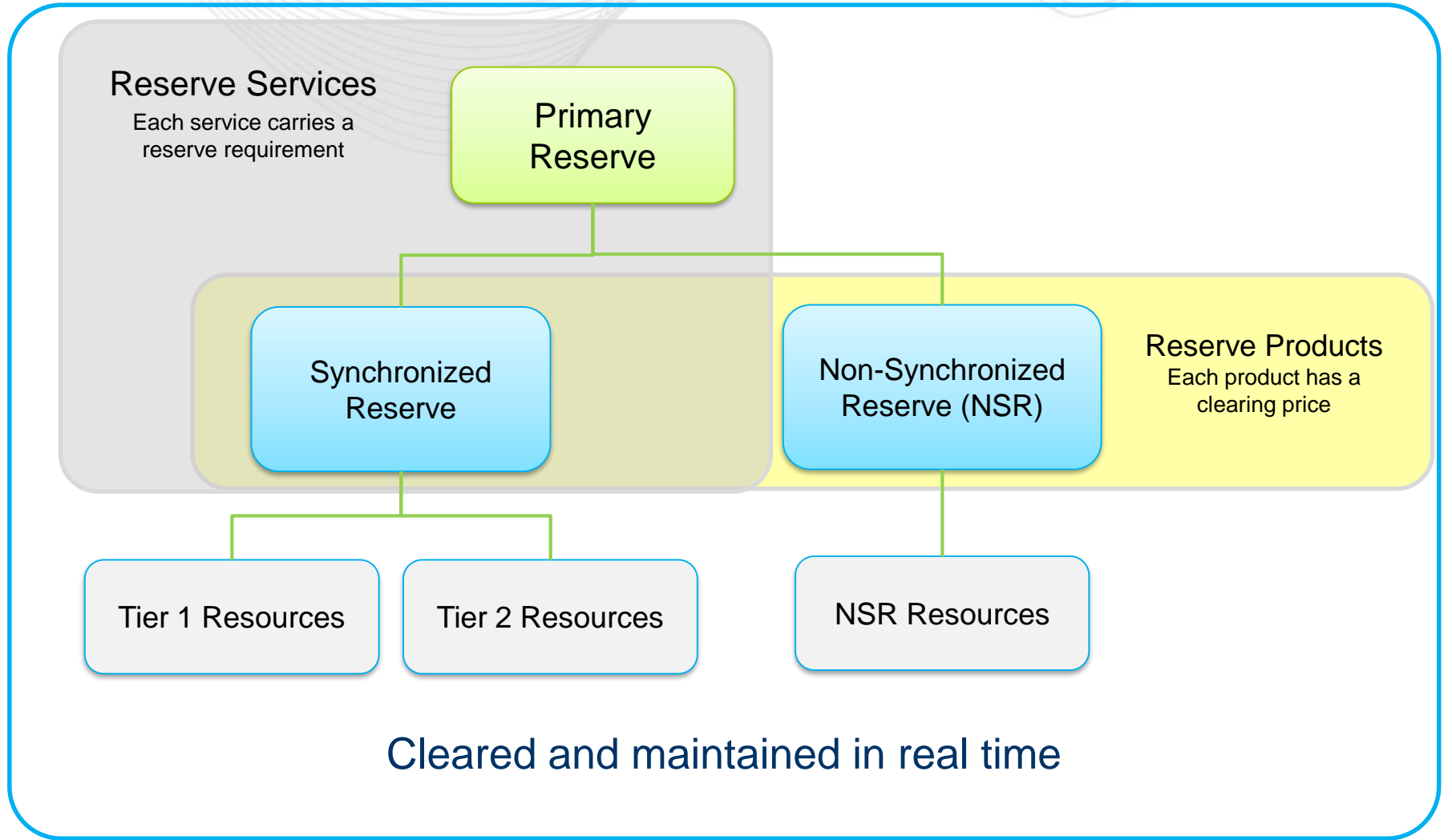
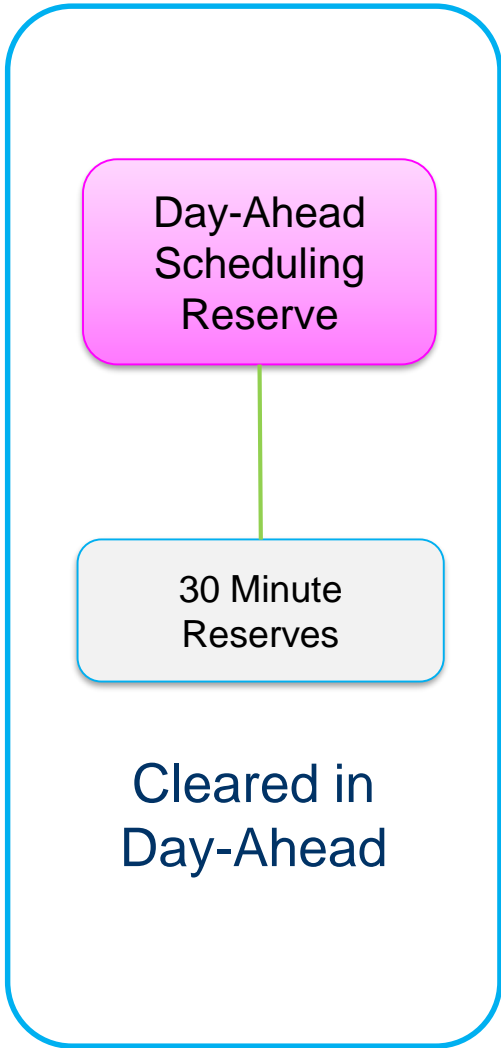
Currently no market

Not maintained in real time

Maintained in real time

Maintained in real time

No virtual transaction products exist in PJM Ancillary Service Markets



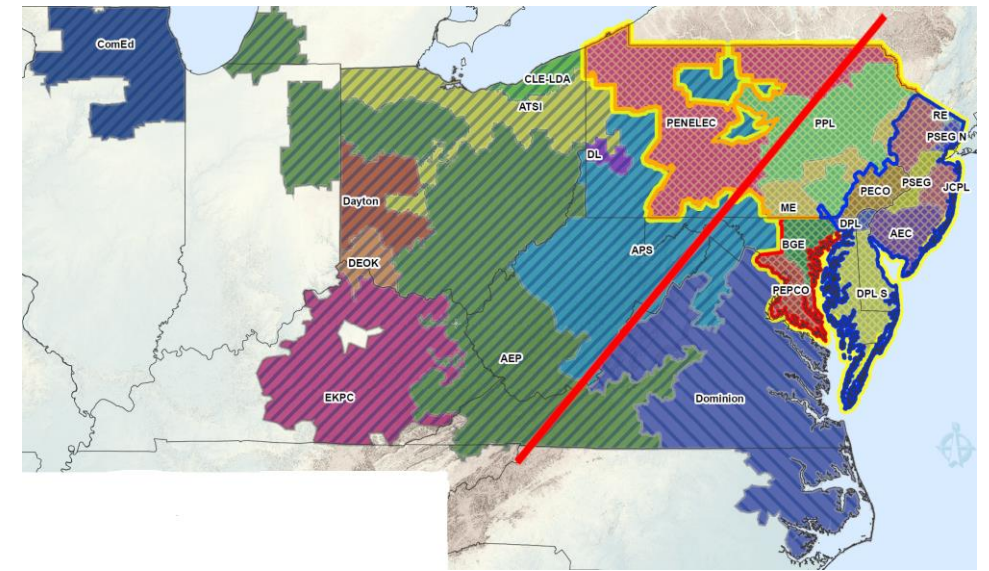
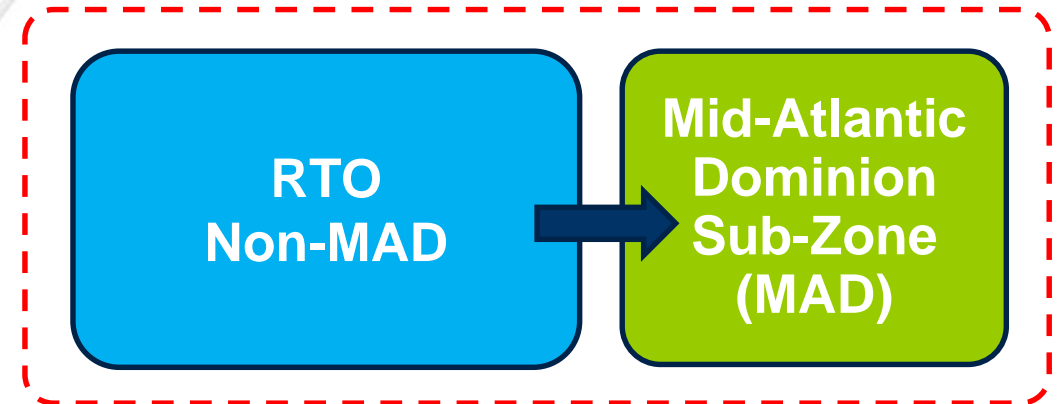
Single reserve zone with a

sub-zone: Mid-Atlantic Dominion (MAD)

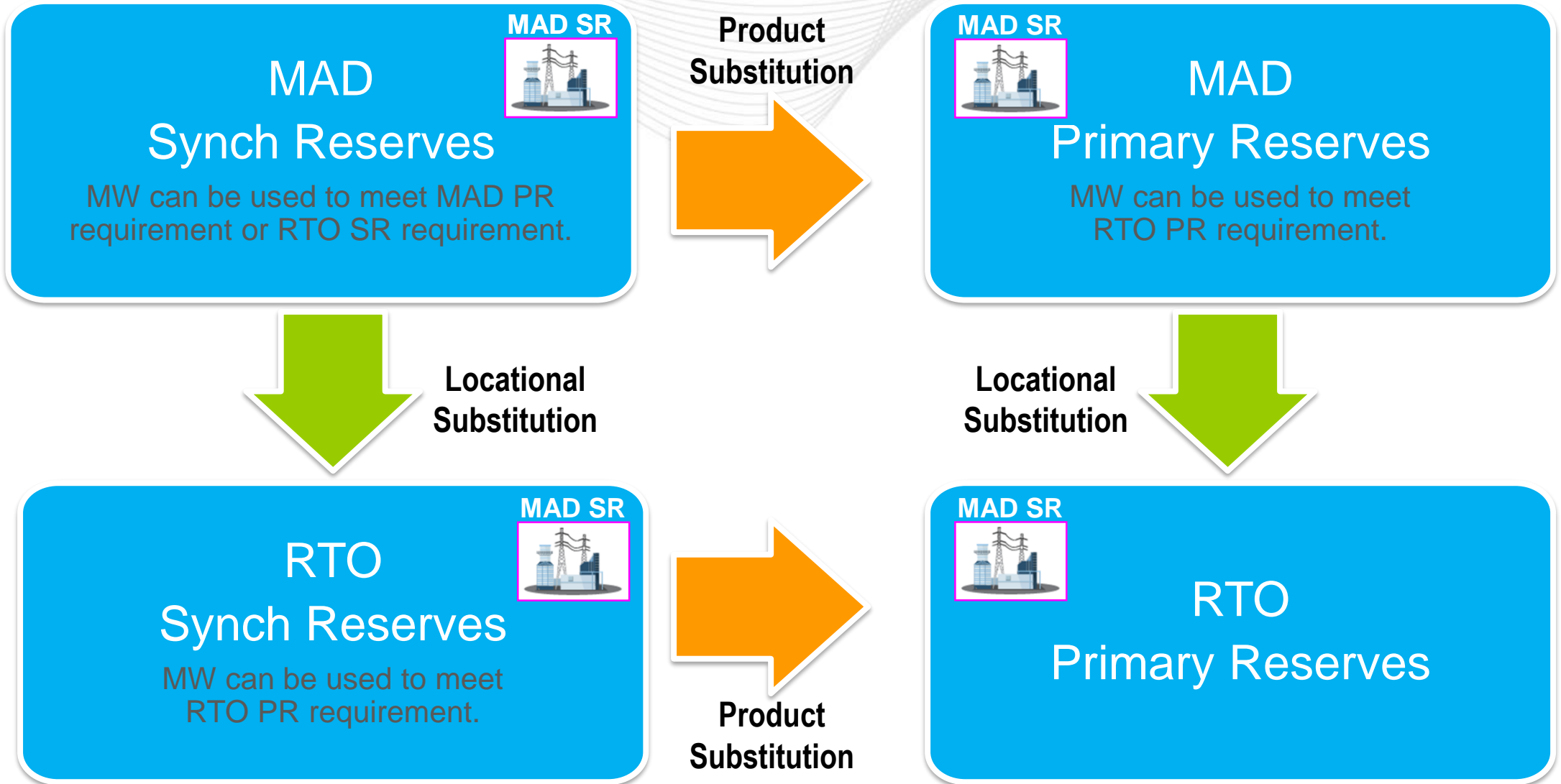
Exists due to potential reserve deliverability issues

- The sub-zone is defined based on the most-limiting transfer interface.
- Resources with **3 percent or greater raise-help distribution factor** on the interface are included in the MAD sub-zone.

RTO Reserve Zone



Relationship Between Reserve Products and Locations



Co-optimization

PJM jointly optimizes energy, synch reserves and non-synch reserves every five minutes.

Regulation and inflexible synch reserve resource are not co-optimized every five minutes, but priced every five minutes

The best method to allocate reserves and energy is to jointly optimize them in real-time.

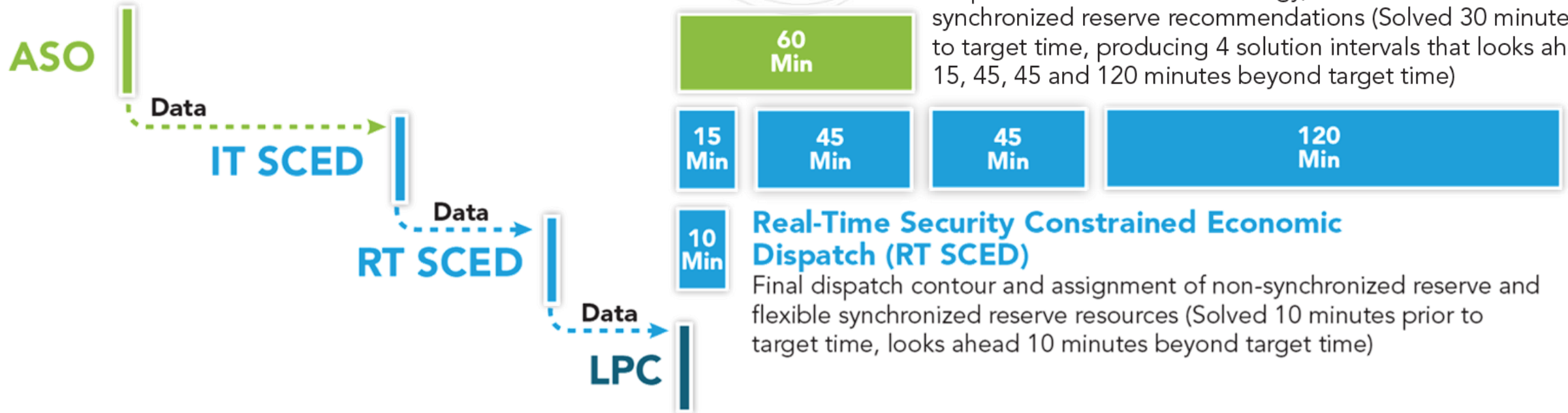
- **Algorithmically**, this adds reserve requirements and commitments into the real-time and look-ahead dispatch algorithms.
- **Operationally**, this results in a more optimal energy dispatch and reserve commitment.
- **Economically**, this results in the lowest-cost solution.

Ancillary Services Optimizer (ASO)

Clearing and assignment of regulation and inflexible reserve resources (Solved 60 minutes prior to target time, looks ahead 60 minutes beyond target time)

Intermediate-Term Security Constrained Economic Dispatch (IT SCED)

Demand Trajectory, generator loading strategy, Demand Response commitment for energy, CT commitment and inflexible synchronized reserve recommendations (Solved 30 minutes prior to target time, producing 4 solution intervals that looks ahead 15, 45, 45 and 120 minutes beyond target time)



Real-Time Security Constrained Economic Dispatch (RT SCED)

Final dispatch contour and assignment of non-synchronized reserve and flexible synchronized reserve resources (Solved 10 minutes prior to target time, looks ahead 10 minutes beyond target time)

Locational Pricing Calculator (LPC)

5 minute energy and ancillary service prices



- The Operating Reserve Demand Curve (ORDC):
 - Sets the reserve requirement for market clearing purposes
 - Puts a defined limit on the cost willing to be incurred to substitute reserves for energy
 - Acts as a cap on the market clearing price to clearly indicate reserves shortages
 - The ORDC only impacts the reserve markets, energy dispatch and LMP when the reserve requirement cannot be met at a price below the penalty factor price

Oct. 2012

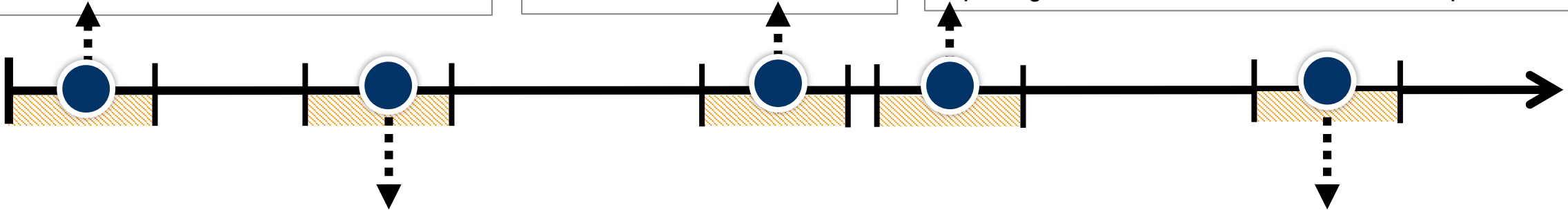
- Initial Shortage Pricing implementation
- Penalty factors escalated from \$250 to \$850 over 2.5 year period
- \$850 penalty factor became effective June 2015

May 2017

- Transient Shortage Pricing
- RTSCED can declare shortage and price off the demand curve without notification from ITSCED

July 2017

- Added permanent second step of the demand curve to reflect 190 MW plus any reserves for conservative operations
- Intended to moderate effects of transient shortage pricing before 5 minute settlements is implemented

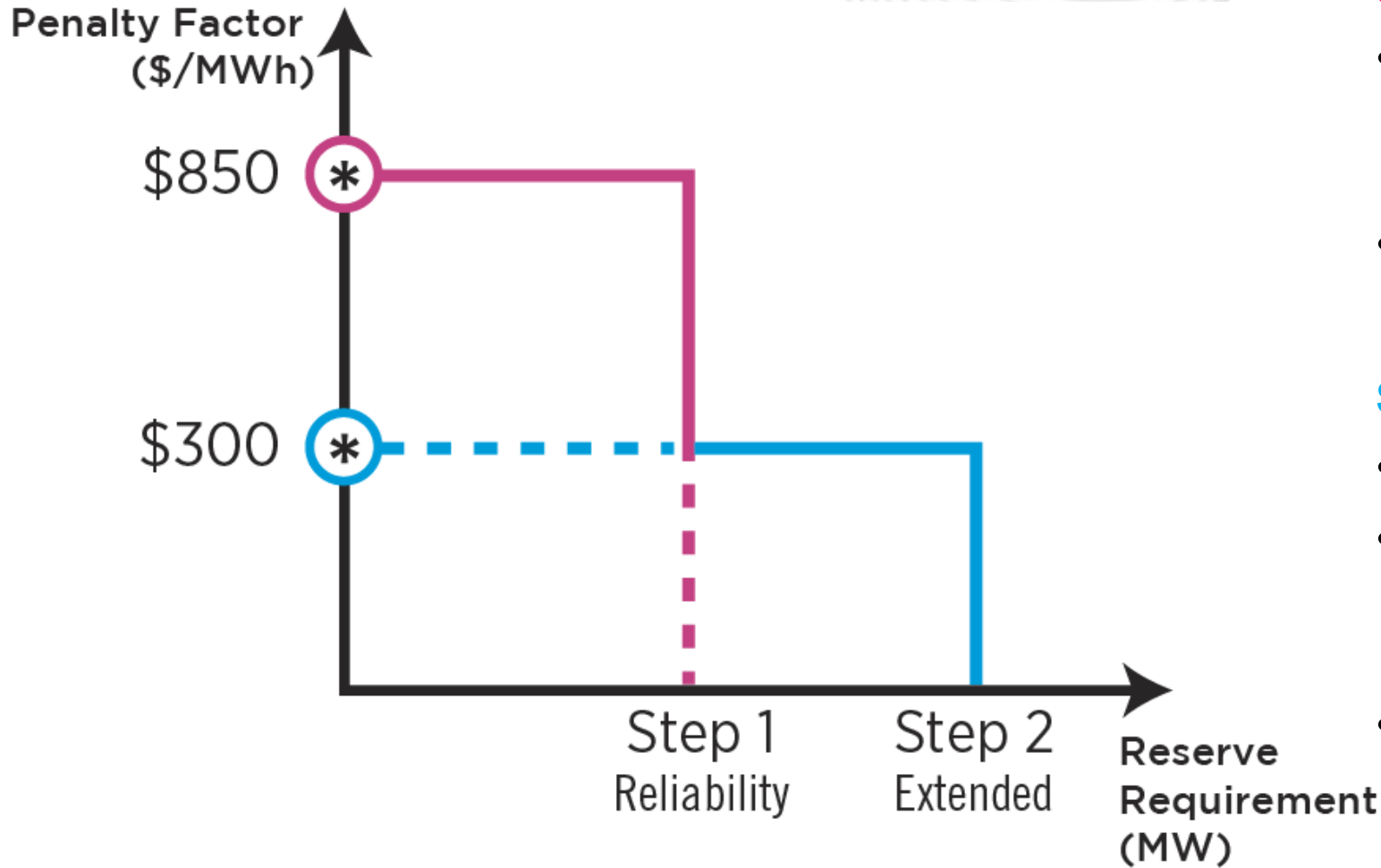


Nov. 2014

- Added a temporary second step to the ORDC at a penalty factor of \$300
- Intended to prevent conservative operator actions from suppressing reserve prices

March 2019

- PJM filed revised ORDC with FERC – *Pending FERC*
- Proposed downward sloping shape with \$2,000/MWh penalty factor
 - Intended to recognize the value of reserves beyond the minimum requirement



Step 1 of Demand Curve

- Represents the Reliability Requirement, which is generally the output of the largest online unit
- Penalty factor for being short Step 1 is \$850/MWh

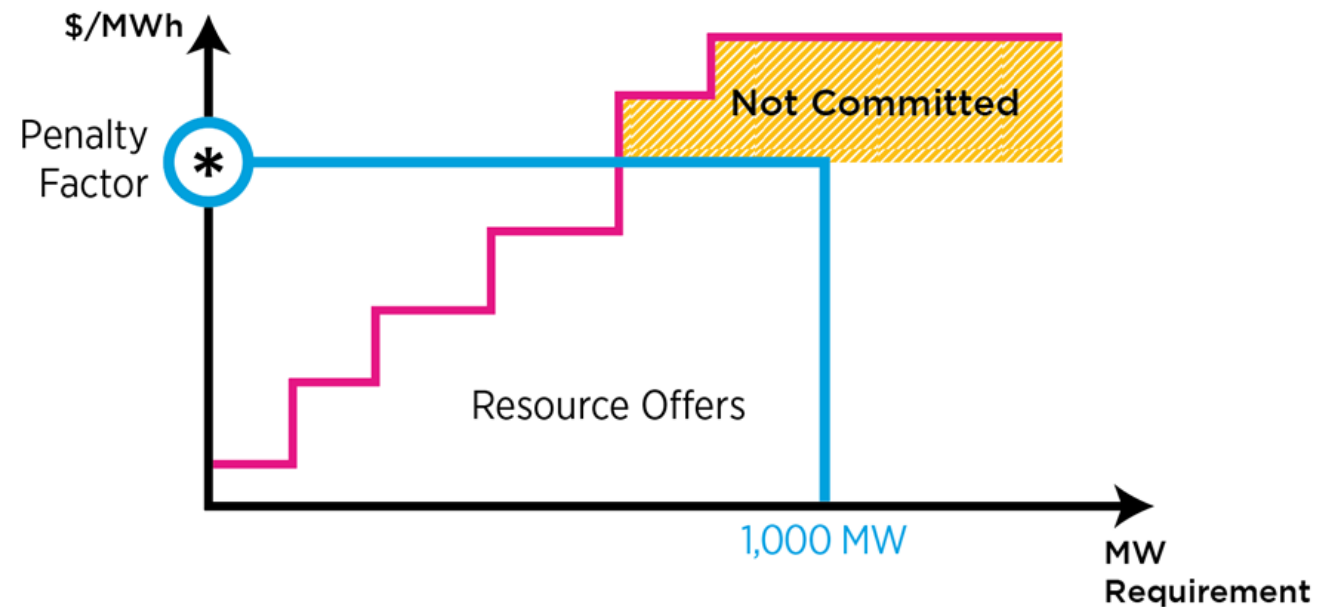
Step 2 of Demand Curve

- Adds 190 MW to the Reliability Requirement
- Also includes an Optional Adder MW that can be used to capture additional reserves that are scheduled for reliability reasons
- Penalty factor for being short Step 2 is \$300/MWh

If the cost for a resource to provide reserves exceeds the penalty factor, it will not be committed for reserves

- PJM Operations would still assign reserves out-of-market if available and the cost of those reserves would be recovered in “uplift” or Balancing Operating Reserve charges

The penalty factor must be set high enough so that shortage being signaled is due to running out of reserves rather than going short for economic reasons.





Joint optimization of energy and reserves provides the following benefits



Reduction of out of market unit-specific opportunity cost payments



Clearing prices that more accurately reflect the true cost of providing reserves since opportunity cost is better reflected in clearing prices



Reduced production costs due to optimized energy and reserve assignments in response to real-time conditions (as opposed to hour ahead reserve assignments)



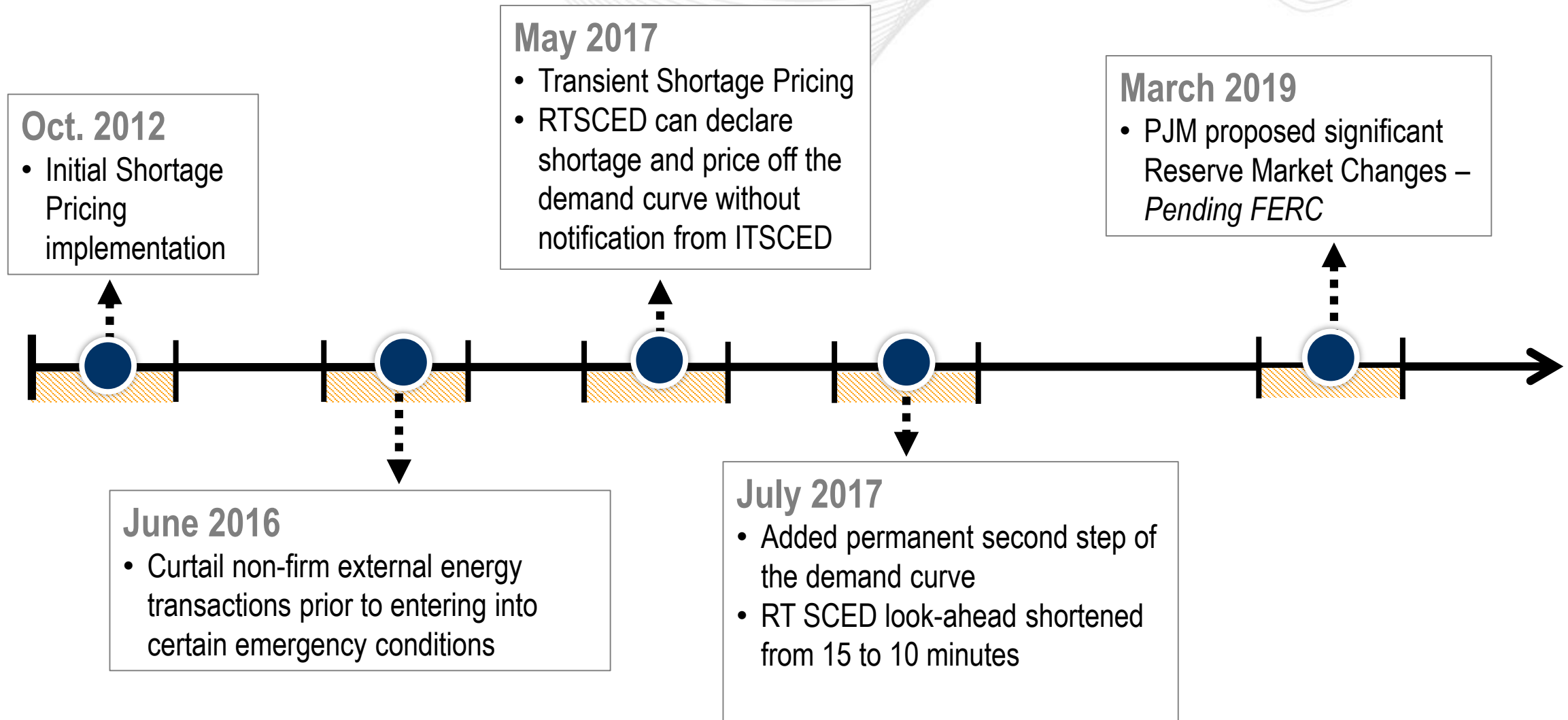
More accurate price signals that better reflect true value of ancillary services and produce better investment signals



Resources that are financially indifferent to whether they provide energy or reserves, thereby enhancing operational reliability

Co-optimization Implementation - Issues and Lessons Learned

Evolution of Changes to Reserve Pricing



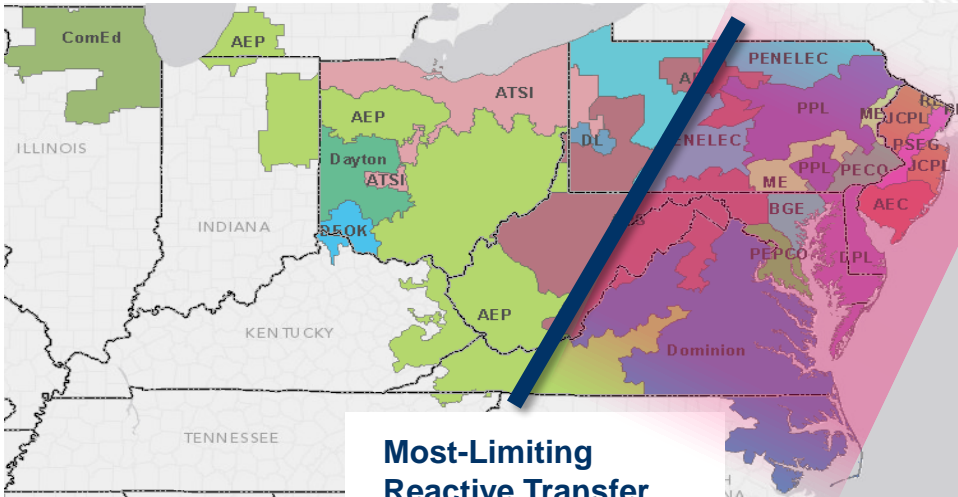
Major Design Changes in Discussion

On March 29, 2019 PJM filed a 206 Filing with FERC, proposing the following Reserve Market Changes:

1. Removal of Tier 1 reserve product. Conform to a single product consistent with other ISO/RTO models.
2. Improved Operating Reserve Demand Curves (ORDC) to better reflect reserve needs and value
3. Consistent Modeling of Reserve Markets in Day-ahead and Real-time with balancing settlement
4. Dynamically Change the Reserve Sub-zone

More Dynamically Change the Sub-Zone

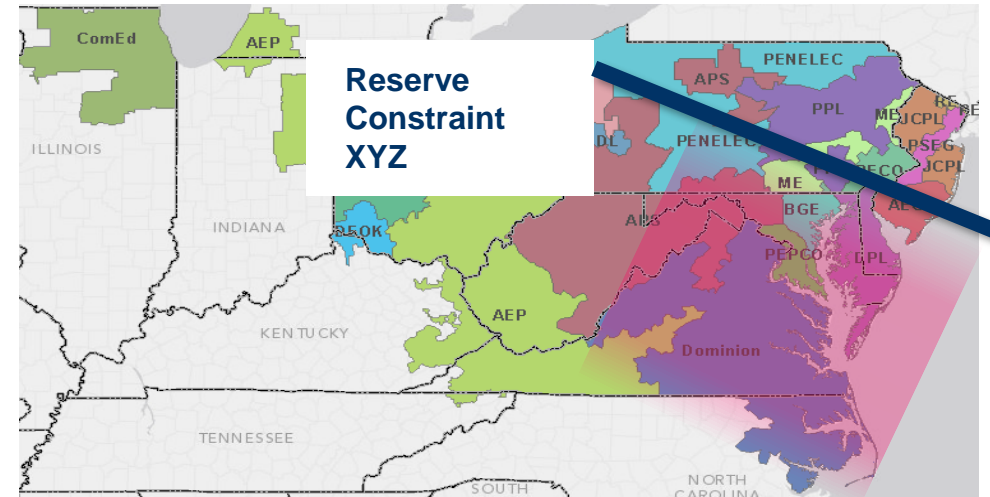
- West-to-east transfers are now not the only bottleneck for reserve deliverability
- PJM also encounters significant transfer limitations from the north-to-south (see below)



Most-Limiting Reactive Transfer Interface

Mid-Atlantic Dominion (MAD) Sub-Zone

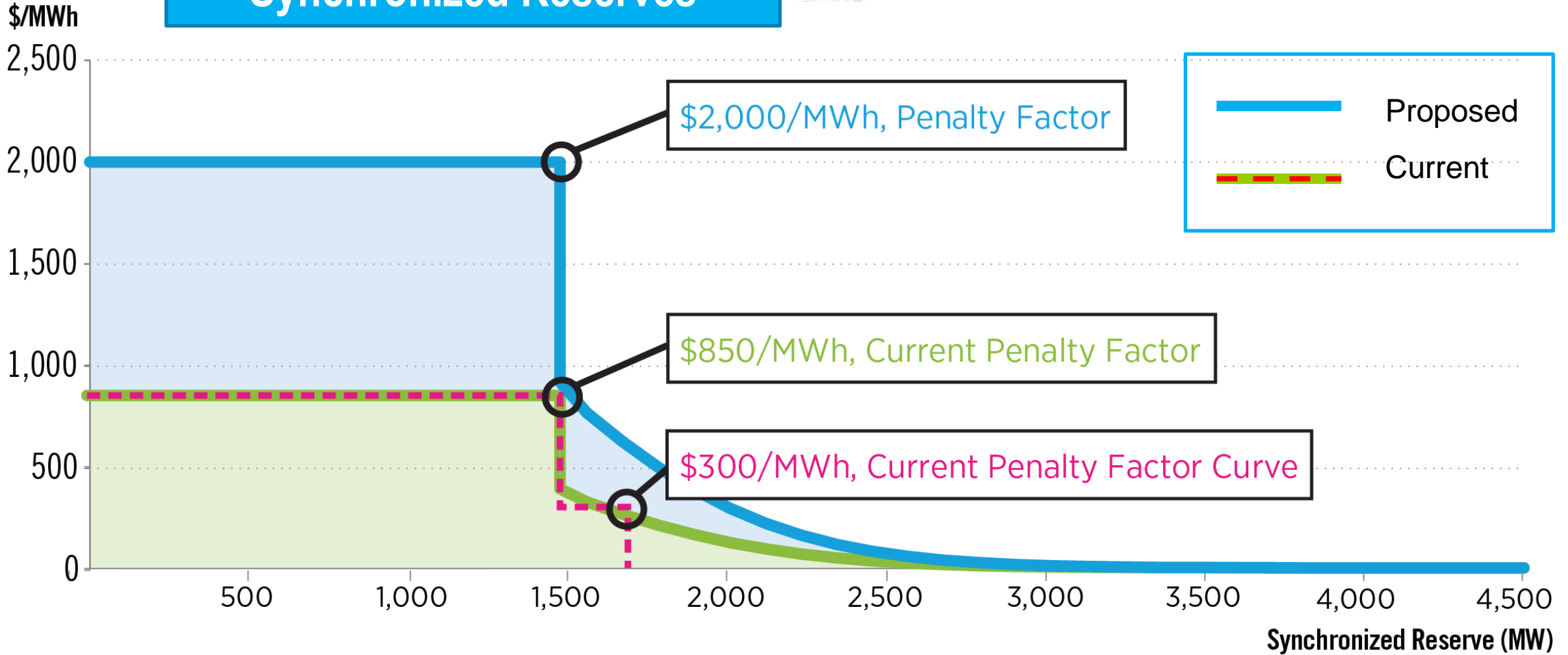
- PJM’s goal is to be able to more dynamically adjust the reserve sub-zone to better reflect system conditions
- This will better enable reliable operations and result in market results that are more consistent with system operations



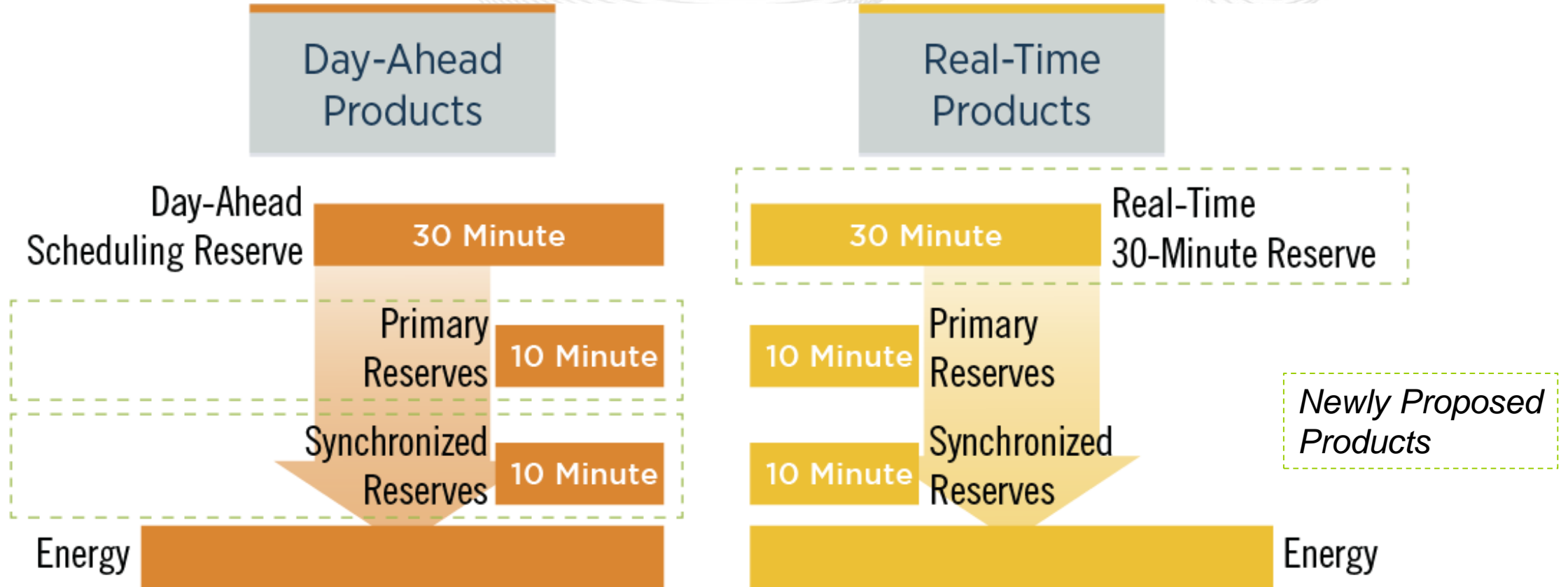
Reserve Constraint XYZ

New Sub-Zone XYZ

Synchronized Reserves



Day-Ahead and Real-Time Product Alignment



Solidify financial incentives to provide reserves when assigned due to day-ahead financial commitment.
 Remove modeling differences between Day-Ahead and Real-Time Energy Markets.

References

1. Reserve and Co-optimization

<https://www.pjm.com/-/media/committees-groups/stakeholder-meetings/price-formation/20180117-am/20180117-price-formation-education-3-updated.ashx>

2. Shortage Pricing and Operating Reserve Demand Curve

<https://www.pjm.com/-/media/committees-groups/stakeholder-meetings/price-formation/20180117-pm/20180117-price-formation-education-4.ashx>

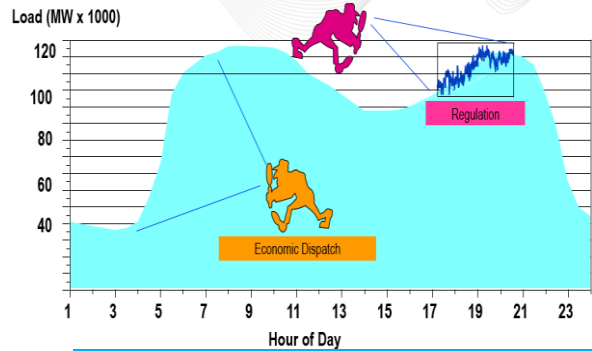
3. Proposed Reserve Market Enhancement

<https://www.pjm.com/-/media/committees-groups/task-forces/epfstf/20181214/20181214-item-04-price-formation-proposal-overview.ashx>

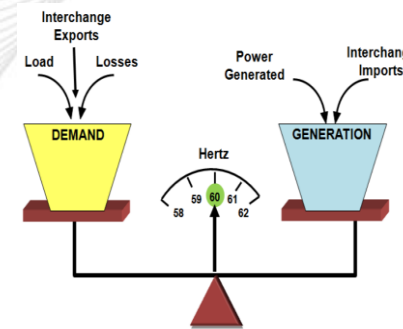
4. Energy and Reserve Joint Optimization (Lost Opportunity Cost: Ancillary Services)

<https://www.pjm.com/-/media/committees-groups/task-forces/epfstf/20180504/20180504-item-07-epfstf-lost-opportunity-cost-ancillary-services.ashx>

Appendix

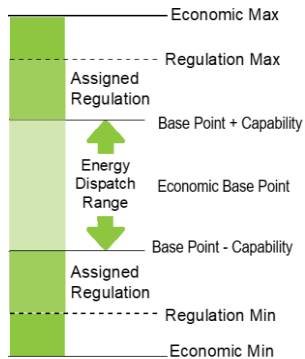


A variable amount of generation under automatic generation control that PJM sends to raise or lower the resource's output to correct for instantaneous changes in load and generation



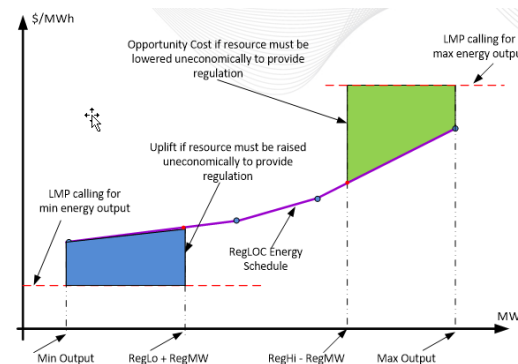
Regulation is priced in real-time every 5 minute along with energy and reserve. This approach helps to minimize potential make-whole payments

Regulation Service corrects for short-term changes in electricity use that might affect the stability of the power system. It helps match generation and load and adjusts generation output to maintain the desired frequency



Regulation is cleared hourly, one hour prior to the operating hour.

- Bidirectional (Reg-up & Reg-down)
- Dispatched within resource's defined range



Regulation is coupled with energy through Lost Opportunity Cost (LOC). LOC captures the foregone energy revenue incurred when a generation resource is raised or lowered uneconomically to provide Regulation

Day-Ahead Scheduling Reserve Market Overview



Day-Ahead, forward market that **clears simultaneously with Day-Ahead Energy Market**



Offer-based market for 30-Minute Reserve that can be provided by both Generation and Demand Resources

Purpose: To encourage and incent generation and demand resources to provide the flexible capability to provide 30-minute reserves



is the additional operating reserves scheduled in the day-ahead market to cover forecast error and generation forced outages



The DASR Market Clearing price represents the cost to serve an additional MW of DASR in the RTO. Energy and DASR are jointly co-optimized.

- DASR clearing is based on DASR offer and LOC
- LOC is the forgone profit in energy market for providing reserve

Tier 1 (Economic)

Online units that are following economic dispatch and are only partially loaded, and therefore are able to increase output within 10 minutes following PJM dispatcher request

Tier 2 (Non-Economic)

Resources that have offered into the Synchronized Reserve Market and cleared

- Condensers (CTs and hydro) transition to online Tier 2 condense mode
- CTs online at min – operating at a point that deviates from economic dispatch
- Steam reduced to provide Tier 2 MW
- Demand response that can drop load

10 Minute Non- Synchronized Reserve

Resources currently not synchronized to the grid

- Shutdown run-of-river hydro
- Shutdown pumped hydro
- Offline industrial combustion turbines, jet engine/expander turbines, etc.

Flexible

Resources

- Online generators following economic dispatch that can be backed down for Tier 2
- Tier 2 DSR that opt to be flexible

Attributes

- Can respond immediately to real-time five-minute commitment
- Has ability to receive Tier 2 commitment via approved telemetry

Inflexible

Resources

- Synchronous condensers that can be committed for Tier 2 from offline state
- Other Tier 2 DSR

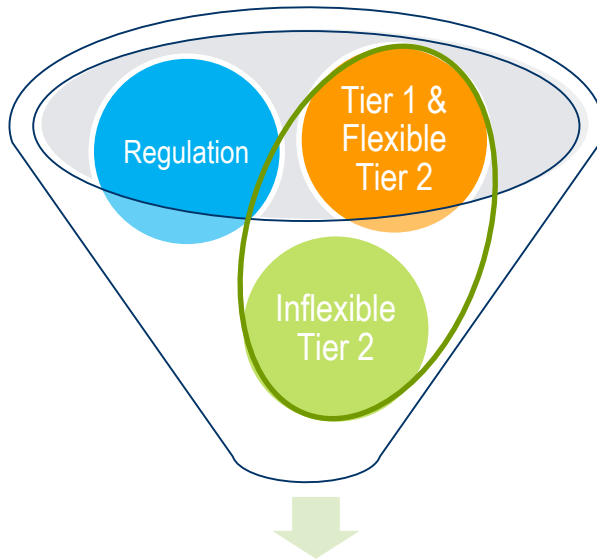
Have limiting parameters, such as:

- Minimum run time of one hour
- Notification/lead time of at least 30 minutes

Tier 2 commitment notification is through Markets Gateway

ASO

1 Hour Ahead

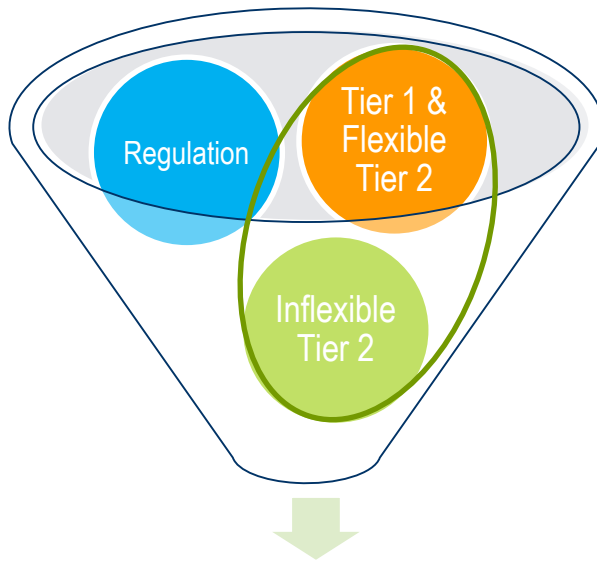


Meet A/S Requirements

- Co-optimization between Energy and A/S
- ASO clears Regulation and 10-minute Reserve to their requirements based on hour look-ahead forecast and most economic set.
- Cleared Regulation resources receive a firm commitment for an hour
- Inflexible Tier 2 reserve resources receive firm commitment for an hour
 - Tier 1 and Flexible Tier 2 are let go for re-evaluation in real-time intra-hour.
- Clearing price from ASO are not firm and not published.

ITSCED

30 Minutes Ahead

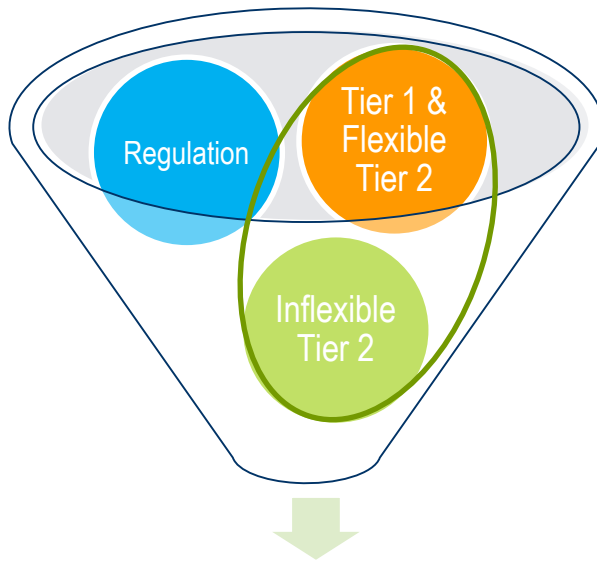


Meet A/S Requirements

- Co-Optimization between Energy & A/S
- ITSCED clears to meet A/S requirements.
 - It honors Regulation and inflexible Tier 2 already committed by ASO.
 - Additional Regulation and inflexible Tier 2 are recommended but do not receive a firm commitment unless manually called by Dispatch
- Tier 1 and Flexible Tier 2 are let go for re-evaluation in real-time intra-hour.
- ITSCED also manages CT commitment/de-commitment recommendation for energy and constraint control, Demand Resource for energy commitments, and clears Coordinated Transaction Scheduling (CTS)
- Clearing price from ITSCED are not firm and not published except for CTS purpose.

RTSCED

10 Minutes Ahead



Meet A/S Requirements

- Co-Optimization between Energy and A/S
- RTSCED clears to meet A/S requirements
 - It honors Regulation and inflexible Tier 2 already committed by ASO and ITSCED
 - Tier 2 flexible resources, and Non-Sync reserve are committed to meet balance of the reserve requirements
- Tier 1 estimate is updated based on current system conditions.
- Tier 2 flexible resources are committed to meet the balance of the requirement.
 - If there is sufficient Tier 1 to meet the requirement, no flexible Tier 2 is committed and the SRMCP is zero.
 - If additional flexible Tier 2 must be committed, the SRMCP is non-zero.

LPC (every 5 minutes in real-time)

- Runs every 5 minutes and provides real-time pricing
 - LPC prices on a five minute basis all valid system pricing points for the energy market: Buses (Gen and Load), Hubs, Aggregates, Interfaces
 - LPC prices on a 5 minute basis all reserve market clearing prices by locale (Regulation, Synchronized Reserve and Non-Synchronized Reserve)
- Performs ***joint optimization*** of energy and reserves
- Current approved RT SCED case is the basis for LPC run