

# Topology Control Algorithms (TCA)

## *Simulations in PJM Day Ahead Market and Outage Coordination*

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# Agenda

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## Topology Control Algorithms (TCA)

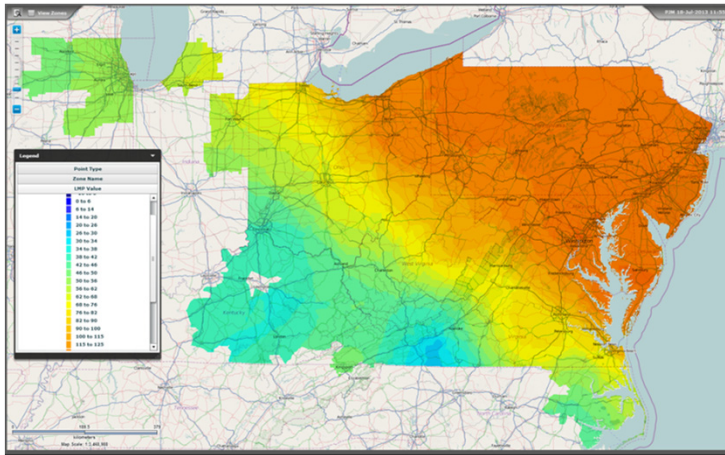
- Motivation and Objectives
- Illustration of Topology Control
- ARPA-E TCA Project
- Applications to Outage Coordination and Op. Guide Development
- Simulation Results on PJM DA Markets – Limited Switchable Set
- Concluding Remarks
- Appendix: TCA Simulation on PJM RT Markets – Full Switchable Set



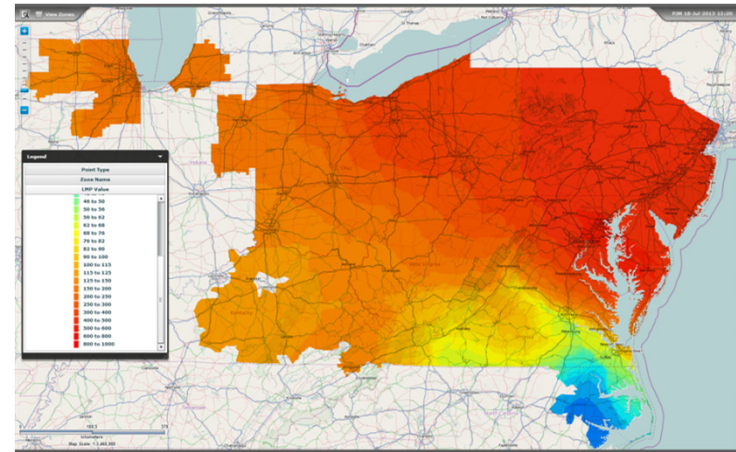
## Motivation and Objectives

# Congestion in Power Markets: PJM

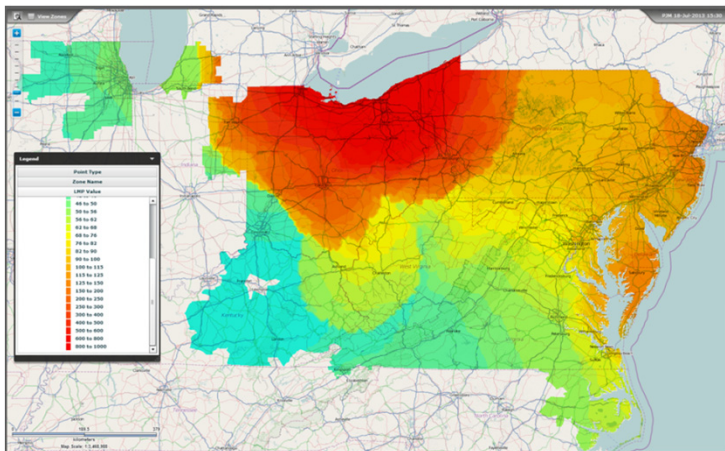
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In the course of a day, congestion patterns and prices can change significantly:

- Fuel diversity
- Lack of flexibility in the resource mix

Having the ability to dynamically increase transfer capability from low price areas to high price areas will help to relieve congestion, improve dispatch of renewable resources, reduce dispatch costs and increase system flexibility.



# Outage Coordination and Operating Guides

- Outage coordination and contingency planning processes are critical to RTO reliable and efficient operation
- RTO staff receives high volumes of transmission outage requests for evaluation and approval/rejection
  - PJM receives well in excess of 100 outage requests daily
- Outage requests that are not expected to impact reliability and/or market efficiency are approved, otherwise they are rejected unless the TO and the RTO staff develop appropriate solutions
  - Many times the solutions involve switching operations
- Operating Guides and contingency plans are developed by RTO staff to aid to operators under specific contingency or outage scenarios

*Currently, switching solutions for outage coordination or Op. Guide are constructed manually using engineering judgment and past experience; there are no automated tools to provide identification of previously unidentified beneficial topology changes*



# Topology Control Algorithm

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By controlling the transmission network topology (line switching and bus splitting), RTOs and TOs extract more value out of the transmission system

1. **Identify additional operational controls to**
  - manage congestion
  - respond during contingency situations
  - accommodate outage requests
2. **Significantly lower generation costs**
3. **Enable higher levels of variable renewable penetration**
4. **Increase system reliability**

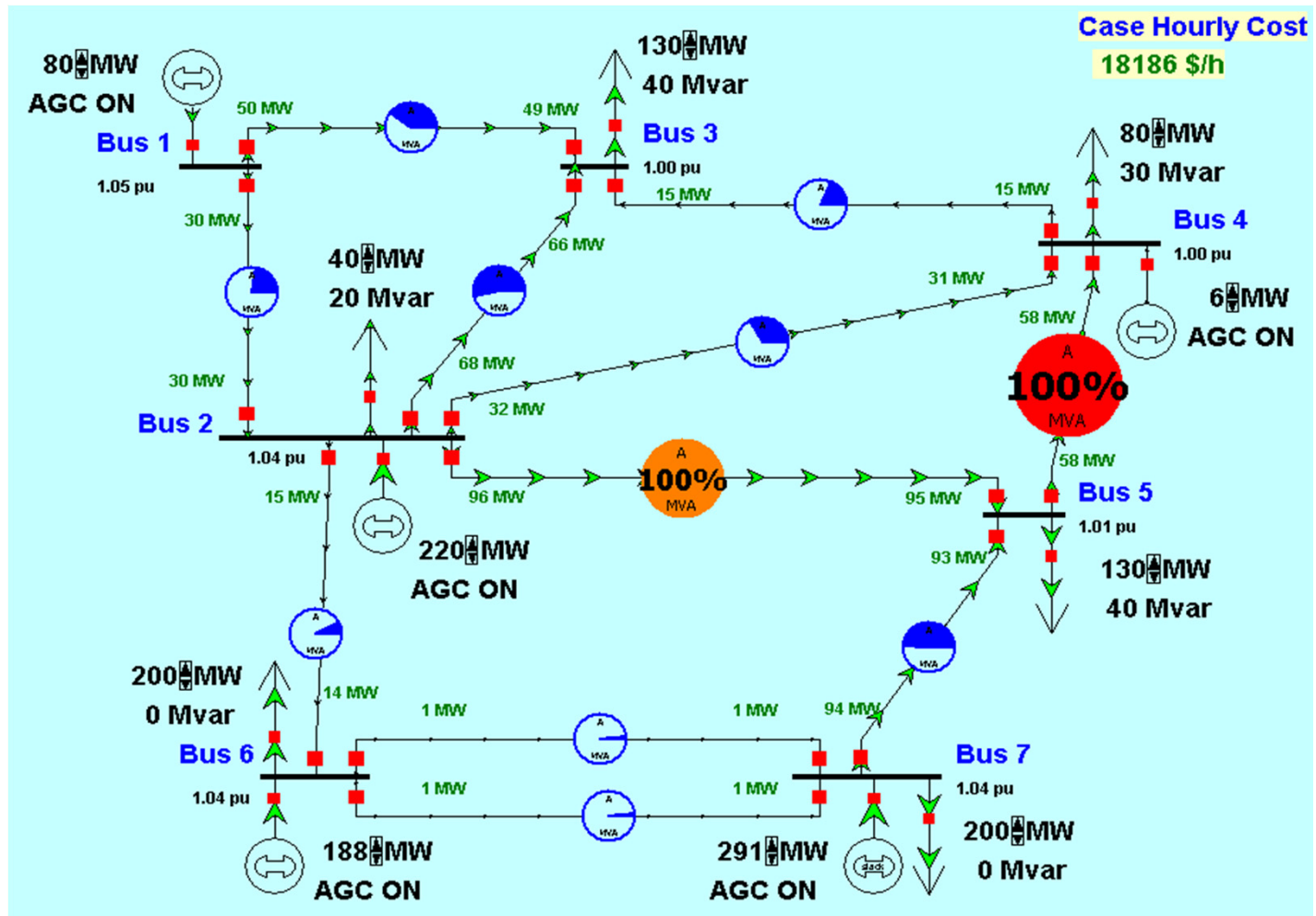
**TCA Timeframe: from operations planning up to real-time operations**





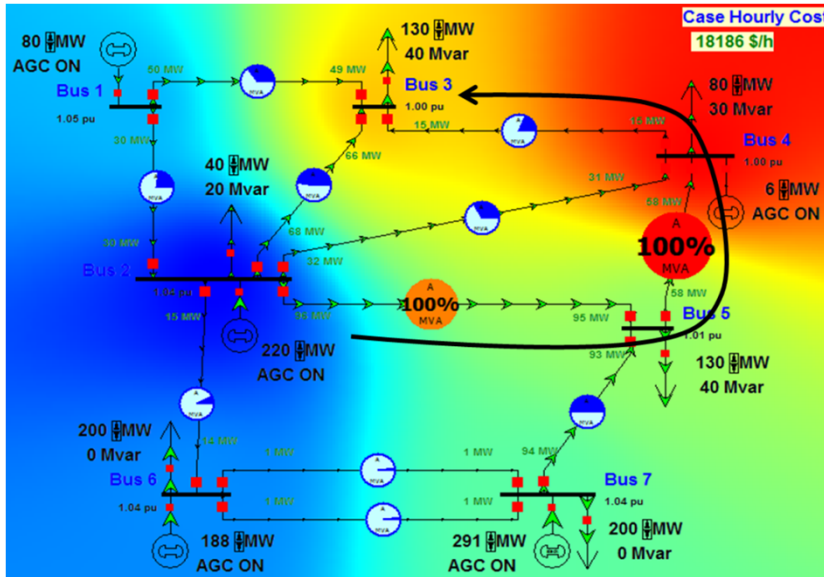
## Illustration of Topology Control

# 7-bus Example: All Lines Closed



## Illustration of Topology Control

# 7-bus Example Results



\$40/MWh



\$15/MWh

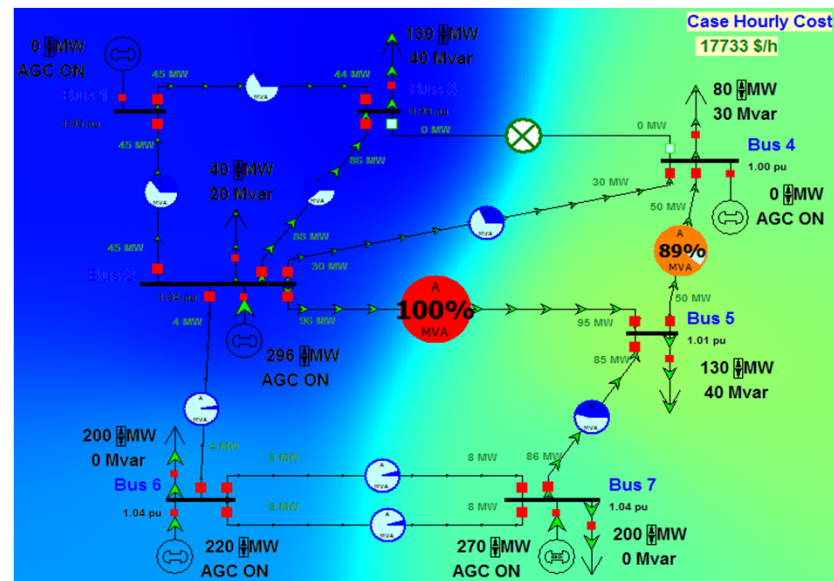
## Hourly Cost

All lines Closed: \$18,186

Line 3-4 Opened: \$17,733

Savings: \$453

Generation	Before TC	After TC
Bus 1	80 MW	0 MW
Bus 2	220 MW	296 MW
Bus 4	6 MW	0 MW
Bus 6	188 MW	220 MW
Bus 7	291 MW	270 MW
Total	785 MW	786 MW



# Objectives and Focus

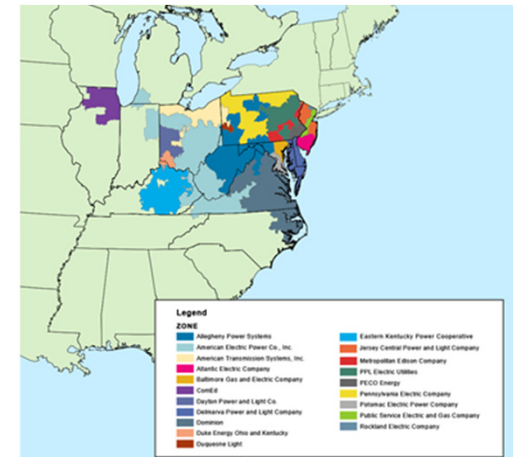
**To develop a full-scale algorithm and software implementation for transmission network topology control**

- Operating in conjunction with existing operations and market tools (including Energy Management Systems, Market Management Systems and contingency planning tools);
- Meeting computational time requirements aligned with operations and market timeframes

**The algorithms developed are being tested in a simulated environment replicating PJM Interconnection's market operations.**

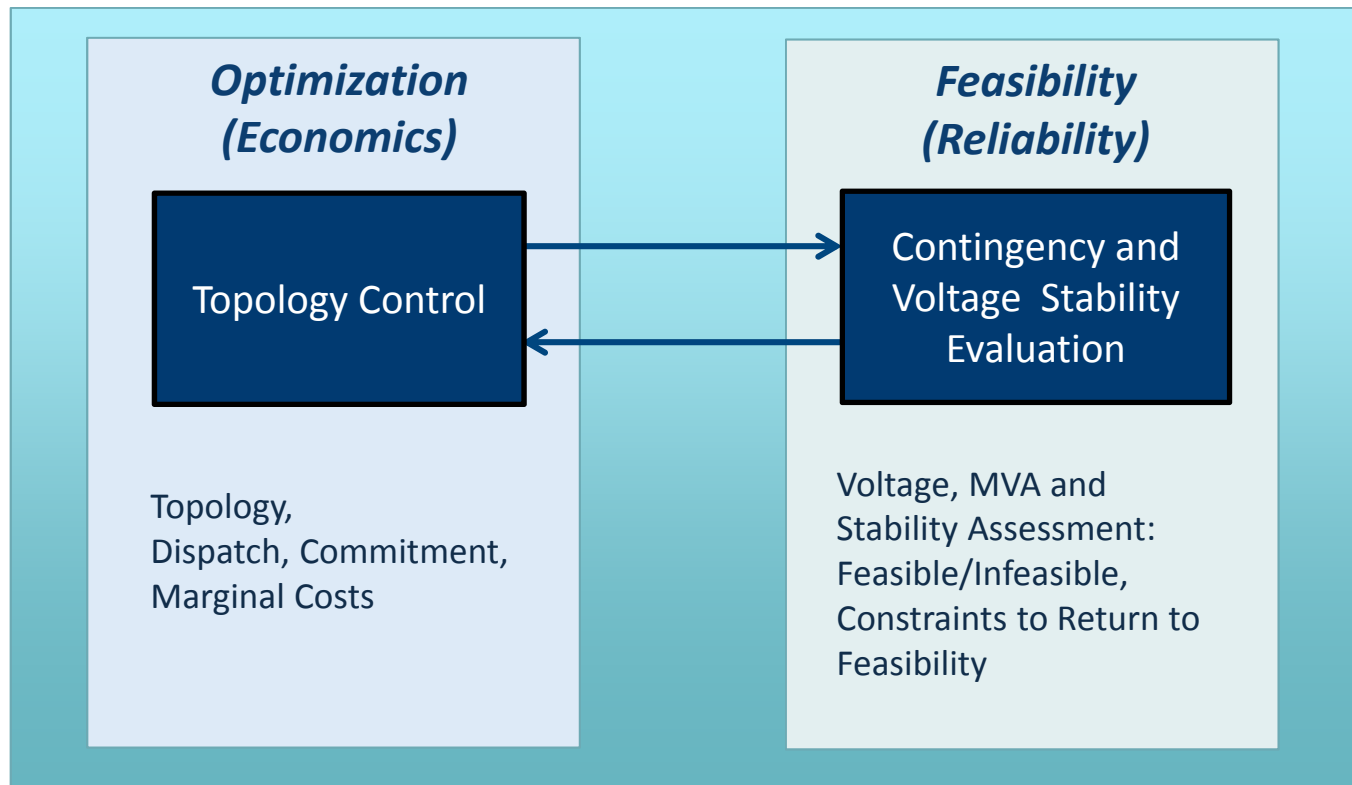
## Focus:

- Tractability: TCA works on 20,000+ bus (and 100,000+ EMS node) systems
- Dynamics: Look-ahead TC decisions in ED and UC
- Reliability: *Connectivity*, security constraints, stability and voltage criteria met
- Impact evaluation: Economic, operations and renewable integration benefit





# Basic TC Software Architecture

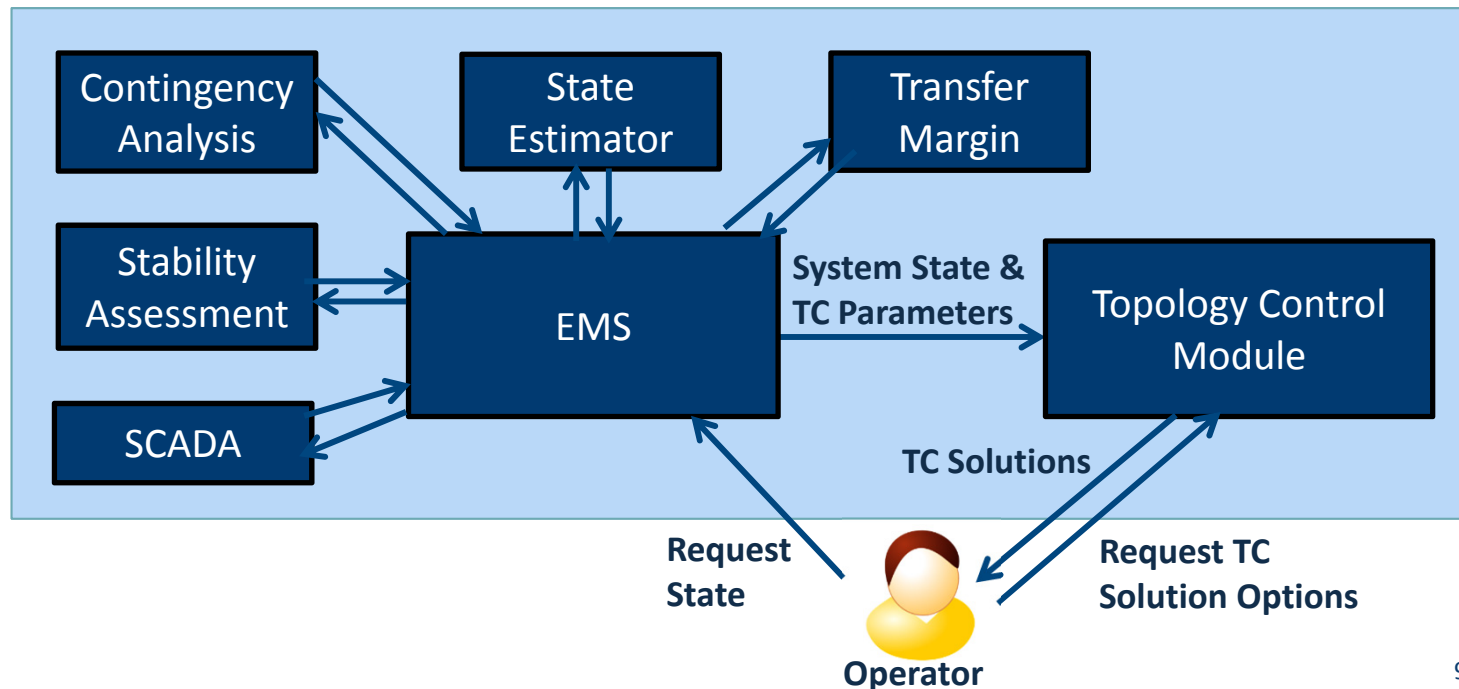


\* The simulation results in this presentation include AC modeling and linear contingency evaluation and enforcement, but do not include transient stability evaluation



## TCA in Operations Planning

- In several operations planning processes, such as outage coordination, TC would provide the engineer with reconfiguration options to select and further analyze
- TC would speed up the process and may lead to more efficient outcomes
  - Reduces outage impacts (congestion and/or reliability)
  - Reduces effort to review outages



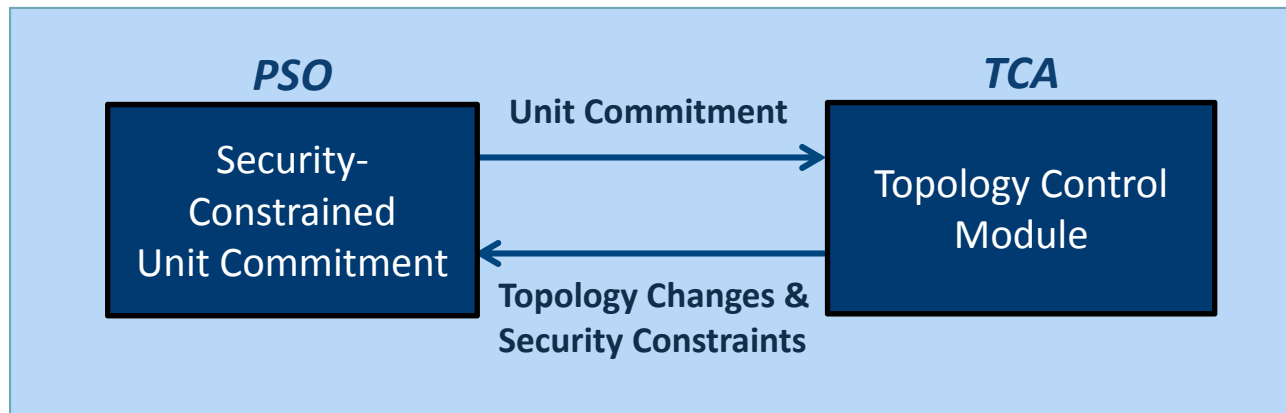
## Stress Test – 500 kV Facility Overload Relief

- We simulated a 300 MW overload on an important contingency constraint of a 500 kV branch by reducing the facility rating on a recent (July 2014) system snapshot
- In this analysis, transmission topology was the only variable allowed to be modified to relieve the induced overload – fixed dispatch
- TCA identified a collection of potential switching solutions, which included between 1 and 5 switching actions
- The potential solutions were tested by PJM staff on the EMS model
- Solutions were able to relieve the overload without causing other post- or pre-contingency violations
- Relieving a large overload on a 500 kV facility required removing other 500 kV facilities from service, to force power flow away from the overloaded branch



## DA Optimization with TCA – Architecture

- SCUC and TCA are solved iteratively until convergence criteria are met
- PSO\* used to provide UC solutions
  - MIP-based security-constrained UC
  - Integrated with TCA
  - Efficiently updates topology of the model
- TCA solves a multi-period problem with topology change constraints enforced
  - Minimum open/close duration of 4 hours used in these simulations



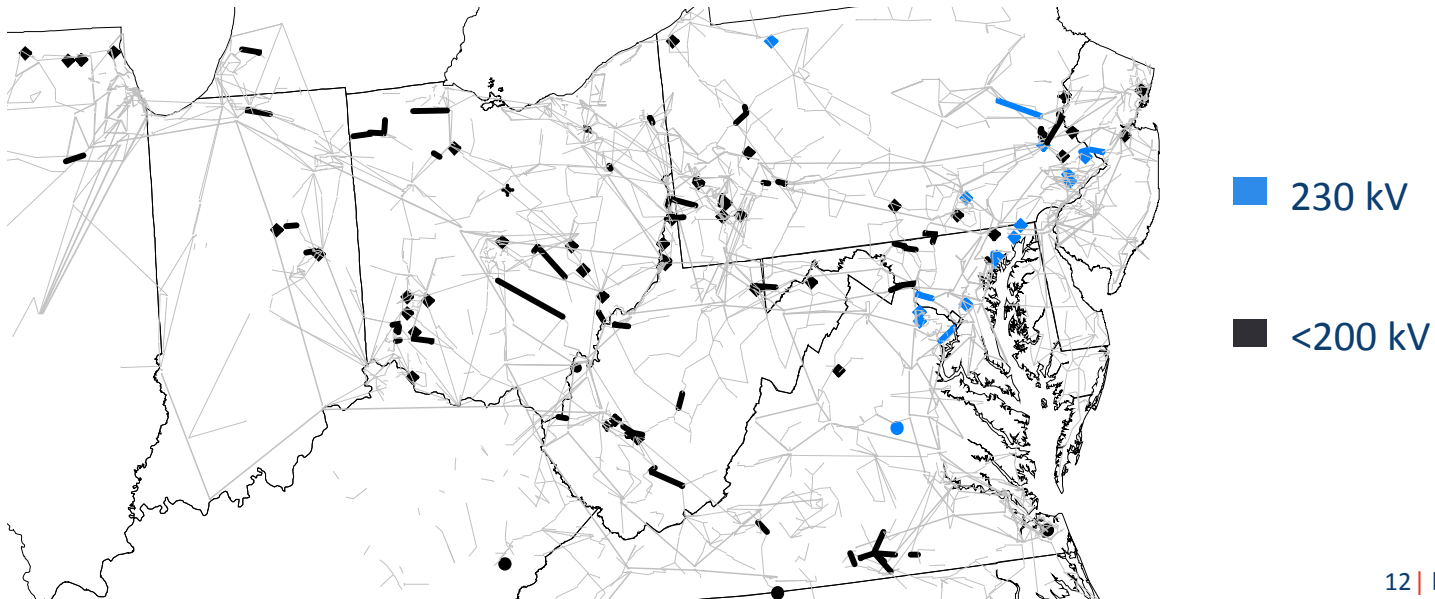
\* Provided by Polaris Systems Optimization, <http://www.psopt.com>



## PJM DA TCA Simulations – Switchable Set

- Topology changes are *restricted* to the set of branches currently included in PJM Switching Solutions\*
  - Allows RTO staff to provide feedback on the solutions based on experience
  - Small set consists of less than 195 branches – many tie breakers are consolidated away in the archived operations power flow cases
  - Expanding the switchable set would provide much greater benefits
- Results in this presentation are limited to 1 iteration between SCUC and TC
  - Results do not materially change after 1 iteration *with the restricted set*.

\* <http://www.pjm.com/markets-and-operations/etools/oasis/system-information/switching-solutions.aspx>





## PJM DA TCA Simulations – Other Settings

- Solution time: under **5 hours** for each DA simulation
- Cost of switching: minimum savings of \$800 per open or close breaker operation required to switch in the summer week, \$400 in the winter and shoulder weeks
- Reliability
  - Full security evaluation (6,000 contingencies) and enforcement (included in the 5 hour time limit)
- Network service requirements for all non-radial loads and generators
- Caveat: The congestion savings and percentages in the slides that follow make the presumption that the TCA solutions are viable. In practice, each solution requires full verification by PJM RTO staff and the individual facility owner(s) to verify the solution's viability



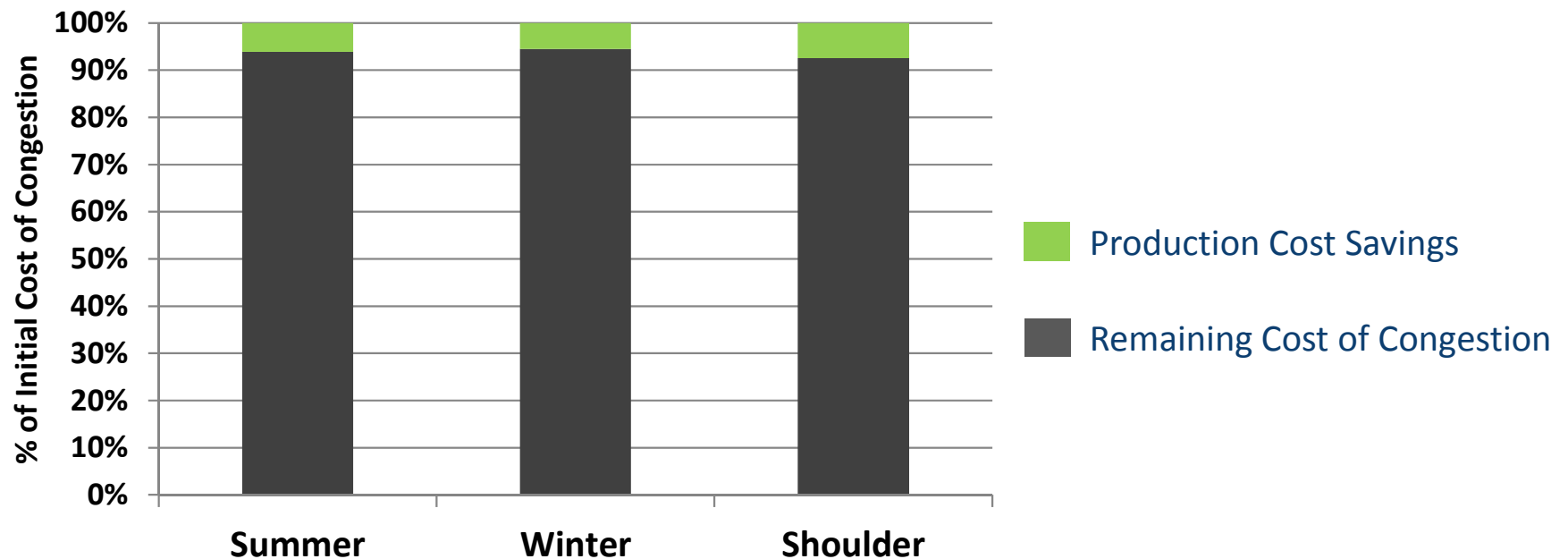
## **PJM DA Market Models: Historical Conditions**

- Models based on one operational power flow real-time snapshot per day for three representative historical weeks of average conditions in 2010 (summer, shoulder and winter weeks). Data used from the power flows:
  - Transmission topology and branch parameters
  - External system conditions (e.g., interchange, reciprocal flowgate use)
  - Dispatch of hydro, wind, landfill, nuclear and reliability must-run thermal units
  - Load time series (adjusted based on DA load forecasts for the day)
- Generation economic and transmission constraint data from operations and historical market conditions
- Model dimensions: up to 15,200 nodes and 650 dispatchable thermal PJM units, about 4,700 monitored branches and 6,100 single and multi-element contingencies



## DA Market Production Cost Savings

Savings in the Representative Weeks



*Savings and remaining cost of congestion shown as a percentage of the initial cost of congestion. Even with a severely limited switchable set, significant cost savings can still be achieved. Daily savings range from 0-11% for June, 3-15% for December, and 3-11% for November*

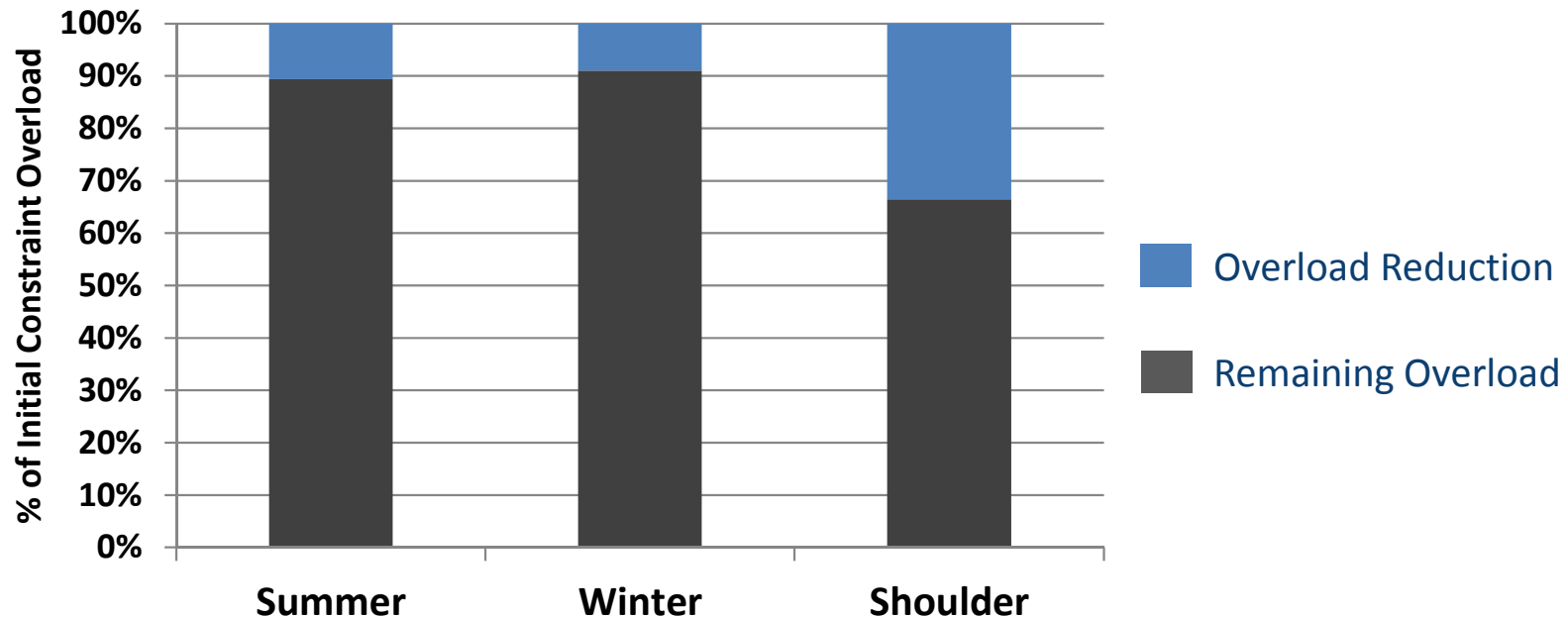
**Production Cost Savings** = production cost without TCA (full topology) – production costs with TCA

**Cost of Congestion** = production cost with transmission constraints – production costs without transmission constraints



## DA Market Constraint Overload Reduction

Overload Reductions in the Representative Weeks



*Overload reduction and remaining overload penalty shown as a percentage of the overload penalty before applying TCA. Even with a severely limited switchable set, significant overload reduction can still be achieved.*

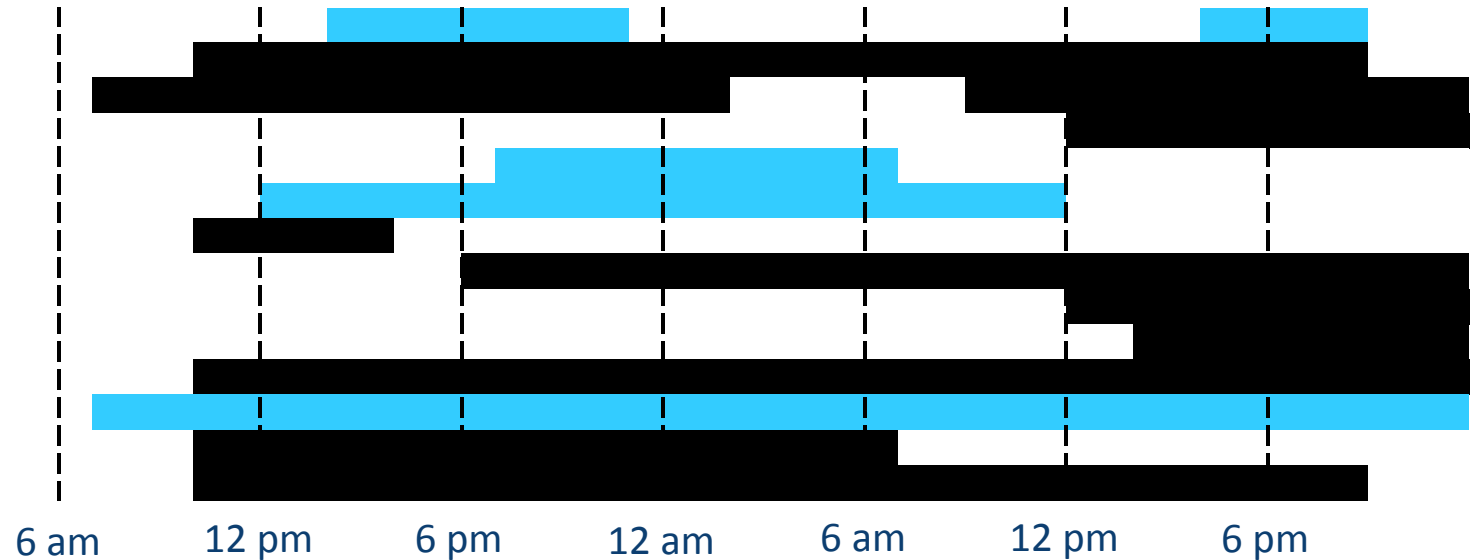


## PJM DA TCA Simulations: Switching

Representative Switching Solutions from June 22<sup>nd</sup> and 23<sup>rd</sup>, 2010

### Branch Opened by TCA

ALBURTIS230 KV TR 1  
BARNJNDP115 KV 33A  
BLACKOAK500 KV TRAN 3  
CRES DUQ138 KV CRE-MON  
DICKERSO230 KV DIC-QUI3  
DICKERSO230 KV DIC-QUI5  
GERMANTO115 KV GER-STR  
GERMANTO138 KV GER-TAN  
GRANDVAP138 KV GRA-HIN1  
HARTFORD138 KV HAR-VAL1  
MTWOOD 138 KV MTW-TRI  
PLVY PS 230 KV BUC-PLV  
WBELLAI2345 KV . 1  
WESCOSVI138 KV 3



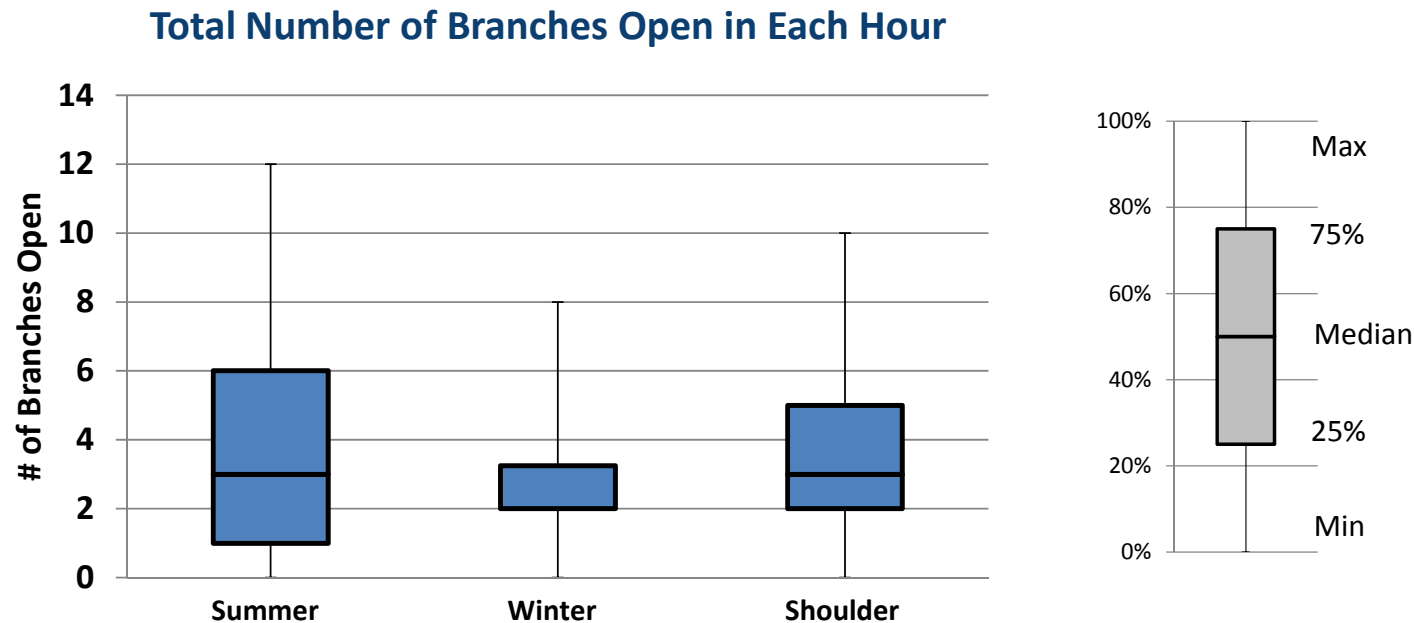
■ 230 kV ■ <200 kV Solid color blocks indicate the branch was opened in that hour

*Branches in the proposed topology trajectories are switched infrequently, and remain either closed or opened for an extended period of time after switching – the average duration for an opened branch is about 10 hours, for all three weeks simulated*





## TCA Topology Change Statistics



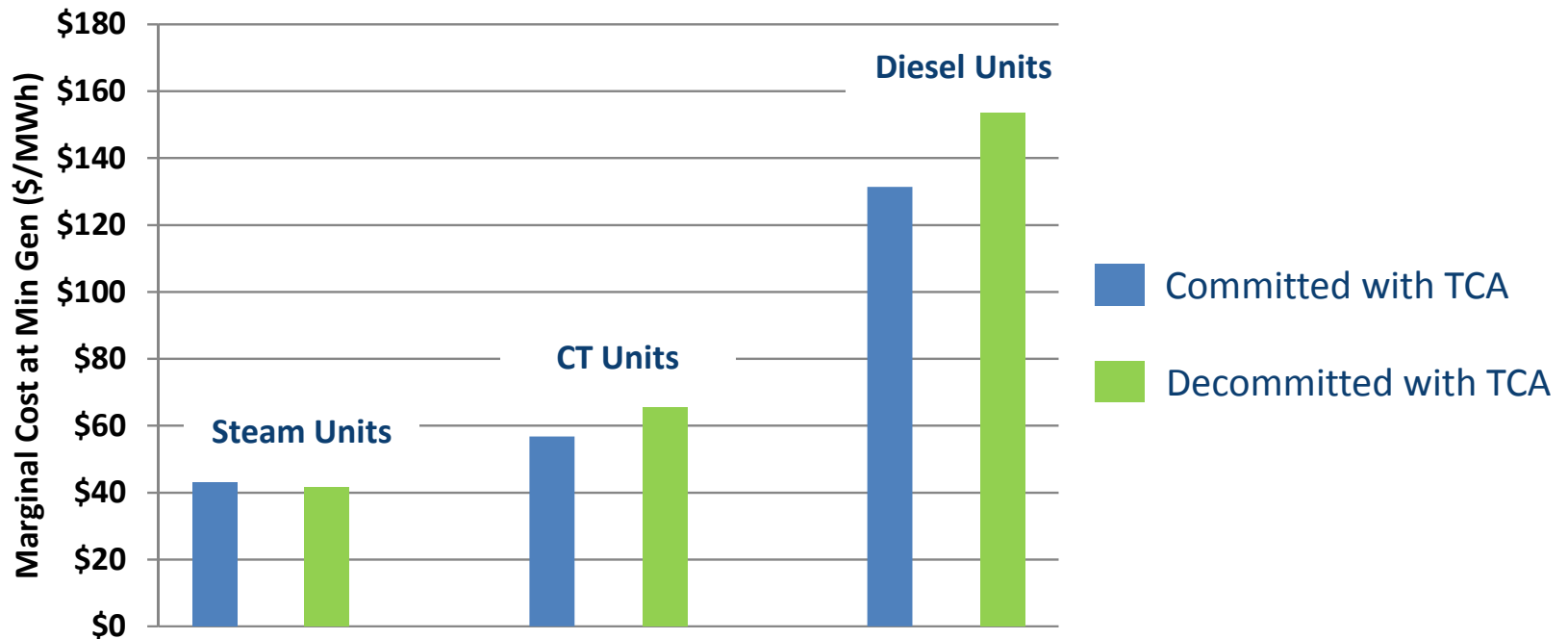
*The total number of branches switched open by TCA at any given hour is below 10 during most of the simulation. This is significantly lower than the number of branches that could be on outage at any given moment in PJM.*

*On average, the proposed topology trajectories indicate one branch switched open every 2 hours.*



## Unit Commitment Changes

Marginal Cost at Min Gen of Units Committed/Decommitted with TCA



*Marginal cost value is calculated using the capacity-weighted average of the units with modified commitment. On average, CTs and diesel units decommitted with TCA have a higher marginal cost at min gen. Steam units with modified commitment do not have a material difference in their marginal cost at min gen.*



# Concluding Remarks

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- Most system operators employ TC today, mainly on an ad-hoc basis using pre-identified solutions
- The TCA project will provide practical technology to enable transparent, consistent and routine identification of topology changes with significant efficiency and reliability gains
- Lessons from the PJM evaluation:
  - Security-constrained TCA solutions with AC, full EMS detail modeling are obtained in only a few minutes. These are very useful to support outage coordination processes and Op. Guide development.
  - Simulations on detailed PJM RT market models indicate that annual savings may be a large fraction of the total costs of congestion (estimated to be over \$100 million under 2010 conditions)
  - Co-optimized topology and unit commitment shows significant benefits even with a very limited switchable set; impacts with a larger switchable set are expected to be significantly larger (analysis ongoing)
  - Evaluation of TCA impacts on FTR settlements and revenue adequacy on the historical PJM models are ongoing (initial results expected by Q3 2015)



# Contact

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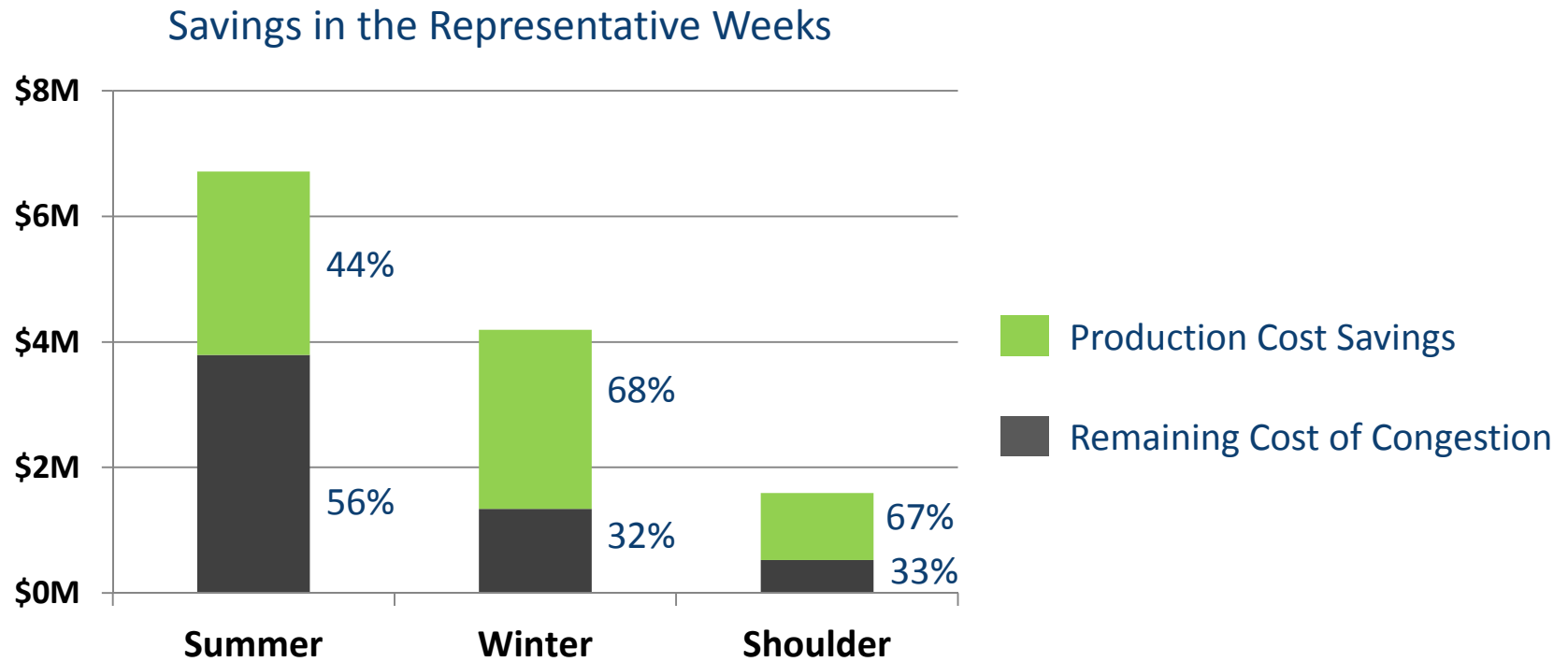
## Acknowledgments

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## RT Market Production Cost Savings



\* Savings and remaining cost of congestion shown as a percentage of the initial cost of congestion

**Production Cost Savings** = production cost without TCA (full topology) – production costs with TCA

**Cost of Congestion** = production cost with transmission constraints – production costs without transmission constraints





# References

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