MISO Market Design Overview and Evolution

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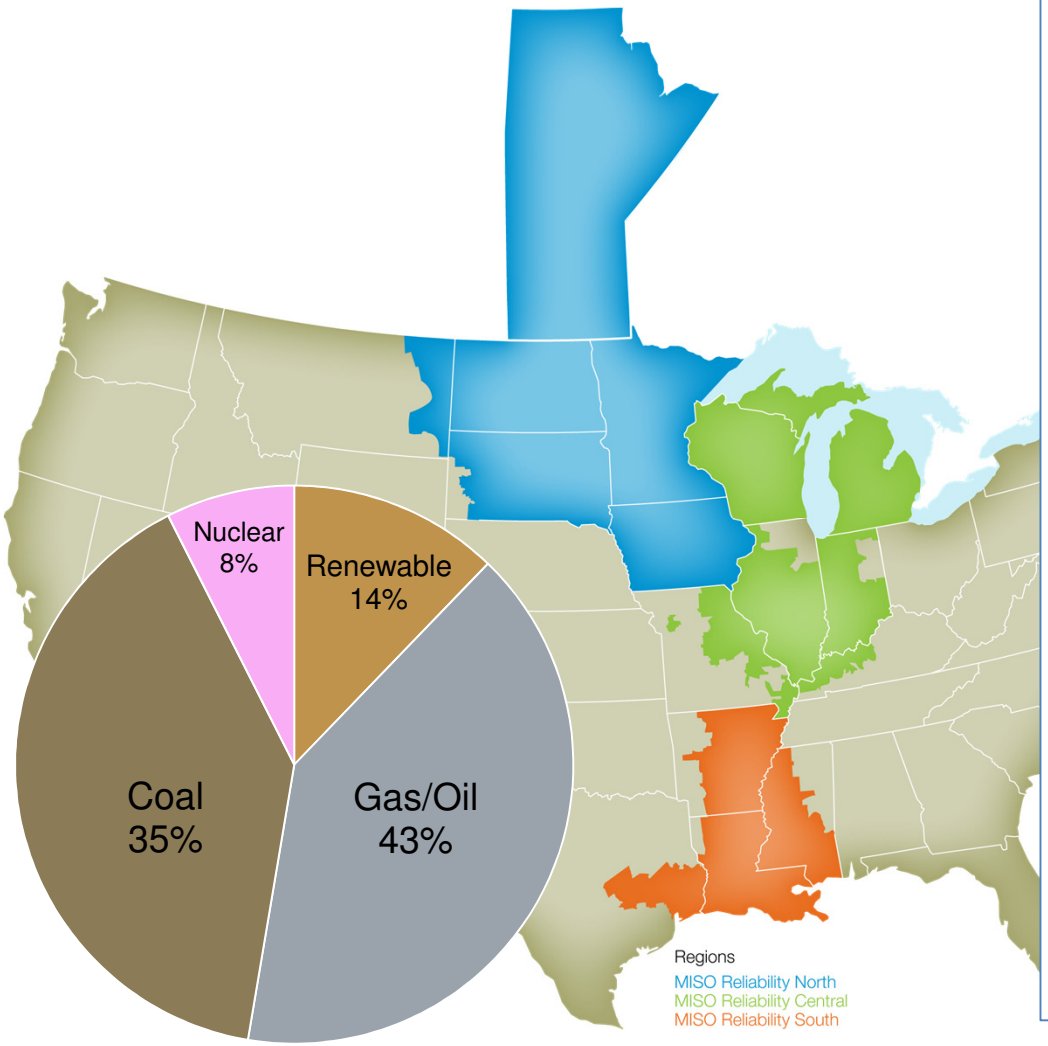
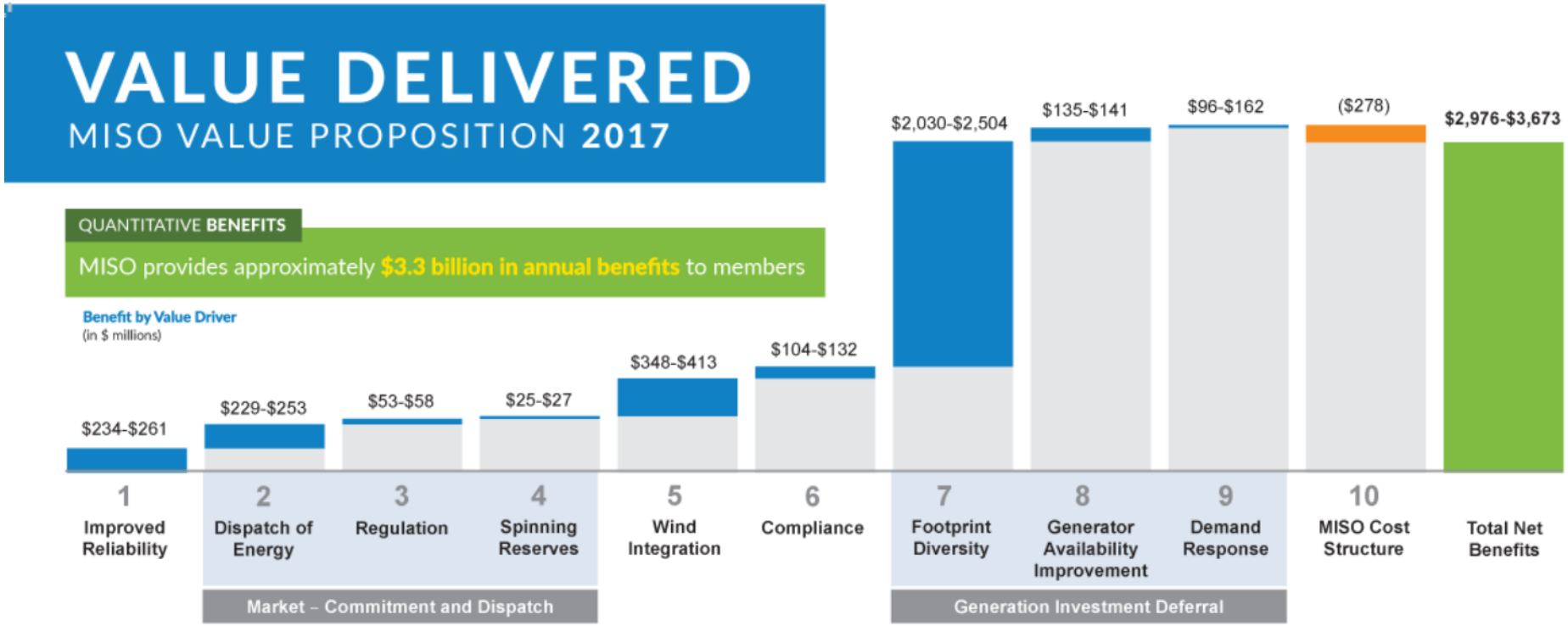
MISO Region

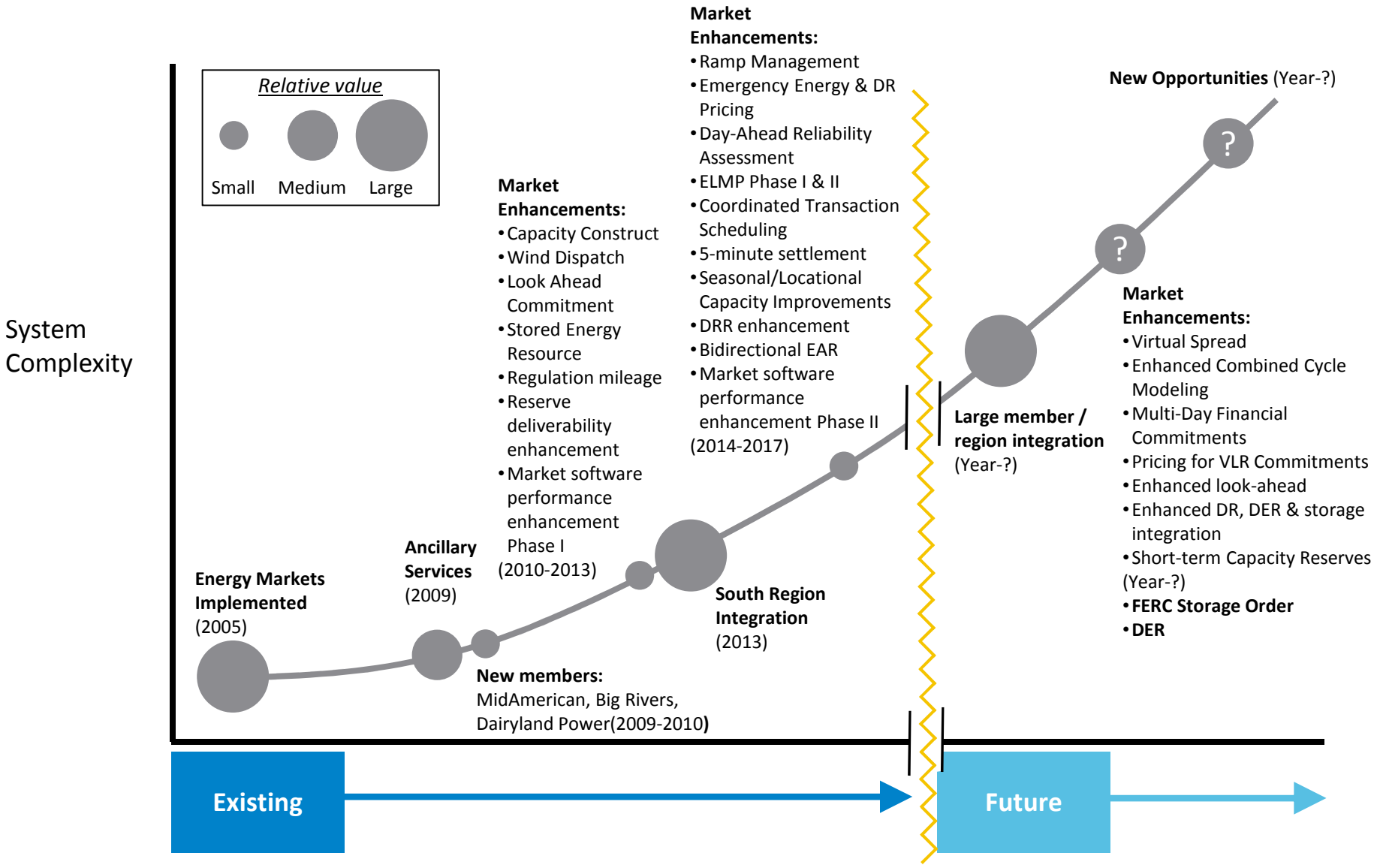


Key Statistics

Market Participants	408
MWs of Generating Capacity (Mkt)	174,874
Peak Load (MW)	127,125
Generating Units	1,401
Network Buses	45,098
Miles of Transmission Lines	65,800
Square Miles of Territory	900,000
States Served	15 Plus Manitoba Province, Canada
Millions of People Served	42

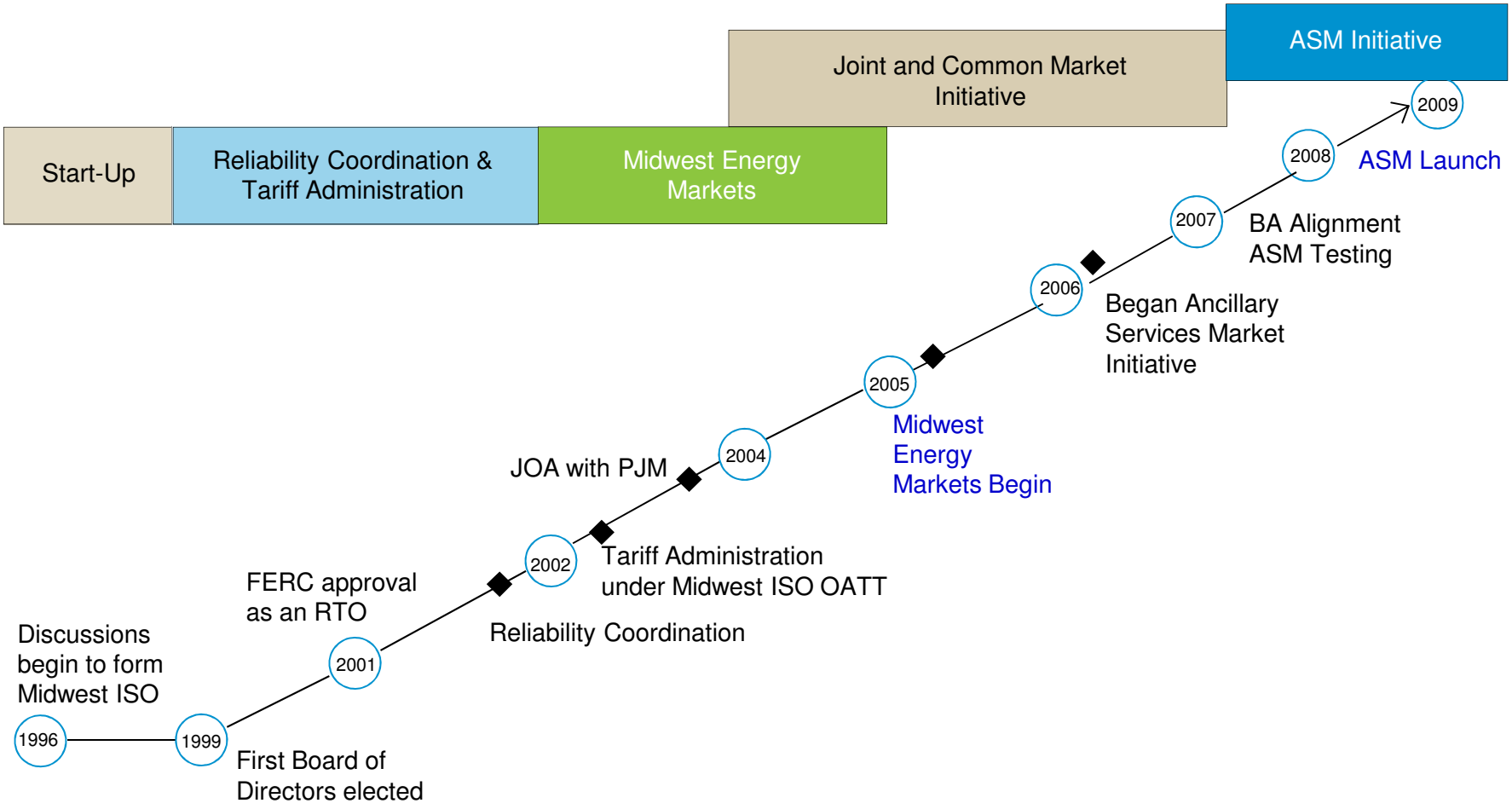


https://www.misoenergy.org/about/miso-value-proposition/


System Complexity
Relative value
Small
Medium
Large
Energy Markets Implemented (2005)
Ancillary Services (2009)
Market Enhancements:
• Capacity Construct
• Wind Dispatch
• Look Ahead Commitment
• Stored Energy Resource
• Regulation mileage
• Reserve deliverability enhancement
• Market software performance enhancement Phase I
(2010-2013)
New members: MidAmerican, Big Rivers, Dairyland Power(2009-2010)
South Region Integration (2013)
Market Enhancements:
• Ramp Management
• Emergency Energy & DR Pricing
• Day-Ahead Reliability Assessment
• ELMP Phase I & II
• Coordinated Transaction Scheduling
• 5-minute settlement
• Seasonal/Locational Capacity Improvements
• DRR enhancement
• Bidirectional EAR
• Market software performance enhancement Phase II
(2014-2017)
Large member / region integration (Year-?)
New Opportunities (Year-?)
?
?
Market Enhancements:
• Virtual Spread
• Enhanced Combined Cycle Modeling
• Multi-Day Financial Commitments
• Pricing for VLR Commitments
• Enhanced look-ahead
• Enhanced DR, DER & storage integration
• Short-term Capacity Reserves (Year-?)
• FERC Storage Order
• DER
Existing
Future

Experience of establishing MISO energy and AS markets

Establishing MISO Market



2001-2009

2001 - Reliability Coordinator

2005 - Energy Market

- Day Ahead, Real Time, FTR
- MISO sent dispatch target and Net Scheduled Interchange to 26 Balancing Authorities
  - Each BA carried its own reserves and ran its own AGC

2009 – Ancillary Service Market

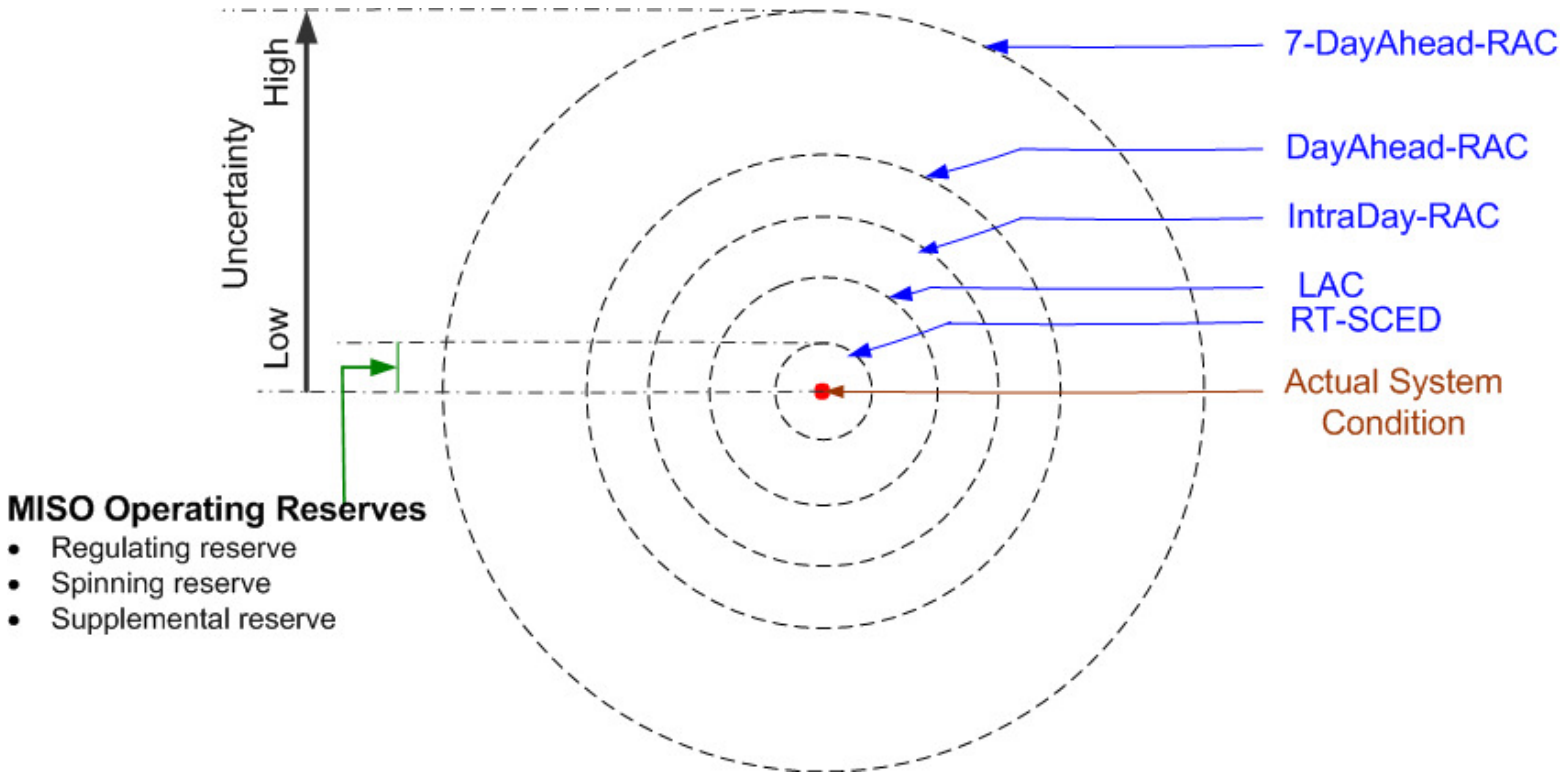
- MISO co-optimizes energy with Regulating Reserve, Spinning Reserve, Supplemental Reserve
- Consolidated into one Balancing Authority
- Benefit from consolidated BA
  - Reduced AS requirement
    - **Regulating reserve: pre-ASM total 1159MW, post-ASM 396MW**
    - **Spinning reserve: pre-ASM total 1482MW, post-ASM 935MW**
  - Efficient commitment and dispatch

Highlights of MISO DA and RT Systems

Co-optimization of Energy, Regulating Reserve and Contingency Reserve	Ex-post pricing	Two-market settlement
• Day Ahead market: SCUC and SCED: 99% of the resources are committed in DA market • Real time market: Forward RAC, Intra-day RAC, Look-ahead commitment, Real Time SCED • 7-day Forward RAC for slow start long lead units	• Implemented Extended LMP in 2015 to incorporate fixed cost from fast start resources into market clearing prices	• DA settlement based on DA LMP and MCP: Congestion can be hedged against FTR, Revenue sufficiency guarantee • RT settlement based on hourly LMP and hourly MCP: Incremental from DA, Price volatility make whole payment

Level of Uncertainty Varies along the Processes

- Expected difference between the actual system condition and the market clearing models



RAC: Reliability Assessment Commitment
LAC: Look-ahead Unit Commitment
RT-SCED: real time Security Constrained Economic Dispatch

Contingency reserve includes spinning and 10-min online and offline supplemental reserves

Market resource and eligibility for market products

	Energy	Regulating Reserve	Spinning Reserve	Supplemental Reserve	Ramp Product	Capacity
Generator	**Y***	**Y***	**Y***	**Y***	**Y***	**Y***
DRR-I	Y*	N	Y*	Y*	N	Y*
DRR-II/SERII	**Y***	**Y***	**Y***	**Y***	**Y***	**Y***
SER	**N**	**Y***	**N**	**N**	**N**	**N**
EAR	Y*	Y*	Y*	Y*	Y*	Y*
DIR	Y*	N	N	N	Y*	Y*

- Subject to qualification, offer status and commitment

- DRR: Demand Response Resource
- EAR: External Asynchronies Resource
- New ESR (Electrical Storage Resource) will be created for Order 841
- SER: Stored Energy Resource
- DIR: Dispatchable Intermittent Resource

Examples of other services not settled through market

- Reactive power supply and voltage control (transmission settlement)
- Blackstart service (transmission settlement)
- Primary frequency response (no compensated)

Co-optimized Energy and ASM Development

- Co-optimized Energy and ASM development (2007-2009)
- Summary
  - Reserve products: regulating, spinning and supplemental reserves
  - **Interesting experience in developing ramp constraints during ASM parallel operation (flexibility management)**
    - A mathematically simple ramp constraint may cause big difference on clearing results and prices
  - **Reserve deliverability**
    - Zonal reserve requirement
    - Post zonal reserve deployment transmission constraints

Reserve Deliverability

- Started with define reserve zones and enforce zonal reserve requirement constraints
  - Enforce reserve zone requirement constraints inside SCUC and SCED
    - Minimum zonal regulating reserve constraints
    - Minimum zonal regulating plus spinning reserve constraints
    - Minimum zonal operating reserve constraints
  - Count on offline study to provide
    - Reserve zone definition (quarterly update)
    - Minimum zonal reserve requirements (three-day ahead study)

Issue with the offline zonal reserve requirements

Differences between offline studies and actual system conditions

- Very difficult to develop proper zonal reserve requirements from offline study

Historical scenario 1:

- Energy on the sending end was dispatched down in a zone to relief congestion
  - 600MW (~75%) of spinning reserve was cleared in that zone: not deliverable if deployed
  - Offline study was not able to identify the congestion issue and provide proper zonal reserve requirements on the receiving end

Historical scenario 2:

- Pre-set zonal reserve requirement caused zonal price spike but didn't improve post-deployment flow at all

Enhanced Approach to Incorporate Post Reserve Deployment Transmission Constraints

- **Solve co-optimized reserve zone requirements to meet deliverability on a zonal basis**
  - Post-Regulating Reserve Deployment Up and Down Transmission Constraints

    "Flow from Energy" + "Flow from regulation deployment"

    - "Flow from load deviation" ≤ Limit
  - Post-Contingency Reserve Deployment Transmission Constraints (one for each reserve zone)

    "Flow from Energy" - "Flow from largest zonal gen trip"

    + "Flow from spin deployment"

    + "Flow from supplemental deployment" ≤ Limit

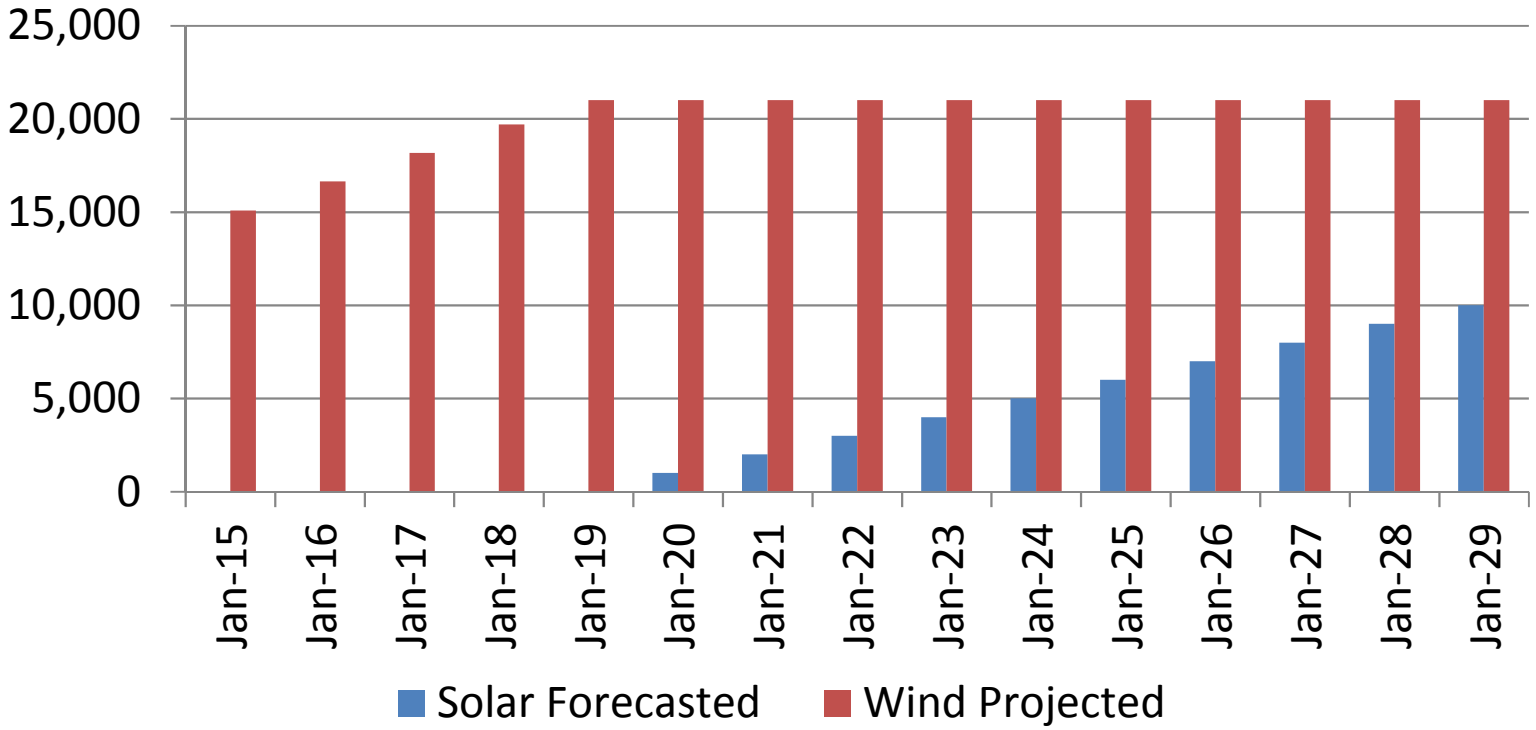
Flexibility

Flexibility Management

Early stage (2005-2008): energy only market

- DA and RT two market settlement
  - Hourly offer, may be changed 30-min prior to the hour in RT market
  - Real time 5-min dispatch, settled on hourly average LMP
    - RT price volatility may cause resources to lose profit. Resources may set limits at DA position or set ramp close to 0 to reduce the risk from RT volatility
- In addition to Day Ahead make whole payment, designed price volatility make-whole-payment:
  - Make resource whole in RT market if losing profit by following RT dispatch
    - $LMP_{RT}*(MW_{RT}-MW_{DA}) < Cost_{RT}(MW_{RT})-Cost_{DA}(MW_{DA})$
  - Ensure that a unit is not losing profit from DA when following MISO RT instructions
  - Eligible to resources not reduce flexibility between DA and RT (i.e., not shrink dispatch range or reduce ramp rate)

MISO Long-Term Forecast of Wind and Solar



Post Ancillary Service Market (2009-)

Challenge to maintain real time ramping capability with increased renewable integration

- Hourly DA and RAC study intervals cannot guarantee enough on-line ramping capability
- Single interval RT-SCED does not optimize ramping capability over ramping up and down periods
- Uncertainties from input data may require additional ramp to respond to the deviations
- Need to call on quick start resources in real time to address real time ramping issues
  - High real time RSG make whole payment

Market enhancement and initiatives to better manage flexibility

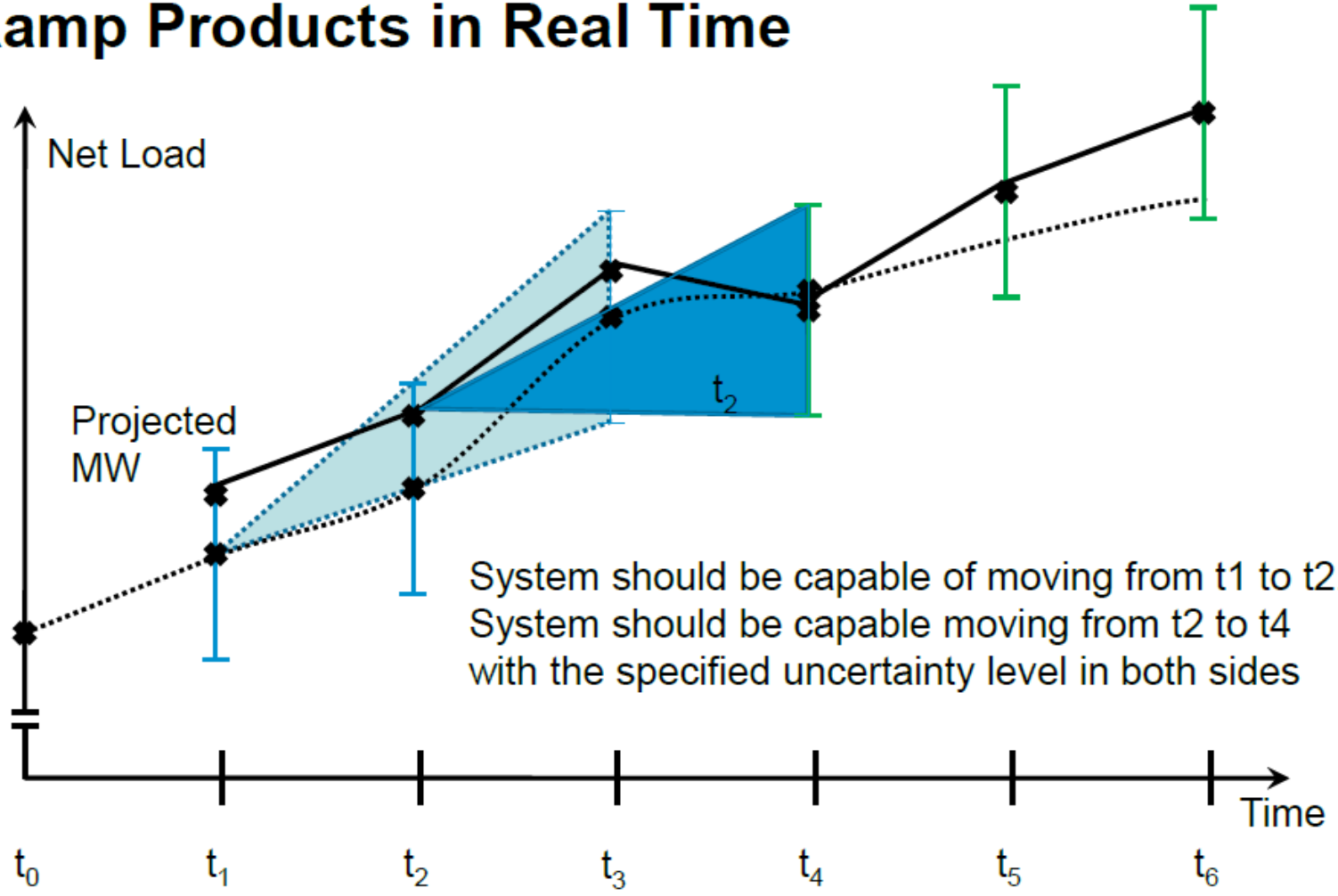
- Implemented Look Ahead Commitment to better commit quick start resources and optimize ramping capability over 3-hour
  - Runs every 15 min
- Implemented 30-min ramp requirement constraints in DA-SCUC and RAC to improve on line resource flexibility
  - Implemented up and down ramp capability products
- Implemented Dispatchable Intermittent Resource (DIR)
- Several enhancements and projects to integrate demand response resources and storages into the market

Look ahead dispatch versus ramp capability products

Ramp capability products

- Up and down 10-min ramp requirements implemented in all the market clearing processes
- Market clearing prices can properly value resources for providing flexibilities
- Ramp capability acts as a buffer to absorb forecasted and unexpected operational variability
  - Ramp retained in previous dispatch is available for energy dispatch in current RT dispatch

Ramp Products in Real Time



Dynamic ramp requirements reflect real-time system needs

- Vary by time to capture different system ramping needs
- Adaptive to evolutions such as wind/solar growth

Short-term forecast of load, wind, etc.

Historical forecast errors, unit deviating from dispatch, etc.

$$R^{up}_{t,10\min} = \max\{0, \hat{p}^{D}_{t+10\min|t} - p^{D}_{t} + a\sigma_{t,10\min}\}$$

Dispatchable Intermittent Resource

What is a “Dispatchable Intermittent Resource”?

A DIR is very similar to a standard generation resource

- Difference: Generation resource supplies Max Limit as an offer-parameter; Dispatchable Intermittent will provide a forecast that will be used as Max Limit
- The resource IS included in the day-ahead and real-time co-optimization, and IS eligible to set price

The resource can submit offers for Energy, and will clear between Min and Max Limits, based on Economics

- **For RT dispatch, a five-minute periodicity, rolling forecast is used as the Maximum Dispatch capability of the resource**

Energy Imbalance and Congestion Management Before/After

Before

- Intermittent Resource is not dispatchable
- Manual curtailment of Intermittent is performed
  - Need to declare emergency for over generation
  - Manual curtailment didn't produce proper price signal

After

- Dispatchable Intermittent Resource can be economically dispatched
  - Much less declaration of over generation emergency
  - Proper price signal (e.g., negative LMP) when wind is dispatched down

Price Formation

MISO Price Formation – *Develop transparent market prices reflective of marginal system cost*

Featured by:

- Nodal network representation
- Energy & Reserve co-optimization
- Efficient Scarcity Pricing
- Market-based approach to integrate renewables and incentivize flexibility
- Transparent pricing including eligibility of demand response

Market Launch
Nodal network model
Hourly Offer Updates
2005

Energy Ancillary Co-optimization
Operating Reserve Demand Curves
2009

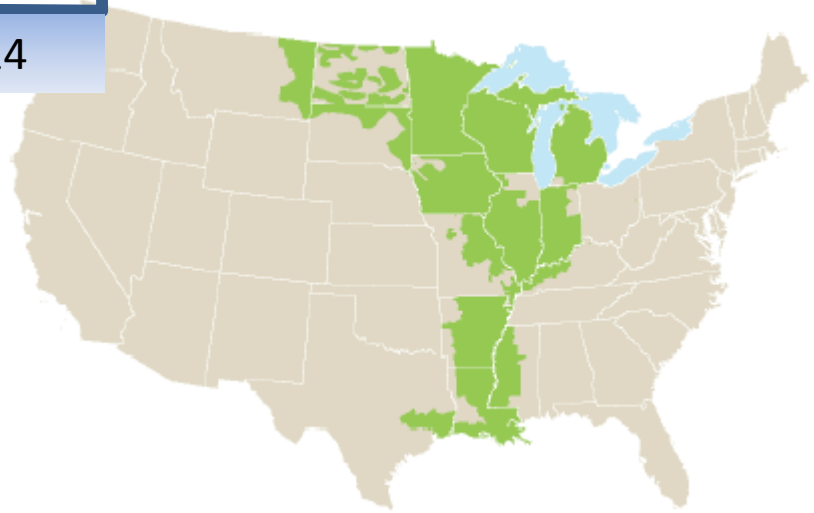
Transmission Constraint Demand Curves
2013

MISO Market Vision & Roadmap Established
2014

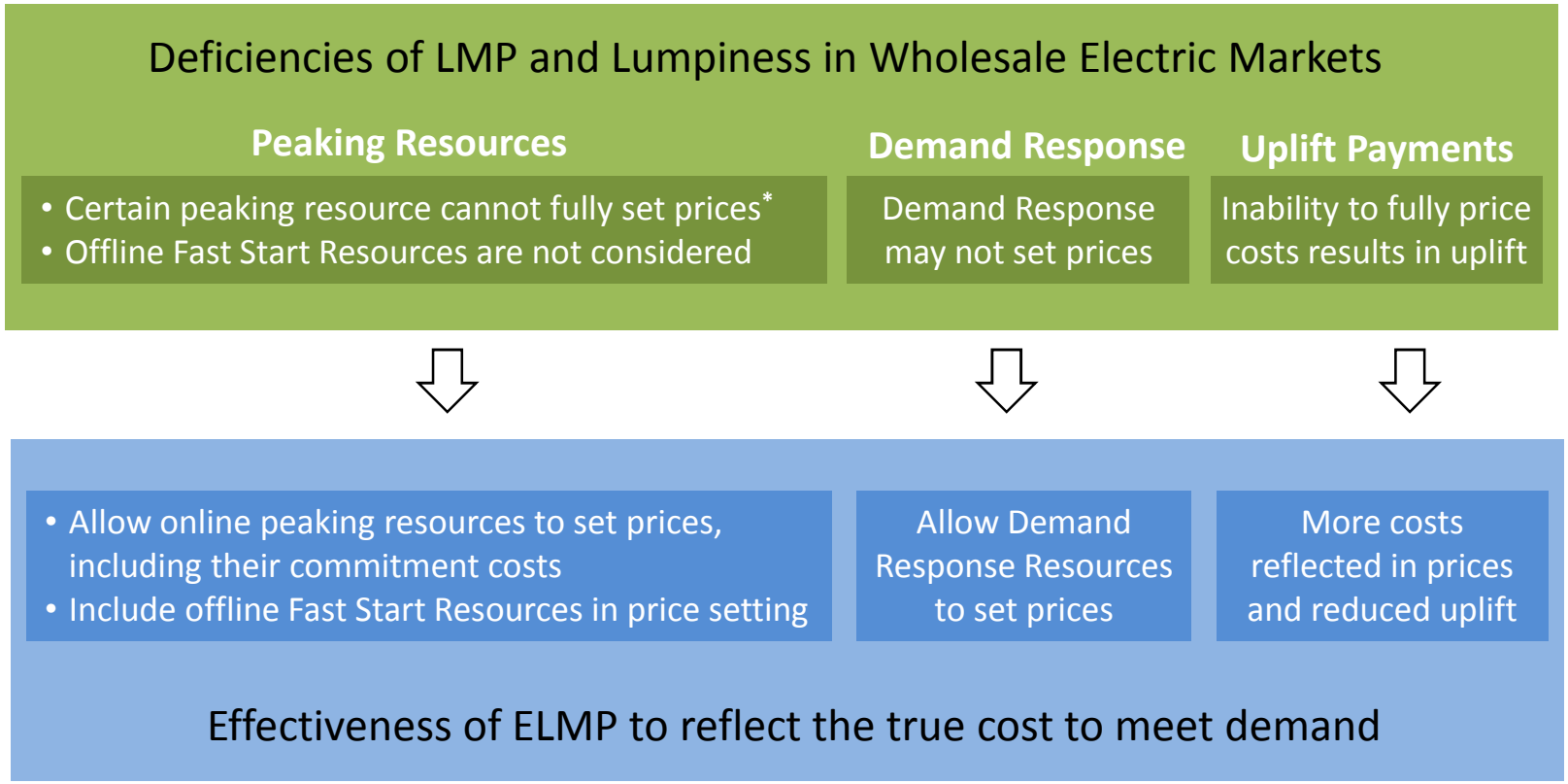
ELMP Phase I
2015

Ramp Capability Product
Emergency Energy and Demand Response Pricing
2016

ELMP Phase II
Five-Minute Settlement
2017



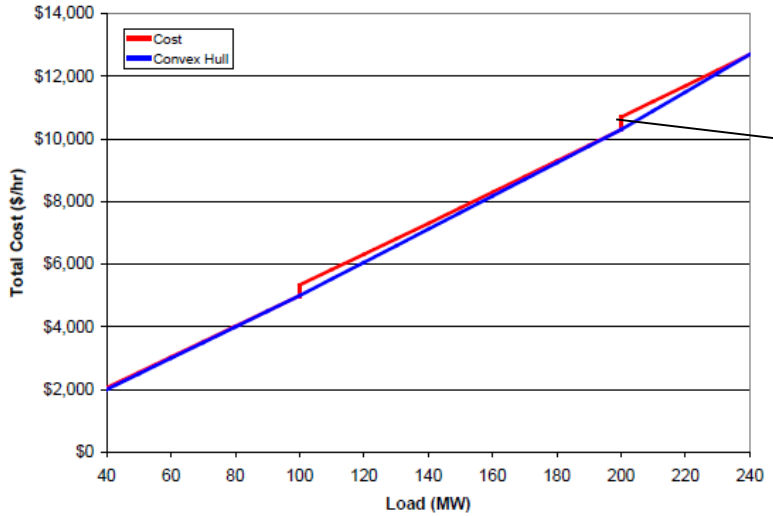
Extended LMP (ELMP) – *Reflect the costs of commitment as well as dispatch (Allow Peaking Resources and Demand Response to set price)*



**Note: Units that are started quickly in real-time to meet demands but dispatched at limits, e.g., block-loaded gas turbines, cannot set prices. Their commitment costs cannot be reflected in prices either and uplift has to be used to cover the costs*

ELMP Methodology

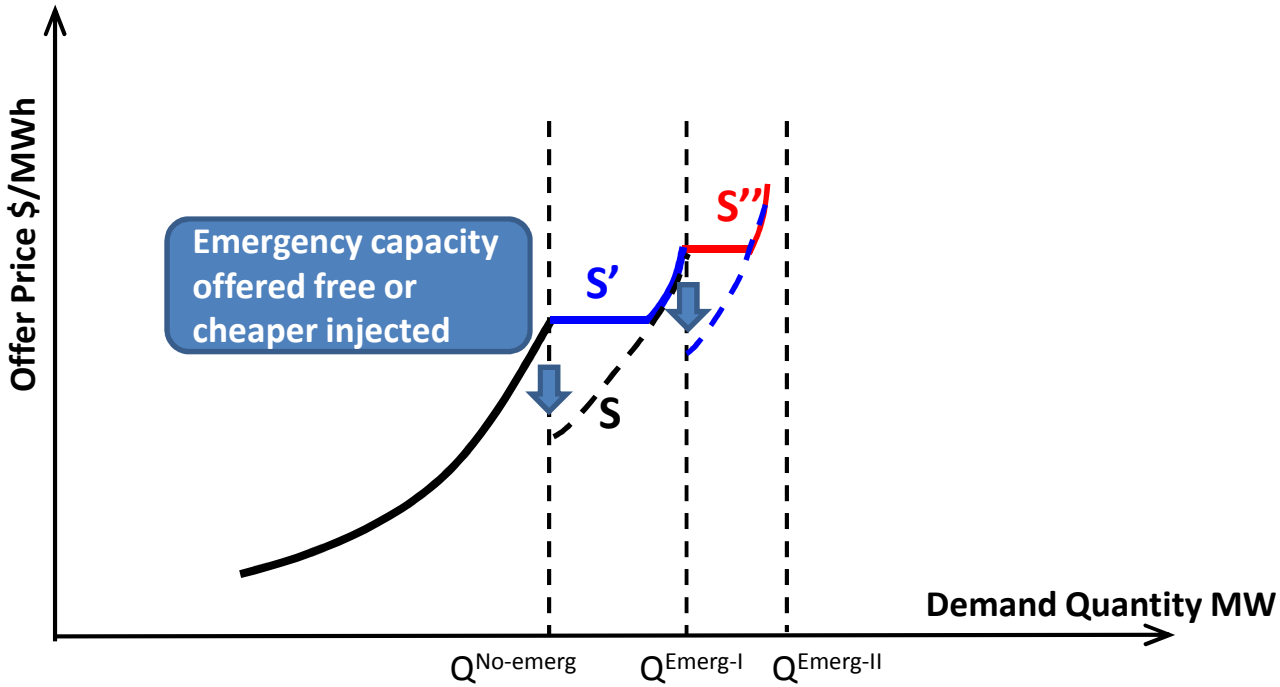
- **Mathematical Foundation**: ELMP is developed from the concept of "Convex Hull" to effectively incorporate commitment costs into prices



Lumpiness/Non-convexity of the least-cost function arising from unit commitment

- **Economic Concepts**: ELMP has been demonstrated closest to the fundamental concepts in defining a market price
  - Market Clearing Price: Prices at which producers would like to produce the same amount that consumers would like to consume
  - Efficient Price: Maximize the societal surplus
  - Core of the Market Game: No producers or consumers could do better than accept their schedules and prices from the market

- Implemented emergency pricing enhancement
  - Emergency Offer Floor to avoid price depression when emergency capacity is called on



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Market enhancement to better utilize non-traditional resources

MISO market facilitates non-discriminatory market participation regardless of resource type, business model, sector or location

In addition to traditional generation resources, MISO tariff allows new resource types to provide energy and ancillary service

- Demand Response Resource Type I (DRR-I)
- Demand Response Resource Type II (DRR-II)
- Stored Energy Resource (SER)
- Stored Energy Resource II (SER II)
- External Asynchronous Resource (EAR)
- Dispatchable intermittent resource (DIR)

Non-traditional resources such as DRR-II, SER-II and EAR can bring large ramping capabilities

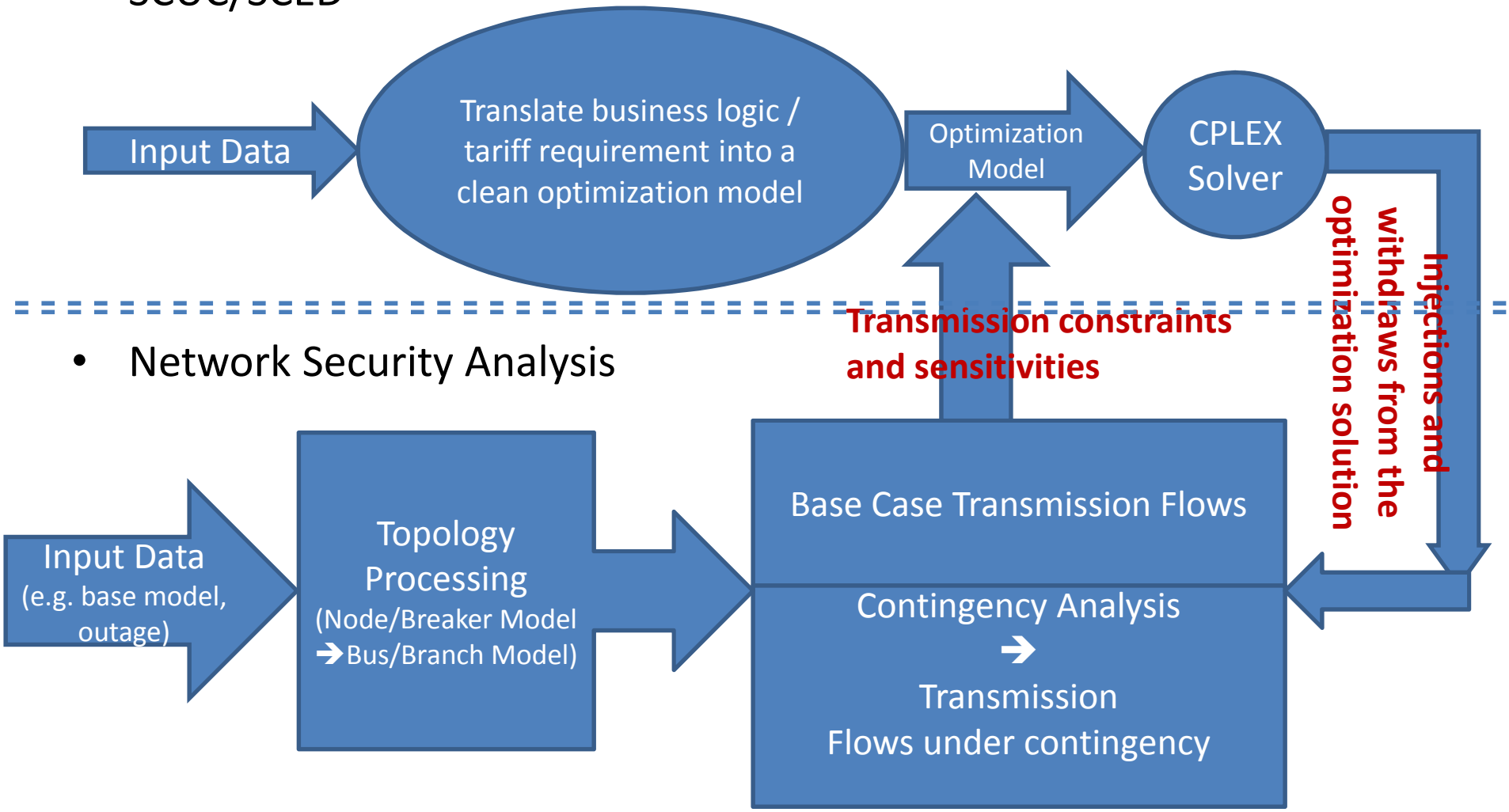
Future resource portfolio and emerging trends

- Storage
  - Introduced Stored Energy Resource (SER): 2010
  - FERC Order 755 – performance based two-part regulating reserve compensation: 2012
  - AGC enhancement on fast ramping resources – create a fast AGC signal to better utilize fast ramping resources
  - Recent FERC Order 841: storage participation model with size down to 0.1MW
- DER
  - Recent FERC tech conference
  - Size, aggregation across multiple locations, T&D interface, regulatory issue, dual usage, …
- Virtual power plant
- Large renewable penetration
- Transmission technology
- …….

- **Challenges: LMP based market under reduced marginal cost**

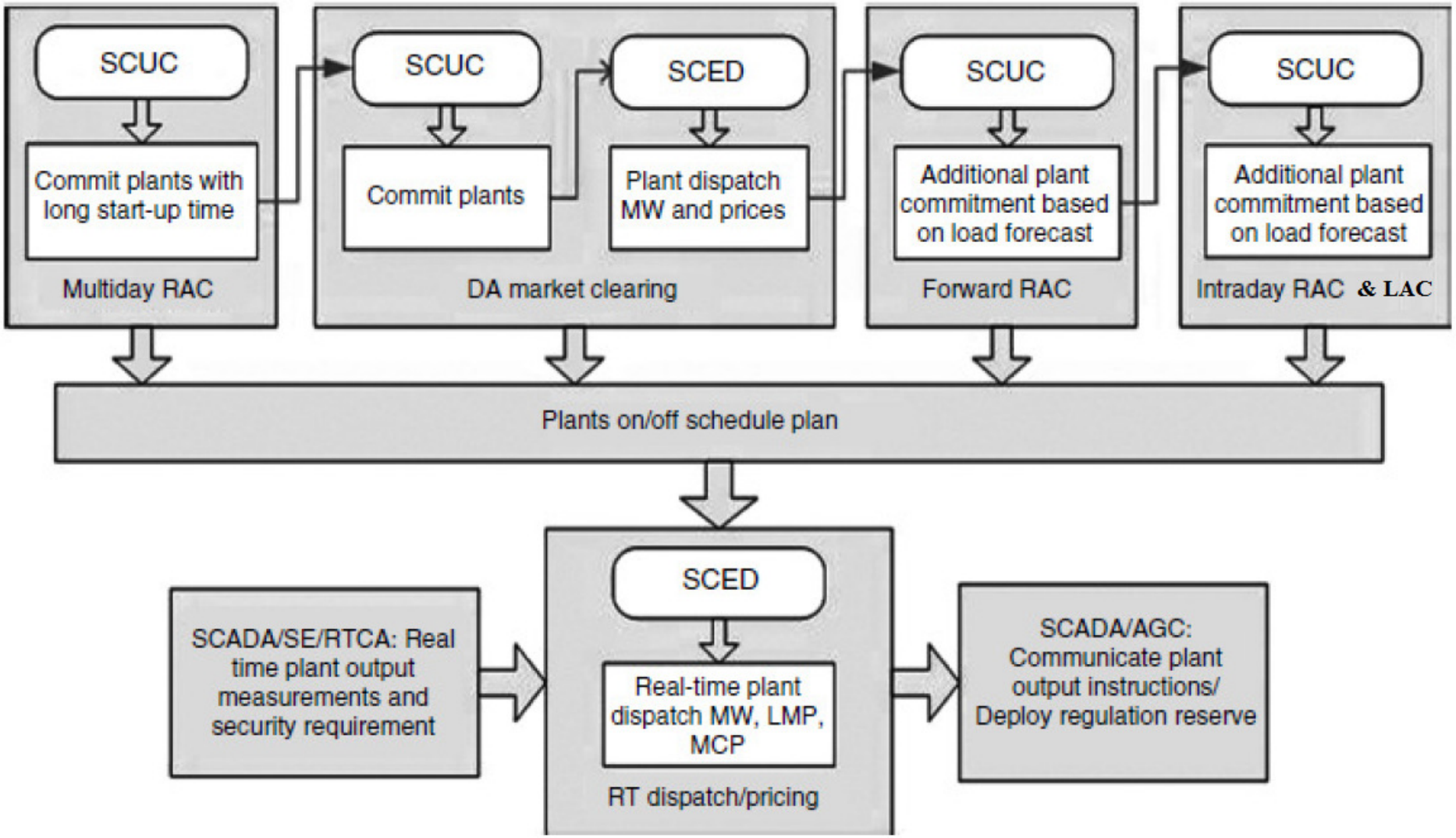
MISO Market Clearing System

- SCUC/SCED



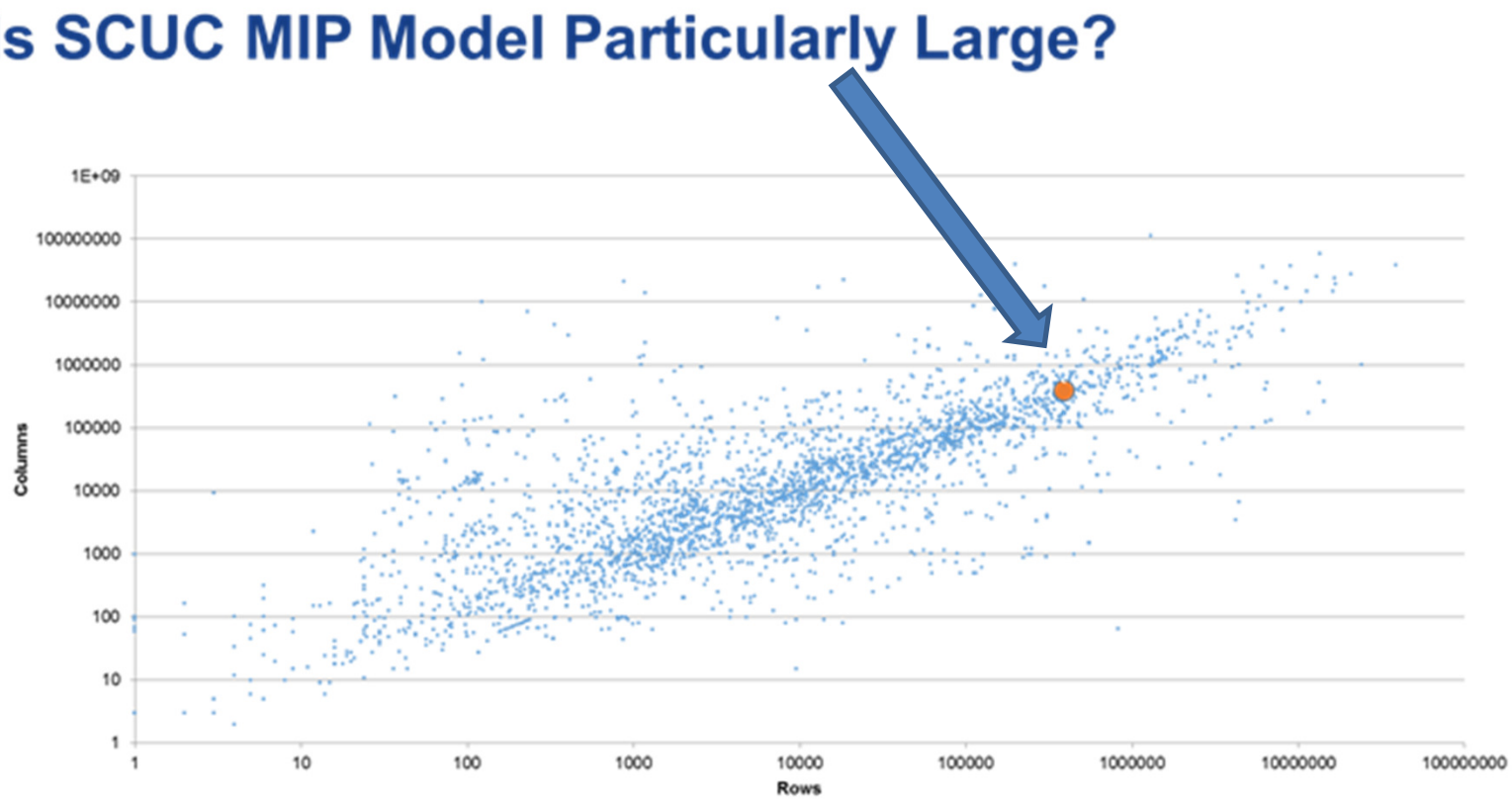
- Network Security Analysis

Multi-stage Market Clearing Processes

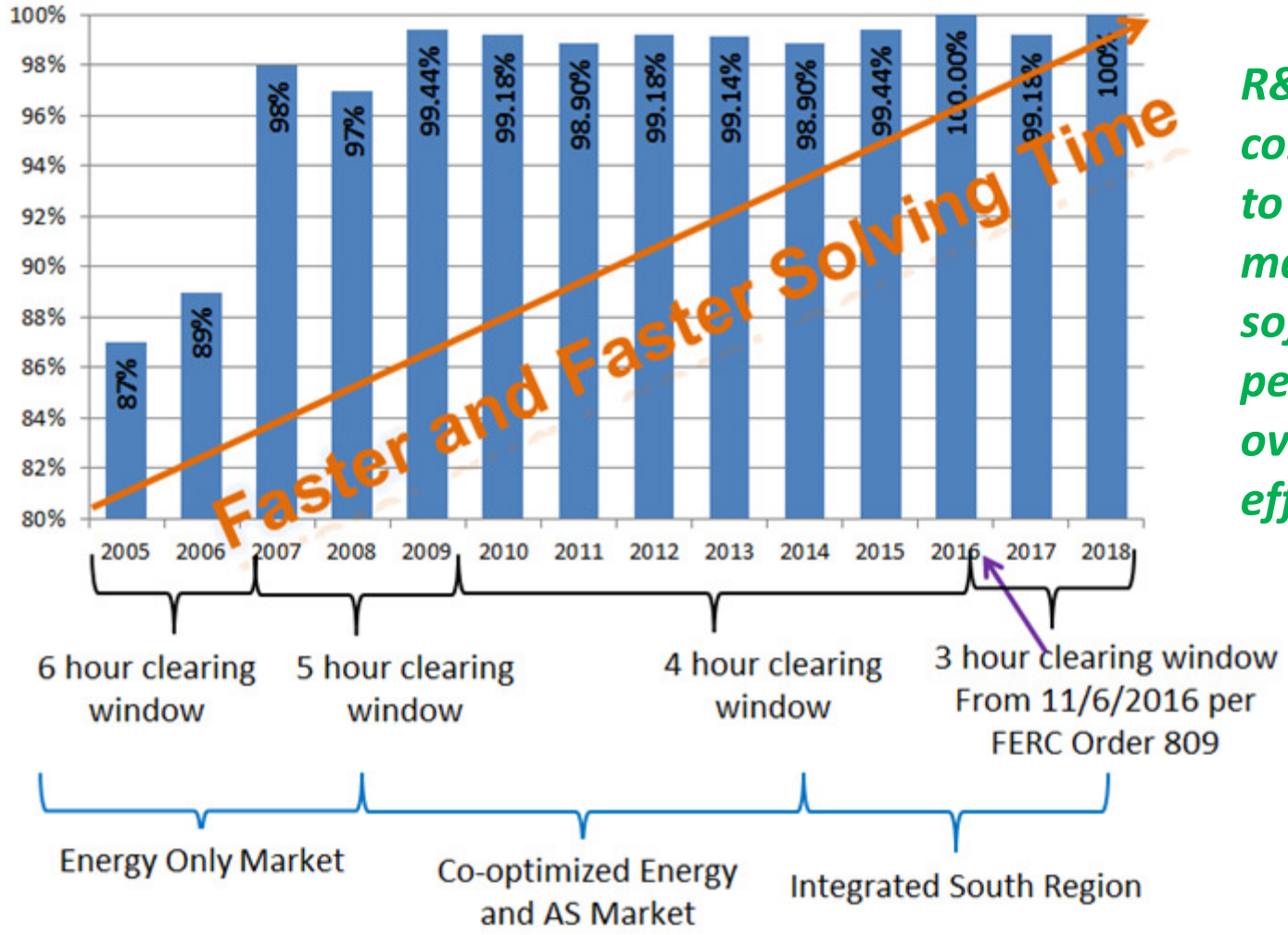


Large size with limited time and high accuracy requirement

- 20 minute and 0.1% MIP gap for each DA SCUC run
- 2-3 runs



MISO strives for enhanced performance of market clearing results as we continue to grow in size and complexity



R&D has contributed greatly to advancing the market clearing software performance and overall market efficiency

MISO is preparing for the future …

Current

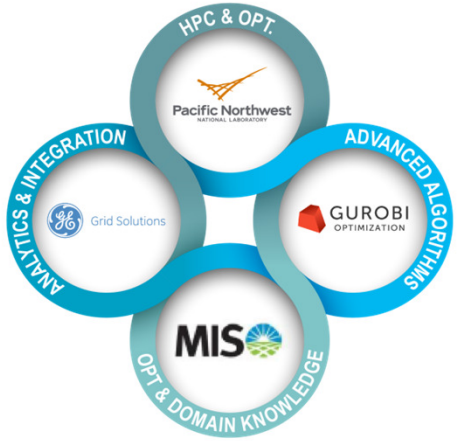
- **System**
  - Centralized power plants over high voltage transmission system
    - Relatively **sparse** transmission flow matrix with generators
      - Distributed virtual transactions that may increase the **density**
  - **Non-convex resource model**
    - Scheduling and pricing challenges
- **Applications**
  - Simplification with DC-OPF
  - Deterministic SCUC/SCED
    - *Day-ahead SCUC is the most computationally challenging application*
    - **Techniques: advanced modeling and commercial MIP solver**

Future

- **System**
  - Portfolio changes
    - Potentially more, **smaller-size distributed resources**
    - More renewable and gas resources
    - More **complicated configurations** (Combined Cycle, Storage, VPP)
  - **Non-convexity + density + uncertainty**
    - Low marginal cost
    - Scheduling and pricing challenges
- **Applications**
  - ***Centralized, or hierarchical, or distributed optimization?***
  - ***DC-OPF sufficient?***
  - ***Existing tools scalable?***
  - ***Multi-scenario / stochastic?***
  - ***Advanced data analytics***

ARPA-E HIPPO Project: Enhance DA SCUC performance through R&D on algorithms & parallel computing

Co-Development



UF UNIVERSITY of FLORIDA THE UNIVERSITY OF TENNESSEE KNOXVILLE Lawrence Livermore National Laboratory

Lead, PNNL. MIP, algorithm development, HPC, implementation and testing

GUROBI. MIP, Gurobi solver and parallel/distributed computing

MISO. domain knowledge, algorithm development, data, model validation, market operations, and Mixed Integer Programming (MIP)

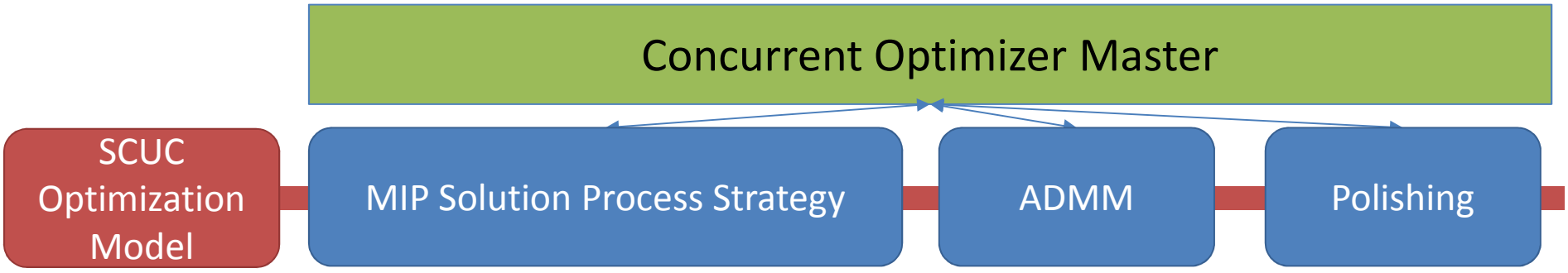
GE. Market simulator, benchmark, domain knowledge, MIP and optimal power flow (OPF).

University of Florida. Optimization, cutting planes, and integer programming.

Lawrence Livermore National Laboratories. Parallel MIP.

MISO also contracted with experts and fellows from other research entities (e.g., UTK)

New solution approaches: Explore parallel computing under ARPA-E HIPPO project



Tighter model

Model used by optimization approaches. [Benchmarked standard solver with 90 cases].

RINS-E and Variable fixing

- **Retrieve interim information** (variable & constraint fixing)
- ***Quicker upper solution, no global LB***

Symmetry & Partition

- **Partition & identify Symmetry** (partition; smart branching)
- ***Promising results***

Decomposition

- **Break a large problem into small pieces** (by generators & time intervals)
- ***Fast but hard to converge***

Neighborhood Search

- **Reduce the problem size** (fix commitment, dispatch variables & set lazy constraints)
- ***Small MIP problem with guaranteed feasible solution, no global LB***

HIPPO concurrent solver milestones:

Hard cases: 2x by 09/2018 and 10x by 09/2019

Easy cases: similar to MIP solver

THANK YOU

ANY QUESTIONS?