Resource Commitment and Dispatch in the PJM Wholesale Electricity Market

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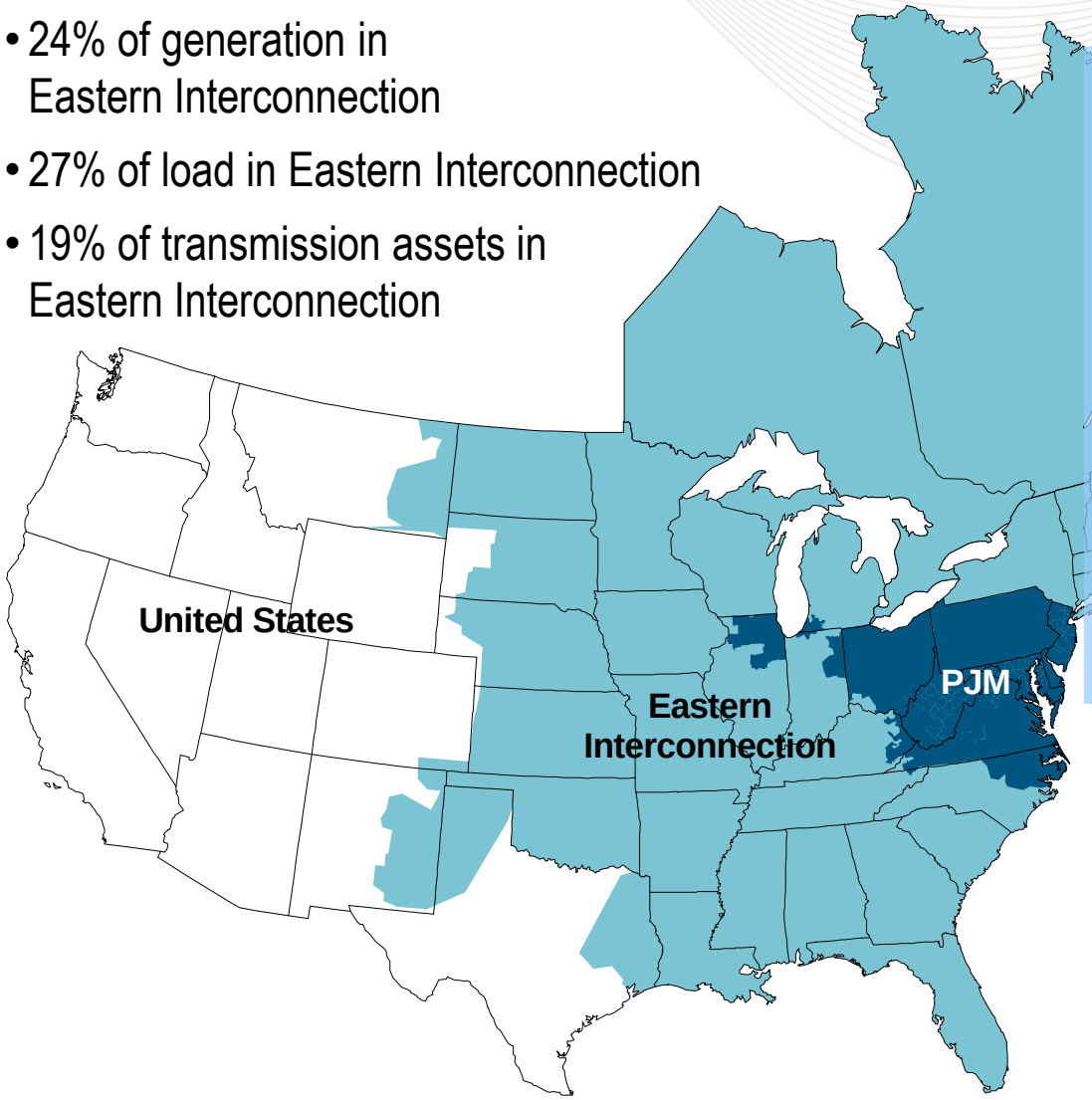
PJM as Part of the Eastern Interconnection with ATSI Integration

- 24% of generation in Eastern Interconnection
- 27% of load in Eastern Interconnection
- 19% of transmission assets in Eastern Interconnection



KEY STATISTICS

PJM member companies	700+
millions of people served	58
peak load in megawatts	158,448
MWs of generating capacity	180,400
miles of transmission lines	61,200
GWh of annual energy	794,335
generation sources	1,365
square miles of territory	211,000
area served	13 states + DC
Internal/external tie lines	142

20% of U.S. GDP produced in PJM

As of 6/1/2011

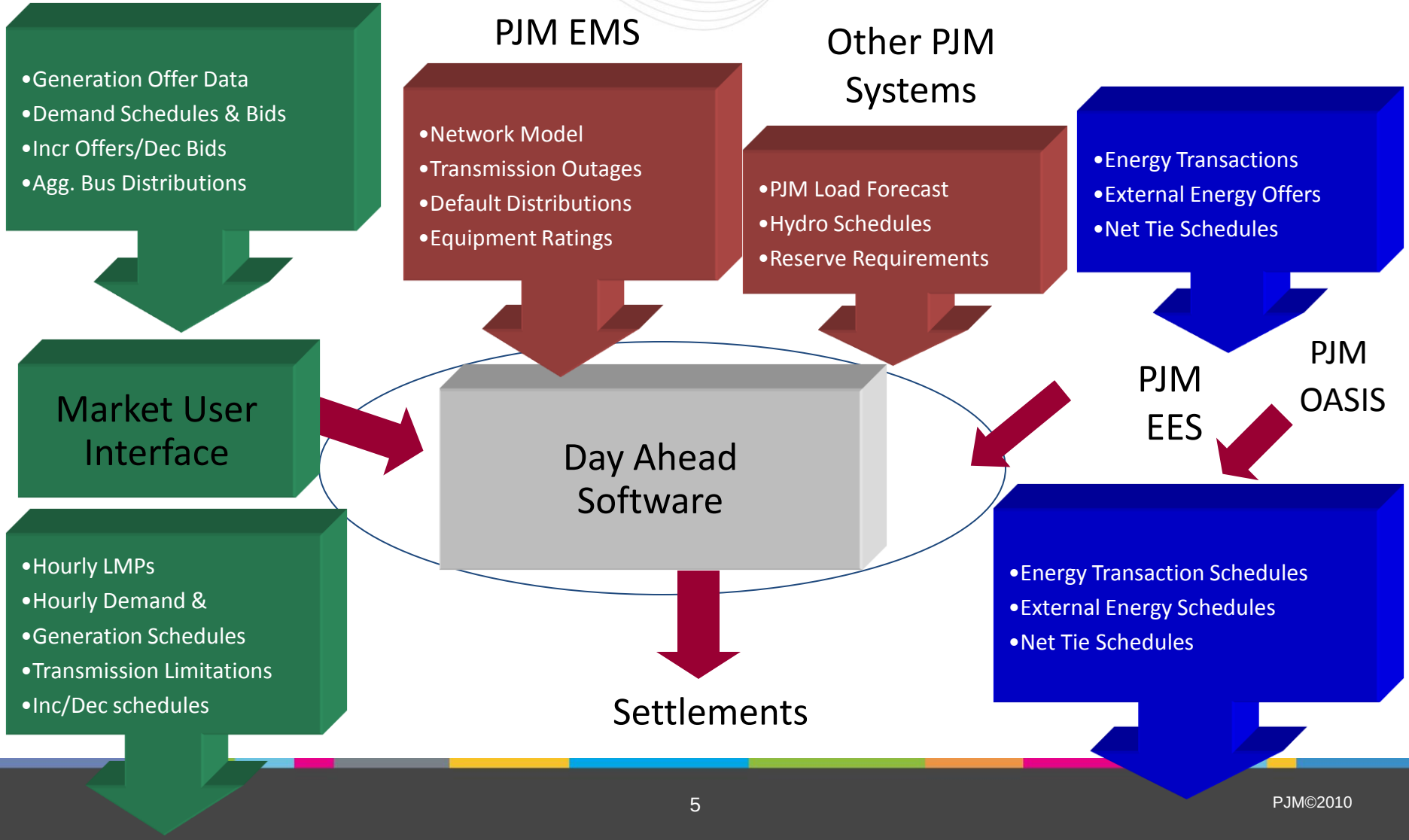
Purpose of the Day-ahead Energy Market

- Develop financially binding hourly quantities and LMPs for next operating day based on participant bids and offers while respecting all transmission security constraints, reserve requirements and generator operating constraints.
- Requires solution of security-constrained unit commitment using full transmission model to maintain consistency with real-time market operations

Day Ahead Market – Average Daily Volumes

- 1,600 generators, 3 part offers (startup, no load, 10 segment incremental energy offer curve)
- 20,000 - Demand bids – fixed or price sensitive
- 60,000 - Virtual bids / offers
- 9,500 - eligible bid/offer nodes (pricing nodes)
- 20,000 - monitored transmission elements
- 6,000 - transmission contingencies modeled

Day Ahead System Data Flow



Day-Ahead / Real-time Market and Dispatch Functions

Day-ahead Market

1200 - Market close

Resource owners, Load Servers and Marketers submit offers / bids

1600 - Results posted

Security-constrained unit commitment and Hourly LMPs

- *Generation schedules*
- *Purchase obligations*

Reliability-based scheduling

1800- Rebid Period

- *Generation schedules adjusted*
- *Demand Forecast update*
- *Updated security analysis Transmission limitations*

Real-time Market

- *Hourly and Real-time operations*
- *5 minute security constrained dispatch and incremental unit commitment / decommitment*
- *LMP-based balancing market*

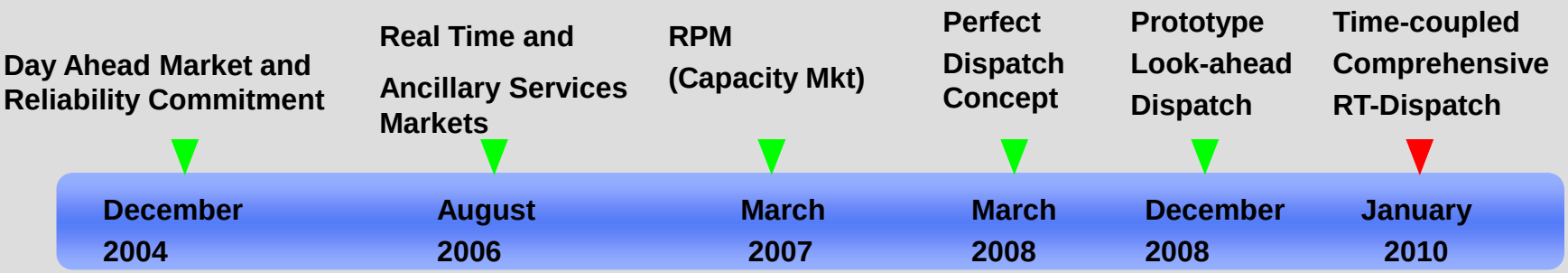
PJM Software Evolution

- **Drivers for software innovation**
- **Mixed Integer Programming based Unit Commitment and Dispatch**
- **Day Ahead Clearing Tools**
- **Pumped Storage Model**
- **Time-coupled dispatch technology**
- **Perfect Dispatch Concept**

- Manage Operational Uncertainty at Least Cost
  - Load Forecast
  - Interregional Transfers
  - Unexplained Loop Flow
  - Resource Performance
  - Contingency Events
- Improve Efficiency
  - Software Performance, New Technology
  - Adaptive Models
  - Automation

Evolution of MIP at PJM

Timeline of MIP Implementation in Production systems



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Benefits of MIP Implementation

1. Global optimality
2. More accurate solution
3. Improved modeling of security constraints
4. Enhanced resource modeling capability
   a) Generation
   b) Demand response
   c) Transmission Devices
5. More adaptable problem definition

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Transition from Lagrangian Relaxation (LR) to MIP

1. MIP tends to solve faster with more complete transmission model, LR had significant performance issues with transmission constraints
2. Conditional constraints initially created performance problems for MIP
3. Combined cycle model, Hydro unit commitment, etc. - very difficult to implement in LR. MIP handles relatively easily
4. MIP solution speed has improved dramatically

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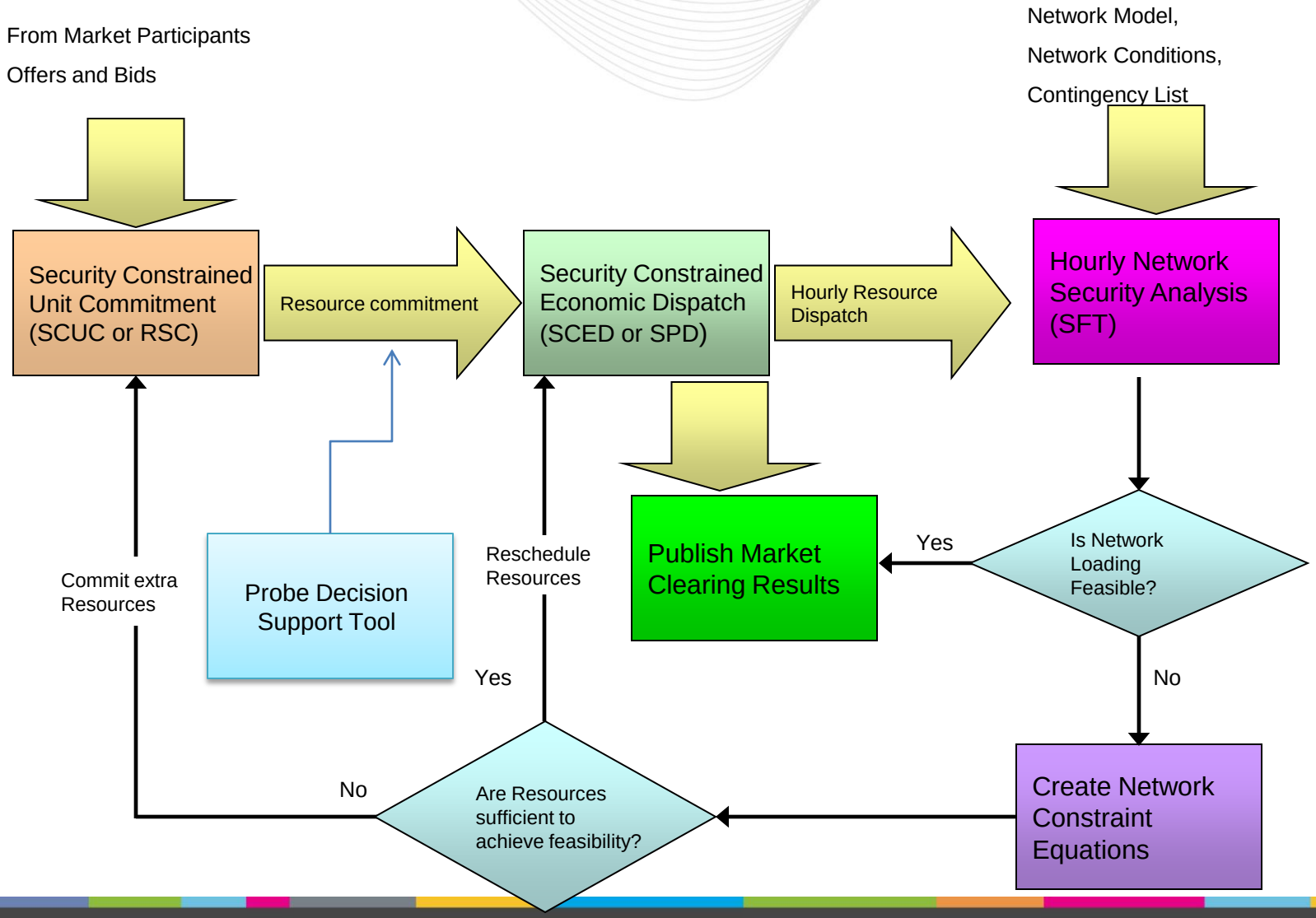
Day-Ahead Market Clearing Workflow



Areva

- MIP Based Unit Commitment
  - 3 minutes to solve
  - Convergence tolerance of 0.04
- Scheduling Pricing and Dispatch (SPD)
  - Run 2 passes, totalling 2 minutes each for 24 hours
- Simultaneous Feasiblity Test (SFT)
  - N-1 conitingency analysis
  - Less than 1 minute to solve per hour for 24 hours

PowerGEM PROBE – DA Decision Support Tool

PROBE complements the PJM DA process by performing enhanced optimization fully consistent with PJM DA market model.

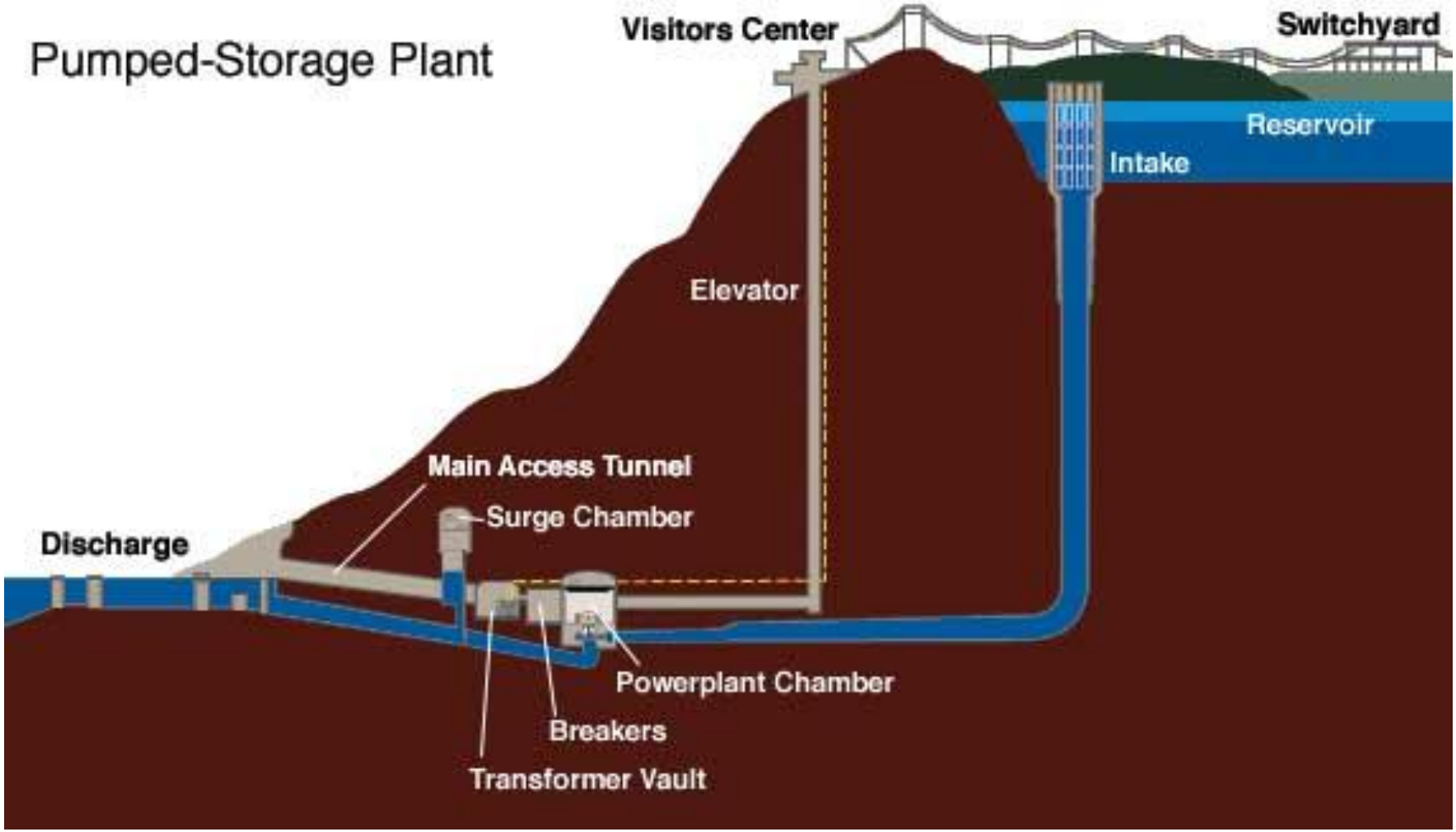
- Pump storage optimization
  - PJM DA procures the largest US pump storage facility (2500 MW), located in a frequently congested area
- DA mitigation via TPS (three pivotal suppliers) test
- Fast performance (~5 minutes)

PROBE

- Used daily since 2005
- Cross-validates other market clearing processes, especially during EMS model seasonal updates and market design changes
  - Example – PJM transitioned to marginal losses on June 1, 2007. PROBE was delivered several months earlier and was used to predict expected outcomes
- Improves the consistency between LMP and commitment
  - Good handling of small units that may otherwise get “below the duality gap” and are not scheduled optimally
- Resulted in a significant reduction in DA reserve (uplift) payments
- Improved on-time DA market closing
- Revenue adequacy analysis by constraints

Pumped Storage Generation and Dispatch

- Pumped storage hydro plants produce energy by moving water between reservoirs
  - During low demand, excess energy is used to pump water into a higher reservoir
  - When demand is higher, water is released through a turbine to generate electricity similar to other hydro
- Pumped storage generation is a complex part of the market optimization and has a significant impact on the PJM markets
  - Can be either a load or a generator



Source: Tennessee Valley Authority website, www.tva.gov

Pumped Storage Generation and Dispatch

- Pumped storage is also financial – they pump (buy & store) when energy is cheap and generate (sell) when energy is expensive
  - PS dispatch is strongly dependent on LMPs
  - If LMPs would be equal through out the day, pump storage units without any inflow would never run
- Pumped storage has additional operating characteristics that make optimization more complex. They have 3 states (rather than two)
  - Pump, off-line, generate

Pumped Storage Generators

- Pumped storage units are optimized in DA market only
  - energy limited resources require simultaneous solution for 24 hours
- Owners of Pump storage do not bid energy cost curve
- DA optimization software will find the optimal pumping and generation schedule to arrive to desired reservoir level (analog of stored energy) at the end of the day
- Pump storage optimization solution algorithm is probably the most complicated algorithm that PowerGEM developed so far for PJM
  - Addition of a single pump plant slowed down PROBE solution in 5-10 times

Pumped Storage Bid data

- Efficiency factors (typically in 0.6-0.8 range
  - 0.8 means that 20% of energy stored during pumping "will be lost" – can't be converted back to energy.
- Initial reservoir level (amount of energy available in MWh)
- Maximum and minimum reservoir level
- Minimum generation and minimum pumping in MW in addition to maximum generation/pumping
- Pump storage unit can ramp very fast and can provide ancillary services

Example of PS Dispatch

HH:MM		LMP	Dispatch	Revenue	ResrLevel	Status	PumpMax	PumpMin	GenMin	GenMax
00:00		47.63	0	$ -	7000	blk_Offl	-440	-200	100	800
01:00		49.86	-303.3	$ (15,123)	7236.6	pump_Marg	-880	-200	100	800
02:00		49.86	-632	$ (31,510)	7729.6	pump_Marg	-880	-200	100	800
03:00		48.98	-880	$ (43,103)	8416	pump_Max	-880	-200	100	800
04:00		49.86	-843.2	$ (42,038)	9073.7	pump_Marg	-880	-200	100	800
05:00		49.86	-271.7	$ (13,546)	9285.6	pump_Marg	-880	-200	100	800
06:00		55.59	0	$ -	9285.6	Offline	-440	-200	100	800
07:00		47.42	-440	$ (20,864)	9628.8	pump_Max	-440	-200	100	800
08:00		40.73	-440	$ (17,923)	9972	pump_Max	-440	-200	100	800
09:00		54.45	0	$ -	9972	Offline	-440	-200	100	800
10:00		61.77	0	$ -	9972	Offline	-440	-200	100	800
11:00		69.44	0	$ -	9972	Offline	-440	-200	100	800
12:00		74.03	419.2	$ 31,029	9552.8	gen_Marg	-440	-200	100	800
13:00		75.84	800	$ 60,670	8752.8	gen_Max	-440	-200	100	800
14:00		85.44	800	$ 68,352	7952.8	gen_Max	-440	-200	100	800
15:00		89.55	800	$ 71,644	7152.8	gen_Max	-440	-200	100	800
16:00		91.83	800	$ 73,463	6352.8	gen_Max	-440	-200	100	800
17:00		85.71	800	$ 68,564	5552.8	gen_Max	-440	-200	100	800
18:00		74.03	661.5	$ 48,970	4891.3	gen_Marg	-440	-200	100	800
19:00		69.53	0	$ -	4891.3	Offline	-440	-200	100	800
20:00		70.96	0	$ -	4891.3	Offline	-440	-200	100	800
21:00		69.67	0	$ -	4891.3	Offline	-440	-200	100	800
22:00		50.6	-440	$ (22,262)	5234.5	pump_Max	-440	-200	100	800
23:00		57.72	-340.3	$ (19,646)	5500	pump_Marg	-440	-200	100	800

MIP – Enables future innovation

1. Distributed resources
2. Dispatchable demand response
3. Non-traditional regulating resources
4. Interregional coordination
5. Transmission device operation

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DA Challenges

- Virtual bidding and impact on load flow solution. Constant increase in the number of virtual bids and MW total.
- DA objective is to minimizes production cost over one day only. Such market design doesn't handle day boundaries well . It is often up to DA operator to stop a unit with long minRun/minDown time or run through the midnight, manual adjustments for units limited by the number of starts per week.
- Combined cycle units
- Impact of intermittent resources on DA market. Should PJM procure more reserve products in DA?

Time-coupled Security Constrained Economic Dispatch Technology

Resulting drivers for software innovation

- At certain times, resource owners perceive dispatch instructions as ‘unrealistic’
- Advances in operator visualization tools have demonstrated value in continued emphasis on operational trend analysis to increase situational awareness.
- Technology advances provide opportunity to integrate trend analysis into optimization and to accommodate more sophisticated and adaptive resource models

Generation, and Demand Resource, Control Application

Design Objective

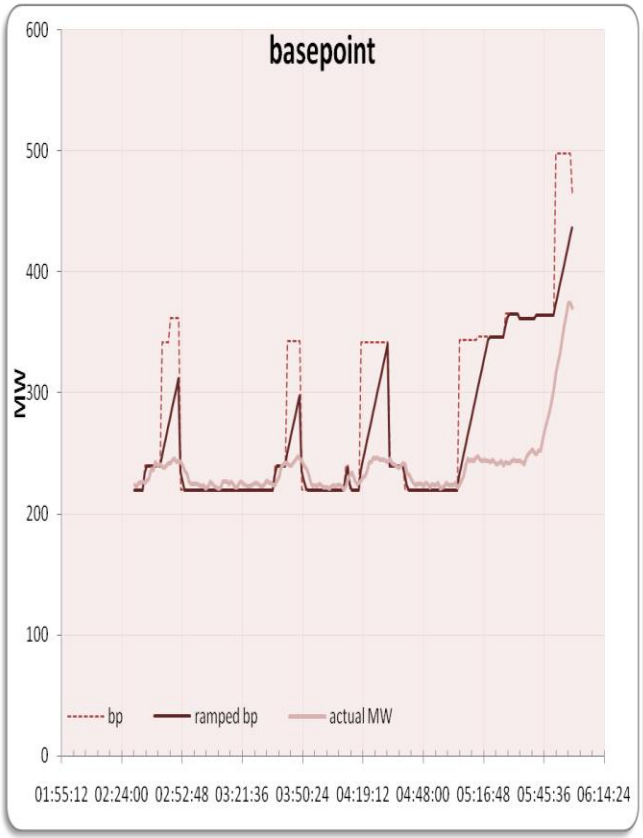
- The objective is to yield a time-coupled resource operating plan
  - Realistic generator characteristics and behavior
  - Intelligent transmission constraint control
  - Multi interval dispatch solution for unit commitment and dynamic contour projection for individual resource dispatch instructions
- Expected Benefits
  - Higher quality resource dispatch instructions
  - Increased situational awareness of operating trends
  - Reduction in operating margins

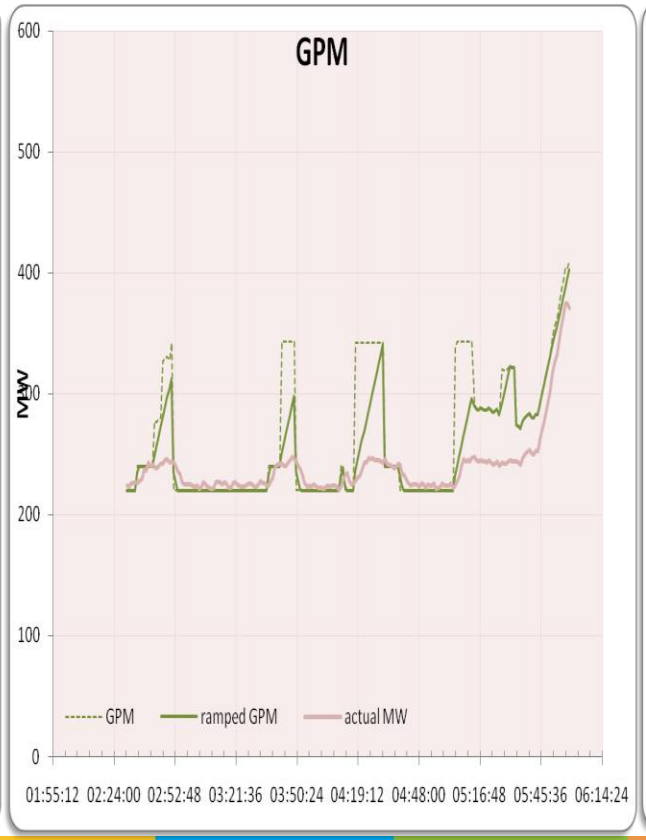
Adaptive Generator Model

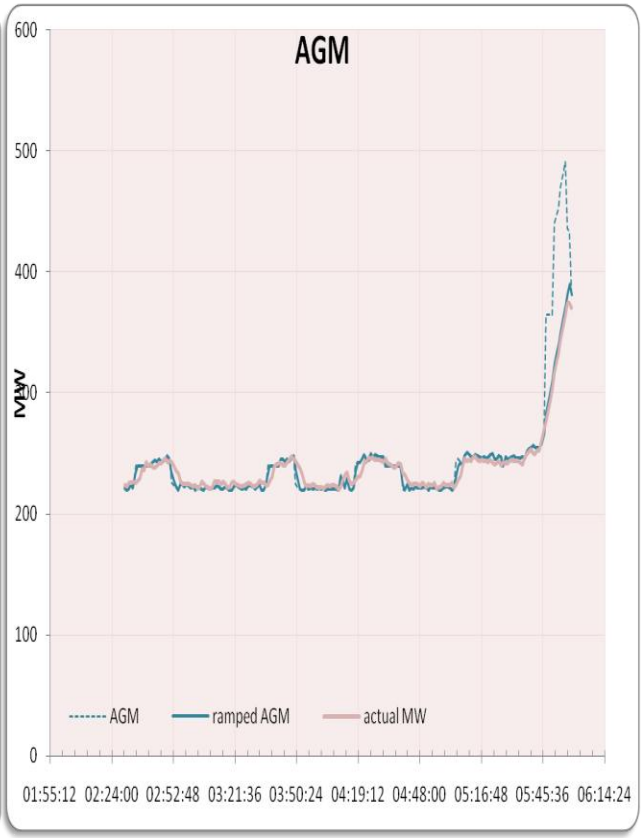
- Operational history of resource used to predict response to certain dispatch instructions
- Predicted response used in determining dispatch instruction to be issued to resource
- Concept is … probabilistic response model replaces need to correct bad offer data or explicitly model mill points, dead bands, forbidden zones etc.

Mill Effects

Volatile basepoint moves through non-operating band







Observations

- Adaptive Models enhance performance of dispatch engines
- Experience indicates adaptive generation models must be ‘re-trained’ every 3 to 4 months
- Trend visualization well received by dispatchers
- Reduction in dispatch base point volatility

Perfect Dispatch Concept

- "Perfect Dispatch" (PD) calculates the after-the-fact hypothetical least bid production cost (BPC) dispatch using the actual load, interchange, system topology and transmission constraints.
  - PD optimizes the dispatch of the online steam units and all the CT commitments.
- PD objectively evaluates PJM's performance in dispatching the real-time system by comparing the actual bid production cost with optimized "Perfect" solution.

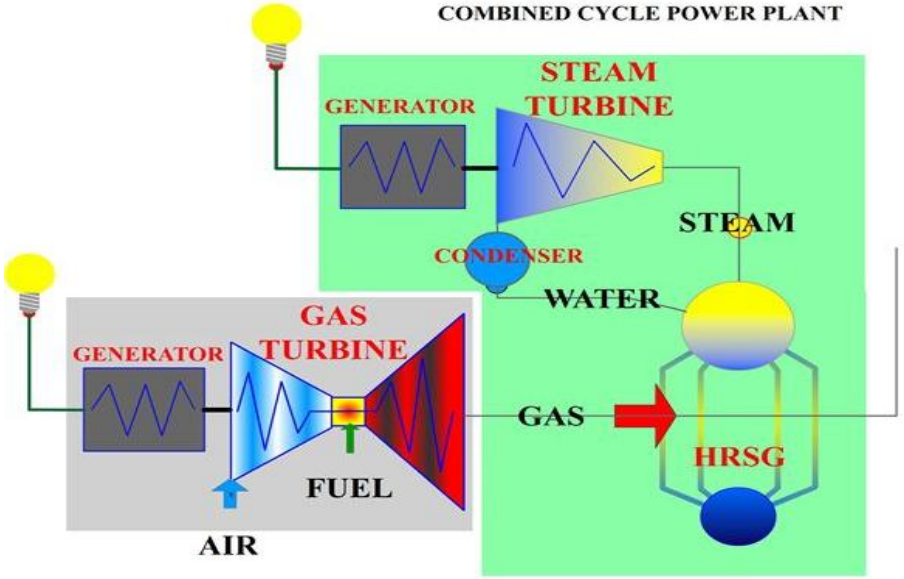
- After-the-fact, calculated, Perfect Dispatch solution could never be achieved in actual operations
- The dispatchers must make dispatch decisions based on forecasts of load, interchange, etc. which will never consistently represent actual values
- The dispatchers must also anticipate failure of generators to follow dispatch signals exactly
- The dispatchers must always act with reliability as their primary consideration, requiring them to err on the side of committing slightly more generation rather than less

- All necessary data files for the operating day are generated after midnight.
- Early in the morning, a PD operator will evaluate the results from the application and distribute a high-level report containing the following information:
  - Overall production cost saving
  - Saving by unit types
  - Top 10 saving units that PD suggested to lower generation
  - Top 10 saving units that PD suggested to raise generation
- Daily recommendations for improvement are developed to provide feedback to the dispatching staff to enhance efficient operations while maintaining system reliability.

Extra Stuff

1. Plant submits
   - Individual Steam and CT bid curves
   - Steam Factor (output of steam per output of CT)
   - All normal operating parameters for each piece

2. MIP commits unit to meet all bids and maximize usage and profitability.



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