Simulation Modeling of Coordinated Operation of Natural Gas and Electric Markets with GECO ENELYTIX®

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Outline

- Background and GECO Project
  - the GECO Project: objectives, project team
  - summary of project achievements
    - Transient optimization of pipeline operations
    - Gas Balancing Market concept
    - Market-based gas-electric coordination
    - Pipeline modeling benchmarking
- GECO ENELYTIX – a system for modeling gas-electric interactions
- Numerical experiments
- Discussion

GECO Project Summary

- Project objective is to develop methods, model, algorithms and an associated market design for a dramatically improved coordination and / or co-optimization of wholesale natural gas and electric physical systems and economic markets on a day-ahead and intra-day basis
- Formal Project Title: *Coordinated Operation of Electric and Natural Gas Supply Networks: Optimization Processes and Market Design*
- Leading Organization: Newton Energy Group LLC
- ARPA-E Program: OPEN-2015
- Project started: April 20, 2016
- Project term: Project completed in July of 2019
- ARPA-E project summary: https://arpa-e.energy.gov/?q=slick-sheet-project/gas-electric-co-optimization

GECO Project Team

Newton Energy Group: Alex Rudkevich, Ph.D. (PI), John Goldis, Ph.D., Alex Beylin, Ph.D.

Los Alamos National Laboratory: Anatoly Zlotnik, Ph.D. ,Scott Backhaus, Ph.D. (formerly with LANL)

Boston University: Pablo Ruiz, Ph.D., Michael Caramanis, Ph.D.

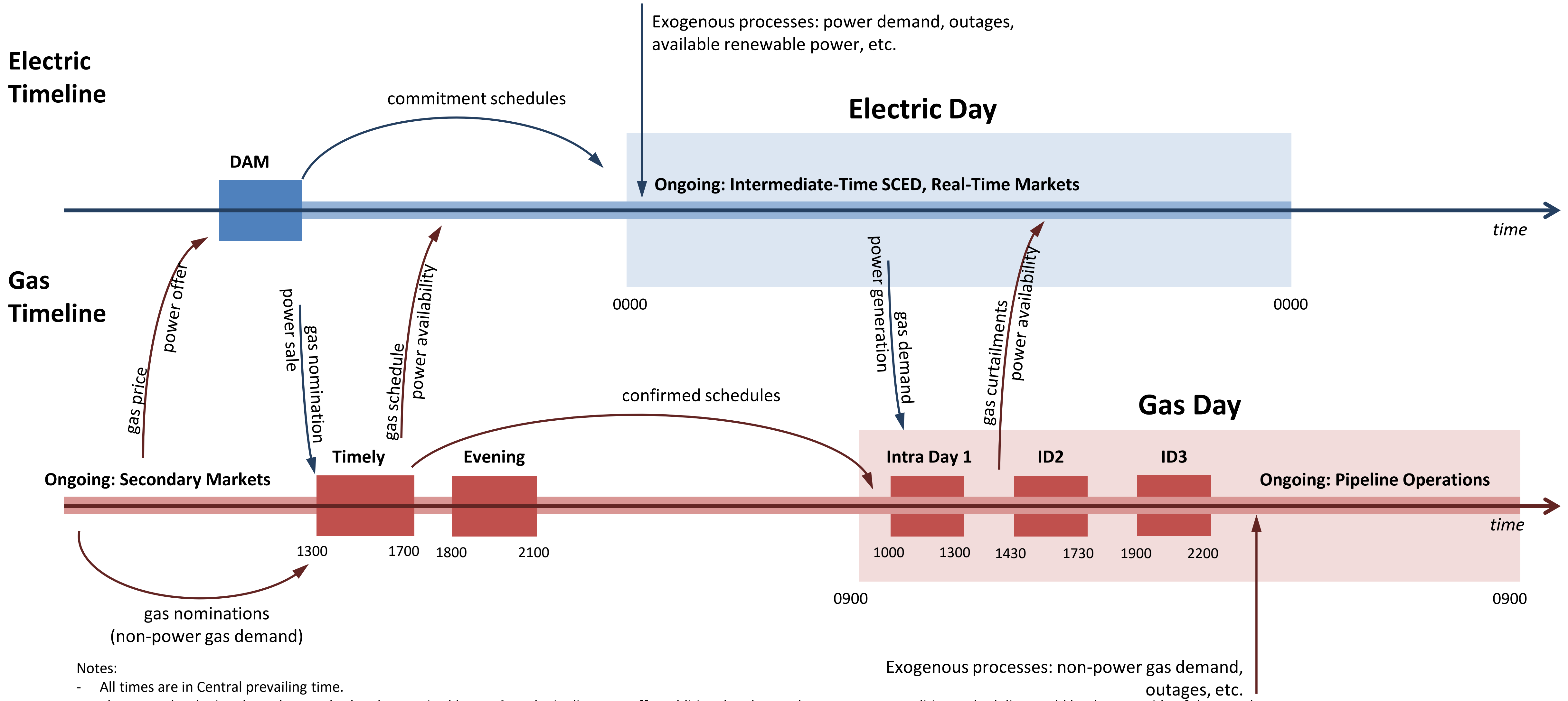
Polaris Systems Optimization: Russ Philbrick, Ph.D., Rafael Castro, Ph.D.

Tabors Caramanis Rudkevich: Richard Tabors, Ph.D., Xindi Li, Rick Hornby

Technical expertise and certain pipeline data provided by **Kinder Morgan**

The opinions presented herein are solely those of the authors and do not necessarily reflect those of the entities of which the authors are a part or those of the full Project Team. Specifically, no opinion or conclusion expressed or implied in this document may be attributed to our cooperating entity -- Kinder Morgan

Current Parallel Operations of Natural Gas and Electric Markets



Notes:
- All times are in Central prevailing time.
- The gas cycles depicted are the standard cycles required by FERC. Each pipeline may offer additional cycles. Under emergency conditions scheduling could be done outside of these cycles.

Summary of Gas–Electric Challenges

- Operational Challenges:
  - Flexible gas-fired generation capacity lacks fuel supply flexibility
    - Flexibility is crucial in power systems, as supply must match demand *continuously and instantaneously* (there is no equivalent to line pack)
  - The variability and unpredictability of gas-fired generation pose challenges to pipeline operations
- Planning/Long-Term Challenges:
  - Gas-fired power plants tend to not procure firm gas transportation
  - Under extreme conditions, there have been severe gas pipeline constraints that limited supply to gas-fired generation
- Anticipated continued growth of the gas-fired generating fleet will exacerbate these challenges

Operational challenges should be addressed first

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Today's Key Gas-Electric Coordination Deficiency

Gas-fired power generators…

- tend to be flexible units capable of generating upon relatively short notice,
- are active in the 5-minute real-time power markets, and can change their outputs frequently, following changes in system needs,
- provide the bulk of operating reserves in some regions – requires the ability to change output immediately, as directed by the power system operator,
- it is difficult to forecast burn rates for these units on a day-ahead basis.

There are no liquid and transparent intra-day gas markets in which gas-fired generators can procure gas as needed, and under relatively short notice.

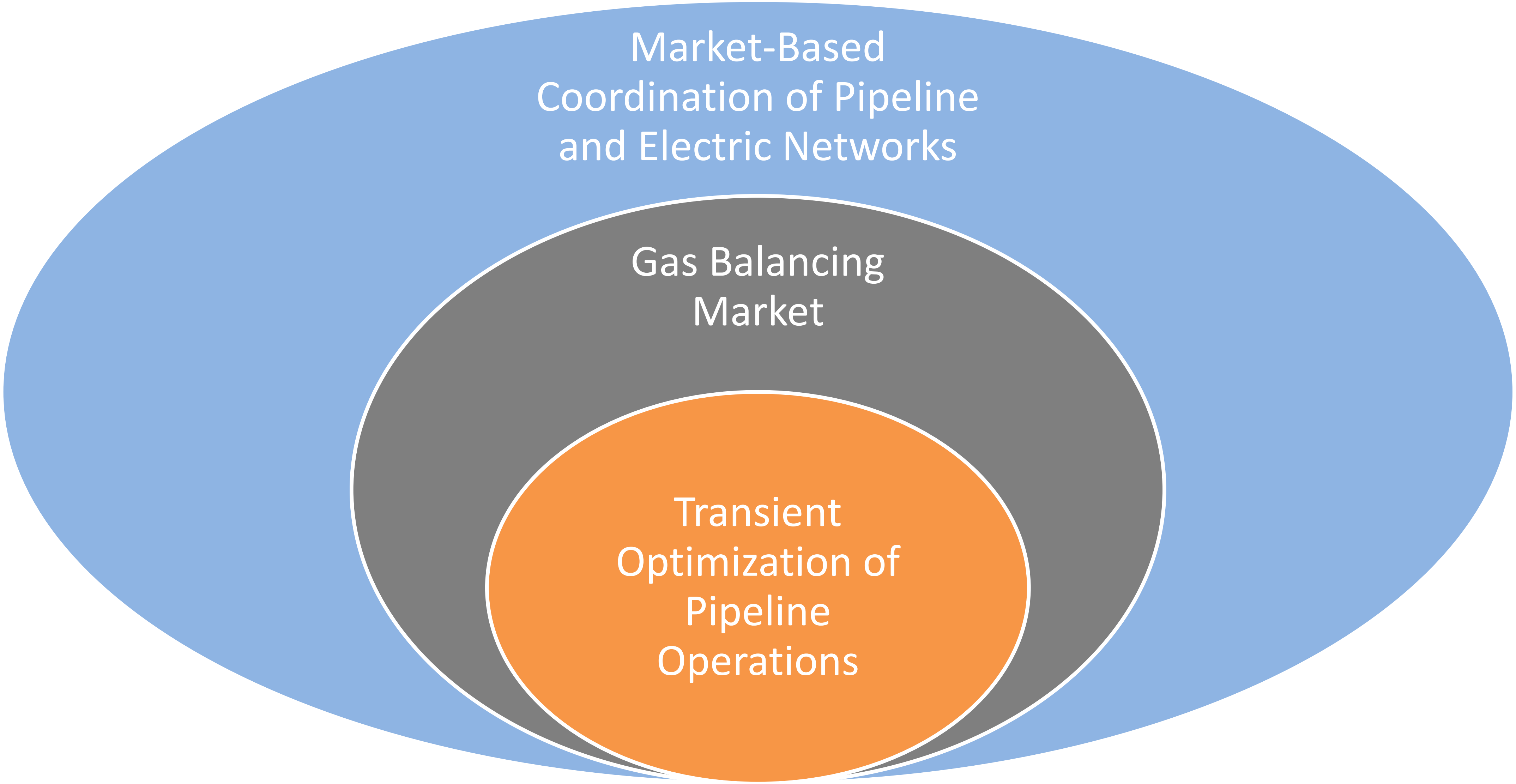
- Most flexible gas-fired power plants purchase gas bilaterally from marketers who manage a portfolio of gas resources.
- An alternative is to purchase gas from a supplier and transportation rights from a shipper – a time consuming, multi-party process in an illiquid market.

Available pipeline modeling tools

- **Physical flow vs. capacity allocation models**
  - Physical flow models represent the relationships between changes in pressure, flow, temperature within the natural gas pipeline network. Reflect engineering constraints on allowed pressure and compressor capabilities
    - Transient
    - Steady-state
  - Capacity allocation models represent re-allocation of pipeline transmission capacity between certain receipt and delivery points. Capacity is a construct reflecting daily transfer under "design" conditions. Determined using physical models.
- **Simulation vs. Optimization**
  - Simulation models compute dynamics for transient, or statics for steady-state, changes in gas flow and pressure with given receipts, deliveries and compressor settings. Rely on PDE representation of gas dynamics in each pipe with common boundary conditions at connections
  - Optimization models can determine receipt and delivery schedules and/or compressor operations to optimize certain objective functions

Operational co-optimization of gas and electric systems require optimization tools based on physical flow transient models which until very recently were mathematically intractable

The GECO Approach



Markets providing granular price signals should be supported by transient optimization

- **Transient optimization methods determine**
  - clearing of supply and demand transactions
  - compressor operation regimes
  - define economic value of natural gas at any point in time and at any location within pipeline network
  - receipt and delivery schedules that could be guaranteed at a price
- **Price guarantee works because prices are consistent with the physics of gas flow and with engineering constraints of pipeline operation**
  - Optimization relies on physical flow models that represent the relationships between changes in pressure, flow and temperature within the pipeline network. Reflect engineering constraints on allowed pressure and compressor capabilities
- **Access to pipeline capacity should be consistent with granular prices**
- **Until very recently transient optimization of a pipeline network was a mathematically and computationally intractable problem**

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Economic Optimization of Pipeline Operation: a Conceptual Formulation

- A two-sided auction
- Conducted on gas pipeline network subject to engineering constraints
- Participants: buyers and sellers of gas submitting Price/Quantity (P/Q) offers/bids
- Offers and bids are node-specific, with hourly time step for an optimization horizon (e.g., 36 hours)
- Auctioneer’s objective function: maximize market surplus between accepted bids and offers less compressor costs of running the pipeline, summed over the optimization horizon

Locational Trade Value of Natural Gas

- Auction clearing will produce Locational Trade Values (LTVs) of natural gas
- LTVs are highly granular:
  - any node, any pipe
  - hourly or sub-hourly time step
- LTVs are fully consistent with the physics of gas flow and the pipeline engineering constraints
- Transacting parties could have a guarantee of gas delivery at settled price

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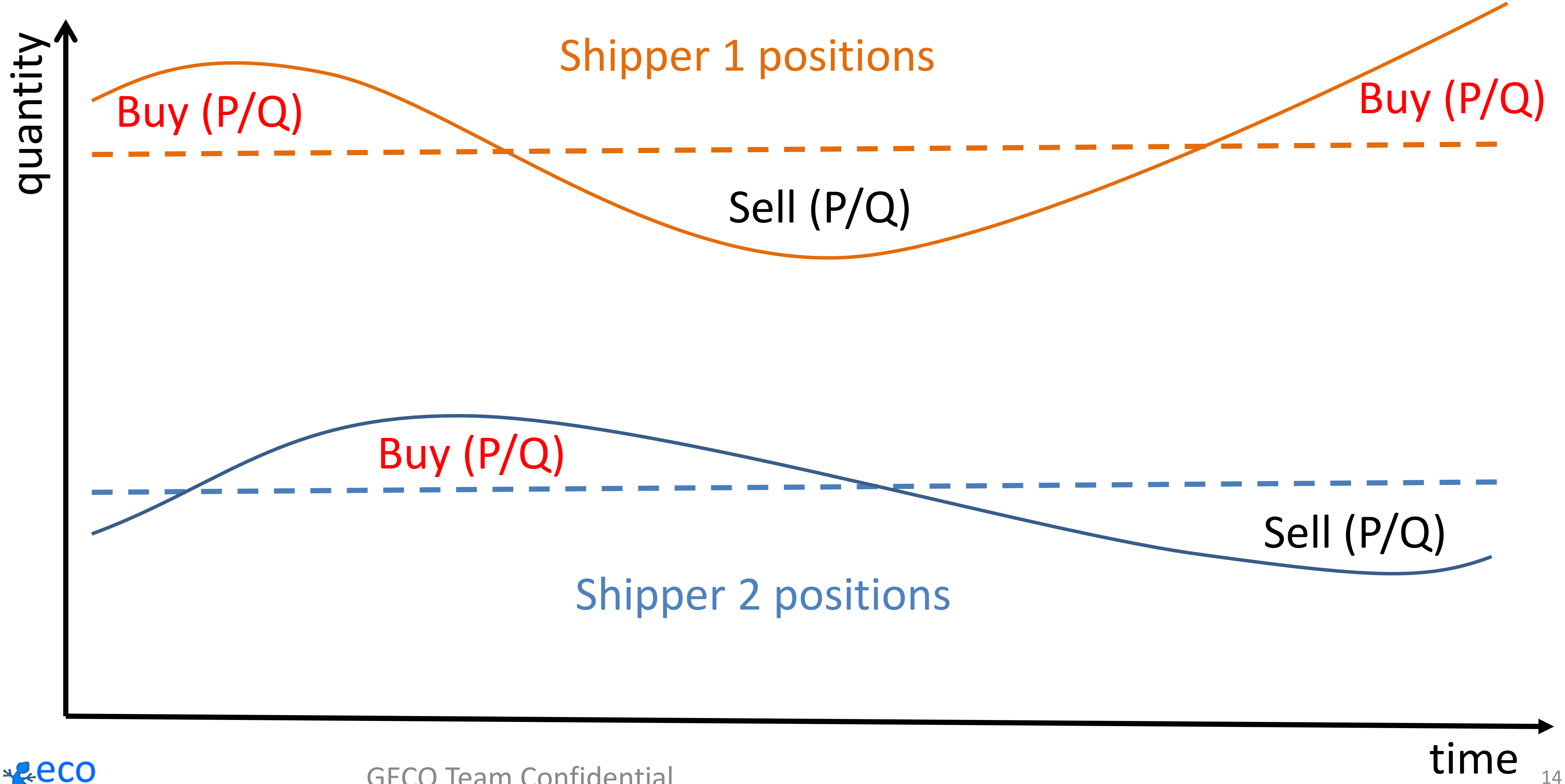
Gas Balancing Market

Gas Balancing Market will trade deviations from ratable schedules



High Level Overview of the Gas Balancing Market

The Gas Balancing Market (GBM) would:

- Be pipeline specific
- Have <u>***voluntary***</u> participation
- Honor existing transportation rights and contracts
- Enable trades of hourly imbalances from ratable schedules
- Assure that intra-day transactions cleared in the market are physically implementable
- Enable intra-day gas transactions between parties in a liquid, transparent, flexible and simple manner
- Provide transparent pricing signals to all gas players to inform decision making
- Enable more economically efficient utilization of the gas and power infrastructures

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GBM Outcome

- Hourly schedules for receipt and delivery:
  - schedules result from
    - Cleared market buy/sell positions and/or
    - Self-schedules
- Hourly Gas Locational Trade Values (LTV) of gas by node (receipt and delivery points)
- Cleared schedules are settled at LTVs

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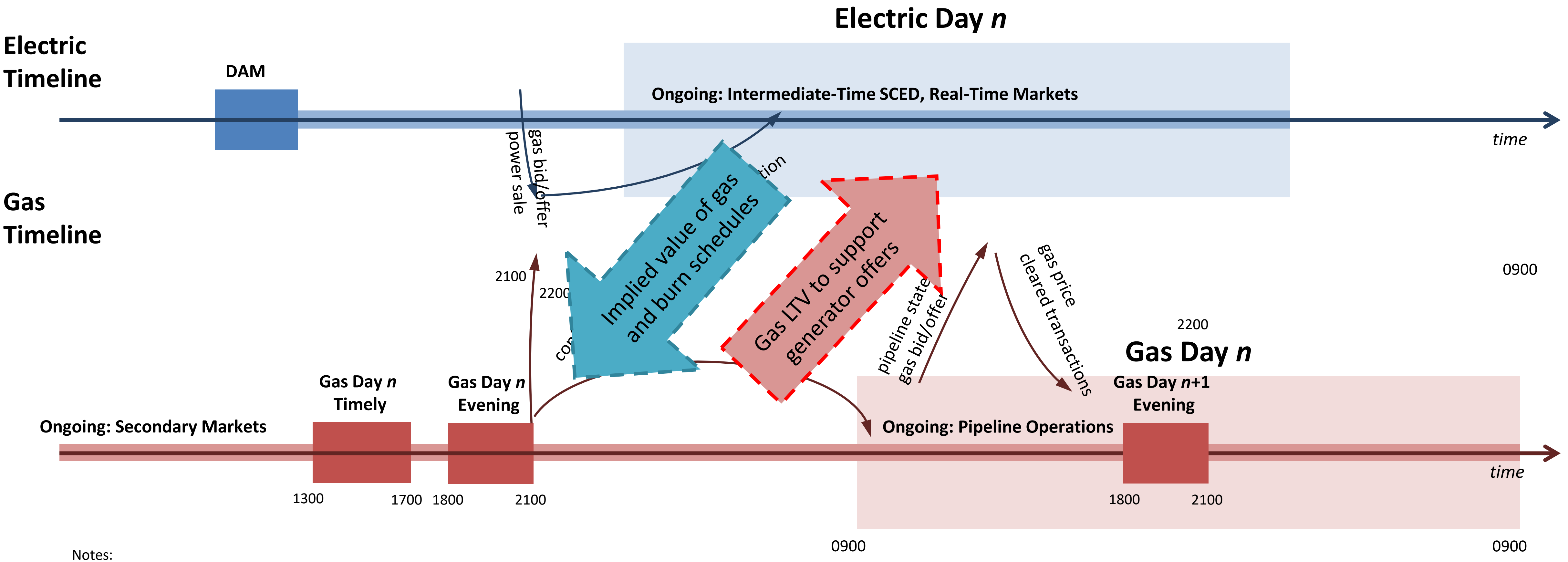
Gas Electric Co-Ordination with GBM

Value based Intra-day coordination of gas and electric systems



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Granular Pricing Signals at Work

- Gas Pipeline Side
  - Relief of pipeline constraints through
    - LTV-sensitive optimization of compressors
    - Redispatch of electric generation
  - Help pipeline customers make investment decisions
  - Help pipeline owners to
    - Identify constrained system elements with better granularity
    - More precisely assess economic benefits of alternative solutions
    - Justify investments into economic solutions before regulatory agencies

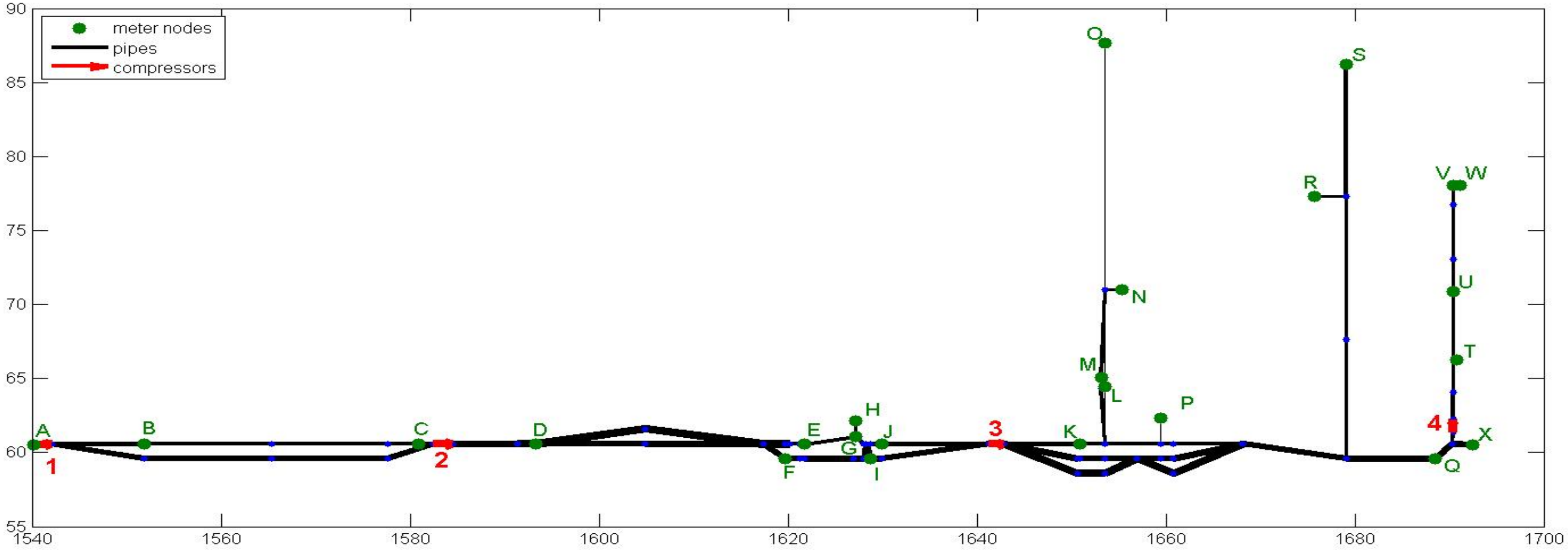
- Electric Network Side
  - Hourly gas trade values (LTVs) to support bidding into DA and RT markets
  - Simplifies gas purchases for gas-fired fast-start power plants that clear in the real-time power markets and/or that are called upon to provide ancillary services
  - Redispatch of electric generation in response to high gas LTV under scarcity caused by pipeline constraints
  - Transparent economic signal to help generating companies to determine the level of FT coverage they need to manage risk

Testbed Model using Real Data

Network topology and SCADA measurements for February – March 2014 provided under NDA by Kinder Morgan

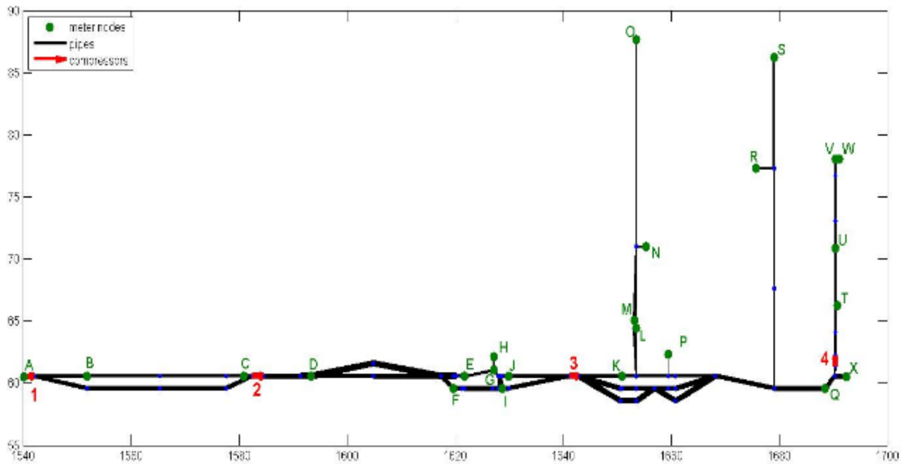
Test System using Real Data

- Reduced model of a real subsystem:
  - 78 nodes, 91 pipes, 4 compressors (labelled 1 to 4)
  - 31 custody transfer meters at 24 locations (labelled A to X)
  - Flow nodes at B to X, pressure (slack) node at A
- Hourly SCADA flow, pressure and temperature data for the Polar Vortex period: February and March of 2014
- Segment serves 3 CCGT power plants

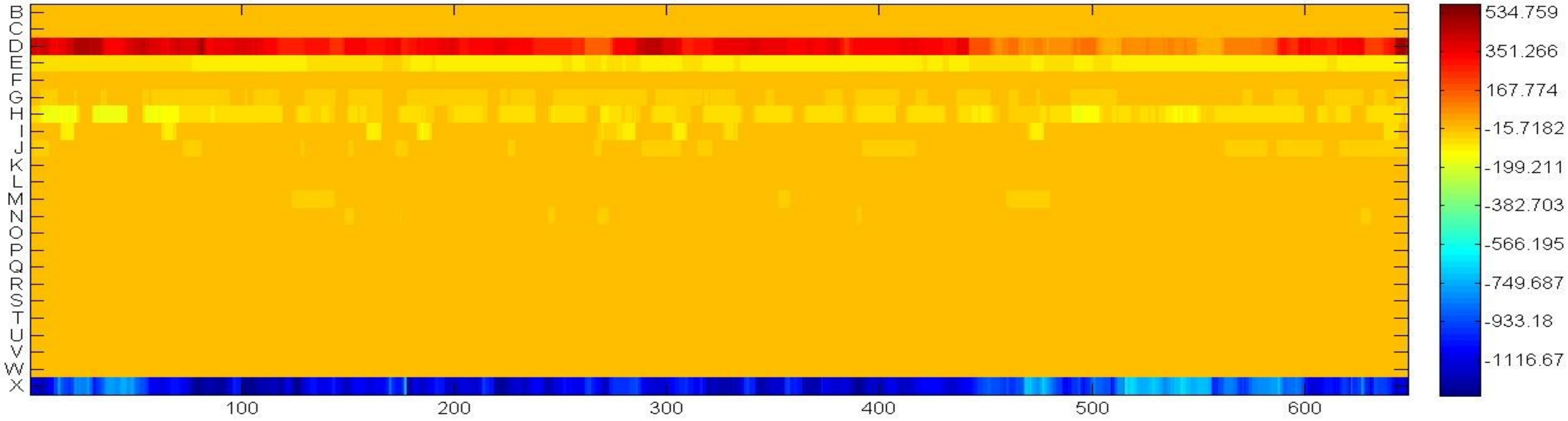


Model Validation: Real Data

- Boundary conditions (from data):
  - Mass flow into system (net injections) at flow nodes B to X
  - Pressure at slack node A



Flow node boundary conditions (mass flow – MMSCFd) from SCADA data



Pressure node boundary conditions (PSIa) from SCADA data

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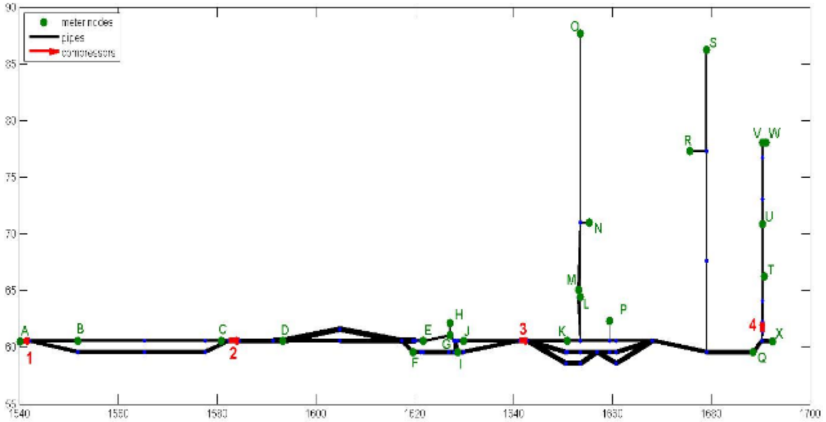
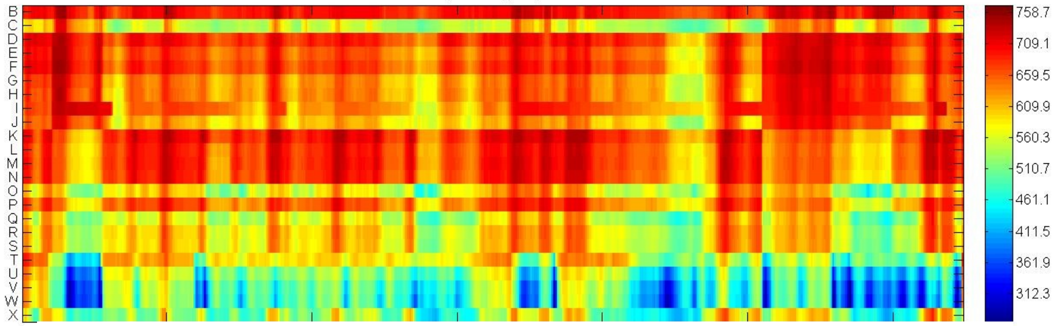
Model Validation: Real Data

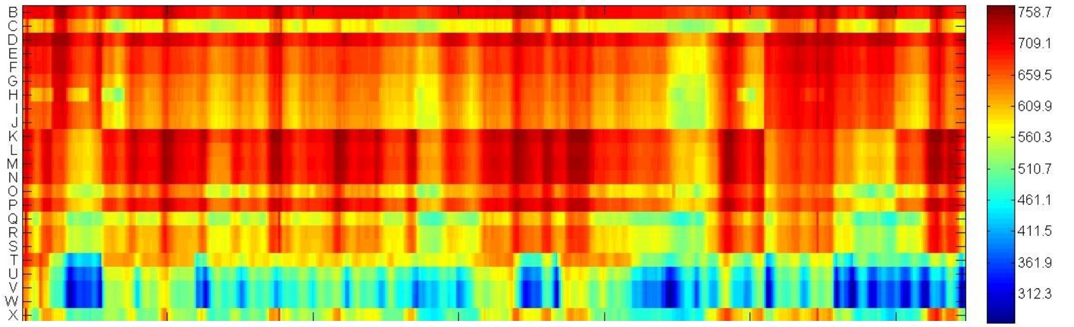
- Corresponding solution (Feb-2014 results shown)
  - Simulation using reduced model, and data
  - Pressure at flow nodes B to X
  - Mass flow into the system at slack node A



SCADA data pressure (PSIa) at flow nodes

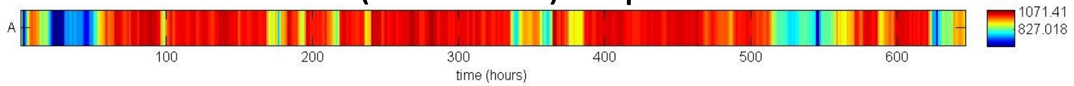


Simulated pressure (PSIa) at flow nodes



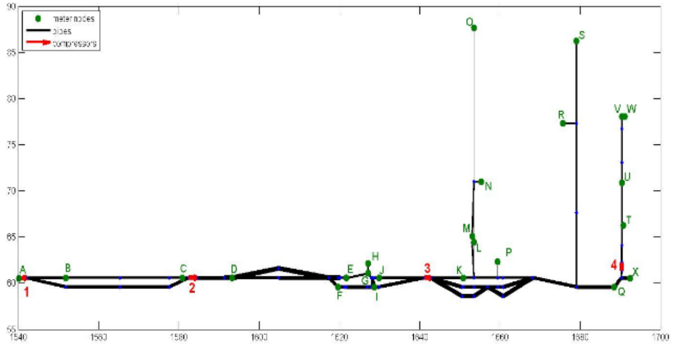
SCADA data flow (MMSCFd) at pressure node

Simulated flow (MMSCFd) at pressure node

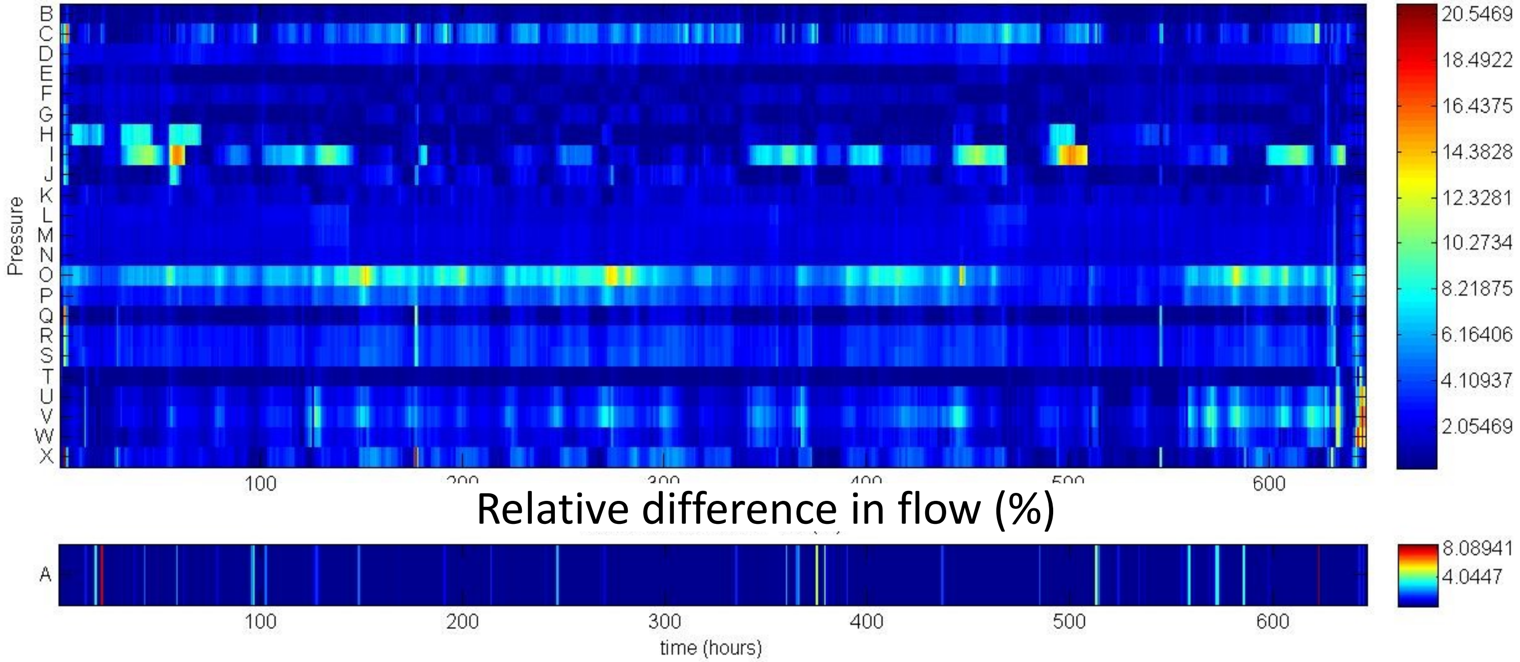


Model Validation: Deviations from Real Data

- Comparison February 2014: relative distance (%)
  - Pressure at flow nodes B to X
  - Mass flow into system at slack node A



Relative difference in pressure (%)



- **Top: Flow node pressures (within 2% - 3% precision)**
- **Bottom: Flow into Pressure node (within 2% precision)**

GECO ENELYTIX®

Commercially available ENELYTIX system consists of:

Power market simulation engine *Power System Optimizer* (PSO) by Polaris. Uses CPLEX MIP Solver

Scalable and flexible cloud-based architecture for massive on-demand parallel execution. Private cloud for each customer implemented in AWS

Efficient self service Business Intelligence: user defined reports to explore simulation results visually and dynamically

Benchmarked and vetted datasets assembled by modeling experts from public sources

Solution Overview: PSO, ENELYTIX Simulation Engine

PSO has features and capabilities of all other similar models

... and unique capabilities

Inputs *)

- Demand forecasts
- Generation mix
- Transmission topology
- Generation and transmission expansion
- Fuel prices
- Emission allowance prices

*) Some inputs could be outputs depending on the model use and configuration

Models

- Loads, demand response
- Transmission: existing, new; constraints, contingencies
- Generation: existing, new; storage; variable generation
- Market rules

Algorithms

- SCUC/SCED; contingency analyses; energy and A/S co-optimization; co-optimized topology control
- Emission policy and RPS compliance; capacity expansion; capacity market modeling
- Maintenance scheduling

Outputs

Physical:
- Generation and reserves schedules
- Power flow
- Fuel use
- Emissions
- Curtailments

Financial:
- Prices
- Revenues
- Costs

Planning:
- New builds
- Retirements

- as a production costing modeling tool

and

- as a system expansion modeling tool

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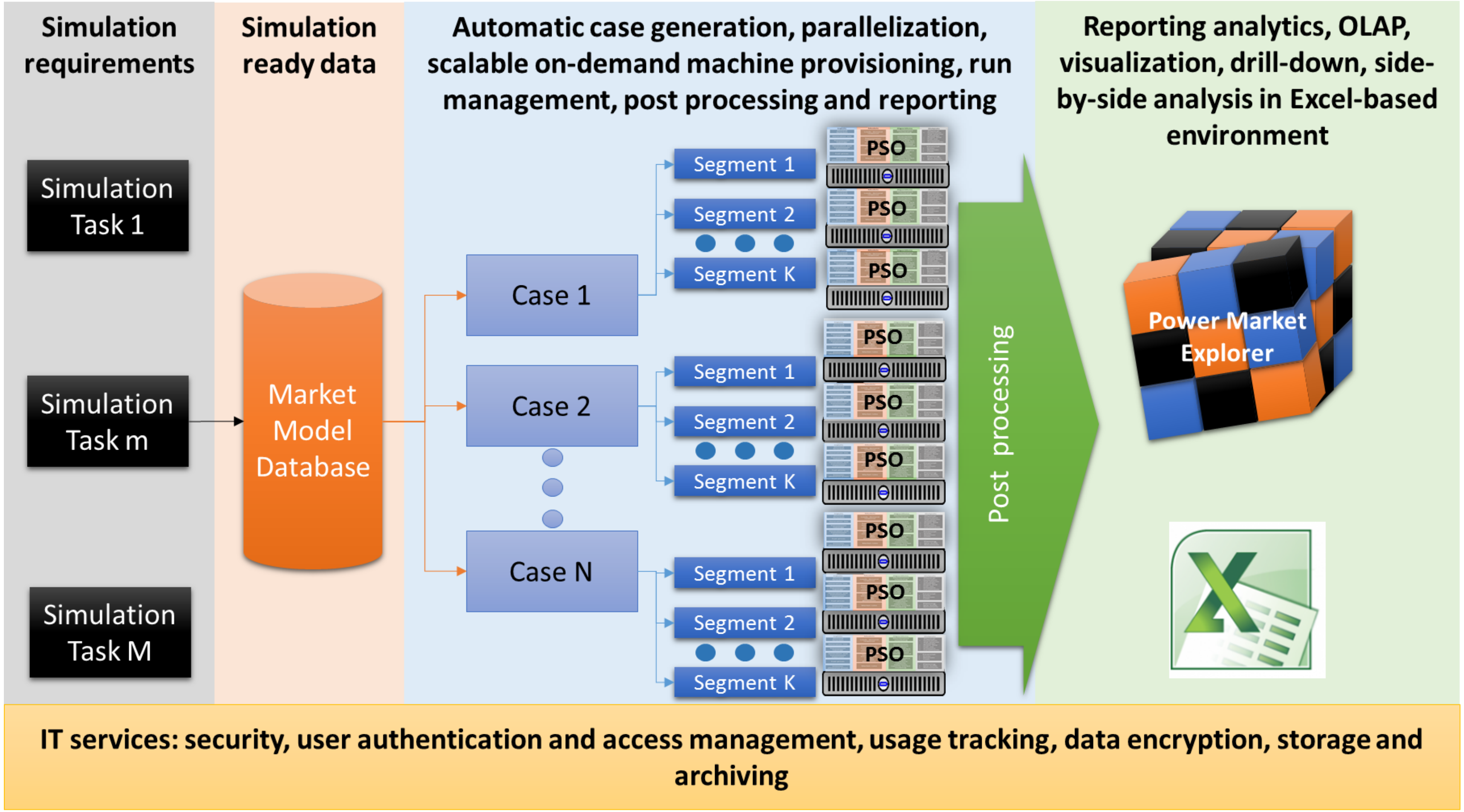
Solution Overview: Workflow and Key Components

ENELYTIX is a comprehensive turn-key solution providing users access to all resources required for market studies



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Scalability at work

- A large multi-case study could be completed within one or several hours for large multi-market systems
- For example,
  - TCR's review of a MA 83C/83D proposals involved for each proposal:
    - a system expansion run looking forward for 30 years
    - chronological nodal simulation of the ISO-NE & NYISO systems over 22 years plus a gas sensitivity scenario and
    - an FCM market modeling for each of the 22 years
  - Each evaluation case used 601 virtual machines on the cloud running in parallel
  - TCR was often running 2 evaluations in parallel using over 1200 virtual machines with entire simulation stage of evaluation completed in 3-4 hours for both evaluations

Gas System Optimizer (GSO)

Transient pipeline optimization solver by LANL

Inputs and models

Fixed and price sensitive demand

Fixed and price sensitive supply

Pipeline topology and pipe characteristics

Compressor stations

Algorithms

Steady state and transient optimization of:

- Market surplus (social welfare)
- Throughput
- Compression energy or cost
- User defined objective function

Rolling horizon modeling

Outputs

Physical:

- Gas flow and pressure dynamics
- Compressor details
- Delivery and curtailments

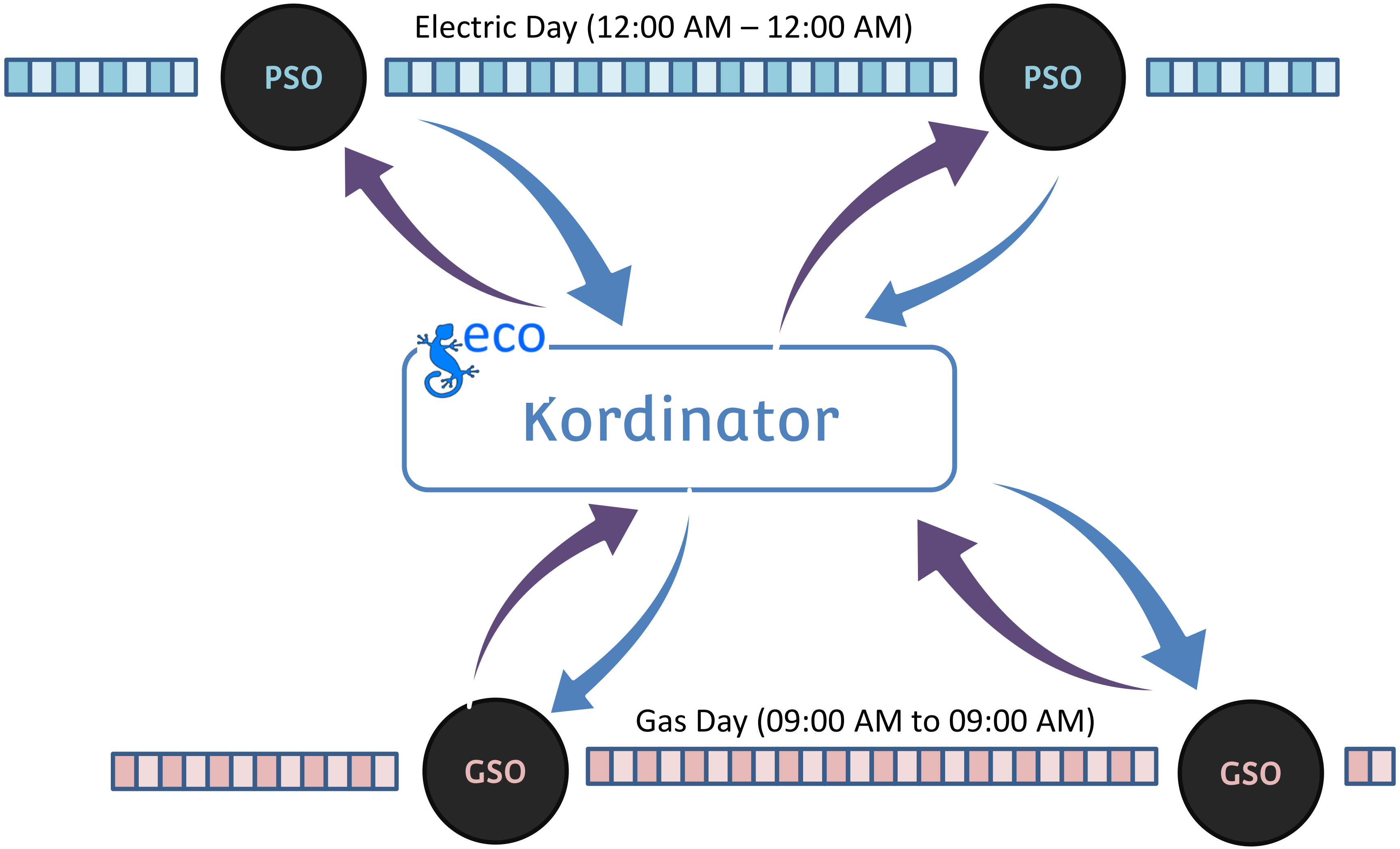
Dual/Financial:

- Shadow values of binding constraints
- Locational value of gas
- Energy costs

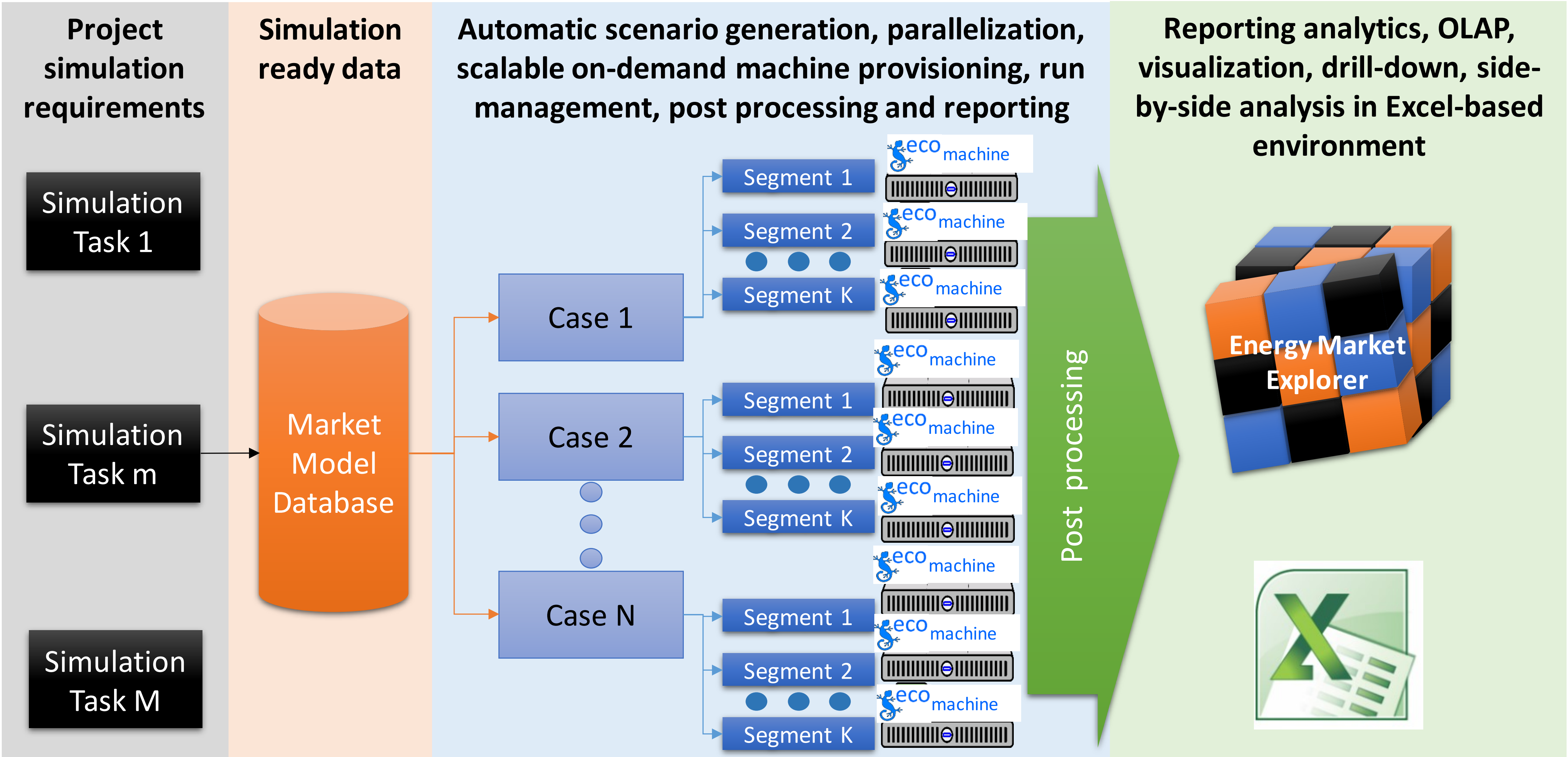
Gas System Optimizer (GSO)

- User controlled linear objective function, such as maximization of market surplus (social welfare)
- Runs optimization using rolling horizon approach
- Successfully benchmarked against hourly SCADA pipeline measurements over two months of the 2014 Polar Vortex
- Integrated into ENELYTIX® cloud-based parallel computing system as Power System Optimizer (PSO) – Gas System Optimizer (GSO) interaction process; implemented on Amazon EC2 cloud
- GSO models, algorithms, key engineering constraints – see A. Zlotnik, M. Chertkov, and S. Backhaus, "Optimal control of transient flow in natural gas networks," in 54th IEEE Conference on Decision and Control, Osaka, Japan, 2015, pp. 4563–4570

The GECO Machine



Schematic Architecture of GECO ENELYTIX



IT services: security, user authentication and access management, usage tracking, data encryption, storage and archiving

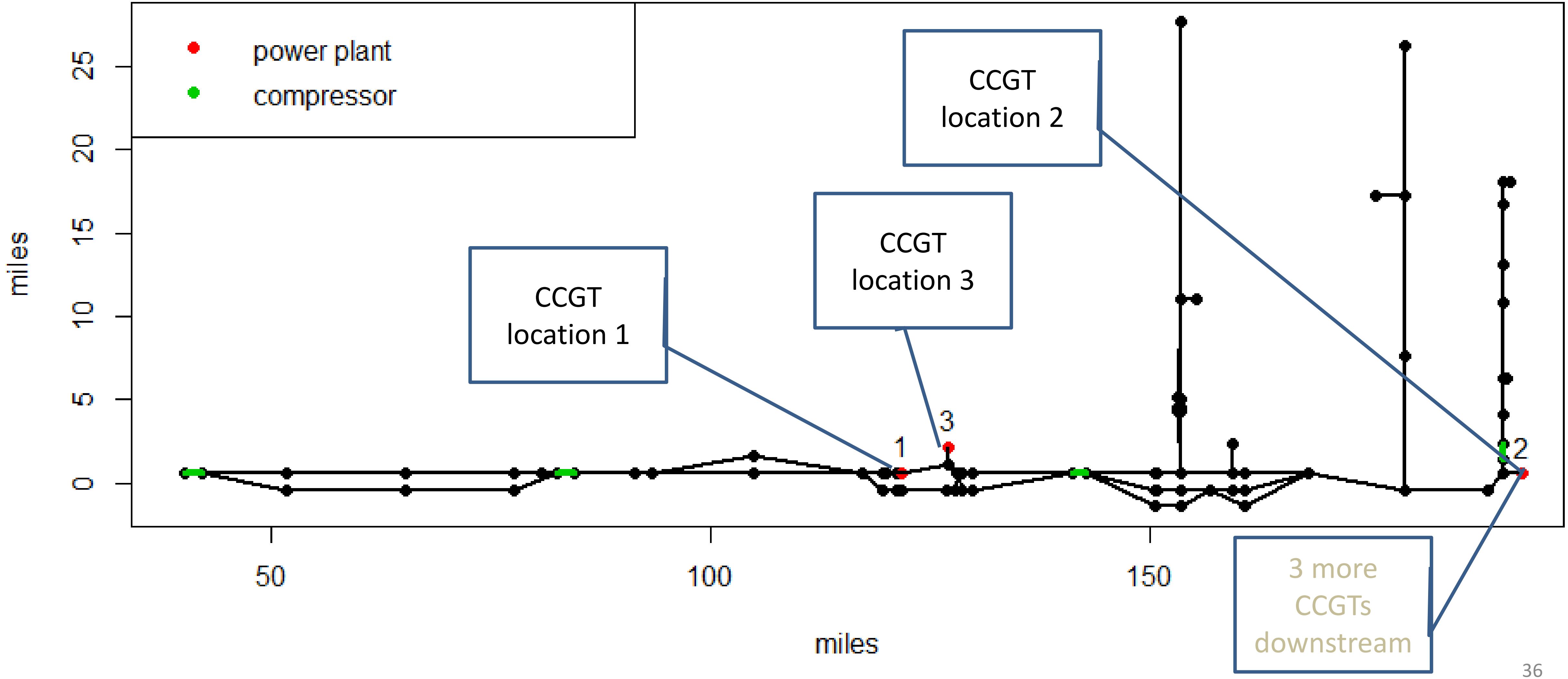
Simulation Results

Gas – Electric Model Used

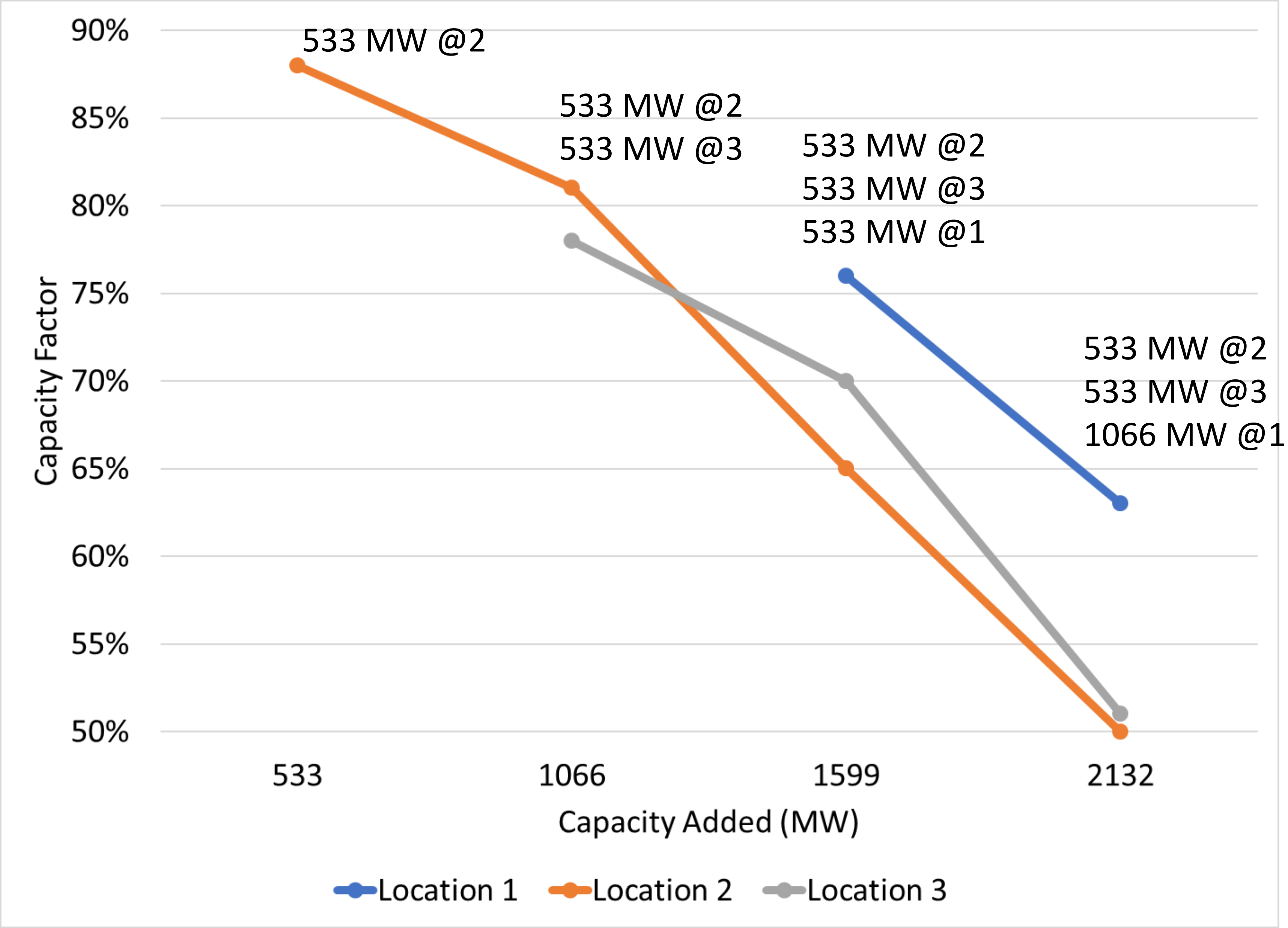
- Electric System
  - Large electrical system with over 50 GW of peak demand
  - Used ENELYTYX nodal dataset representing that system during February 2014 (Polar Vortex)
  - PSO results benchmarked to historical data in terms of replicating actual generation and LMPs
- Natural Gas System – the above discussed model used for benchmarking
  - Segment of actual pipeline network (over 400 miles of pipes, 4 compressor stations)
  - Historical data for February 2014 (Polar Vortex)
- Gas Electric Intersection
  - 3 CCGT plants directly served by the pipeline segment modeled (1% of thermal capacity, 1.7% of gas capacity)
  - 3 more CCGT plants located downstream (together 3% thermal, 4.7% of gas capacity)

Numerical Experiment: how much bigger CCGT capacity this system could serve?

Assumptions: 1)Each CCGT is 533 MW and has a heat rate of 6400 Btu/kWh. 2) New CCGTs to be co-located with existing CCGTs on the system. 3) The system continues to serve existing customers at the same hourly rate as w/o new power plants

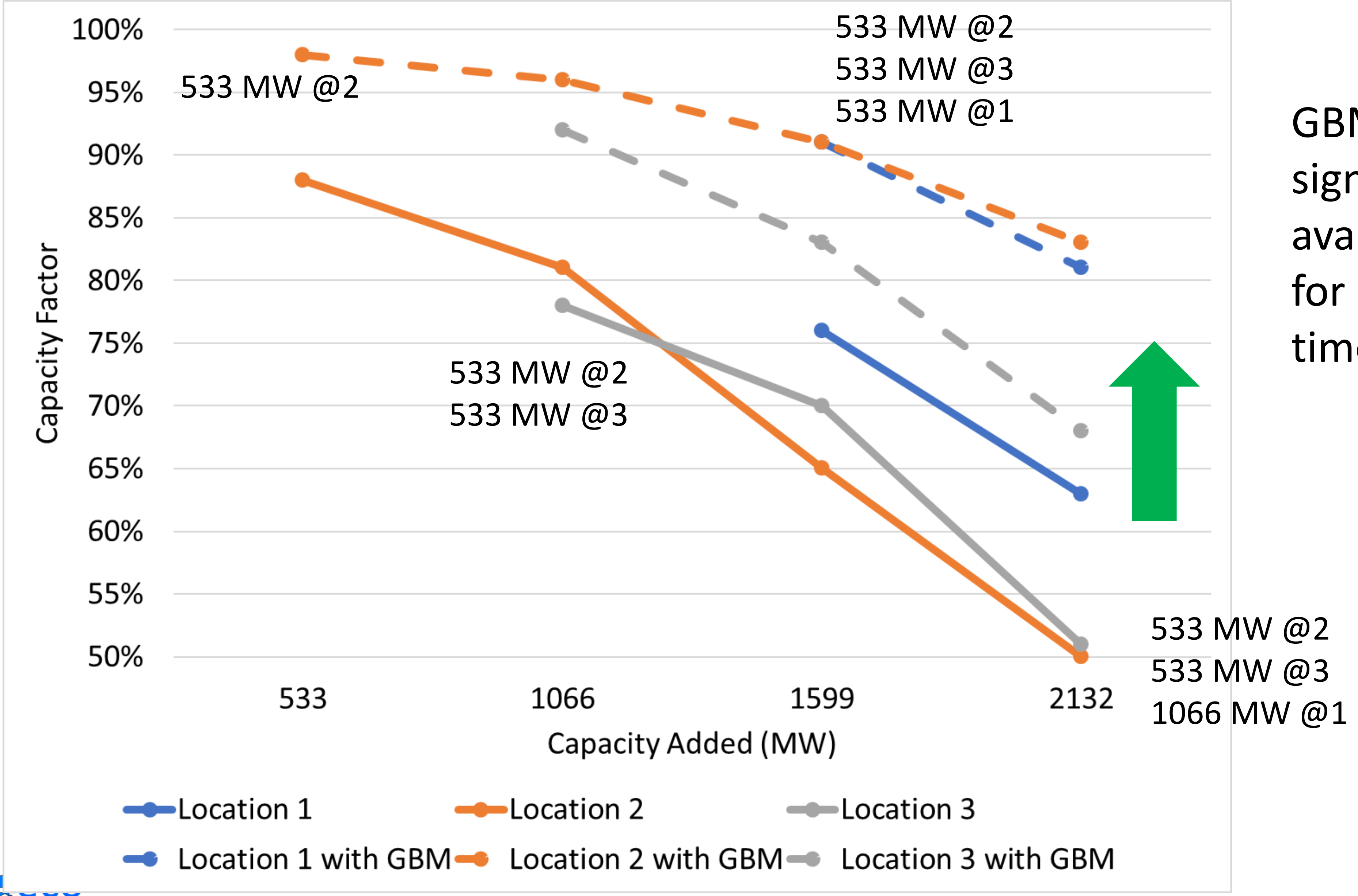


Capacity factors for added CCGTs pipeline can support using transient optimization



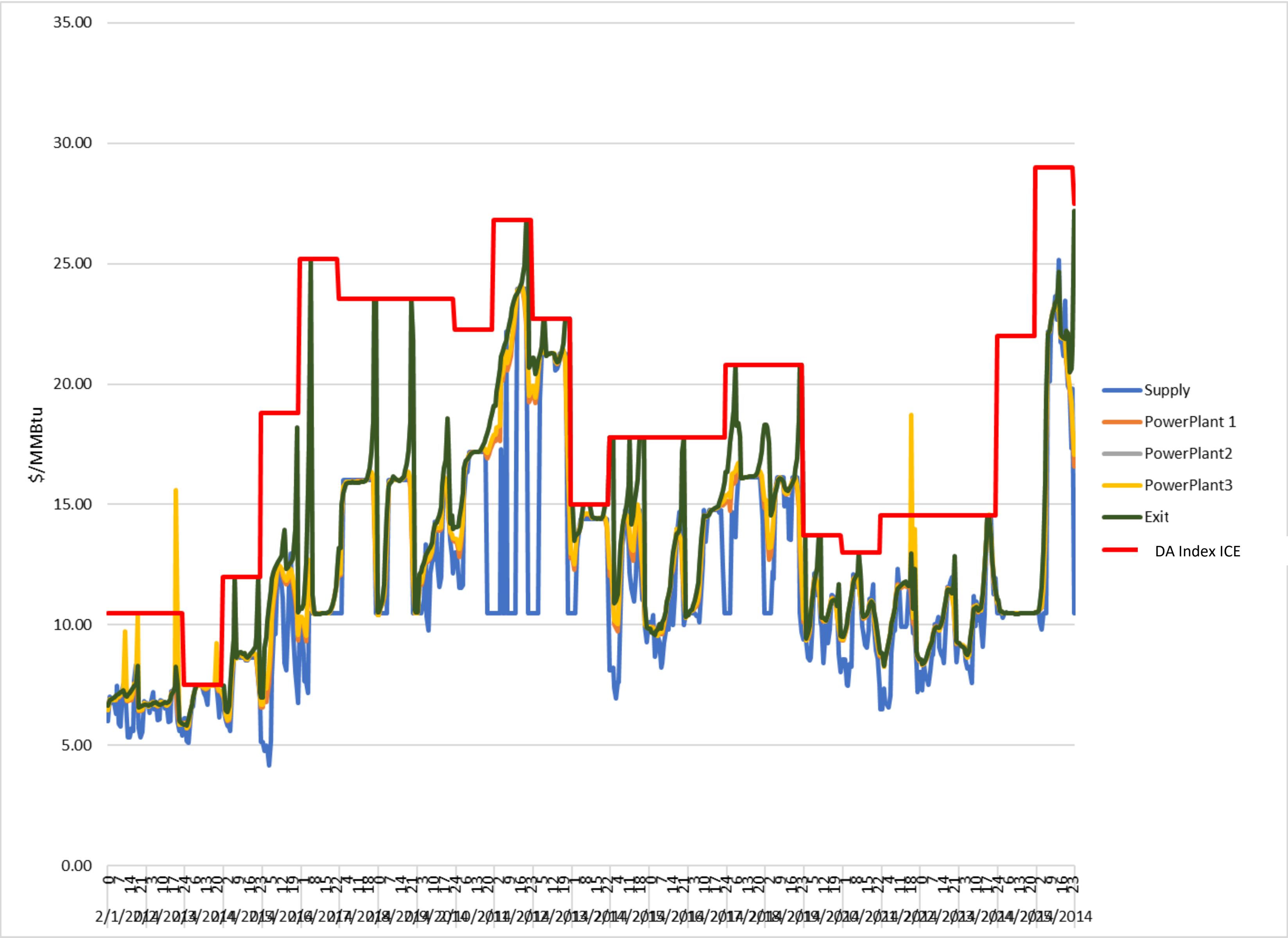
Assume that at all nodes buyers are willing to sell up to 5% of hourly purchases at the Base Case LTV

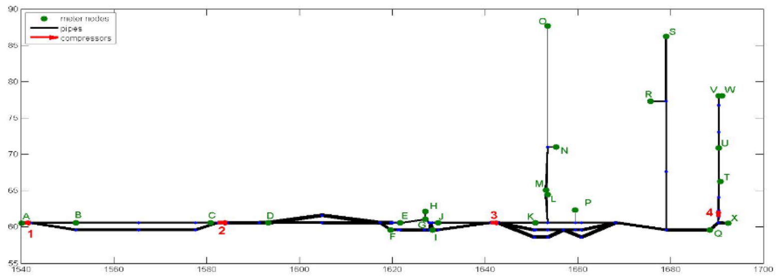
Simulated Effect of Gas Balancing Market



GBM trading can significantly increase availability of natural gas for electric generation at time of need

Simulated LTVs compared to Hub Day-ahead Index Cleared on ICE – Hourly

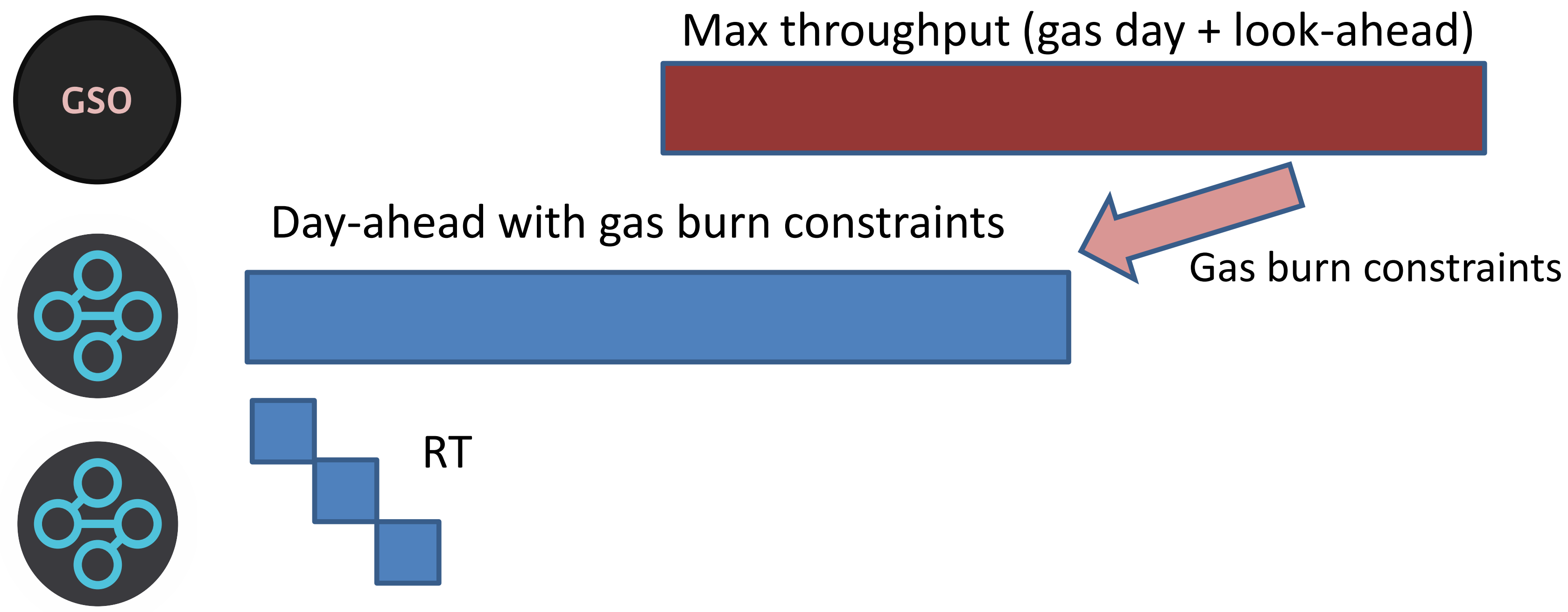




Gas Electric Co-Ordination with GBM

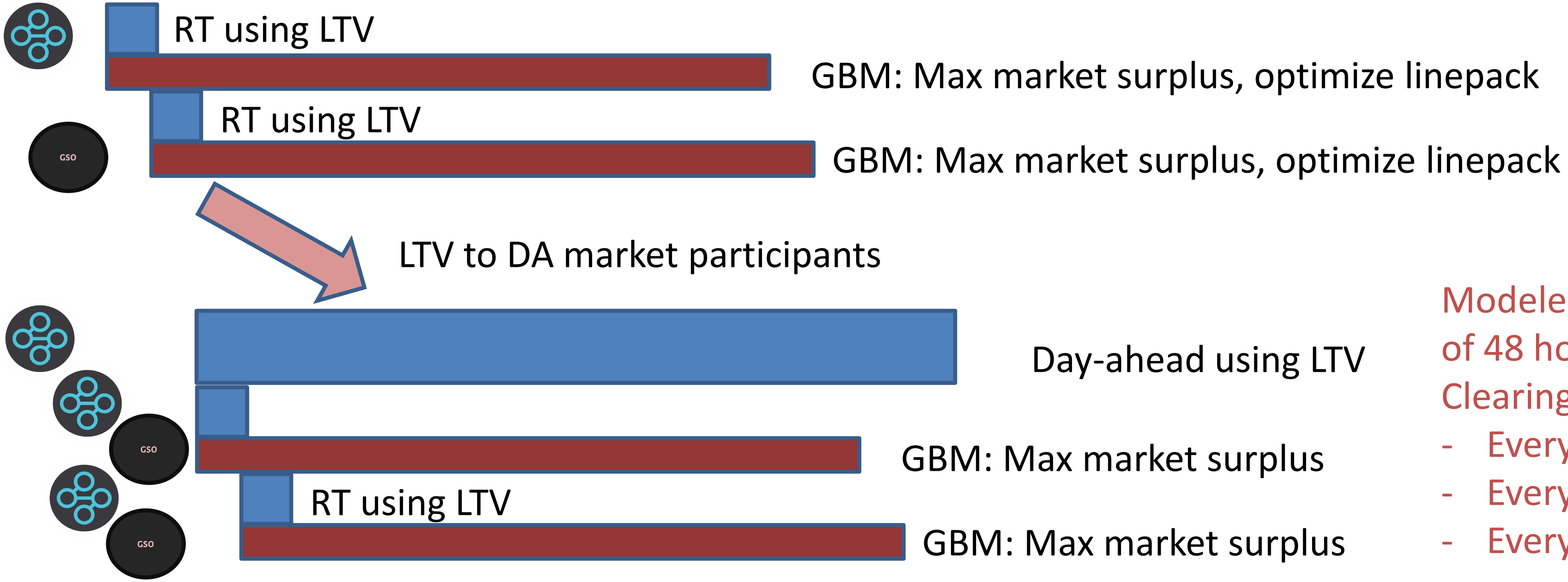
Modeling Business as Usual (BAU) in GECO ENELYTIX

- Business as Usual Description
  - Indicative day-ahead gas procurement by generators
  - Generators schedule output and gas burn day-ahead
  - Generators schedule/confirm gas deliveries with pipeline
  - Generators burn gas and produce power in real-time



Modeling GBM in GECO ENELYTIX

- Interactions of DA and RT with GBM
  - GBM interacts with RT but it has long look-ahead
  - GBM look-ahead provides hourly price discovery for DA



Modeled GBM horizon of 48 hours

Clearing scenarios
- Every hour
- Every 4 hours
- Every 12 hours

Summary of Results

- Gas price impact for GBM participants
  - Depending on the location GBM participants would see 3% to 12% in gas price reduction from the actual day-ahead zonal index paid
  - Participating generators see increase in operating margin by 45% - 380% depending on the location
  - **With just 3 units trading in GBM, most of the instantaneous congestion in that pipeline segment could have been eliminated**
- With 3 units in GBM (1% of thermal capacity), we did not observe significant impact on the electricity market – the change it too small to produce discernable differences
- With 6 units in GBM (3% of thermal capacity), we observed reductions in production costs and prices
  - System-wide RT production costs reduced by 2.2% to 2.8%
  - Reduction in LMPs within the zone where most of the affected capacity is located by 2.1% - 2.3%

Conclusions

- Adoption of transient optimization and implementation of market-based intra-day coordination mechanism would benefit both gas and electric industry
- Transient optimization should become a standard tool used by the pipeline industry. This is just “good utility practice”
- FERC should provide an incentive mechanism to pipelines to expedite adoption of transient optimization and adoption of transparent and liquid market for intra-day trading
- Electric industry needs models like GECO ENELYTIX for planning studies, reliability assessment, integration of renewables, market design and other applications. These models need gas industry data. Data sets could be developed with sufficient funding

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