eco

arpa-e Advanced Research Projects Agency • ENERGY

MASSACHUSETTS CLEAN ENERGY CENTER

Economic Optimization of Intra-Day Transient Gas Pipeline Flow, Locational Values of Natural Gas and their use for Gas – Electric Coordination

Presented at the FERC Technical Conference: Increasing Real-Time and Day-Ahead Market Efficiency through Improved Software

June 26, 2017

Aleksandr Rudkevich (NEG), Anatoly Zlotnik (LANL), John Goldis (NEG), Pablo Ruiz (BU), Richard Tabors (TCR), Scott Backhaus (LANL), Michael Caramanis (BU), Richard Hornby (TCR)

Project Team

Newton Energy Group | Los Alamos National Laboratory Est. 1943 | POLARIS Systems Optimization | Boston University | AIMMS

External Technical Expertise

Kinder Morgan | pjm

- About GECO, Project Team
- Gas Balancing Market
- Transient Pipeline Optimization
- Locational Trade Value of Natural Gas
- LTV Case Study
- Conclusions

Disclaimer

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 entities -- the PJM Interconnection and Kinder Morgan.

- 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: 2 years through April 19, 2018
- ARPA-E project summary: https://arpa-e.energy.gov/?q=slick-sheet-project/gas-electric-co-optimization

GECO Project Team and Technical Expertise

Institution	Expertise
Newton Energy Group	• ENELYTIX® Cloud platform for parallel modeling and analytics of energy systems • Optimal dynamic pricing and market design • Commercialization
Los Alamos National Laboratory EST. 1943	• Advanced computational methods and algorithms for simulation and optimization of gas & electric networks
POLARIS Systems Optimization	• Advanced power systems simulator engine within ENELYTIX® • Power systems optimization expertise
Boston University	• Market design, coordination algorithms
AIMMS	• Modeling language, optimization

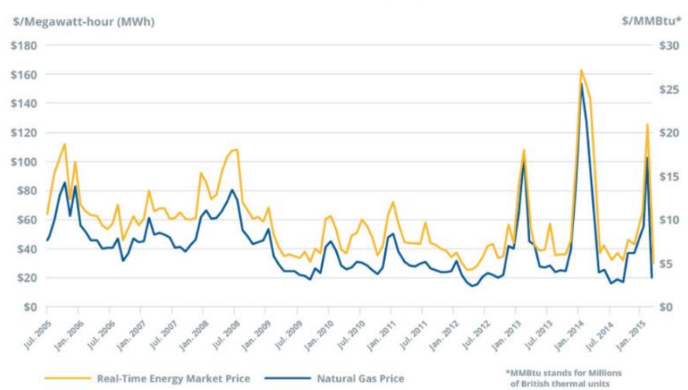
External Technical Expertise

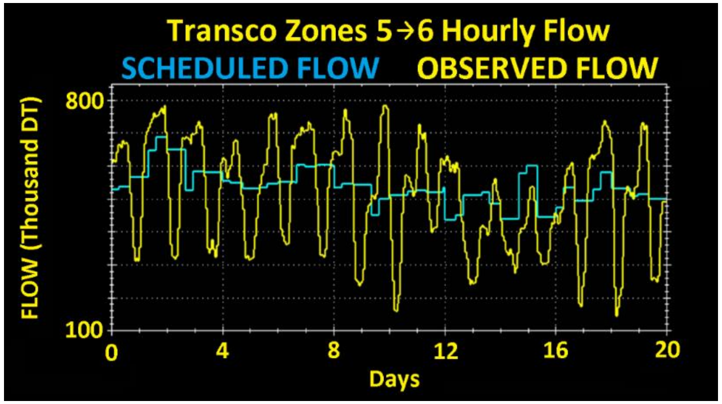
pjm

KINDER MORGAN

Motivation

- Rapidly increasing role of gas-fired generation both as energy and A/S needed to integrate renewable resources
- Price of natural gas drives the price of electricity
- Gas fired generation is a “marginal consumer” of natural gas → gas-fired generation drives the price of natural gas
- Lack of coordination between natural gas and electric grids may produce massive simultaneous price spikes for natural gas and electricity consumers (e.g. Polar Vortex of 2014)
- Radical improvement in coordination of natural gas and electric operations is necessary for the advancement of modern electricity and natural gas delivery systems
- Recent advancements in pipeline simulation and optimization methods developed by the LANL team create an opportunity to achieve such radical improvements





Opportunity

- Advancement of the GECO project creates a unique opportunity to:
  - Optimize pipeline operation using economic criteria
  - Develop near real-time pricing of natural gas that is consistent with the real-time physics of gas flow in the pipeline
  - Efficiently coordinate the gas and electric networks through optimization methods and market signals based on locational prices for electricity and natural gas

GECO Objectives and Program Elements

Objectives: algorithms, software and an associated market design to dramatically improve coordination and / or co-optimization of natural gas and electric physical systems and wholesale markets on a day-ahead and intra-day basis

Program Elements

Program Element	
Software & Algorithms	• Modules for pipeline simulations and optimization • PSO SCUC/SCED for electric system simulation • Data, cloud-based system simulating gas - electric interactions
Market Design	• Joint gas-electric theory and computation methods of granular prices consistent with the physics of operations • Market design proposal including coordination mechanisms using granular prices
Realistic Market Simulations	• Gas-electric simulation model using realistic data • Simulated scenarios comparing performance of gas-electric coordination policies under different assumptions

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

In this project we address Operations Coordination Challenges

eco

Today's Key Gas–Electric Coordination Deficiency

Gas-fired power generators…

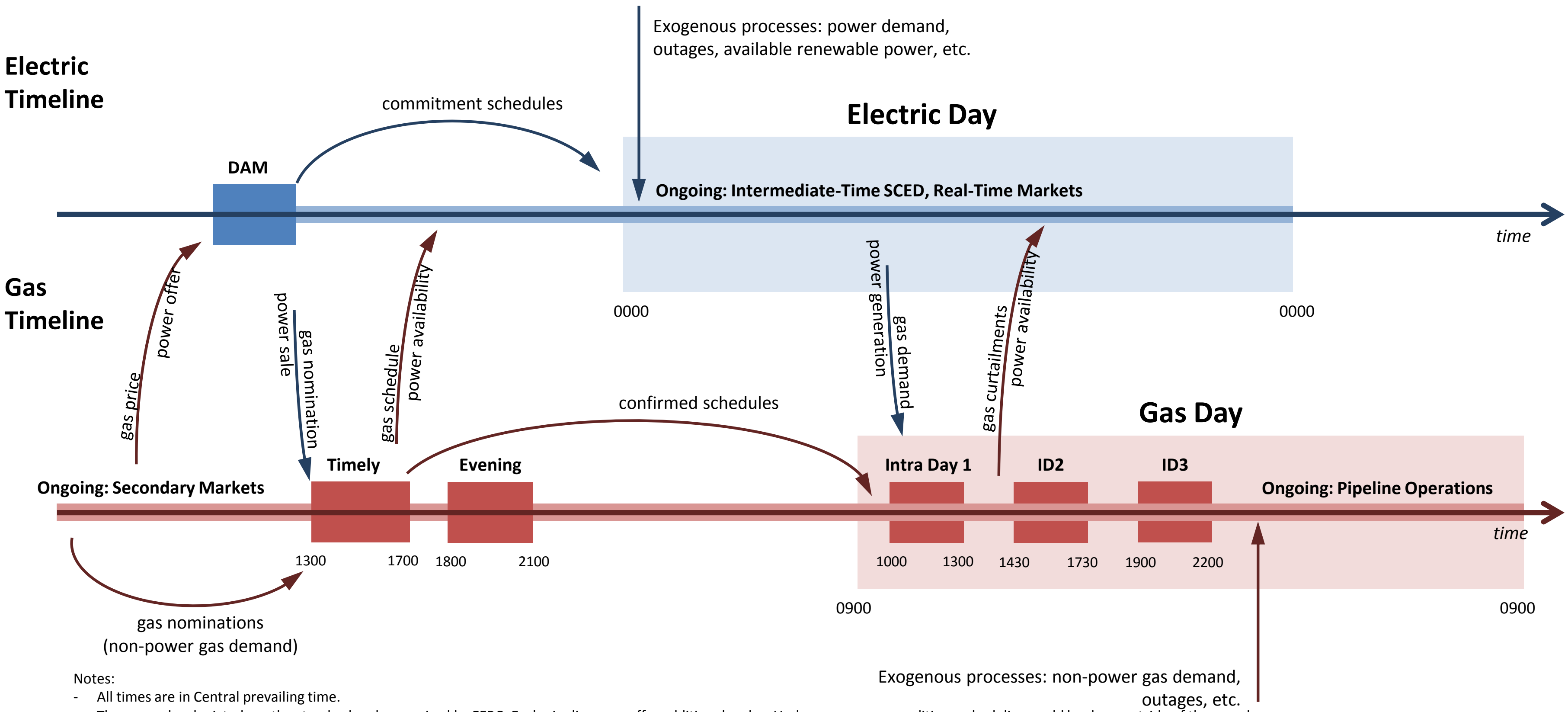
- Tend to be flexible units capable of generating upon relatively short notice,
- Are active in the 5-minute real-time power markets, and can change their outputs frequently, following changes in system needs,
- Provide the bulk of operating reserves in some regions – requires the ability to change output 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.

The Proposed Coordination Mechanism with Gas Balancing Market (GBM)

Current Gas-Electric Decision Cycles



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.

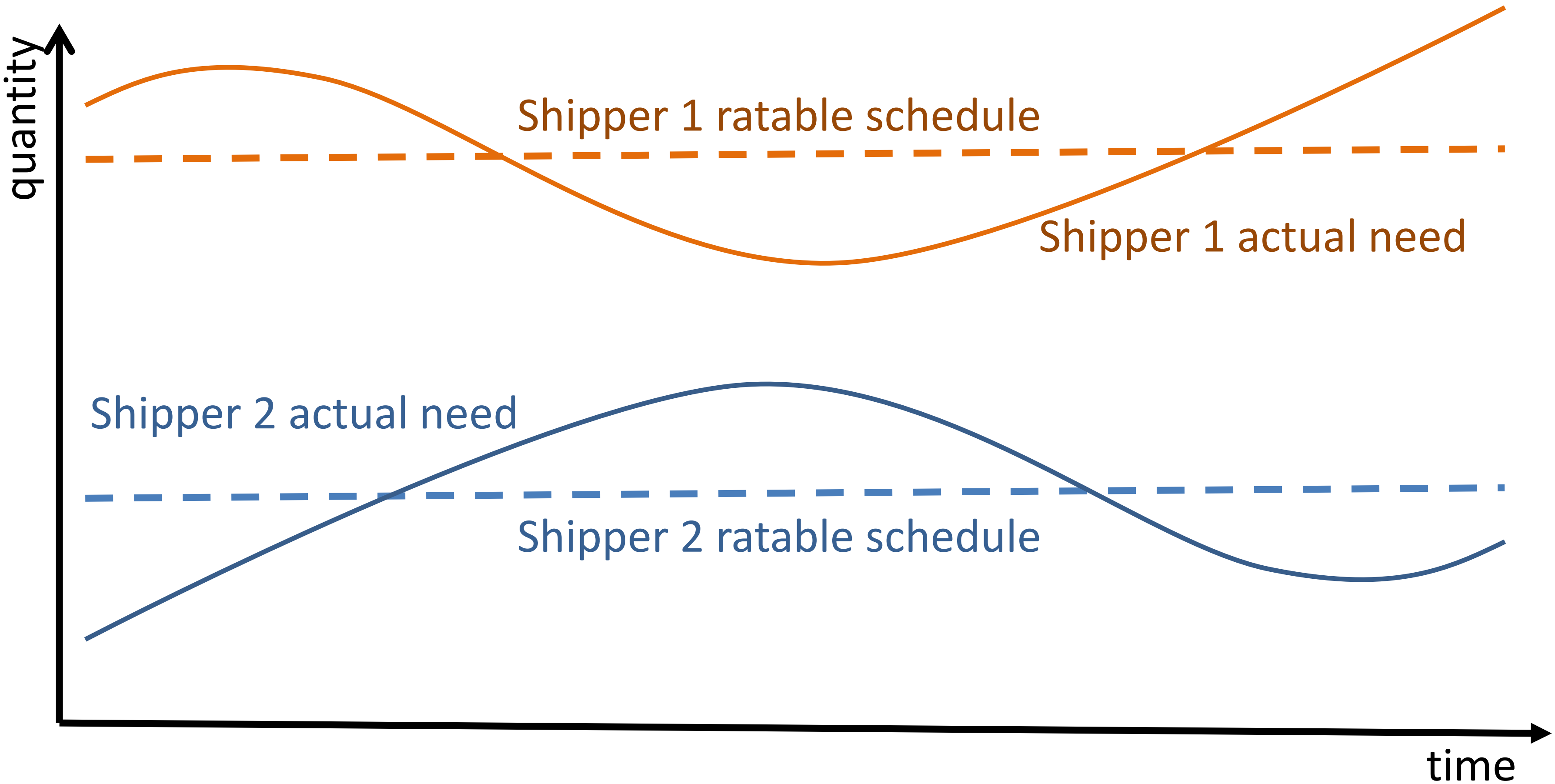
Gas Balancing Market

The Gas Balancing Market (GBM) would:

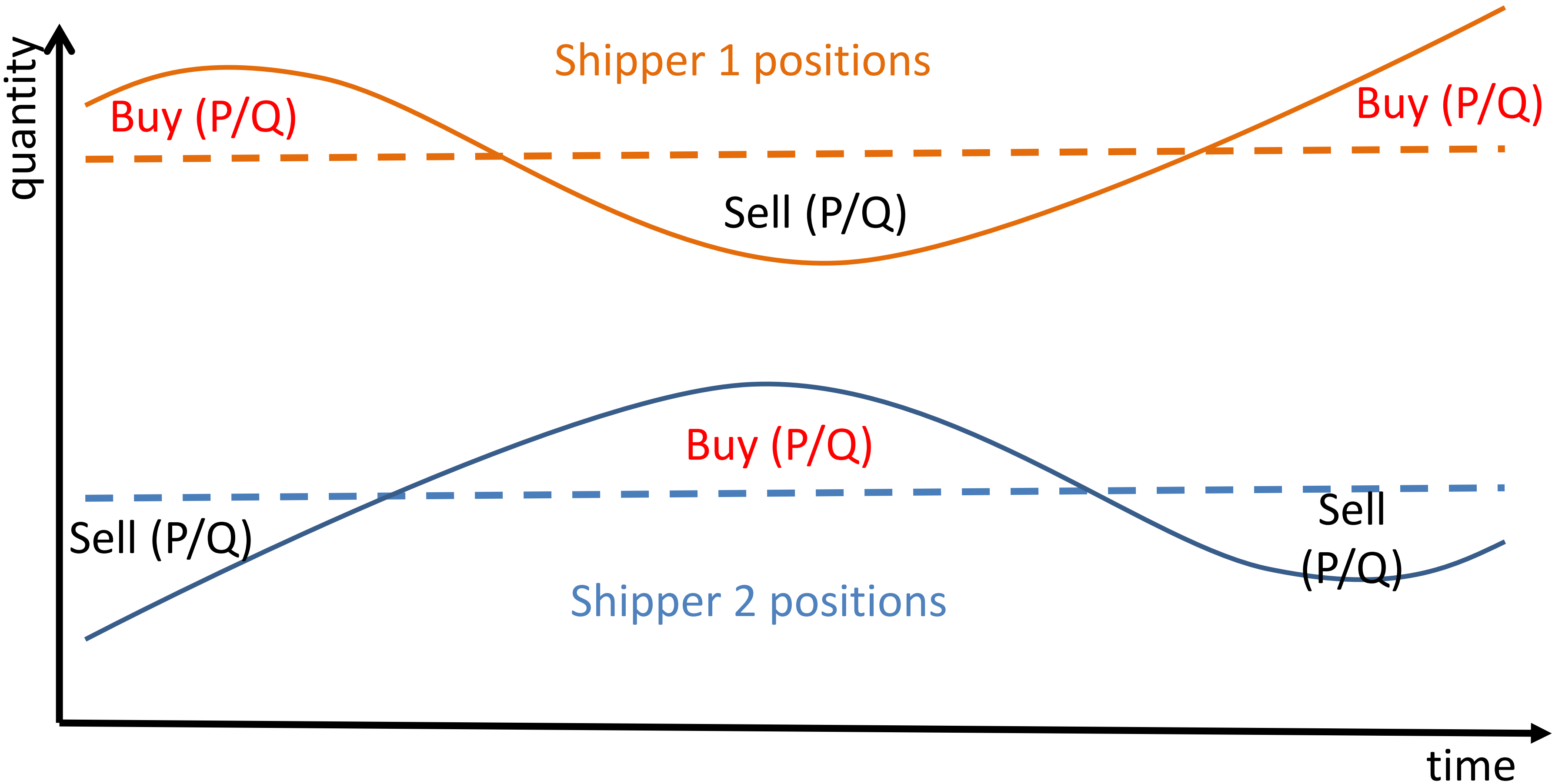
- Be pipeline specific
- Have ***voluntary*** participation
- Honor existing transportation rights and contracts
- Enable trades of hourly imbalances from ratable schedules
- Assure that intra-day transactions cleared in the market are physically implementable
- Enable intra-day gas transactions between 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

eco

Ratable schedules vs. non-ratable needs



Need > schedule –> buy. Need < schedule –> sell

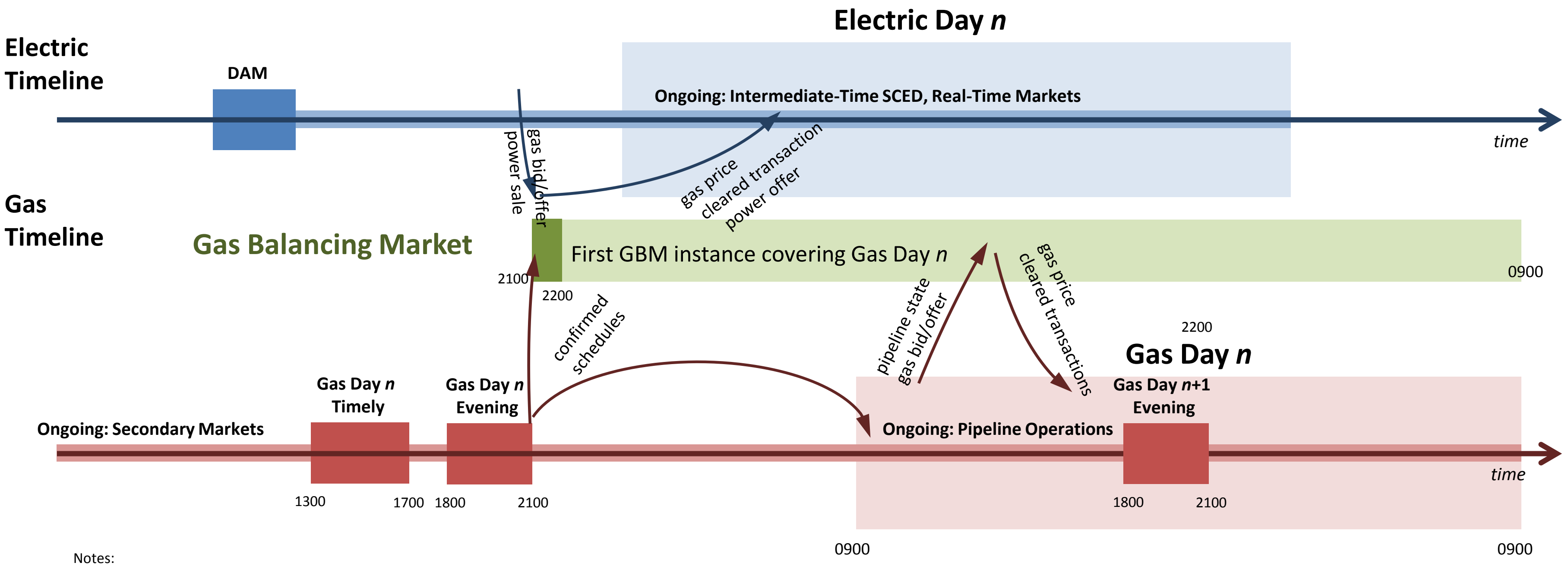


Gas Balancing Market through Economic Optimization of Pipeline Operation

- A two-sided auction
- Conducted subject to engineering constraints on gas pipeline network
- Network nodes are custodial meter stations (places where gas changes hands) and compressor stations
- Network edges – pipes physically connecting nodes
- Participants: seller submitting Price/Quantity (P/Q) offers to sell gas and buyers submitting P/Q bids to buy gas. Seller and buyers may or may not hold pipeline capacity
- Offers and bids are node-specific
- Offers and bids are submitted with hourly time step for an optimization horizon (e.g., 36 hours)
- Auctioneer's objective function is to maximize summed over the optimization horizon market surplus between accepted bids and offers less compressor costs of running the pipeline

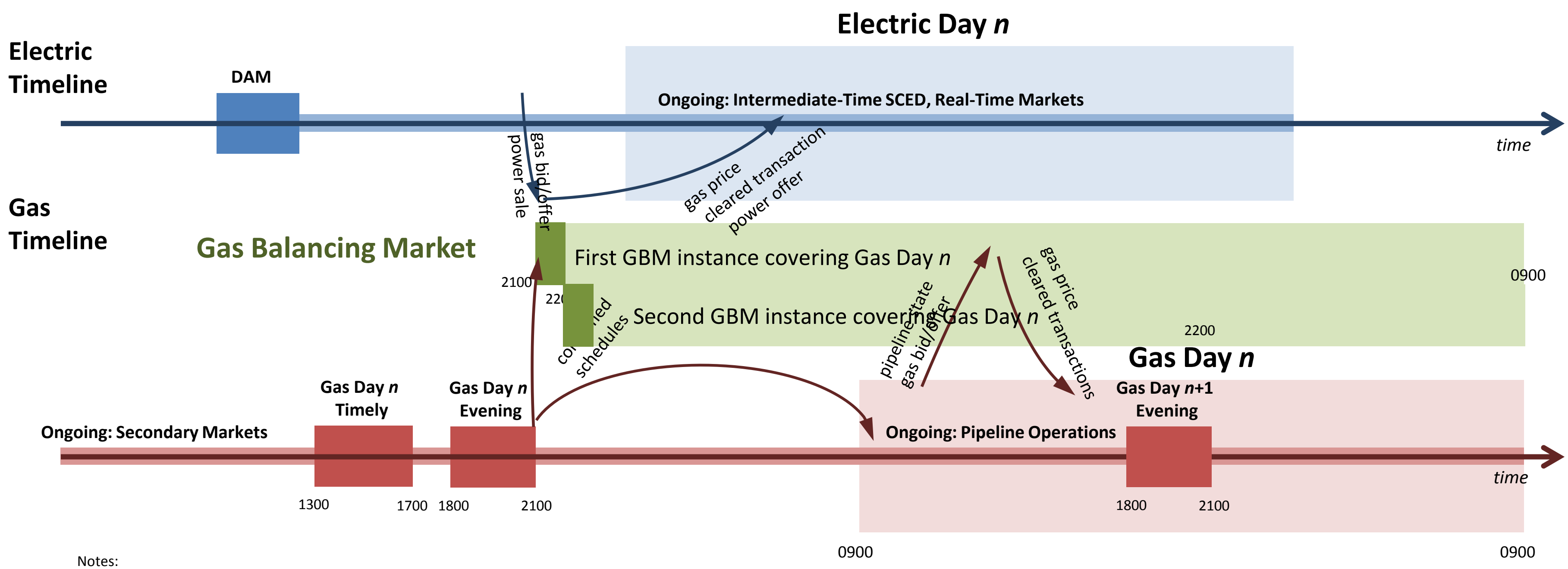
eco

Proposed Timing of the Gas Balancing Market



Notes:
- All times are in Central prevailing time.
- Standard gas cycles required by FERC are shown. Pipelines may offer additional cycles. Under emergency conditions scheduling could be done outside of these cycles.

Proposed Timing of the Gas Balancing Market



Notes:
- All times are in Central prevailing time.
- Standard gas cycles required by FERC are shown. Pipelines may offer additional cycles. Under emergency conditions scheduling could be done outside of these cycles.

Market 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

eco

Granular Pricing Signals at Work

- Electric 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

- Gas 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 in economic solutions before regulatory agencies

eco

eco

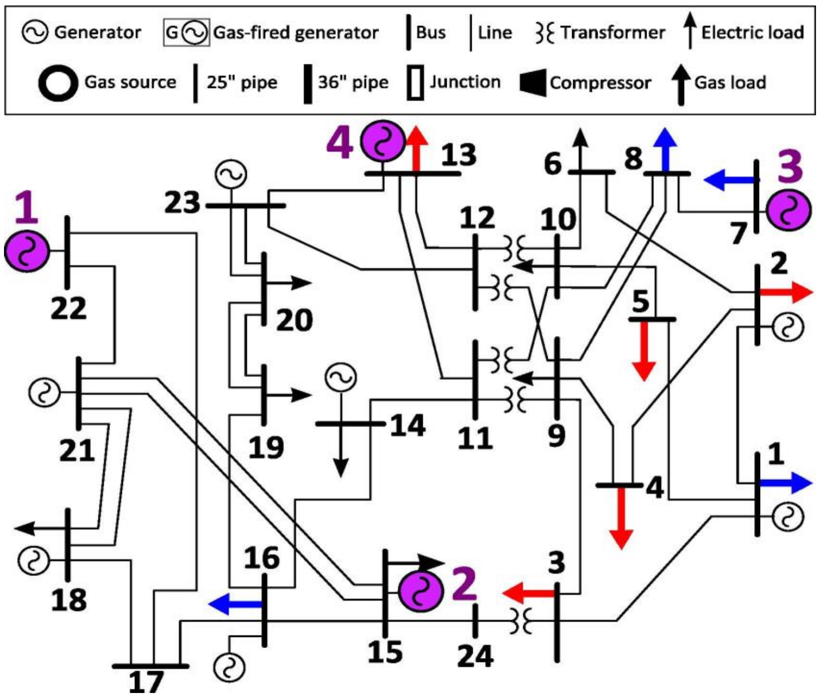
What would Make the Gas Balancing Market Possible?

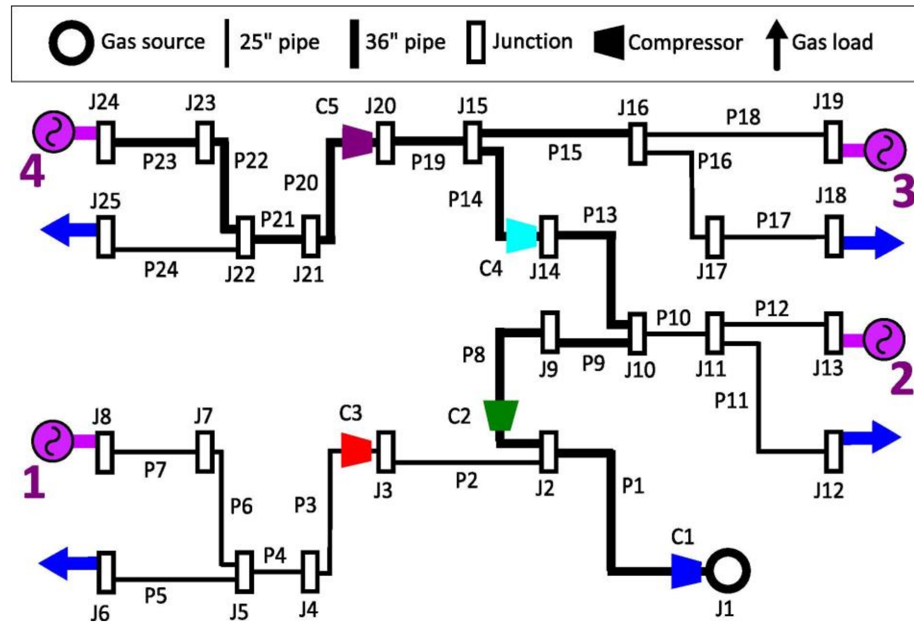
(1) Transient Pipeline Optimization
and
(2) Locational Trade Value (LTV) of Natural Gas

Economic optimization of pipeline operation is the critical technology breakthrough

Electric industry made tremendous successes in optimizing operations of power networks

Our capability to optimally operate gas networks is lagging behind





To better coordinate gas-electric infrastructure, we should learn how to dynamically optimize operations of gas pipelines

eco

Key Pipeline Modeling and Optimization Capabilities

- Transient optimization of pipeline operations
  - Optimal dynamic operation of compressors
  - Economically optimal gas purchases and sales, line pack and use of storage
- Scalable methods and algorithms
  - Can optimize a large pipeline network
  - Can solve optimization problems for real size systems in a matter of minutes
- Development of economic signals that are:
  - Granular in time (e.g. hourly)
  - Granular in space (e.g. at each meter station)
  - Consistent with the physics of gas flow and engineering constraints on pipeline operations

eco

Pipeline Physics—Equations and Intuitive Understanding

Fundamental variables

- Gas density in the pipe: $\rho(x,t)$
- Mass flow rate through the pipe: $\phi(x,t)$

Basic physical phenomena

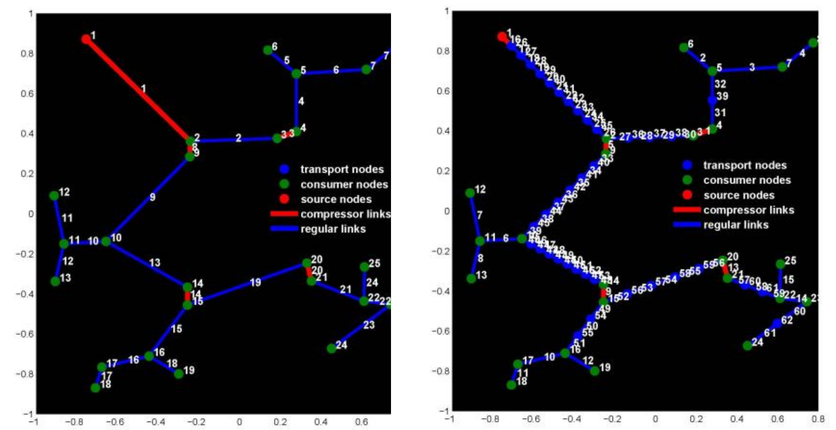
- Mass flow and momentum are conserved along the pipe

$$\text{mass conservation:} \quad \partial_t \rho + \partial_x \phi = 0$$

$$\text{momentum balance:} \quad \partial_t \phi + a^2 \partial_x \rho = -\frac{\lambda}{2D}\frac{\phi|\phi|}{\rho}$$

- Mass flow is conserved at pipe junctions

$$\sum_{i \in \partial_+ j} X_{ij} \overline{\phi}_{ij}(t) - \sum_{k \in \partial_- j} X_{jk} \underline{\phi}_{jk}(t) = d_j(t) + \hat{d}_j(t)$$



Continuous equations are OK, but we need to represent networks

Pipeline Network Equations—Node & Edge Representation

Mass conservation: $$\partial_t p_{ij} + \frac{a^2}{A_{ij}}\partial_x \phi_{ij} = 0, \qquad \forall (i,j) \in \mathcal{E},$$

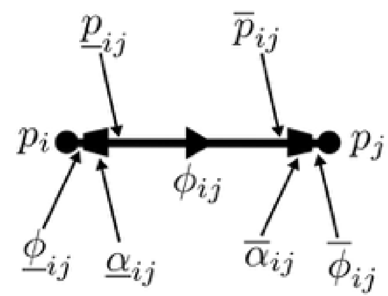
Momentum conservation: $$\frac{1}{A_{ij}}\partial_t \phi_{ij} + \partial_x p_{ij} = -a^2 r_{ij}(\phi_{ij}, p_{ij}), \qquad \forall (i,j) \in \mathcal{E},$$

Nodal flow balance: $$\sum_{k \in \partial_- j} \underline{\phi}_{jk}(t) - \sum_{i \in \partial_+ j} \overline{\phi}_{ij}(t) - \bar{q}_j(t) - \sum_{m \in \partial_g j} (\hat{s}_m(t) - \hat{d}_m(t)) = 0, \qquad \forall j \in \mathcal{V},$$

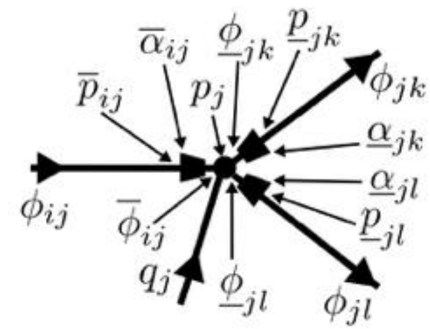
Pressure compatibility: $$\underline{p}_{ij}(t) = \underline{\alpha}_{ij}(t) p_i(t), \qquad \forall (i,j) \in \mathcal{E},$$
$$\overline{p}_{ij}(t) = \overline{\alpha}_{ij}(t) p_j(t), \qquad \forall (i,j) \in \mathcal{E},$$

The network equations are discretized in space and time for integration into optimization (or simulation). The form of discretization is important for tractability

Edge view



Nodal view

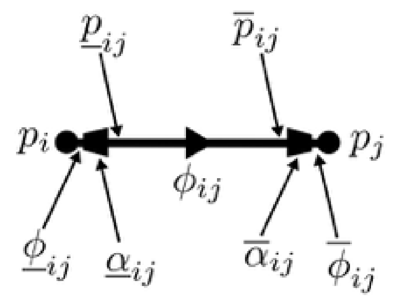


eco

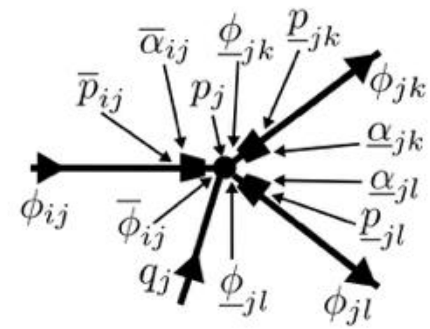
Pipeline Network Node Constraints

$$
\begin{array}{rll}
\text{Pressure limits:} & p_{ij}^{\min} \le p_{ij}(t,0) \le p_{ij}^{\max}, & \forall (i,j) \in \mathcal{E}, \\
 & p_{ij}^{\min} \le p_{ij}(t,L_{ij}) \le p_{ij}^{\max}, & \forall (i,j) \in \mathcal{E}, \\
\text{Boost upper limits:} & \underline{\varepsilon}_{ij}|\underline{\phi}_{ij}(t)|\left((\underline{\alpha}_{ij}(t))^{h}-1\right) \le \underline{E}_{ij}^{\max}, & \forall (i,j) \in \mathcal{E}, \\
 & \overline{\varepsilon}_{ij}|\overline{\phi}_{ij}(t)|\left((\overline{\alpha}_{ij}(t))^{h}-1\right) \le \overline{E}_{ij}^{\max}, & \forall (i,j) \in \mathcal{E}, \\
\text{Boost lower limits:} & \underline{\alpha}_{ij}(t) \ge 1, \quad \overline{\alpha}_{ij}(t) \ge 1 & \forall (i,j) \in \mathcal{E}, \\
\text{Supply limits:} & s_m^{\min}(t) \le s_m(t) \le s_m^{\max}(t) & \forall m \in \mathcal{G}, \\
\text{Demand limits:} & d_m^{\min}(t) \le d_m(t) \le d_m^{\max}(t) & \forall m \in \mathcal{G},
\end{array}
$$

Edge view



Nodal view



Nodal constraints are technical/engineering limits on operations, but they also create different forms of congestion that lead to nodal price differentiation

Locational Trade Values (LTVs) of Natural Gas

- Mathematical formulation of the optimization problem
  - A two-sided auction over pipeline network
  - Uses non-linear dynamic PDEs of gas flow in the pipeline
  - Equation of state for compressible flow
  - Dynamic Optimization with market surplus summed over multiple hours
  - Optimizes purchases and sales quantities, compressor operation and line pack
- Shadow prices (dual variables)
  - For mass balance at nodes (Locational Trade Value or LTV)
  - For pressure and compressor limits (capacity values)
  - Formal proof of revenue adequacy for the Auctioneer over optimization horizon

eco

Locational Trade Values (LTVs) of Natural Gas

- Transient LTVs
  - reflect increase in system-wide costs of serving incremental locational demand incurred over entire optimization horizon
  - cost increase may not coincide with demand increase
  - depend on the timing, location and cost of marginal resources used to serve incremental demand subject to all engineering constraints
  - reflect current and anticipated conditions of the pipeline system during the optimization horizon

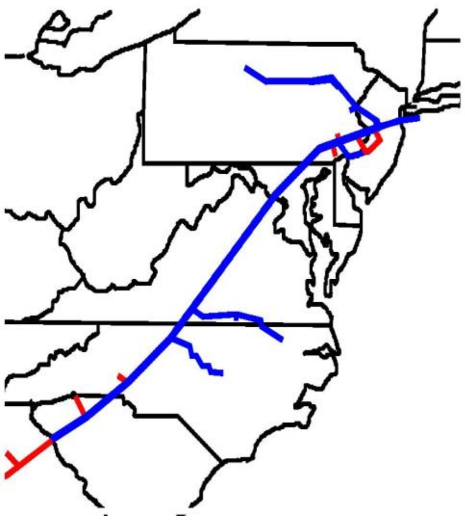
eco

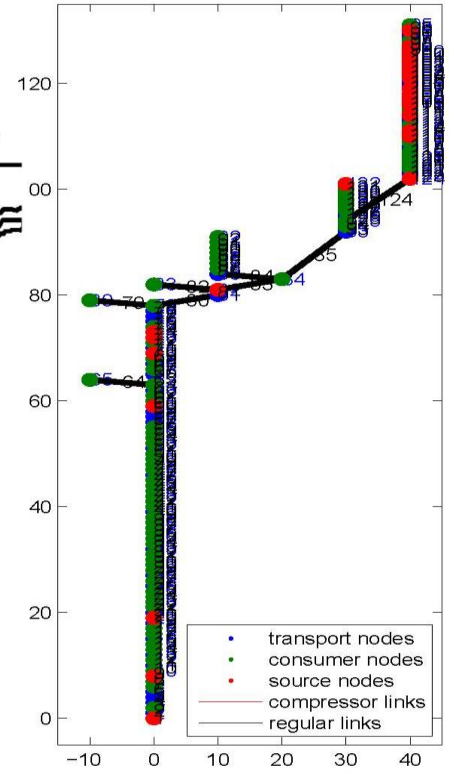
LTV Case Study

LTV Case Study: a 1600+ mile pipeline network

Results: 1500+ mile model

- Based on data for Williams – Transco pipeline Zones 5 and 6
- Spans Georgia to New York City, includes Pennsylvania
- 132 nodes, 131 pipes, 31 compressors
- Total network length of 2679 km (1664.9 miles)

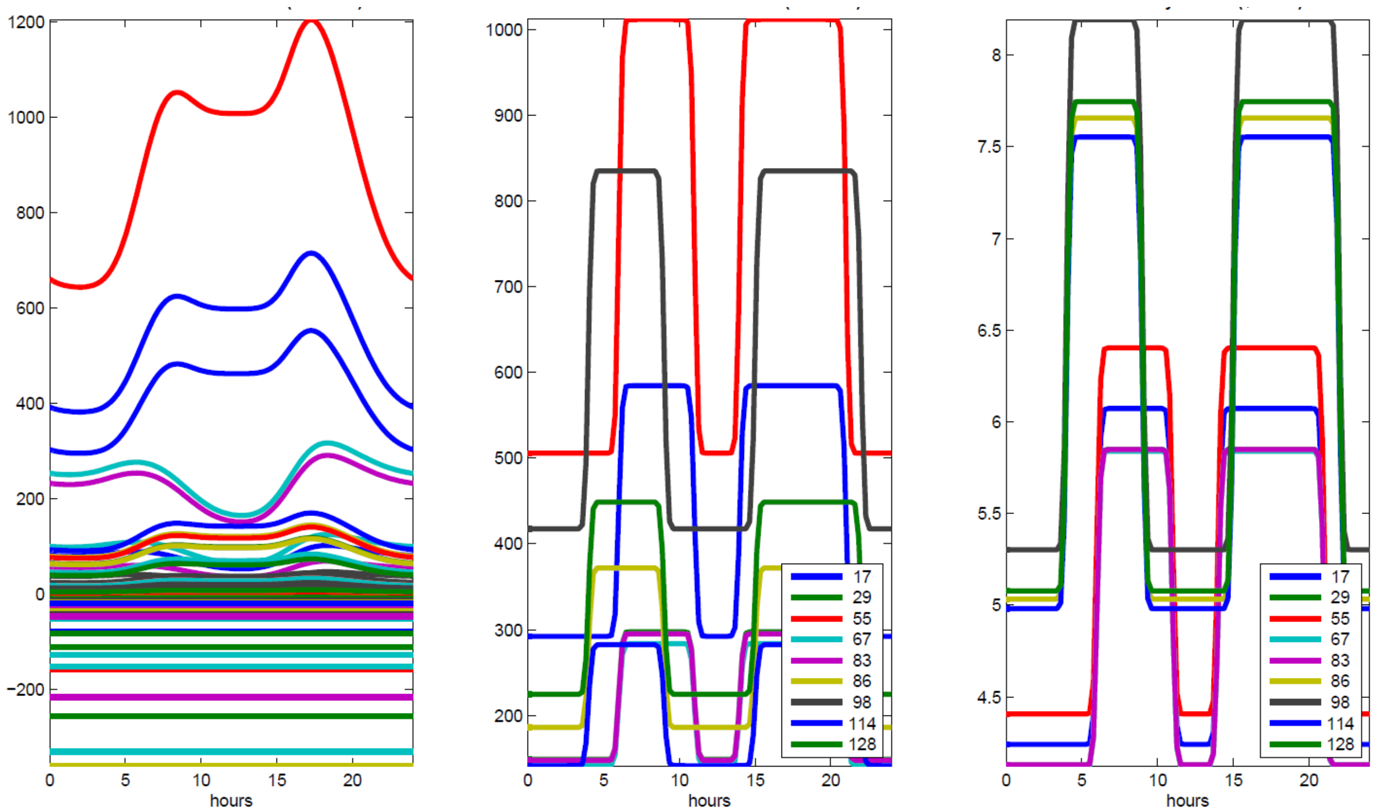




Self schedules and price sensitive bids/offers

Self schedules for firm receipts/deliveries (mcf)

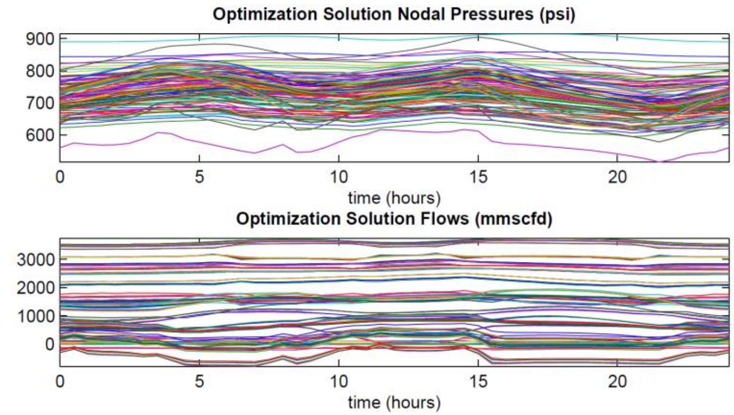
Quantity/Price bids and offers
(mcf) **($/mcf)**

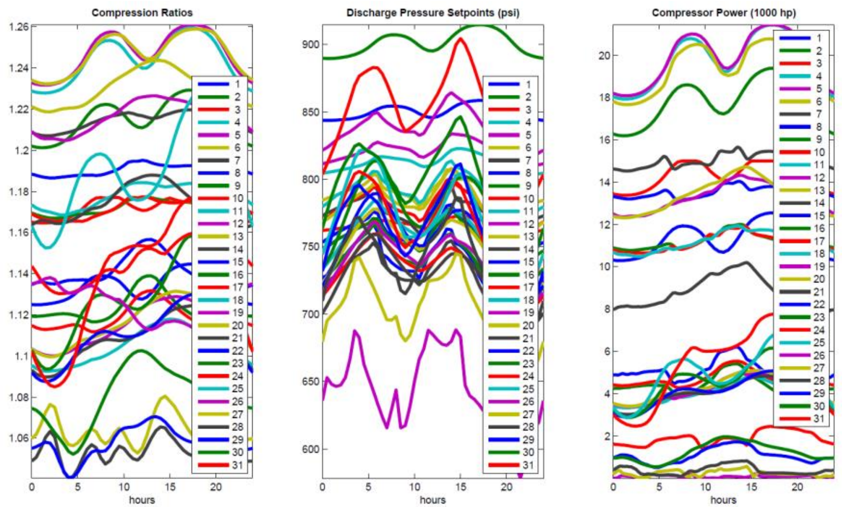


Market clearing engine guides operational regime for the pipeline

- Market engine algorithm computes time dependent pressure regime for each node and gas flow through each pipe and compressor station

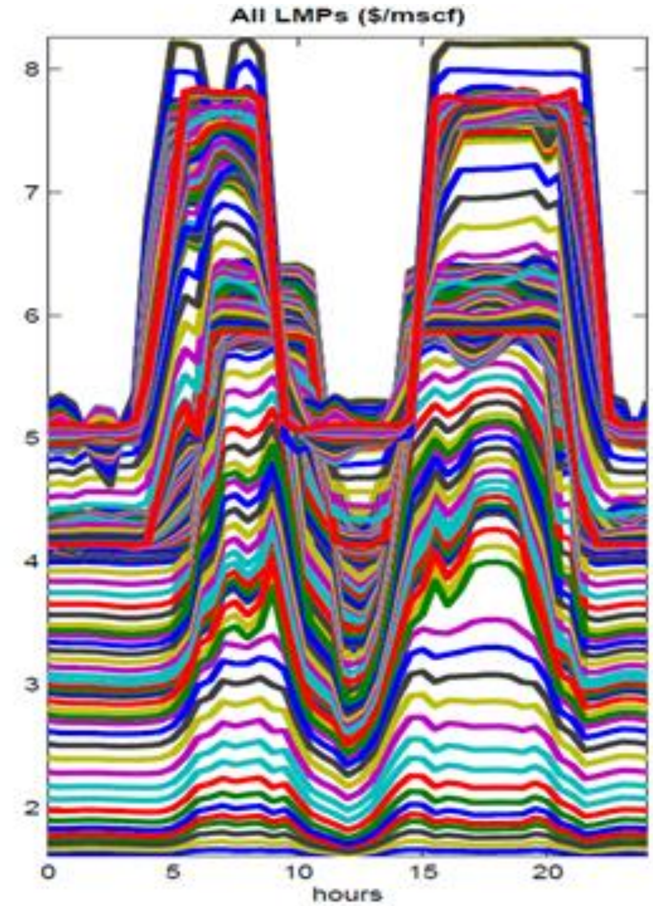
- Market engine defines compression ratios, discharge pressure settings and horsepower use for each compressor





Market clearing engine determines accepted bids and offers and LTV

- Market engine determines accepted receipt and delivery schedules by location
- In parallel, the engine sets LTVs at all network nodes
- At time of constrained operation, LTVs vary significantly by location
- LTVs reflect *actual* physical capacity of the pipeline system under *current* and *anticipated* conditions



eco

Conclusions

GECO Novel Technology

Innovation	
Optimized intraday pipeline operation	• Fast and scalable optimization methods and software for operations of large pipeline networks
Gas-electric coordination	• Exchange of dynamic pricing data enables co-optimized operation of both infrastructures
Market design for intra-day gas trading	• Two-sided auction for trading hourly deviations from ratable schedules • Pipeline clears the auction subject to gas flow physics and engineering constraints using novel optimization methods
Gas price formation mechanism	• Dynamic Locational Trade Values of natural gas (LTV). Clearing mechanism sets *hourly* prices of natural gas at *each pipeline network node* • Prices are consistent with the physics of gas flow • Prices reflect pipeline engineering constraints
Delivery and price guarantee	• Gas delivery quantity, timing and prices are guaranteed for market cleared quantifies • Financially binding gas use schedules

Conclusions

- Advancement of the GECO project creates a unique opportunity to:
  - Optimize pipeline operation using economic criteria
  - Develop near real-time pricing of natural gas that is consistent with the real-time physics of gas flow in the pipeline
  - Efficiently coordinate the gas and electric networks through optimization methods and market signals based on locational prices for electricity and natural gas
- Realizing this opportunity is very important for both electric and gas industries

For more information

Alex Rudkevich
Newton Energy Group
arudkevich@negll.com

Anatoly Zlotnik
Los Alamos National Laboratory
azlotnik@lanl.gov