New Tools for Coordination of Gas and Electric System Planning

Utility Variability Integration Group 2018 Spring Technical Workshop

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Outline

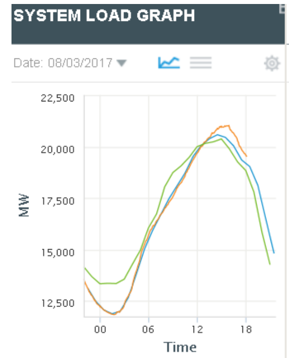
- **Vision for gas-electric system coordination**
  - Enabled by new concept for transient pipeline optimization
  - Integration of markets, flow scheduling, and gas control
- **Locational Trade Values (LTVs) for natural gas**
  - Obtained by single price two-sided auction mechanism
  - Account for pipeline structure, physics and engineering
- **Gas Balancing Market**
  - Voluntary intra-day auction mechanism
  - Fits within existing practices and regulations

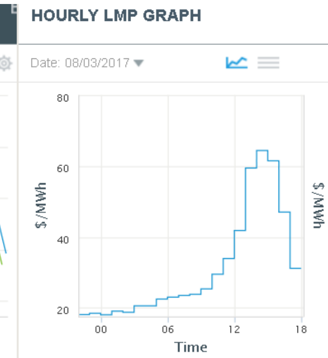
Gas-Electric Challenges

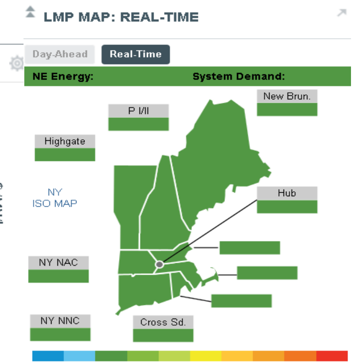
- **Operational Challenges:**
  - Flexible gas-fired generation lacks fuel supply flexibility
  - ***Flexibility is crucial in power systems*****:** supply must match demand *continuously and instantaneously* (there is no equivalent to line pack)
  - Variability and unpredictability of gas-fired generation challenges pipeline operations
  - Anticipated continued growth of the gas-fired generating fleet
- **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
- **Addressing continued growth of gas-fired generation**
  - New optimization and control technology
  - Engineering economic methods

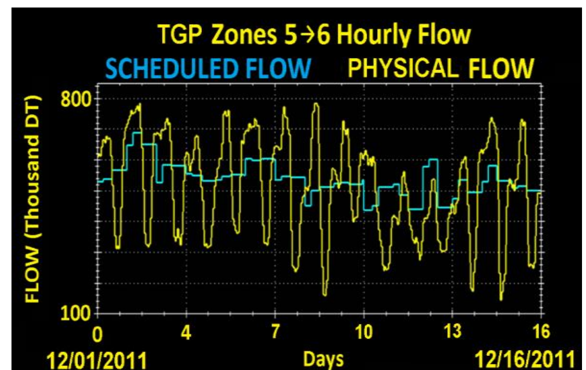
ARPA-e GECO Goals

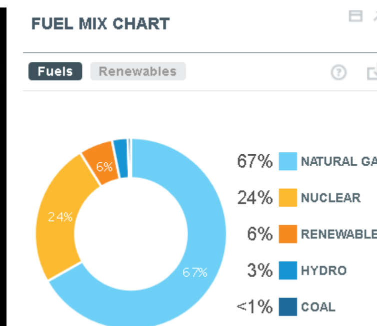
- **Radically improve coordination of natural gas and electric operations**
  - ***Price formation:*** for power systems, now done by optimization, every 10 minutes
  - for gas pipelines: by bilateral trades → hub-based, 5 times per week. **GOAL: HOURLY**
- **Develop Physics- & engineering-based models, market-based optimal control formulations, & optimization algorithms for economically optimal scheduling of intra-day pipeline flows**
  - Similar to day-ahead unit commitment and economic dispatch for power systems
  - Hourly, locational pricing of gas accounts for value to power system & pipeline capacity











- ***<u>Quantify advantages of market-based gas-electric coordination</u>***

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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
  - Active in the 5-minute real-time power markets, change their outputs frequently
  - Provide the bulk of operating reserves in some regions
  - require 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**
  - Gas-fired generators cannot procure gas as needed under relatively short notice
  - Most flexible gas-fired power plants purchase gas bilaterally from marketers who manage a portfolio of gas resources
  - Purchasing gas from a supplier and transportation rights from a shipper is time consuming, multi-party process in an illiquid market

- R. D. Tabors and S. Adamson, "Measurement of energy market inefficiencies in the coordination of natural gas & power," in 47th Hawaii International Conference on System Sciences (HICSS). IEEE, 2014, pp. 2335–2343.

Traditional Transient Pipeline Optimization Goals

- **Intra-day operations are done without real-time optimization/analytics**
  - Optimization and simulation is traditionally used for capacity planning
  - Does not take advantage of full pipeline capacity
- **Given expected/forecasted natural gas load profiles**
  - Determine flow schedule and compute compressor controls
- **Previously suggested approaches**
  - Simulation-based, complex "full-physics" modeling
  - High performance computing
- **Possible issues**
  - Load profiles are uncertain and may change intra-day
  - Computing solutions is costly for large-scale systems
- ***<u>Reactive to decisions made by market actors</u>***

- H. H. Rachford Jr, R. G. Carter, and T. F. Dupont. "Using optimization in transient gas transmission." PSIG Annual Meeting. Pipeline Simulation Interest Group, 2009.

New Transient Pipeline Optimization Concept

- **Responsive intra-day gas pipeline flow scheduling using optimization**
- **Given bids by market participants (shippers)**
  - Allocate deliveries according to bids and capacity
  - Compute compressor controls and flow schedule
- **Our approach**
  - Optimization-based, simplified "reduced" modeling
  - Fast computation on commodity platform (e.g. a laptop)
- **Advantages**
  - Integration of market and physical operations
  - Fast compute to enable intra-day shipping requests
- ***<u>Voluntary balancing market over current daily nominations</u>***

- 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.

Economic Optimization of Intra-day Pipeline Operation

- **A "two-sided auction" for buyers and sellers on entire pipeline network**
  - Network nodes: custodial meters & compressor stations
  - Network edges: pipes that physically connect nodes
- **Subject to engineering constraints**
  - Pipeline flow equations, limitations on the capability of compressors
  - Maximum Allowed Operational Pressure, Minimum pressure contractual requirements
- **Market Bids by Suppliers and Offtakers:**
  - Submitting Price/Quantity (P/Q) offers to sell/buy gas
  - Offers and bids submitted with hourly time step for optimization horizon (e.g., 36 hours)
- **Auctioneer's objective function**
  - To maximize *market surplus* over the optimization horizon (accounting for accepted bids and offers less compressor costs of running the pipeline)
  - Maximize payments for delivery minus costs of supply

- A. Rudkevich, and A. Zlotnik. "Locational Marginal Pricing of Natural Gas subject to Engineering Constraints." Proceedings of the 50th Hawaii International Conference on System Sciences, pp. 3092-3101, 2017.

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
- **Shadow prices (dual variables)**
  - For mass flow withdrawal at nodes (congestion price)
  - For pressure and compressor limits (capacity price)
  - Proved that there is revenue adequacy for the Auctioneer
- **Transient LTVs**
  - reflect increase in system-wide costs of serving incremental locational demand incurred over entire optimization horizon, 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 pipeline during the optimization horizon

Mathematics of Gas Balancing Market

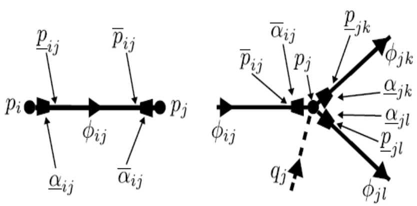
$$
\begin{array}{llll}
\max & \text{Social Welfare:} & \displaystyle\sum_{m\in\mathcal{G}}\int_0^T c_m^d(t)\hat{d}_m(t)\mathrm{d}t - \sum_{m\in\mathcal{G}}\int_0^T c_m^s(t)\hat{s}_m(t)\mathrm{d}t & \\
\text{s.t.} & \text{Mass conservation:} & \partial_t p_{ij} + \dfrac{a^2}{A_{ij}}\partial_x \phi_{ij} = 0, & \forall (i,j)\in\mathcal{E}, \quad \mu_{ij}(t,x) \\
& \text{Momentum conservation:} & \partial_x\left(\frac{1}{2}p_{ij}^2\right) + a^2 r_{ij}\phi_{ij}|\phi_{ij}| = 0, & \forall (i,j)\in\mathcal{E}, \quad \eta_{ij}(t,x) \\
& \text{Nodal flow balance:} & \displaystyle\sum_{k\in\partial_- j}\underline{\phi}_{jk}(t) - \sum_{i\in\partial_+ j}\overline{\phi}_{ij}(t) - \bar{q}_j(t) & \\
& & \displaystyle - \sum_{m\in\partial_g j}(\hat{s}_m(t) - \hat{d}_m(t)) = 0, & \forall j\in\mathcal{V}, \quad \lambda_j(t) \\
& \text{Pressure compatibility:} & \underline{p}_{ij}(t) = \underline{\alpha}_{ij}(t)p_i(t), & \forall (i,j)\in\mathcal{E}, \quad \underline{\Delta}_{ij}(t), \\
& & \overline{p}_{ij}(t) = \overline{\alpha}_{ij}(t)p_j(t), & \forall (i,j)\in\mathcal{E}, \quad \overline{\Delta}_{ij}(t) \\
& \text{Pressure limits:} & p_{ij}^{\min} \le p_{ij}(t,0) \le p_{ij}^{\max}, & \forall (i,j)\in\mathcal{E}, \quad \underline{\beta}_{ij}^{\min}(t), \underline{\beta}_{ij}^{\max}(t) \\
& & p_{ij}^{\min} \le p_{ij}(t,L_{ij}) \le p_{ij}^{\max}, & \forall (i,j)\in\mathcal{E}, \quad \overline{\beta}_{ij}^{\min}(t), \overline{\beta}_{ij}^{\max}(t) \\
& \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}, \quad \underline{\gamma}_{ij}(t) \\
& & \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}, \quad \overline{\gamma}_{ij}(t) \\
& \text{Boost lower limits:} & \underline{\alpha}_{ij}(t) \ge 1, \quad \overline{\alpha}_{ij}(t) \ge 1 & \forall (i,j)\in\mathcal{E}, \quad \underline{\theta}_{ij}(t), \overline{\theta}_{ij}(t) \\
& \text{Supply limits:} & s_m^{\min}(t) \le s_m(t) \le s_m^{\max}(t) & \forall m\in\mathcal{G}, \quad \sigma_m^{\min}(t), \sigma_m^{\max}(t) \\
& \text{Demand limits:} & d_m^{\min}(t) \le d_m(t) \le d_m^{\max}(t) & \forall m\in\mathcal{G}, \quad \zeta_m^{\min}(t), \zeta_m^{\max}(t) \\
& \text{Time periodicity:} & p_{ij}(0,x) = p_{ij}(T,x), & \forall (i,j)\in\mathcal{E}, \quad \tau_{ij}^{p}(x) \\
& & \phi_{ij}(0,x) = \phi_{ij}(T,x), & \forall (i,j)\in\mathcal{E}, \quad \tau_{ij}^{\phi}(x)
\end{array}
$$

Parameter	Set	Domain	Units (SI)
$c_m^s(t)$, $c_m^d(t)$	$m\in\mathcal{G}$	$[0,T]$	$\$\cdot\mathrm{kg}^{-1}$
$s_m^{\min}(t)$, $s_m^{\max}(t)$, $d_m^{\min}(t)$, $d_m^{\max}(t)$	$m\in\mathcal{G}$	$[0,T]$	$\mathrm{kg}\cdot\mathrm{s}^{-1}$
$\bar{q}_j(t)$	$j\in\mathcal{V}_F$	$[0,T]$	$\mathrm{kg}\cdot\mathrm{s}^{-1}$
$p_j(t)$	$j\in\mathcal{V}_P$	$[0,T]$	$\mathrm{kg}\cdot\mathrm{m}^{-1}\cdot\mathrm{s}^{-2}$ (Pa)

Table 1: Market Parameters

Variables	Set	Domain	Units (SI)
$\hat{s}_m(t)$, $\hat{d}_m(t)$	$m\in\mathcal{G}$	$[0,T]$	$\mathrm{kg}\cdot\mathrm{s}^{-1}$
$p_j(t)$	$j\in\mathcal{V}_F$	$[0,T]$	$\mathrm{kg}\cdot\mathrm{m}^{-1}\cdot\mathrm{s}^{-2}$ (Pa)
$p_{ij}(t,x)$	$(i,j)\in\mathcal{E}$	$[0,T]\times[0,L_{ij}]$	$\mathrm{kg}\cdot\mathrm{m}^{-1}\cdot\mathrm{s}^{-2}$ (Pa)
$\phi_{ij}(t,x)$	$(i,j)\in\mathcal{E}$	$[0,T]\times[0,L_{ij}]$	$\mathrm{kg}\cdot\mathrm{s}^{-1}$
$\underline{\alpha}_{ij}(t)$, $\overline{\alpha}_{ij}(t)$	$(i,j)\in\mathcal{E}$	$[0,T]$	-

Table 2: Primal Variables



Variable	Set	Domain	Units (SI)
$\lambda_j(t)$	$j\in\mathcal{V}$	$[0,T]$	$\$\cdot\mathrm{kg}^{-1}$
$\sigma_m^{\min}(t)$, $\sigma_m^{\max}(t)$, $\zeta_m^{\min}(t)$, $\zeta_m^{\max}(t)$	$m\in\mathcal{G}$	$[0,T]$	$\$\cdot\mathrm{kg}^{-1}$
$\mu_{ij}(t,x)$	$(i,j)\in\mathcal{E}$	$[0,T]\times[0,L_{ij}]$	$\$\cdot\mathrm{s}^2\cdot\mathrm{kg}^{-1}$
$\eta_{ij}(t,x)$	$(i,j)\in\mathcal{E}$	$[0,T]\times[0,L_{ij}]$	$\$\cdot\mathrm{s}^3\cdot\mathrm{m}^2\cdot\mathrm{kg}^{-2}$ ($\$\cdot\mathrm{Pa}^{-2}\cdot\mathrm{s}^{-1}$)
$\underline{\Delta}_{ij}(t)$, $\overline{\Delta}_{ij}(t)$	$(i,j)\in\mathcal{E}$	$[0,T]$	$\$\cdot\mathrm{s}\cdot\mathrm{m}\cdot\mathrm{kg}^{-1}$ ($\$\cdot\mathrm{Pa}^{-1}\cdot\mathrm{s}^{-1}$)
$\underline{\beta}_{ij}^{\min}(t)$, $\underline{\beta}_{ij}^{\max}(t)$, $\overline{\beta}_{ij}^{\min}(t)$, $\overline{\beta}_{ij}^{\max}(t)$	$(i,j)\in\mathcal{E}$	$[0,T]$	$\$\cdot\mathrm{s}\cdot\mathrm{m}\cdot\mathrm{kg}^{-1}$ ($\$\cdot\mathrm{Pa}^{-1}\cdot\mathrm{s}^{-1}$)
$\underline{\gamma}_{ij}(t)$, $\overline{\gamma}_{ij}(t)$	$(i,j)\in\mathcal{E}$	$[0,T]$	$\$\cdot\mathrm{W}^{-1}\cdot\mathrm{s}^{-1}$
$\underline{\theta}_{ij}(t)$, $\overline{\theta}_{ij}(t)$	$(i,j)\in\mathcal{E}$	$[0,T]$	-
$\tau_{ij}^{p}(x)$, $\tau_{ij}^{\phi}(x)$	$(i,j)\in\mathcal{E}$	$[0,T]$	$\$\cdot\mathrm{s}\cdot\mathrm{kg}^{-1}$

Table 3: Dual Variables

- **A two-sided auction over pipeline network**
- **Shadow prices (dual variables)**
  - On mass flow withdrawal at nodes (congestion price)
  - On pressure and compressor limits (capacity price)
  - Proof of revenue adequacy for the Auctioneer
- **Optimization of prototype 1500+ mile system in <5 mins at 98% accuracy (<2% error w.r.t. simulation)**

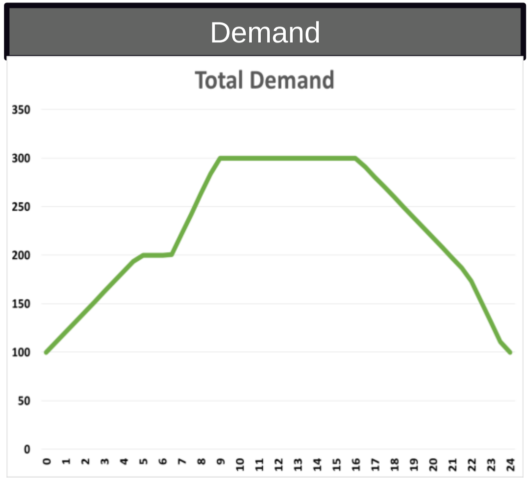
Mathematics: *• Constrained optimal control of hyperbolic PDEs on large graphs*

• Fielding “transient optimization” is a long-standing grand challenge in the pipeline industry

Illustrative Example of LTVs: a 2-Node Model

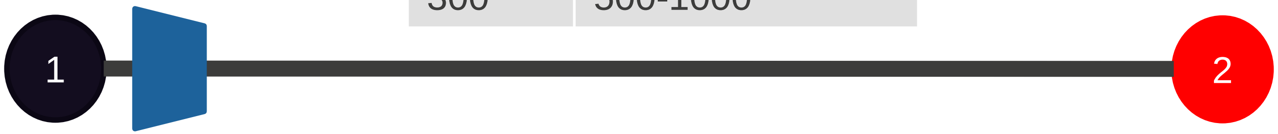
Objective function:

$$\min \int_0^{24} [c_1 S_1(t) + c_2 S_2(t) + c_3 S_3(t)]\,dt$$



Supply	MaxQ	Price
S1	220	$2
S2	20	$3

Pmin	Pmax (MAOP)
300	500-1000



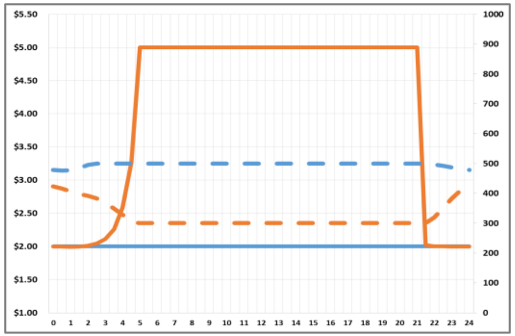
HPmax	CRmax
1000	2.0

Supply	MaxQ	Price
S3	200	$5

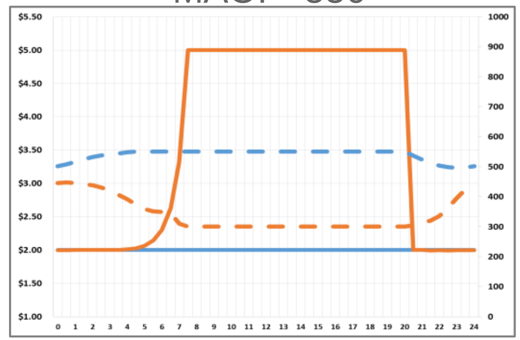
We explore a range of dynamic solutions by considering systems with different MAOP ranging between 500 and 1000

LTVs vs Nodal Pressure by Scenario

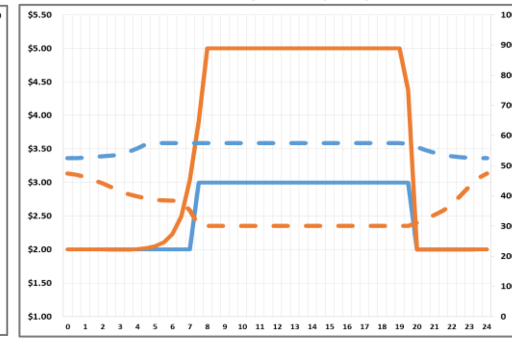
MAOP=500



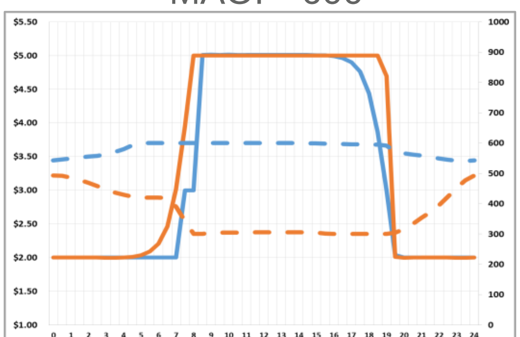
MAOP=550



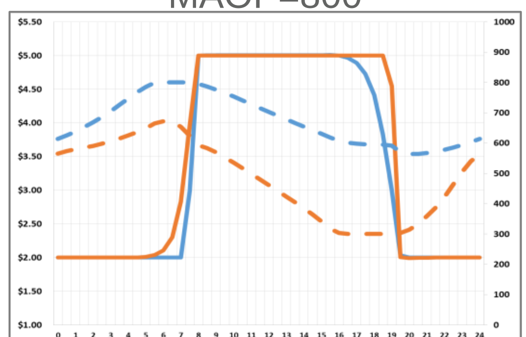
MAOP=575



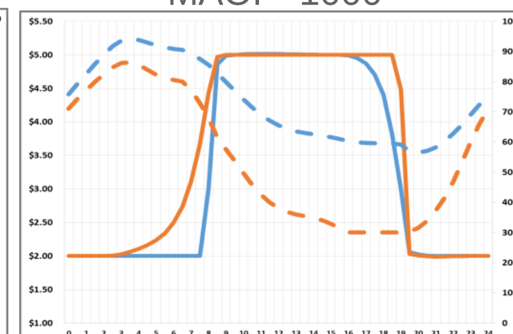
MAOP=600



MAOP=800



MAOP=1000

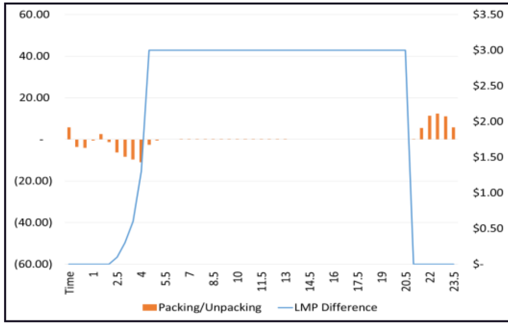


Solid lines – LTVs, dash lines –pressures

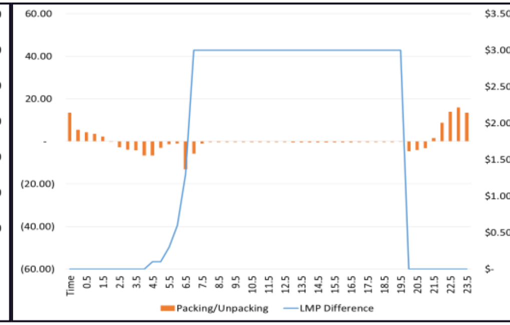
Blue – Node 1, Orange – Node 2

Line Pack by Scenario

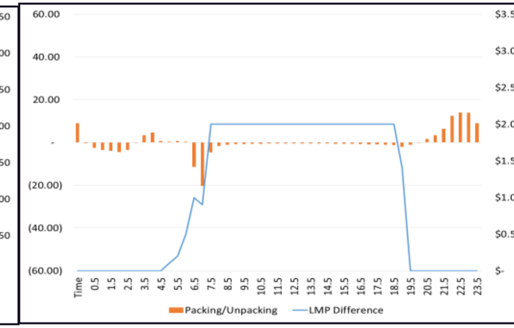
MAOP=500



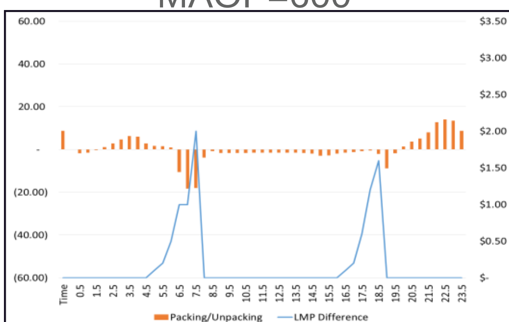
MAOP=550



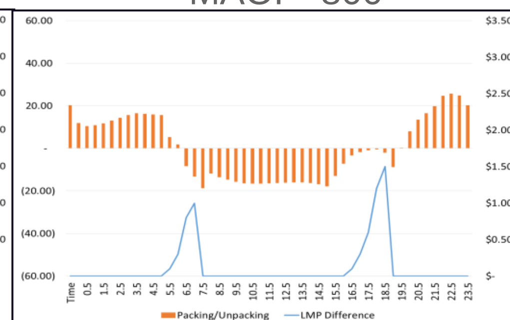
MAOP=575



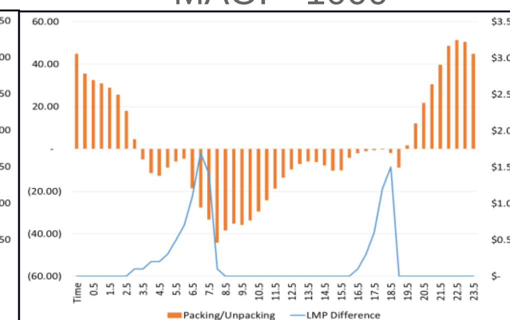
MAOP=600



MAOP=800



MAOP=1000



Blue line – LTV difference between nodes

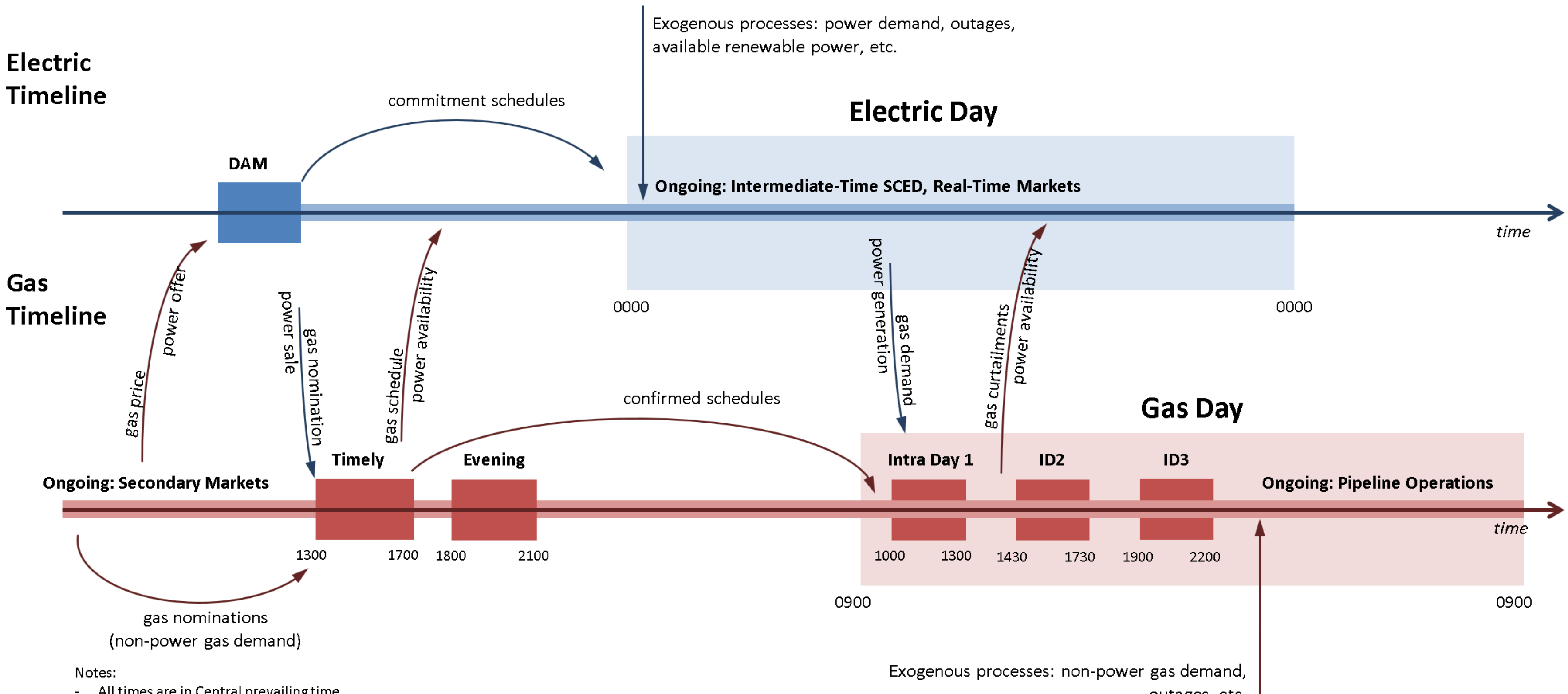
Orange bars – line pack difference between incoming & outgoing flow

Positive – packing, negative – unpacking

Proposed Solution: Gas Balancing Market

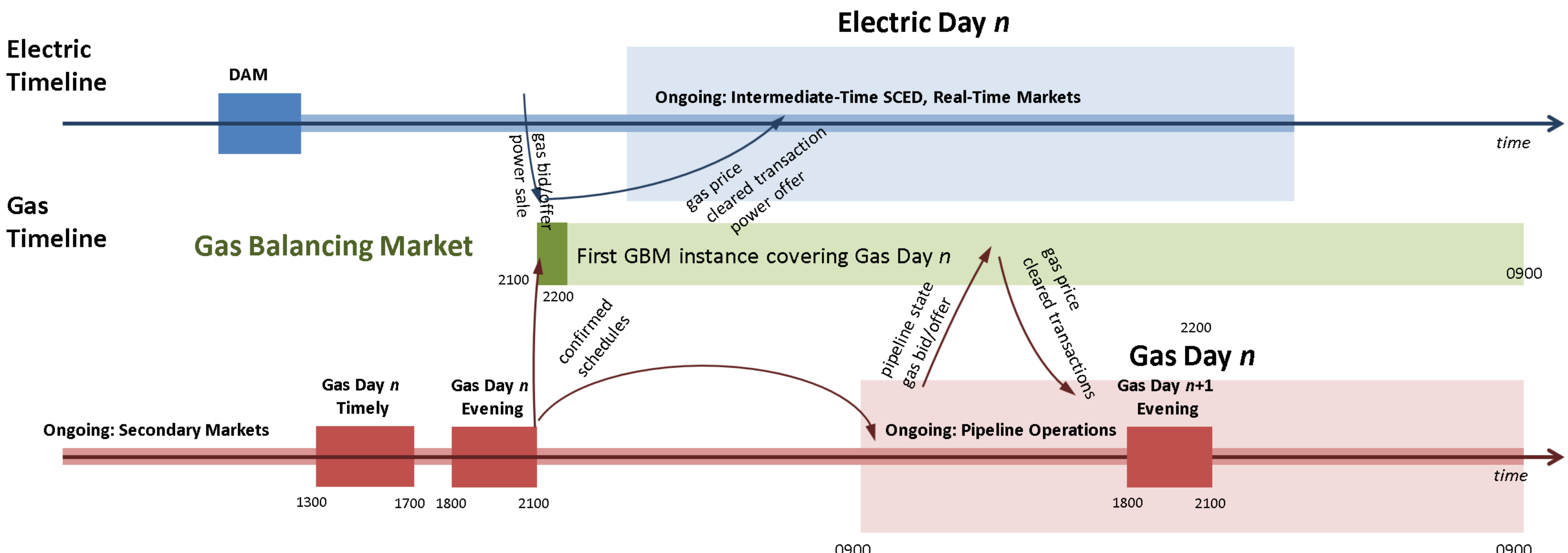
- **We propose a Gas Balancing Market (GBM) that:**
  - Would have voluntary participation, honor existing transportation rights and contracts
  - Enable trades of hourly imbalances from ratable schedules
  - Assure that intra-day transactions cleared in the market are physically implementable
  - Enable 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
- **Participants**
  - Suppliers and offtakers submit Price/Quantity (P/Q) offers to sell/buy gas
  - Shippers submitting P/Q offers to sell/buy gas relative to ratable schedule
  - ***Buyers and sellers submitting opportunistic P/Q bids to buy/sell gas not backed by reserved capacity***

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.

Proposed Timing of the Gas Balancing Market

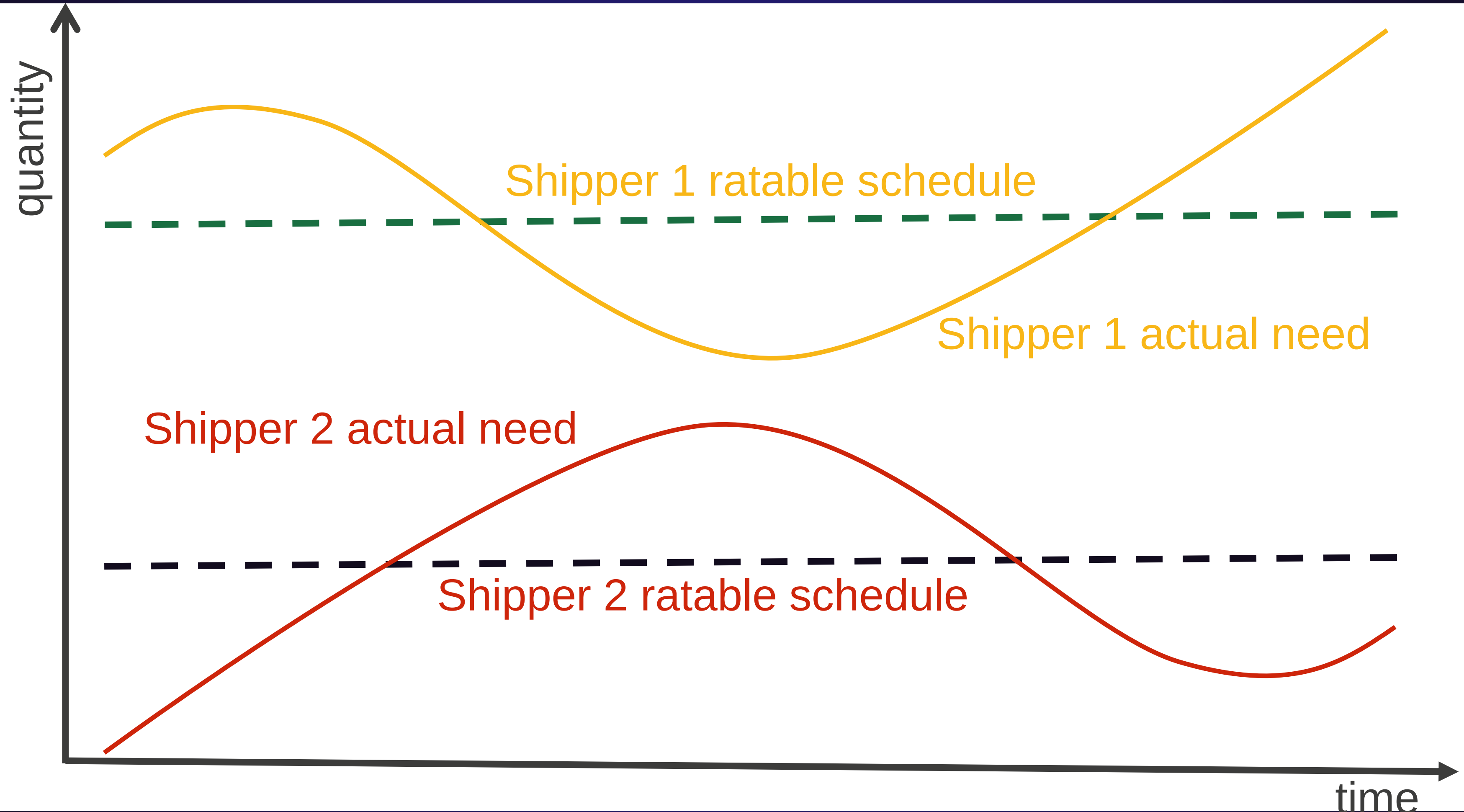


Notes:
- All times are in Central prevailing time.
- Standard gas cycles required by FERC are shown. Pipelines may offer additional cycles. Under emergency conditions scheduling could be done outside of these cycles.

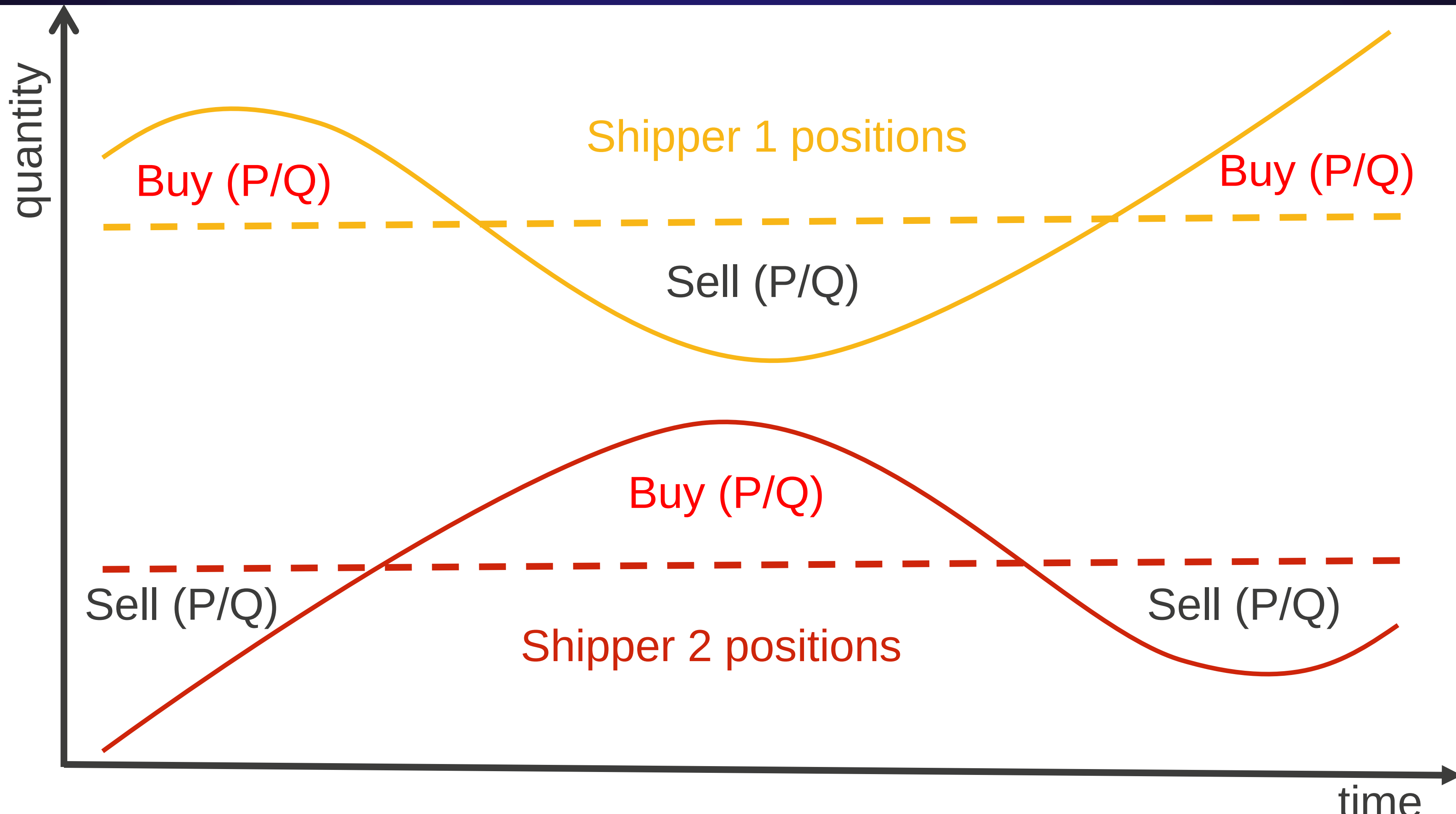
An Auction for Shippers & other Buyers and Sellers

- **Opportunistic buyers and sellers**
  - may have no reserved capacity rights but are allowed to participate to increase liquidity
  - No capacity rights = no congestion hedging
- **Offers and bids are node-specific**
  - submitted with hourly time step for the optimization horizon (e.g., 36 hours)
- **Auctioneer’s objective function is to maximize market surplus over the optimization horizon**
  - accounting for accepted bids & offers less pipeline operating costs

Ratable schedules vs. non-ratable needs



Need more - schedule buy; Need less - schedule sell

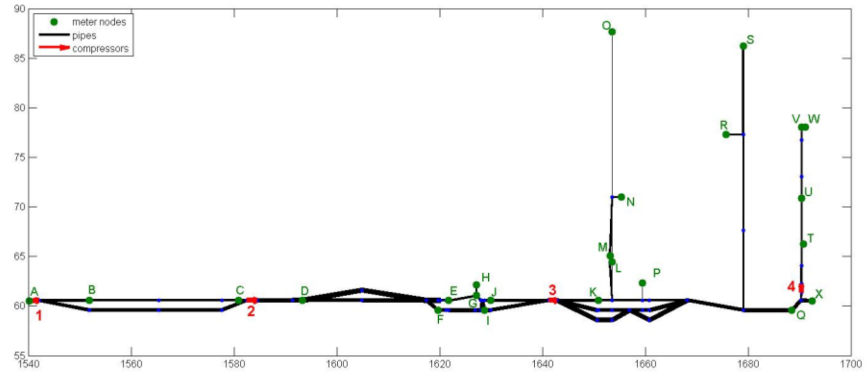


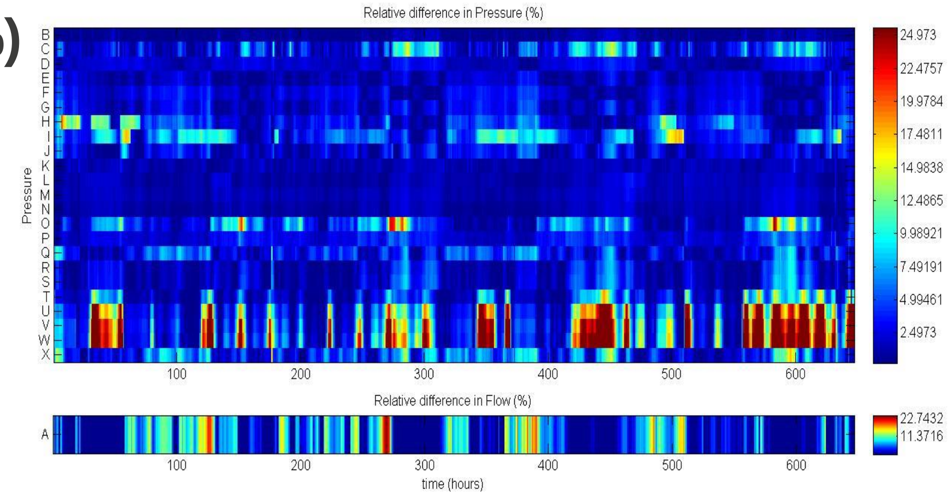
GBM Support of Gas-Electric Coordination

- **Provides intra-day forward prices**
  - Inform gas-fired generation bids for real-time power markets
  - Simplify gas purchases for gas-fired fast-start power plants that clear in the real-time power markets and are called upon to provide ancillary services
- **Provides many rounds of forward market clearings**
  - For gas-fired units scheduled to operate in day-ahead power market to purchase gas
  - especially between HE 2400 and HE 0900 (belong to different Gas and Electric days)
- **Under scarcity conditions in a gas pipeline**
  - high gas prices will immediately lead to real-time re-dispatch of gas-fired generating units receiving these high gas prices
  - These units will be replaced by gas-fired units not affected by scarcity or other generating units
- **GBM pricing information**
  - enables economic re-dispatch of gas-fired generators
  - relieves scarcity events, simplifies pipeline operations

Model Precision Validation – a pipeline in the Northeast

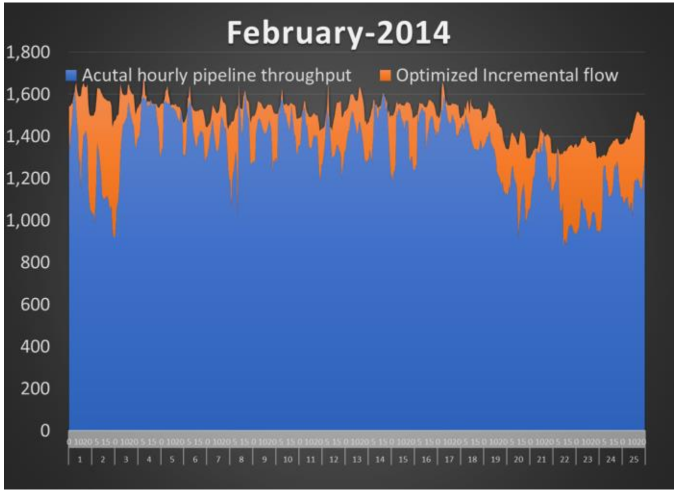
- **Reduced model of subsystem:**
  - 78 nodes, 91 pipes, 4 compressors 31 custody transfer meters at 24 locations (labelled A to X)
  - Flow from meters at B to X, pressure at source at node A
- **Comparing relative distance (%) of SCADA vs. simulation**
  - Pressure at flow nodes B to X
  - mean: 4.17%, (2.94% w/o U,V,W)
  - Mass flow into system at node A
  - mean (max) 2.45% (23.7%)

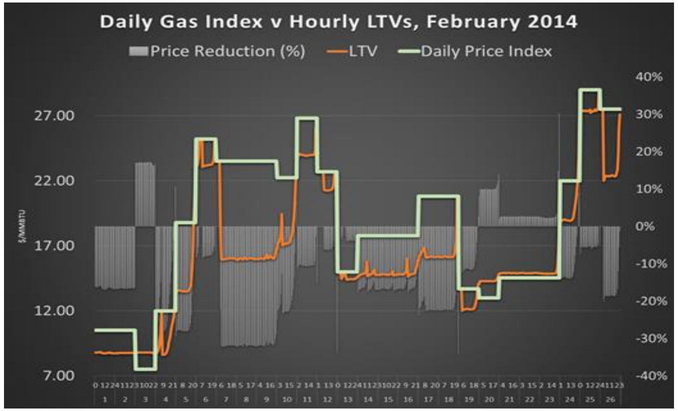




Impact of Gas Balancing Market

- **Optimized throughput under the backcast of extreme *<u>2014 Polar Vortex conditions</u>*:**
- **<u>Increased Pipeline Deliverability by 12%</u>**
- **Using LTVs for intra-day gas trading could reduce gas prices for constrained pipeline**
  - LTVs computed using transient optimization under backcast of extreme *2014 Polar Vortex conditions*
- **LTVs significantly lower than prevailing daily price indices:**
  - Average price reduction: 11%
  - Times of high prices: up to 30%





Conclusion

- **New concept for gas-electric coordination**
  - Enabled by transient pipeline optimization (new tools developed by GECO team)
  - Integration of markets, flow scheduling, and gas control
- **Locational Trade Values (LTVs) for natural gas**
  - Obtained by single price two-sided auction mechanism
  - Account for pipeline structure, physics and engineering
- **Gas Balancing Market**
  - Voluntary intra-day auction mechanism
  - Fits within existing practices and regulations
- **Results Using Pipeline Model and Data**
  - Validated modeling with respect to SCADA time-series
  - Quantify advantage of LTV market mechanism (capacity and price)

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