Intra-day Co-optimization of the Natural Gas and Electric Networks: the GECO Project

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

Washington, DC
June 27-29, 2016

Motivation: reliable fuel supply to gas-fired power plants

Gas-fired power generation is expanding:

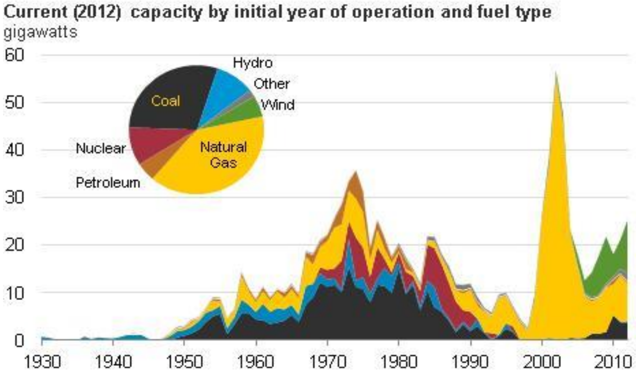
- Fast to permit, fast to build
- Economic & environmental advantages
- Replacing retiring coal & nuclear

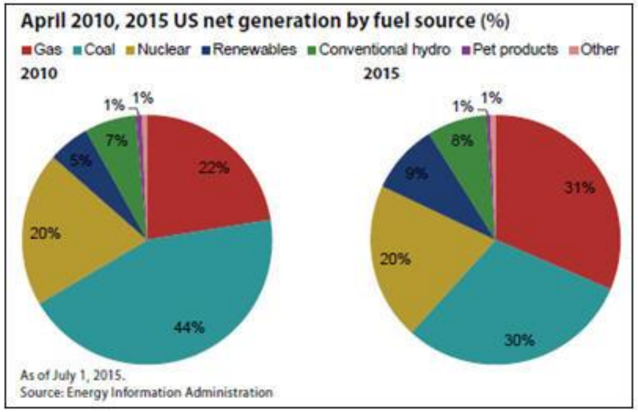
Gas pipeline Loads are changing:

- Increasing in volume & variation
- More intermittent & uncertain

Regulatory environment is evolving:

- FERC 787— need for information sharing
- FERC 809— market timing and coordination

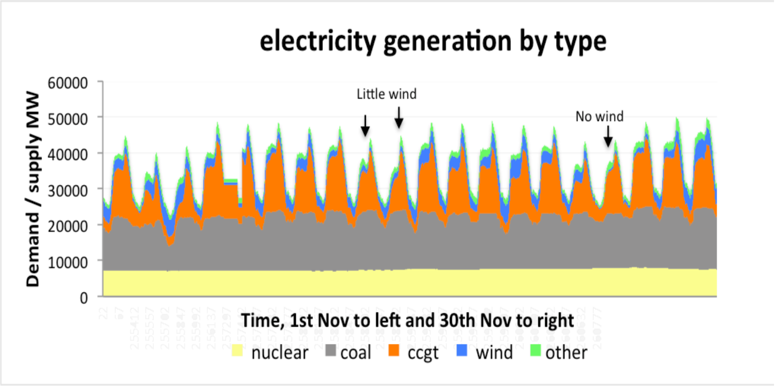




Motivation: new challenges to intra-day gas pipeline operations

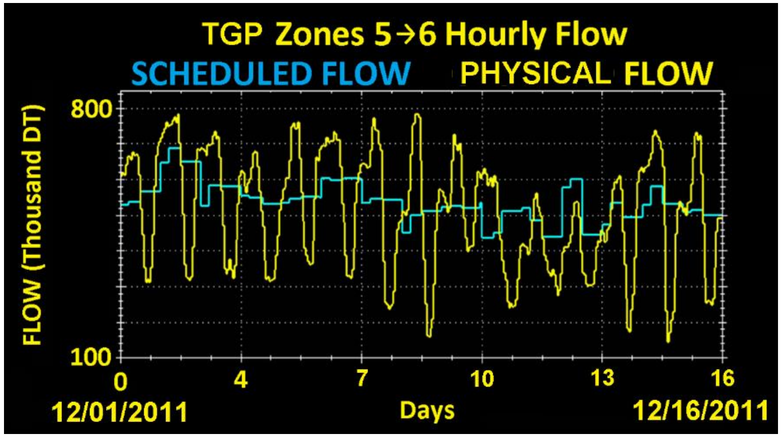
Gas-fired generation fills power demand curve:

- Power plants activate and shut down daily
- Gas markets & flow schedules by static models cause mismatch of scheduled & observed flows



Challenges to intra-day pipeline operations:

- **Variability:** intra-day dynamic flows that change daily with power-plant schedules
- **Coordination:** "burn sheets" & real-time information must be shared
- **Uncertainty:** power grid operations change quickly and unpredictably
- **Integration:** gas markets, flow scheduling, & physical operations done separately
- **Economics**: lack of meaningful economic signals exchanged between gas and power systems



GECO Team

Institution	Expertise
Newton Energy Group & Consultants	Cloud platform for parallel modeling and analytics of energy systems. Data structures. Optimal pricing, market design, commercialization
Los Alamos National Laboratory	Advanced computational methods and algorithms for simulation and optimization of gas & electric networks
Polaris Systems Optimization	Advanced power systems simulator native to NEG cloud platform. Power systems optimization expertise
Boston University	Market design, market coordination, algorithms
AIMMS	Modeling language, optimization
Kinder Morgan	Pipeline operation, market expertise and information
PJM	Power system operation, market expertise and information

Statement of Project Objectives

The objective of this project is to develop algorithmic structures and an associated market design that would enable 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.

The key technology of the project will be:

1) novel methods, algorithms and software for simulation modeling and optimization of natural gas pipeline operation at the day-ahead and intra-day time scale;
2) a novel mechanism for pricing of natural gas delivered to end users and in particular to gas-fired power plants; and
3) novel mechanisms for coordinating natural gas and electric operations both day ahead and in real-time, based on locational prices of natural gas and electricity.

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Program Elements and Objectives

Program Elements

Software & Algorithms

- Software modules for pipeline simulations and optimization
- PSO SCUC/SCED with representation of pipeline constraints and decision cycles recognizing pipeline cycles and power system cycles
- Market model database, cloud infrastructure integrating PSO and pipeline modules and coordination modules

Market Design

- Joint gas-electric theory of locational marginal prices (LMPs) and methods for computing gas LMPs
- Market design proposal including coordination mechanisms

Realistic Market Simulations

- Gas-electric simulation model within the PJM footprint
- Set of simulated scenarios comparing performance of gas-electric coordination policies under different assumptions
- Results vetted with Kinder Morgan and PJM

Approach

Program Elements

Software & Algorithms	• Will explicitly reflect dynamic simulations and dynamic optimization of pipeline operations subject to intra-day operational constraints; • Interactions between natural gas flows in pipelines and the power flow; • Periodically repeating decision cycles of generation bidding and deployment decisions and natural gas nomination decisions
Market Design	• Development of the joint gas-electric theory of locational marginal prices (LMPs) • Theoretical foundations for the provision of the access to pipeline capacity based on economic principles rather than on physical rights. • Gas-electric coordination mechanisms combining the exchange of physical and locational price data between gas and electric • The market design acceptable to market participants in both the gas and electric sector
Realistic Market Simulations	• Will develop gas-electric simulation model within the PJM footprint; will use historical operational data to evaluate the feasibility of various possible market designs and to benchmark efficiency improvement achieved through coordination under each design relative to the status quo and/or to fully optimized joint system • Will be based on the modeled representation of the PJM electrical system and pipelines serving their footprints. • results reviewed and validated by PJM and by Kinder Morgan

Project Objectives and Implications

Algorithmic Structures	Market Design
Co-optimization of physical systems	Coordination of gas and electric markets

	Current Technology	GECO Technology
Pipeline operation control methods	Primarily steady state modeling with "rule-based" compressor operations. Transient analysis performed in reliability context	Fast dynamic optimization of compressor operations incorporating transient effects
Primary objectives of pipeline operation	Maintaining security at least cost of compressor operations	Maintaining security at least cost of meeting system demand
Price formation mechanisms	Daily on weekdays only. Prices formed by traders at certain pipeline delivery points. Prices do not reflect intra-day pipeline operational constraints	Hourly 24/7 at each pipeline node. Prices formed by the optimization engine and are consistent with engineering and physics of pipeline operations
Coordination		
Scheduling	Daily quantity over a standard day. Intra-day profiling is opaque	Transparent intra-day scheduling
Receipt and delivery points	Rigid, based on priorities as specified in the shipping contract	Flexible, based on locational prices
Delivery guarantee	No guarantee for interruptible service customers	Economic mechanism to guarantee structured price/quantity delivery

Gas pipeline optimization: status & why transients are a challenge

Gas pipeline dynamics and control:

- Dynamics – **highly nonlinear, no simple model**
- Nominations – deliveries for next 12 to 24 hours
- Scheduling – compute flows to deliver nomination
- Control – real-time compressor adjustment

Day-ahead market:

- Cleared daily to give nominations for flows
- Bilateral trading
- Ad-hoc, and capacity often based on static models

Intra-day trading:

- Ad-hoc search for supply on spot market
- Simulation-informed manual tuning of flows

- **Gas pipeline physics:**

(pressure, flow, line pack) **changes propagate slowly**, boundary flows always changing, **never stabilizes to steady-state**

- **Gas pipeline optimization:**

(choosing compressor setpoints) Current methods use **steady-state models** – they work when there is low variation. **Very inaccurate given significant changes on an hourly basis**

Gas Pipeline Simulation: meaning & state of the art

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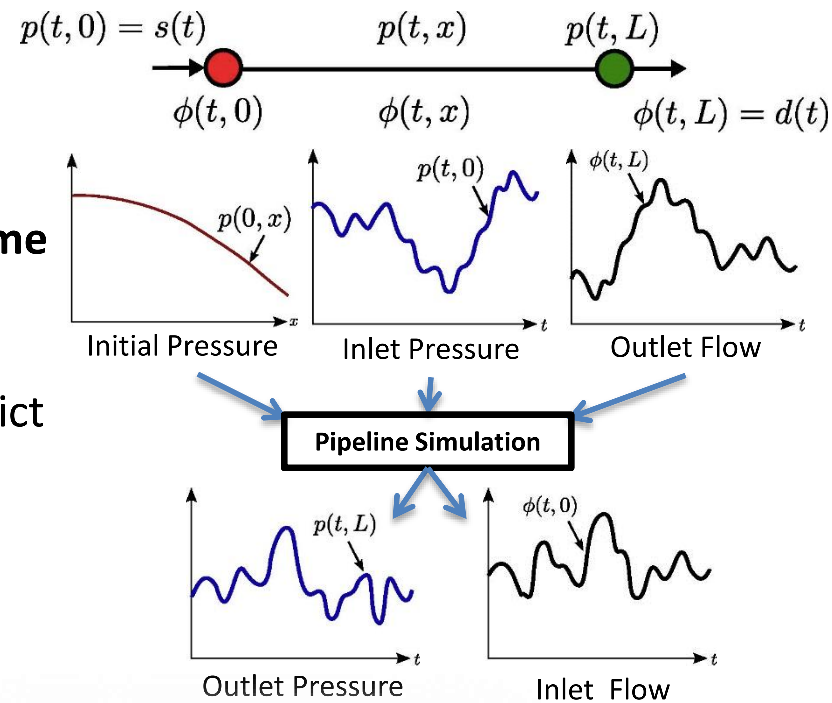


Simulation: an initial value problem (IVP)

- State: instantaneous condition of system
- Parameters: initial state, boundary conditions
- **Start with initial state and evolve forward in time**

Pipeline simulation:

- Given operating protocols of compressors, predict future flow & pressure based on physics
- At a space point, state is time-dependent trajectory (e.g. pressure as function of time)

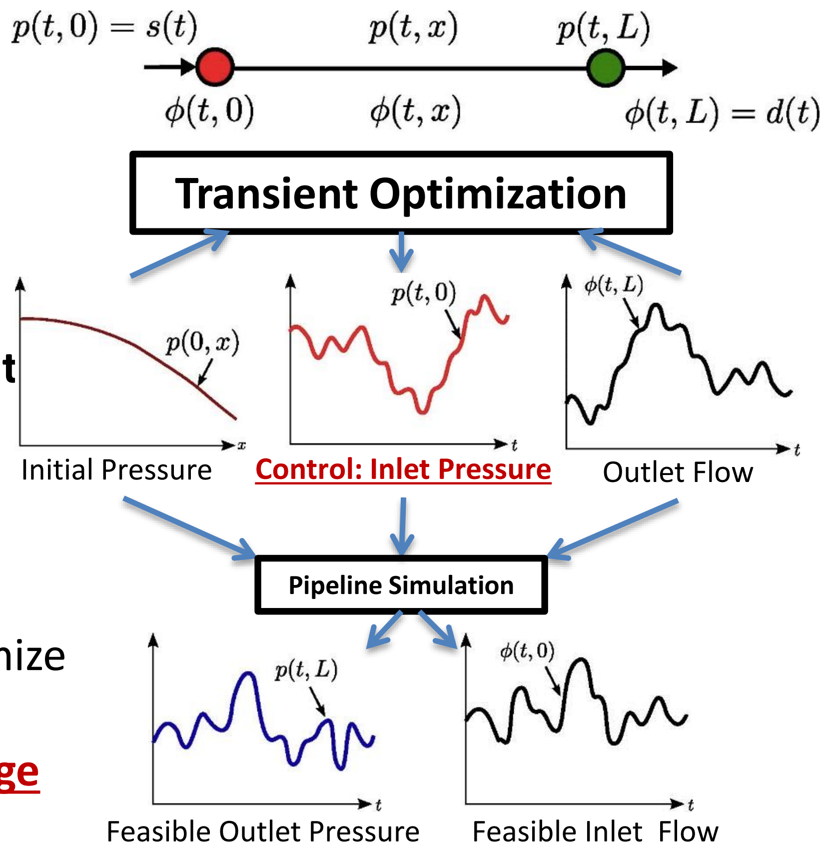
State of the art:

- Highly developed, sophisticated physics & engineering models, e.g., precise to < 1 psi

PSIG Pipeline Simulation Interest Group

Gas Pipeline Transient Optimization: meaning & state of the art

Optimization: an optimal control problem (OCP)
- State: instantaneous condition of system
- Parameters: initial state, boundary conditions
- Controls: parameters that can be chosen
- **Find controls & state as functions of time $t \in [0, T]$ that satisfy feasibility & physics constraint while minimizing a cost objective**



Pipeline Optimization:
- Given consumptions & pressure at a “slack” junction, compute compressor controls to minimize compressor power or maximize throughput

State of the art: long-standing and current challenge
- **New tractable & scalable method from LANL**

Continuous (PDE) Gas System Model to Reduced Network Flow

Complete PDE model of gas pipeline network:

- Junctions $j \in \mathcal{V} = \mathcal{V}_S \cup \mathcal{V}_D$ with given density s_j for $j \in \mathcal{V}_S$ and given flux withdrawal (injection) d_j for $j \in \mathcal{V}_D$
- Pipes $\{i,j\} \in \mathcal{E}$ of length L_{ij}, diameter D_{ij}, and friction coefficient λ_{ij}
- Flow $\phi_{ij}(t, x_{ij})$ and density $\rho_{ij}(t, x_{ij})$ with

mass conservation: $\partial_t \rho_{ij} + \partial_x \phi_{ij} = 0$

momentum balance: $\partial_t \phi_{ij} + a^2 \partial_x \rho_{ij} = -\frac{\lambda}{2D} \frac{\phi_{ij}|\phi_{ij}|}{\rho_{ij}}$

- Define nodal densities $\rho_j(t)$ for $j \in \mathcal{V}_D$
- Pressure continuity for $\forall \{i,j\} \in \mathcal{E}$:

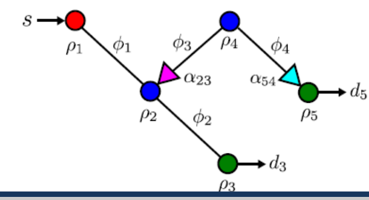
$$\begin{aligned}
\rho_{ij}(t,0) &= \alpha_{ij}(t) s_i(t), \quad \forall i \in \mathcal{V}_S, \\
\rho_{ij}(t,L_{ij}) &= \alpha_{ji}(t) s_j(t), \quad \forall j \in \mathcal{V}_S, \\
\rho_{ij}(t,0) &= \alpha_{ij}(t) \rho_i(t), \quad \forall i \in \mathcal{V}_D, \\
\rho_{ij}(t,L_{ij}) &= \alpha_{ji}(t) \rho_j(t), \quad \forall j \in \mathcal{V}_D,
\end{aligned}$$

- Flow balance for $\forall j \in \mathcal{V}_D$:

$$d_j(t) = \sum_{i \in \mathcal{V}} \phi_{ij}(L_{ij}, t) - \sum_{k \in \mathcal{V}} \phi_{jk}(0, t)$$

Weighted incidence matrix B and incidence matrix $A = \text{sign}(B)$

$$B_{ik} = \begin{cases} \alpha_{ij} & \text{edge } k = \pi_e(ji) \text{ enters node } i, \\ -\alpha_{ij} & \text{edge } k = \pi_e(ij) \text{ leaves node } i, \\ 0 & \text{else} \end{cases} \quad \text{where } \pi_e : \mathcal{E} \to \{1, \dots, |\mathcal{E}|\}$$

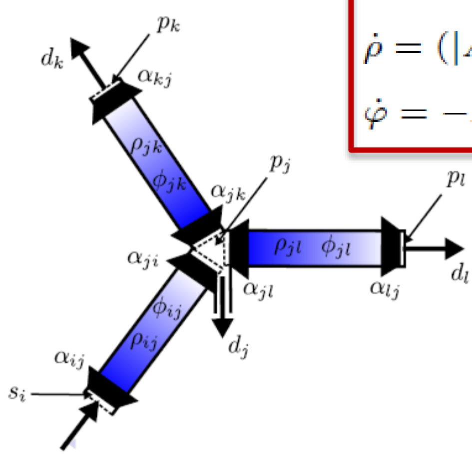


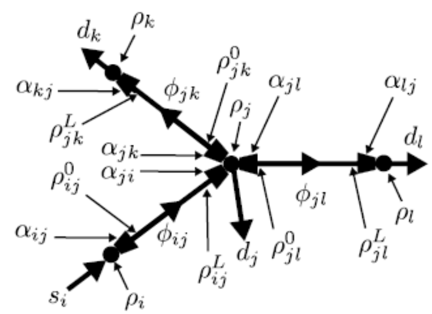
$$\begin{array}{c|cccc|l}
 & \varphi_1 & \varphi_2 & \varphi_3 & \varphi_4 & \\
\rho_1 & -1 & 0 & 0 & 0 & \to B_s \\
\rho_2 & 1 & -1 & -\alpha_{23} & 0 & \\
\rho_3 & 0 & 1 & 0 & 0 & \to B_d \\
\rho_4 & 0 & 0 & 1 & -1 & \\
\rho_5 & 0 & 0 & 0 & \alpha_{54} &
\end{array}$$

Reduced Equations:

$$\dot{\rho} = (|A_d|\Lambda|B_d^T|)^{-1}[4(A_d\varphi - d) - |A_d|\Lambda|B_s^T|\dot{s}]$$

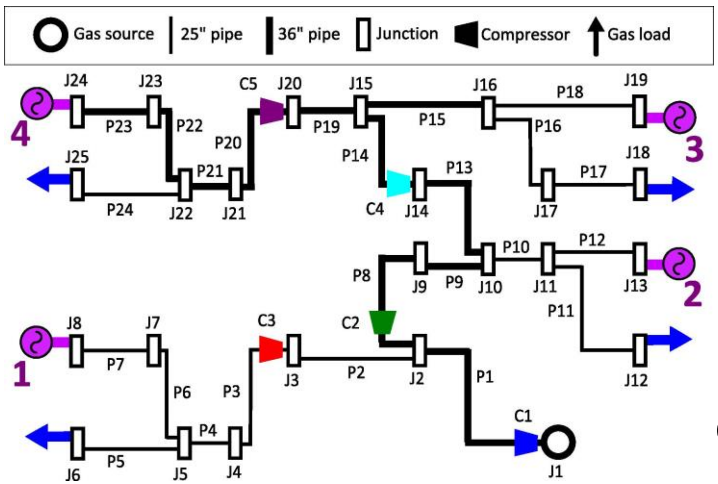
$$\dot{\varphi} = -\Lambda^{-1}(B_s^T s + B_d^T \rho) - Kg(\varphi, |B_s^T|s + |B_d^T|\rho)$$



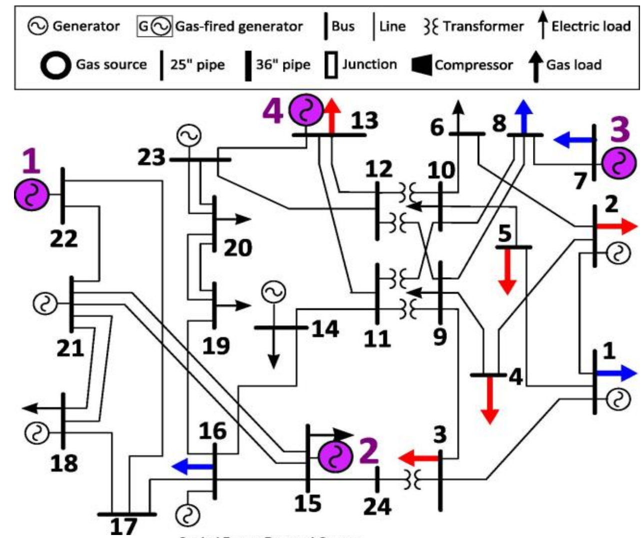


Intra-day gas-grid interdependency case study

Gas pipeline network model

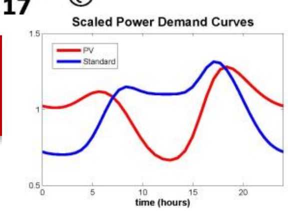


Power system model



Dynamic constraints on gas availability

Simple model:
Fixed gas price $6/mmBTU,
Quadratic heat rate curves,
Quadratic generation cost curves



Interdependency Simulation & Dynamic Gas-Grid Scheduling

Gas-grid coordination & co-optimization scenarios

3. Co-optimization (static)

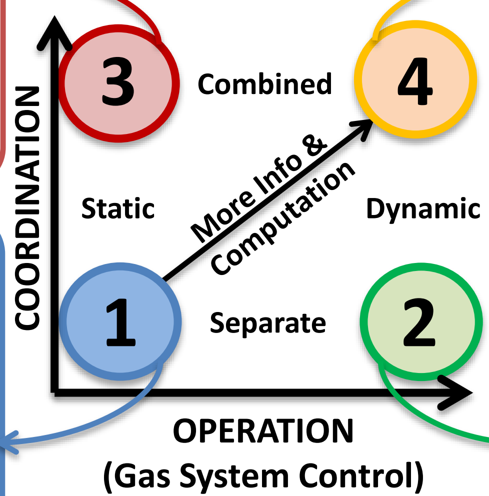
Pipeline model and data → Grid operator

Grid operator acts based on steady gas compressor operation

Gas feasible at high power system cost

4. Co-optimization (dynamic)

Goal for the future:
Both systems optimized together
Both systems secure and optimal



1. Status Quo Systems and Markets

Gas-fired generator fuel schedule→ Pipeline operator

Pipeline operator uses steady state model for gas system, checks feasibility

Gas pressure fluctuations, hidden costs

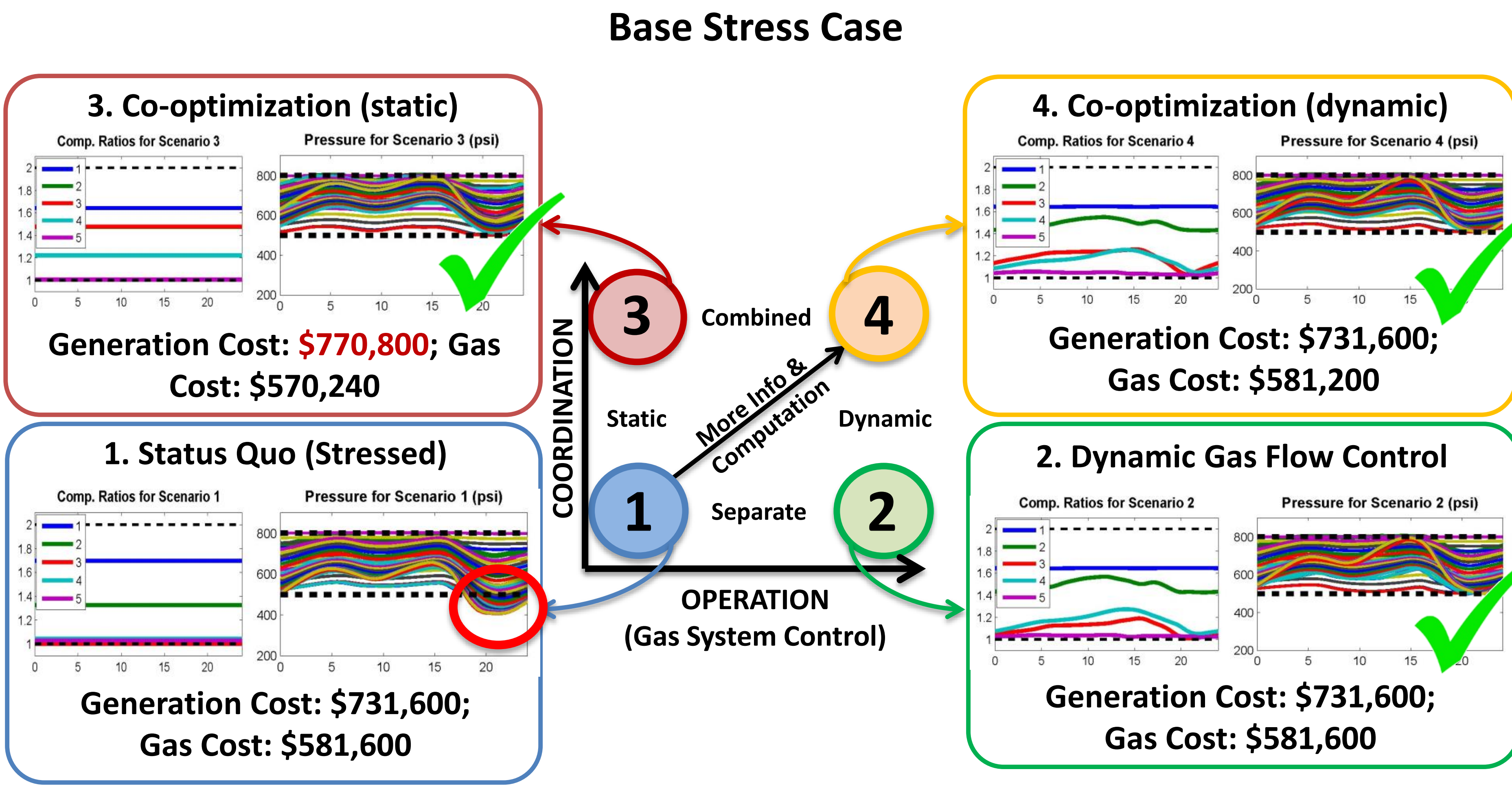
2. Dynamic Gas Flow Control

Gas-fired generator fuel schedule→ Pipeline operator

Optimal dynamic compressor operation (new technology)

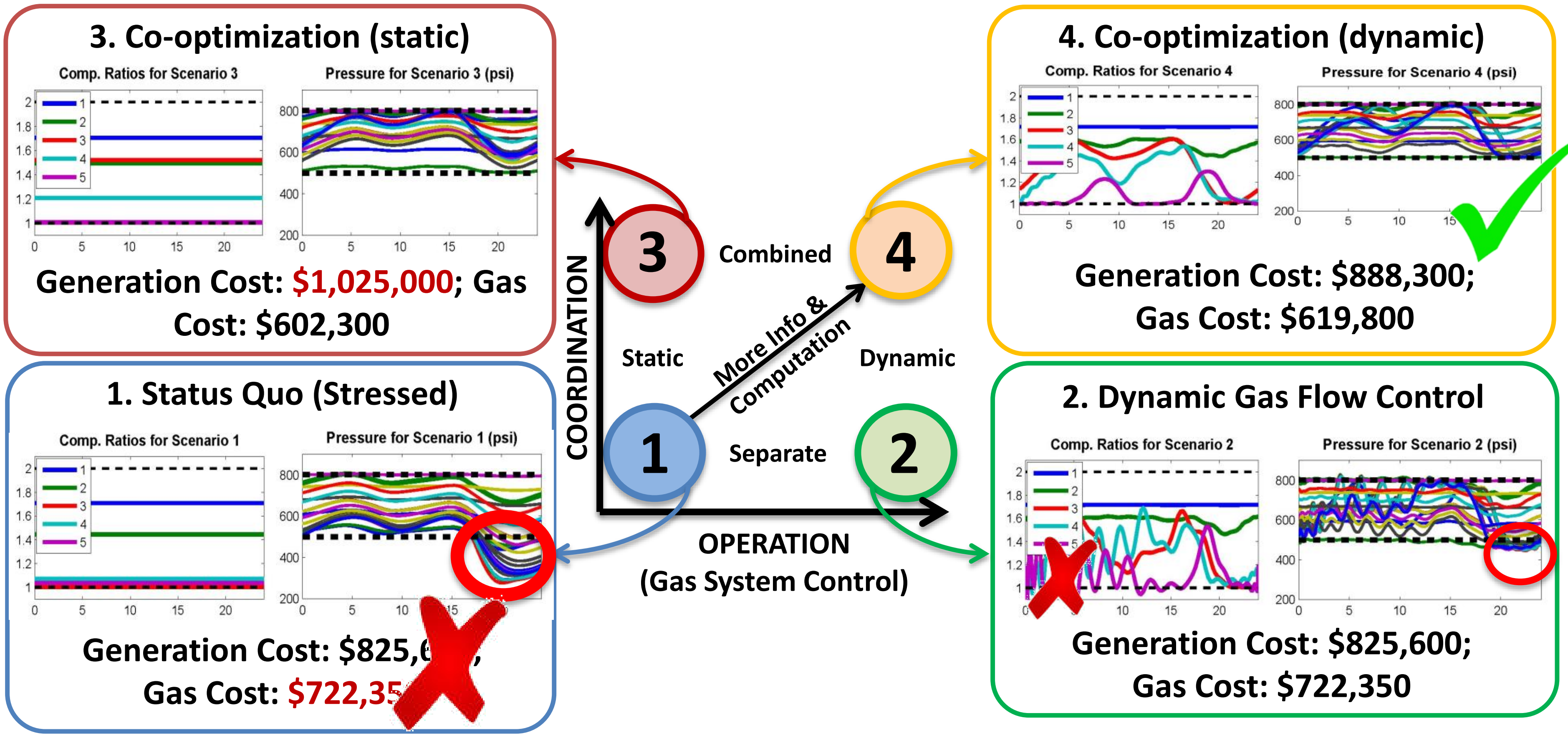
Improved efficiency for normal conditions

Benefits of Coordination & Information Exchange



Benefits of Coordination & Information Exchange

High Stress Case



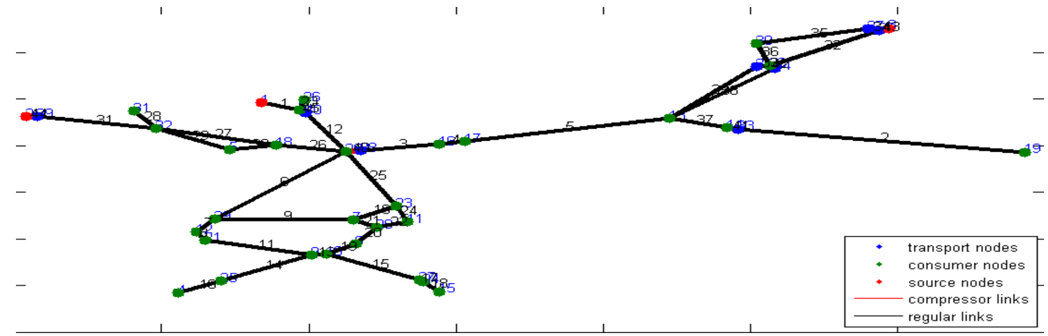
"Gaslib40+" gas network case study

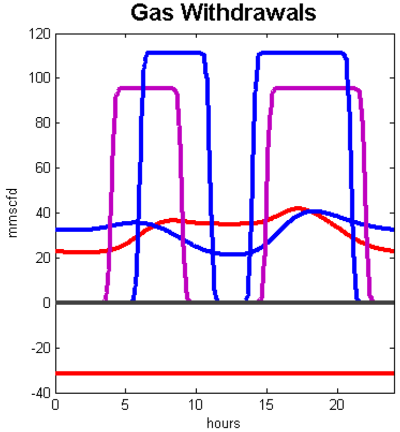
Total system length: 2796km

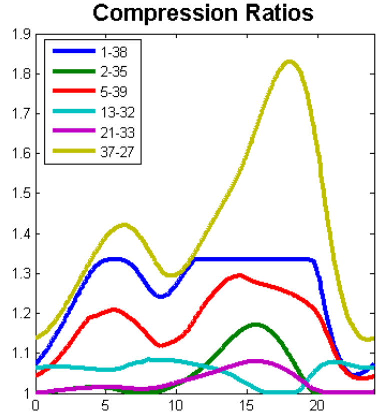
- Compressors: 6
- Supply points: 5
- Pressure nodes: 3
- Power plants: 7
- LDCs/other: 22

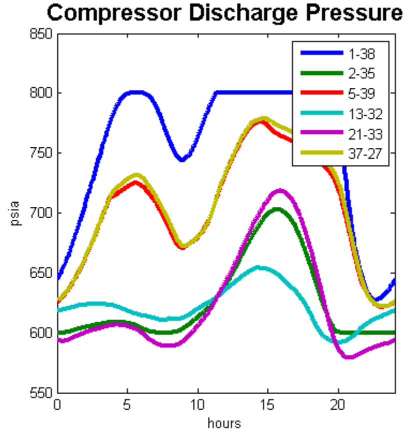
Min. compressor power

- 17.5km space disc
- 28min time disc
- Optimization time:
  256 sec
- Simulation time:
  5.88 sec (24h)



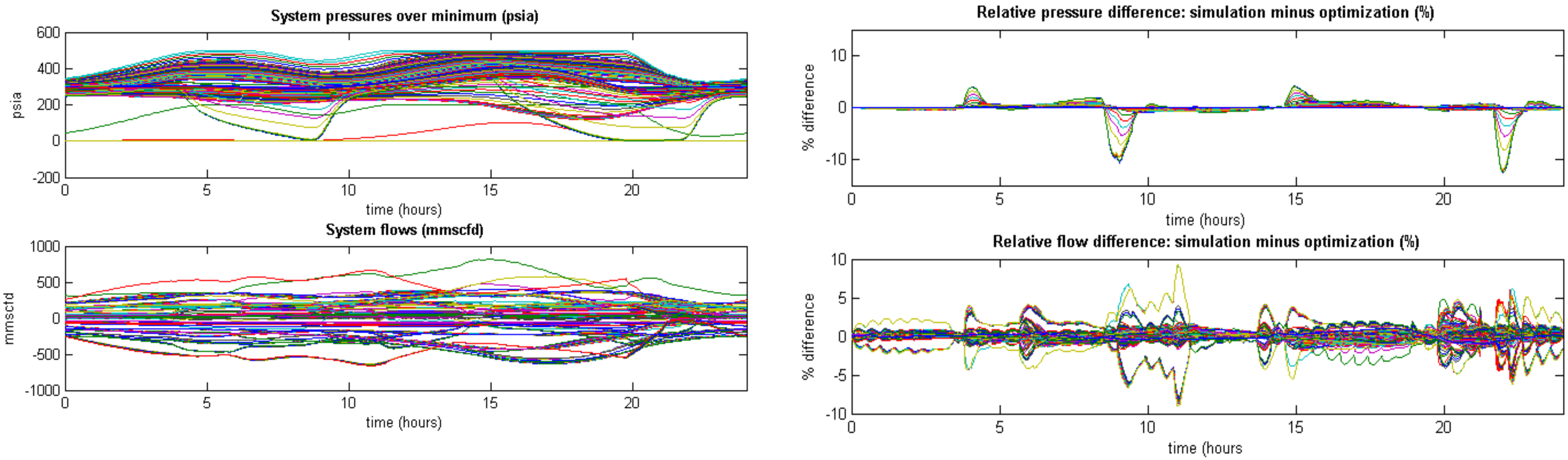






“Gaslib40+” gas network case study

Comparison of simulation and optimization results:



Precision can be improved by finer discretization on better computing platform

A glimpse of gLMPs

A steady state version

General Gas Supply Optimization Formulation

- Considering a pipeline network
- Suppliers submit locational offers to sell gas into the pipeline system. These may include supplies received at interconnection points with other pipelines
- Off-takers submit locational bids to buy gas
- Maximize Social Welfare

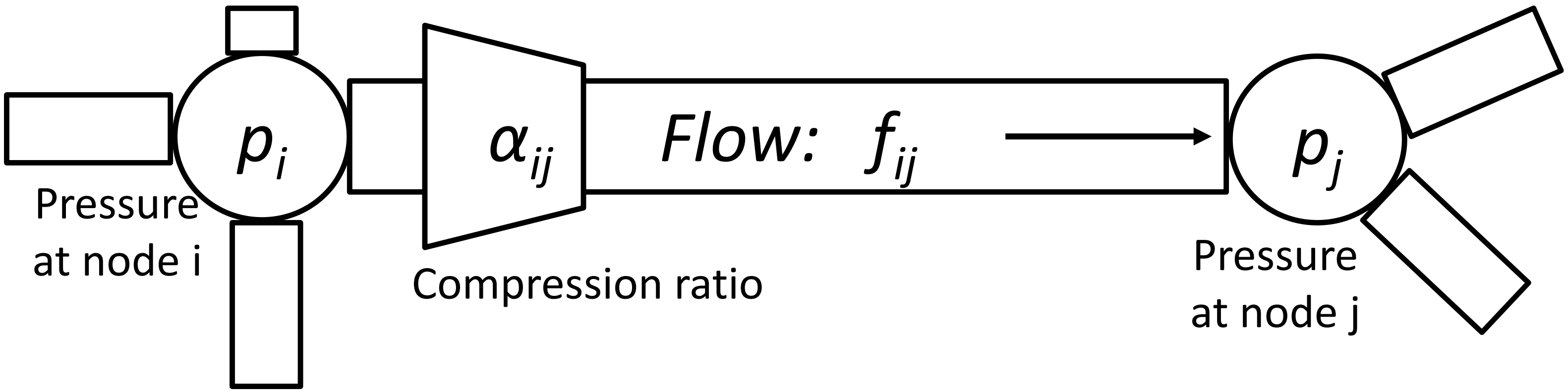
  = Sum {bid to buy times off-take volume}

  - Sum {offer to sell times supply volume}

  - Non-gas*) compressor costs
- Dynamic optimization over one or several days

*) Gas used for compression is accounted for explicitly through supplies

Steady State Model



$$(\alpha_{ij} p_i)^2 - p_j^2 = \beta_{ij} f_{ij} \mid f_{ij} \mid$$

Steady state flow equation

$$\alpha_{ij} p_i \le p^{\max}, p_j \ge p^{\min}$$

Pipe pressure limit constraints

$$E_{ij} = \eta_{ij} f_{ij} (\alpha_{ij}^{2m} - 1), E_{ij} \le E_{ij}^{\max}$$

Compressor energy use and capacity constraint

$$\alpha_{ij} \ge 1$$

Gas LMP Structure in the Steady State Model

$$LMP_j - LMP_i = Compression_{ij} + Congestion_{ij}^{c} + Congestion_{ij}^{p}$$

$$Compression_{ij} = LMP_i^{*}\eta_{ij}\left[(\alpha_{ij}^{2m}-1)+2m\alpha_{ij}^{2m}\left(1-\frac{p_j^2}{\alpha_{ij}^2 p_i^2}\right)\right]-\theta_{ij}\frac{\beta_{ij} f_{ij}}{\alpha_{ij} p_i^2}\geq 0$$

$$Congestion_{ij}^{c} = \gamma_{ij}\eta_{ij}\left[(\alpha_{ij}^{2m}-1)+2m\alpha_{ij}^{2m}\left(1-\frac{p_j^2}{\alpha_{ij}^2 p_i^2}\right)\right]\geq 0$$

$$Congestion_{ij}^{p} = \xi_{ij}\frac{\beta_{ij} f_{ij}}{\alpha_{ij} p_i}\geq 0$$

LMP_i^*	Gas or electric LMP depending on the compressor
θ_{ij}	Dual variable for $\alpha_{ij} \geq 1$
γ_{ij}	Dual variable for compressor capacity constraint
ξ_{ij}	Dual variable for pipe pressure constraint

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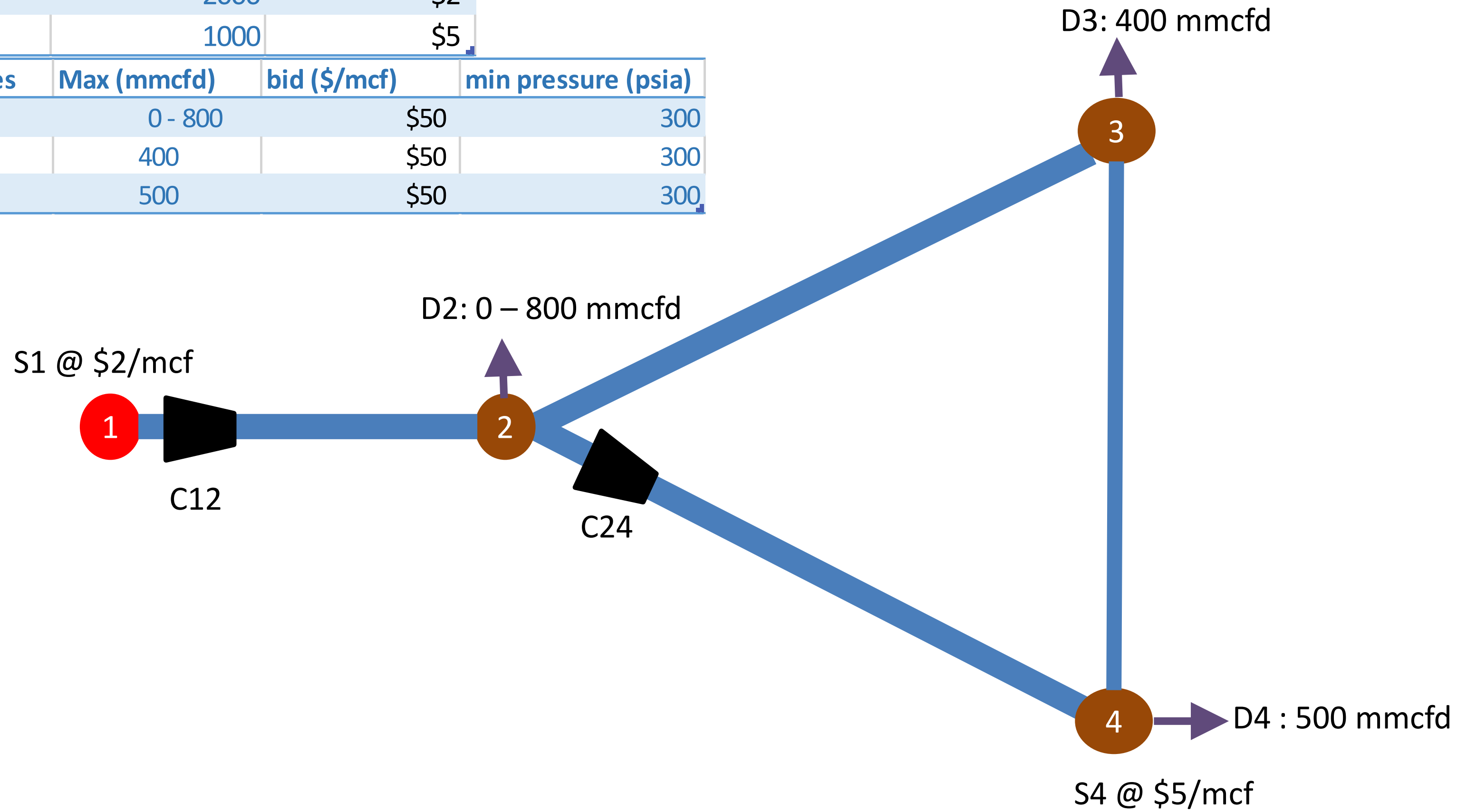
Numerical Example

Supply nodes	Max (mmcfd)	price ($/mcf)
1	2000	$2
4	1000	$5

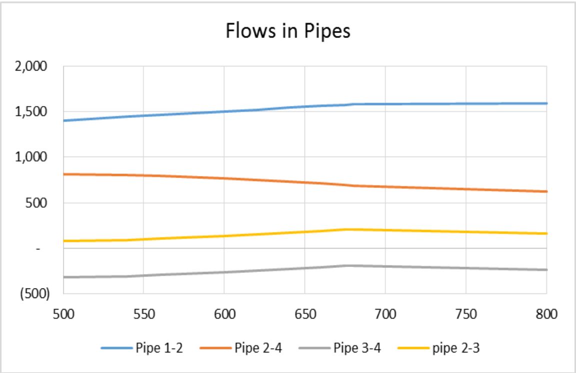
Demand nodes	Max (mmcfd)	bid ($/mcf)	min pressure (psia)
2	0 - 800	$50	300
3	400	$50	300
4	500	$50	300

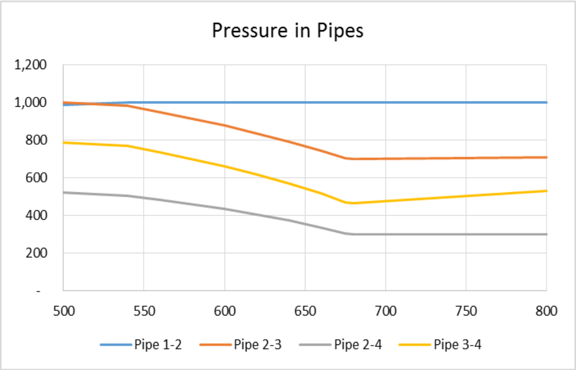


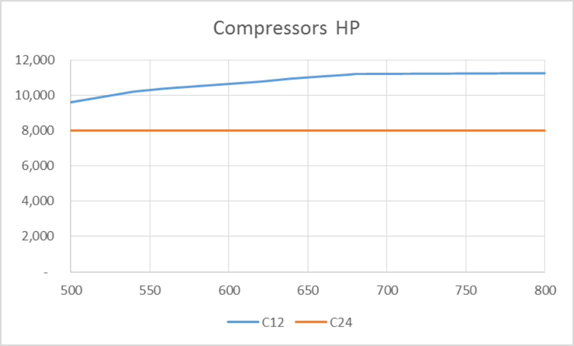
Pipes	length (miles)	diameter (in)	β	max pressure (psia)
1 - 2	50	36	0.35	1000
2 - 3	80	36	0.6	1000
2 - 4	80	36	0.6	1000
3 - 4	80	25	3.53	1000

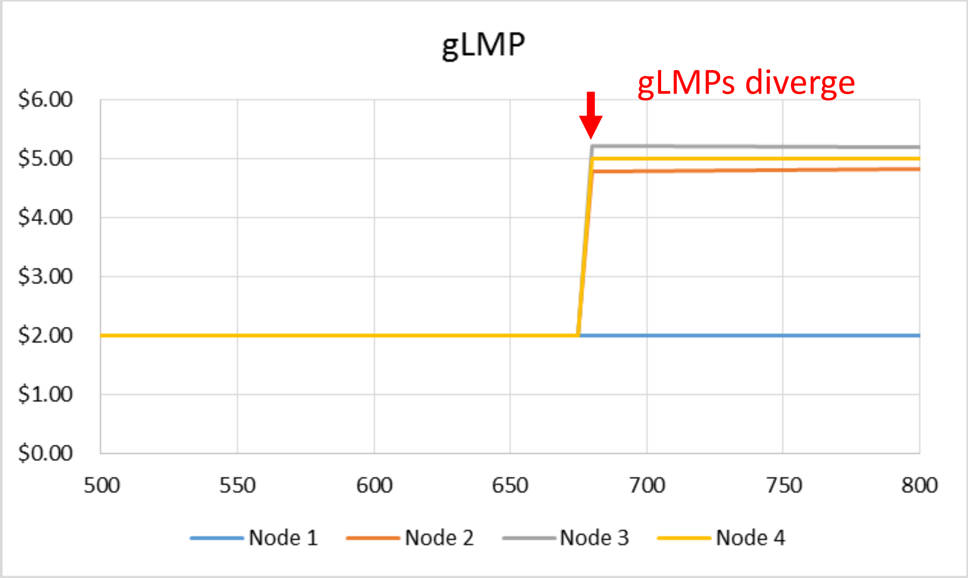
Compressors	HP	η (HP/mmcfd)	m
12	12000	8.4	0.6
24	8000	8.4	0.6

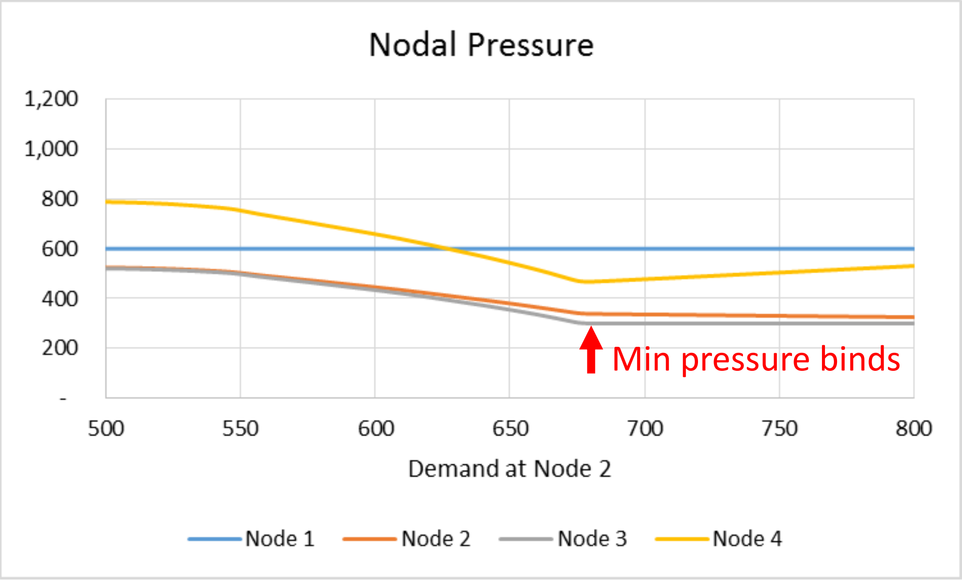
Optimal Solutions as a Function of Demand at Node 2











Some Observations from gLMP Analysis

- Congestion does not necessarily translate into constrained pipe flows
  - Flow in pipe 1-2 continues to grow with demand at Node 2 despite pressure constraint
  - Flow in pipe 2-4 changes significantly while compressor C24 operates at maximum capacity
- In gas networks not every binding constraint triggers additional marginal resource
- Binding minimum pressure constraints may play major role in causing price separation

Conclusions

- The opportunity exists to
  - radically change practical methods and algorithms of pipeline operations
  - Develop near real time pricing of natural gas that is consistent with the near real-time operations and with physics of the gas flow
- Realizing this opportunity is very important for gas and electric industry

Information

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Acknowledgments

Funding for the GECO project is provided by the Advanced Research Projects Agency – Energy (ARPA-E), U.S. Department of Energy, under the Open 2015 program, Award Number DE-AR0000673, by the Massachusetts Clean Energy Center (MassCEC), and by the team member institutions.