Coordinated Operation of Electric and Natural Gas Supply Networks: Optimization Processes and Market Design

Gas-Electric Co-Optimization (GECO)

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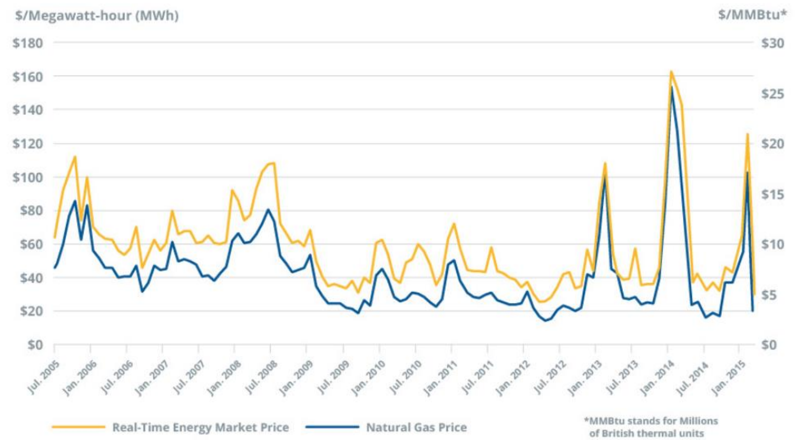
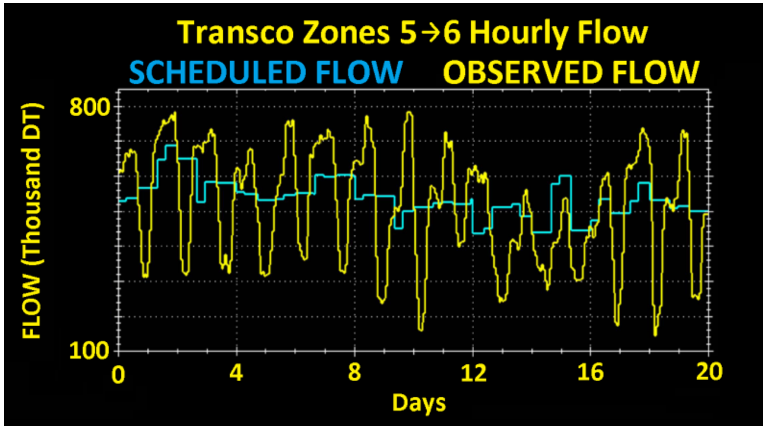
Motivation

- 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 power systems
- Recent advancements in pipeline simulation and optimization methods developed by the LANL team create an opportunity to achieve such radical improvements





GECO Team

Institution	People	Expertise
Newton Energy Group & Consultants	Alex Rudkevich, PI John Goldis, Richard Tabors, Rick Hornby, John Rosenkranz	Cloud platform for parallel modeling and analytics of energy systems. Data structures. Optimal pricing, market design, commercialization
Los Alamos National Laboratory	Scott Backhous, Russel Bent, Michael Chertkov, Anatoly Zlotnik	Advanced computational methods and algorithms for simulation and optimization of gas & electric networks
Polaris Systems Optimization	Russ Philbrick	Advanced power systems simulator native to NEG cloud platform. Power systems optimization expertise
Boston University	Michael Caramanis, Pablo Ruiz	Market design, market coordination, algorithms
AIMMS	Peter Niewesteeg	Modeling language, optimization
Kinder Morgan	Nancy Barton	Pipeline operation, market expertise and information
PJM	Adrien Ford	Power system operation, market expertise and information

GECO Objectives

- Gas-Electric Co-Optimization (GECO) project's objective is to develop algorithmic structures 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

Program Elements

Software & Algorithms Newton Energy Group, Los Alamos National Laboratory, Polaris Systems Optimization, Boston University, AIMMS	• 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 Newton Energy Group, Los Alamos National Laboratory, Boston University, Polaris Systems Optimization, pjm, Kinder Morgan	• Joint gas-electric theory of locational marginal prices (LMPs) and methods for computing gas LMPs • Market design proposal including coordination mechanisms
Realistic Market Simulations Newton Energy Group, Los Alamos National Laboratory, pjm, Polaris Systems Optimization, Kinder Morgan	• Gas-electric simulation model within the PJM footprint • Set of simulated scenarios comparing performance of gas-electric coordination policies under different assumptions

GECO Outcome vs. Status Quo

	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 optimal 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

Key activities by program element

Program Elements

Software & Algorithms (Newton Energy Group, Los Alamos National Laboratory, Polaris Systems Optimization, Boston University, AIMMS)	• 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 (Newton Energy Group, Los Alamos National Laboratory, Boston University, Polaris Systems Optimization, pjm, Kinder Morgan)	• 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 sectors
Realistic Market Simulations (Newton Energy Group, Los Alamos National Laboratory, pjm, Polaris Systems Optimization, Kinder Morgan)	• 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

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 $\forall \{i,j\} \in \mathcal{E}$:

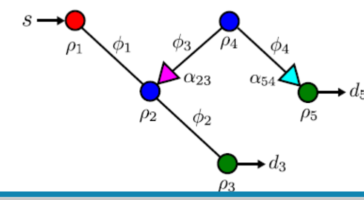
$$
\begin{aligned}
\rho_{ij}(t,0) &= \alpha_{ij}(t) s_i(t), \quad \forall i \in \mathcal{V}_S, \\
\rho_{ij}(t,L_{ij}) &= \alpha_{ji}(t) s_j(t), \quad \forall j \in \mathcal{V}_S, \\
\rho_{ij}(t,0) &= \alpha_{ij}(t) \rho_i(t), \quad \forall i \in \mathcal{V}_D, \\
\rho_{ij}(t,L_{ij}) &= \alpha_{ji}(t)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

- 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 $A = \mathrm{sign}(B)$

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

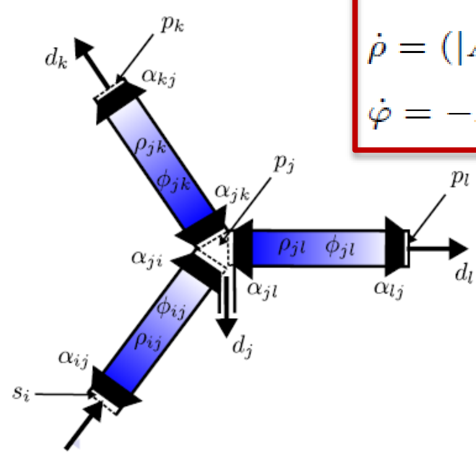


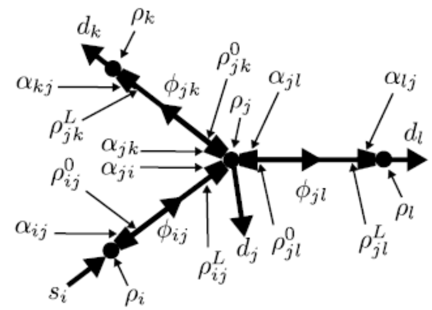
	φ_1	φ_2	φ_3	φ_4	
ρ_1	-1	0	0	0	B_s
ρ_2	1	-1	$-\alpha_{23}$	0	B_d
ρ_3	0	1	0	0	
ρ_4	0	0	1	-1	
ρ_5	0	0	0	α_{54}	

Reduced Equations:

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

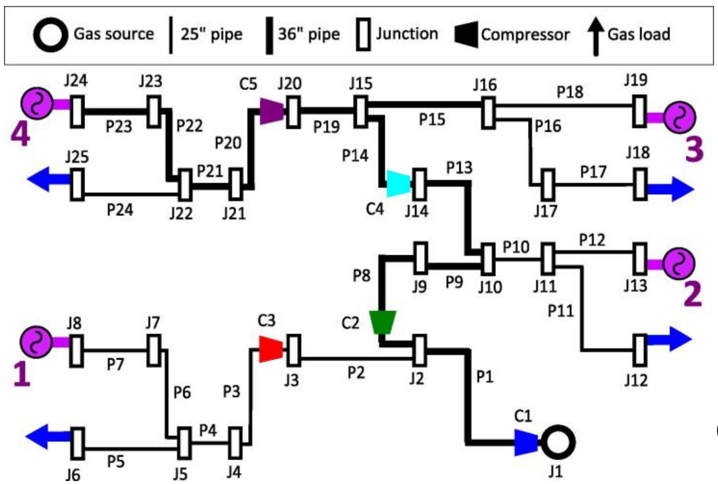
$$\dot{\varphi} = -\Lambda^{-1}(B_s^T s + B_d^T \rho) - K g(\varphi, |B_s^T|s + |B_d^T|\rho)$$





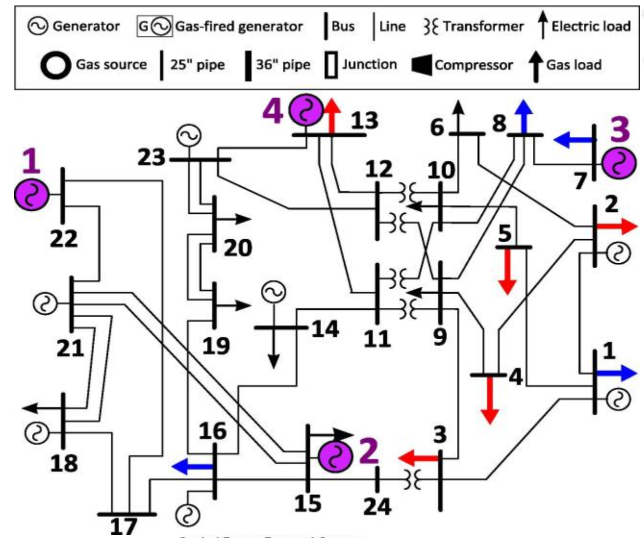
Intra-day gas-grid interdependency case study

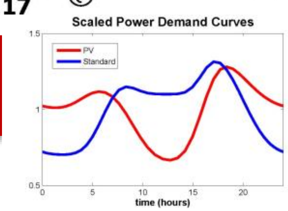
Gas pipeline network model



Dynamic constraints on gas availability

Power system model





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)

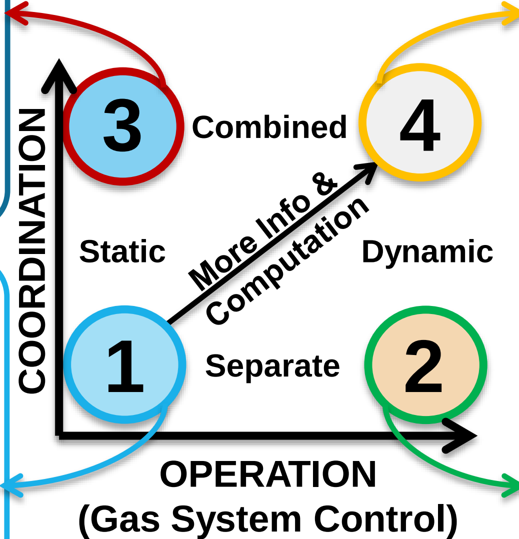
Pipeline model and data → Grid operator

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

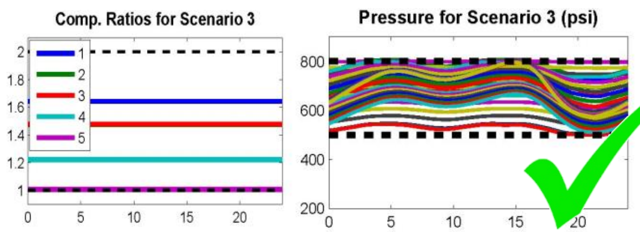
Optimal dynamic compressor operation (new technology)

Improved efficiency for normal conditions

Benefits of Coordination & Information Exchange

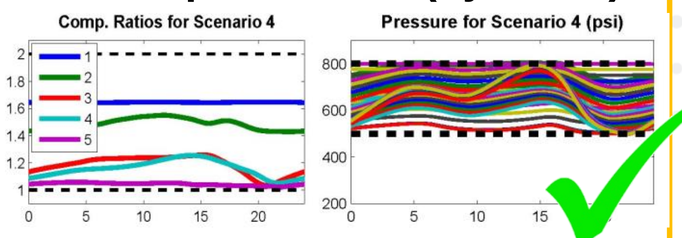
Base Stress Case

3. Co-optimization (static)

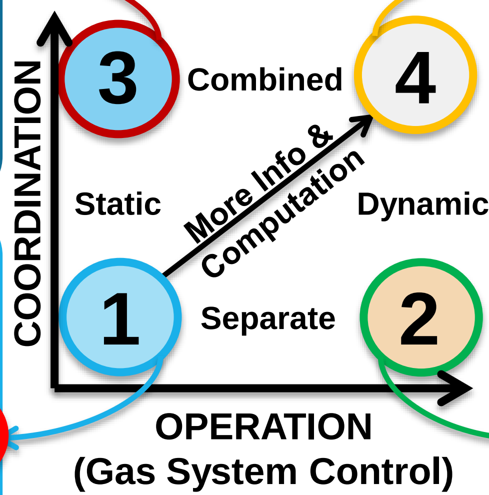


Generation Cost: $770,800; Gas Cost: $570,240

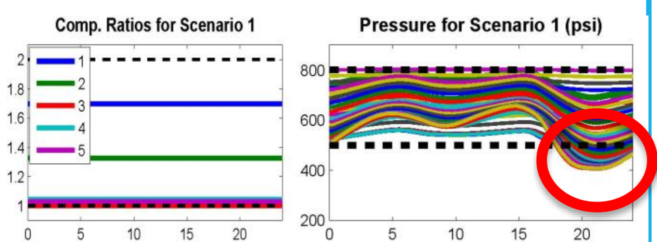
4. Co-optimization (dynamic)



Generation Cost: $731,600; Gas Cost: $581,200

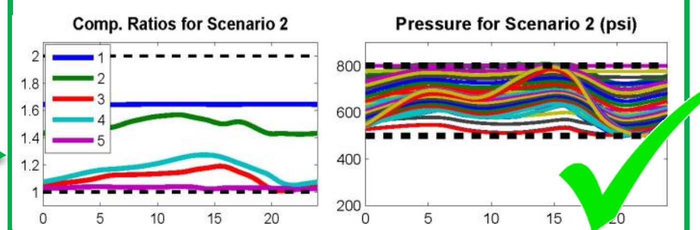


1. Status Quo (Stressed)



Generation Cost: $731,600; Gas Cost: $581,600

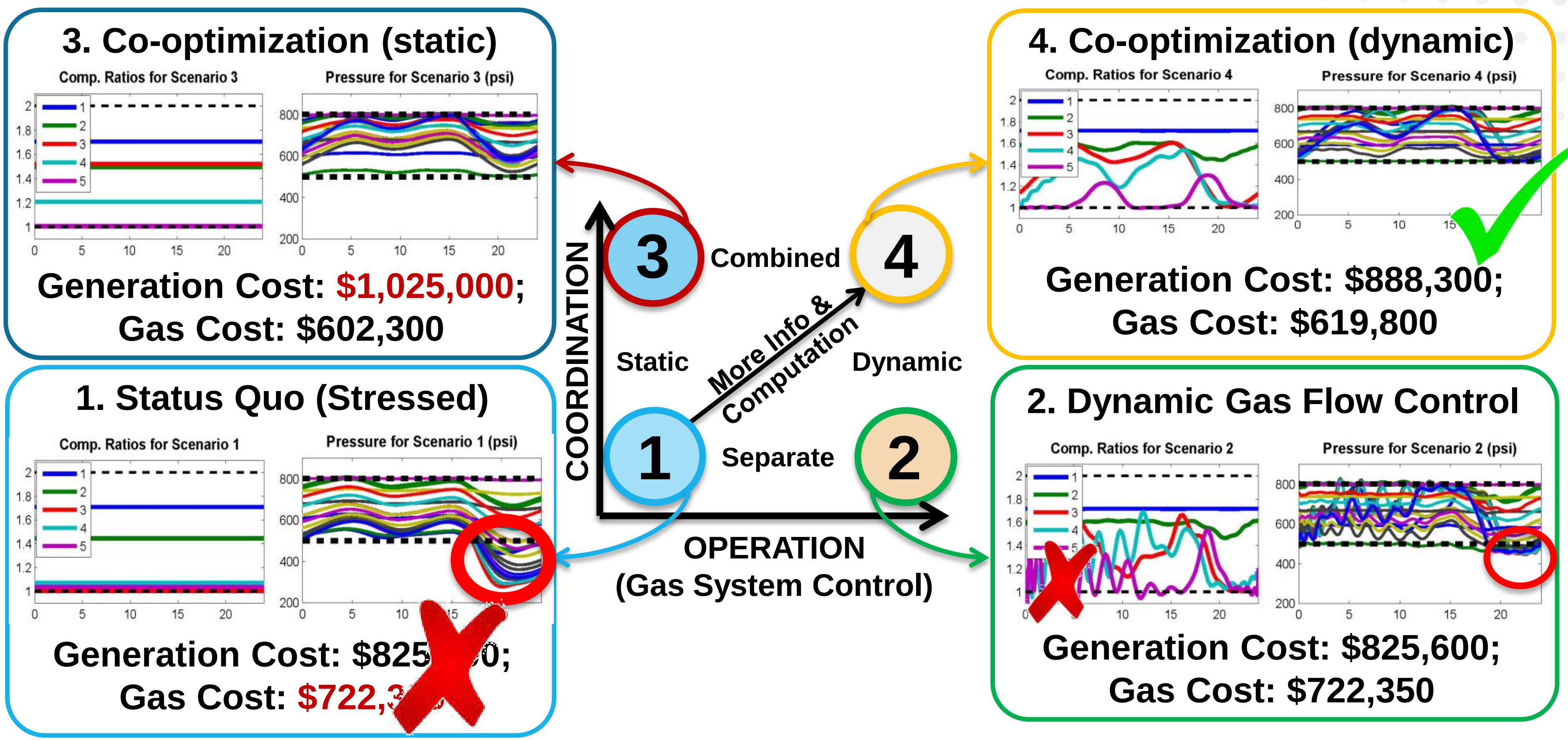
2. Dynamic Gas Flow Control



Generation Cost: $731,600; Gas Cost: $581,600

Benefits of Coordination & Information Exchange

High Stress Case



First year milestones

- 1500+ miles pipeline – RNF-based transient simulation for a 24-hour horizon with 1 min time step - solve time < 1 min. Solution validated by high fidelity transient modeling
- 1500+ miles pipeline - RNF-based transient optimization for a 24-hour horizon with 1 min time step - solve time < 1 hr
- High level software architecture
- Theory and computational methodology for joint gas-electric LMPs
- Development and validation of the gas-electric model using real data from PJM and Kinder Morgan
- Simulation results for a joint optimization gas transients + SCOPF (pre-defined SCUC solution) on a joint gas-electric model

Technology-to-Market: products and users

	RTOs	Pipelines	Generators	Traders	Regulatory Agencies
Software Modules	X	X	X	X	
Software as a Service	X	X	X	X	X
Market design and other consulting	X	X	X	X	X

Key partners/advisers: PJM on the electric side and Kinder Morgan on the gas side

First year activities: (1) validate models and results with industry advisers; (2) identify use cases where newly developed methods and tools could be used w/o the need for market reform; (3) begin publicizing results to industry stakeholders; (4) Develop understanding of the regulatory landscape of the problem

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
- Realizing this opportunity is very important for electric industry