Gas-Electricity System Coupling

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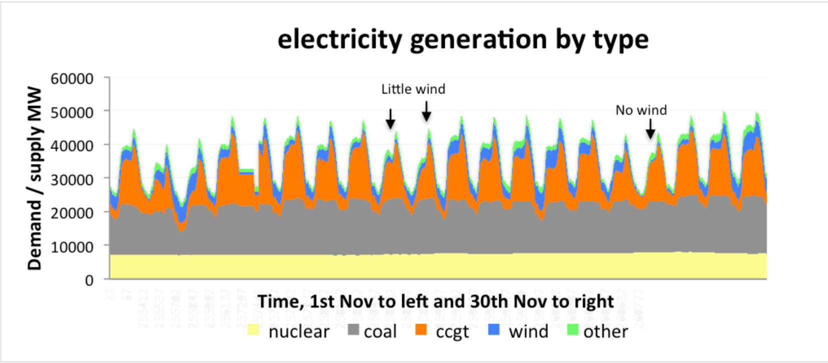
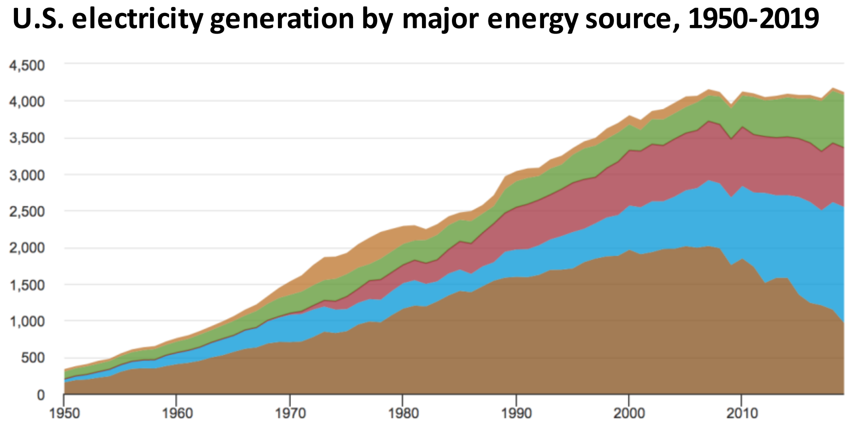
Increasing Gas-Electricity Interdependency

Gas-fired power generation is expanding:

- Economic: Availability of cheap gas
- Environmental: Replacing coal



Source: www.nationalgrid.com/uk



Source: U.S. Energy Information Administration

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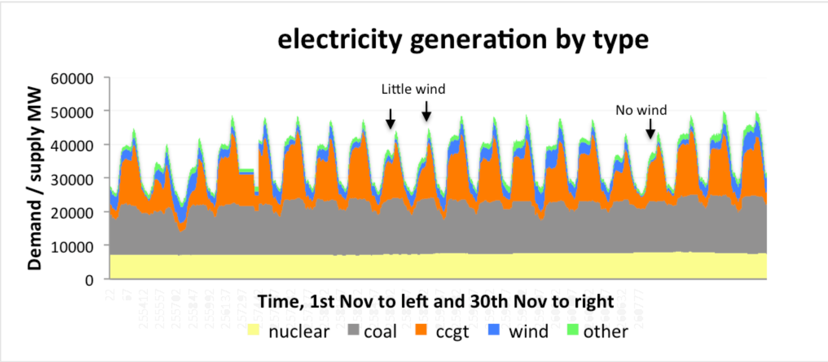

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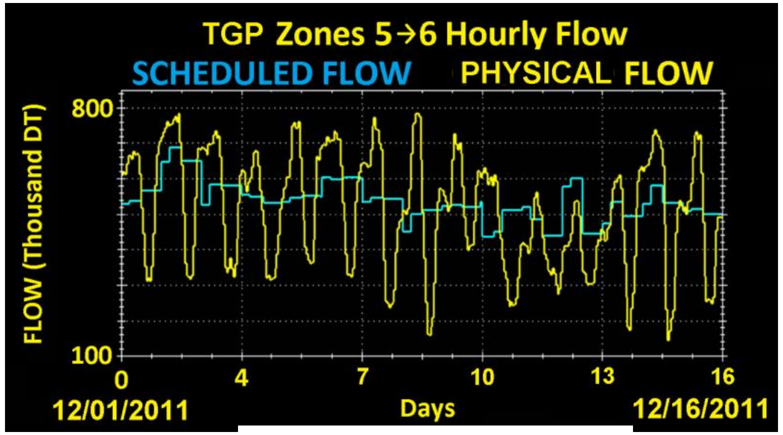
Gas pipeline loads are changing:

- Increasing in volume & variation
- More intermittent & uncertain



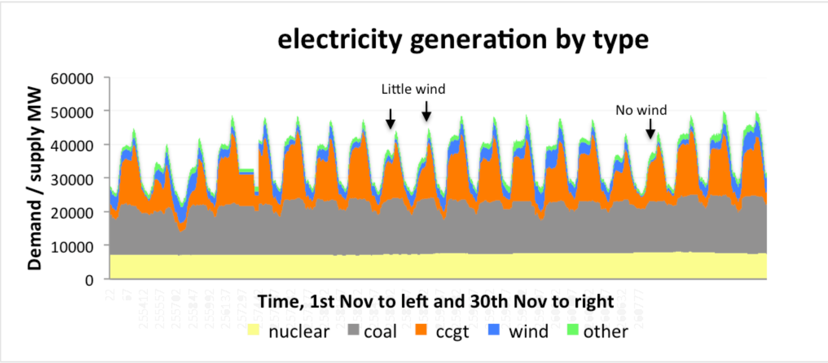
Source: El Paso Pipeline

Reliable Supply to Gas-Fired Power Plants

Motivation: Reliable Supply of Gas

- Lack of coordination!
  - Need for information sharing
  - Market timing and coordination

- Better operational practices
  - Predict pressure drops
  - Mitigate using compressor control



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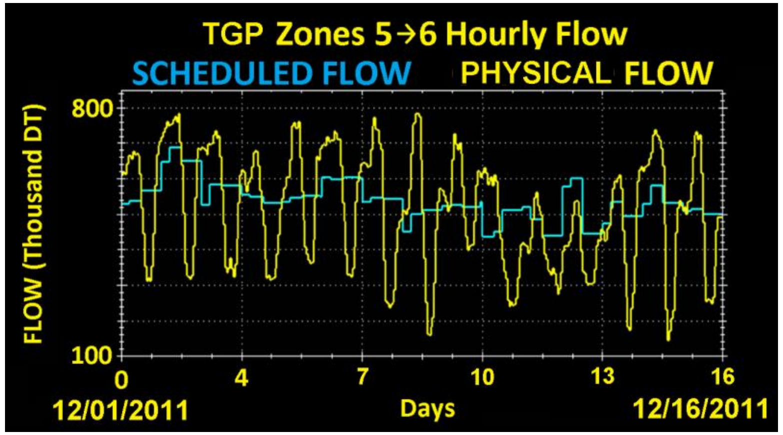

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Challenges: Gas-Electric Differences

<u>**POWER GRIDS**</u>	<u>**GAS PIPELINES**</u>
• **Real-time** balancing	• **Daily or monthly** balancing
• Storage is **costly**	• System has **internal storage** (linepack)
• Electric reliability for **all customers**	• Gas power plants can typically be **curtailed**
• Power day is 12 a.m. to 12 a.m. (by region)	• Gas day is 10 a.m. to 10 a.m. EST
• Steady-state **in seconds**	• Steady-state **in hours** (“never” achieved)

Challenges: Gas-Electric Differences

POWER GRIDS

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Steady-state vs dynamic gas modelling?

[Conor O Malley, Line Roald and Gabriela Hug, "Importance of Dynamic Modeling of Gas Networks for Energy System Reliability", Grid Science Winter School, 2017]

Steady-state vs dynamic gas modelling

Steady-state gas system modelling:

Assume that system dynamics have time to settle down

Dynamic gas system modelling:

Accounting for the effect of changing conditions

Steady-state vs dynamic gas modelling

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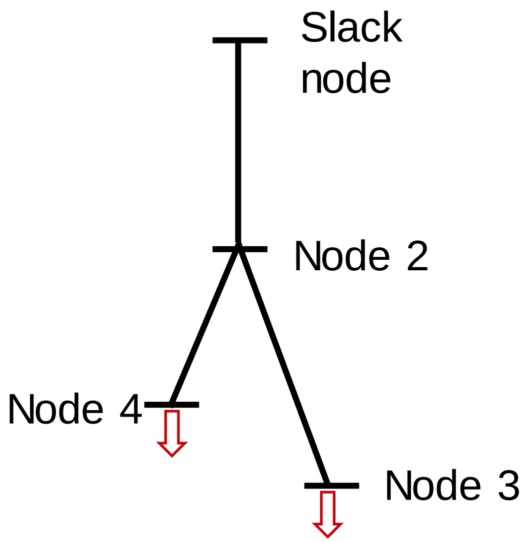

Start from steady state then swap the loads

Steady-state vs dynamic gas modelling

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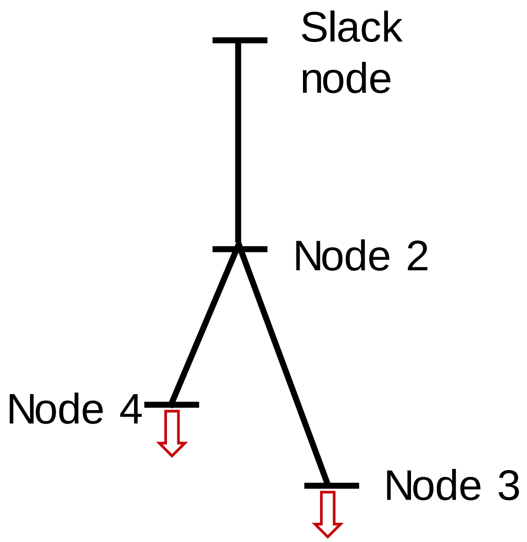
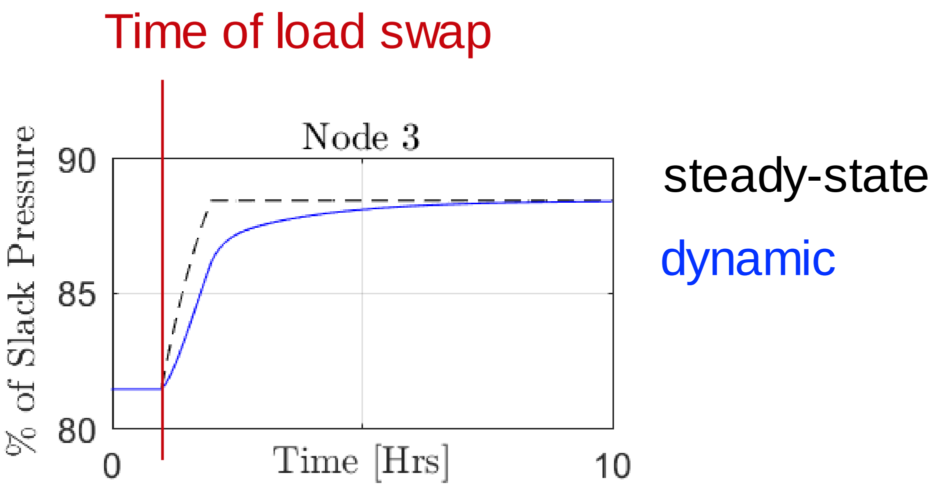
Dynamic gas system modelling:

Accounting for the effect of changing conditions





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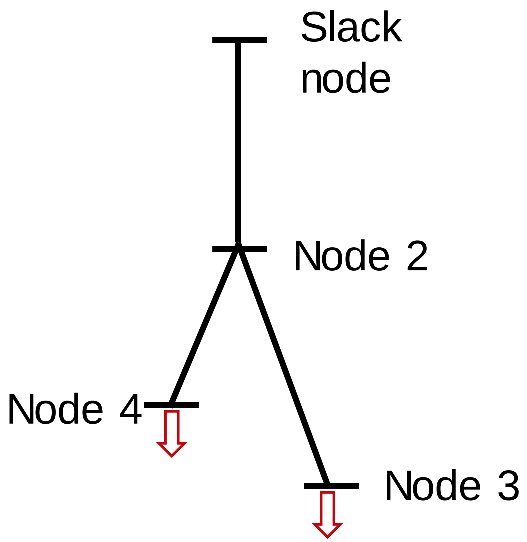
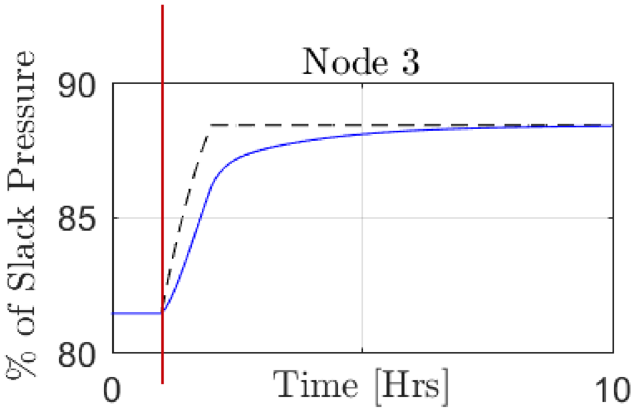


Time of load swap



steady-state

dynamic

It takes a LONG time for the steady-state solution to settle down, more than 5h!

Steady-state vs dynamic gas modelling

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Dynamic gas system modelling:

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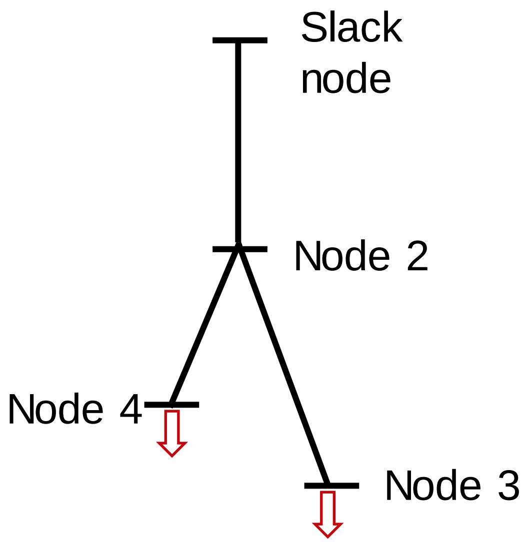

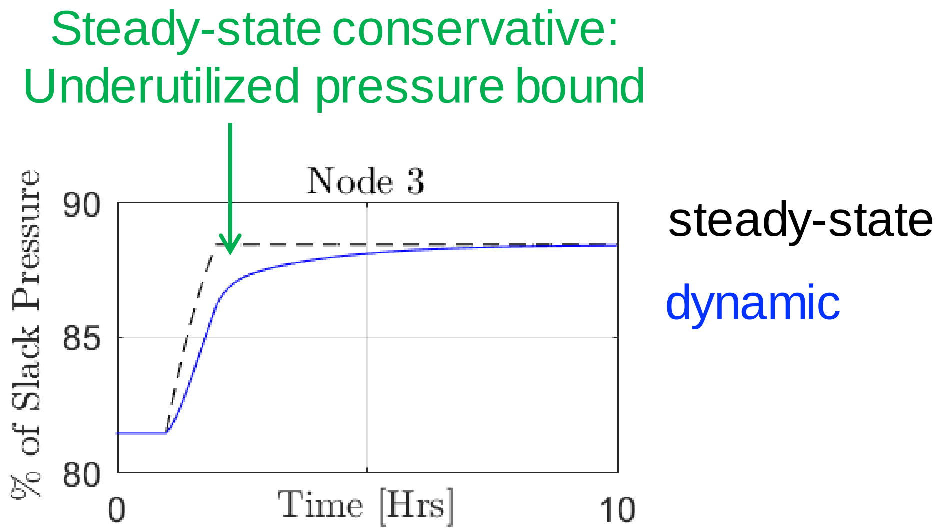

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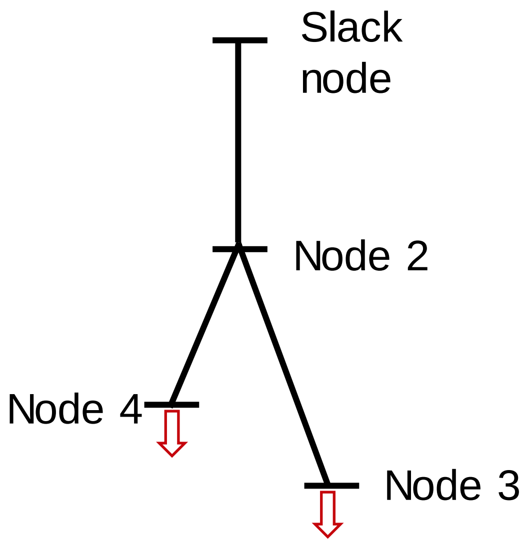

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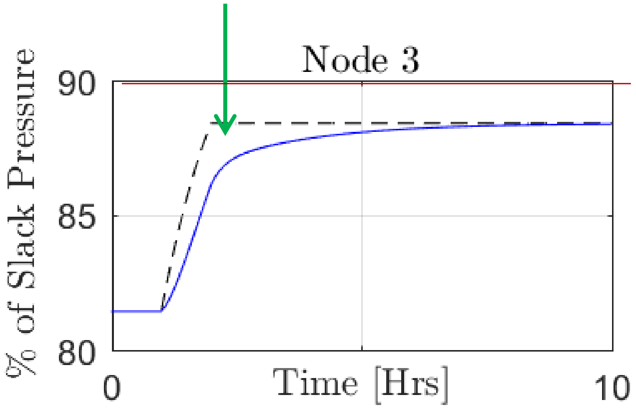
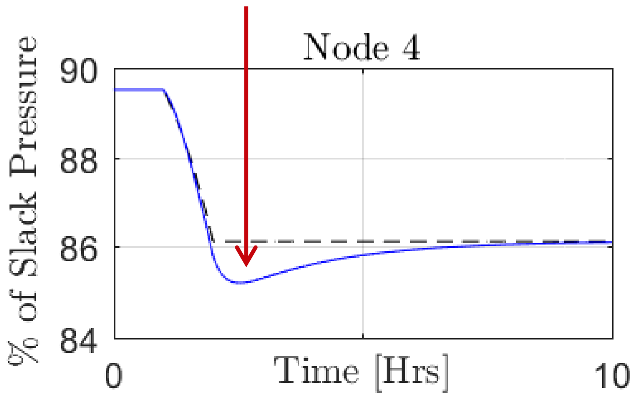
Accounting for the effect of changing conditions

Steady-state conservative:
Underutilized pressure bound



Steady-state dangerous:
Pressure drop larger than expected



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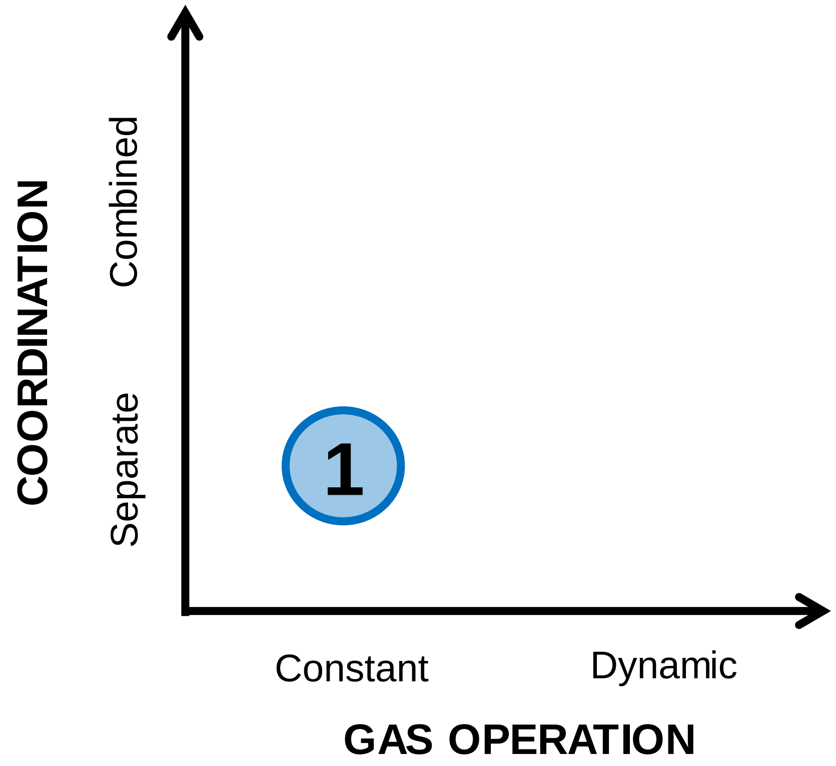
What is the value of coordination and control?

[Anatoly Zlotnik, Line Roald, Scott Backhaus, Michael Chertkov, Göran Andersson,
"Coordinated Scheduling for Interdependent Electric Power and Natural Gas Infrastructures", IEEE Transactions on Power Systems, 2017]

Value of Coordination and Control

Considered Operational Scenarios

Scenario #1 – Operation Today
Coordination: Separate
Operation: Constant compression ratios (steady state)



Considered Operational Scenarios

Scenario #1 – Operation Today
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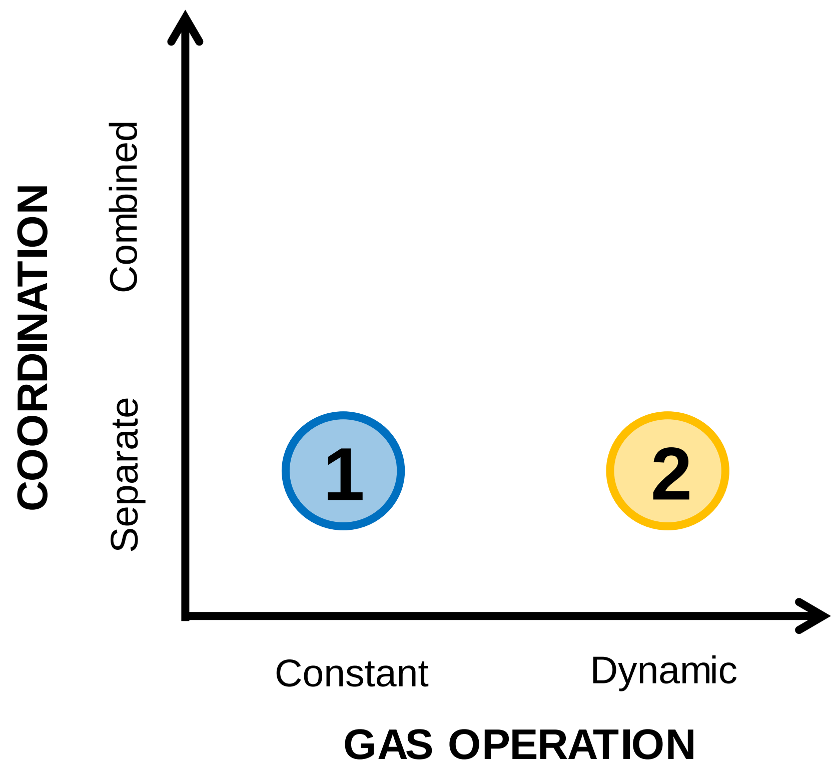
Operation: Constant compression ratios (steady state)

Scenario #2 – Improved Gas Operation
Coordination: Separate
Operation: Dynamic compression



Value of Coordination and Control

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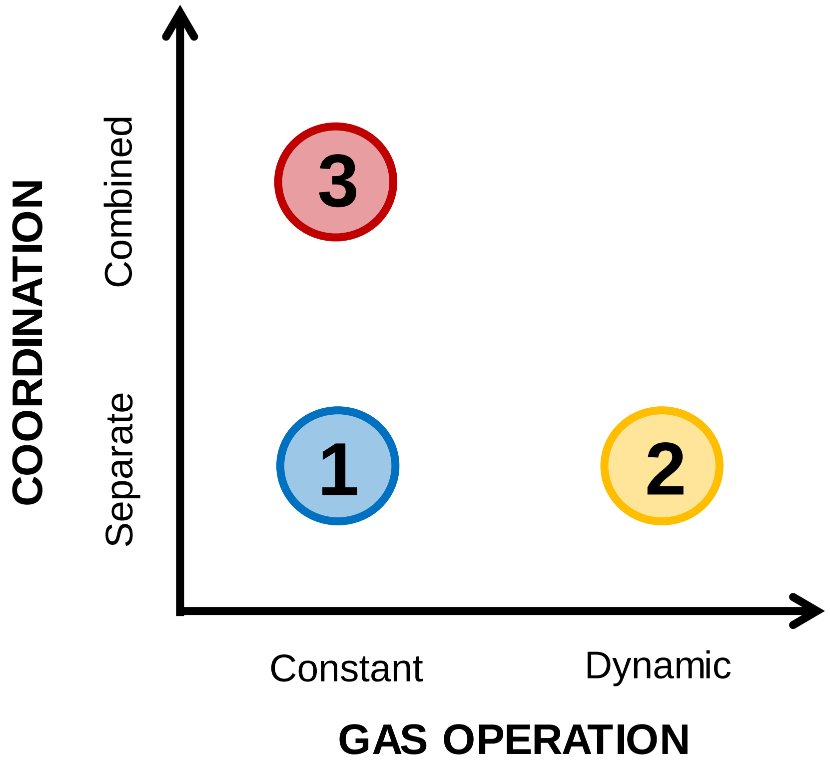
Operation: Dynamic compression

Scenario #3 – Coordinated Operation
Coordination: Combined
Operation: Constant compression



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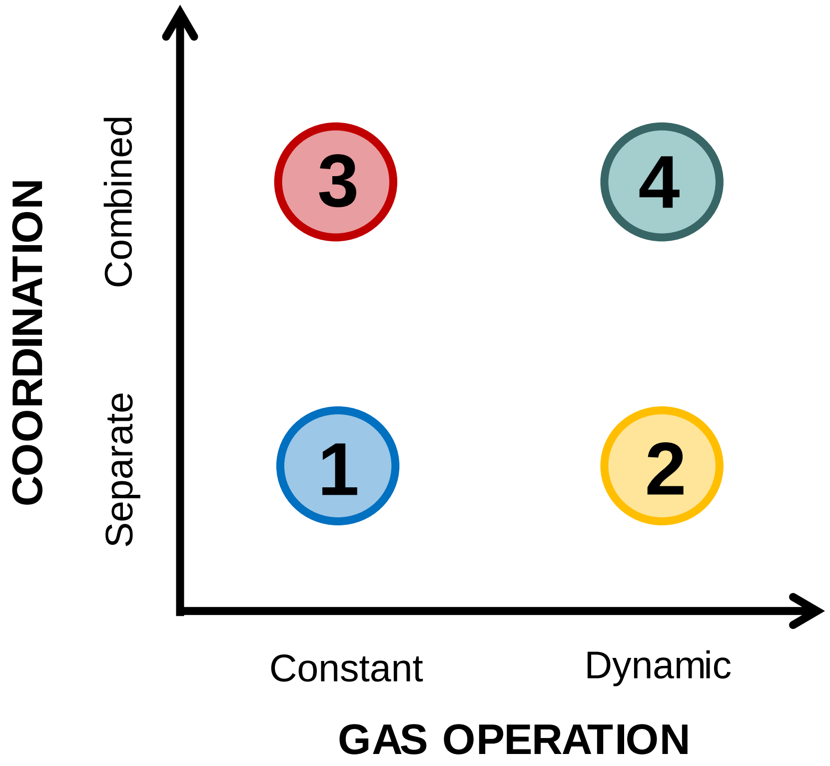
Operation: Constant compression

Scenario #4 – Coordination and Improved Gas
Coordination: Combined
Operation: Dynamic compression



Value of Coordination and Control

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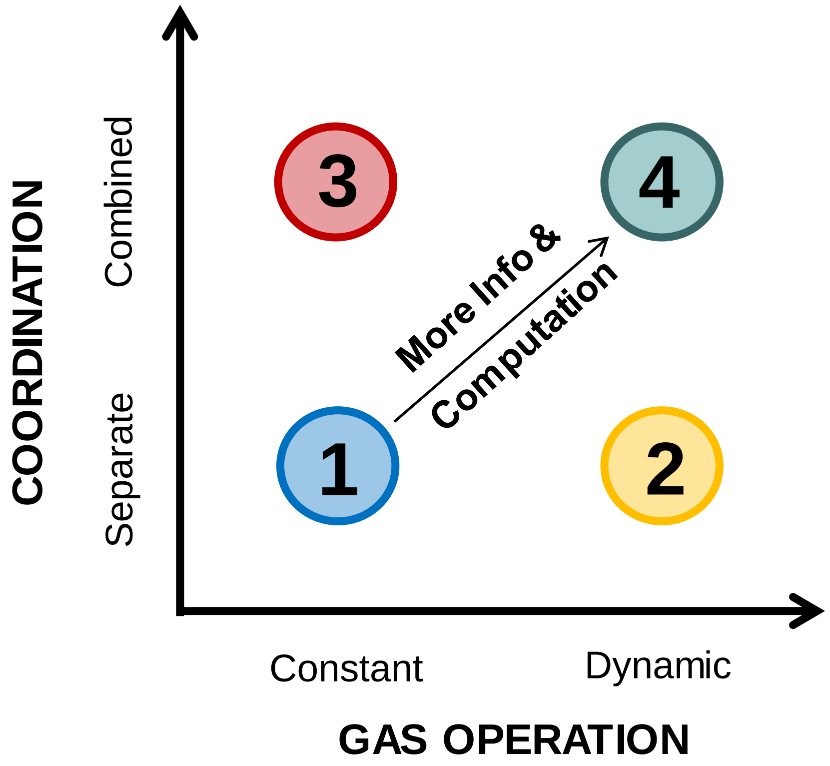
Scenario #4 – Coordination and Improved Gas
Coordination: Combined
Operation: Dynamic compression



Solving the Gas-Electric Problem

Minimize cost of generation: $J_P \triangleq \sum_{i \in \mathcal{G}} \int_0^T c_g \cdot q(p_i(t)) \mathrm{d}t$

Power balance (1): $\sum_{i \in \mathcal{V}} (p_i(t) - h_i(t)) = 0, \quad \forall\, t \in [0, T]$

Power production limits (2): $0 \leq p_i(t) \leq p_i^{max}, \quad \forall\, i \in \mathcal{G}, \quad \forall\, t \in [0, T]$

Line flow limits (3): $-f_{ij}^{\max} \leq \mathrm{M}_{(ij,\cdot)}(p(t) - h(t)) \leq f_{ij}^{\max}$

$\forall\, \{ij\} \in \mathcal{E}, \;\forall\, t \in [0, T]$

DC Optimal Power Flow

Minimize cost of compression: $J_G \triangleq \sum_{\{i,j\} \in \mathcal{C}} \int_0^T \frac{|\varphi_{\pi_e(ij)}(t)|}{\eta_{ij}} \left((\max\{\alpha_{ij}(t), 1\})^{2m} - 1 \right) \mathrm{d}t$

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

Flux Dynamics (5): $\dot{\varphi} = -\Lambda^{-1}(B_s^T s + B_d^T \rho) - Kg(\varphi, |B_s^T|s + |B_d^T|\rho)$

Density constraints (6): $\rho_i^{\min} \leq \alpha_{ij}(t)\rho_i(t) \leq \rho_i^{\max}$

Compression constraints (7): $1 \leq \alpha_{ij}(t) \leq \alpha_{ij}^{\max}, \quad \forall\, \{i,j\} \in \mathcal{C}$

Time boundary conditions (8): $\rho(0) = \rho(T), \;\; \varphi(0) = \varphi(T), \;\; \alpha_{ij}(0) = \alpha_{ij}(T), \;\; \forall\, \{i,j\} \in \mathcal{C}$

Dynamic Optimal Gas Flow

- Spatial discretization: 10 km
- Steady-State:
  Remove time dependency

Combined Objective: $\min_{p(t),\, \alpha_{ij}(t)} \quad \beta_P J_P + \beta_G J_G$

System constraints: $s.t.$ all constraints (1)-(8)

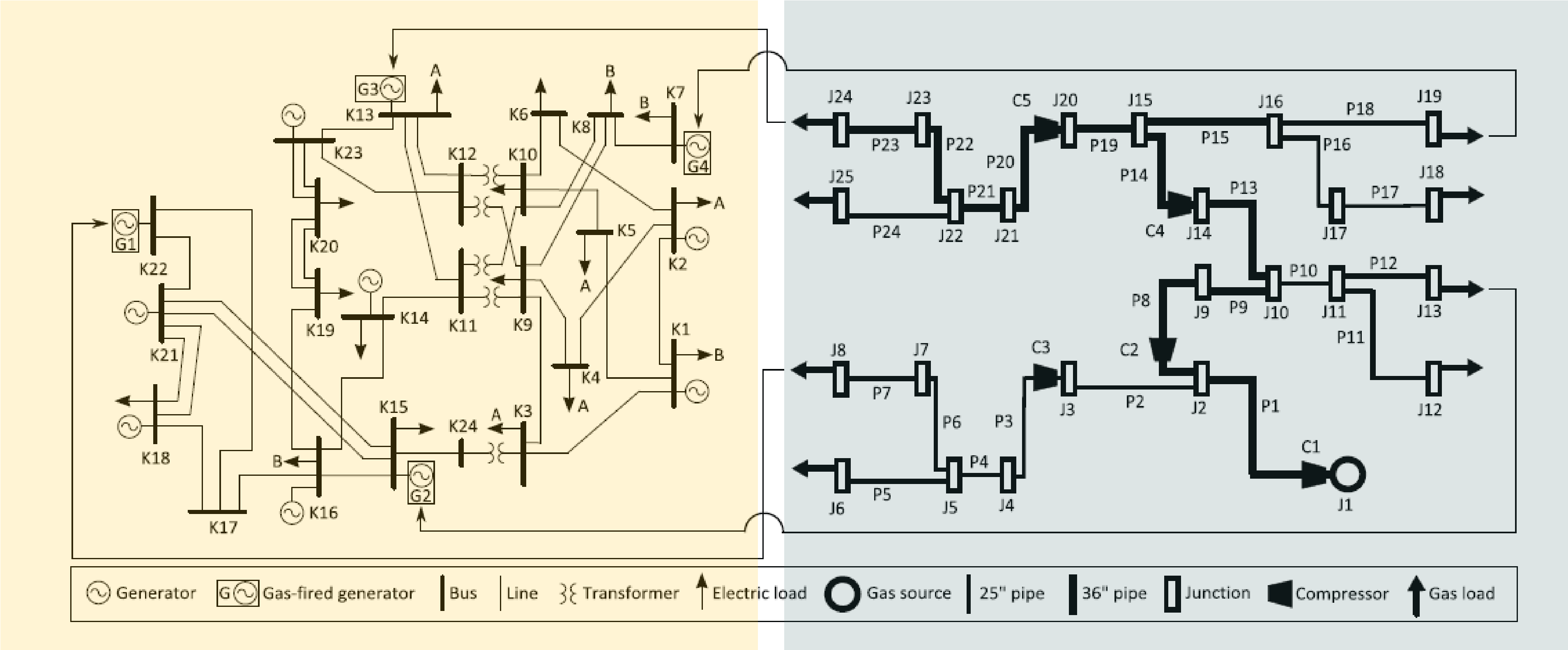
Heat-rate curve coupling: $d_i(t) = q(p_i(t)) = q_0 + q_1 p_i(t) + q_2 p_i^2(t)$

Coupling constraints

- Generator heat rate curves

What is more valuable:

Better coordination or better control?



ELECTRIC SYSTEM

- Time-varying load
- 40% gas generation

GAS SYSTEM

- 4 gas generation nodes (50% of demand)
- 5 compressors

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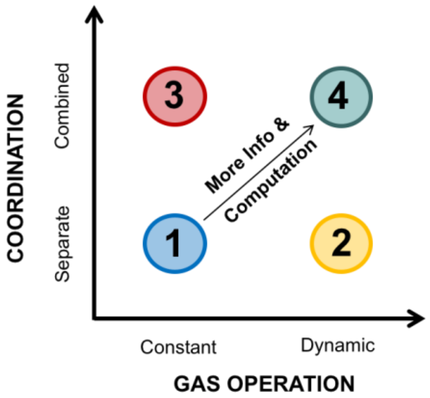
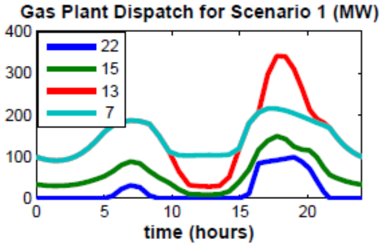
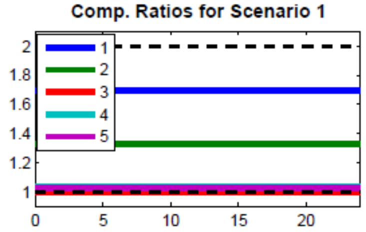


Scenario #1

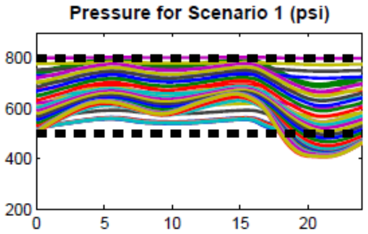
Today



Generation dispatch from OPF



Compression ratios from **steady-state** OGF



Pressure violations!

What is more valuable:

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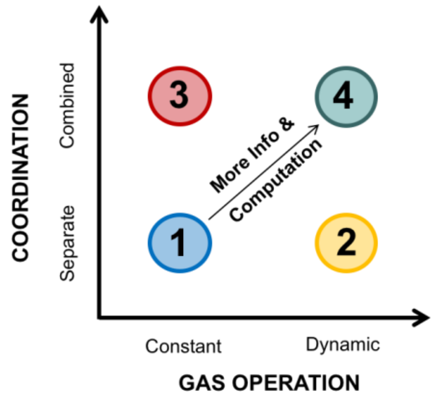
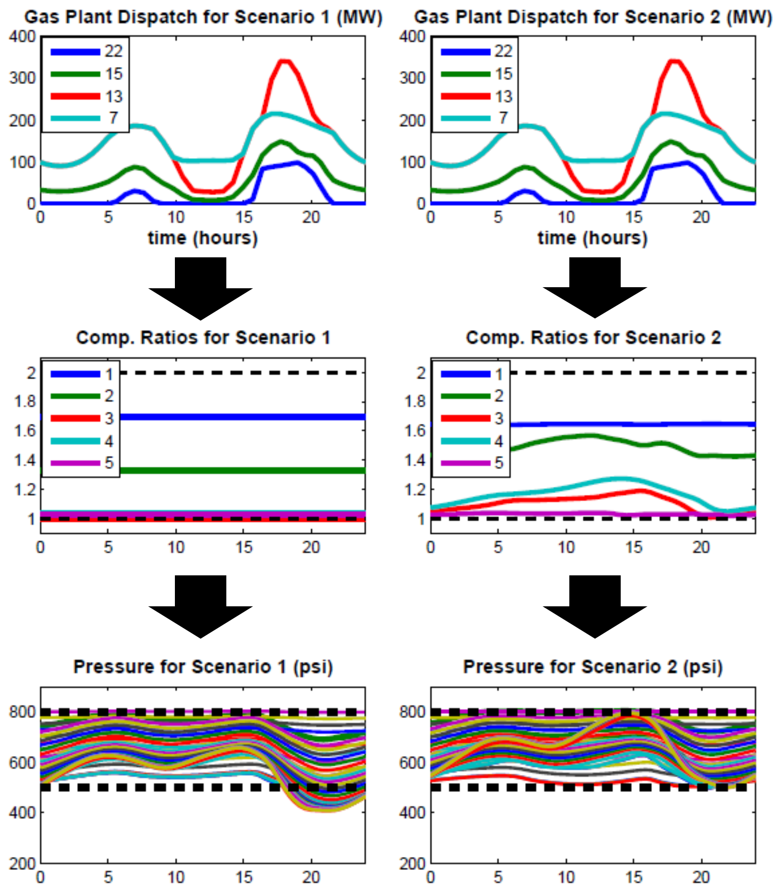


Scenario #1
Today

Scenario #2
Better Control



Generation dispatch from OPF

Compression ratios from **dynamic** OGF

Pressure OK!

What is more valuable:

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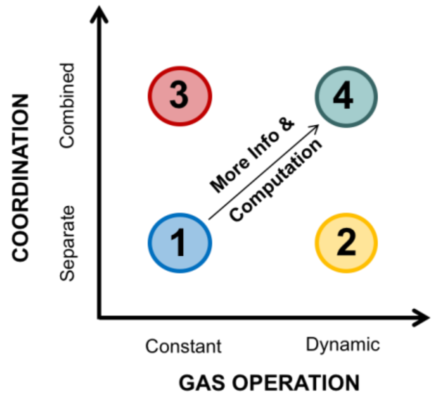
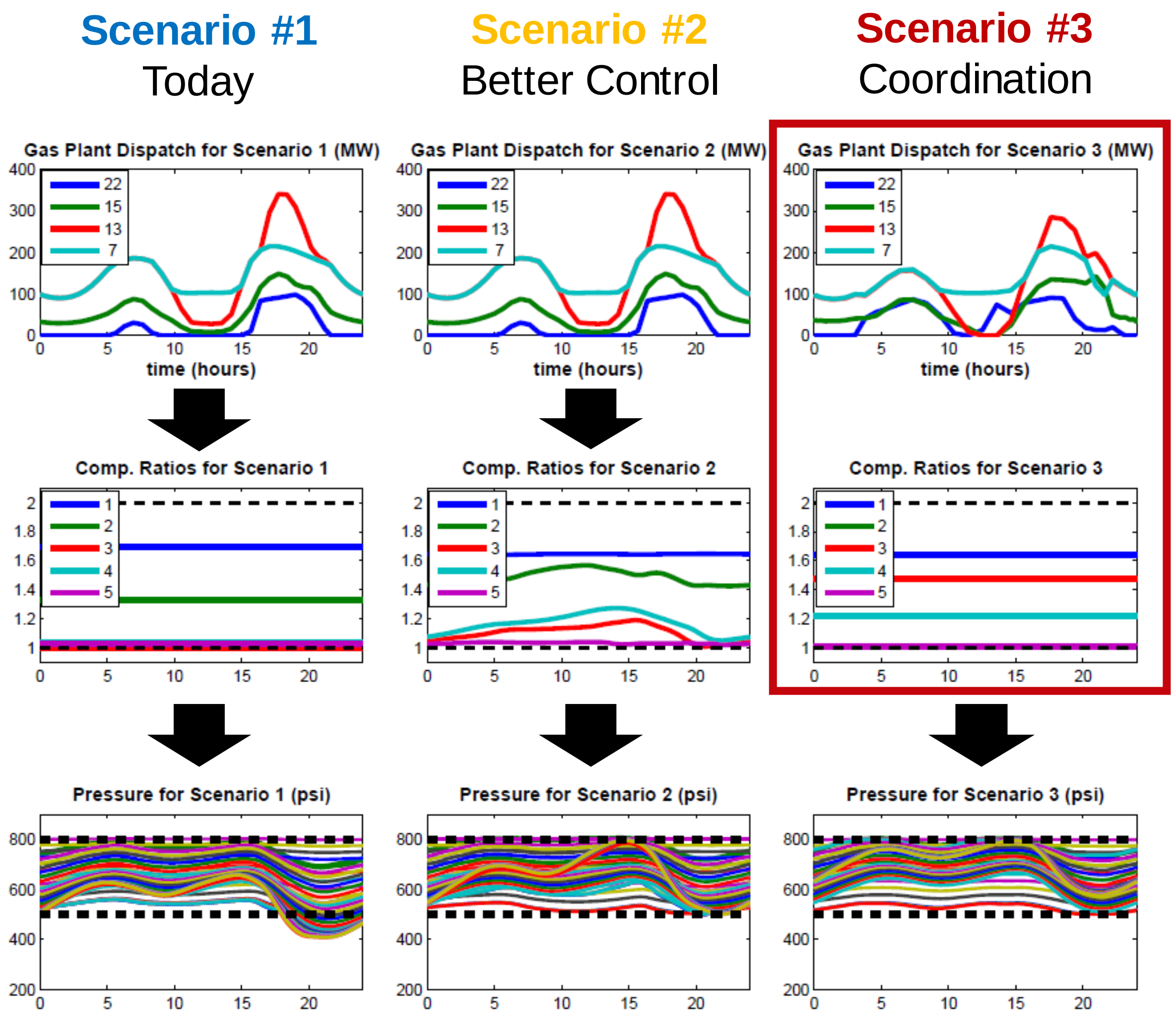




Generation dispatch and **constant** compression ratios from **combined** OGPF

Pressure OK, but **higher cost!**

What is more valuable:

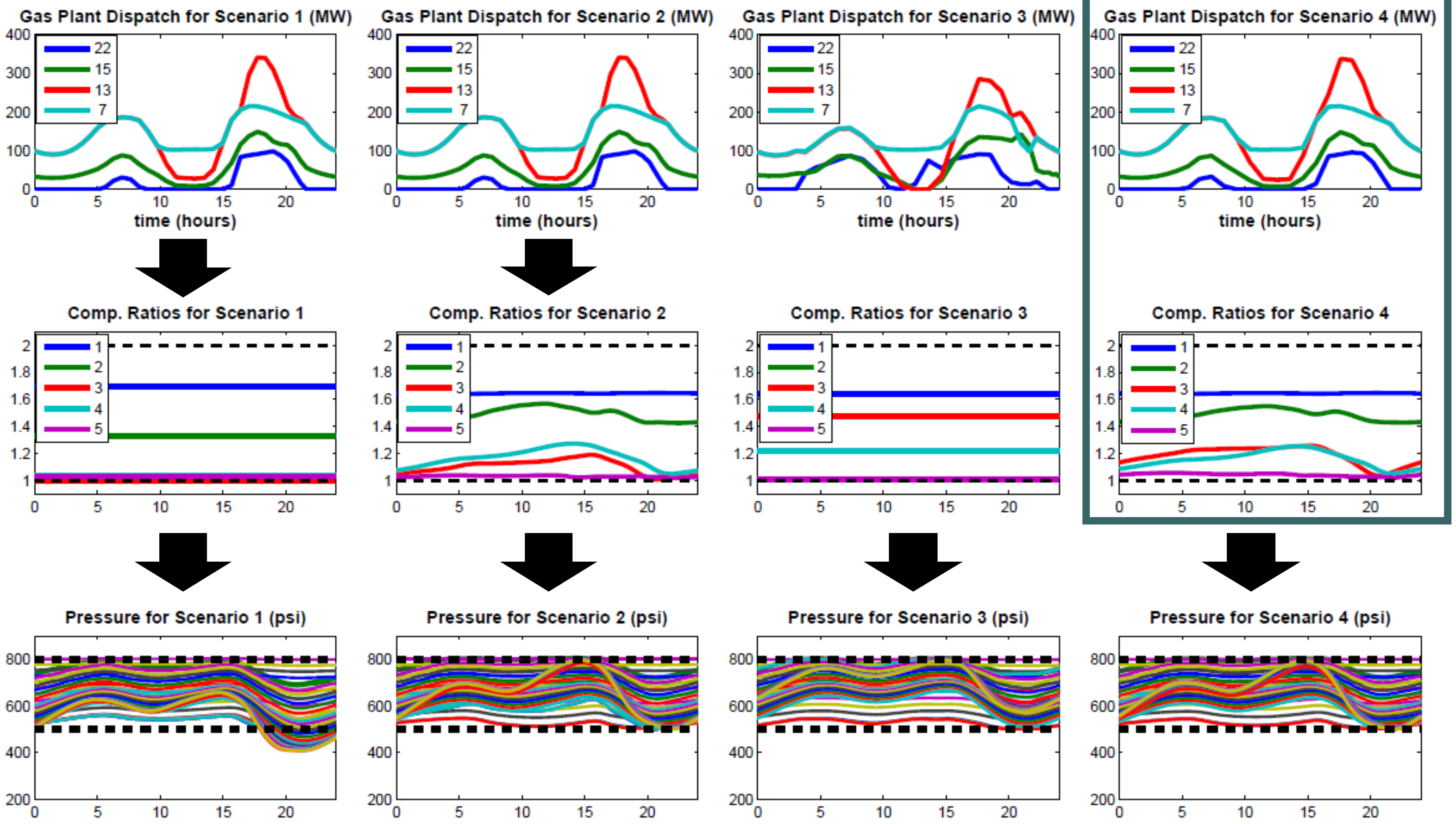
Better coordination or better control?

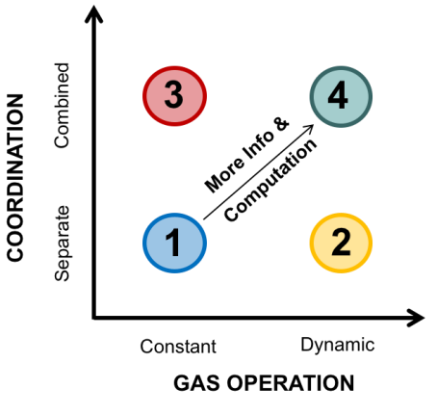
Scenario #1
Today

Scenario #2
Better Control

Scenario #3
Coordination

Scenario #4
Both!





Generation dispatch and **dynamic** compression ratios from **combined** OGPF

Same as Scenario #2!

What is more valuable:

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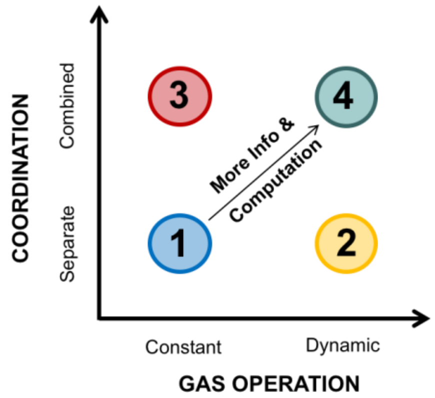

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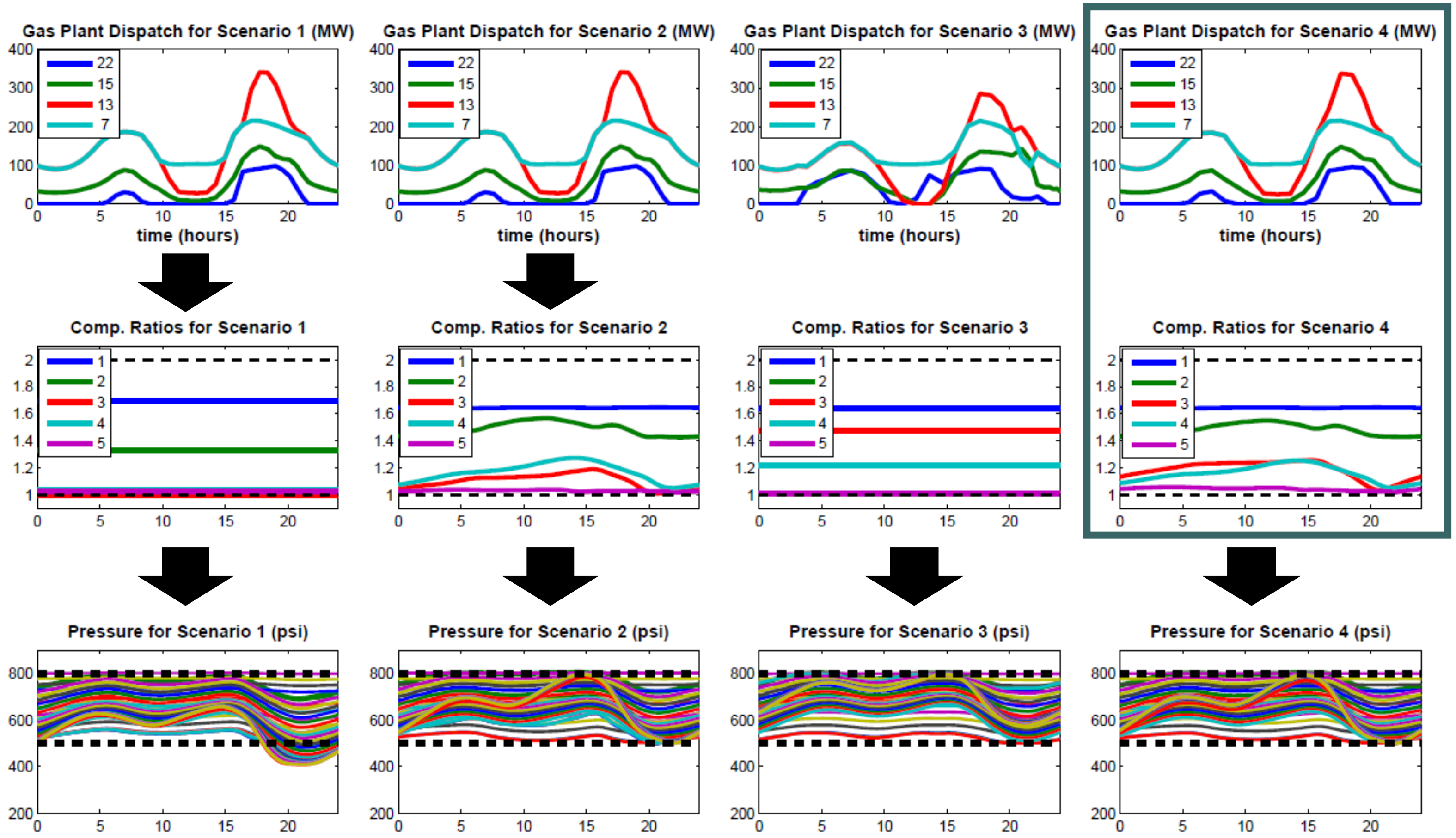

- Better control is more important
- Problem is separable with dynamic gas control

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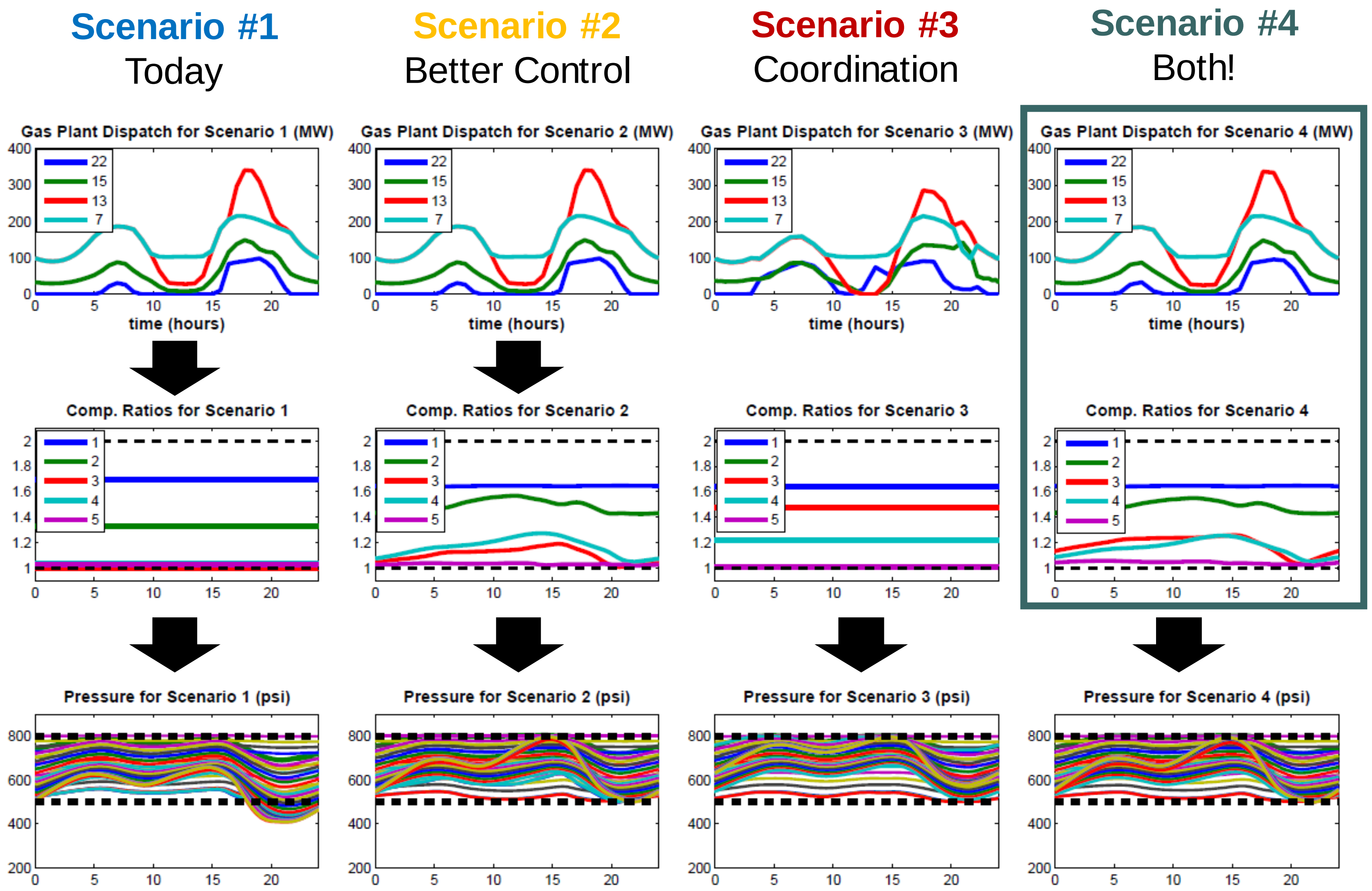

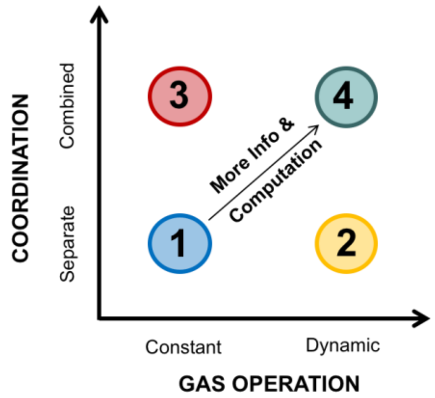

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Problem is separable with dynamic gas control

Higher loading?

What is more valuable:

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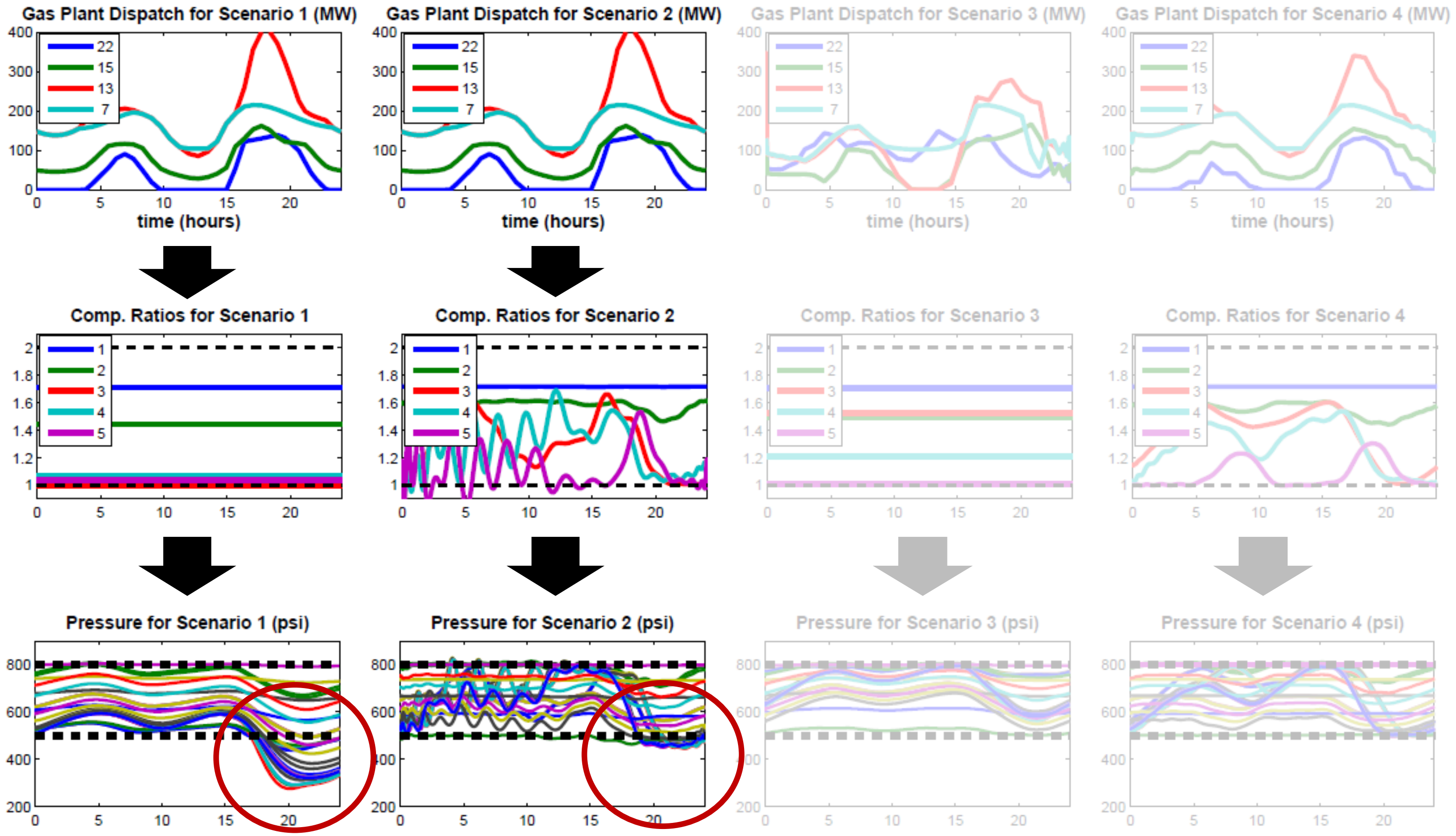
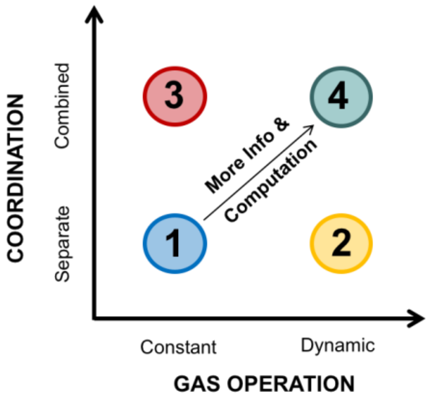
Scenario #1	Scenario #2	Scenario #3	Scenario #4
Today	Better Control	Coordination	Both!





Problem **infeasible** without coordination!

Much lower cost with dynamic compression

Higher loading!

What is more valuable:

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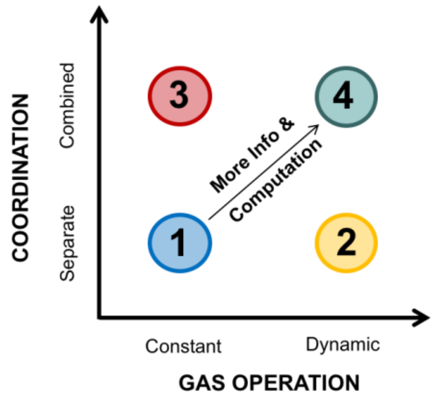

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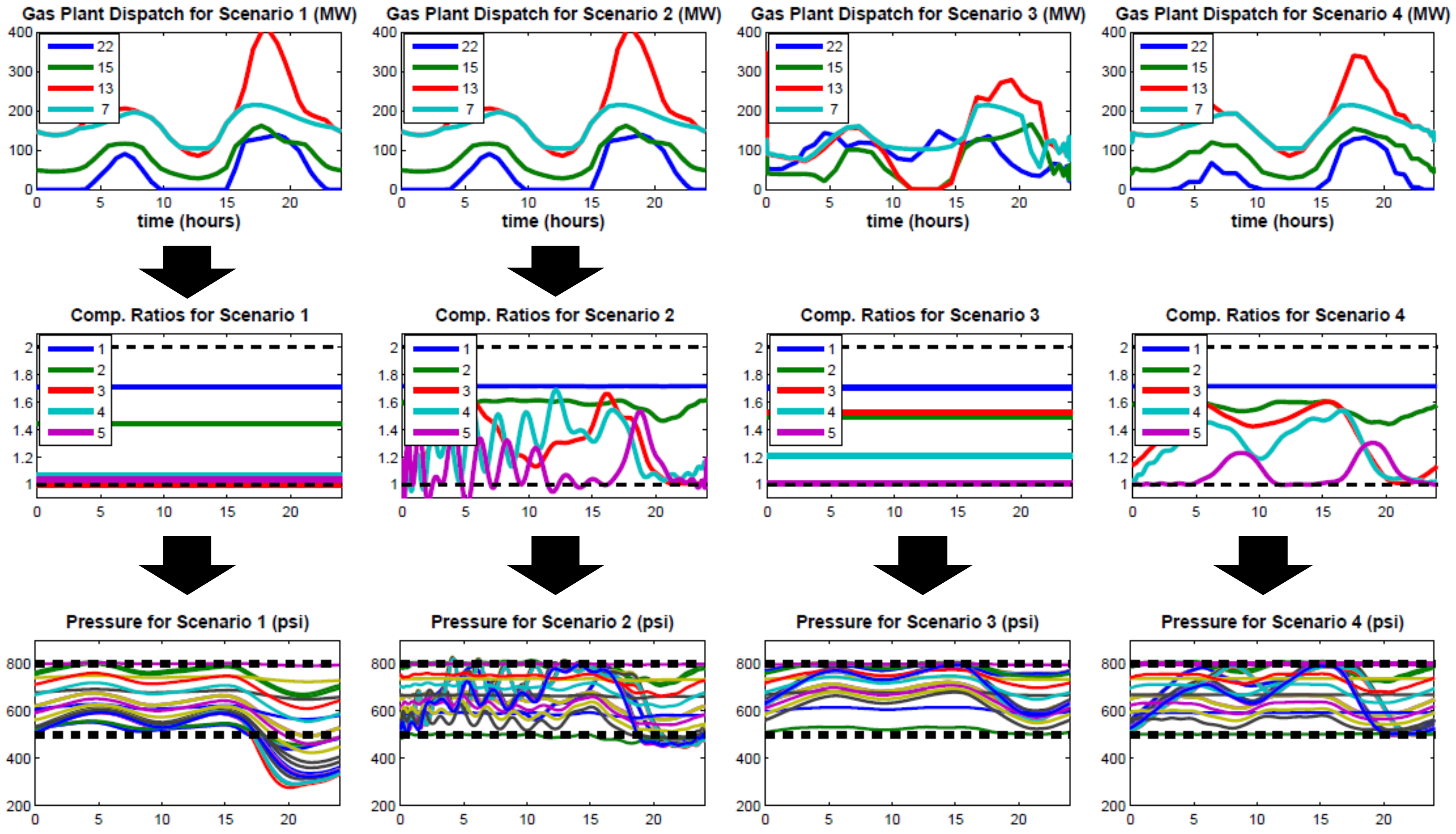

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Summary

- **Important to account for the gas system dynamics!**

- Operation of gas-electric infrastructures can be improved through
  - **Better control** which accounts for gas system dynamics
  - **Better coordination** with electric operators considering gas system constraints

- In **low-medium** load cases, better control is sufficient.

- In **high load cases**, improved coordination is also necessary.

Thank you!

roald@wisc.edu

Conor O Malley, Line Roald and Gabriela Hug, “Importance of Dynamic Modeling of Gas Networks for Energy System Reliability”, Grid Science Winter School, Santa Fe, 2017

Anatoly Zlotnik, Line Roald, Scott Backhaus, Michael Chertkov, Göran Andersson, “Coordinated Scheduling for Interdependent Electric Power and Natural Gas Infrastructures”, IEEE Transactions on Power Systems, 2017

Solving the Gas-Electric Problem

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System constraints: $s.t.$ all constraints (1)-(8)

Heat-rate curve coupling: $d_i(t) = q(p_i(t)) = q_0 + q_1 p_i(t) + q_2 p_i^2(t)$

Time discretization: Legendre-Gauss-Lobatto (LGL) pseudospectral collocation scheme

(Time steps automatically chosen to approximate problem well)

A-posteriori evaluation of pressures through simulation