



Gas-Electricity System Coupling

Line A. Roald
University of Wisconsin

ESIG Session – April 21, 2020



Anatoly
Zlotnik



Scott
Backhaus



Misha
Chertkov



Göran
Andersson



Conor
O'Malley



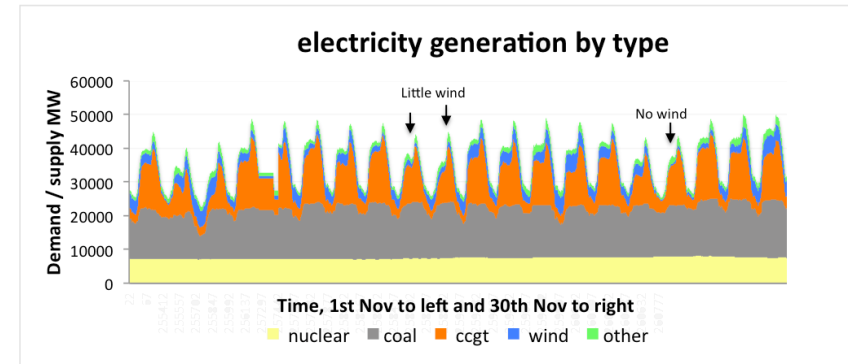
Gabriela
Hug



Increasing Gas-Electricity Interdependency

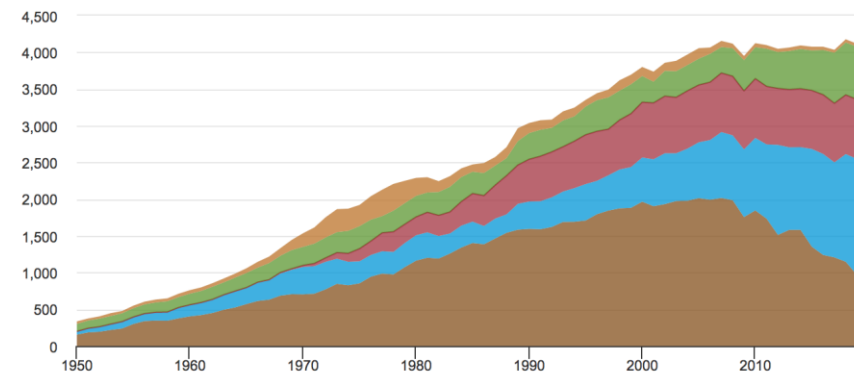
Gas-fired power generation is expanding:

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



Source: www.nationalgrid.com/uk

U.S. electricity generation by major energy source, 1950-2019

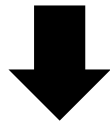


Source: U.S. Energy Information Administration

Increasing Gas-Electricity Interdependency

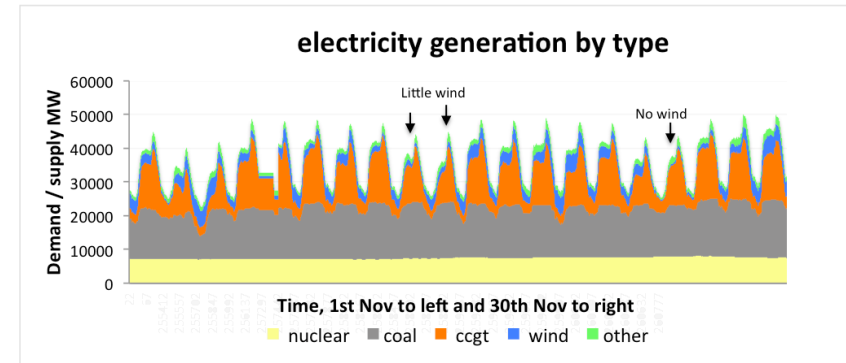
Gas-fired power generation is expanding:

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

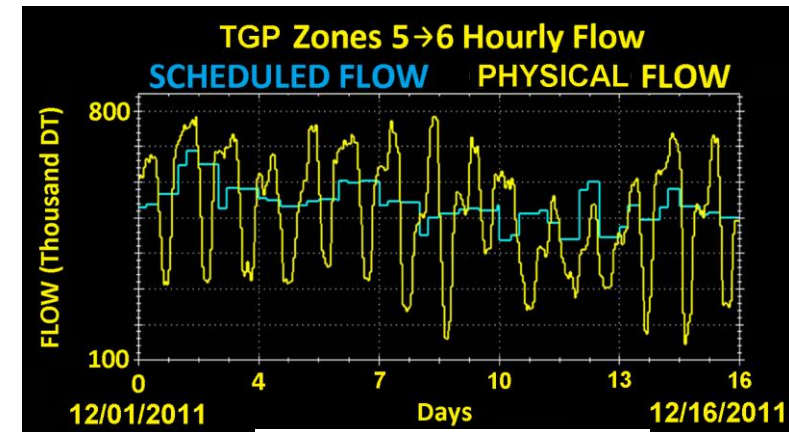


Gas pipeline loads are changing:

- Increasing in volume & variation
- More intermittent & uncertain



Source: www.nationalgrid.com/uk

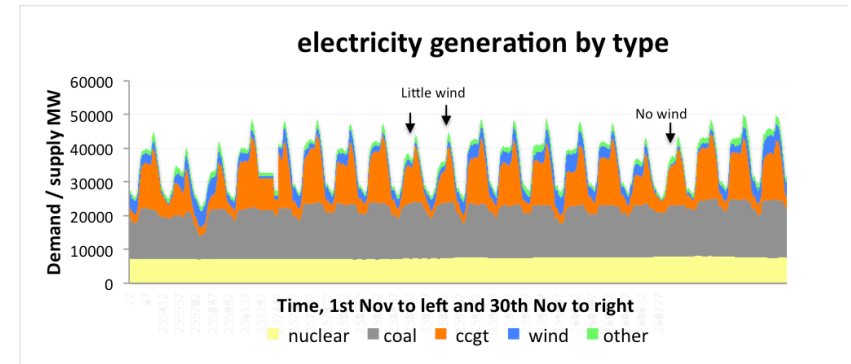


Source: El Paso Pipeline

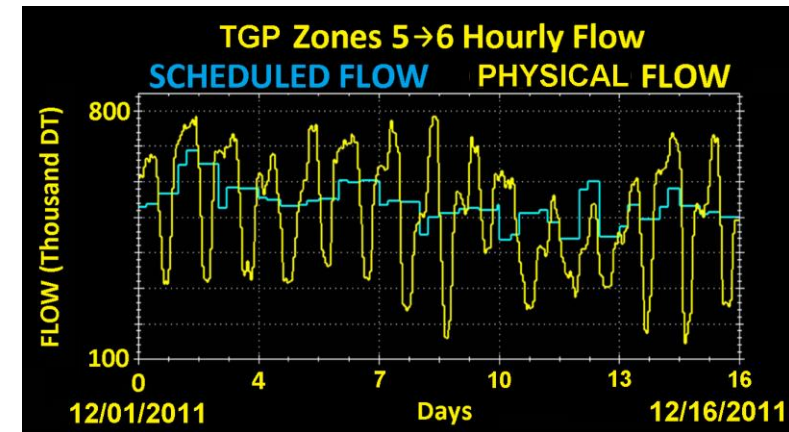
Reliable Supply to Gas-Fired Power Plants

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



Source: www.nationalgrid.com/uk



Source: El Paso Pipeline

Challenges: Gas-Electric Differences

POWER GRIDS

- **Real-time** balancing
- Storage is **costly**
- Electric reliability for **all customers**
- Power day is 12 a.m. to 12 a.m. (by region)
- Steady-state **in seconds**

GAS PIPELINES

- **Daily or monthly** balancing
- System has **internal storage** (linepack)
- Gas power plants can typically be **curtailed**
- Gas day is 10 a.m. to 10 a.m. EST
- Steady-state **in hours** (“never” achieved)

Challenges: Gas-Electric Differences

POWER GRIDS

- **Real-time** balancing
- Storage is **costly**
- Electric reliability for **all customers**
- Power day is 12 a.m. to 12 a.m. (by region)
- Steady-state **in seconds**

GAS PIPELINES

- **Daily or monthly** balancing
- System has **internal storage** (linepack)
- Gas power plants can typically be **curtailed**
- Gas day is 10 a.m. to 10 a.m. EST
- Steady-state **in hours** (“never” achieved)

Steady-state vs dynamic gas modelling?

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

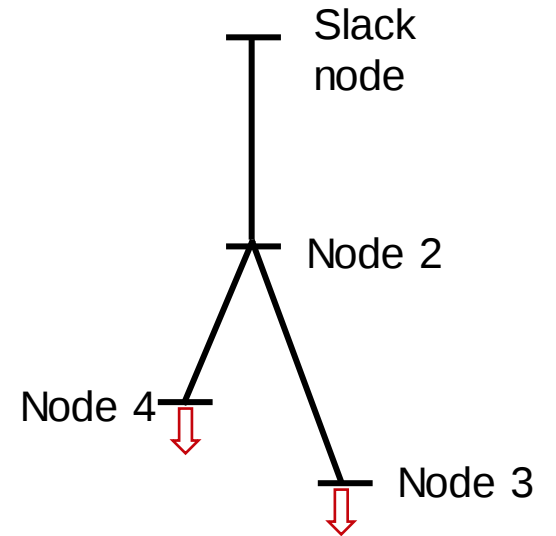
Steady-state vs dynamic gas modelling

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



Start from steady state
then swap the loads

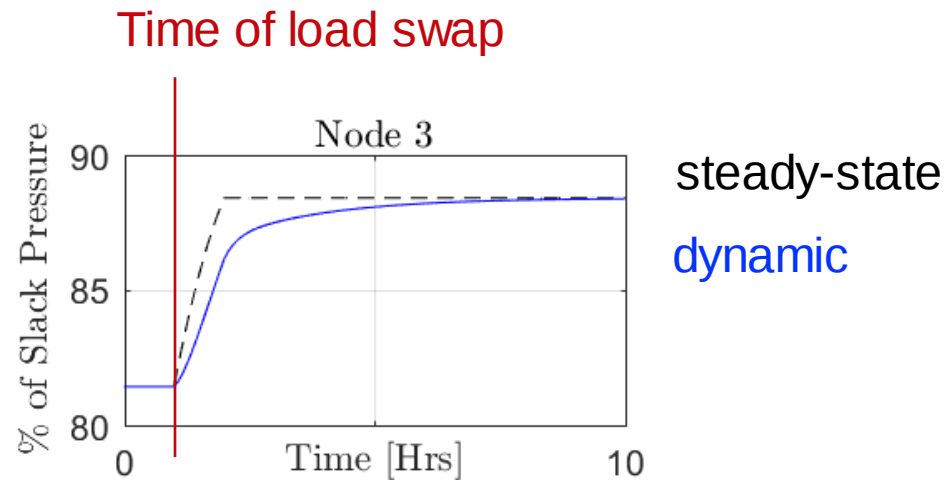
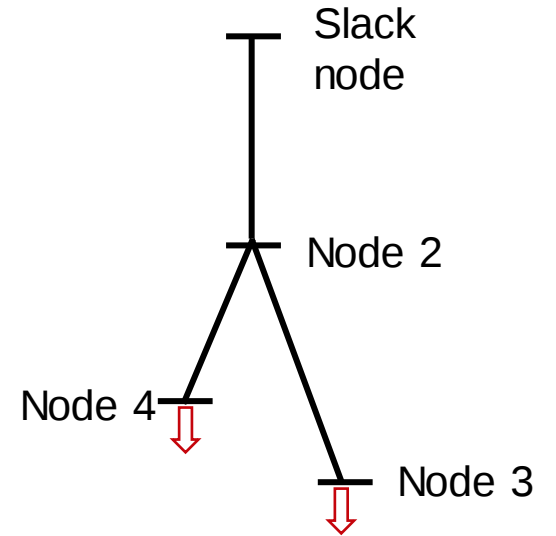
Steady-state vs dynamic gas modelling

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



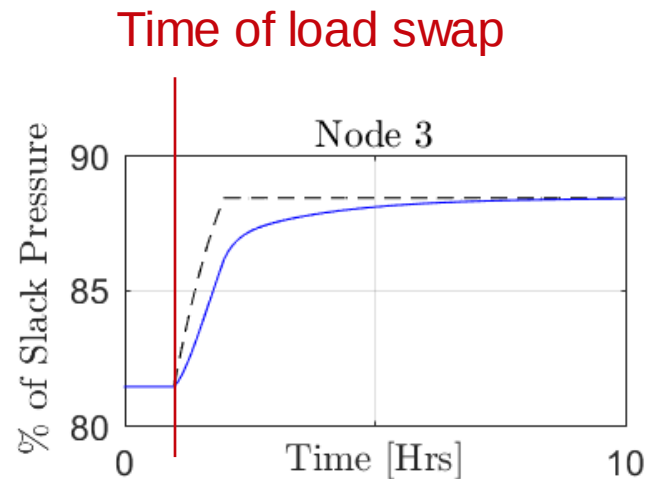
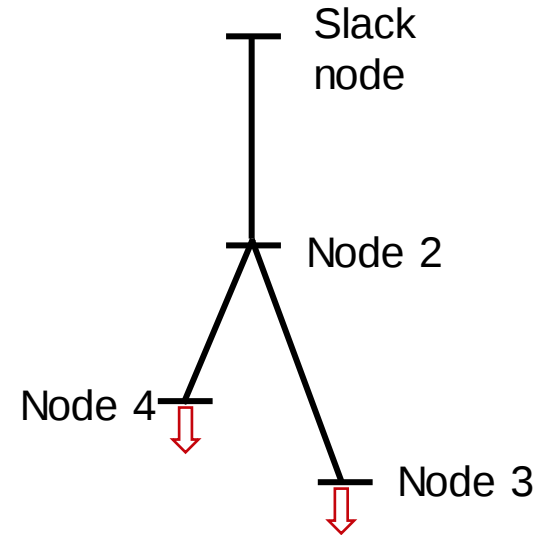
Steady-state vs dynamic gas modelling

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
dynamic

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

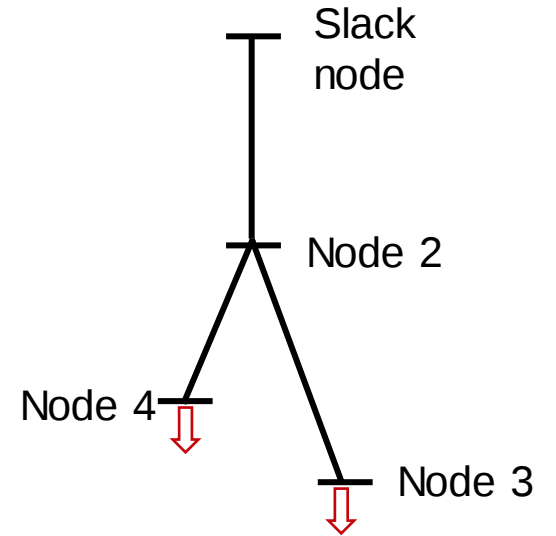
Steady-state vs dynamic gas modelling

Steady-state gas system modelling: -----

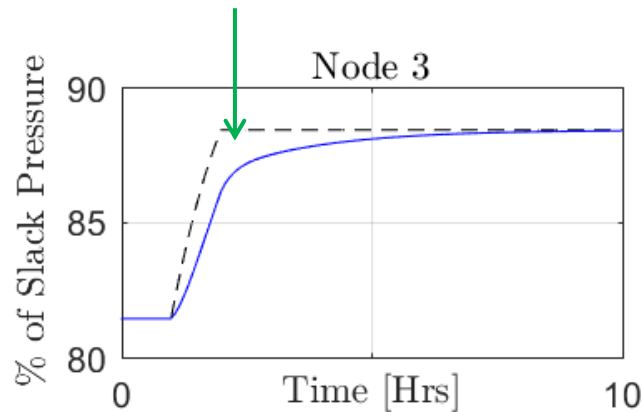
Assume that system dynamics have time to settle down

Dynamic gas system modelling: _____

Accounting for the effect of changing conditions



Steady-state conservative:
Underutilized pressure bound



steady-state
dynamic

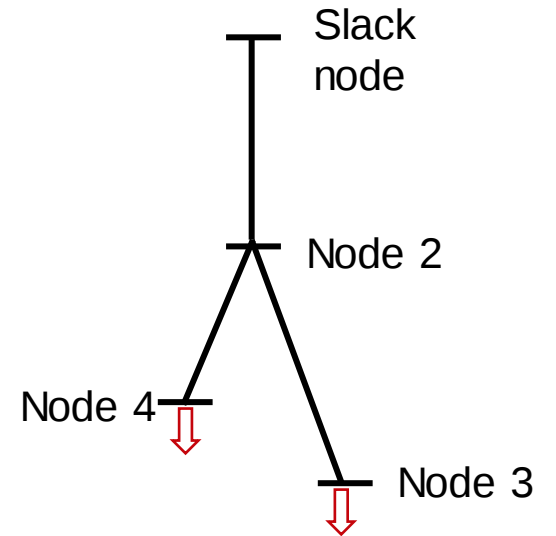
Steady-state vs dynamic gas modelling

Steady-state gas system modelling: -----

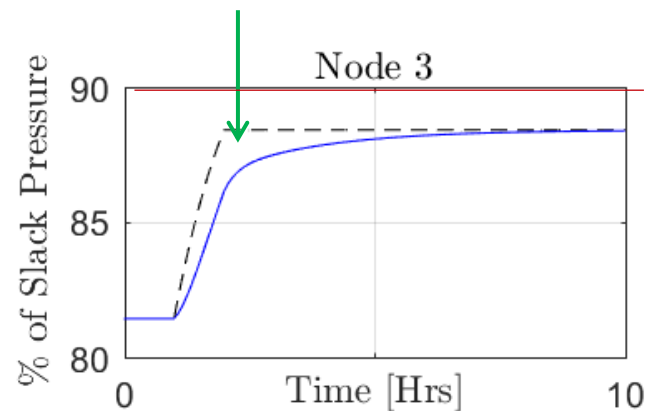
Assume that system dynamics have time to settle down

Dynamic gas system modelling: _____

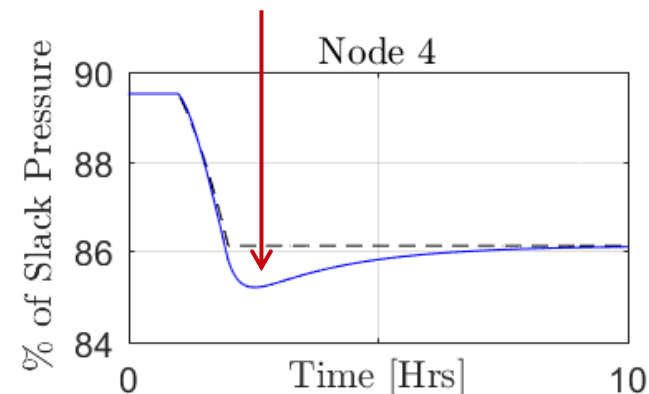
Accounting for the effect of changing conditions



Steady-state conservative:
Underutilized pressure bound



Steady-state dangerous:
Pressure drop larger than expected



Challenges: Gas-Electric Differences

POWER GRIDS

- **Real-time** balancing
- Storage is **costly**
- Electric reliability for **all customers**
- Power day is 12 a.m. to 12 a.m. (by region)
- Steady-state **in seconds**

GAS PIPELINES

- **Daily or monthly** balancing
- System has **internal storage** (linepack)
- Gas power plants can typically be **curtailed**
- Gas day is 10 a.m. to 10 a.m. EST
- Steady-state **in hours** (“never” achieved)

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]

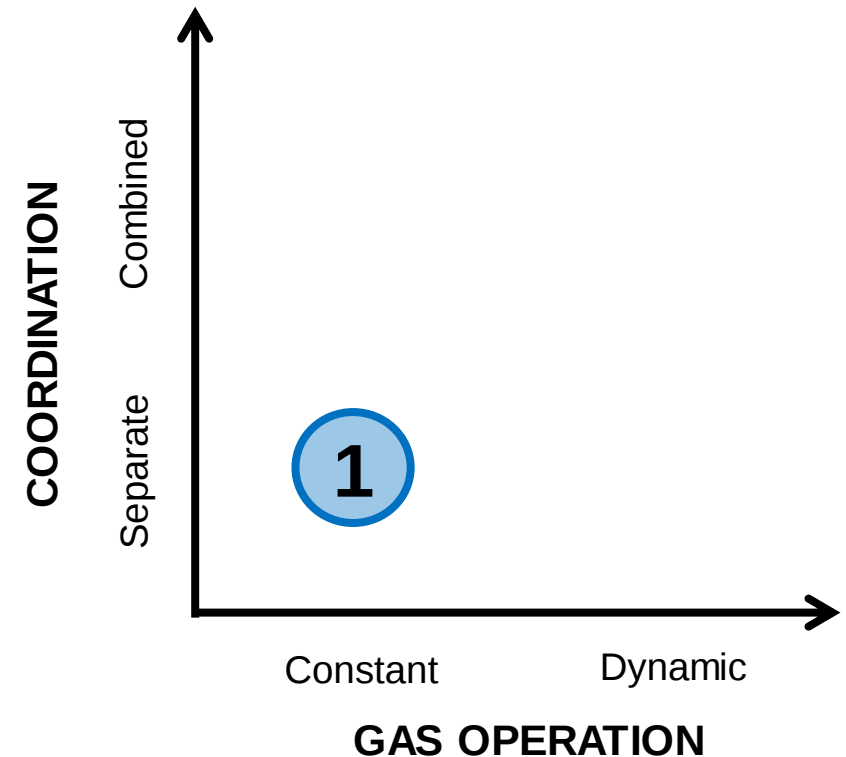
Value of Coordination and Control

Considered Operational Scenarios

Scenario #1 – Operation Today

Coordination: **Separate**

Operation: **Constant** compression ratios (steady state)



Value of Coordination and Control

Considered Operational Scenarios

Scenario #1 – Operation Today

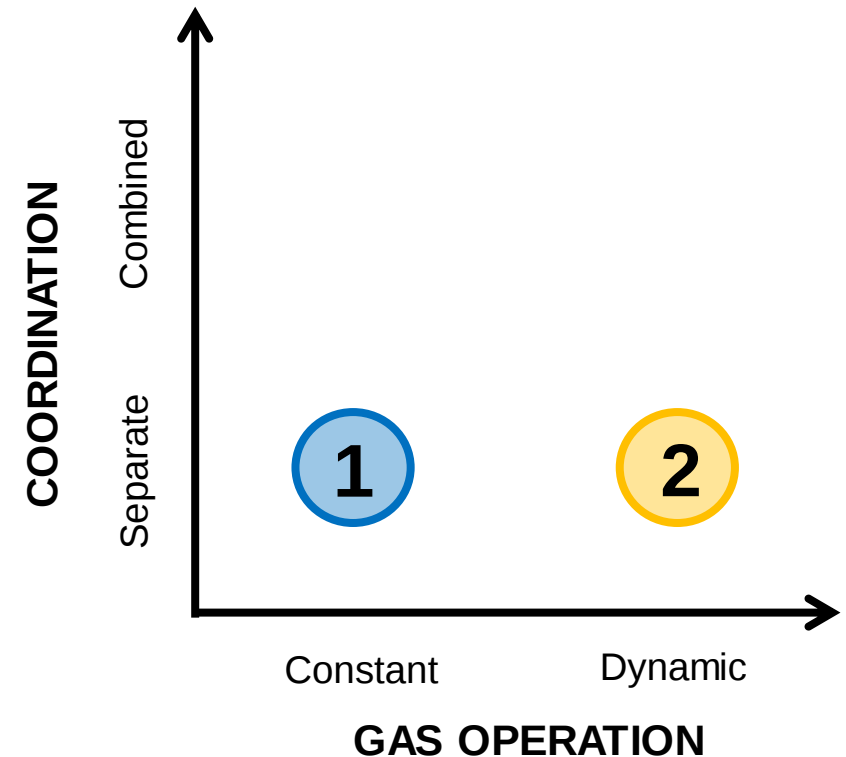
Coordination: **Separate**

Operation: **Constant** compression ratios (steady state)

Scenario #2 – Improved Gas Operation

Coordination: **Separate**

Operation: **Dynamic** compression



Value of Coordination and Control

Considered Operational Scenarios

Scenario #1 – Operation Today

Coordination: **Separate**

Operation: **Constant** compression ratios (steady state)

Scenario #2 – Improved Gas Operation

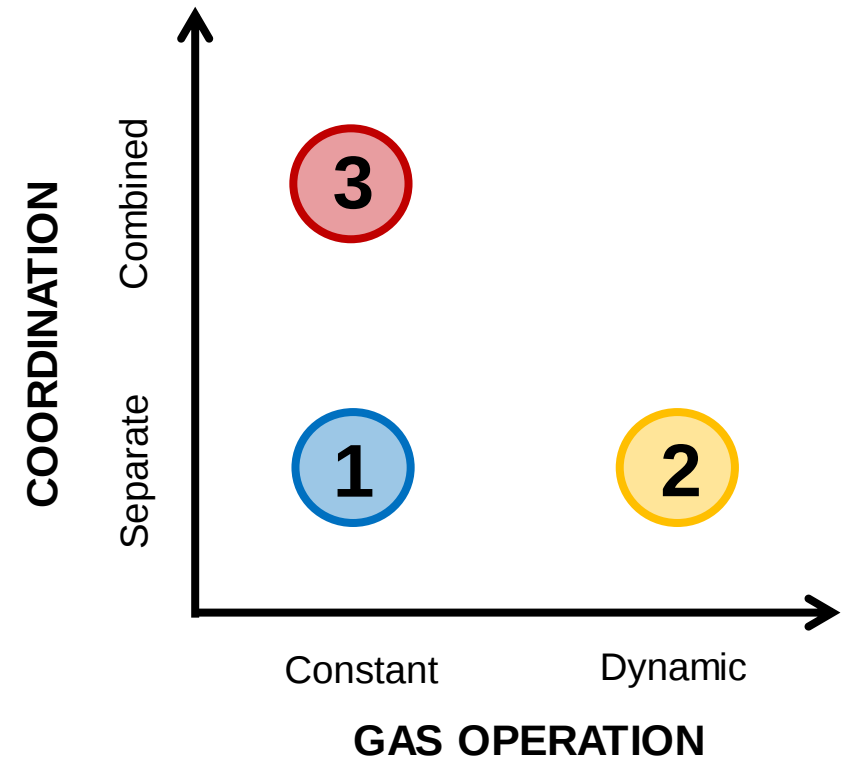
Coordination: **Separate**

Operation: **Dynamic** compression

Scenario #3 – Coordinated Operation

Coordination: **Combined**

Operation: **Constant** compression



Value of Coordination and Control

Considered Operational Scenarios

Scenario #1 – Operation Today

Coordination: **Separate**

Operation: **Constant** compression ratios (steady state)

Scenario #2 – Improved Gas Operation

Coordination: **Separate**

Operation: **Dynamic** compression

Scenario #3 – Coordinated Operation

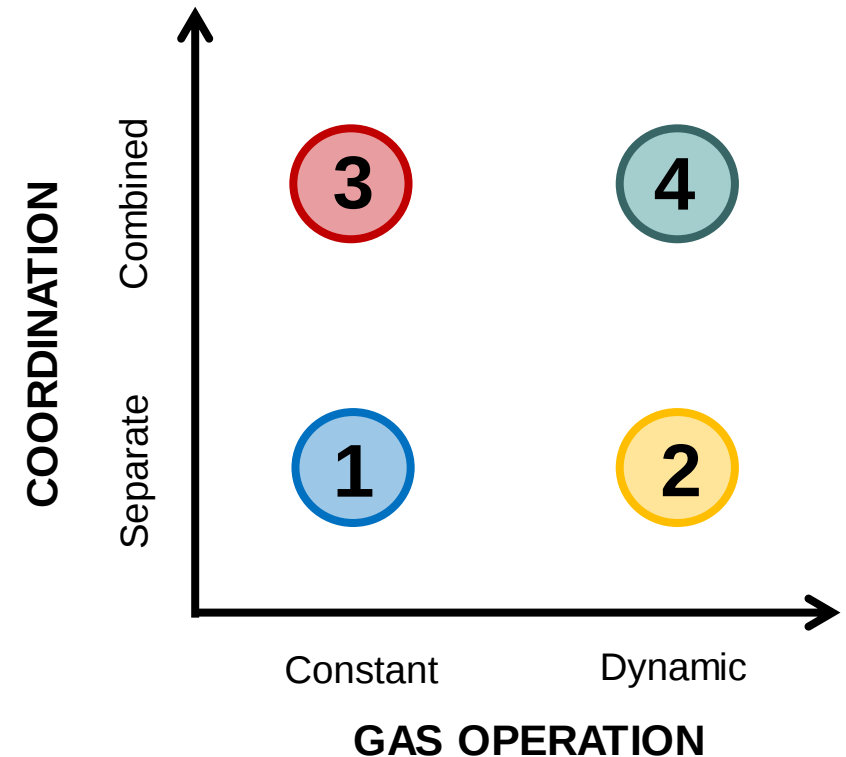
Coordination: **Combined**

Operation: **Constant** compression

Scenario #4 – Coordination and Improved Gas

Coordination: **Combined**

Operation: **Dynamic** compression



Value of Coordination and Control

Considered Operational Scenarios

Scenario #1 – Operation Today

Coordination: **Separate**

Operation: **Constant** compression ratios (steady state)

Scenario #2 – Improved Gas Operation

Coordination: **Separate**

Operation: **Dynamic** compression

Scenario #3 – Coordinated Operation

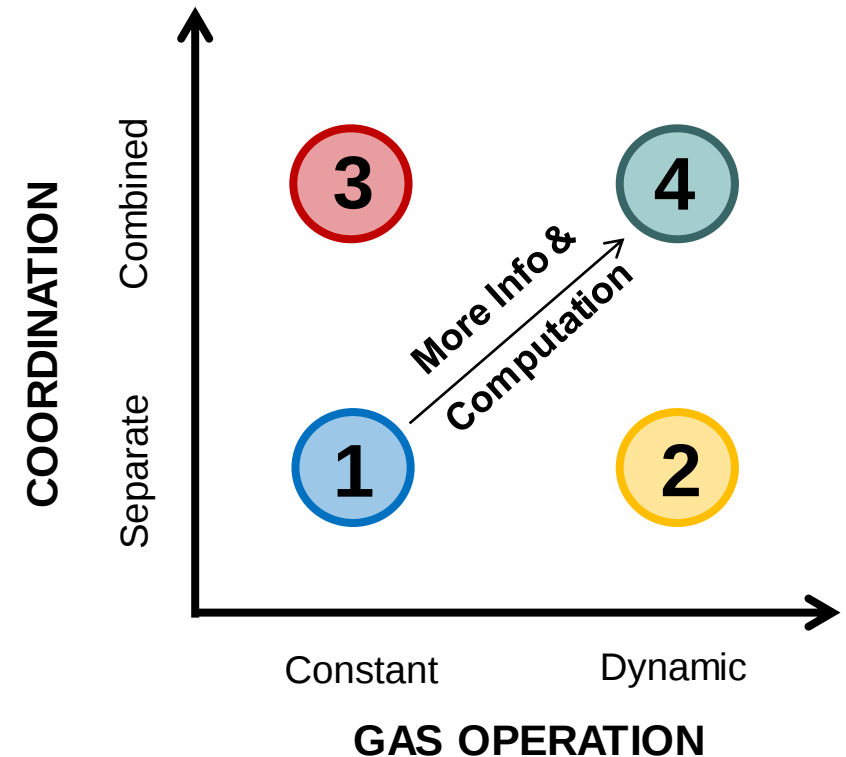
Coordination: **Combined**

Operation: **Constant** compression

Scenario #4 – Coordination and Improved Gas

Coordination: **Combined**

Operation: **Dynamic** compression



Solving the Gas-Electric Problem

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

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): $-f_{ij}^{\max} \leq M_{(ij, \cdot)}(p(t) - h(t)) \leq f_{ij}^{\max}$
 $\forall \{ij\} \in \mathcal{E}, \quad \forall t \in [0, T]$

DC Optimal Power Flow

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

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

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): $\rho(0) = \rho(T), \quad \varphi(0) = \varphi(T), \quad \alpha_{ij}(0) = \alpha_{ij}(T), \quad \forall \{i, j\} \in \mathcal{C}$

Dynamic Optimal Gas Flow

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

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

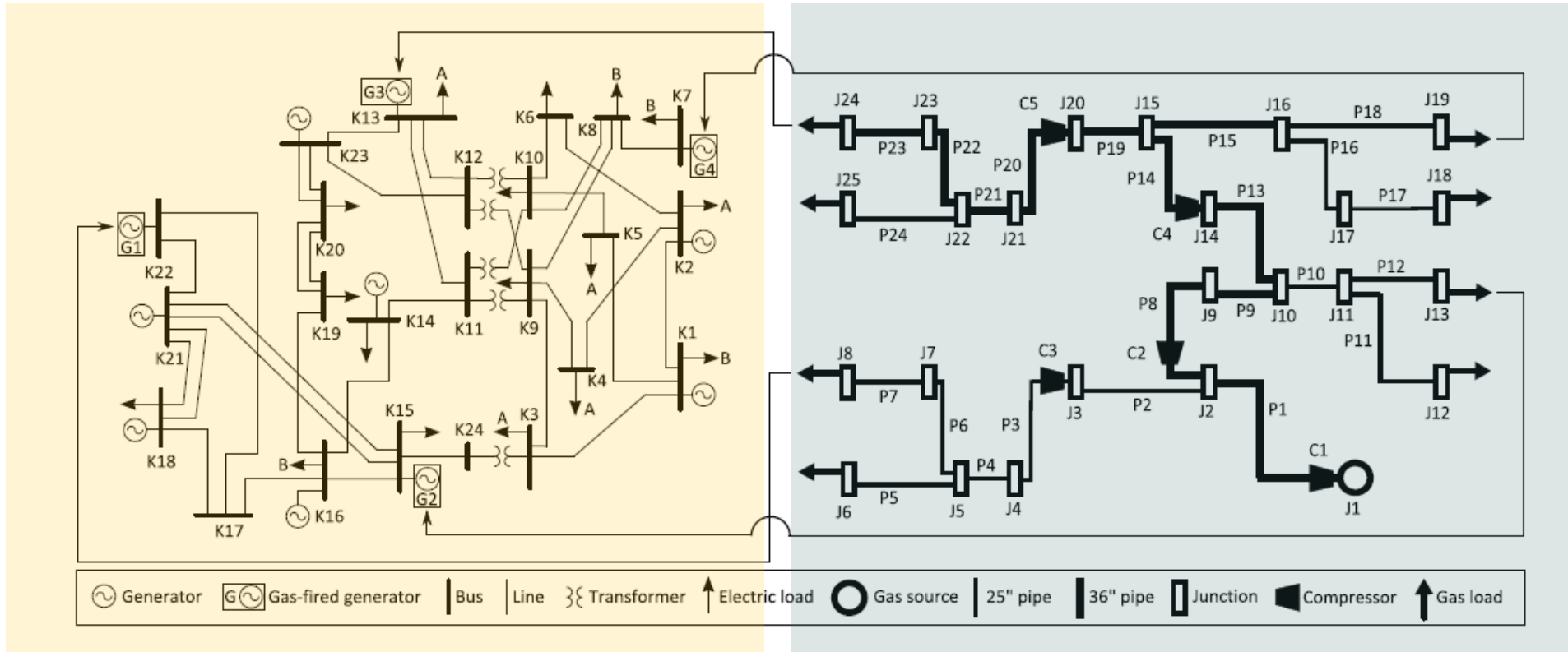
System constraints: $s.t.$ all constraints (1)-(8)

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

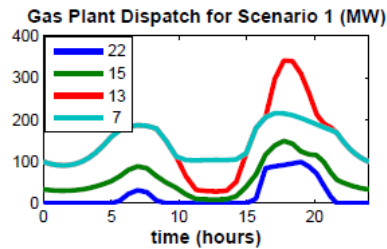
GAS SYSTEM

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

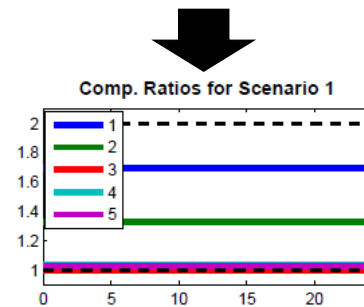
What is more valuable: Better coordination or better control?

Scenario #1

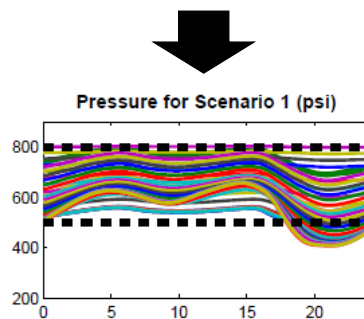
Today



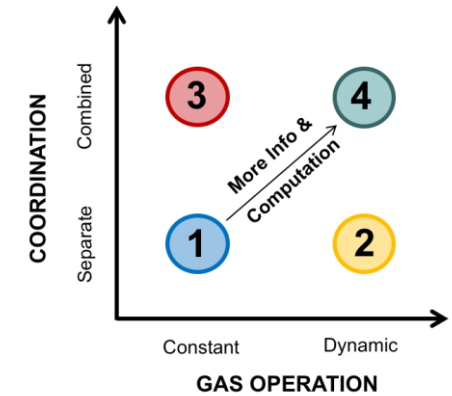
Generation dispatch from OPF



Compression ratios from
steady-state OGF

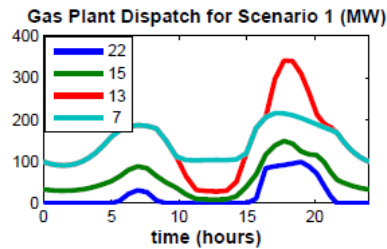


Pressure violations!

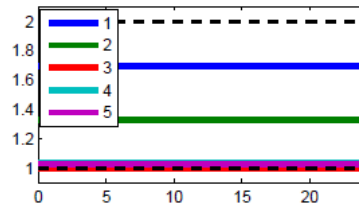


What is more valuable: Better coordination or better control?

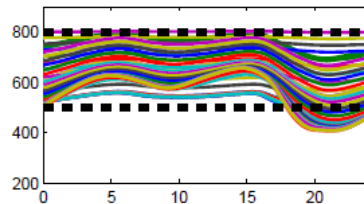
Scenario #1
Today



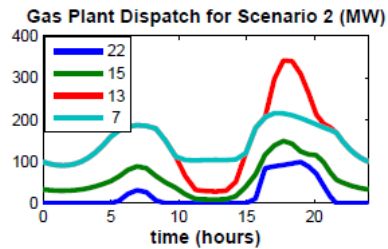
Comp. Ratios for Scenario 1



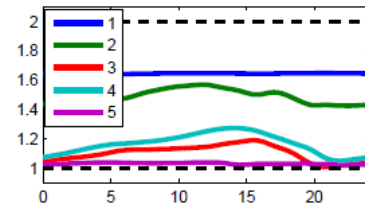
Pressure for Scenario 1 (psi)



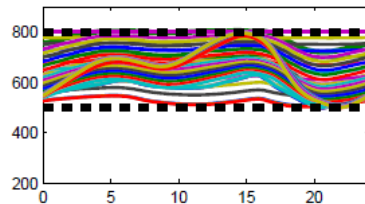
Scenario #2
Better Control



Comp. Ratios for Scenario 2



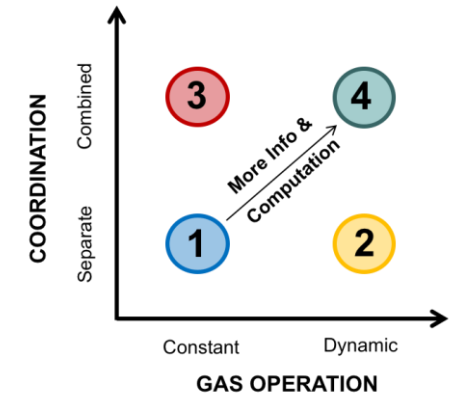
Pressure for Scenario 2 (psi)



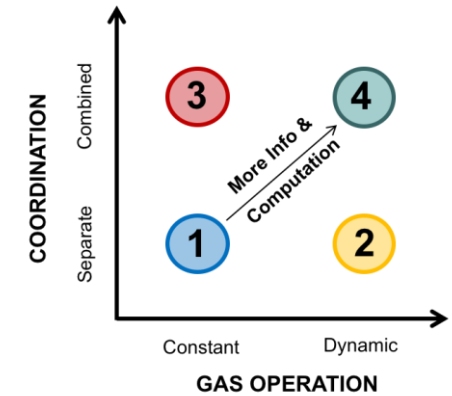
Generation dispatch from OPF

Compression ratios from
dynamic OGF

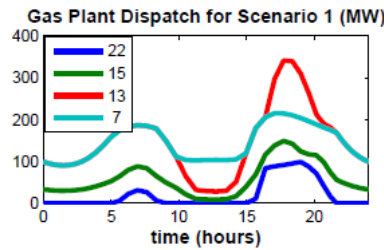
Pressure OK!



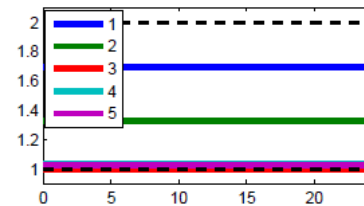
What is more valuable: Better coordination or better control?



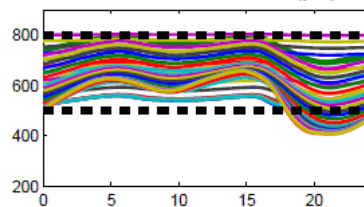
Scenario #1
Today



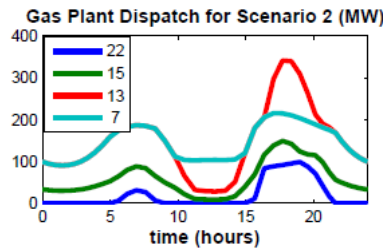
Comp. Ratios for Scenario 1



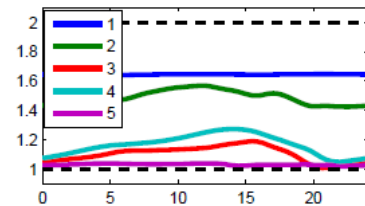
Pressure for Scenario 1 (psi)



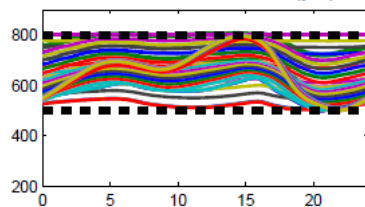
Scenario #2
Better Control



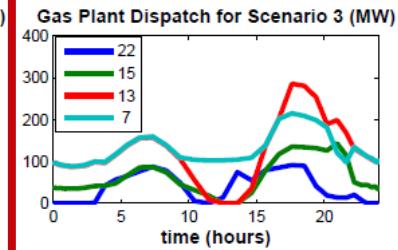
Comp. Ratios for Scenario 2



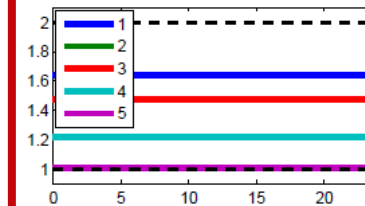
Pressure for Scenario 2 (psi)



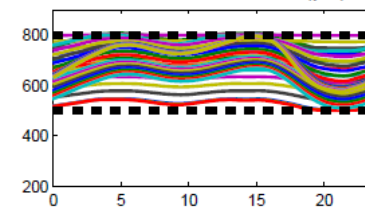
Scenario #3
Coordination



Comp. Ratios for Scenario 3



Pressure for Scenario 3 (psi)

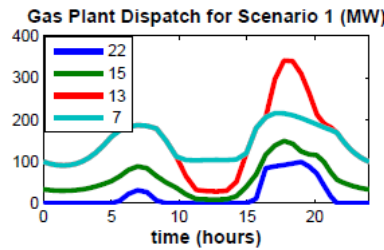


Generation dispatch and
constant compression ratios
from **combined** OGPF

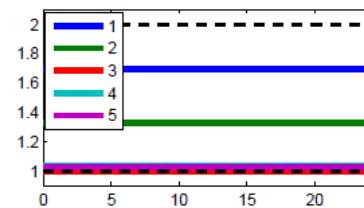
Pressure OK, but
higher cost!

What is more valuable: Better coordination or better control?

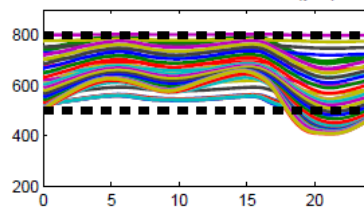
Scenario #1
Today



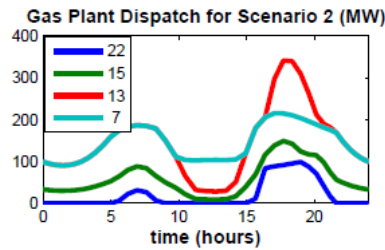
Comp. Ratios for Scenario 1



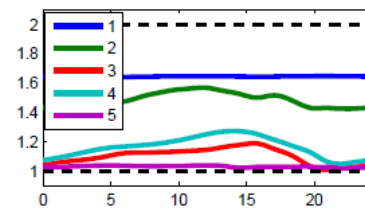
Pressure for Scenario 1 (psi)



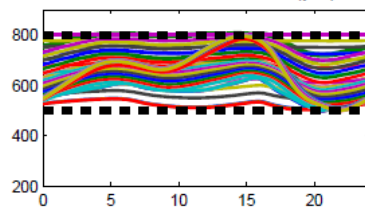
Scenario #2
Better Control



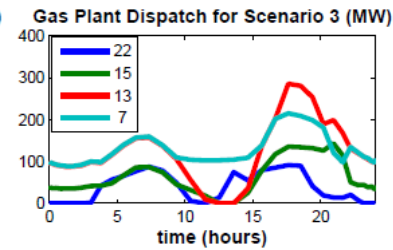
Comp. Ratios for Scenario 2



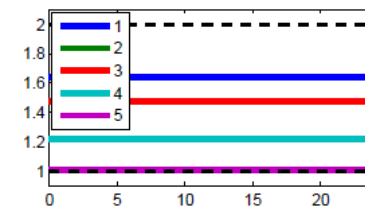
Pressure for Scenario 2 (psi)



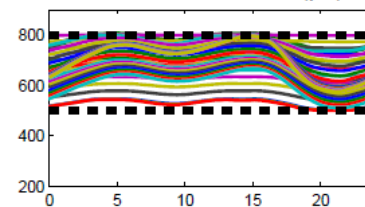
Scenario #3
Coordination



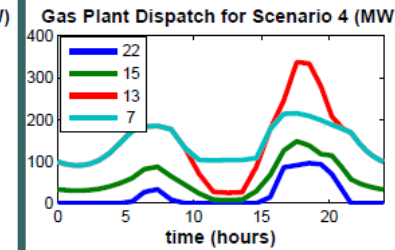
Comp. Ratios for Scenario 3



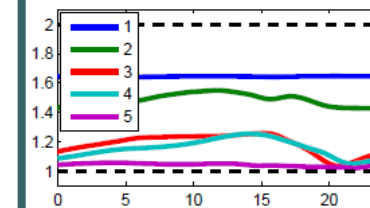
Pressure for Scenario 3 (psi)



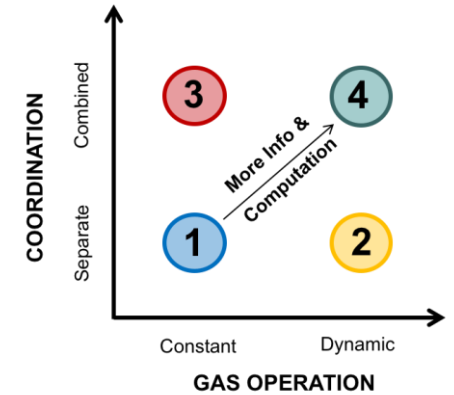
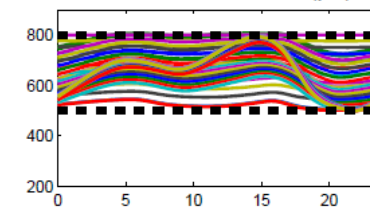
Scenario #4
Both!



Comp. Ratios for Scenario 4



Pressure for Scenario 4 (psi)

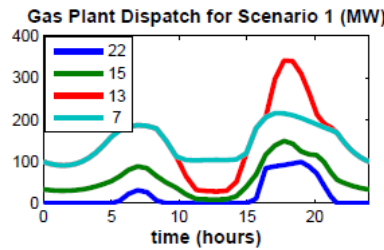


Generation dispatch and **dynamic** compression ratios from **combined** OGPf

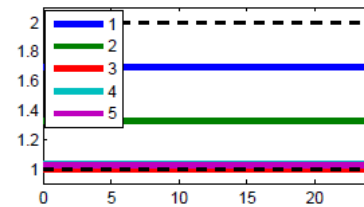
Same as Scenario #2!

What is more valuable: Better coordination or better control?

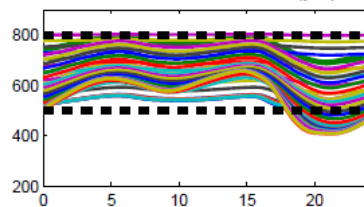
Scenario #1
Today



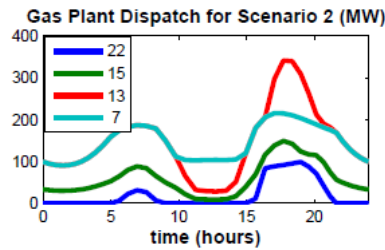
Comp. Ratios for Scenario 1



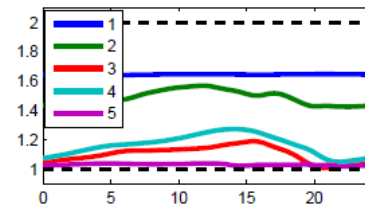
Pressure for Scenario 1 (psi)



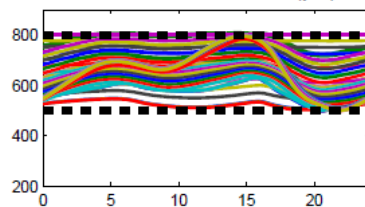
Scenario #2
Better Control



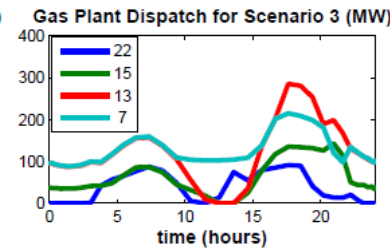
Comp. Ratios for Scenario 2



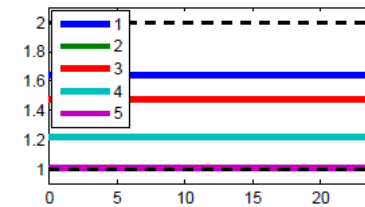
Pressure for Scenario 2 (psi)



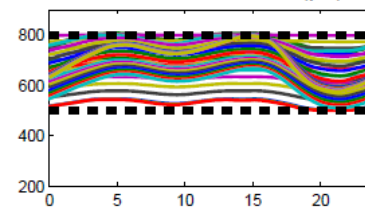
Scenario #3
Coordination



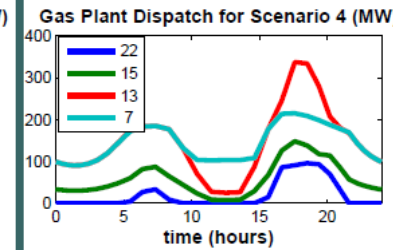
Comp. Ratios for Scenario 3



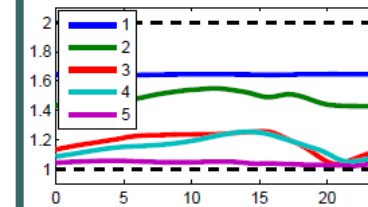
Pressure for Scenario 3 (psi)



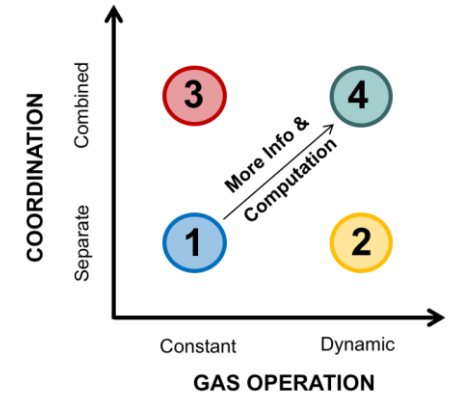
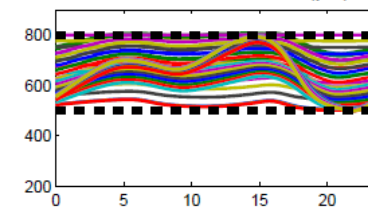
Scenario #4
Both!



Comp. Ratios for Scenario 4



Pressure for Scenario 4 (psi)

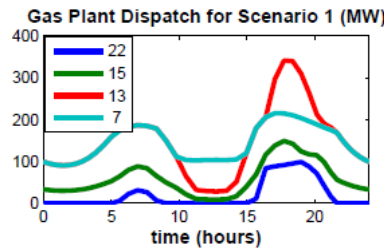


➡ Better control is more important

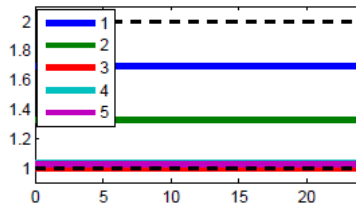
➡ Problem is separable with dynamic gas control

What is more valuable: Better coordination or better control?

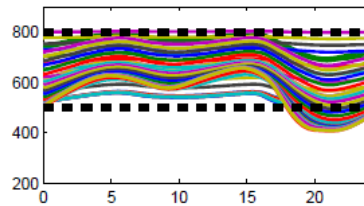
Scenario #1
Today



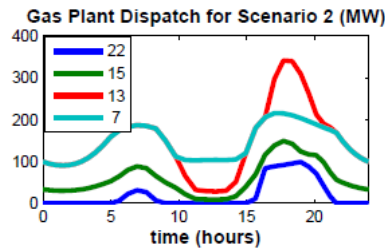
Comp. Ratios for Scenario 1



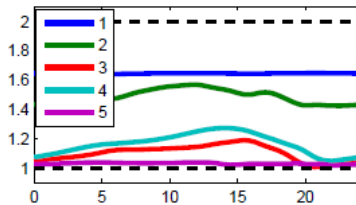
Pressure for Scenario 1 (psi)



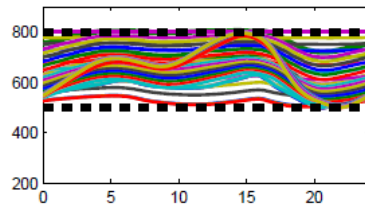
Scenario #2
Better Control



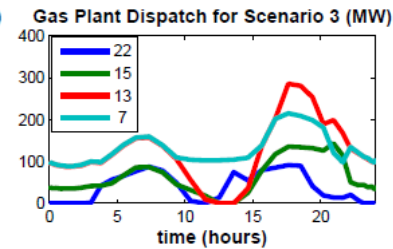
Comp. Ratios for Scenario 2



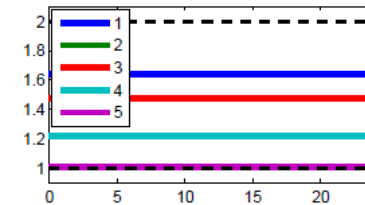
Pressure for Scenario 2 (psi)



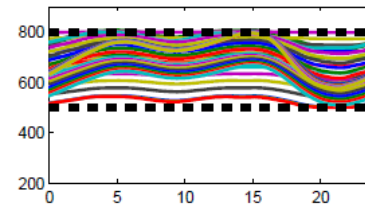
Scenario #3
Coordination



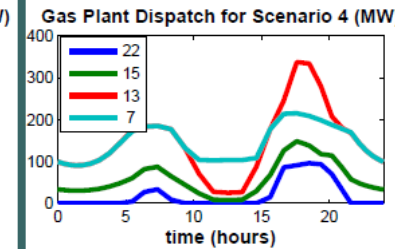
Comp. Ratios for Scenario 3



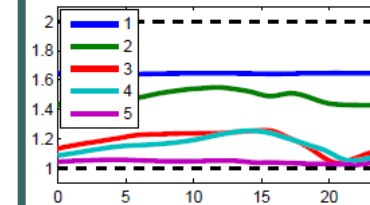
Pressure for Scenario 3 (psi)



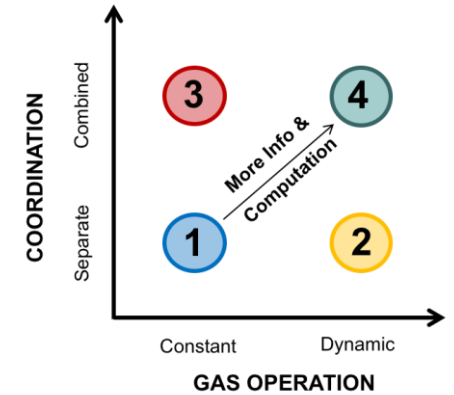
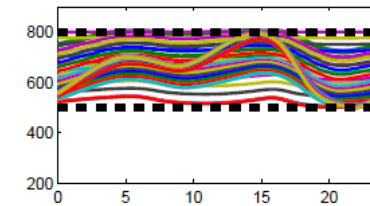
Scenario #4
Both!



Comp. Ratios for Scenario 4



Pressure for Scenario 4 (psi)



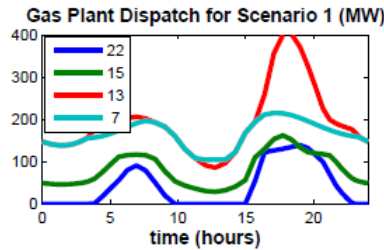
➡ Better control is more important

➡ Problem is separable with dynamic gas control

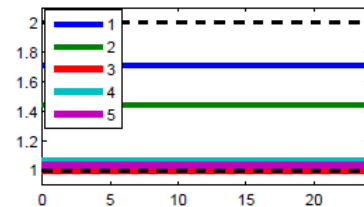
Higher loading?

What is more valuable: Better coordination or better control?

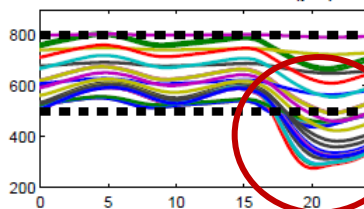
Scenario #1
Today



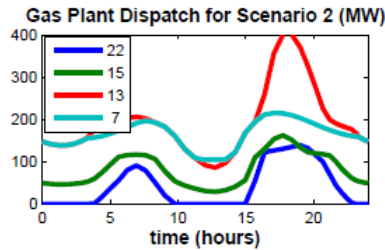
Comp. Ratios for Scenario 1



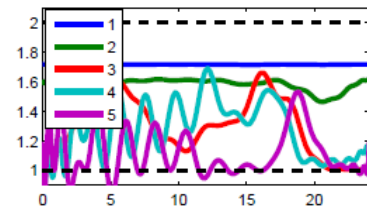
Pressure for Scenario 1 (psi)



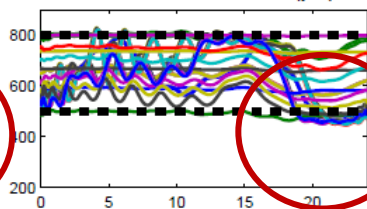
Scenario #2
Better Control



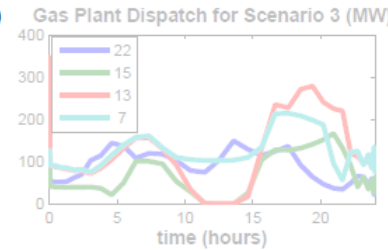
Comp. Ratios for Scenario 2



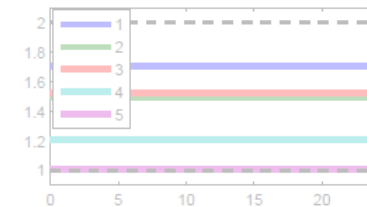
Pressure for Scenario 2 (psi)



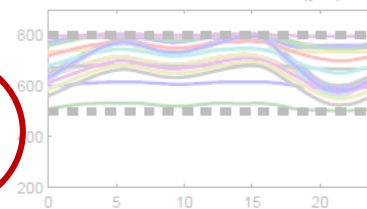
Scenario #3
Coordination



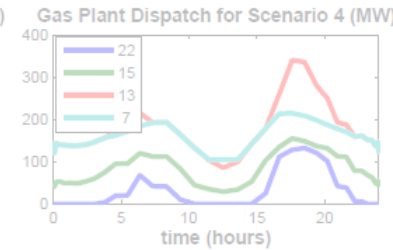
Comp. Ratios for Scenario 3



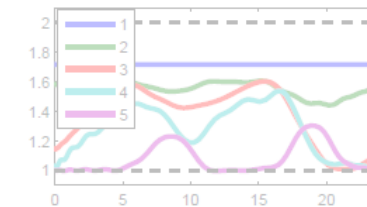
Pressure for Scenario 3 (psi)



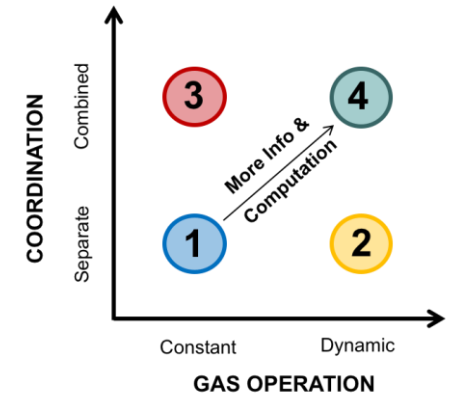
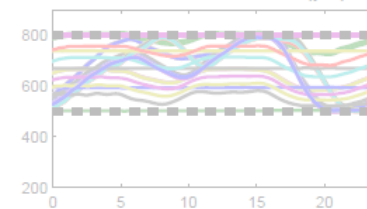
Scenario #4
Both!



Comp. Ratios for Scenario 4



Pressure for Scenario 4 (psi)



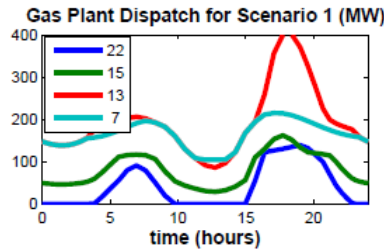
Problem **infeasible** without coordination!

Much lower cost with dynamic compression

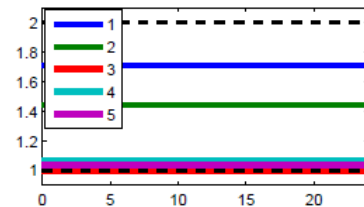
Higher loading!

What is more valuable: Better coordination or better control?

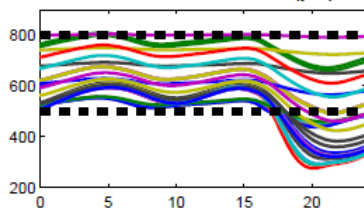
Scenario #1
Today



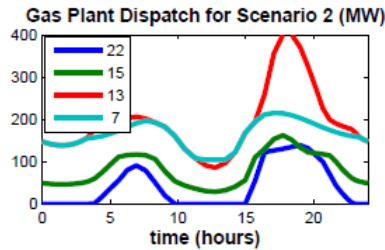
Comp. Ratios for Scenario 1



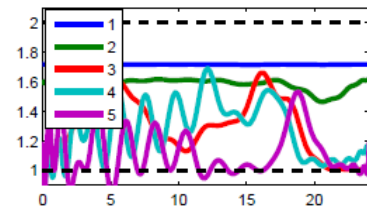
Pressure for Scenario 1 (psi)



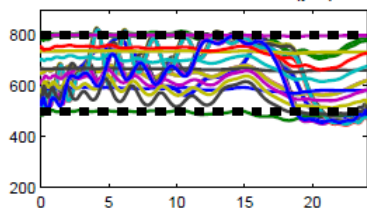
Scenario #2
Better Control



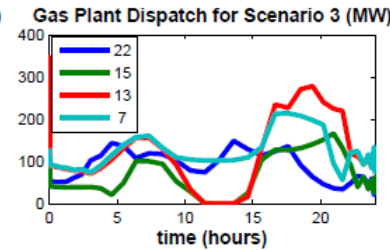
Comp. Ratios for Scenario 2



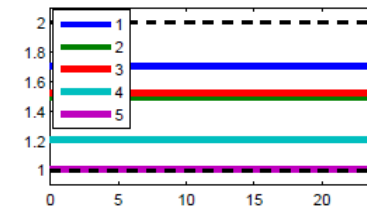
Pressure for Scenario 2 (psi)



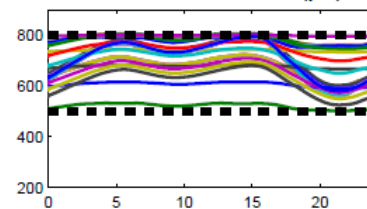
Scenario #3
Coordination



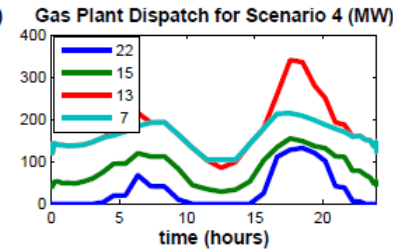
Comp. Ratios for Scenario 3



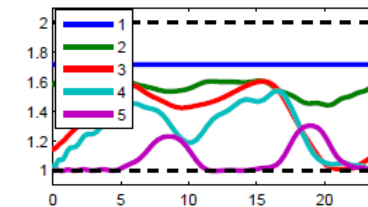
Pressure for Scenario 3 (psi)



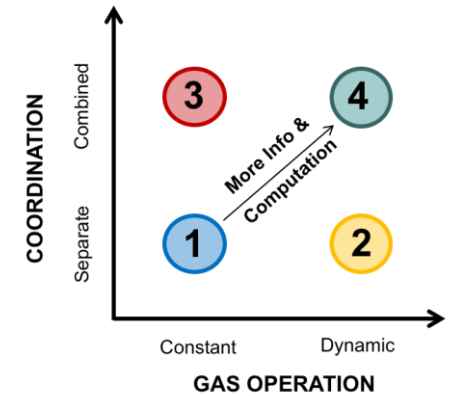
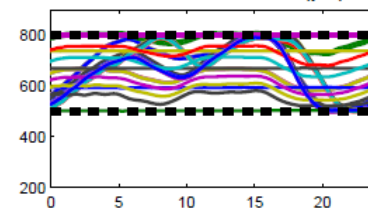
Scenario #4
Both!



Comp. Ratios for Scenario 4



Pressure for Scenario 4 (psi)



Problem
infeasible without
coordination!

Much **lower cost**
with dynamic
compression

Higher loading!

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

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

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): $-f_{ij}^{\max} \leq M_{(ij, \cdot)}(p(t) - h(t)) \leq f_{ij}^{\max}$
 $\forall \{ij\} \in \mathcal{E}, \quad \forall t \in [0, T]$

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

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

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): $\rho(0) = \rho(T), \quad \varphi(0) = \varphi(T), \quad \alpha_{ij}(0) = \alpha_{ij}(T), \quad \forall \{i, j\} \in \mathcal{C}$

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

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

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



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

(Time steps automatically
chosen to approximate
problem well)



**A-posteriori evaluation
of pressures through
simulation**