

Gas-Grid Resilience Planning

The Grid of the Future Workshop

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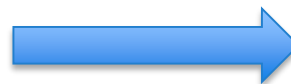


August 22, 2018



Emerging Gas-Grid Challenges

- **Natural Gas variability increasing beyond historical norms**
 - Largely driven by the electric power sector
 - Variability limits the ability to ship gas
 - Southern California Gas—Aliso Canyon capacity studies
 - Max capacity is 4.56 B CFD in winter
 - Max capacity is 3.60 B CFD in summer
- **Correlated Vulnerabilities**
 - Polar vortex, catastrophic pipeline failure
 - Failures in natural gas propagate to electric power and vice-versa
 - Risk posture of electric power increases
 - Power industry nervous about dependencies
 - Our Goal: Reduce risk through coordinated design and/or operations



DOCKETED	
Docket Number:	17-1EPR-11
Project Title:	Southern California Energy Reliability
FN #:	217639
Document Title:	Aliso Canyon Risk Assessment Technical Report Summer 2017 Assessment
Description:	Prepared by staff of the California Utilities Commission, California Energy Commission, the California Independent System Operator, the Los Angeles Department of Water and Power with input from Southern California Gas Company, May 19, 2017
Filer:	Patty Paul
Organization:	California Energy Commission
Submitter:	Commission Staff
Role:	
Submission Date:	5/19/2017 10:48:02 AM
Docketed Date:	5/19/2017

Modeling Gas-Grid Coordination

- In the US, gas and power transmission have very different planning processes and very different price formation processes
- Few large-scale gas transmission models
- Limited US public domain computational test beds for gas-grid simulation (no equivalent to GasLib or IEEE test systems)

The screenshot shows the Federal Energy Regulatory Commission (FERC) website. The header includes the FERC logo and the text 'Federal Energy Regulatory Commission'. Below the header is a navigation menu with links for 'ABOUT', 'MEDIA', 'DOCUMENTS & FILINGS', 'INDUSTRIES', 'LEGAL RESOURCES', 'MARKET OVERSIGHT', 'ENFORCEMENT', 'CAREERS', and 'CONTACT'. A search bar is located in the top right corner.

The main content area is titled 'Natural Gas - Electric Coordination'. It features a left-hand navigation menu with categories such as 'Electric', 'Annual Charges', 'Safety and Inspections', 'Environment', 'Industry Activities', 'Smart Grid', 'Demand Response', 'Integration of Renewables', 'Order No. 1000 - Transmission Planning and Cost Allocation', 'Electric Reliability', 'Increasing Efficiency through Improved Software', 'Electric Competition', and 'RTO/ISO'. The 'Industry Activities' category is expanded to show 'Natural Gas - Electric Coordination'.

The main text on the page reads: 'The natural gas and electricity industries provide a service that is critical to health and safety in this nation. Yet recent events have illustrated why the interdependence of these industries merits careful attention. In short, this nation must ensure that outages and reliability problems are not the result of the lack of coordination between the electricity and gas industries.'

Below this text, it states: 'As we have seen over the last few years, natural gas is being used much more heavily in electricity generation. This trend appears likely to accelerate as coal-powered generation is retired, renewable energy resources require more backup by natural gas plants, and low natural gas prices encourage more use of gas. And recent problems, most importantly, the Southwest outage in February 2011, suggest that more resources must be allocated to planning for the increased use of natural gas to generate electricity.'

At the bottom of the page, it mentions: 'In February 2012 Commissioner Moeller requested comments on the Coordination between the Natural Gas and Electricity Markets Request' with links to 'Notice of Docket No.' and 'Comments Filed'.

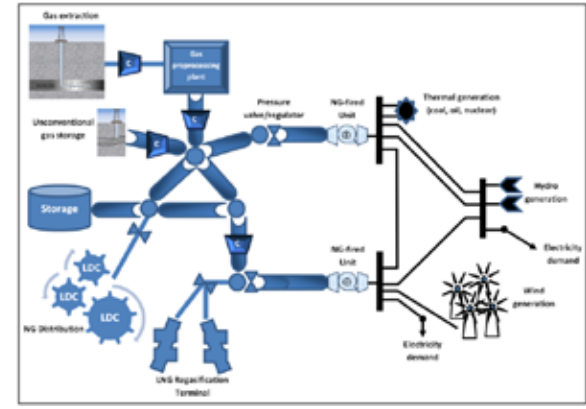
Gas Grid Expansion Planning

Operational options:

- § EP: power generation dispatch (Optimal power flow)
- § NG: load locations and quantities, compressor dispatch

Infrastructure options:

- § EP: new transmission lines and generation or converted generation
- § NG: new/upgraded pipelines, compressor stations



Joint gas-grid model's main blocks:

$$\min_{\Lambda, \omega} (C_{exp}(\Lambda) + G_{mix}(\omega))$$

subject to:

<p>(Power grid constraints)</p> <p>Power flow equations Line limits Voltage limits (AC) Generation bounds</p>	<p>(Gas flow constraints)</p> <p>Gas flow equations Pressure bounds Mass flow balance Compressor ratio limits</p>
<p><i>Coupling constraints</i></p>	
<p><i>Expansion/design constraints</i></p>	

where the objective represents the capital expenditures (upgrades) and generation mix costs (generation dispatch):

$$C_{exp} =$$

(Capital expenditures)

EP generation capital +
EP transmission capital +
NG transmission capital +
NG compression capital

$$G_{mix} =$$

(Generation mix)

$$\min \sum_i \sum_t C(g_i^t)$$

where: $C(g_i^t)$ = cost of power generation (g) of fuel type t at bus i

Develop principled formulations and solvers to find synergistic expansion planning solutions across electrical power and natural gas infrastructures

Power Flow Formulation – AC Steady State Formulation

Voltage and Reactive Power often sources of problems during extreme events

$$\theta_0 = 0,$$

$$\sum_{j \in \Gamma_i} p_j^g - p_i^l - g s_i v_i^2 = \sum_{j \in N_i^e} p_{ij},$$

$$\sum_{j \in \Gamma_i} q_j^g - q_i^l + b s_i v_i^2 = \sum_{j \in N_i^e} q_{ij},$$

Kirchhoff's Current Law

$$p_{ij} = \frac{g_a}{r_a^2 + \Delta_a^2} v_i^2 - \frac{g_a r_a + b_a \Delta_a}{r_a^2 + \Delta_a^2} v_i v_j \cos(\theta_i - \theta_j) - \frac{b_a r_a - g_a \Delta_a}{r_a^2 + \Delta_a^2} v_i v_j \sin(\theta_i - \theta_j),$$

Ohm's Law

$$p_{ji} = g_a v_j^2 - \frac{g_a r_a - b_a \Delta_a}{r_a^2 + \Delta_a^2} v_i v_j \cos(\theta_j - \theta_i) - \frac{b_a r_a + g_a \Delta_a}{r_a^2 + \Delta_a^2} v_i v_j \sin(\theta_j - \theta_i),$$

$$q_{ij} = -\frac{b_a + \frac{c_a}{2}}{r_a^2 + \Delta_a^2} v_i^2 + \frac{b_a r_a + g_a \Delta_a}{r_a^2 + \Delta_a^2} v_i v_j \cos(\theta_i - \theta_j) - \frac{g_a r_a + b_a \Delta_a}{r_a^2 + \Delta_a^2} v_i v_j \sin(\theta_i - \theta_j),$$

$$q_{ji} = (-b_a + \frac{c_a}{2}) v_j^2 + \frac{b_a r_a - g_a \Delta_a}{r_a^2 + \Delta_a^2} v_i v_j \cos(\theta_j - \theta_i) - \frac{g_a r_a - b_a \Delta_a}{r_a^2 + \Delta_a^2} v_i v_j \sin(\theta_j - \theta_i),$$

$$p_{ji}^2 + q_{ji}^2 \leq \xi_a^2, \quad p_{ij}^2 + q_{ij}^2 \leq \xi_a^2,$$

Thermal Limits

$$-\bar{\theta} \leq \theta_i - \theta_j \leq \bar{\theta},$$

Phase Angle Limits

$$\underline{p}_j^g \leq p_j^g \leq \bar{p}_j^g, \quad \underline{q}_j^g \leq q_j^g \leq \bar{q}_j^g,$$

Generator Output

$$\underline{v}_i \leq v_i \leq \bar{v}_i,$$

Voltage Limits

<https://github.com/lanl-ansi/PowerModels.jl>

Gas Flow Formulation—Weymouth Formulation

Pressure often a source of problems during extreme events

$$\sum_{a=a_{ij} \in A^g} x_a - \sum_{a=a_{ji} \in A^g} x_a = s_i - d_i - \hat{d}_i, \quad \left. \vphantom{\sum} \right\} \text{Flow Balance}$$

$$\left. \begin{aligned} & y_a^- U \leq x_a \leq y_a^+ U, \\ & y_a^- \underline{\pi}_i \leq \pi_i - \pi_j \leq y_a^+ \bar{\pi}_i, \\ & y_a^- + y_a^+ = 1, \\ \beta_a \geq \pi_i - \pi_j + (\underline{\pi}_i - \bar{\pi}_j)(y_a^+ - y_a^- - 1), \quad \beta_a \geq \pi_j - \pi_i + (\underline{\pi}_i - \bar{\pi}_j)(y_a^+ - y_a^- + 1), \\ \beta_a \leq \pi_i - \pi_j + (\underline{\pi}_i - \bar{\pi}_j)(y_a^+ - y_a^- - 1), \quad \beta_a \leq \pi_j - \pi_i + (\underline{\pi}_i - \bar{\pi}_j)(y_a^+ - y_a^- + 1), \\ & \beta_a = w_a x_a^2, \end{aligned} \right\} \text{Weymouth Relationships}$$

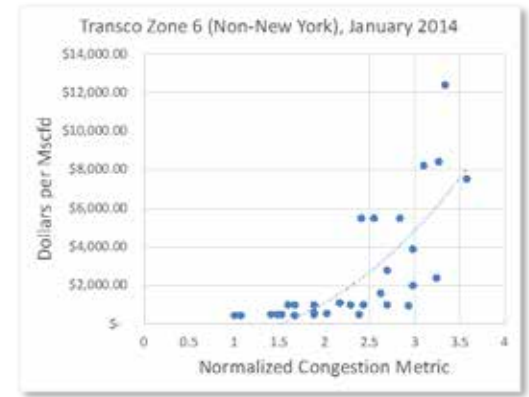
$$\left. \begin{aligned} & \pi_i \underline{\alpha}_a - y_a^- (\bar{\pi}_i \underline{\alpha}_a - \underline{\pi}_j) \leq \pi_j \leq \pi_i \bar{\alpha}_a + y_a^- (\bar{\pi}_j - \underline{\pi}_i \bar{\alpha}_a), \\ & \pi_j \underline{\alpha}_a - y_a^+ (\bar{\pi}_j \underline{\alpha}_a - \underline{\pi}_i) \leq \pi_i \leq \pi_j \bar{\alpha}_a + y_a^+ (\bar{\pi}_i - \underline{\pi}_j \bar{\alpha}_a), \end{aligned} \right\} \text{Compression Limits}$$

$$\left. \begin{aligned} & \underline{d}_i \leq d_i \leq \bar{d}_i, \\ & \underline{s}_i \leq s_i \leq \bar{s}_i, \end{aligned} \right\} \text{Injection Limits}$$

$$\left. \underline{\pi}_i \leq \pi_i \leq \bar{\pi}_i, \right\} \text{Pressure Limits}$$

Elasticity Formulation—Endogenous Pricing

- Locational Marginal Pricing for Electricity
- Historical price and pressure data used to calibrate a pressure-price relationship for natural gas



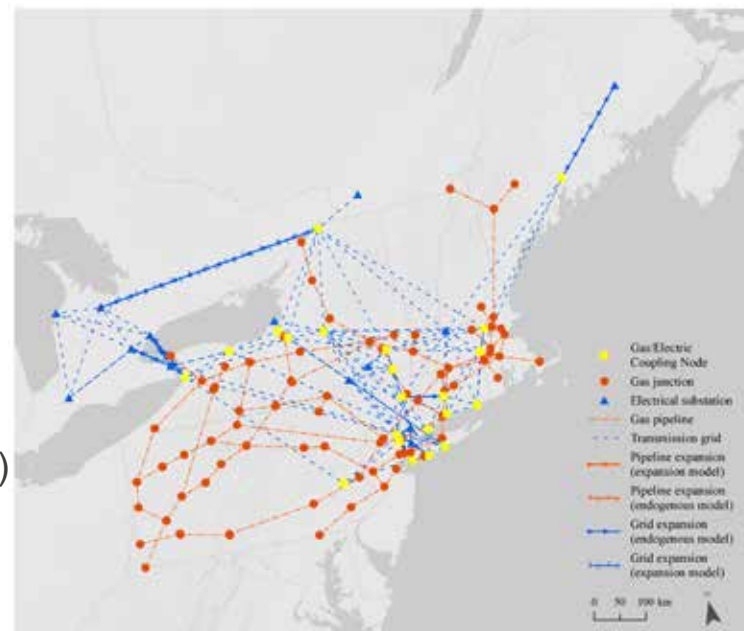
$$d_i = \sum_{j \in \Gamma} (h_1^j + h_2^j p_j^g + h_3^j (p_j^g)^2), \quad \text{Heat rate consumption curve}$$

R. Bent, S. Blumsack, P. van Hentenryck, C. Borraz-Sanchez, M. Shahriari. *Joint Electricity and Natural Gas Transmission Planning with Endogenous Market Feedbacks*. IEEE Transactions on Power Systems, to appear

$$\text{Cost} = \underbrace{\sum_{a \in A^e} \kappa_a^e z_a^e}_{\text{Cost of expanding power lines}} + \underbrace{\sum_{a \in A^g} \kappa_a^g z_a^g}_{\text{Cost of expanding pipelines}} + \underbrace{\sum_{i \in \Gamma} (\mu_1^i + \mu_2^i p_i^g + \mu_3^i (p_i^g)^2)}_{\text{Cost of Non-gas fired generation}} + \underbrace{\sum_{\zeta \in Z} Z(\sum_{i \in \zeta} d_i)}_{\text{Elastic cost of gas}}$$

Extreme Event Formulation

- **Objective: Model Extreme Temperature Induced Stress**
 - Polar-vortex like events
 - Modeled as increased firm gas load
 - Causes congestion in pipes
 - Raises gas prices
 - Limits gas to non-firm gas load (gas-fired generators)
- **Formulation**
 - Split gas load into firm and non-firm load
 - Introduce zone-based, firm load scaling factors

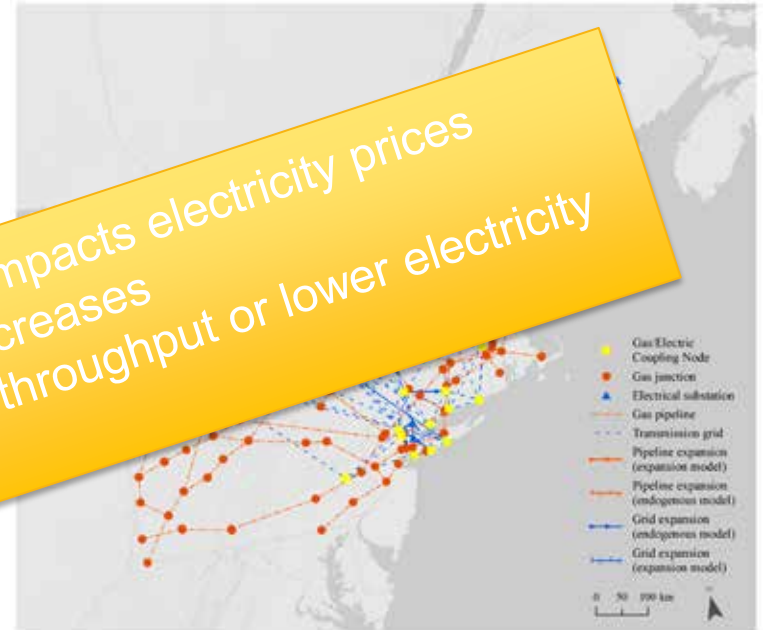


Extreme Event Formulation

- **Objective: Model Extreme Temperature Induced Stress**

- Polar-vortex like events
- Modeled as increased firm gas load
 - Causes congestion in pipes
 - Raises gas prices
 - Limits gas

- **F**
 - Analyze how increased demand for gas impacts electricity prices
- **S**
 - Understand where gas-fired capacity decreases
- **I**
 - Explore network expansion to increase throughput or lower electricity prices
- **fac**
 - non-firm load
 - increased, firm load scaling



Solution Methodology

- **Challenging (NP-Hard) Optimization Problem**

- Power equations and gas equations are not convex
- Example
 - $\beta_a = w_a x_a^2$
 - Relates pipeline pressure squared difference to flux squared

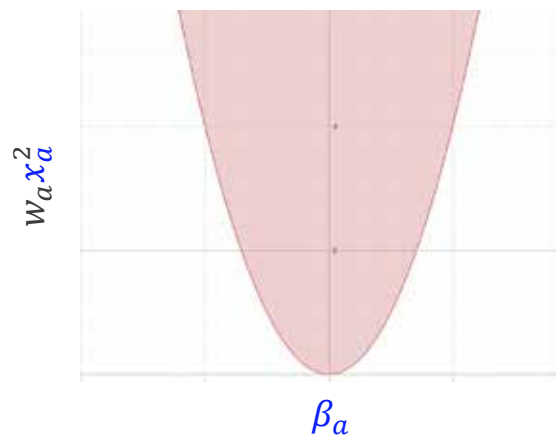
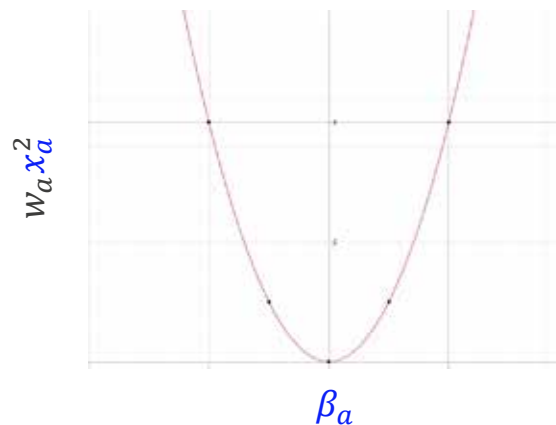
- **Approach**

- Relax the non-convexities—Special approximation

- Relaxed solution is a lower bound of the original problem's best solution
- If relaxed solution says electricity price is 15 cents per kwh, the actual solution is ≥ 15 cents

- Example

- $\beta_a \geq w_a x_a^2$



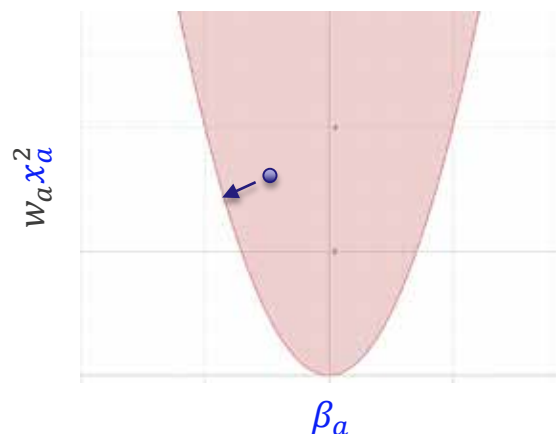
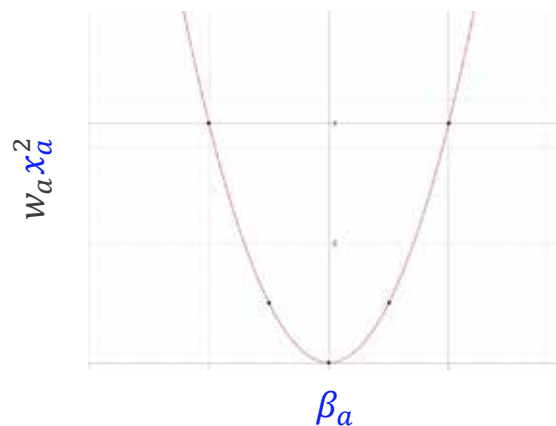
Solution Methodology

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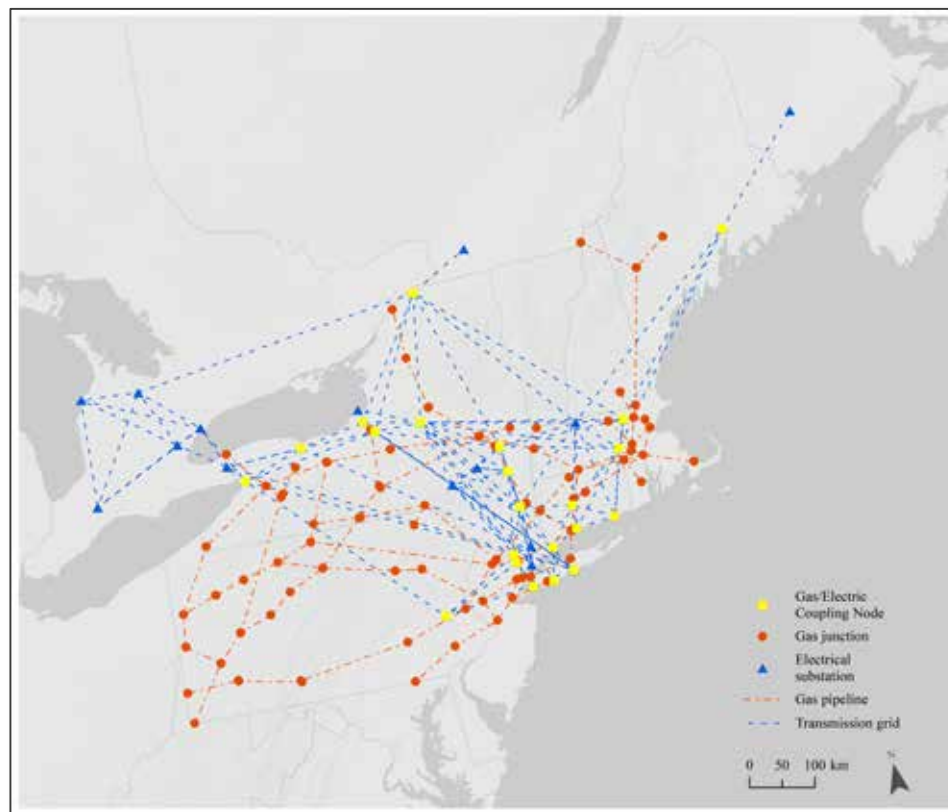
- **Approach**

- Use gradient descent to find a feasible solution from the relaxed solution
 - Feasible solution is an upper bound of the original problem's best solution
 - If feasible solution says electricity price is 20 cents per kwh, the actual solution is ≤ 20 cents
 - Combined, we have an actual solution that is 20 cents and we can't do better than 15 cents



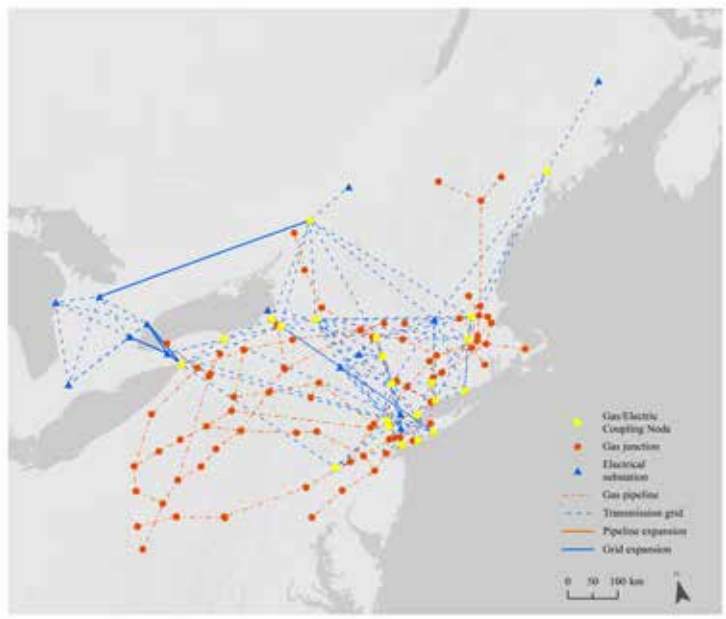
Gas-Grid Test System

- **Grid model is the 36-node Allen-Lang-Ilic northeastern test system (IEEE Transactions on Power Systems. 2008)**
- **Gas transmission model assembled from public operator data**
- **Stress Cases**
 - Increase gas demand by up to 200%
 - Increase electricity demand by up to 35%
 - Uniform and non-uniform demand increases
 - Expansions needed to avoid extreme price spikes

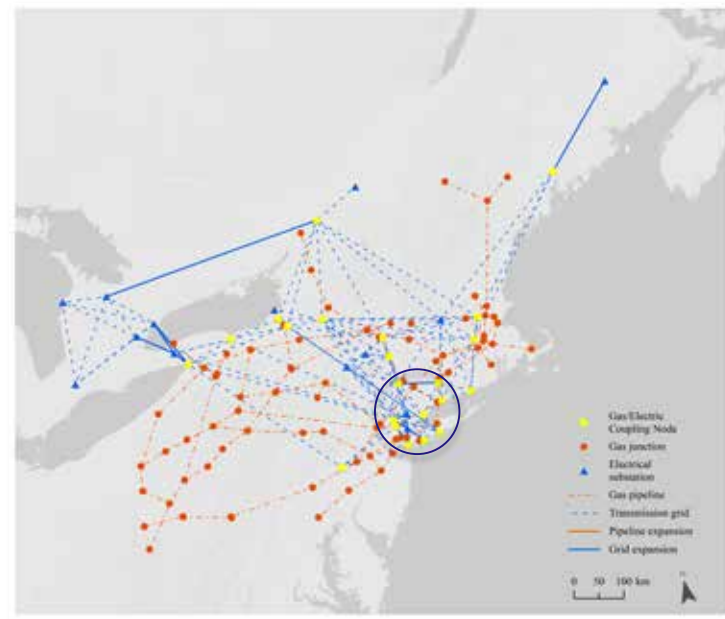


* In these examples, we treated this model as single market, single area

Example Results – 225% Gas Stress, 35% Gas Stress



- Expansions for demand growth only—5 power line upgrades
- Relieves thermal congestion in the west



- Expansions for demand growth and electricity price reductions—13 power lines upgrades
- Electric power upgrades in southern New York and New England to support “Gas-by-wire”
 - Move gas from low congestion areas (in the form of electricity)

Questions

Publications

R. Bent, S. Blumsack, P. van Hentenryck, C. Borraz-Sanchez, M. Shahriari. *Joint Electricity and Natural Gas Transmission Planning with Endogenous Market Feedbacks*. IEEE Transactions on Power Systems, to appear.

R. Bent, S. Blumsack, P. van Hentenryck, C. Borraz Sanchez, and S. Backhaus. *Joint Expansion Planning for Natural Gas and Electric Transmission with Endogenous Market Feedbacks*. Proceedings of the 51st Hawaii International Conference on System Sciences (HICSS-51), Jan. 2018, Big Island, Hawaii.

C. Borraz-Sanchez, R. Bent, P. van Hentenryck, S. Blumsack, and H. Hijazi. *Elasticity Model for Joint Gas-Grid Expansion Planning Optimization*. Proceedings of the Pipeline Simulation Interest Group (PSIG) (PSIG 2016), May 2016, Vancouver, BC.

C. Borraz-Sanchez, R. Bent, S. Backhaus, S. Blumsack, H. Hijazi, and P. van Hentenryck. *Convex Optimization for Joint Expansion Planning of Natural Gas and Power Systems*. Proceedings of the 49th Hawaii International Conference on System Sciences (HICSS-49) (HICSS 2016), Jan. 2016, Grand Hyatt, Kauai.

C. Borraz-Sanchez, R. Bent, S. Backhaus, H. Hijazi, and P. van Hentenryck. *Convex Relaxations for Gas Expansion Planning*, INFORMS Journal of Computing, 28 (4): 645-656, 2016.

This work was partially funded by the US National Science Foundation under CMMI-1638331 and the DOE Office of Electricity Advanced Grid Modeling Program.