LA-UR-17-27955

Gas-Grid Resilience Planning

The Grid of the Future Workshop

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Joint work with Pascal van Hentenryck, Seth Blumsack, Conrado Borraz-Sanchez

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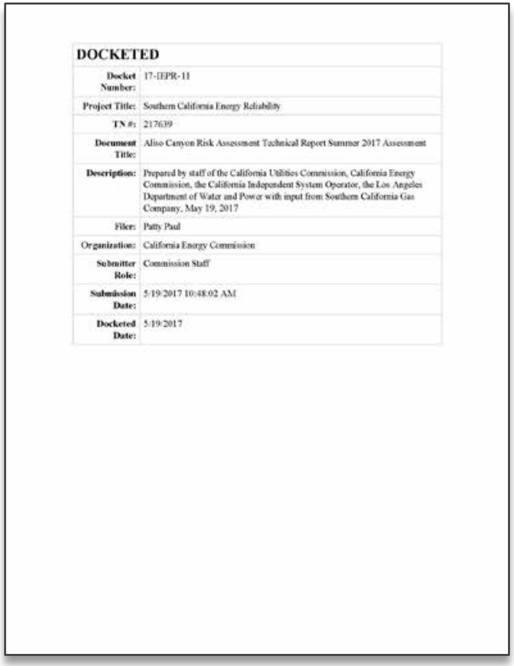
Emerging Gas-Grid Challenges

- **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

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Project Title:	Southern California Energy Reliability
TN #:	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
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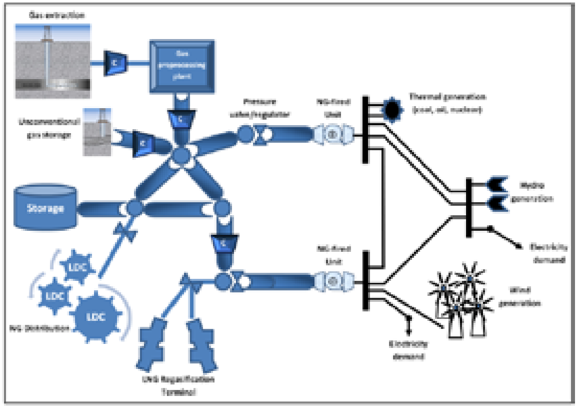
Modeling Gas-Grid Coordination

- 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)

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:

$$\min_{\Lambda,\omega} \left(\mathcal{C}_{exp}(\Lambda) + \mathcal{G}_{mix}(\omega)\right)$$

subject to:

(Power grid constraints)	(Gas flow constraints)
Power flow equations	Gas flow equations
Line limits	Pressure bounds
Voltage limits (AC)	Mass flow balance
Generation bounds	Compressor ratio limits

Coupling constraints

Expansion/design constraints

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

$\mathcal{C}_{exp} =$ (Capital expenditures):

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

$\mathcal{G}_{mix} =$ (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

$$\theta_0 = 0,$$

Kirchhoff's Current Law

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

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

Ohm's Law

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

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

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

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

Thermal Limits

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

Phase Angle Limits

$$-\overline{\theta} \le \theta_i - \theta_j \le \overline{\theta},$$

Generator Output

$$\underline{p}_j^g \le p_j^g \le \overline{p}_j^g, \quad \underline{q}_j^g \le q_j^g \le \overline{q}_j^g,$$

Voltage Limits

$$\underline{v}_i \le v_i \le \overline{v}_i,$$

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

Gas Flow Formulation—Weymouth Formulation

Pressure often a source of problems during extreme events

$$\sum_{a=a_{ij}\in A^g} x_a - \sum_{a=a_{ji}\in A^g} x_a = s_i - d_i - \hat{d}_i\,,$$

Flow Balance

$$y_a^- U \le x_a \le y_a^+ U,$$
$$y_a^- \underline{\pi}_i \le \pi_i - \pi_j \le y_a^+ \overline{\pi}_i,$$
$$y_a^- + y_a^+ = 1,$$
$$\beta_a \ge \pi_i - \pi_j + (\underline{\pi}_i - \overline{\pi}_j)(y_a^+ - y_a^- - 1),\quad \beta_a \ge \pi_j - \pi_i + (\underline{\pi}_i - \overline{\pi}_j)(y_a^+ - y_a^- + 1),$$
$$\beta_a \le \pi_i - \pi_j + (\underline{\pi}_i - \overline{\pi}_j)(y_a^+ - y_a^- - 1),\quad \beta_a \le \pi_j - \pi_i + (\underline{\pi}_i - \overline{\pi}_j)(y_a^+ - y_a^- + 1),$$
$$\beta_a = w_a x_a^2,$$

Weymouth Relationships

$$\pi_i \underline{\alpha}_a - y_a^- \left(\overline{\pi}_i \underline{\alpha}_a - \underline{\pi}_j\right) \le \pi_j \le \pi_i \overline{\alpha}_a + y_a^- (\overline{\pi}_j - \underline{\pi}_i \overline{\alpha}_a),$$
$$\pi_j \underline{\alpha}_a - y_a^+ \left(\overline{\pi}_j \underline{\alpha}_a - \underline{\pi}_i\right) \le \pi_i \le \pi_j \overline{\alpha}_a + y_a^+ (\overline{\pi}_i - \underline{\pi}_j \overline{\alpha}_a),$$

Compression Limits

$$\underline{d}_i \le d_i \le \overline{d}_i,$$
$$\underline{s}_i \le s_i \le \overline{s}_i,$$

Injection Limits

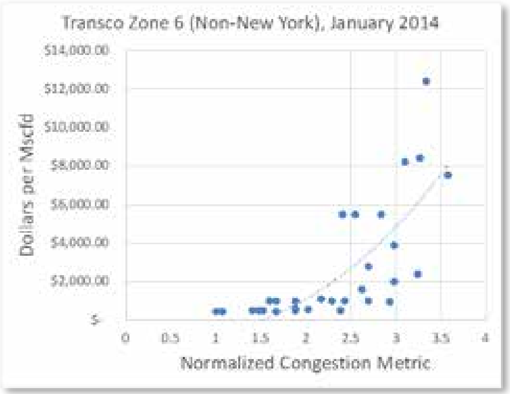
$$\underline{\pi}_i \le \pi_i \le \overline{\pi}_i,$$

Pressure Limits

https://github.com/lanl-ansi/GasModels.jl

Elasticity Formulation—Endogenous Pricing

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



$$d_i = \sum_{j\in\Gamma} (h_1^j + h_2^j p_j^g + h_3^j \left(p_j^g\right)^2 ,$$

Heat rate consumption curve

Cost

$$\sum_{a\in A^e} \kappa_a^e z_a^e + \sum_{a\in A^g} \kappa_a^g z_a^g + \sum_{i\in\Gamma} (\mu_1^i + \mu_2^i p_i^g + \mu_3^i \left(p_i^g\right)^2) + \sum_{\zeta\in Z} \mathrm{Z}(\sum_{i\in\zeta} d_i) ,$$

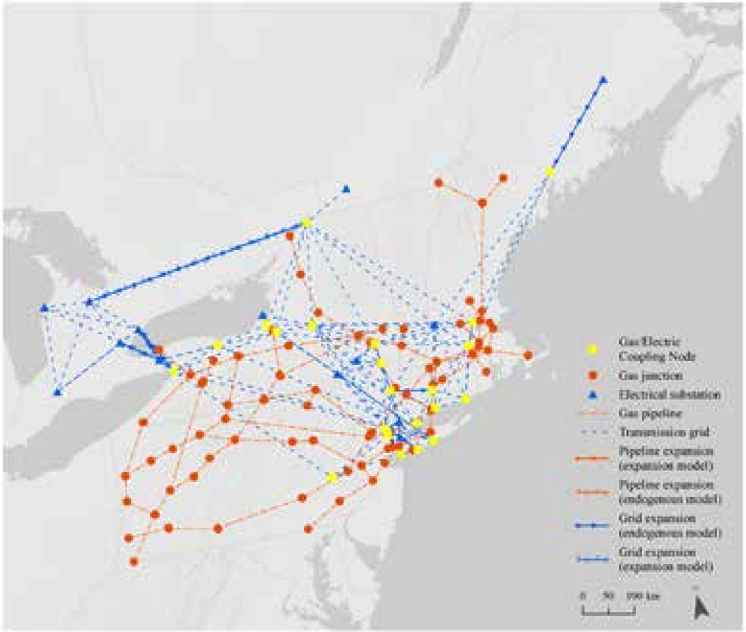
- Cost of expanding power lines
- Cost of expanding pipelines
- Cost of Non-gas fired generation
- Elastic cost of gas

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

https://github.com/lanl-ansi/GasGridModels.jl

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



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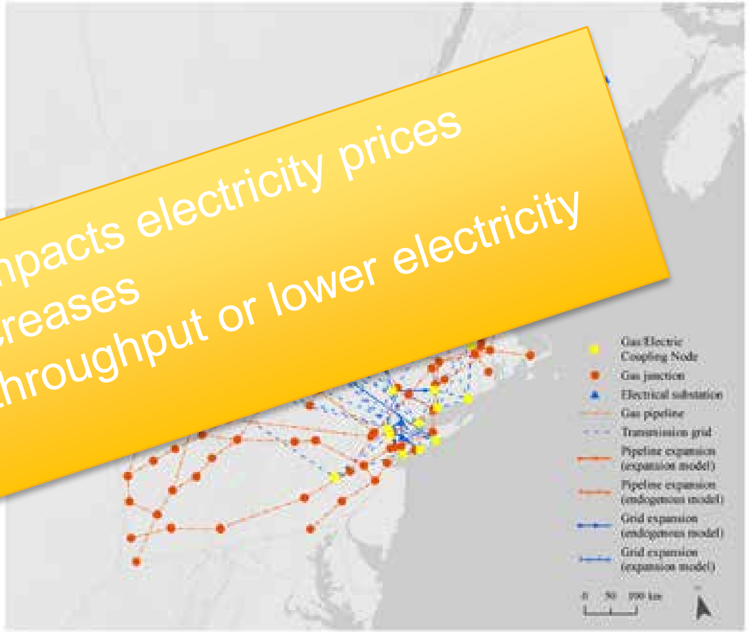
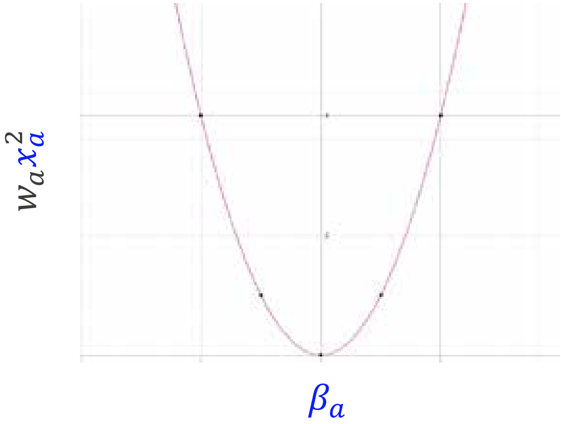
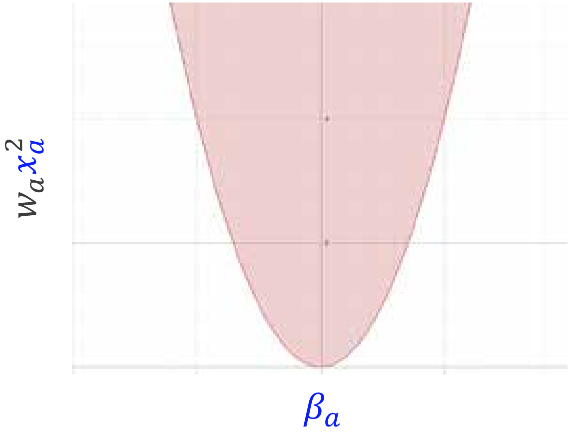


- Analyze how increased demand for gas impacts electricity prices
- Understand where gas-fired capacity decreases
- Explore network expansion to increase throughput or lower electricity prices

Solution Methodology

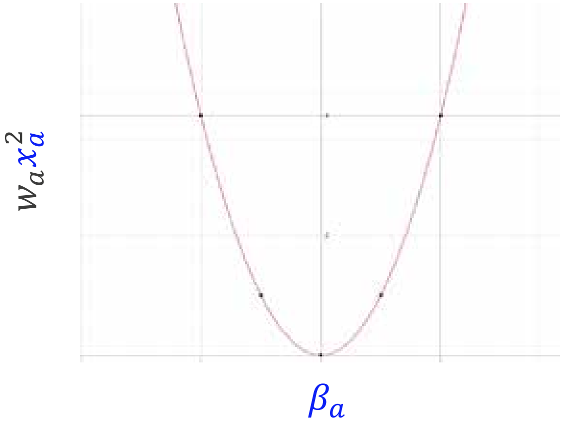
- **Challenging (NP-Hard) Optimization Problem**
  - Power equations and gas equations are not convex
  - Example
    - $\beta_a = w_a x_a^2$
    - Relates pipeline pressure squared difference to flux squared
- **Approach**
  - Relax the non-convexities—Special approximation
    - Relaxed solution is 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
    - $\beta_a \geq w_a x_a^2$

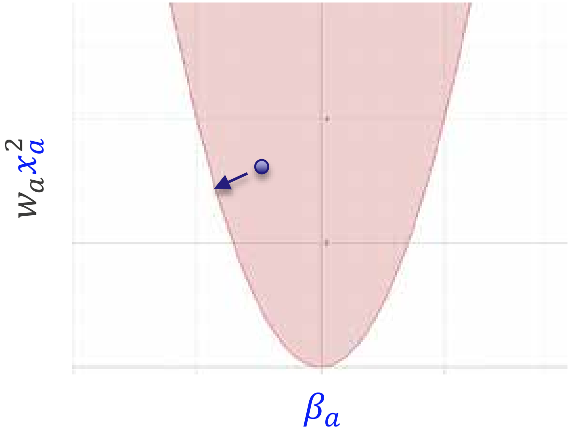




Solution Methodology

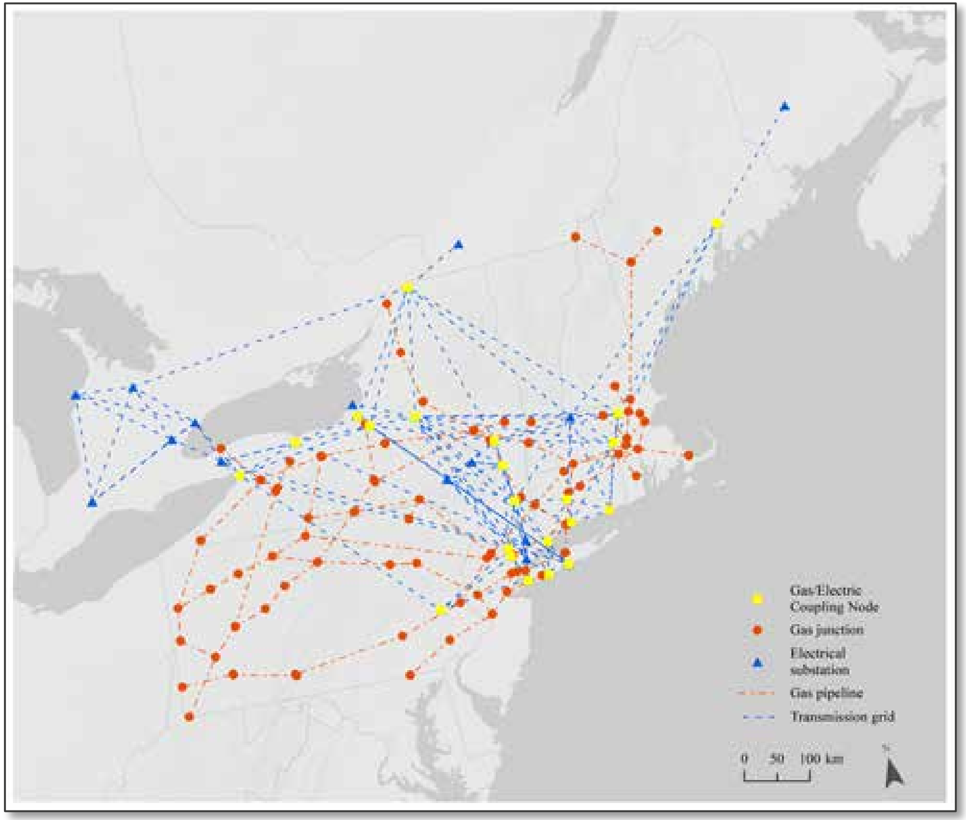
- **Challenging (NP-Hard) Optimization Problem**
  - Power equations and gas equations are not convex
  - Example
    - $\beta_a = w_a x_a^2$
    - Relates pipeline pressure squared difference to flux squared
- **Approach**
  - Use gradient descent to find a feasible solution from the relaxed solution
    - 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





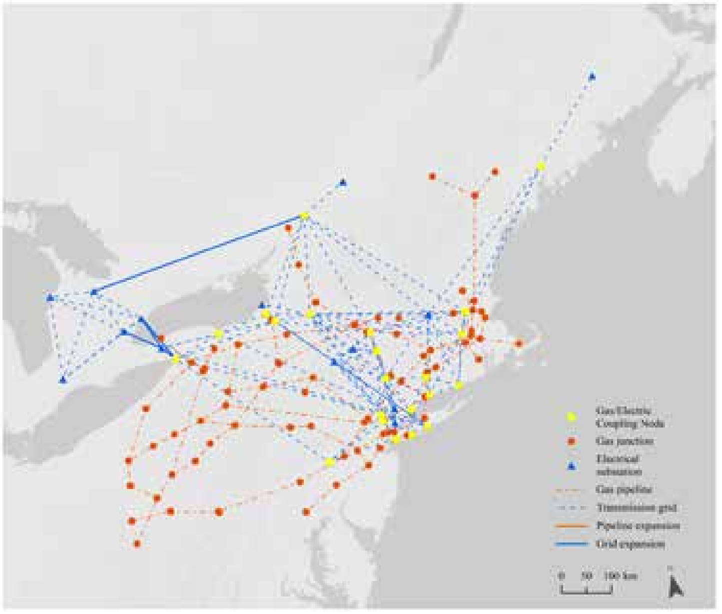
Gas-Grid Test System

- **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

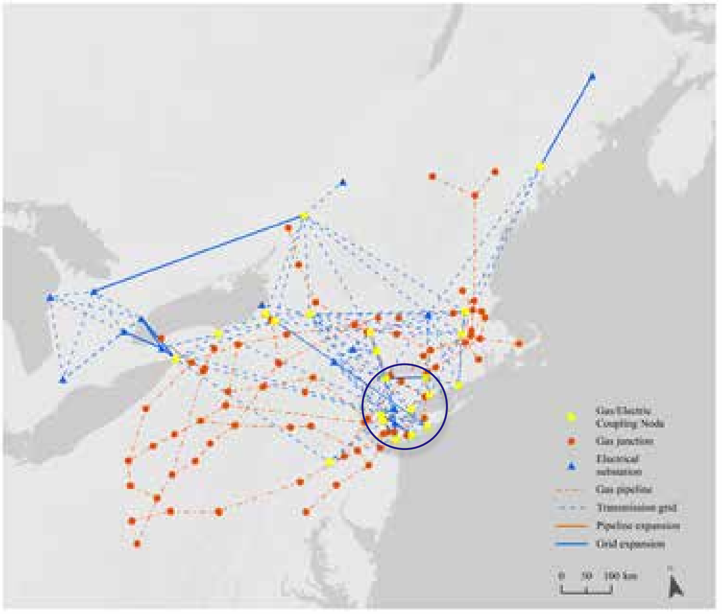


* In these examples, we treated this model as single market, single area

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.

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