Preparing for the extremes: Modeling and Mitigating Risk of Wildfire and Natural Gas Shortages

Line A. Roald

PSERC Webinar
April 20, 2021

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

Risk Modeling and Mitigation

Risk = Probability • Impact

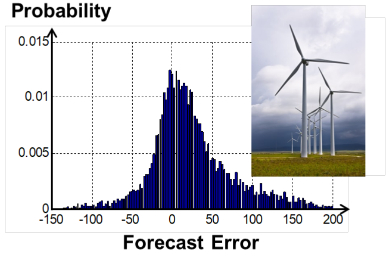
Component failures

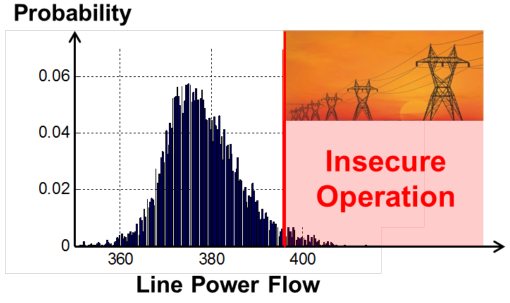
- Probability of a fault (assume only one at a time)
- Impact of the resulting outage (overload, cascading, power outages)

N-1

Renewable energy variability

- Probability of different levels of generation
- Impact on system reserves, overloads





Risk Modeling and Mitigation

Risk = Probability • Impact

Wildfire ignitions?

Natural gas shortages?

Impacts that go beyond the electric power system.

Part I: Wildfire Risk Modeling and Mitigation

Wildfire Risk = **Probability** of ignition • **Impact** of resulting fire

Measures to reduce the risk of wildfire ignitions may increase the risk of power outages (Public safety power shutoffs, blocking reclosing)

Power Outage Risk = **Probability** of outage • **Impact** of outage

Part II: Natural Gas Shortages

Natural Gas Risk = **Probability** of low pressure • **Impact** of low pressure

Measures to reduce the risk of pressure drops in the natural gas system can curtailment of gas supply to generators, which again can cause electric load shedding

Power Outage Risk = **Probability** of outage • **Impact** of outage

How to operate a power system in conditions with high wildfire risk?

Noah Rhodes

Lewis Ntaimo

N. Rhodes, L. Ntaimo and L. Roald, "Balancing Wildfire Risk and Power Outages through Optimized Power Shut-Offs," in *IEEE Transactions on Power Systems* (Early Access), doi: 10.1109/TPWRS.2020.3046796

Electric faults cause sparks and arcing

Sparks from a downed power line.

Arc between electric line and the ground.

Source: C.L. Benner, B.D. Russell, J.A. Wischkaemper, K. Muthu-Manivannan, and R.E. Taylor. *DFA Technology Detects Circuit Device Failures–Experience of Mid-South Synergy*. Annual Conference for Protective Relay Engineers, 2019

Source: Carolina Country, “Shocking news”, https://www.carolinacountry.com/departments/departments/feature-story/shocking-news

Wildfires ignited by electric power grids

Pacific Gas & Electric equipment is blamed for 2019 Kincade fire in Sonoma County

Los Angeles Times

PG&E inspections of equipment that sparked deadly Camp fire were flawed, state regulators say

Helicopters perform airdrops on the Camp fire in November 2018 outside of Pulga, Calif., on the North Fork of the Feather River. (Carolyn Cole / Los Angeles Times)

Los Angeles Times

Kilmore East fire, deadliest of the Black Saturday Fires 2009, was started by a power line and killed 159

national museum australia

Ignition events are not uncommon

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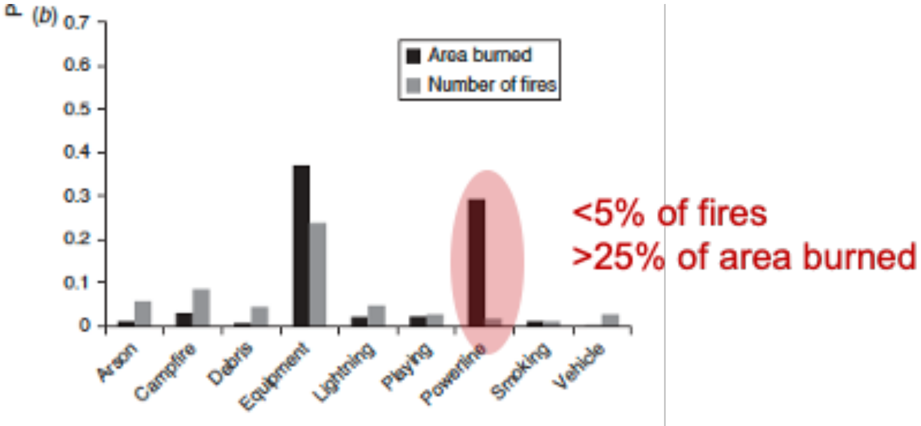
- PG&E reported more than **400** ignition events in 2015-2017
- In Texas, more than **1000 fires** estimated to be ignited by power lines every year.

Wildfires ignited by power lines are often large

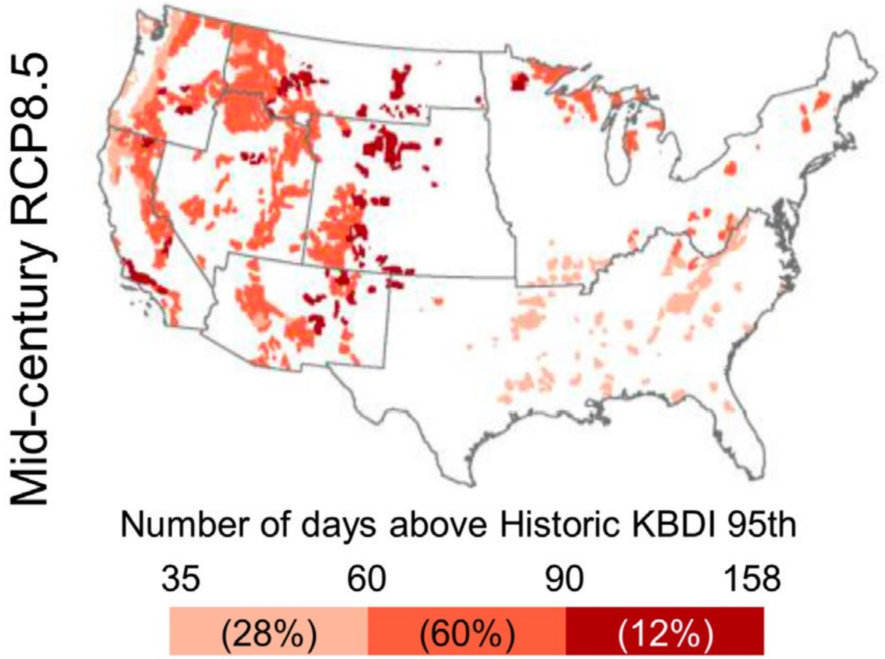


Wildfires in San Diego County. Figure from Syphard, Alexandra D., and Jon E. Keeley. "Location, timing and extent of wildfire vary by cause of ignition." *International Journal of Wildland Fire* 24.1 (2015): 37-47.

Fires ignited by power lines tend to be **larger** than other fires.

High wind
= higher probability of power line ignitions
+ higher probability of large fires

… and the wildfire risk is increasing.



Martinuzzi et al, *Future changes in fire weather, spring droughts, and false springs across U.S. National Forests and Grasslands*, Ecological Applications, 29(5), 2019,

Increase in number of days with high wildfire potential on public lands, high emission scenario

Modelling and Mitigating Wildfire Risk

Wildfire Risk

Wildfire risk $\mathcal{R}$ = Probability of ignition x Size and intensity of resulting fire x Damage caused

Wildfire Risk

Wildfire risk $\mathcal{R}$ = **Probability of ignition** x Size and intensity of resulting fire x Damage caused

↑

Utilities mostly control one aspect

Risk Reduction Strategies

- Infrastructure Upgrades
- Vegetation Management
- More Frequent Maintenance

Long-term solutions

+ mitigates wildfire risk
+ improves reliability
- investment and time for implementation

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Long-term solutions

+ mitigates wildfire risk
+ improves reliability
- investment and time for implementation

- Disable automatic reclosers
- Public Safety Power Shutoffs

Short-term solutions

+ mitigates wildfire risk
+ fast to implement
- reduces reliability

Public Safety Power Shut-Offs

PG&E could shut off power across Bay Area starting Wednesday

PG&E could conduct a "public safety power shutoff" across most of Northern California this week. Photo: Tracey Taylor

Update, Oct. 8, 10:30 a.m.: A PG&E spokeswoman said the utility still hasn't decided whether to shut off power for portions of an unprecedented 30 counties throughout Northern California. If the "public safety power shutoff" occurs, it would most likely begin early Wednesday morning, the start of a high-wind period expected to last through Thursday afternoon, said Tamar

October 2019

Approximately 3 million people lost power

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October 2019

Approximately 3 million people lost power

but

100 potential wildfires were avoided

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Which lines should be turned off?

Public Safety Power Shut-Offs

	OUTAGE PRODUCING WINDS	UTILITY FIRE POTENTIAL INDEX
PURPOSE	Forecasts when **unplanned outages associated with wind events** are more likely to occur.	Forecasts when a **potential ignition is most likely to result in a major wildfire**.
FACTORS	Analyzes **wind speed for every unplanned outage** that occurred over the last decade.	Analyzes 30 years of **weather, fuel moisture and climatology data** and 26 years of **wildfire data** in our service area.
FINDINGS	**Wind-driven outages can create ignition sources** for wildfires, from: • Vegetation/debris blowing into lines • Wind-related damage to equipment • Lines coming into contact with one another	A fire's growth potential increases as **vegetation dries and wind speeds increase**.
TIMING	Model is updated and run **four times daily**.	Model is updated and run **four times daily**.

PG&E, Public Safety Power Shut-Off Policies and Procedures

Which lines should be turned off?

Transmission risk threshold

$$R_l \geq R_l^{max}$$

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PG&E, Public Safety Power Shut-Off Policies and Procedures

Can we do better?

Explicit consideration of resulting load shed

Optimal power shutoff

Objective Function

$$\max \quad (1 - \boldsymbol{\alpha}) D_{Tot} - \boldsymbol{\alpha} R_{Fire}$$

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Maximizing delivered load

$$D_{Tot} = \sum_{d \in \mathcal{D}} x_d w_d \boldsymbol{D}_d,$$

Sum of weighted demand at each node

x_d fraction of load that is shed due to power shut-off

Objective Function

$$\max \quad (1-\alpha)D_{Tot} - \alpha R_{Fire}$$

Maximizing delivered load
while minimizing wildfire risk

$$D_{Tot} = \sum_{d \in \mathcal{D}} x_d w_d \boldsymbol{D}_d,$$

Sum of weighted demand at each node

$$R_{Fire} = \sum_{d \in \mathcal{D}} x_d \boldsymbol{R}_d + \sum_{g \in \mathcal{G}} z_g \boldsymbol{R}_g + \sum_{l \in \mathcal{L}} z_l \boldsymbol{R}_l + \sum_{i \in \mathcal{B}} z_i \boldsymbol{R}_i$$

Sum of risk for each component

Binary variables to describe whether a component is on/off

Off: $z_j = 0$ zero risk

On: $z_j = 1$ non-zero risk

Objective Function

$$\max \quad (1-\boldsymbol{\alpha})D_{Tot} - \boldsymbol{\alpha} R_{Fire}$$

$$D_{Tot} = \sum_{d \in \mathcal{D}} x_d w_d \boldsymbol{D}_d,$$

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Best trade-off???

α is a parameter which determines trade-off between load delivery and wildfire risk mitigation:

$\alpha \to 1$ focus on wildfire risk mitigation

$\alpha \to 0$ focus on load delivery

Constraints

$$\max \quad (1-\boldsymbol{\alpha})D_{Tot} - \boldsymbol{\alpha} R_{Fire}$$

s.t.: Component relationship

Generator constraints

Power flow constraints

Constraints: Component Interactions

- If a bus is disabled, all connected components are also disabled

$$z_i \geq x_d \qquad \forall d \in \mathcal{B}_i^{\mathcal{D}} \ , \quad \forall i \in \mathcal{B}$$

$$z_i \geq z_g \qquad \forall g \in \mathcal{B}_i^{\mathcal{G}} \ , \quad \forall i \in \mathcal{B}$$

$$z_i \geq z_l \qquad \forall l \in \mathcal{B}_i^{\mathcal{L}} \ , \quad \forall i \in \mathcal{B}$$

Constraints: Generator Constraints

- If a generator is disabled, its power output is 0

$$z_g \underline{\boldsymbol{P}_g} \leq P_g^G \leq z_g \overline{\boldsymbol{P}_g} \quad \forall g \in \mathcal{G}$$

Constraints: Power Flow Constraints

- If a power line is disabled, the power flow is 0

$$P^{L}_{l,i,j} \leq -\boldsymbol{b}_l(\theta_i - \theta_j + \boldsymbol{\theta}^{max}(1 - z_l)) \qquad \forall l \in \mathcal{B}^{\mathcal{L}}_{i,j}$$

$$P^{L}_{l,i,j} \geq -\boldsymbol{b}_l(\theta_i - \theta_j + \boldsymbol{\theta}^{min}(1 - z_l)) \qquad \forall l \in \mathcal{B}^{\mathcal{L}}_{i,j}$$

$$-\boldsymbol{T_l} z_l \leq P^{L}_{l,i,j} \leq \boldsymbol{T_l} z_l \qquad \forall l \in \mathcal{L}$$

- Power balance must hold at each node

$$\sum_{g \in \mathcal{B}^{\mathcal{G}}_i} P^{G}_{g} + \sum_{l \in \mathcal{B}^{\mathcal{L}}_i} P^{L}_{l,i,j} - \sum_{d \in \mathcal{B}^{\mathcal{D}}_i} x_d \boldsymbol{D}_d = 0 \quad \forall i \in \mathcal{B}$$

Constraints

$$\max \quad (1-\boldsymbol{\alpha})D_{Tot} - \boldsymbol{\alpha} R_{Fire}$$

s.t.:

$$D_{Tot} = \sum x_d w_d \boldsymbol{D}_d,$$

Total load served

$$R_{Fire} = \sum_{d \in \mathcal{D}} x_d \boldsymbol{R}_d + \sum_{g \in \mathcal{G}} z_g \boldsymbol{R}_g + \sum_{l \in \mathcal{L}} z_l \boldsymbol{R}_l + \sum_{i \in \mathcal{B}} z_i \boldsymbol{R}_i$$

Wildfire risk

$$\sum_{g \in \mathcal{B}_i^{\mathcal{G}}} P_g^G + \sum_{l \in \mathcal{B}_i^{\mathcal{L}}} P_{l,i,j}^L - \sum_{d \in \mathcal{B}_i^{\mathcal{D}}} x_d \boldsymbol{D}_d = 0 \quad \forall i \in \mathcal{B}$$

Power balance

$$P_{l,i,j}^L \leq -\boldsymbol{b}_l(\theta_i - \theta_j + \boldsymbol{\theta}^{max}(1 - z_l)) \qquad \forall l \in \mathcal{B}_{i,j}^{\mathcal{L}}$$
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Power flow

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Generation

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Component relationships

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Wildfire risk

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Component relationships

Mixed-integer linear program

Integer variables

Continuous variables

Case study

Test case

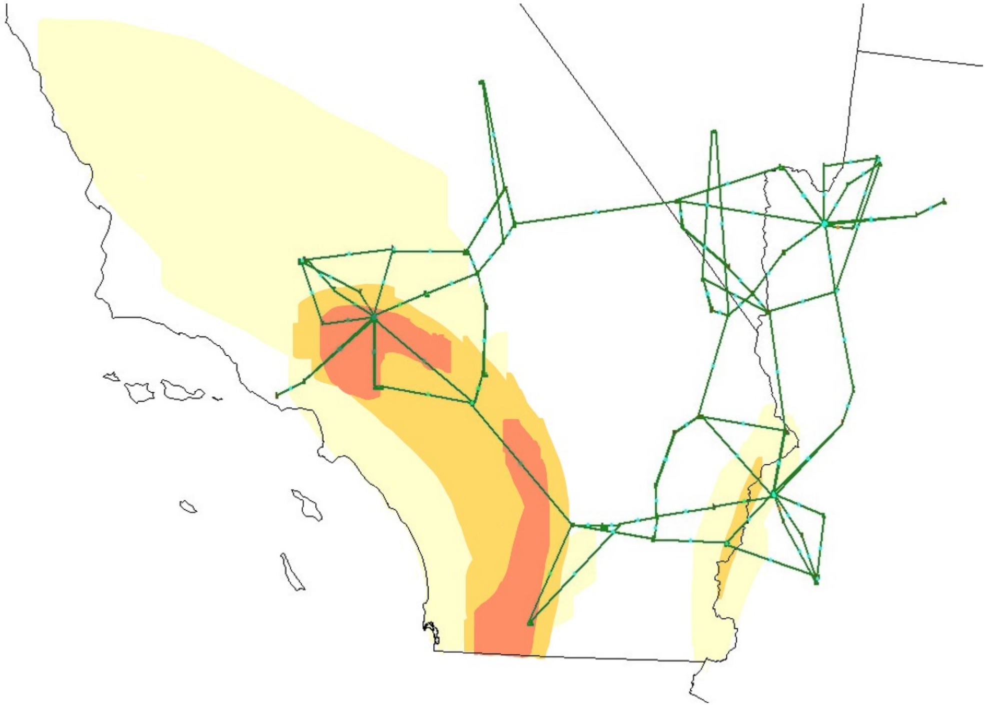
- IEEE RTS-GMLC:
  Standard test case, “located in” California

- Risk values based on California Oct 2019 risk

Devices risk estimated from its location:

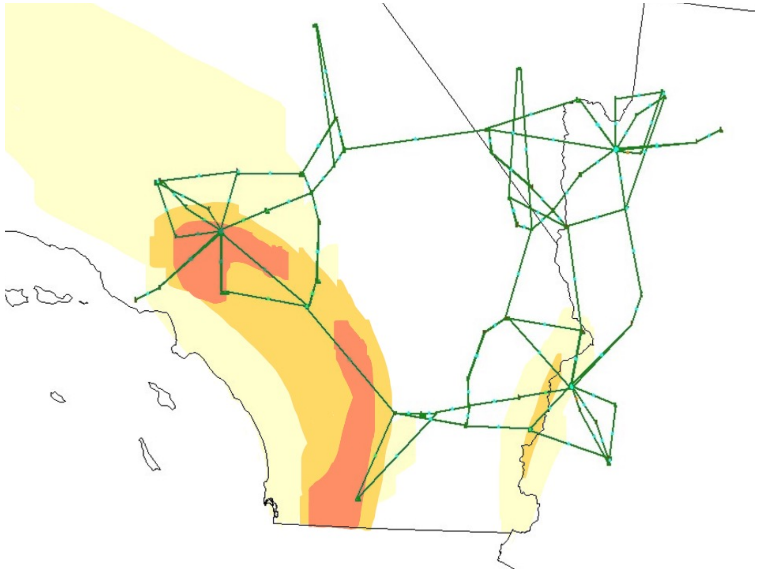
Transmission line risk is averaged, and scaled for the length of the line

Risk adjusted based on voltage level: ↓ KV = ↑ Risk



Low Risk
Medium Risk
High Risk
Very High Risk

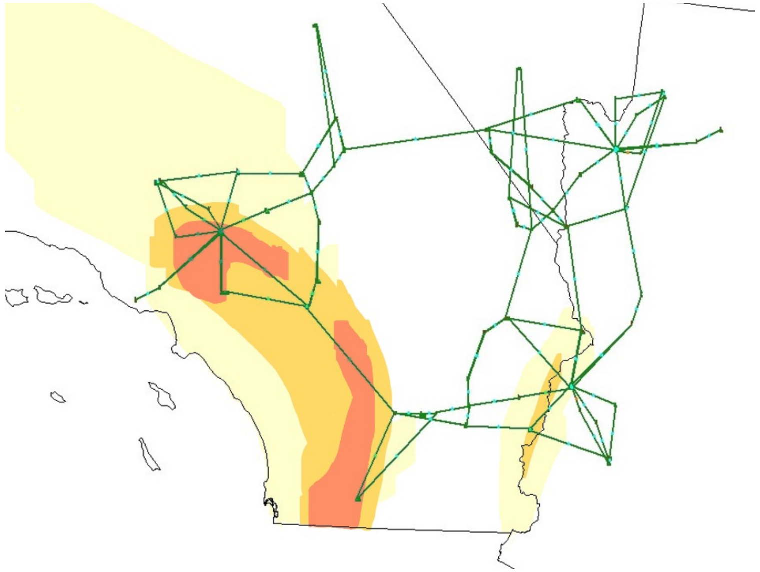
Results



Original (high risk)

- Total risk: 746.2
- Load served: 8550 MW

Results



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Medium risk ($\alpha = 0.01$) ?

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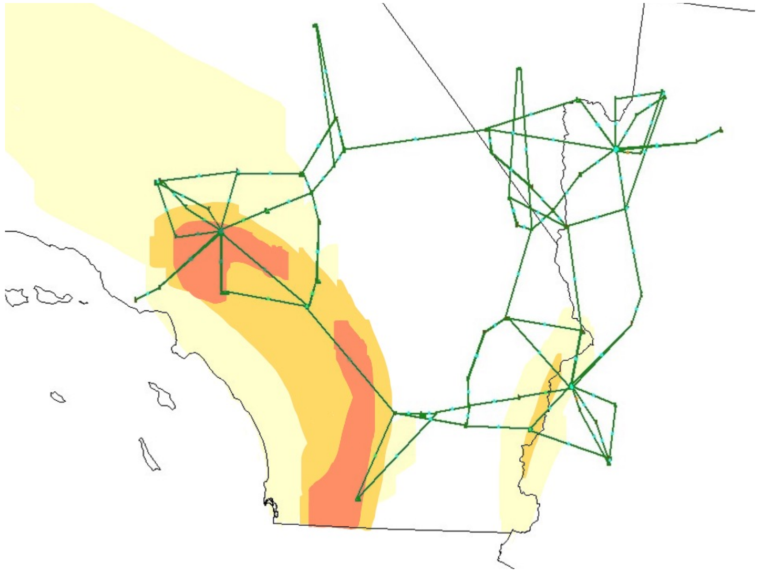

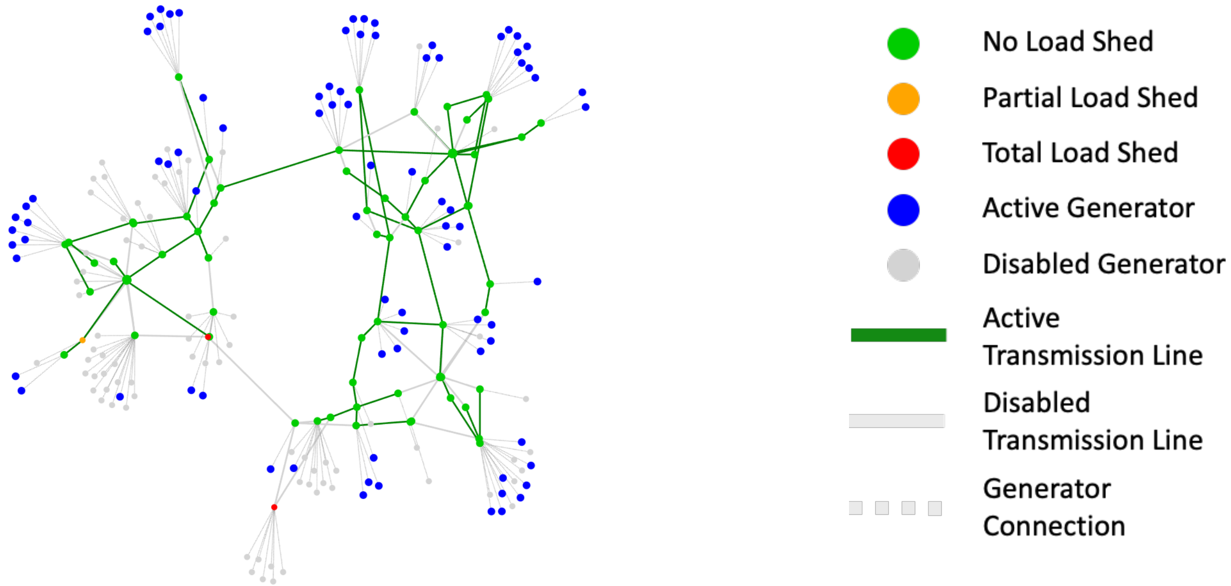

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Medium risk ($\alpha = 0.01$)

Total risk: 319.5 **(-57%)**

Load served: 8540 MW **(-0.1%)**

Solve time: 0.34 sec

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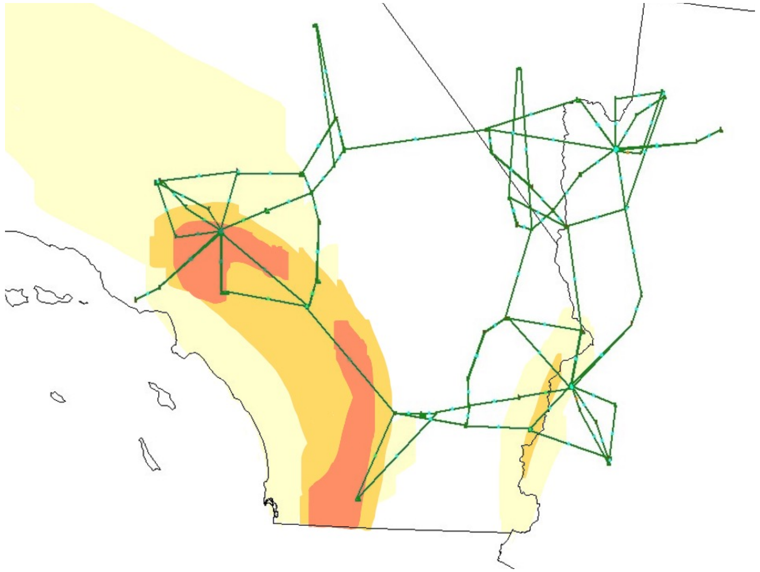

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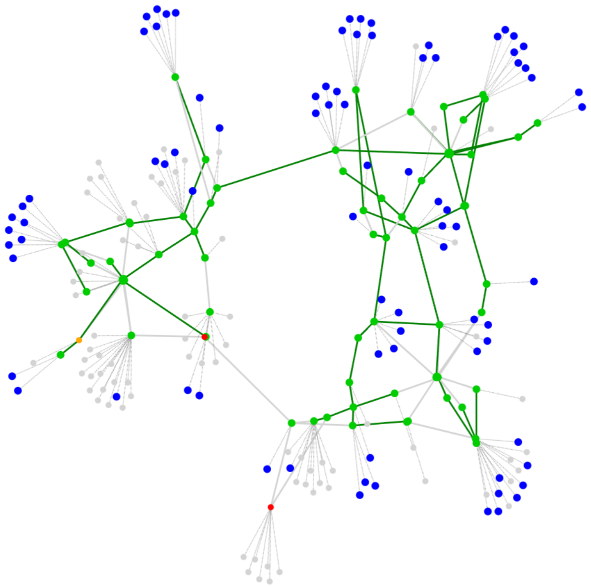

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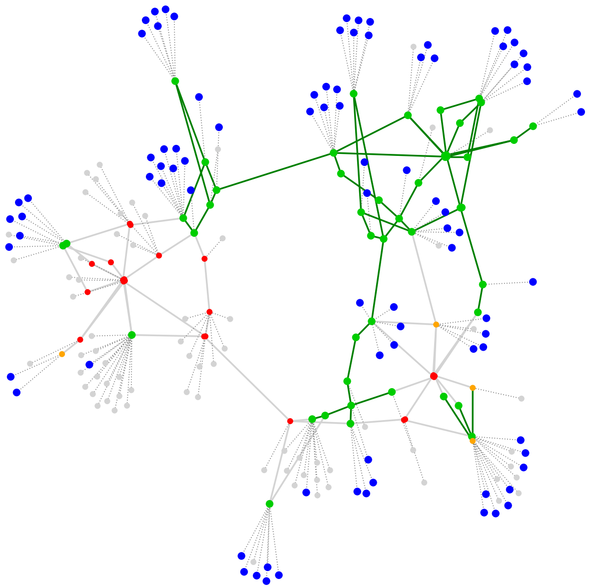


Low risk ($\alpha = 0.15$)

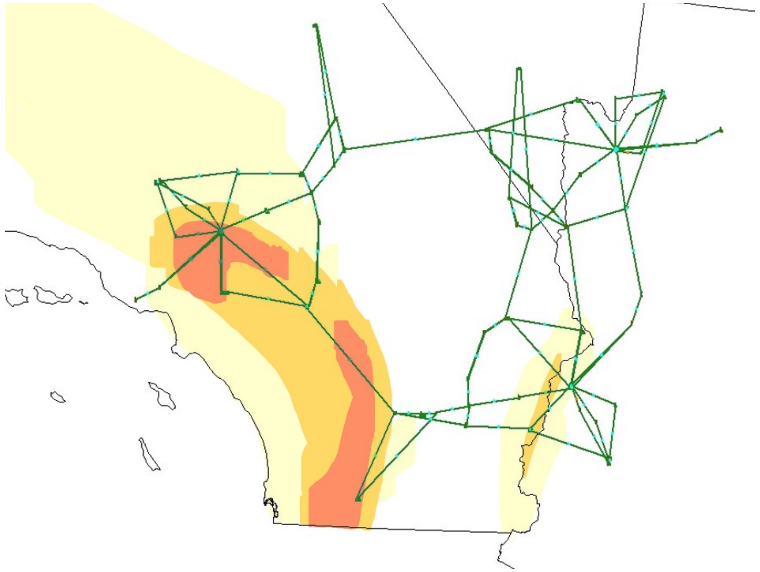
Total risk: 57.4 **(-92%)**

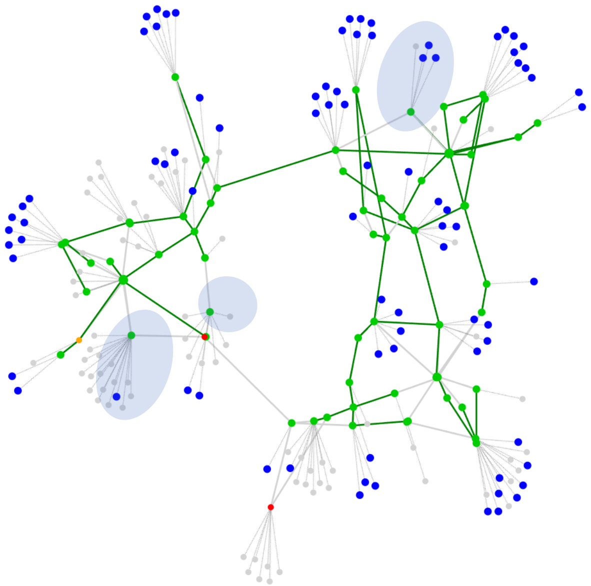
Load served: 7210 MW **(-15.7%)**

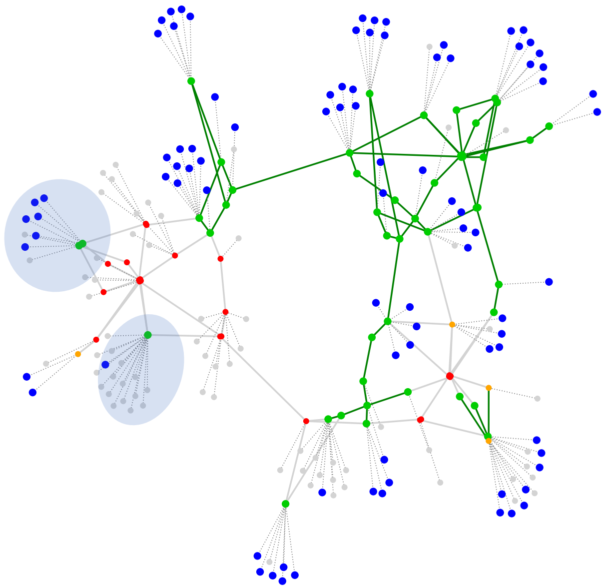
Solve time: 0.33 sec

$$\max \quad (1-\boldsymbol{\alpha})D_{Tot} - \boldsymbol{\alpha}R_{Fire}$$

Results







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Benefits of distributed generation!

Benchmarking

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Transmission risk threshold

$$R_l \geq R_l^{max}$$

- Risk threshold measures **the wildfire risk**, not the resulting impact of electricity delivery

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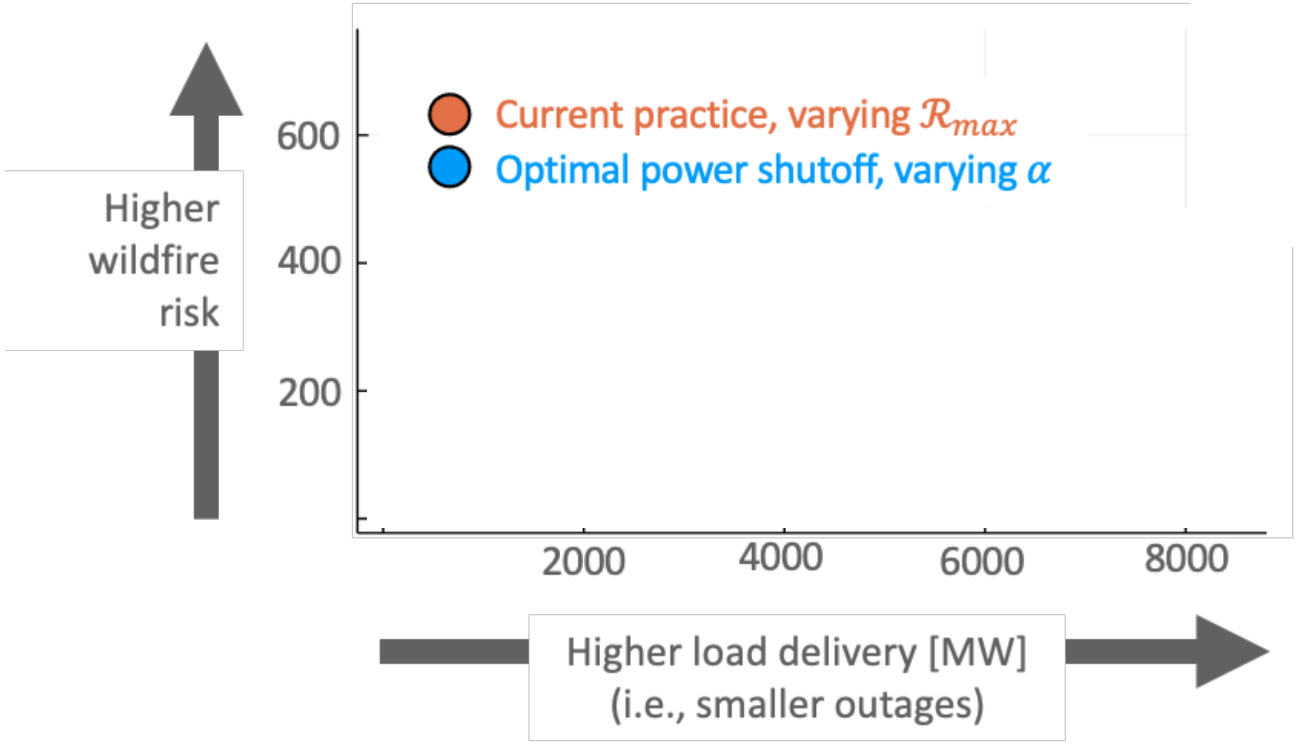
Transmission risk threshold

$$R_l \geq R_l^{max}$$

- Risk threshold measures **the wildfire risk**, not the resulting impact of electricity delivery
- Comparison: Wildfire risk levels and total load delivery obtained with

Current practice Wildfire risk threshold $\boldsymbol{R_l^{max}}$	vs	Optimal Power Shutoff Trade-off parameter $\boldsymbol{\alpha}$

Comparison of performance

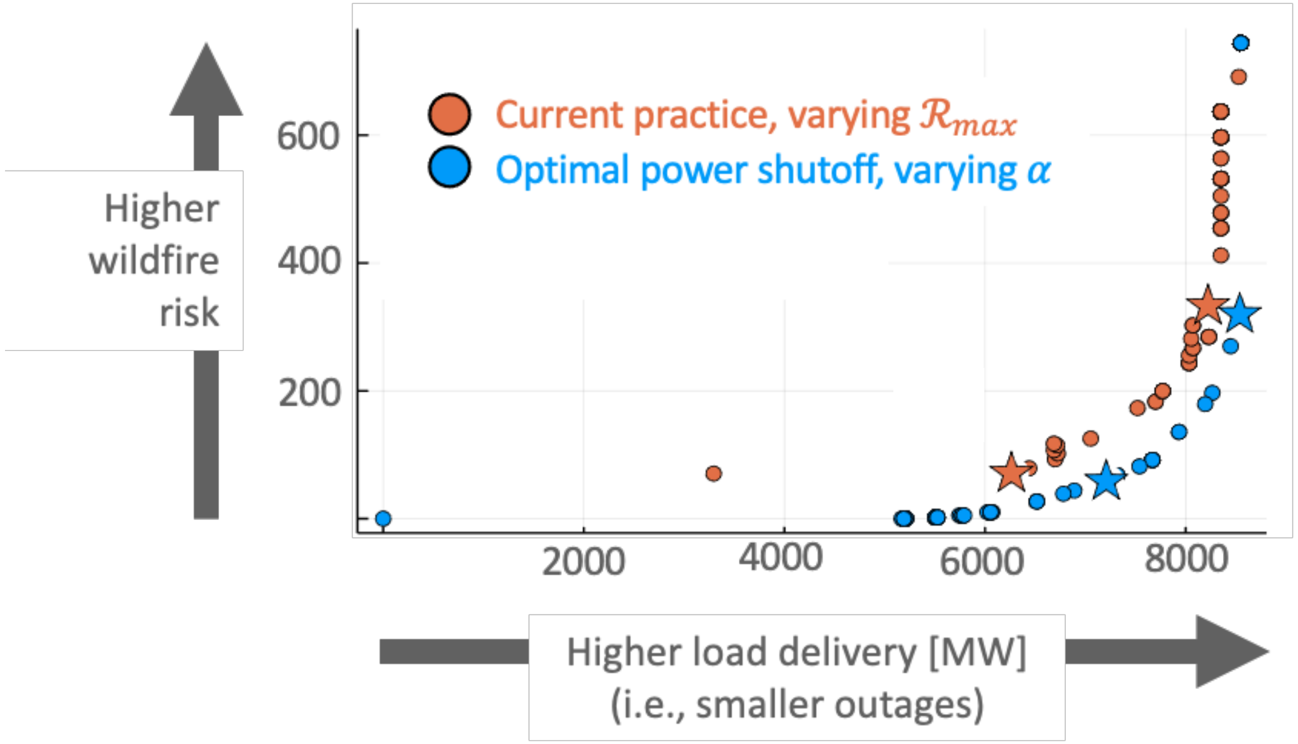


Current practice:
choose risk threshold R_{max}

Optimal power shutoff:
choose trade-off parameter α

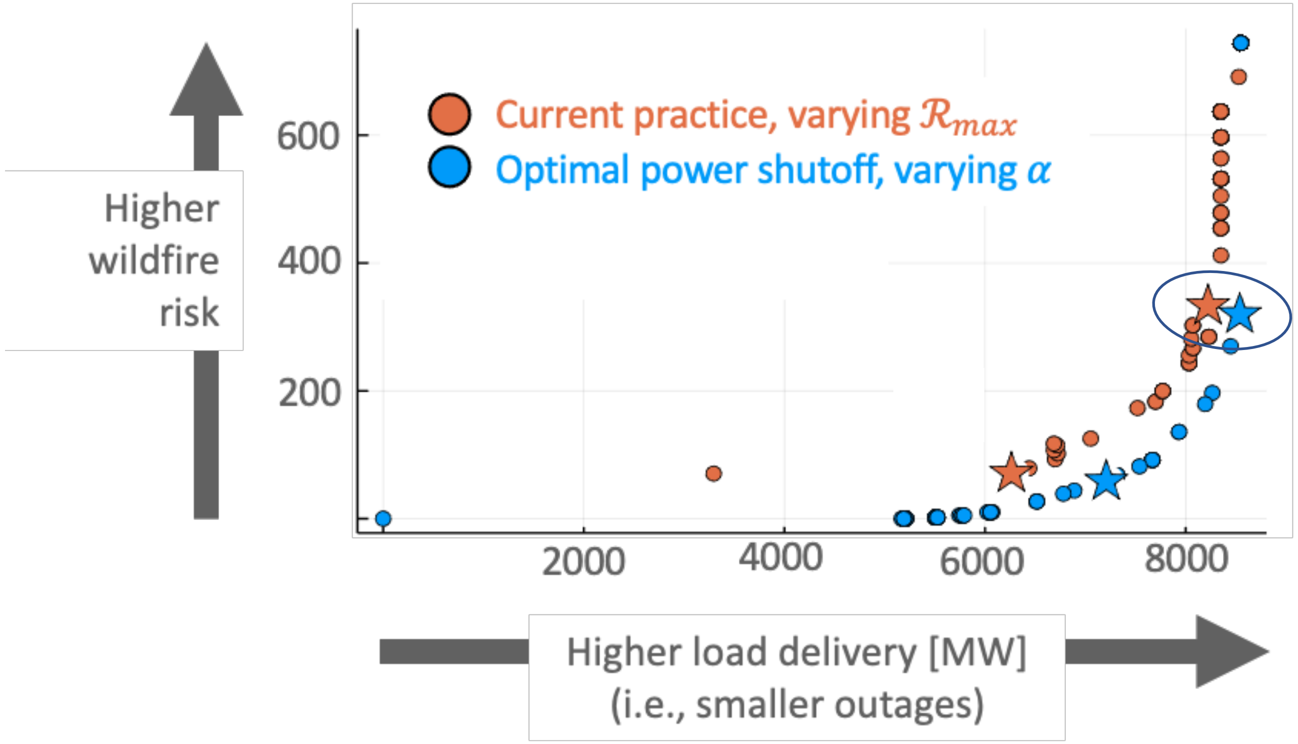
Evaluate wildfire risk and load delivery for different values of R_{max} and α

Comparison of performance



Optimized shutoffs:
lower risk ***and***
smaller outages

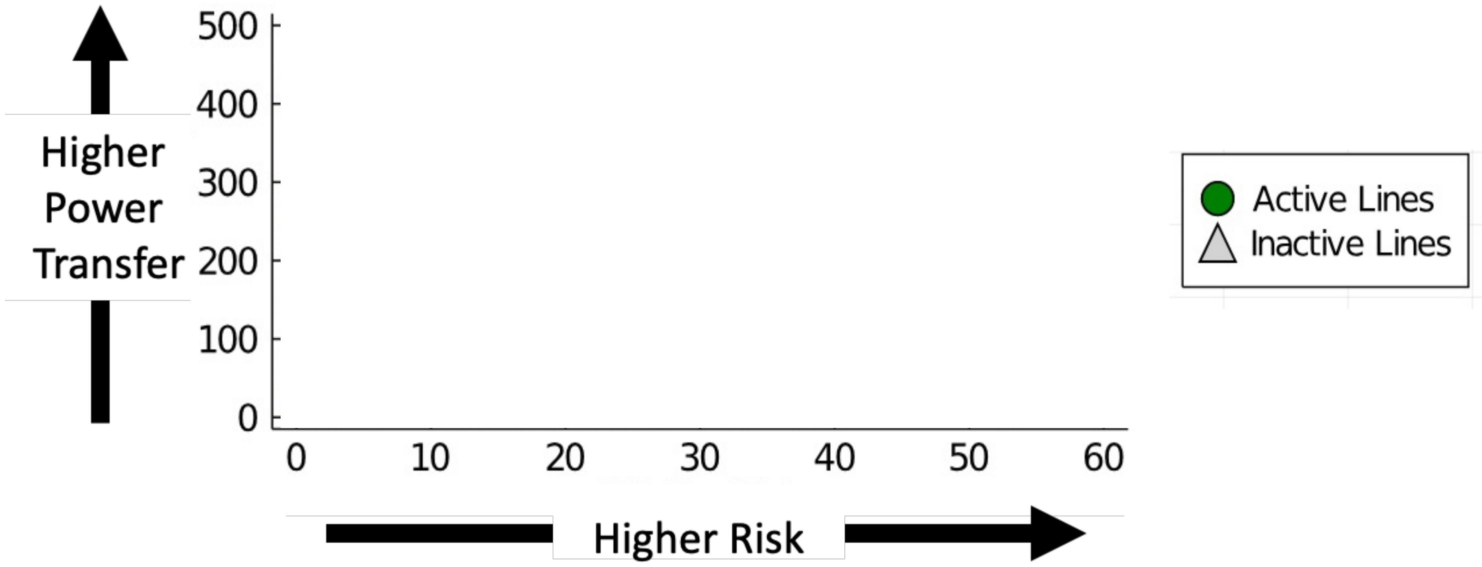
Comparison of performance



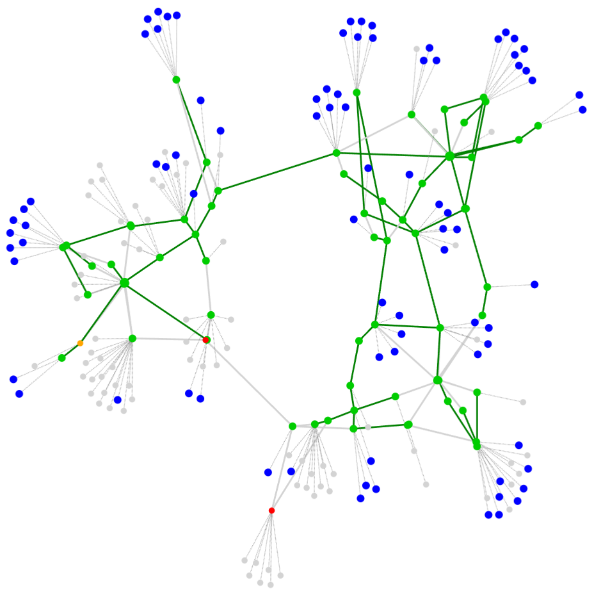
Optimized shutoffs:
*lower risk **and** smaller outages*

How is this possible?

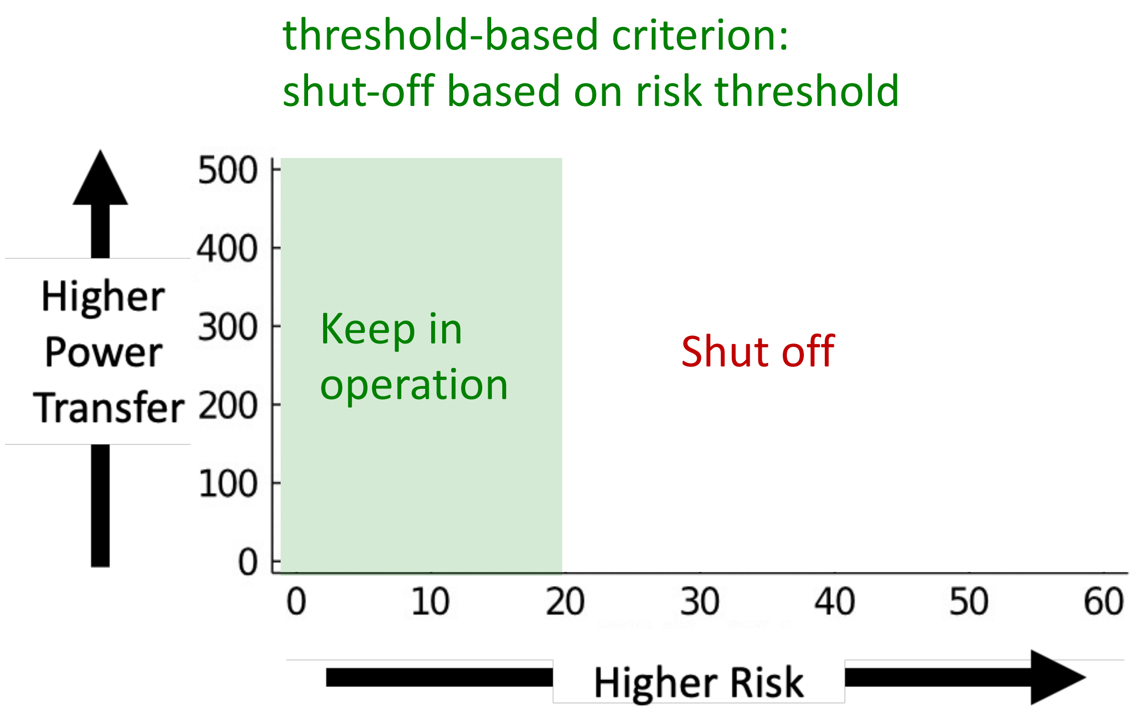
Solutions: Risk and Power Delivery

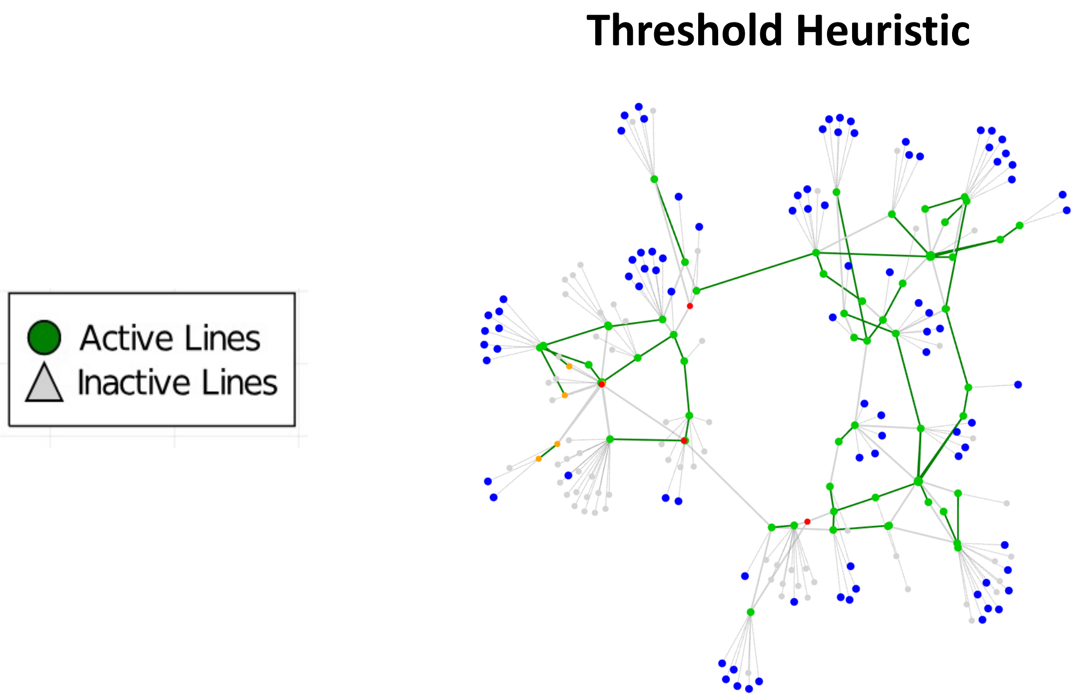


Optimized Shutoff



Solutions: Risk and Power Delivery

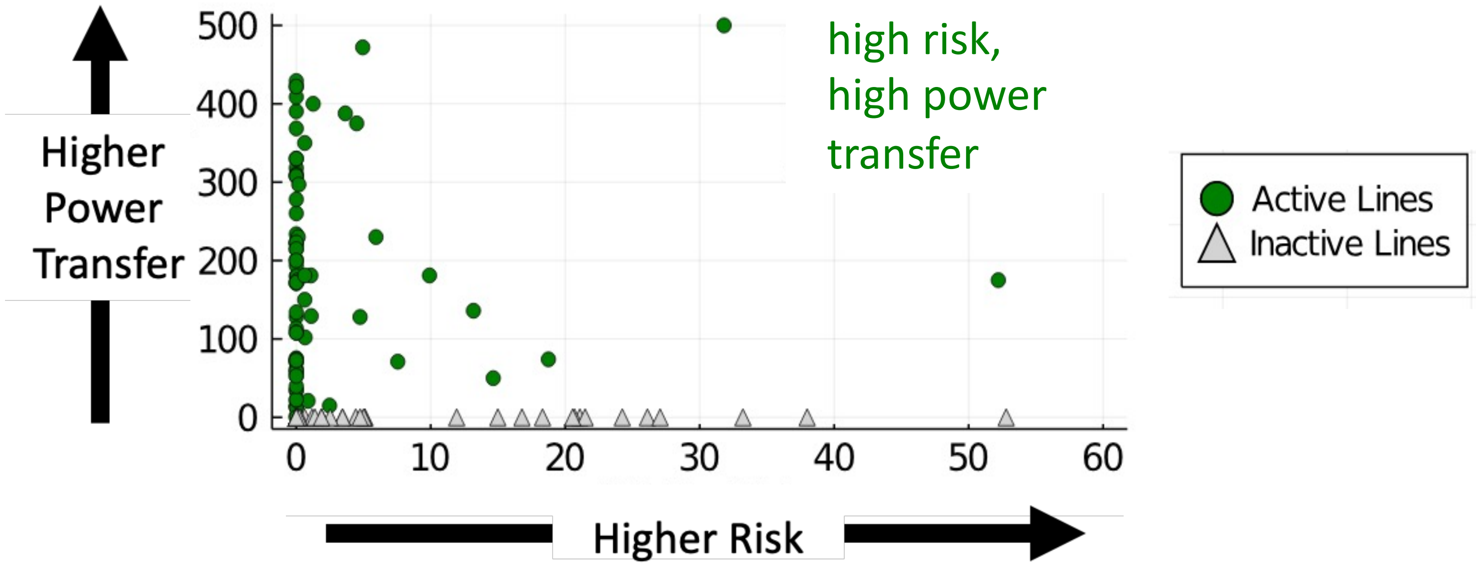




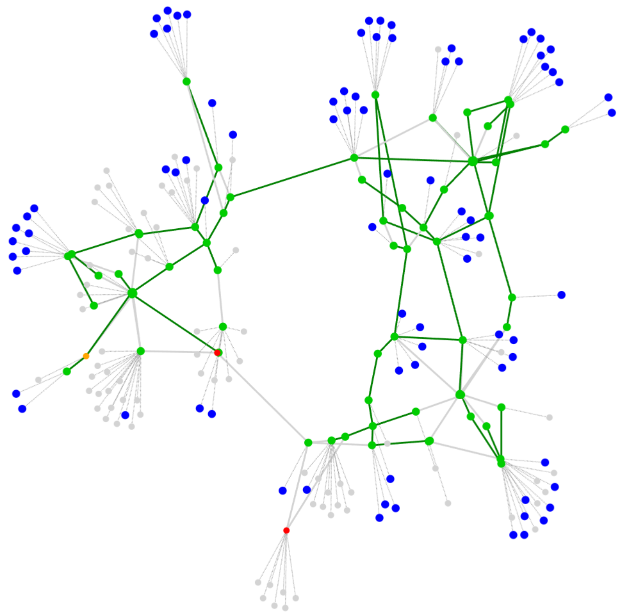
Threshold-based criterion: Shut-off all high-risk lines
Keep all low-risk lines in operation

Prioritize only based on risk !

Solutions: Risk and Power Delivery



Optimized Shutoff



Optimal power shut-off: Some high-risk lines in operation
More medium-risk lines turned off

Prioritize based on risk and power transfer !

Does it scale?

- Randomly assigned risk values, 20 replications

name	buses	min [s]	max [s]	mean [s]	median [s]
case57_ieee	57	0.0290756	0.132359	0.0603549	0.0544262
case73_ieee_rts	73	0.142912	1.09224	0.356261	0.313352
case_89_pegase	89	4.70637	21081.6	3076.19	1042.06
case118_ieee	118	0.160437	1.82306	0.533203	0.443321
case200_activ	200	0.13139	0.632896	0.403812	0.470308
case300_ieee	300	3.26983	163.526	32.6725	11.193
case500_goc	500	0.754107	6.32029	3.12189	2.112

Does it scale?

- Randomly assigned risk values, 20 replications

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- Some outliers…

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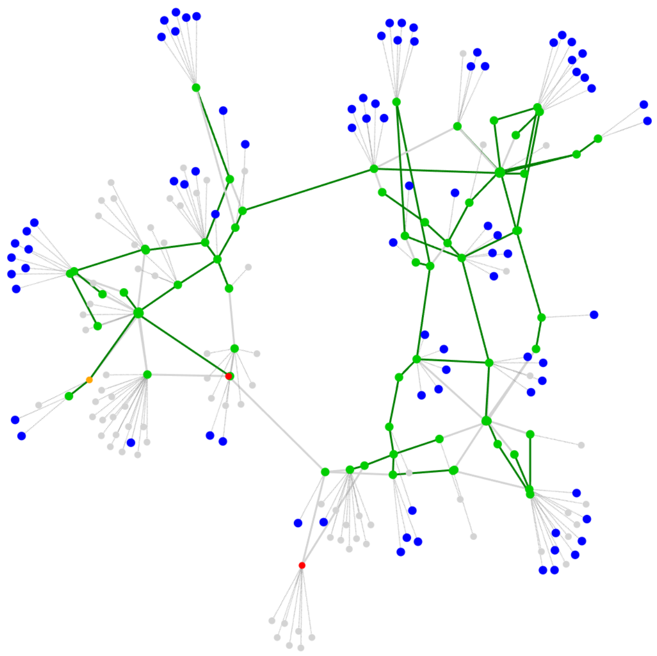
- Most systems solve within a **few seconds** ⇒ indicates that continuous relaxation is tight
- Some **outliers**…

Conclusions

- First method for optimizing public safety power shutoffs, which considers both load delivery and wildfire risk
- Performs consistently better than current practice
- Keeps some high risk lines in operation to keep the lights on for more customers
- Scales surprisingly well!
- Lots of open questions in risk modeling, system optimization, …



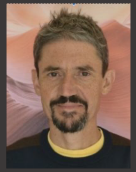
Natural gas and electric grids

Managing shortages and contingencies in the natural gas system

Anatoly Zlotnik (LANL)

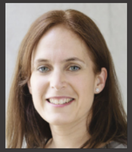






Conor O'Malley (ETH)





A. Zlotnik, L. Roald, S. Backhaus, M. Chertkov, G. Andersson, "Coordinated Scheduling for Interdependent Electric Power and Natural Gas Infrastructures", IEEE Trans. Power Systems, 2017

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C. O'Malley, G. Hug and L. Roald, "Impact of Gas System Modelling on Uncertainty Management of Gas-Electric Systems", submitted

C. O'Malley, G. Hug and L. Roald, "Stochastic Hybrid Approximation for Uncertainty Management in Gas-Electric Systems", submitted, https://arxiv.org/abs/2103.12246

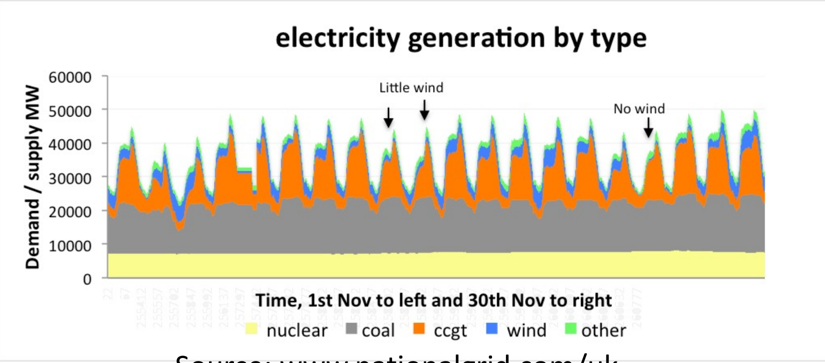
Natural gas – electric system interdependence

Gas-fired power generation is expanding:

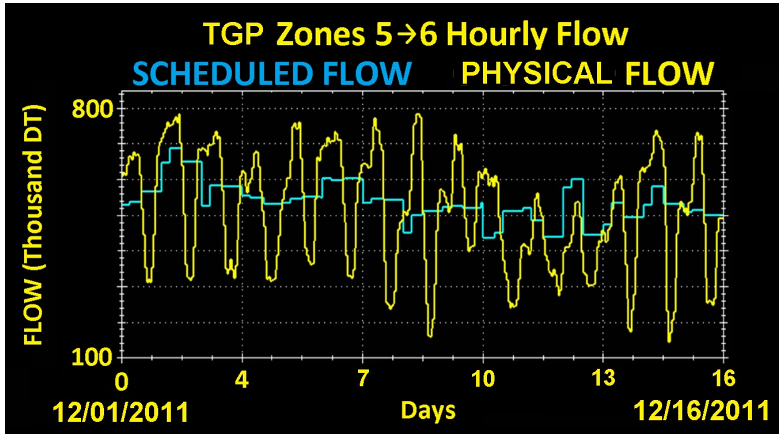
- Economic: Availability of cheap gas
- Environmental: Lower emissions, more flexibility

Gas pipeline loads are changing:

- Increasing in volume & variation
- More intermittent & uncertain



Source: www.nationalgrid.com/uk



Source: El Paso Pipeline

Natural gas - electric system interdepence

Gas-fired power generation is expanding:

- Economic: Availability of cheap gas
- Environmental: Lower emissions, more flexibility

Electric system is vulnerable to disruptions in the natural gas supply chain!

- Residential customers have priority

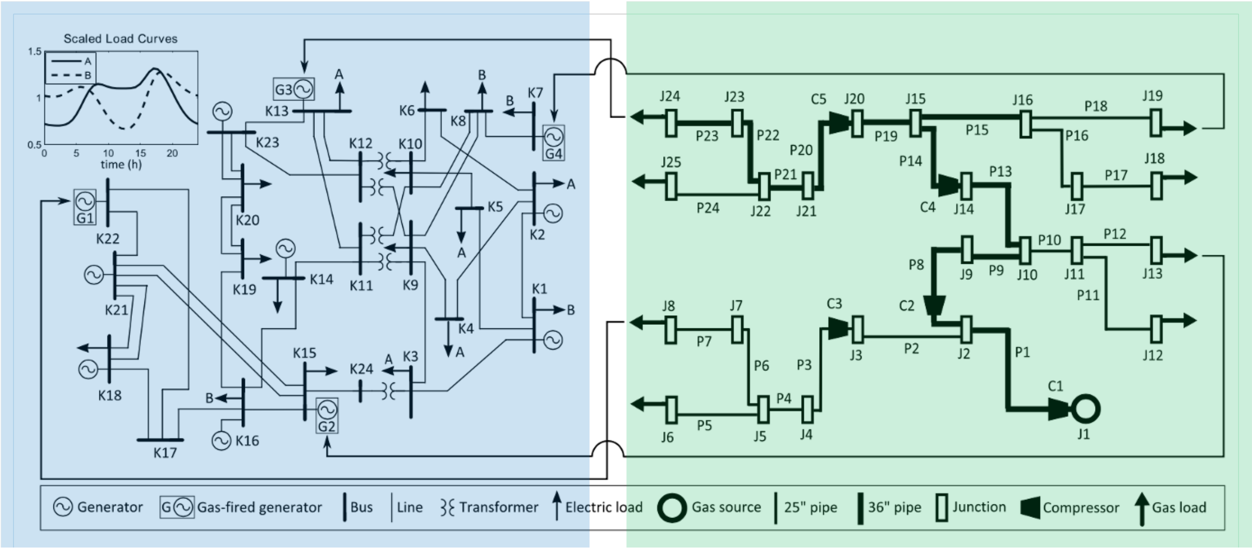
Winter freeze in Texas (Eli Hartman, AP)

Gas leak in Aliso Canyon (EDF)

Avoiding disruption by keeping the gas system safe

- Electric grids reach steady state in seconds
- Electric grids have no internal storage

Electric grid ⟵ Gas demand from gas-fired generation ⟶ **Gas system**

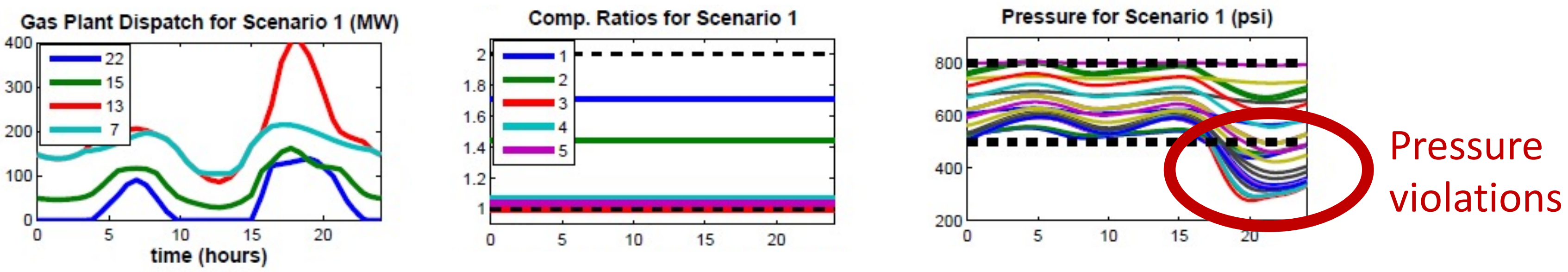


- Gas systems are always operating in a transient dynamic state
- Gas pipelines store a lot of gas internally

Avoiding disruption by keeping the gas system safe

- Dispatch of gas-fired generation can cause pressure violations

With no coordination, dispatch leads to **pressure violations**



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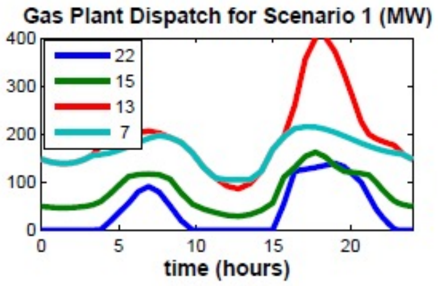
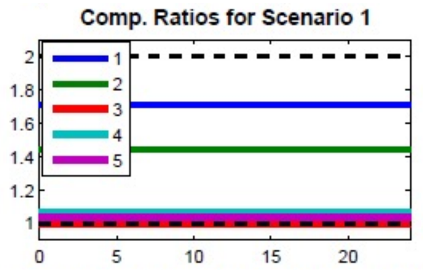
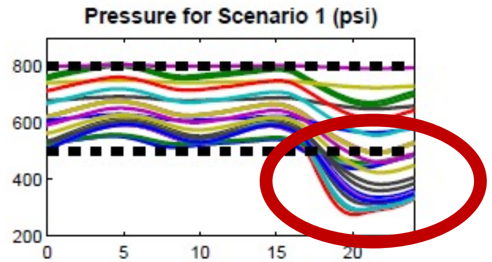
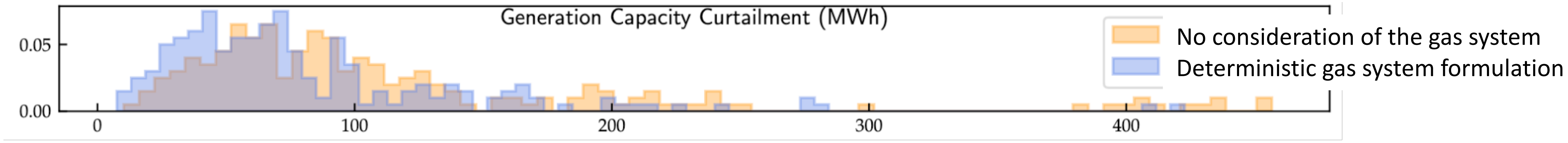






Pressure violations

Pressure drops in the gas system → Curtail gas supply to gas generators → Potential for load shed in the electric grid!



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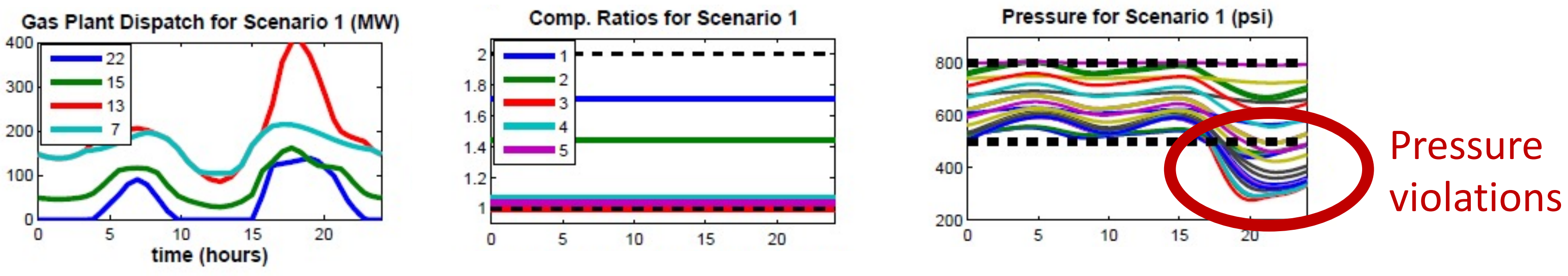
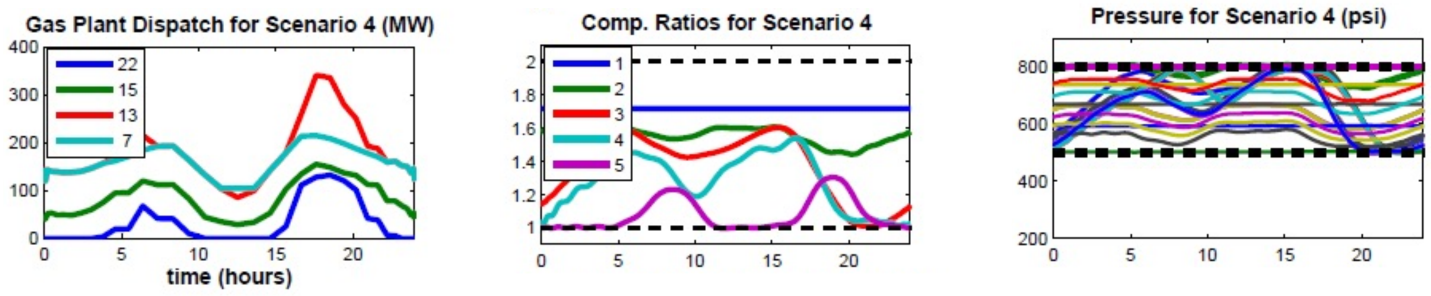


Gas-system aware electric dispatch and predictive modeling **prevents pressure violations**



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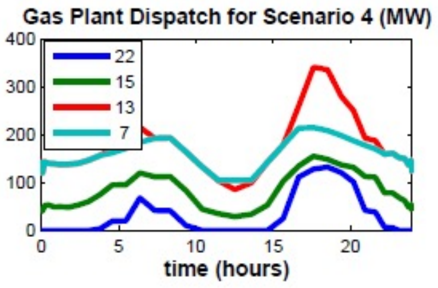
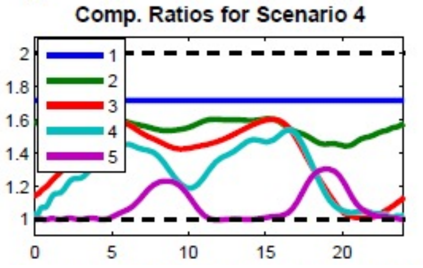
Avoiding disruption by keeping the gas system safe

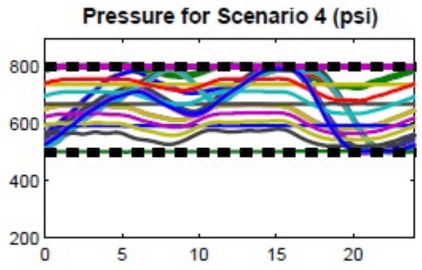
How do we predict how much gas it is safe to withdraw?

Maximum gas constraints: Limit amount of gas drawn

Gas-system aware electric dispatch and predictive modeling **prevents pressure violations**







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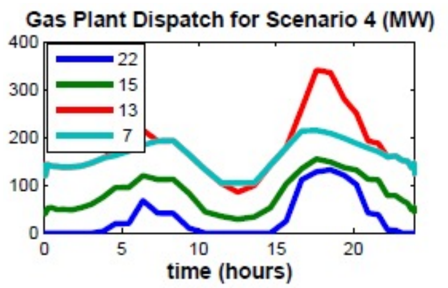
Avoiding disruption by keeping the gas system safe

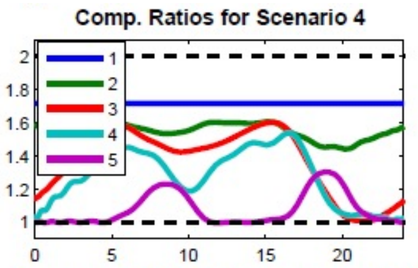
How do we predict how much gas it is safe to withdraw?

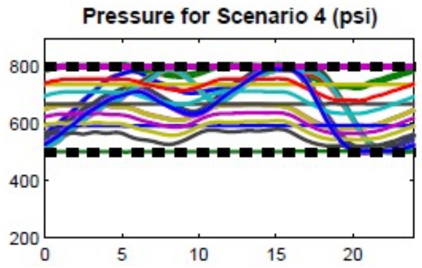
Dynamic gas system models!

Model slow evolution of gas pressure and inherent storage (linepack)

Gas-system aware electric dispatch and predictive modeling **prevents pressure violations**







A. Zlotnik, **L. Roald**, S. Backhaus, M. Chertkov, G. Andersson, "Coordinated Scheduling for Interdependent Electric Power and Natural Gas Infrastructures", IEEE Trans. Power Systems, 2017

Steady-state vs dynamic gas modelling

Steady-state gas system modelling:

Assume that system dynamics have time to settle down

Easier to model and solve!

Dynamic gas system modelling:

Accounting for the effect of changing conditions

More accurate and realistic!

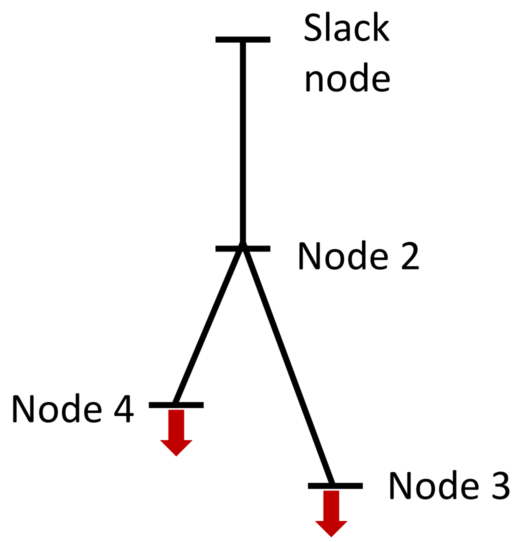
Steady-state vs dynamic gas modelling

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

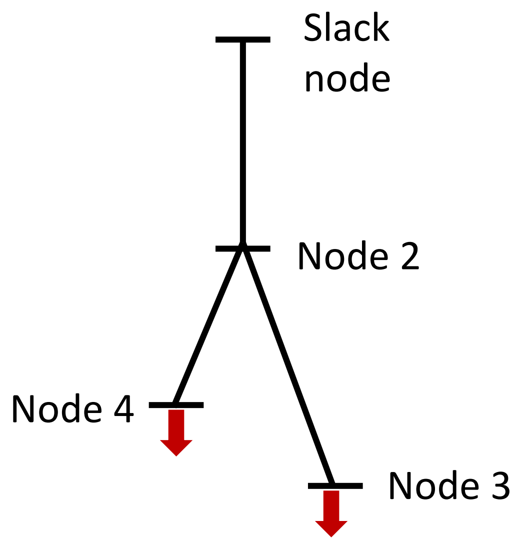
Steady-state vs dynamic gas modelling

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

Assume that system dynamics have time to settle down

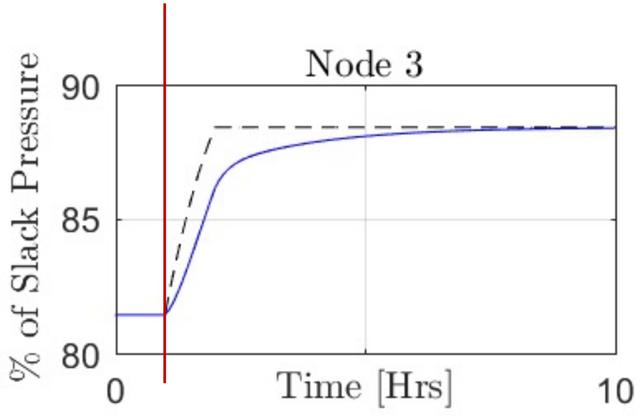
Dynamic gas system modelling:

Accounting for the effect of changing conditions



Start from steady state then swap the loads

Time of load swap



steady-state

dynamic

It takes a LONG time for to reach steady state (more than 5h)!

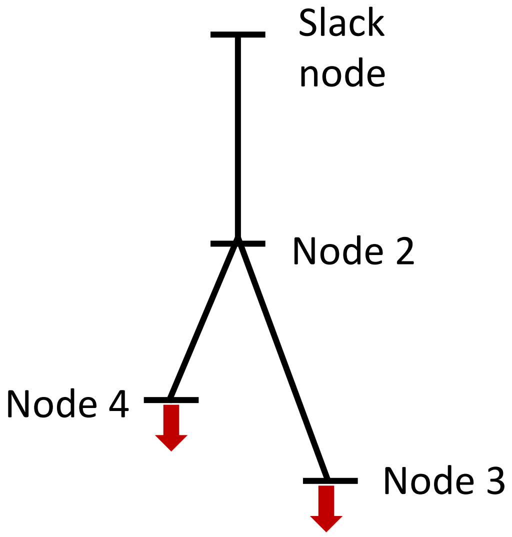
Steady-state vs dynamic gas modelling

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

Assume that system dynamics have time to settle down

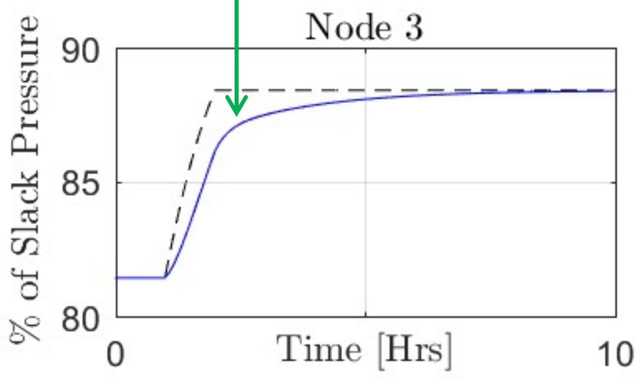
Dynamic gas system modelling: ———————

Accounting for the effect of changing conditions



Start from steady state
then swap the loads

Steady-state conservative:
Underutilized pressure bound



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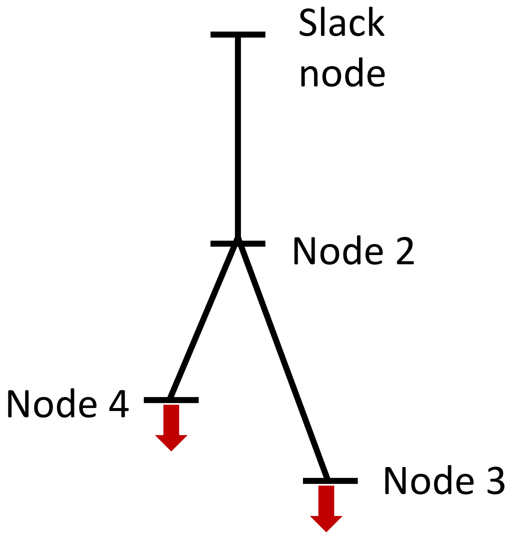

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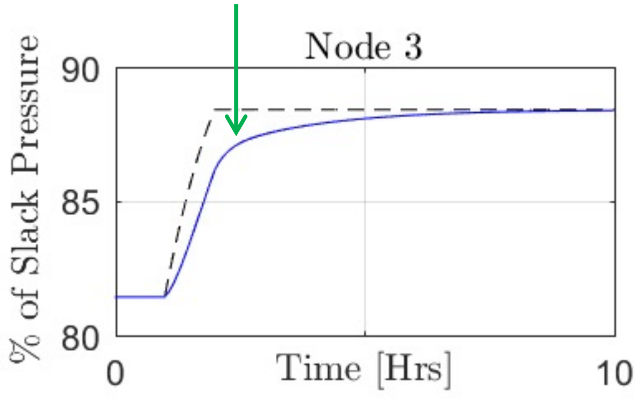
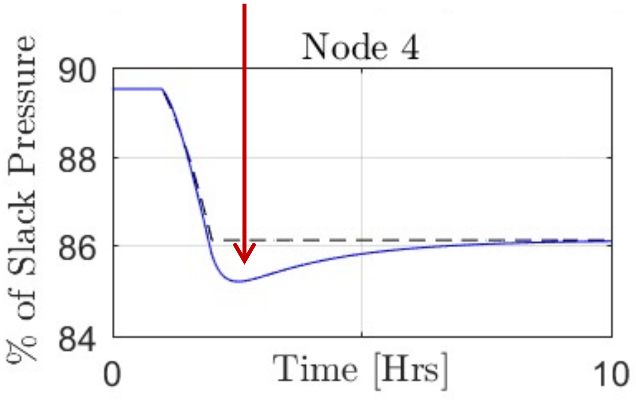


steady-state

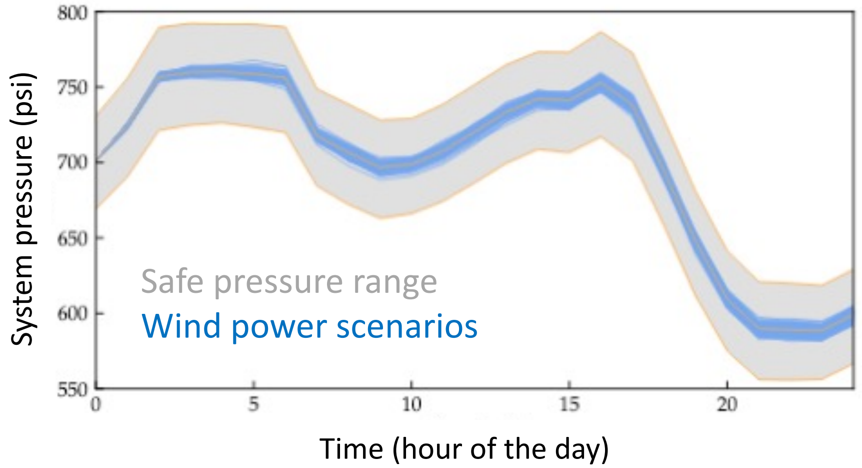
dynamic

Steady-state dangerous:
Pressure drop larger than expected



Why are dynamic models important?

- What happens now impacts the state of the system later!
- Important to predict long-term evolution and build in robustness to uncertain events



Determining safe system operation ranges for different wind power trajectories

L. Roald, K. Sundar, A. Zlotnik, S. Misra and G. Anderson, “An Uncertainty Management Framework for Integrated Gas-Electric Energy Systems”, Proceedings of the IEEE, 2020

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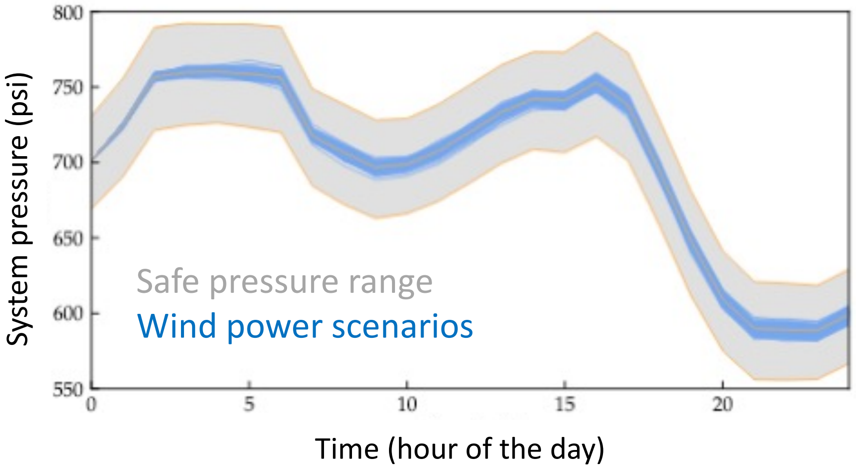

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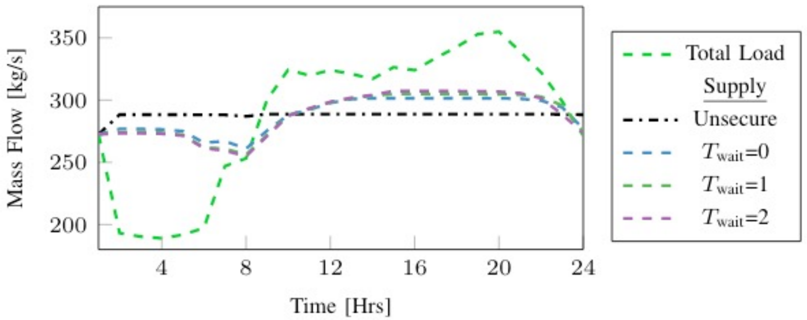


Fig. 4. Total gas supply and demand in network

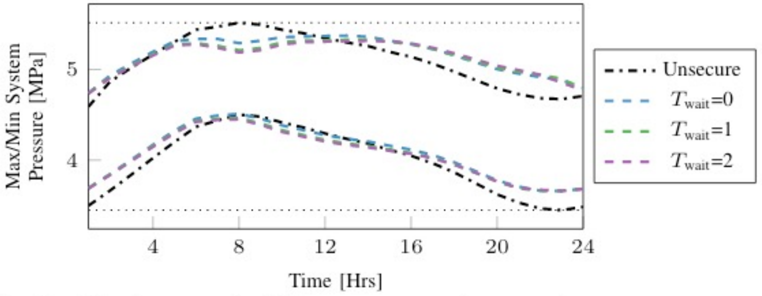


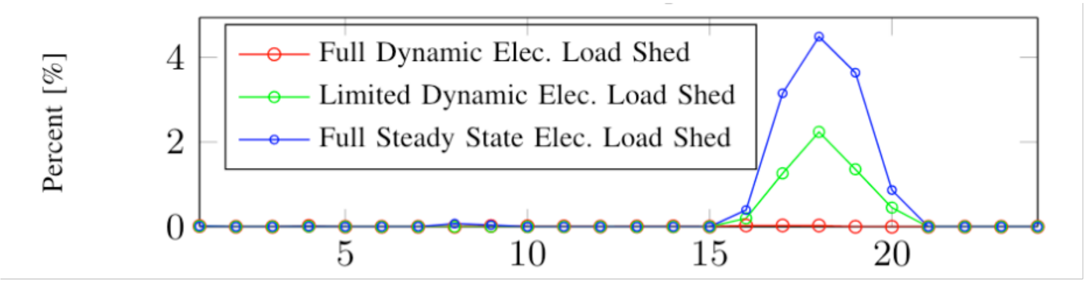
Fig. 5. Maximum and minimum pressure in network

Prepositioning the system to withstand different **gas-system contingencies**

C. O'Malley, **L. Roald**, D. Kourounis, O. Schenk and G. Hug, "Security Assessment in Gas-Electric Networks", Power System Computation Conference, 2018

Why are dynamic models important?

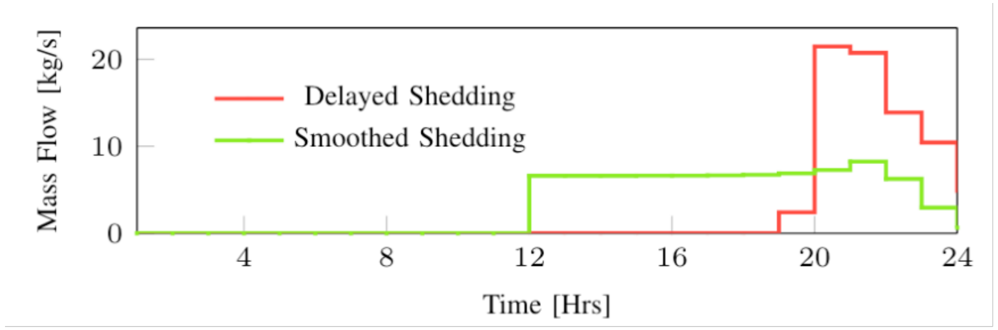
- Gas systems can operate in unbalanced mode: **gas demand > gas supply**



Dynamic models enable larger amount of generation and lower load shed

C. O'Malley, G. Hug and **L. Roald**, "Impact of Gas System Modelling on Uncertainty Management of Gas-Electric Systems", submitted

- Gas system state changes slowly: **there is time to react**!

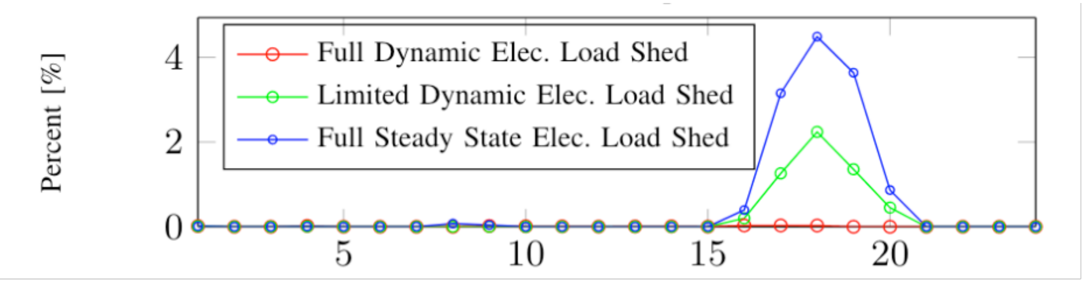


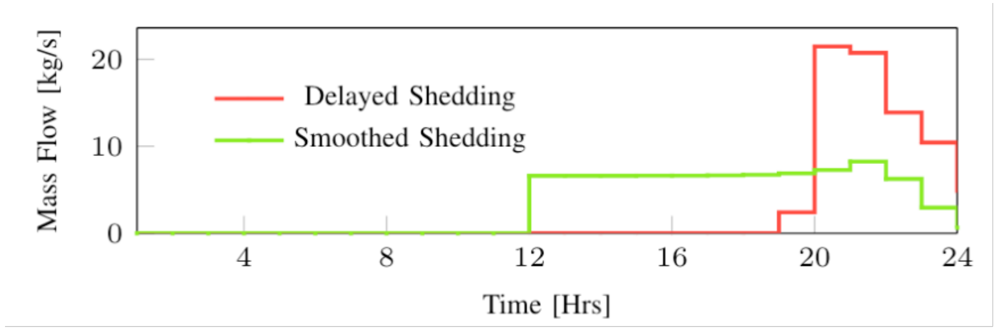
Delaying load shedding after a natural gas contingency may give the electric system time to adapt

C. O'Malley, **L. Roald**, D. Kourounis, O. Schenk and G. Hug, "Security Assessment in Gas-Electric Networks", Power System Computation Conference, 2018

Conclusions

- Gas-fired generation is vulnerable to disruption in natural gas supply
- Understanding gas system dynamics is important to assess limitations and abilities of gas system operation
- Slowly evolving dynamics provide system operators with ability to plan for unbalanced operation and gives more time to react to contingencies





Thank you!

Line A. Roald
roald@wisc.edu