Robust Transmission Planning under Uncertain Generation Investment and Retirement

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PSERC Webinar

April 19, 2016

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Outline

Introduction

Transmission planning is **important** for

- Serving increased demand
- Enhancing reliability
- Relieving congestion
- Facilitating renewable energy penetration

Transmission planning is **challenging** because of

- Long planning horizon
- Multiple stakeholders
- Many sources of uncertainty
- Assessment criteria

Literature review

Literature	Objective	GEP	Uncertainty	Model	Buses	Horizon	AC/DC
[Akbari12]	I + O + L	none	load	SP, multi-obj	24	12 yrs	AC
[Alguacil03]	I + O	none	none	MILP	46	1 period	AC
[Carrion07]	I + L	none	line	SP	48	2 periods	DC
[Chen15]	I + O + L	range	load, GEP	minimax	118	20 yrs	DC
[Choi05]	I	none	line	MILP	21	1 period	DC
[Escobar04]	I + O	none	none	MINP	93	1 period	DC
[Garces09]	I + O	bilevel	load, line	stochastic bilevel	24	10 yrs	DC
[Hemmati14]	I + O	none	load, wind	MINP	24	15 yrs	AC
[Khodaei13]	I + O + L	central	line	MINP	118	20 yrs	DC
[Maghouli11]	I + O	uncertainty	GEP	robust	51	15 yrs	DC
[Moeini12]	I + O + L	none	load, wind	MINP, multi-obj	51	10 yrs	DC
[Munoz14]	I + O	central	policy, fuel	SP	240	3 periods	DC
[Orfanos12]	I + L	none	load, wind	MINP	24	1 period	DC
[Pozo13]	I + O	bilevel	load, wind	trilevel	34	1 period	DC
[Sepasian09]	I	central	none	MINP	49	10 yrs	DC
[Shrestha04]	I + O	none	none	MINP	24	8 yrs	DC
[Torre08]	I + O	none	load, fuel, GEP	MINP	23	1 yr	AC
[Weijde12]	I + O	central	load, policy	SP	7	2 periods	DC
[Yu09]	I	none	load, wind	chance MINP	24	1 period	DC
[Zhang12]	I + O	none	none	MINP	118	10 yrs	DC
[Zhao09]	I + L	uncertainty	load, fuel, GEP	MINP	14	1 period	DC
This model	I + O + L	uncertainty	GEP, policy, fuel	min-max-min	240	20 yrs	DC

I: Investment cost. O: Operations cost. L: Load curtailment. GEP: Generation expansion planning. SP: Stochastic programming.

Outline

Proposed model

- **Planning horizon:** Multiple decision-making periods
- **Decisions:** Candidate transmission lines
- **Uncertainty:** Candidate generators investment and retirement, gas prices, and policies
- **Objective:** Minimize cost (investment, operations, and load-curtailment costs) under the worst case scenario

Robust optimization illustration

	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}	s_{12}
d_1	1	4	8	4	8	3	5	9	6	2	3	6
d_2	9	9	6	1	4	4	3	7	4	3	9	3
d_3	1	2	4	3	7	6	7	5	4	5	4	6
d_4	7	3	5	9	4	1	2	4	5	3	2	7
d_5	8	2	4	5	1	1	7	5	4	8	9	2
d_6	8	2	1	5	2	2	2	3	9	2	9	2
d_7	1	8	3	4	7	6	4	5	2	3	4	3
d_8	4	6	2	9	9	7	6	5	5	2	2	3
d_9	3	5	2	4	6	6	8	8	6	3	3	4
d_{10}	8	2	3	2	1	5	1	8	6	4	4	5

Robust optimization illustration

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Robust optimization illustration

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d_5	8	2	4	5	1	1	7	5	4	8	9	2
d_6	8	2	1	5	2	2	2	3	9	2	9	2
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Robust optimization illustration

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d_8	4	6	2	9	9	7	6	5	5	2	2	3
d_9	3	5	2	4	6	6	8	8	6	3	3	4
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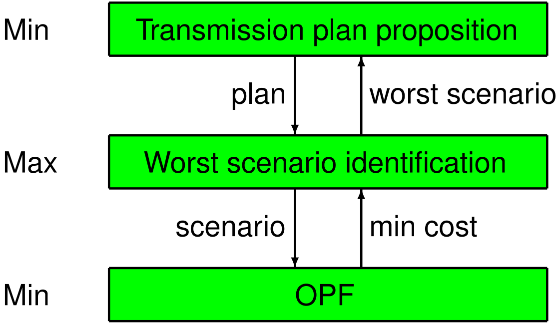
- Decision space: 3×10^{12}
- Scenario space: 1×10^{49}

Trilevel modeling framework



Trilevel formulation

$$\min_{x\in\mathcal{X}} \left\{ C^{\mathsf{I}}(x) + \max_{g\in\mathcal{G}} \min_{z\in\mathcal{Z}(x,g)} C^{\mathsf{O}}(x,g,z) \right\}$$

- $x \in \mathcal{X}$: Transmission planning decisions, upper level
- $C^{\mathsf{I}}(x)$: Investment cost
- $g \in \mathcal{G}$: Generation scenarios, middle level
- $z \in \mathcal{Z}(x,g)$: Operations decisions, lower level
- $C^{\mathsf{O}}(x,g,z)$: Operations and load curtailment cost

Algorithm – Motivation

$$\min_{x \in \mathcal{X}} \left\{ C^{\mathsf{I}}(x) + \max_{g \in \mathcal{G}} \min_{z \in \mathcal{Z}(x,g)} C^{\mathsf{O}}(x, g, z) \right\}$$

$$\Updownarrow$$

$$\min_{x \in \mathcal{X}, z(g) \in \mathcal{Z}(x,g)} \left\{ C^{\mathsf{I}}(x) + \zeta : \zeta \geq C^{\mathsf{O}}(x, g, z(g)), \forall g \in \mathcal{G} \right\}$$

For any $\hat{\mathcal{G}} \subseteq \mathcal{G}$, the following is a relaxation.

$$\min_{x \in \mathcal{X}, z(g) \in \mathcal{Z}(x,g)} \left\{ C^{\mathsf{I}}(x) + \zeta : \zeta \geq C^{\mathsf{O}}(x, g, z(g)), \forall g \in \hat{\mathcal{G}} \right\}$$

Algorithm – Steps

Step 0: Initialize $\hat{\mathcal{G}} \subseteq \mathcal{G}$ and go to Step 1.
Step 1: Solve the following, get optimal x^{R}, and go to Step 2.

$$\min_{x \in \mathcal{X}, z(g) \in \mathcal{Z}(x,g)} \left\{ C^{\mathsf{I}}(x) + \zeta : \zeta \geq C^{\mathsf{O}}(x, g, z(g)), \forall g \in \hat{\mathcal{G}} \right\}$$

Step 2: Solve the following and get optimal g^{W}.

$$\max_{g \in \mathcal{G}} \min_{z \in \mathcal{Z}(x^{\mathsf{R}}, g)} C^{\mathsf{O}}(x^{\mathsf{R}}, g, z)$$

if $g^{W} \in \hat{\mathcal{G}}$ **then**
  Stop. x^{R} is optimal.
else
  Update $\hat{\mathcal{G}} \leftarrow \hat{\mathcal{G}} \cup \{g^{\mathsf{W}}\}$ and go to Step 1.
end

Algorithm – Illustration

	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}	s_{12}
d_1	1	4	8	4	8	3	5	9	6	2	3	6
d_2	9	9	6	1	4	4	3	7	4	3	9	3
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d_4	7	3	5	9	4	1	2	4	5	3	2	7
d_5	8	2	4	5	1	1	7	5	4	8	9	2
d_6	8	2	1	5	2	2	2	3	9	2	9	2
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Algorithm – Illustration

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Algorithm – Illustration

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Algorithm – Illustration

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Algorithm – Illustration

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d_6	8	2	1	5	2	2	2	3	9	2	9	2
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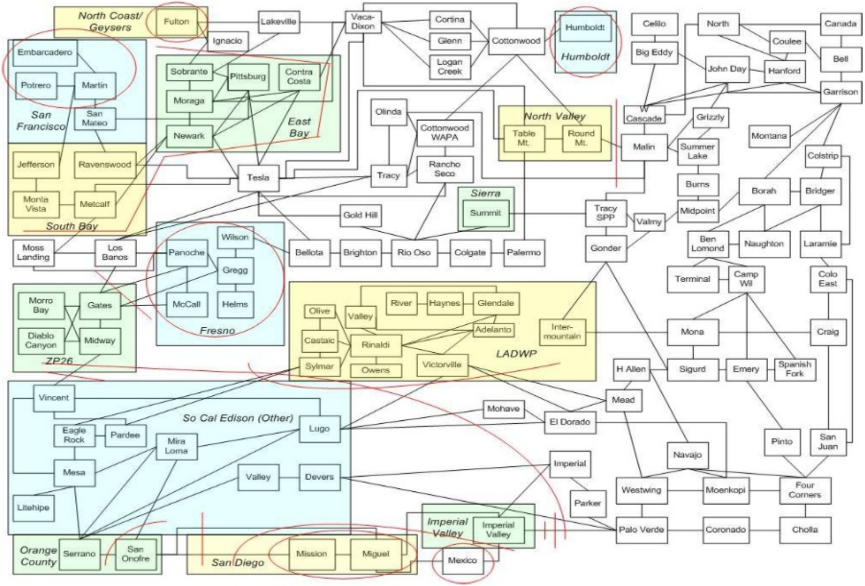
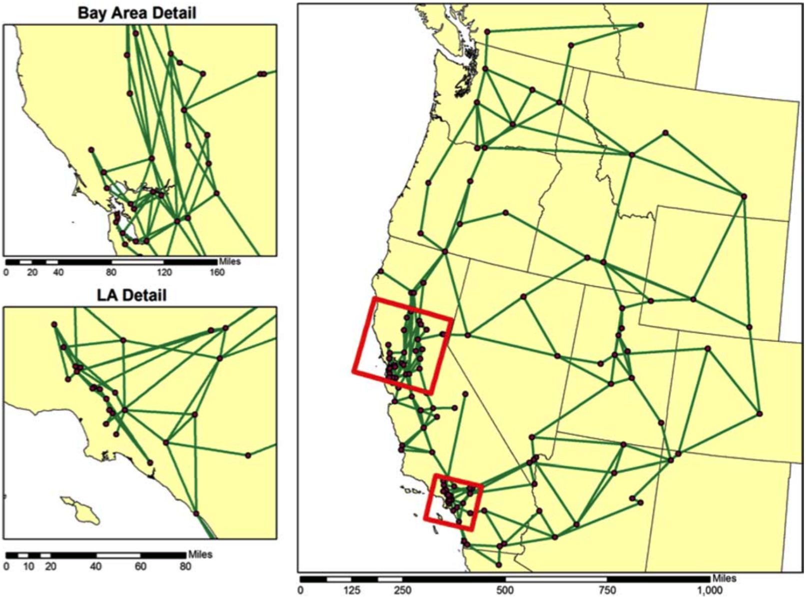
Outline

WECC 240-bus test system [Price2011]



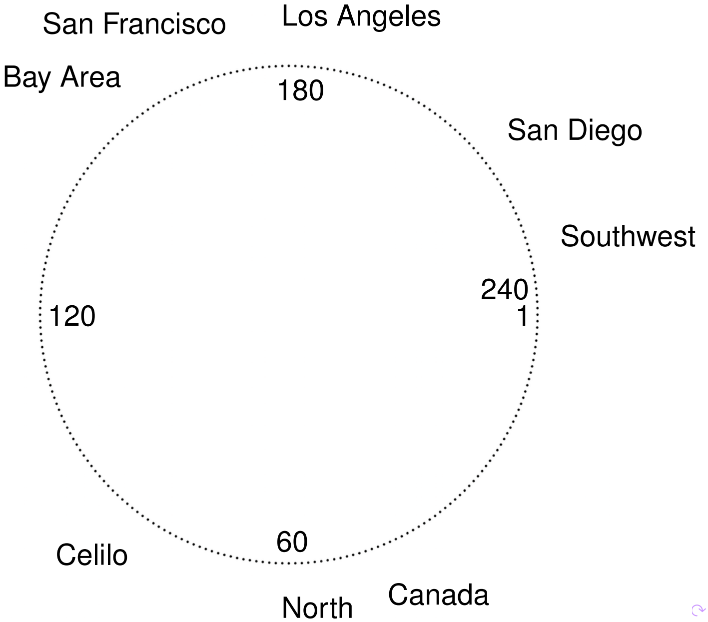
WECC 240-bus test system [Munoz14]



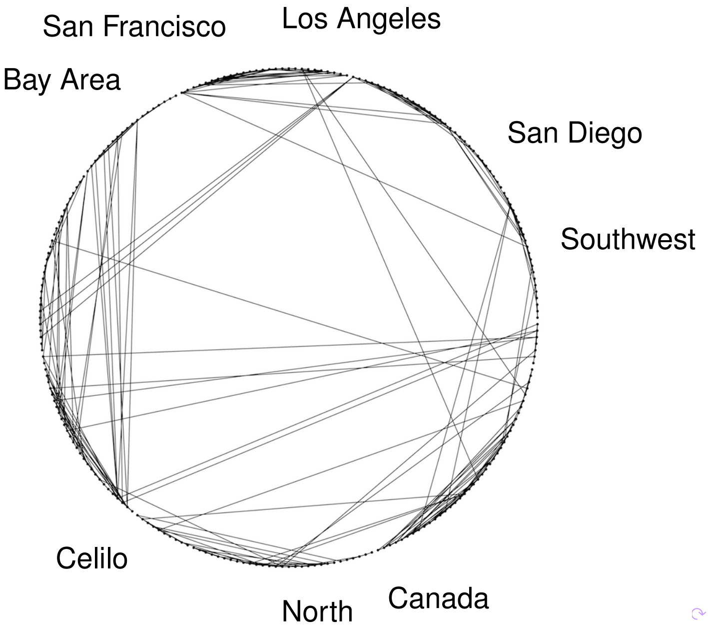
Assumptions

- **Planning horizon:** Four 5-year periods.
- **Solution space:** 18 candidate lines. More than 3×10^{12} (three trillion) feasible solutions.
- **Uncertainty space:**
  - **GEP:** 53 candidate generators for investment and 17 coal generators for retirement. Almost 10^{49} scenarios.
  - **Policy:** 20% or 40% mandate of new renewables
  - **Natural gas prices:** Low or high
  - **Demand:** Constant 0.1% annual load growth [EIA 2015].

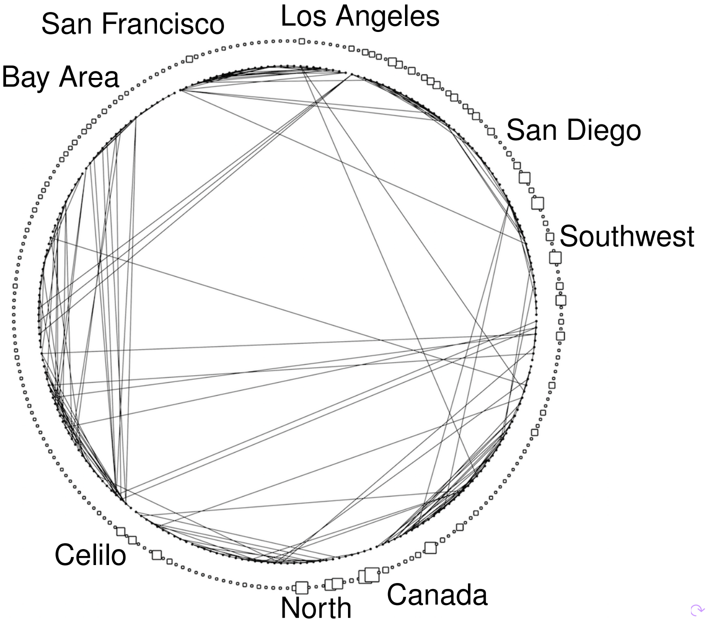
240 buses


San Francisco
Los Angeles
Bay Area
180
San Diego
Southwest
240
1
120
60
Celilo
Canada
North

448 lines

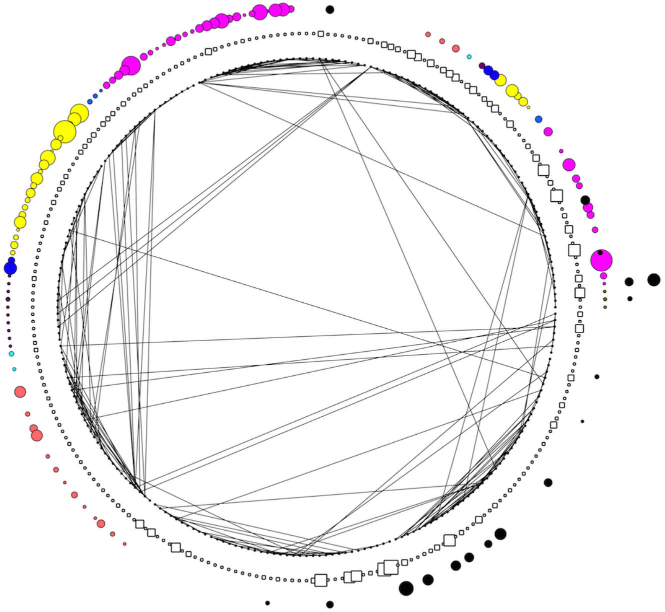

San Francisco
Los Angeles
Bay Area
San Diego
Southwest
Celilo
Canada
North

Demand

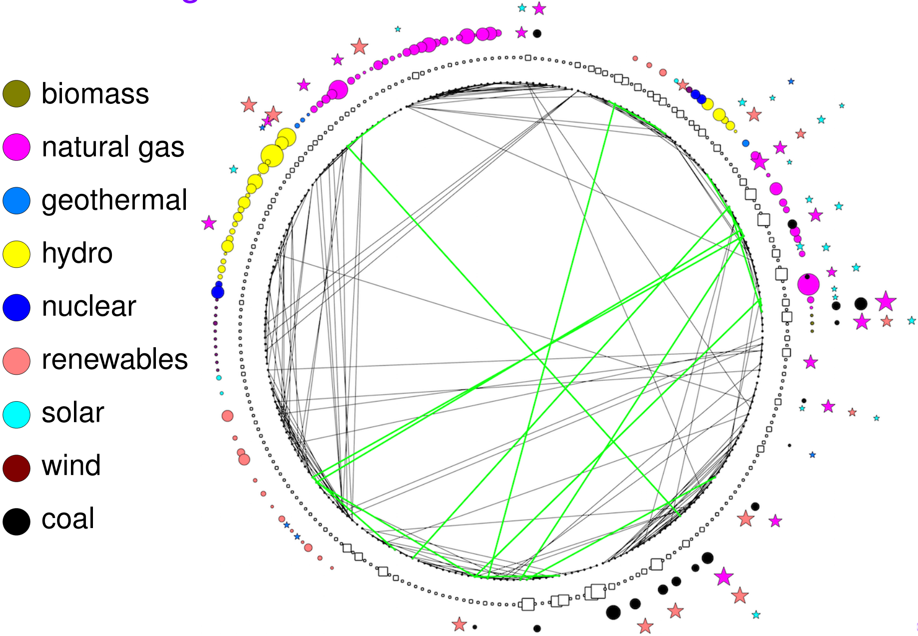

San Francisco
Los Angeles
Bay Area
San Diego
Southwest
Celilo
Canada
North

Existing generators

- biomass
- natural gas
- geothermal
- hydro
- nuclear
- renewables
- solar
- wind
- coal



Candidate generators and transmission lines



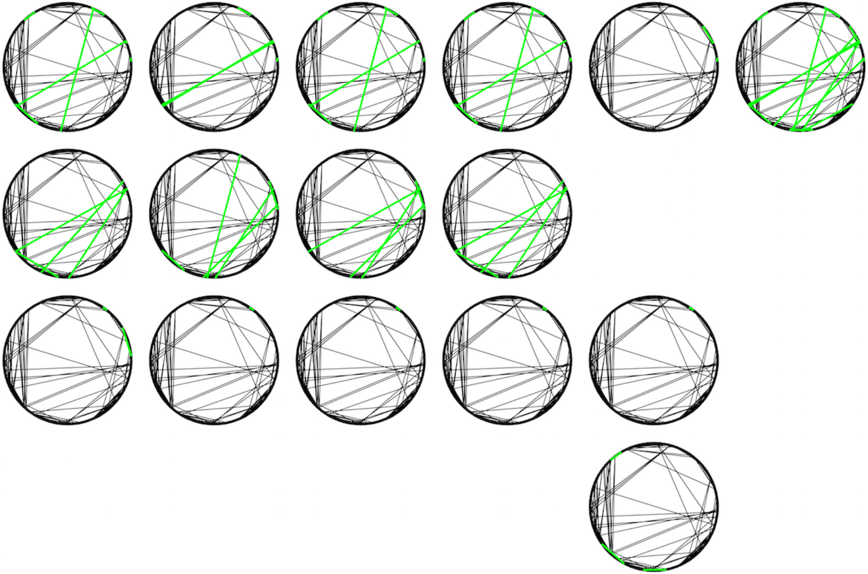
Four futures

- Future 1: 20% new renewables and high gas prices
- Future 2: 20% new renewables and low gas prices
- Future 3: 40% new renewables and high gas prices
- Future 4: 40% new renewables and low gas prices

Six transmission expansion plans

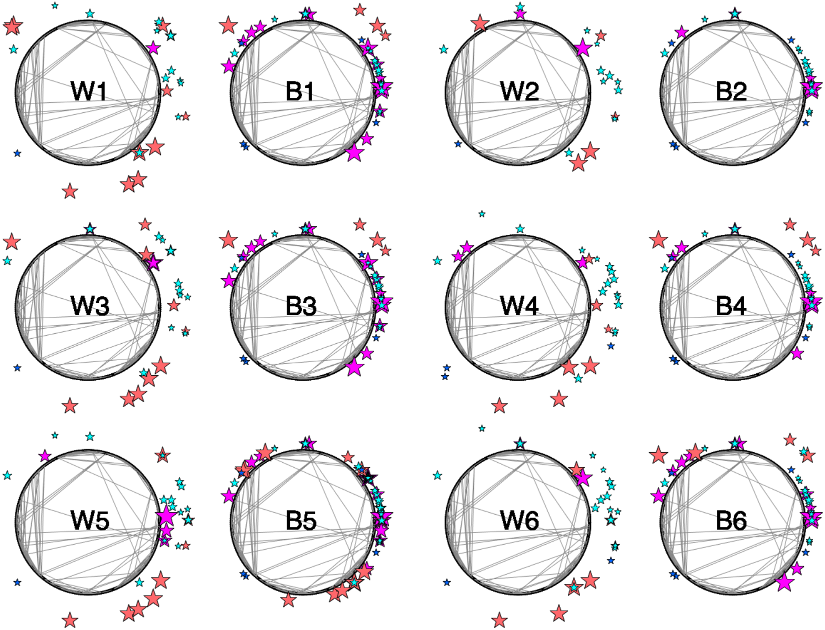
- Plan 1: Optimal under future 1
- Plan 2: Optimal under future 2
- Plan 3: Optimal under future 3
- Plan 4: Optimal under future 4
- Plan 5: Too little and too late investment
- Plan 6: Too much and too early investment

Six transmission plans

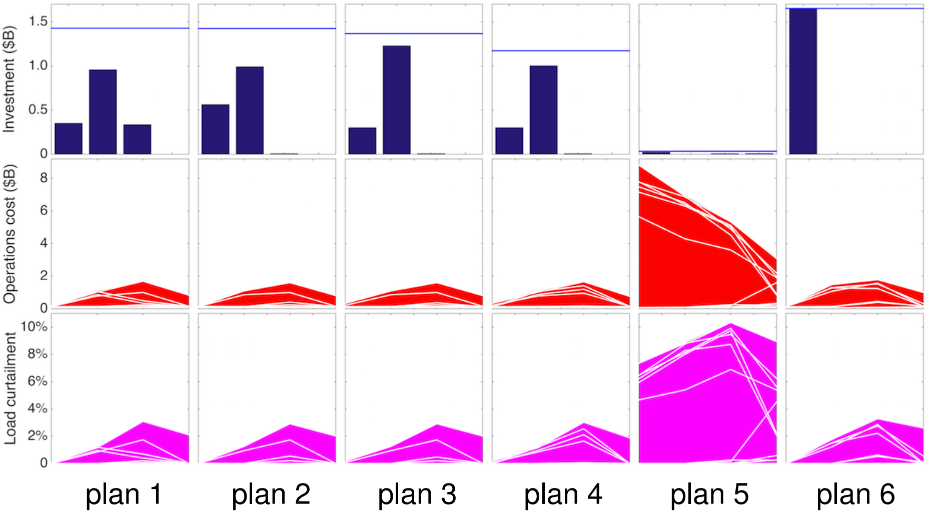


plan 1 plan 2 plan 3 plan 4 plan 5 plan 6

Twelve scenarios



Investment, operations, and load curtailment costs



Summary

- Uncertainty in generator investment and retirement
- Robust optimization model for assessment of transmission planning
- Trilevel optimization model and algorithm
- New visualization techniques
- Bokan Chen and Lizhi Wang, “Robust transmission planning under uncertain generation investment and retirement,” to appear in *IEEE Transactions on Power Systems*.

Thank you

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