Assessing Transmission Investments Under Uncertainty

CERTS
Reliability & Markets

Internal Program Review

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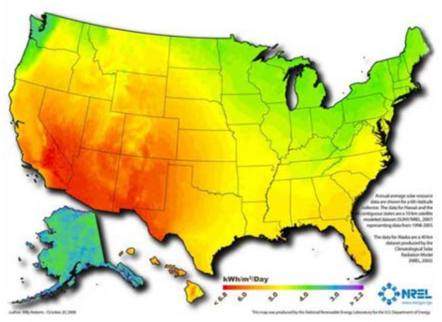
Benjamin F. Hobbs
Francisco D. Munoz
Saamrat Kasina
Jonathan Ho

Outline

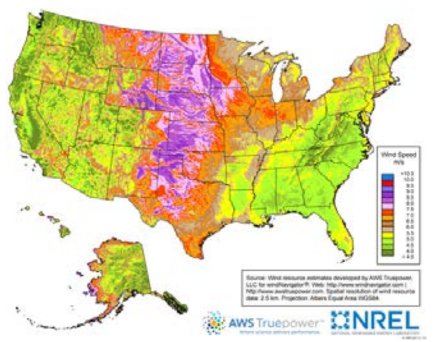
1. Introduction
2. Model Overview, Realistic Test-Case: WECC 240
3. Results
4. Bounding & Decomposition Approaches
5. MATPower/SuperOPF as Planning Subproblem
6. Conclusions

1.1 Introduction

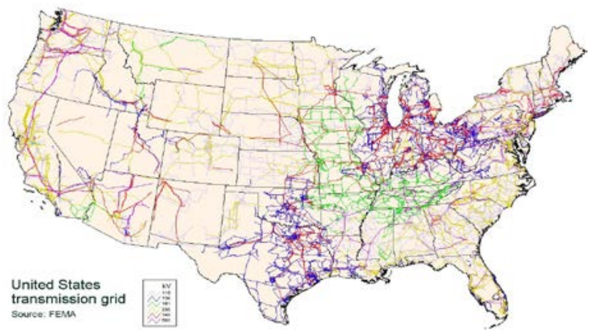
Solar Resources (NREL)



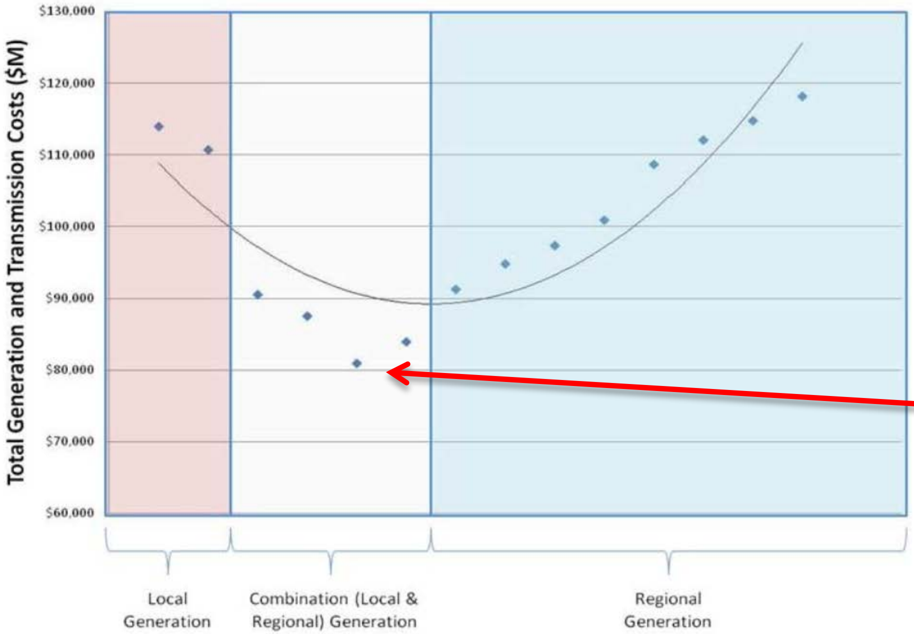
Wind Resources (NREL)



U.S. Transmission System



Zone Scenario Generation and Transmission Cost (MISO 2010)



1.2 More Challenges

- Hyper uncertainty:
  - Fuel Costs
  - Demand Growth
  - Technology Costs
  - Carbon Tax
  - Demand Response
  - PEV
  - RPS
  - Distributed Generation
- Unbundled Electricity Market
  - Trans & gen planning separated
  - Transmission takes longer to build
  - Price signals guide gen investment

We need <u>practical methods</u> that can handle:

- Large-scale networks
- Uncertainty
- Generators' response
- Kirchhoff's Laws

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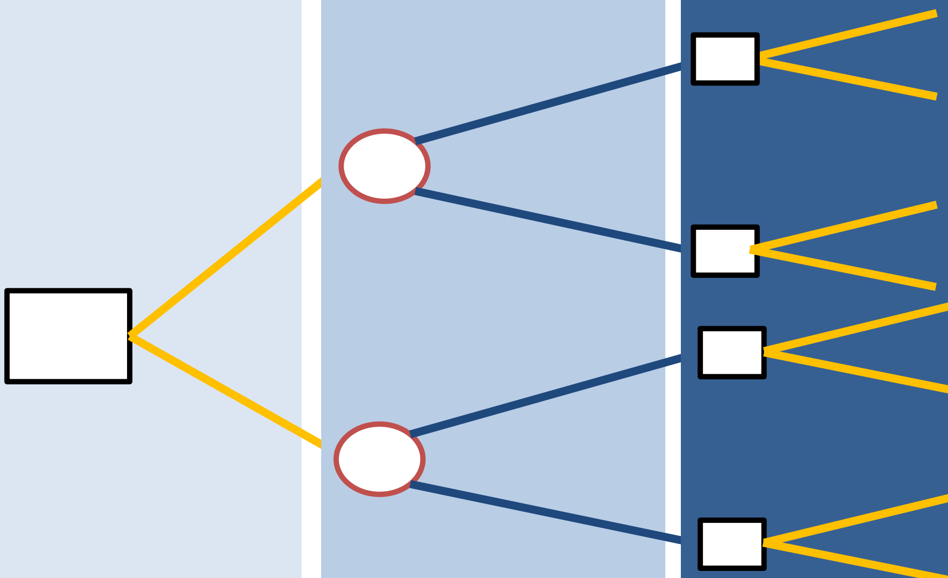
2.1 Multi-Stage Stochastic Transmission Planning

"Today's Choices"	Uncertainty	"Tomorrow's Choices"



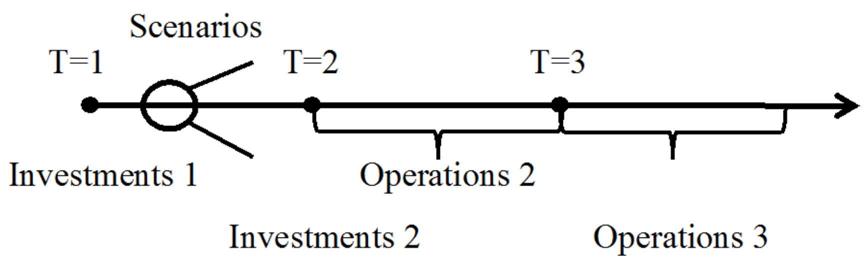
"Today's Choices"	Uncertainty	"Tomorrow's Choices"
• Transmission • Generation	• $ Fuels • $ Technology • Policies • Imports	• Transmission • Generation • Operations

Assumptions

- **Aligned generation and transmission objectives**
  - Nodal pricing + Perfect Competition
- **Generation**
  - No unit commitment constraints/costs
- **Demand**
  - No demand response
- **Renewable targets met in most efficient way**

2.2 Model Formulation

$$\min \quad I^1 + \sum_s p_s (I_s^2 + O_s^2 + O_s^3)$$



Max generation investments : $\sum_{t\in U_t} y^t_{b,k,s} \le Y^{\max}_{b,k,s}$

Max transmission investments : $\sum_{l\in L_C} x^t_{l,s} \le 1$

Installed reserve margins : $\sum_{u\in U_t}\sum_{b\in B}\left(\sum_{k\in NI} y^u_{b,k,s} + \sum_{k\in I} ELCC_k y^u_{b,k,s}\right) \ge (1+RM)\sum_{b\in B} D^t_{b,h^*,s}$

KCLs : $\sum_{t\in U_t}\sum_{l\in L} f^t_{l,h,s} + \sum_{b\in B}\left(\sum_{k\in K} g^t_{b,k,h,s} + r^t_{b,h,s}\right) = D^s_{b,h,s}$

KVLs : $f^t_{l,h,s} - \gamma_l(\theta^t_{b,h,s} - \theta^t_{p,h,s}) = 0$

$\left| f^t_{l,h,s} - \gamma_l(\theta^t_{b,h,s} - \theta^t_{p,h,s}) \right| \le M_l\left(1 - \sum_{l\in L_C} x^t_{l,s}\right)$

Thermal limits : $\left| f^t_{l,h,s} \right| \le F^{\max}_l$

$\left| f^t_{l,h,s} \right| \le F^{\max}_l \sum_{l\in L_C} x^t_{l,s}$

Intermittent generation : $g^t_{b,k,h,s} \le W_{b,k,s} \sum_{u\in U_t} y^s_{b,k,s}$

Non-intermittent generation : $g^t_{b,k,h,s} \le \sum_{u\in U_t} y^s_{b,k,s}$

Renewable Portfolio Standards : $\sum_{k\in R}\sum_{h\in H}\sum_{b\in B} g^t_{b,k,h,s} + nonc^t \ge RPS^t_s \sum_{k\in K}\sum_{h\in H}\sum_{b\in B} g^t_{b,k,h,s}$

Emissions Cap : $\sum_{k\in K}\sum_{h\in H}\sum_{b\in B} g^t_{b,k,h,s} e_k \le E\_CAP^t_s$

2.3 WECC 240-bus Test Case

WECC 240-bus system:

(Price & Goodin, 2011)

140 Generators (200 GW)
448 Transmission elements
21 Demand regions
28 Flowgates

Renewables data (Time series, GIS)

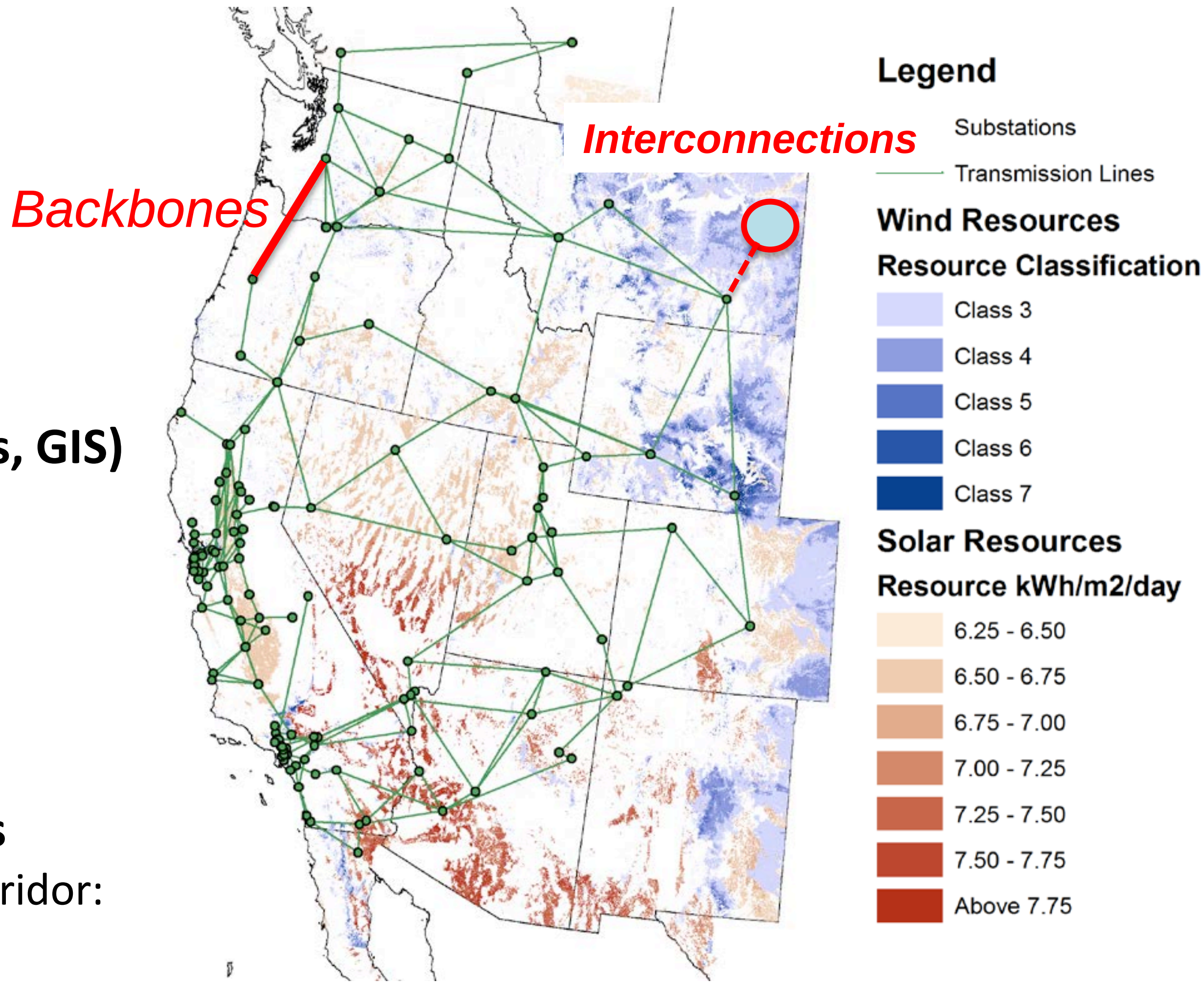
(NREL, WREZ, RETI)

54 Wind profiles
29 Solar profiles
31 Renewable Hubs (WREZ)

Candidate Transmission Lines

Max number of circuits per corridor:

2 for Backbones
4 for Interconnections to Renewable Hubs



2.4 Scenarios

- Focus on environmental policy and fuel prices

Differentiated State RPS	33% WECC-wide RPS	Carbon Cap & Trade
• State RPS • >75% from in-state resources • Average fossil fuel prices	• 33% WECC-wide RPS • Efficient REC markets • High fossil fuel prices	• 17% below 2005 levels by 2020 • 45% below 2005 levels by 2030 • Low fossil fuel prices

- Experiments
  - **Scenario Planning** (Deterministic)
  - **Stochastic Approach**
  - **Heuristics:**
    1. Heuristic I: Build lines needed in all the scenarios
    2. Heuristic II: Build lines needed in "most" scenarios (at least 2)

       } "Least-regrets" or "Multi-Value Projects"

    3. Heuristic III: Build all lines

       } "Congestion-free"

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3.1 Results

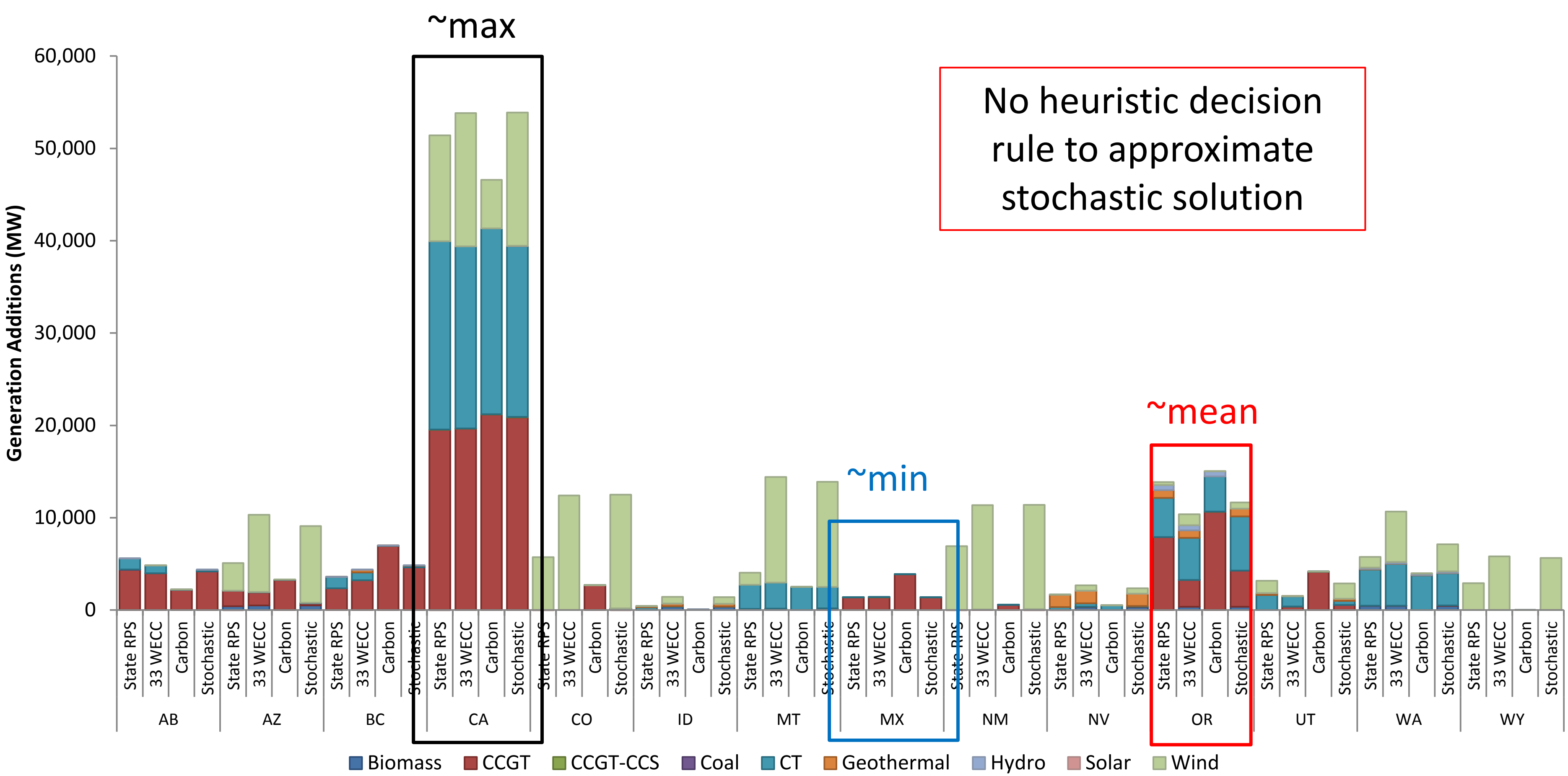
First-Stage Transmission Investments: Backbones

Approach	B19	B37	B56	B68	B72	B73	B74	B92	B95	B125	B133	B136	B137	B143	B151	B157	B168	B169	B201	B202	B218	B222	B237	B238
D-Carbon				1					1	1	1		1	2								2	1	2
D-33% WECC		1			1	1	2		1								1	1	1		1	1	2	
D-State RPS	2	1	1					2		2		1								1		1		2

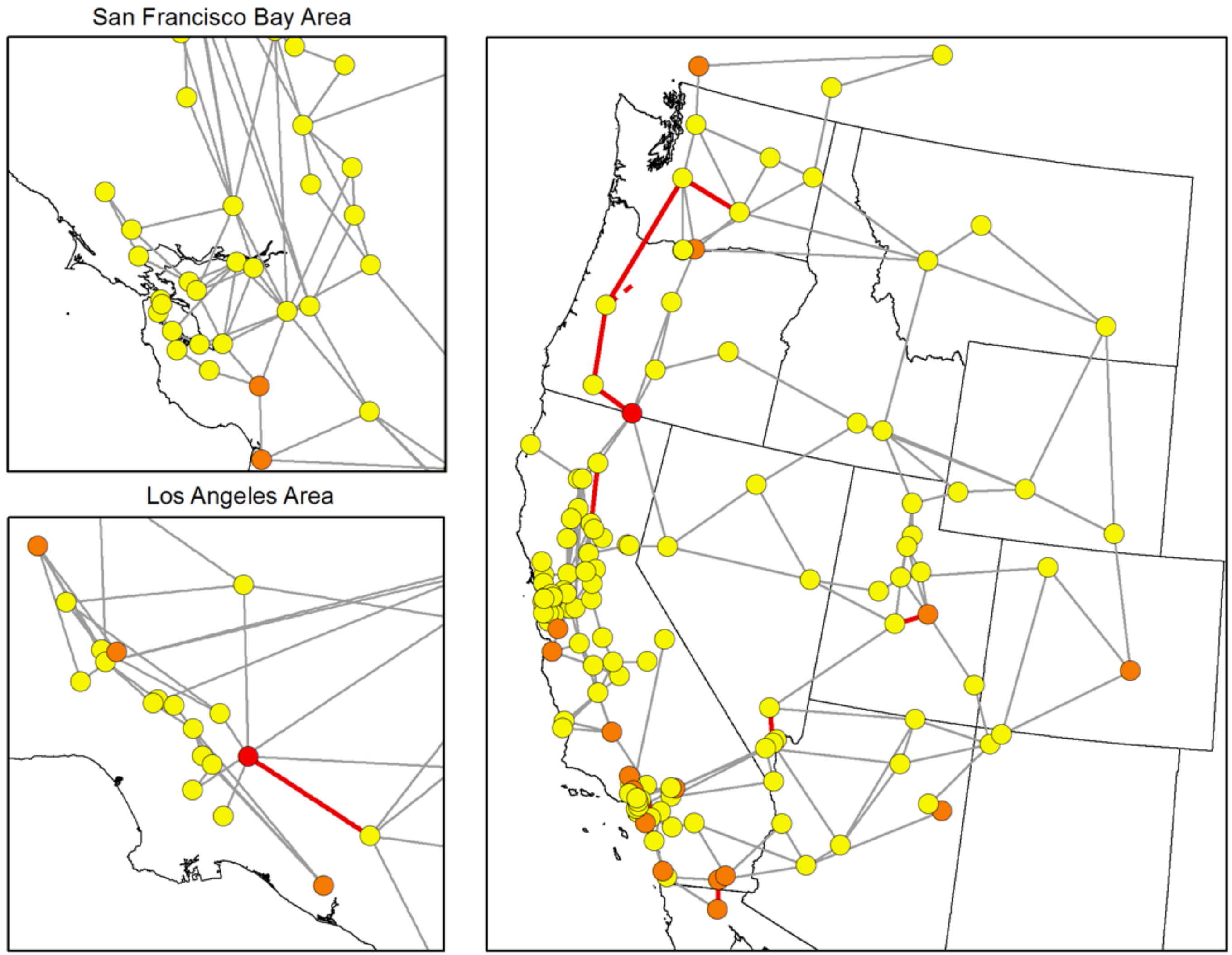
Flexible plans are suboptimal in retrospect!!

3.2 Results

First Stage Generation Investments: Deterministic vs Stochastic Solutions

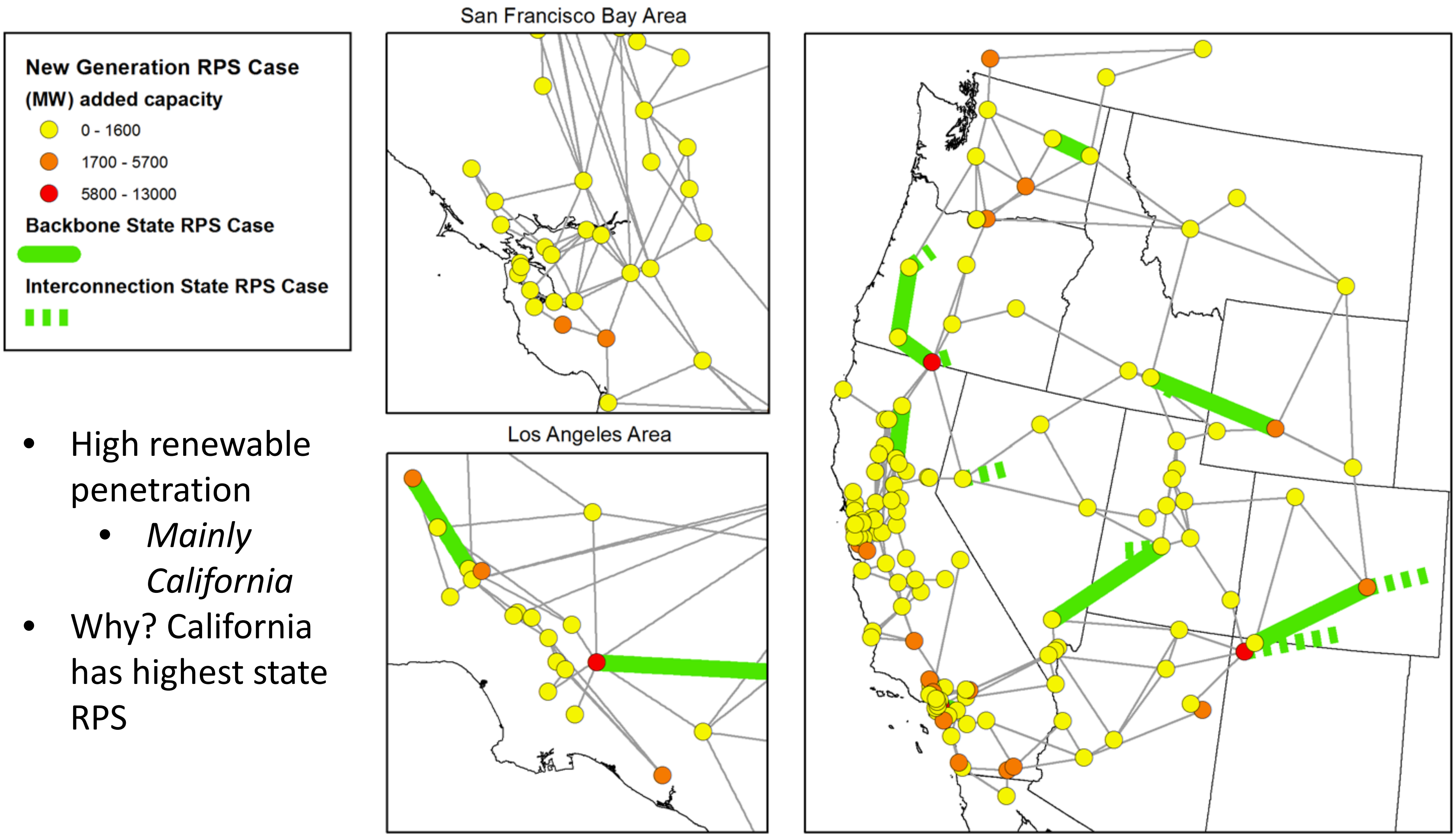


3.3 Results: Carbon Cap Case



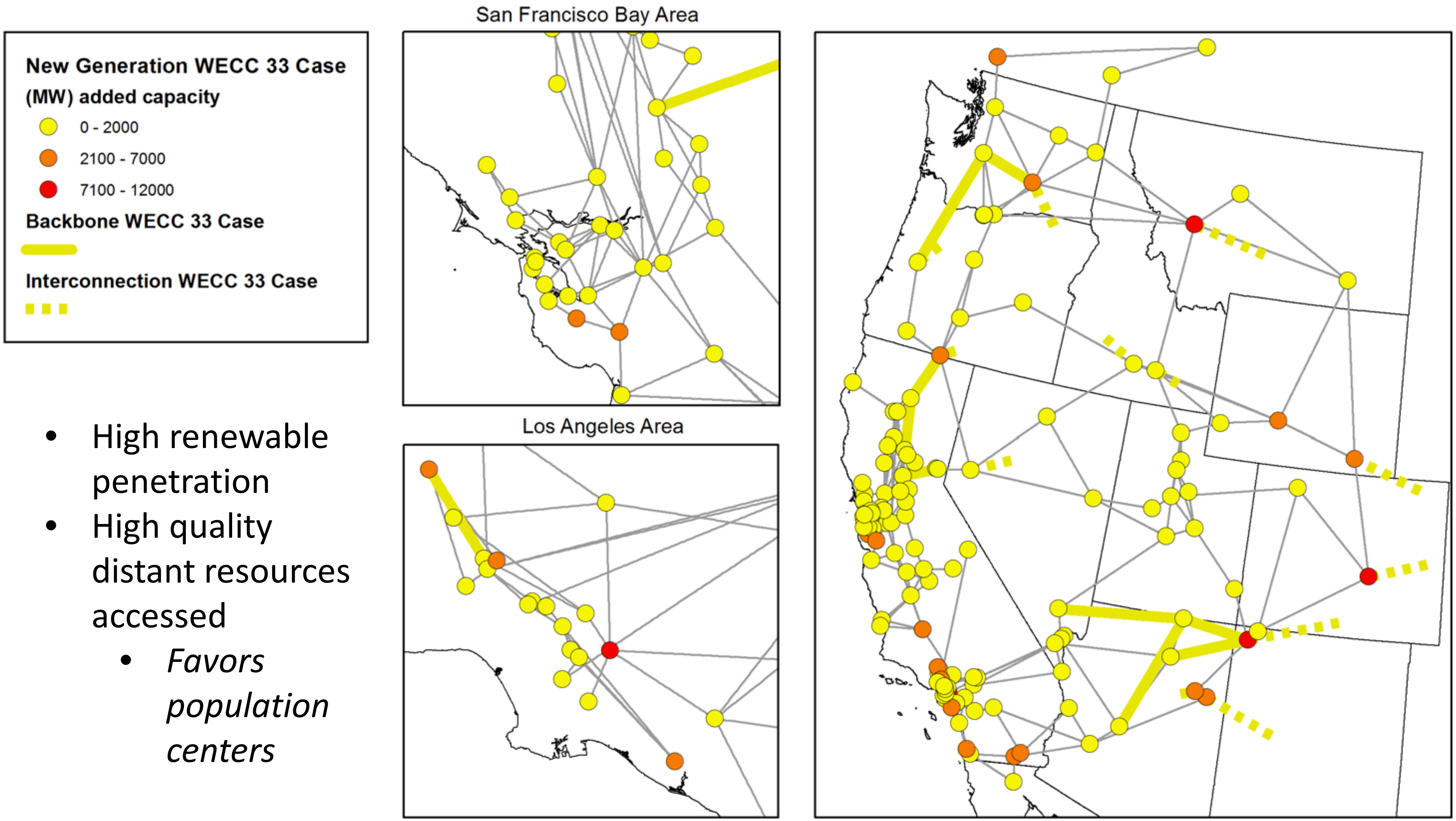
- Gen added near demand
- Low penetration of renewables
- Carbon cap only within US

3.4 Results: State RPS Case



- High renewable penetration
  - *Mainly California*
- Why? California has highest state RPS

3.5 Results: WECC 33% Case



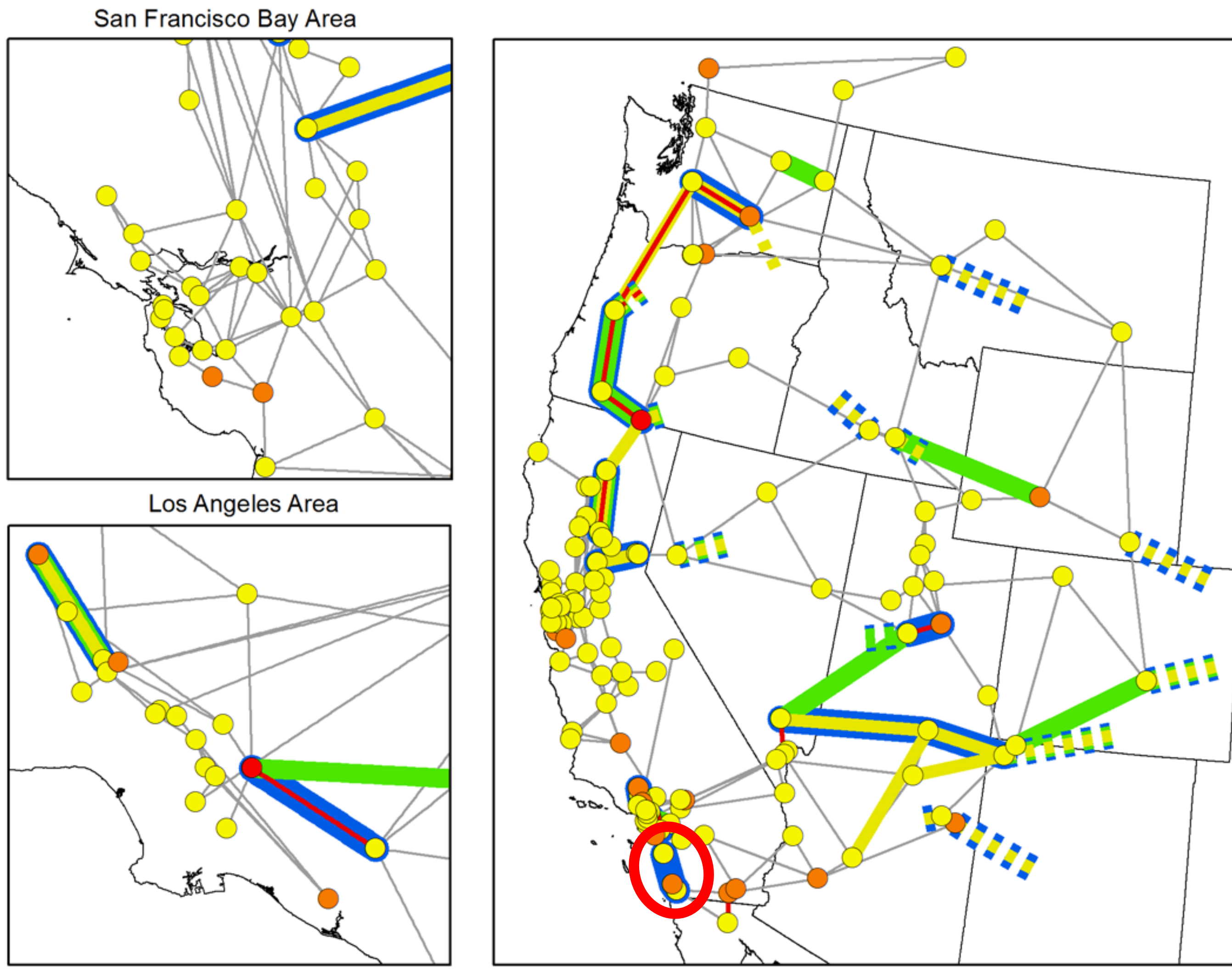
- High renewable penetration
- High quality distant resources accessed
  - *Favors population centers*

3.6 Results: Stocahstic Solution

New Generation Stochastic (MW) added capacity
- 0 - 1700 MW
- 1800 - 6100 MW
- 6200 - 16000 MW

Backbone Stochastic

Interconnection Stochastic



- Hi renewables
  - *Generation closer to California*
- **<u>Unique stochastic lines</u>**

3.7 Results Summary

Economic Performance of Investment Strategies

Approach	First-Stage Transmission Investments [$B]			E(System Costs) across scenarios [$B]
	Backbones	Interconnections	Total	
D-Carbon	4.0	0.1	4.1	728.2
D-33% WECC	6.1	9.3	15.4	653.6
D-State RPS	7.2	4.1	11.3	667.0

- **Expected Value of Perfect Information (EVPI) = $45.4 Billion**
- **Value of Stochastic Solution (VSS) = $46.7 Billion**
- **WECC 10-Year Regional Transmission Plan:**
  - Estimates of $20 Billion in transmission investments to meet demand forecasts and renewable targets by 2020.

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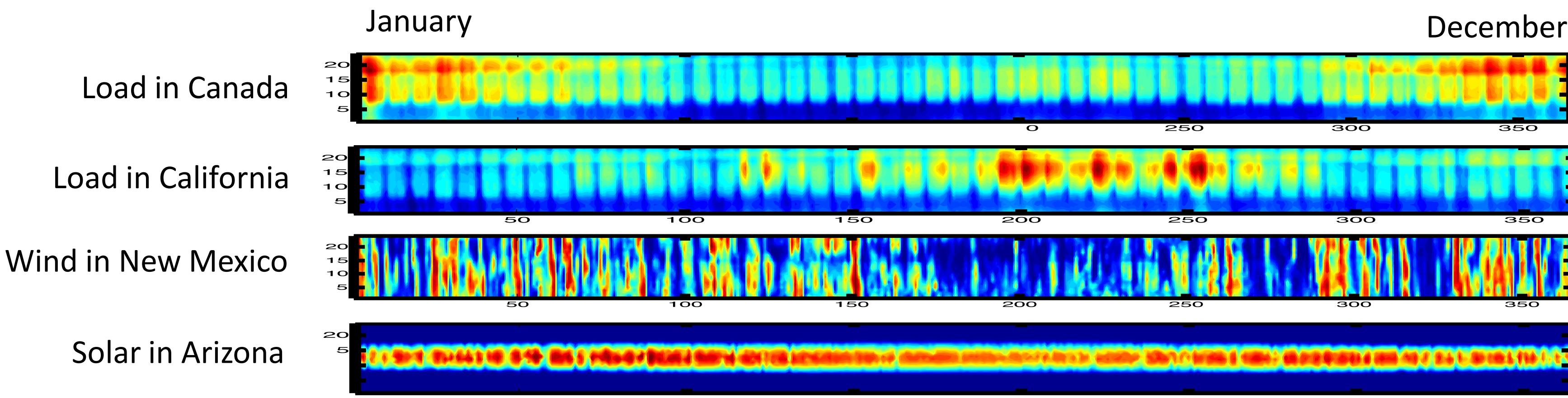
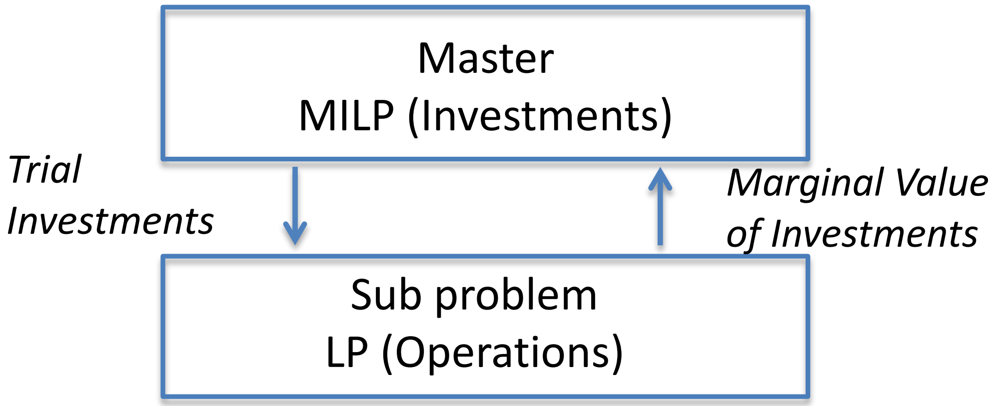
4.1 Ongoing Research

Challenge: Accurate representation of intermittent resources



Benders Decomposition: Theoretical convergence vs actual performance



Issue: # of cuts needed
for convergence
≈ # of investment variables
in master problem

4.2 Stylized Planning Model

Objective: MIN present worth of capital + operating costs

Capital cost

$$\min_{x} \quad e^T x + f(x,\Omega)$$

Operating Cost

$$Ax = b$$

$$x \geq 0$$

x : Investment decisions,
some discrete (transmission)

Operations problem formulated as *a probabilistic production cost model (LP)*:

$$f(x,\Omega) = \min_{y_h} \sum_{h \in \Omega} p_h c^T y_h$$

$$Wy_h = r_h - T_h x \qquad \forall h \in \Omega$$

$$y_h \geq 0 \qquad \forall h \in \Omega$$

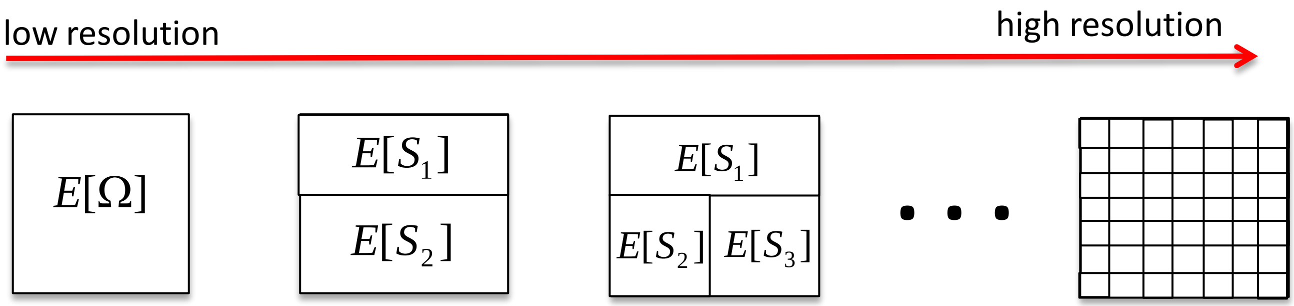
Block-diagonal constraints, separable

Time-dependent parameters are RHS

4.3 Tight Lower Bound

Lower Bound:

- Time-dependent parameters are RHS $Wy_h = r_h - T_h x$
- LP: Optimal cost convex on RHS



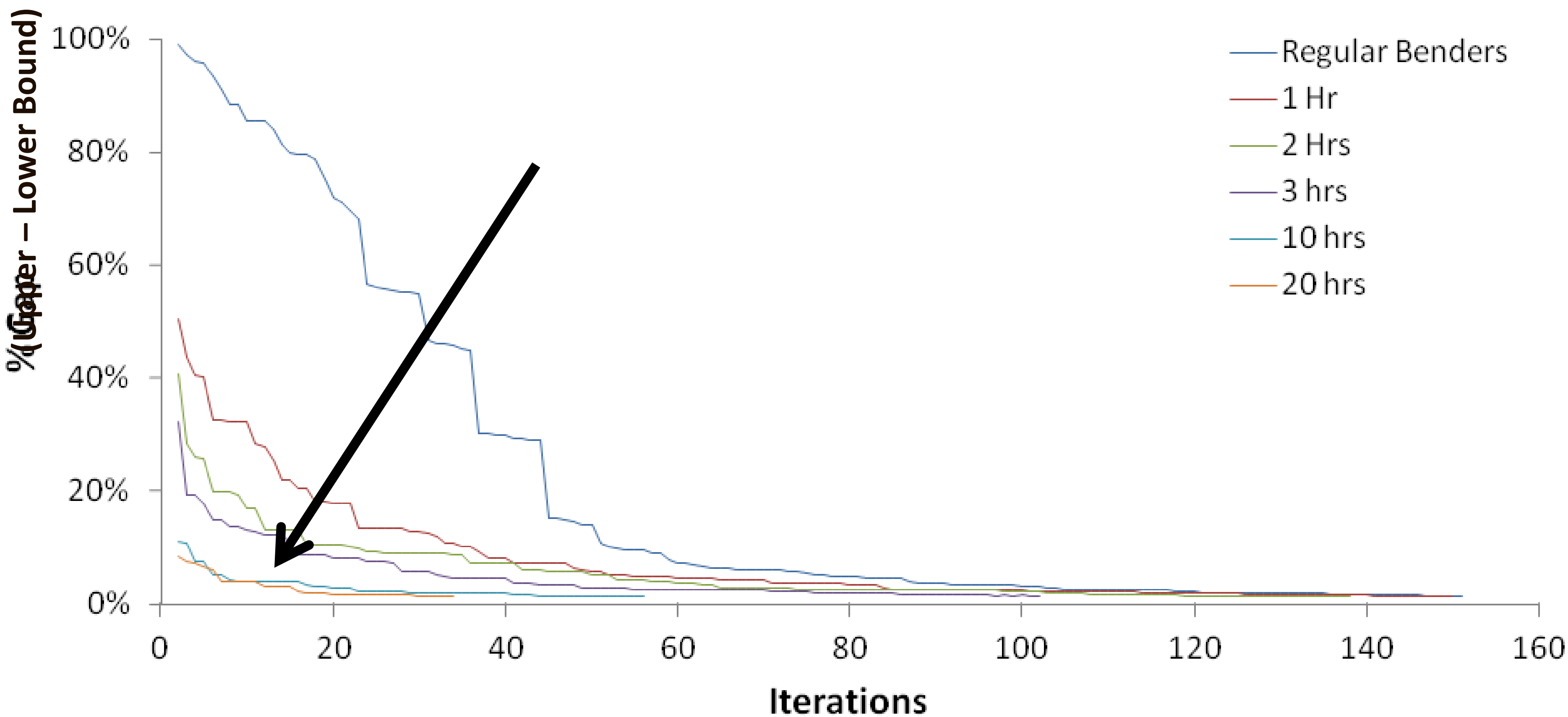
E.g. 8760 observations of hourly demand and capacity factors

$$f(x,\Psi^1) \leq f(x,\Psi^2) \leq f(x,\Psi^3) \leq \bullet\bullet\bullet \leq f(x,\Omega)$$

Algorithm:

1) Create k partitions of load/variable resources space **Ω** (e.g. K-Means)
2) Add deterministic operating problem for each to Benders Master Problem: *Augmented Benders Decomposition*
3) Solve in usual Benders fashion

4.4 Acceleration of Convergence (17 Bus Problem)



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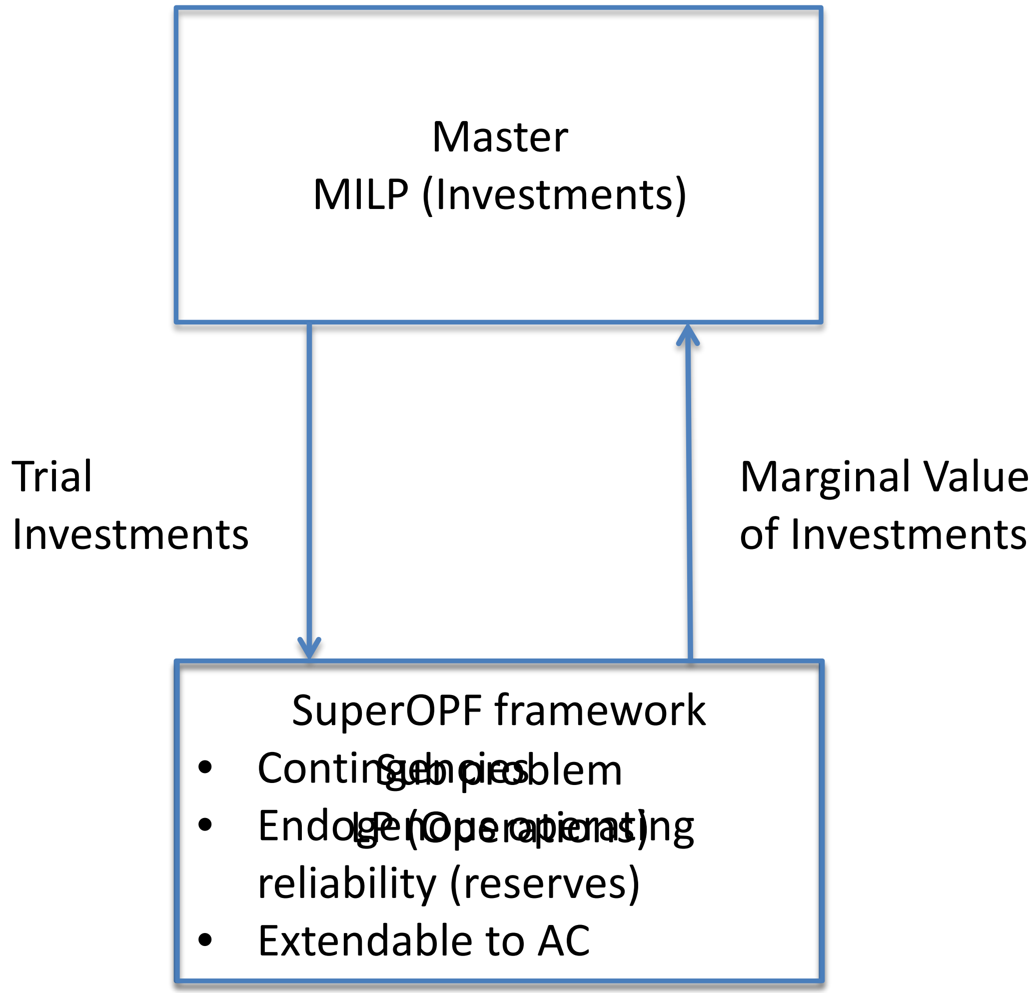
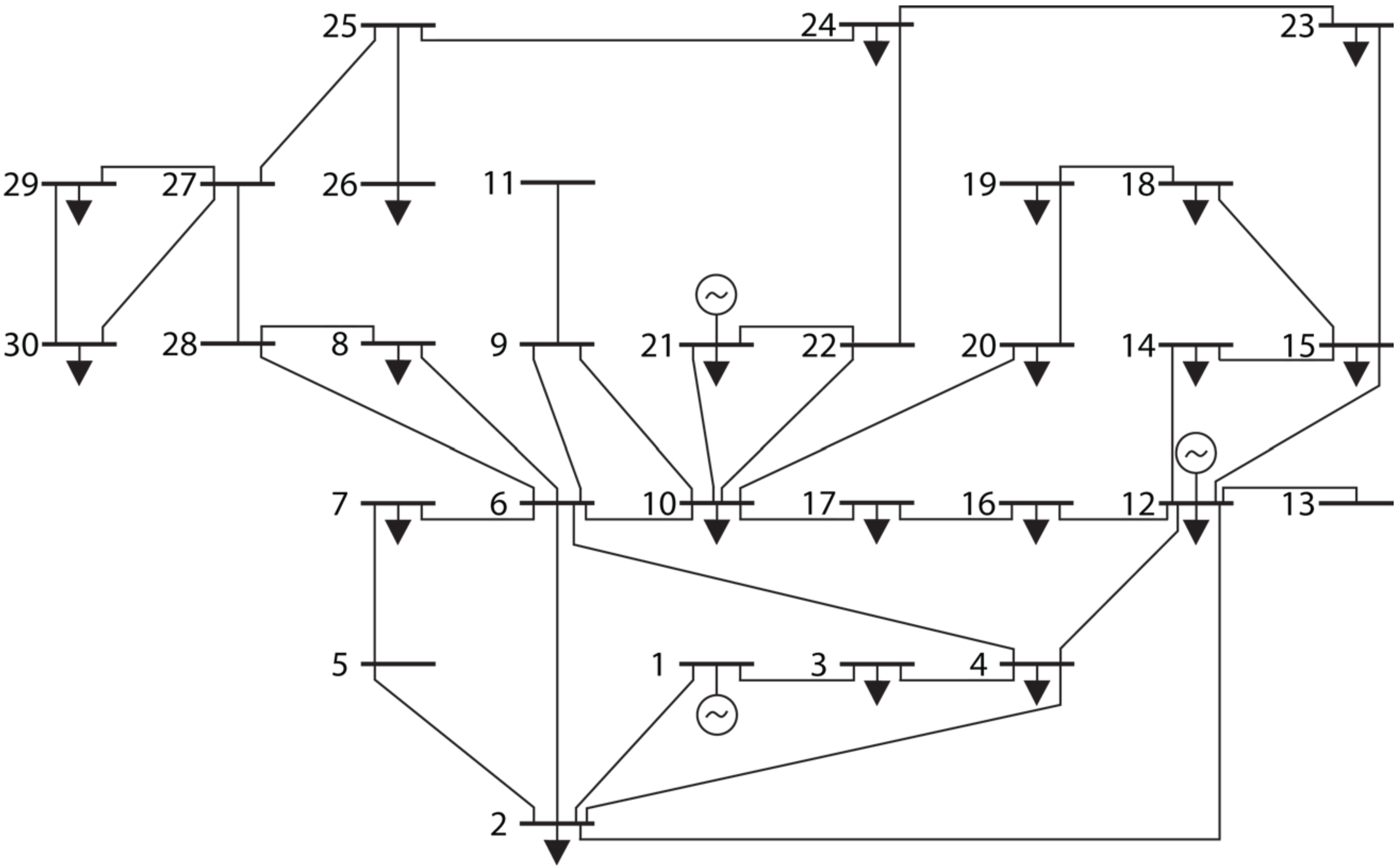
5.1 Contingency-based Transmission planning

The research problem:

- Can the SuperOPF framework be adapted for optimal transmission planning?
- Approach
  - *Benders Decomposition*



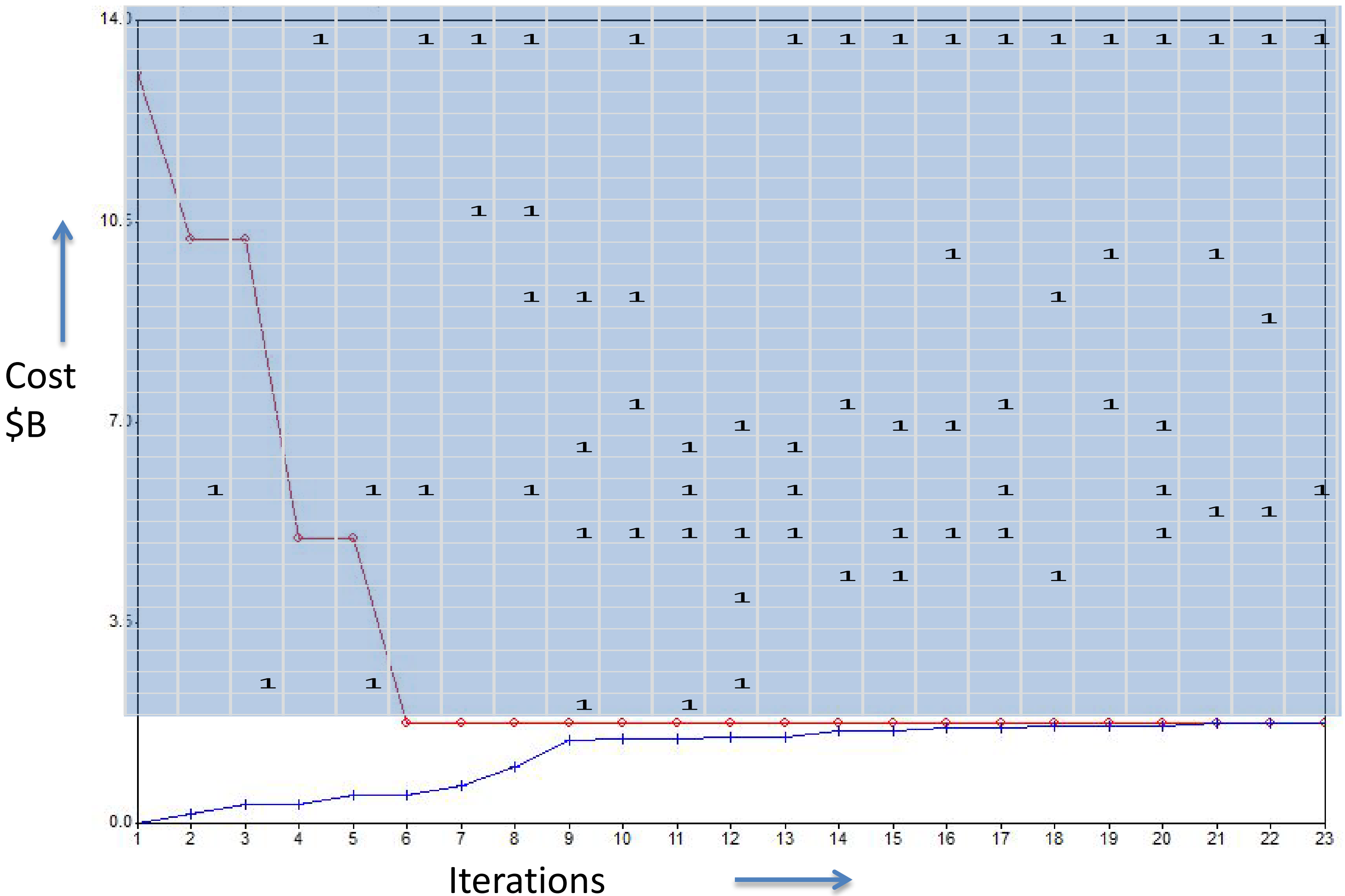
5.2 MATPOWER 30-bus system



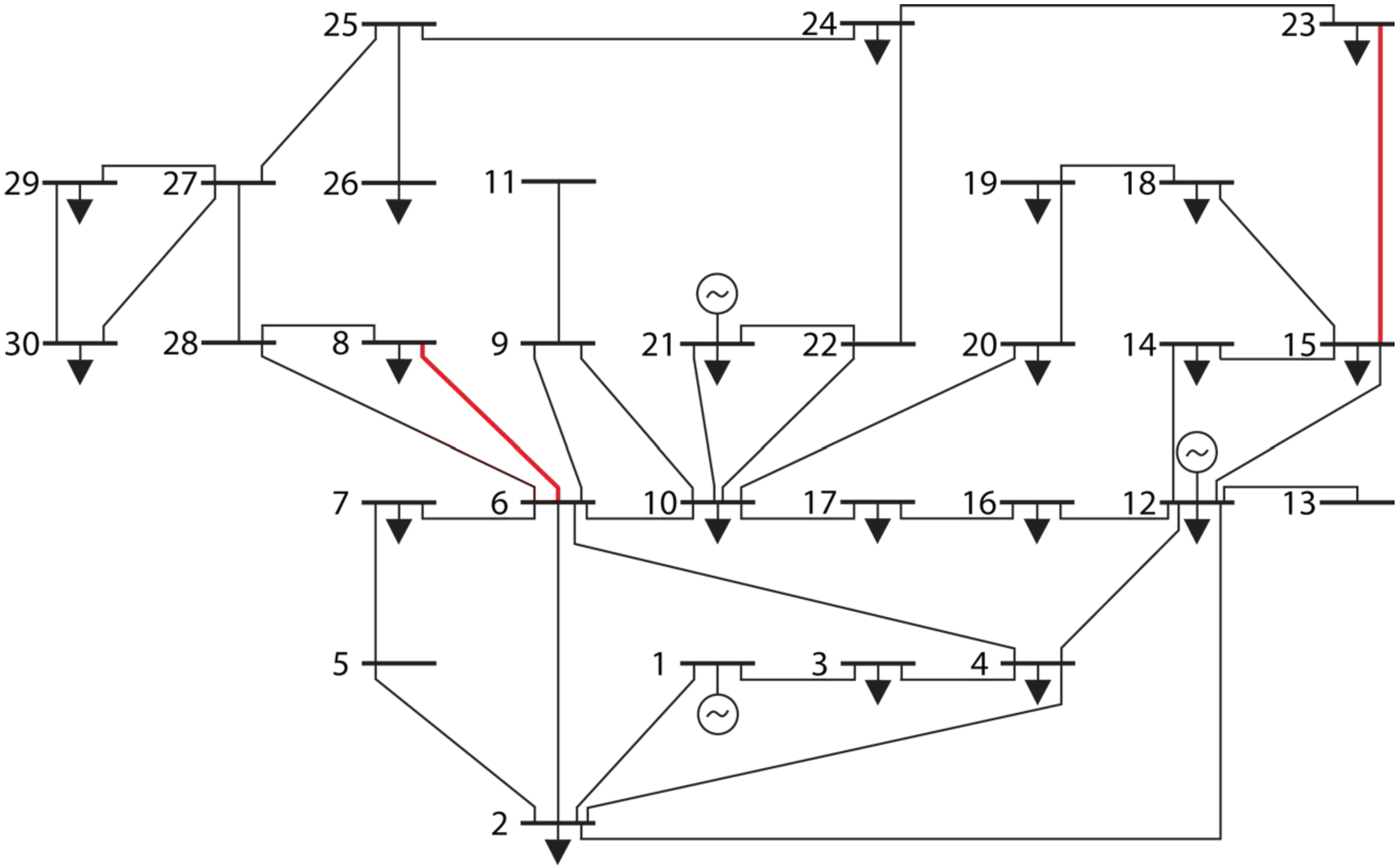
5.3 Contingencies (Lamadrid et al., 2008)

	Contingency	Probability
0	Base Case	95.0%
1	Line 1: 1-2 (between gens 1 and 2)	0.2%
2	Line 2: 1-3 (from gen 1)	0.2%
3	Line 3: 2-4 (from gen 2)	0.2%
4	Line 5: 2-5 (from gen 2)	0.2%
5	Line 6: 2-6 (from gen 2)	0.2%
6	Line 36: 27-28	0.2%
7	Line 15: 4-12	0.2%
8	Line 12: 6-10	0.2%
9	Line 14: 9-10	0.2%
10	Gen 1	0.2%
11	Gen 2	0.2%
12	Gen 3	0.2%
13	Gen 4	0.2%
14	Gen 5	0.2%
15	Gen 6	0.2%
16	10% increase in load	1.0%
17	10% decrease in load	1.0%

5.4 MATPOWER 30-bus test case results



5.5 MATPOWER 30-bus system results



5.6 Contingency-based Transmission planning

- ✓ Compatible with MATPOWER OPF results
- ✓ Demonstrate calculation of Benders cuts
- ✓ Demonstrate integration of SuperOPF framework (DC) in Benders: 30 bus example

Next?

- DCOPF with losses, ACOPF
- Coordination with E.I. generation and/or transmission expansion (Bill Schulze, Dan Tvlavsky)

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- Scenario Planning is a weak tool for decisions under uncertainty

  Deterministic plans don't account for flexibility

- Heuristic planning rules can perform worse than myopic deterministic plans

- "Value of Stochastic Solution": up to ~3 times the cost of transmission.

- Bounding & decomposition approaches are practical for improving granularity in operations

  MATPower/SuperOPF promising for operations subproblem

Questions?

Francisco Munoz:
francisco.munoz@jhu.edu

Benjamin Hobbs:
bhobbs@jhu.edu

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Our Method

Algorithm:

- Apply Benders decomposition with an auxiliary lower bound in master problem.

$$\min_{x,\alpha} \; e^T x + \alpha$$
$$Ax = b$$
$$\alpha \geq Benders\_cuts(x, \Omega)$$
$$x \geq 0$$
$$\boxed{\alpha \geq f(x, \Psi^k)}$$

Polyhedral lower bound on $f(x, \Omega)$ for any x