What Investments Should Be Made Now?

Long Run Transmission Planning Under Uncertainty

PSERC Webinar
April 22, 2014

Benjamin F. Hobbs

Director, JHU Environment, Energy, Sustainability & Health Institute
Theodore & Kay Schad Professor of Environmental Management, JHU
Chair, CAISO Market Surveillance Committee

Thanks to:

Funding agencies:

- Consortium for Electric Reliability Technology Solutions (CERTS) with funding provided by the U.S. DOE
- NSF
- U.K. Engineering & Physical Sciences Research Council

Collaborators:

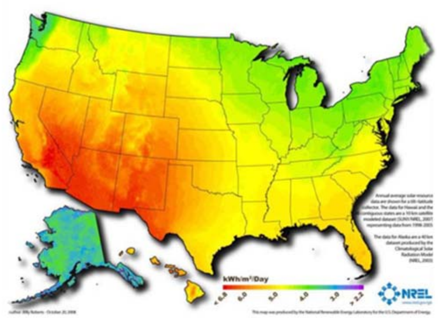
- Francisco Munoz, Jean-Paul Watson (Sandia)
- Saamrat Kasina, Jonathan Ho, Pearl Donohoo (JHU)
- Adriaan van der Weijde (U. Amsterdam)
- Richard Schuler (Cornell)

Outline

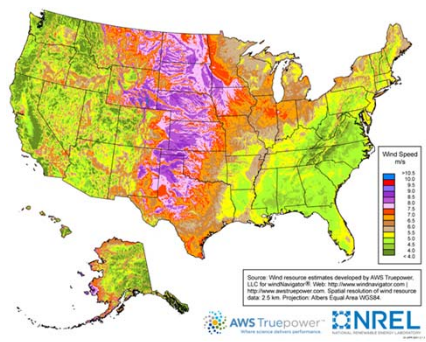
1. Introduction
2. Model Overview, Realistic Test-Case: WECC 240
3. Results
4. Dealing with Large Problems
5. Conclusions

1.1 Introduction

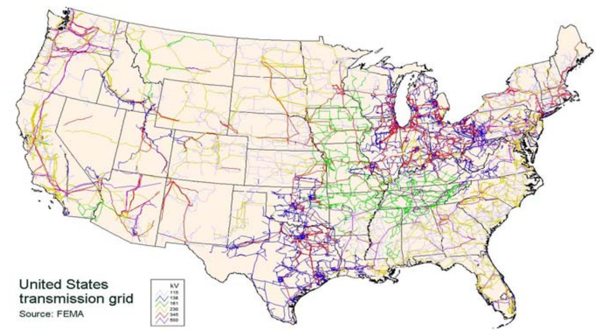
Solar Resources (NREL)



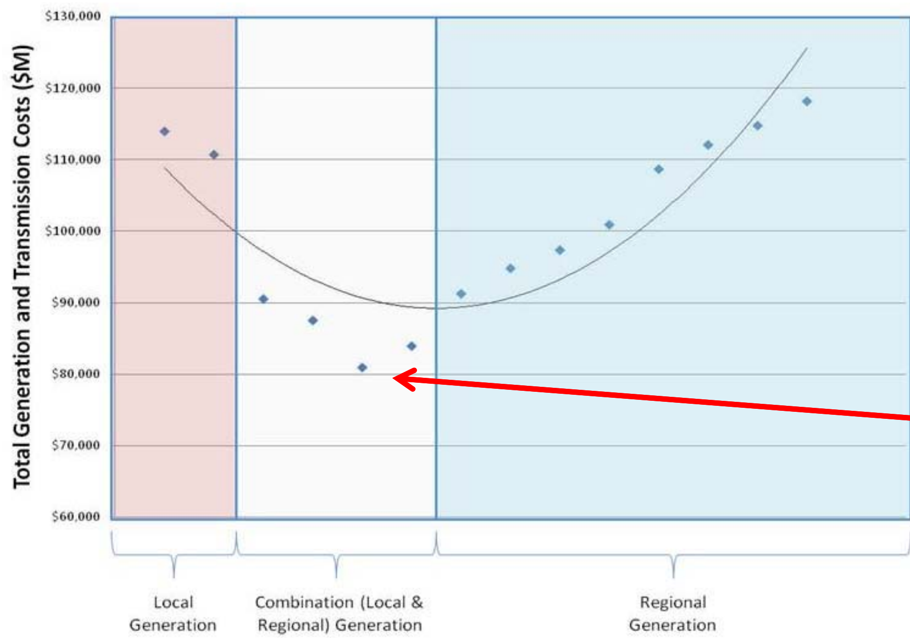
Wind Resources (NREL)



U.S. Transmission System



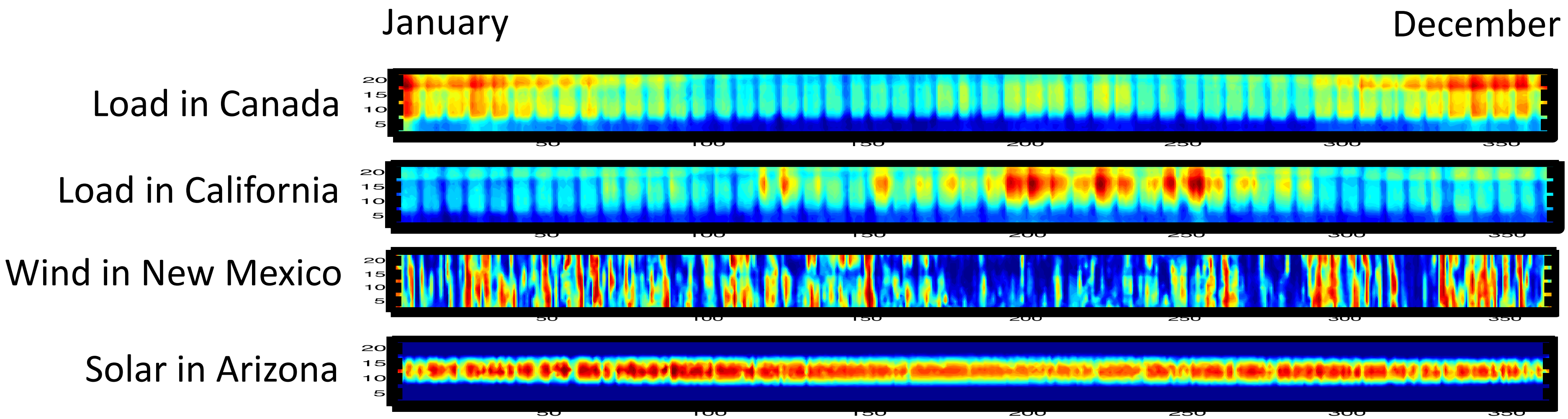
Generation & Transmission Cost (MISO 2010)



Transmission Investments

Optimal:
Combination of Local & Regional Generation

1.2 The Challenge of Variability



→ ***Need to capture true economic value of renewables!***

- System-wide analysis of transmission & generation investments
- Improve time resolution of operations subproblems

1.3 More Challenges

- **Hyper uncertainty in long run:**
  - Fuel Costs
  - Demand Growth
  - Technology Costs
  - Carbon Tax
  - Demand Response
  - PEV
  - RPS
  - Distributed Generation

→ ***Need <u>multi-scenario</u> transmission planning***

- **Unbundled transmission & generation markets**
  - Transmission takes longer to build
  - Price signals guide gen investment

→ ***Need <u>anticipative</u> transmission planning***

→ **We need <u>practical methods</u> that can handle:**
- Variable renewables
- Long-run uncertainties
- Response of generator siting & operations
- Large networks & Kirchhoff's Laws

1.4 The New Paradigm

*"(C)apturing long-term benefits of transmission investments requires processes more akin to **integrated resource planning** in order to evaluate 'long-term resource cost' benefits (such as)… the ability to build new generation in lower-cost locations … (in order to) find lower-cost **combinations of transmission & generation** investments to satisfy policy requirements"*

(Pfeifenberger & Hou, 2012)

"Anticipative" planning in practice:

- FERC Order 1000 – Transmission Planning and Cost Allocation (FERC, 2013)
- California ISO (Awad et al. 2010)
- Eastern Interconnection States Planning Council (2013) "Co-optimization" White Paper

1.5 Transmission Planning in Practice

Commercial tools used by ISOs and RTOs:

- SIEMENS PSS-E
- ABB GridView
- Ventyx PROMOD IV

} Dispatch optimization, not investment (O'Neill et al. 2012)

- PSR NETPLAN

} Optimizes network
Load/VER variability, but no long run uncertainties

Treatment of uncertainty and hedging strategies:

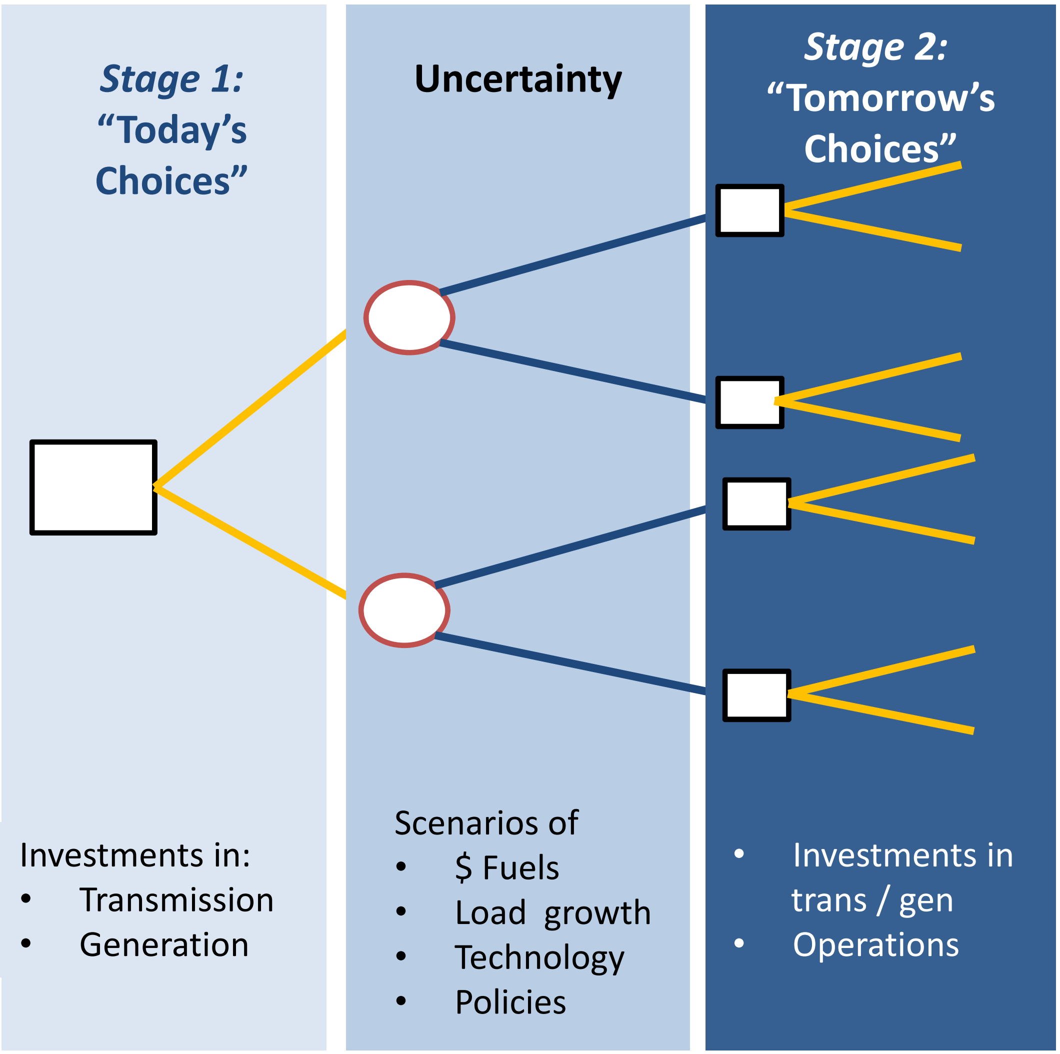
- MISO Multi-Value Projects (MISO 2010)
- CAISO Least-Regrets Approach

"The 'least regrets' approach (evaluates)… a range of plausible scenarios made up of different generation portfolios, and identif(ies) the transmission reinforcements found to be necessary in a reasonable number of those scenarios" (CAISO 2012)

Outline

1. Introduction
2. Model Overview, Realistic Test-Case: WECC 240
3. Results
4. Dealing with Large Problems
5. Conclusions

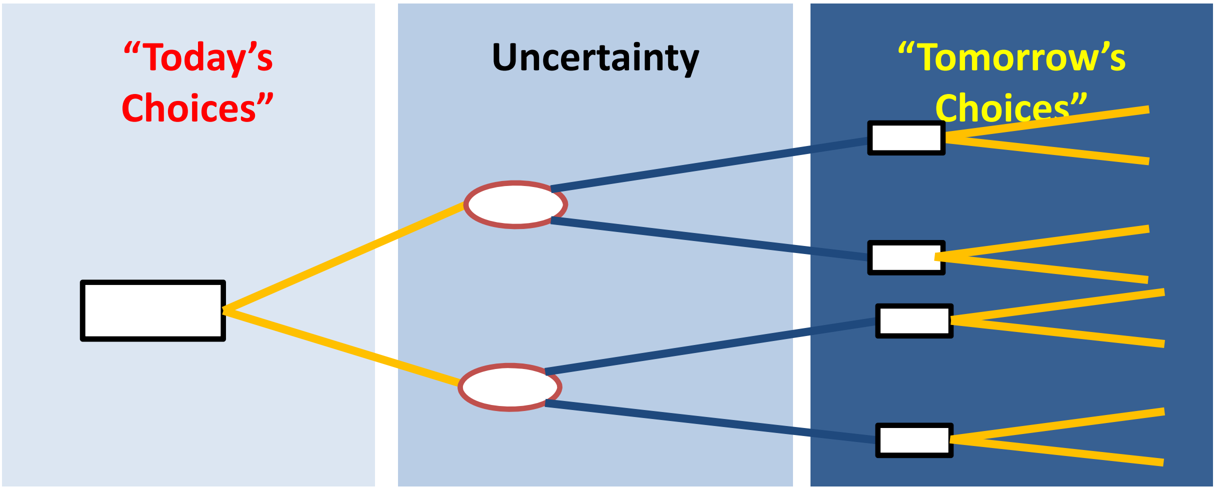
2.1 Multi-Stage Stochastic Transmission Planning



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 Multi-Stage Stochastic Transmission Planning II



$$\text{MIN} \quad C_1 X_1 + \Sigma_{\text{scenarios } S}\, P_S * C_2 X_{2,S}$$

$$A_{1,1} X_1 \leq B_1$$

$$\{A_{2,1,S} X_1 + A_{2,2,S} X_{2,S} \leq B_{2,S}\}, \forall S$$

- **Constraints include:**

  -Kirchhoff's Laws

  -Generator and transmission capacity / operating restrictions

  -Siting restrictions

  -Emissions caps, renewable portfolio standards

2.3 WECC 240-bus Test Case: 2023 + 2033 Investments

WECC 240-bus system:
(Price & Goodin, 2011)

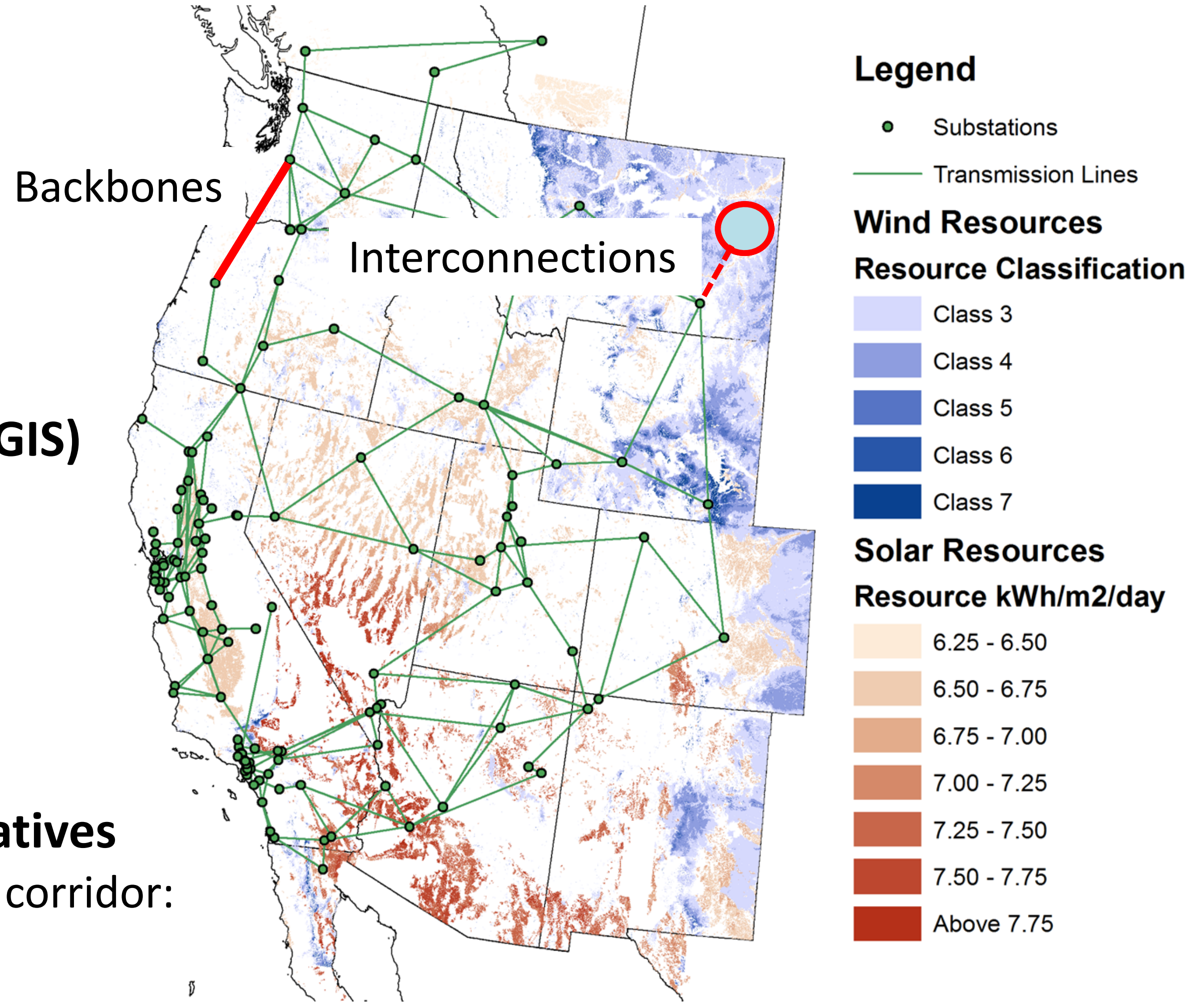
140 Generators (200 GW)
448 Transmission elements
21 Demand regions
28 Flowgates

Renewables data (Time series, GIS)
(NREL, WREZ, RETI)

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

Candidate Transmission Alternatives
Maximum number of circuits per corridor:

2 for Backbones
4 for Interconnections to Renewable Hubs



2.4 Stage 2 (2023) Scenarios

Focus: Environmental policy & fuel prices

U.S. Carbon Cap & Trade

- 2020 $CO_2 \leq$ 85% 2005 levels
- 2030 $CO_2 \leq$ 55% 2005 levels
- Low fuel prices

Differentiated State RPS

- Each state requires $\geq$75% from in-state resources
- Average fossil fuel prices

33% WECC-wide RPS

- Efficient REC trading
- High fuel prices

Experiments

- **Single Scenario Planning** (Deterministic)
- **Stochastic Approach**
- **Heuristics for Stage 1 (2023) Transmission Builds:**
  1. Heuristic I : Build lines needed in each & every scenario
  2. Heuristic II : Build lines needed in "most" scenarios (at least 2)
  3. Heuristic III: Build all lines

(Heuristics I and II:) "Least-regrets" or "Multi-Value Projects"

(Heuristic III:) "Congestion-free"

Outline

1. Introduction
2. Model Overview, Realistic Test-Case: WECC 240
3. Results
4. Dealing with Large Problems
5. Conclusions

3.1 Results

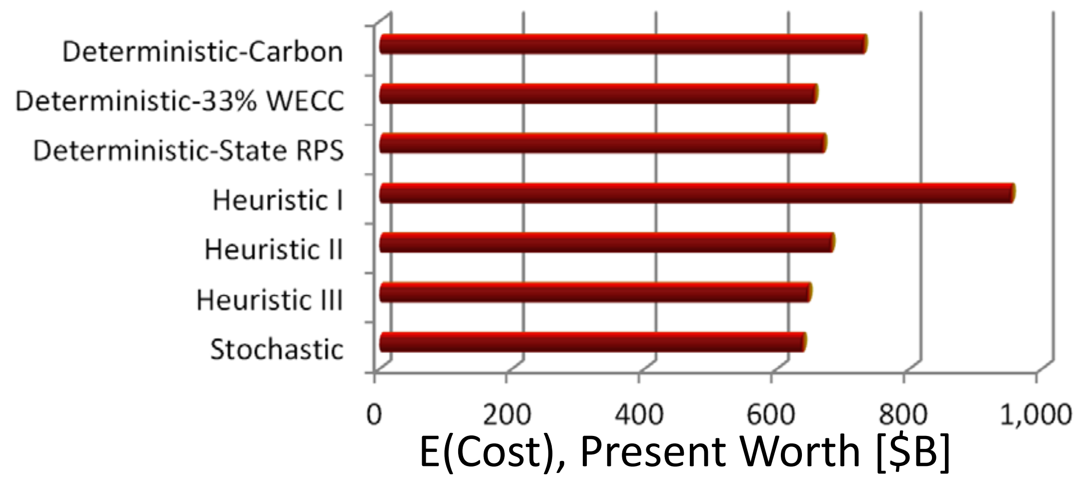
1st Stage (2023) Transmission Investments: Backbones

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
Heuristic I																						1		
Heuristic II		1							1	1												1	1	2
Heuristic III	2	1	1	1	1	1	2	2	1	2	1	1	1	2			1	1	1	1	1	2	2	2
Stochastic		1		1			2		1	2			1		1	1	1				1	1		2

- **Flexible plans are not best in any single scenario!**
- ***Heuristics can do worst of all!***

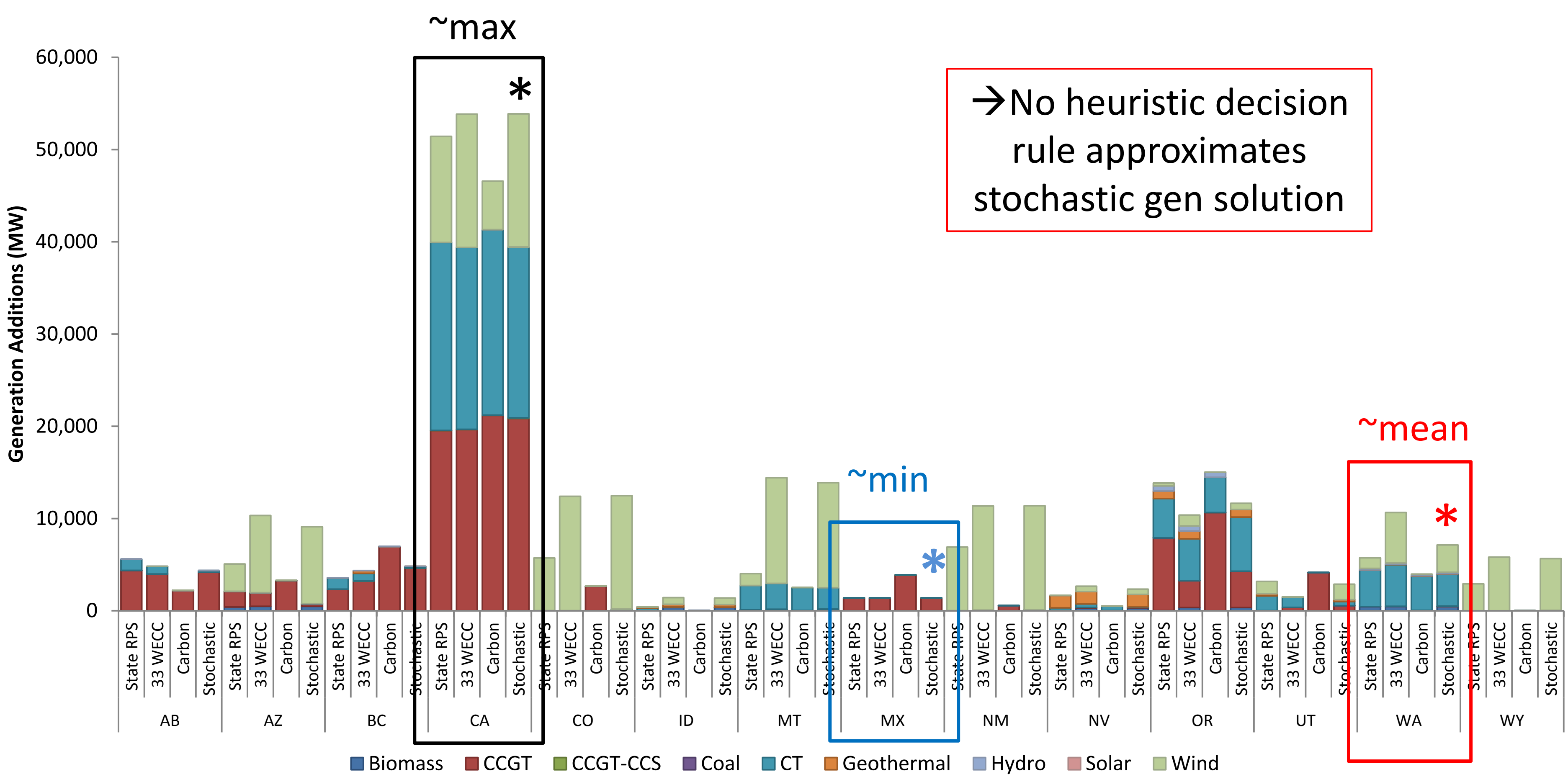
2023 Interconnections to Renewable Hubs

Approach	I2	I5	I6	I8	I9	I10	I11	I14	I20	I23	I24	I25	I26
D-Carbon												1	
D-33% WECC	1	4	1	3	1	1	2	1	1	1	1	1	
D-State RPS		2		2	1				1		1	1	1
Heuristic I												1	
Heuristic II		2		2	1				1		1	1	
Heuristic III	1	4	1	3	1	1	2	1	1	1	1	1	1
Stochastic	1	4	1	3	1	1	2	1	1		1	1	1

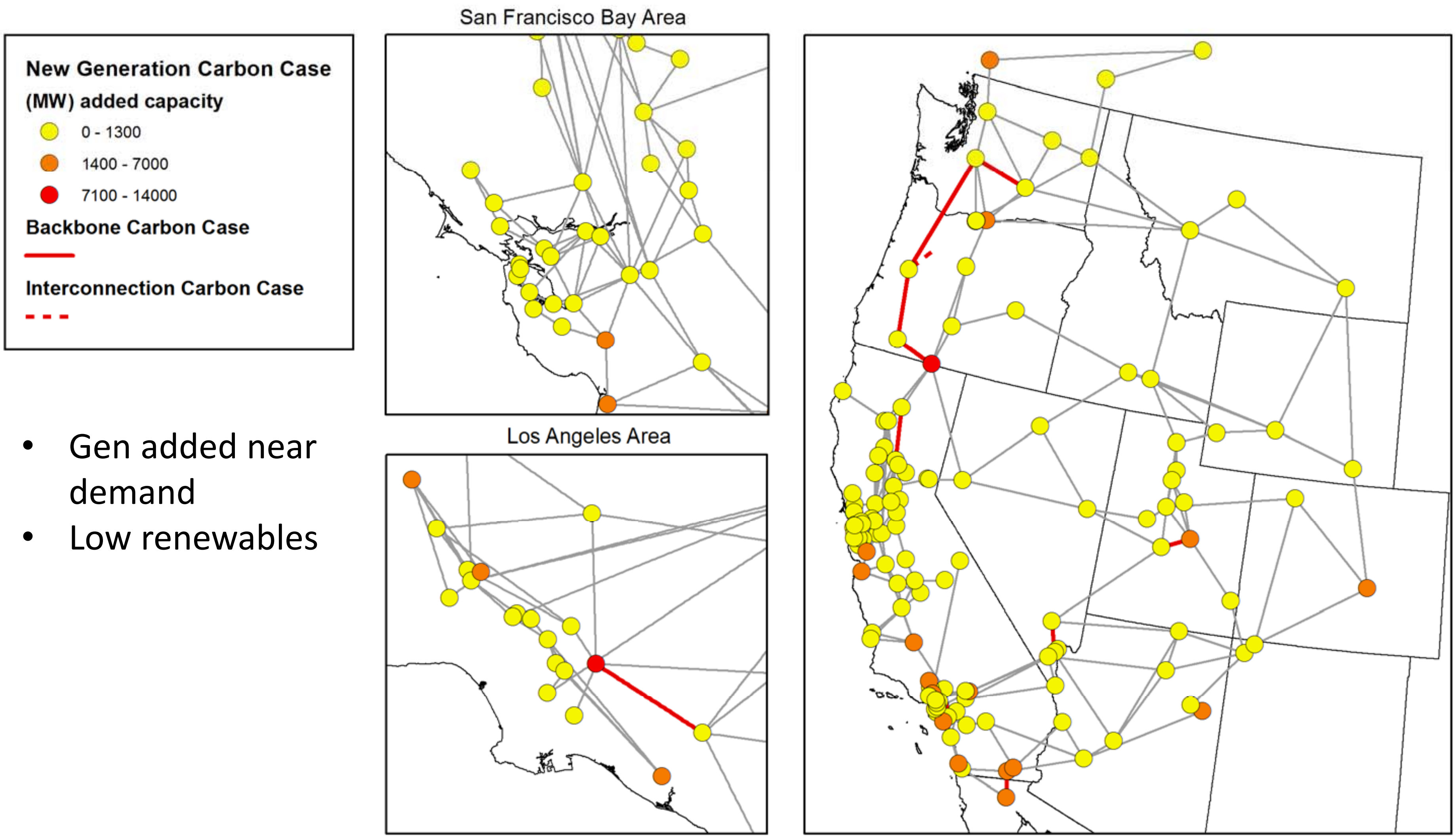


3.2 Results

First Stage (2023) Generation Investments: Deterministic vs Stochastic (*) Solutions

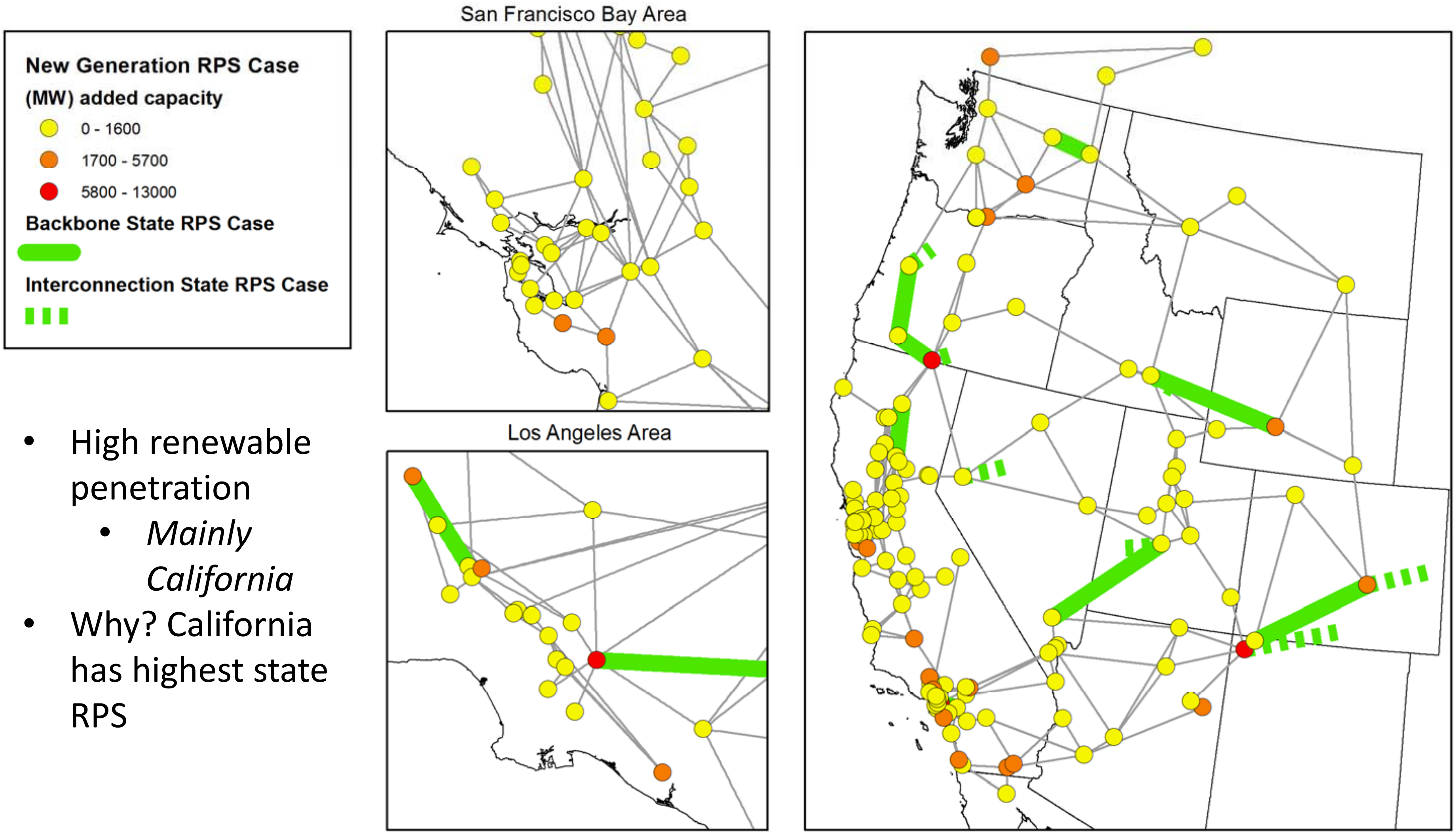


3.3 Deterministic 2023 Results: Plan 1: U.S. WECC Carbon Cap



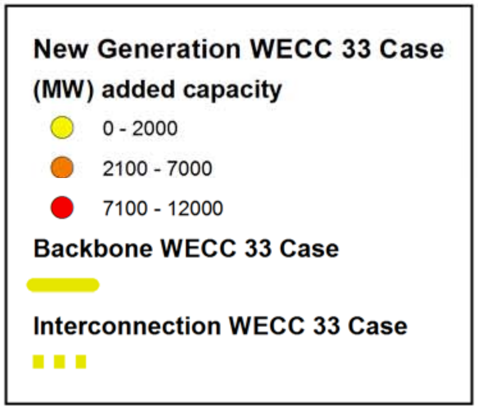
- Gen added near demand
- Low renewables

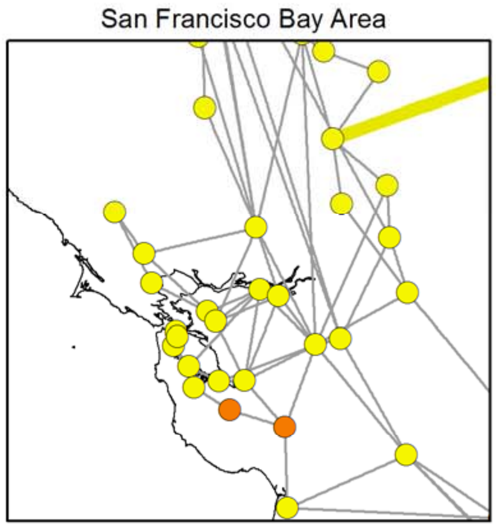
3.4 Plan 2: State RPS Case

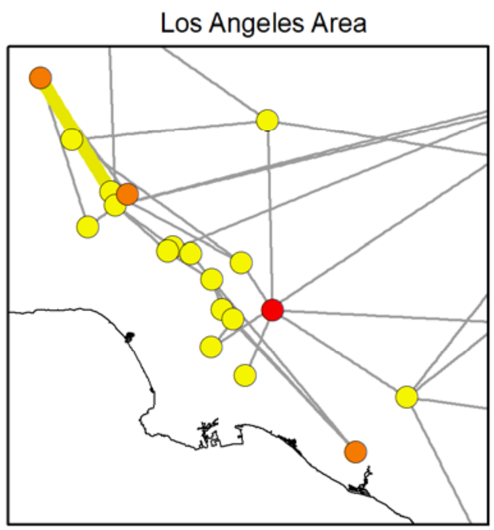


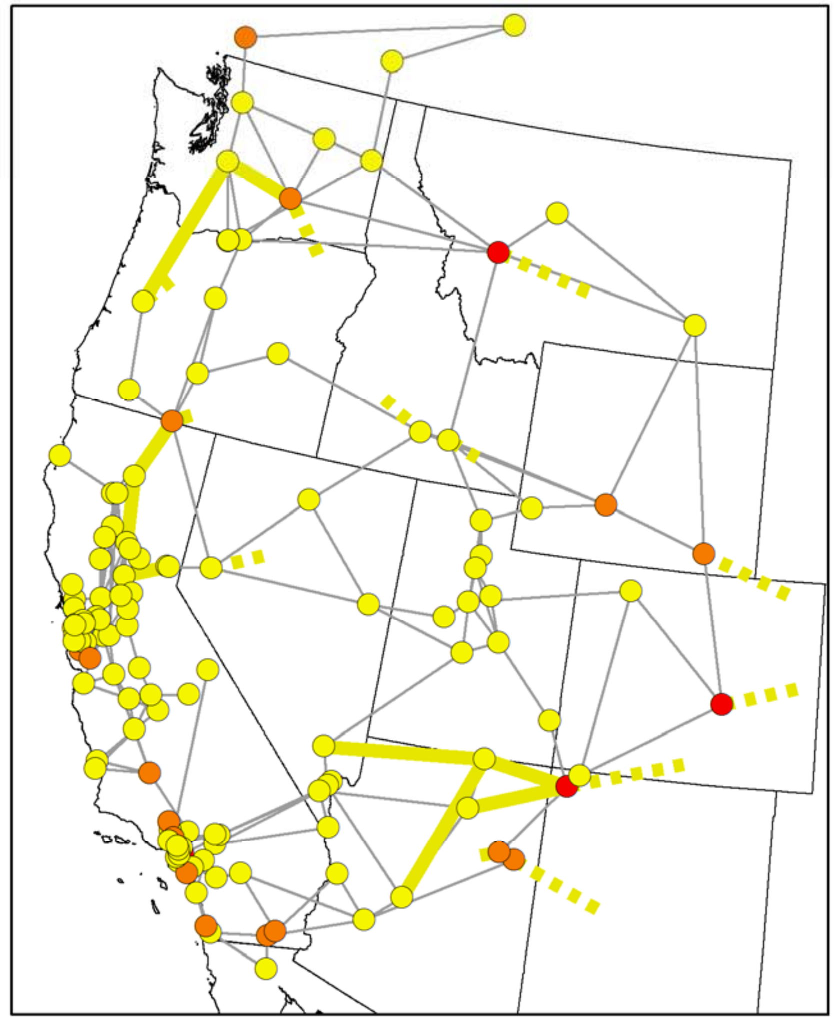
- High renewable penetration
  - *Mainly California*
- Why? California has highest state RPS

3.5 Plan 3: WECC 33% Case



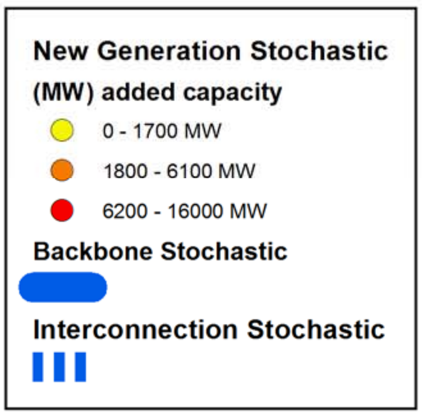


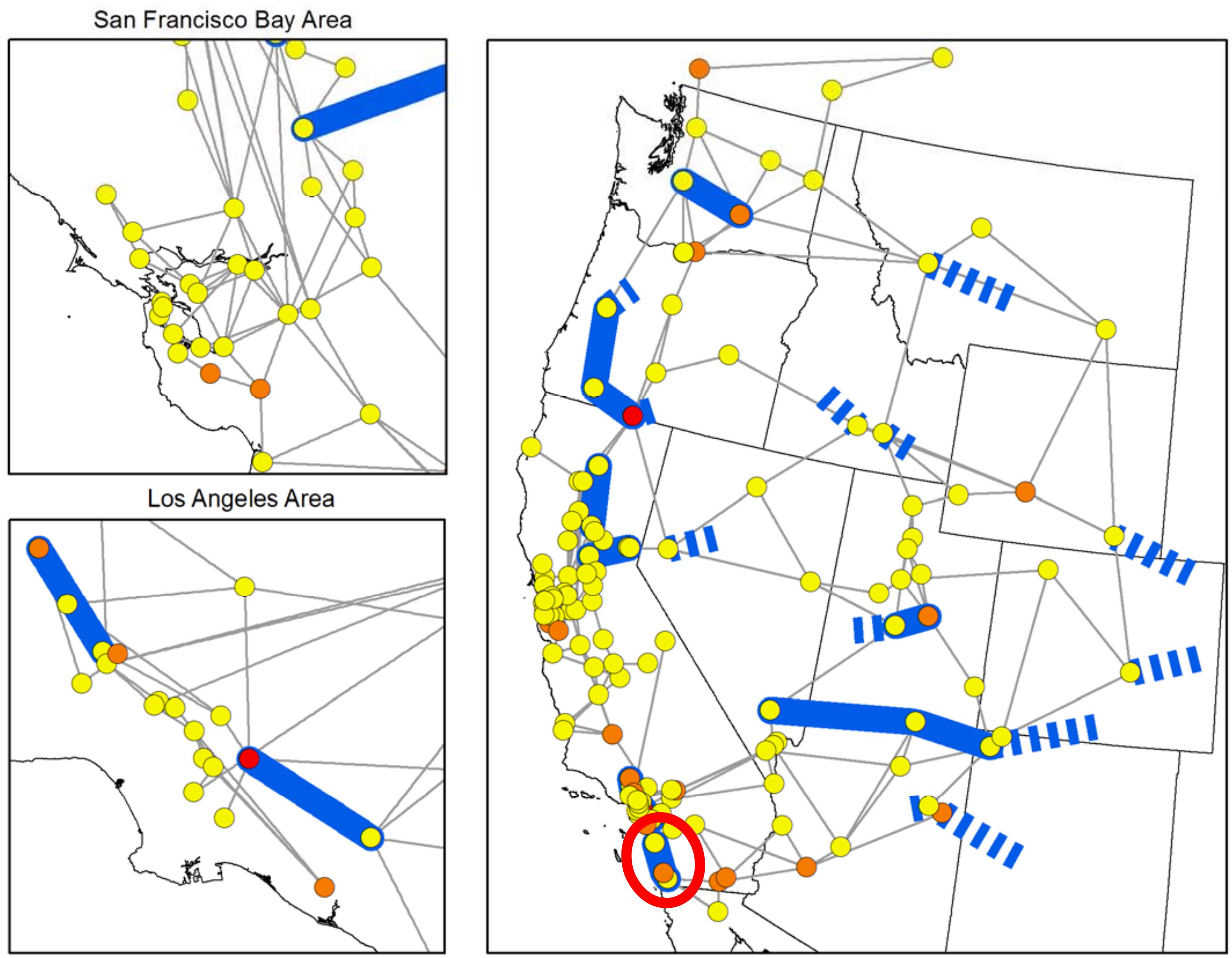




- High renewable penetration
- High quality distant resources accessed

3.6 *Stochastic* 2023 Plan

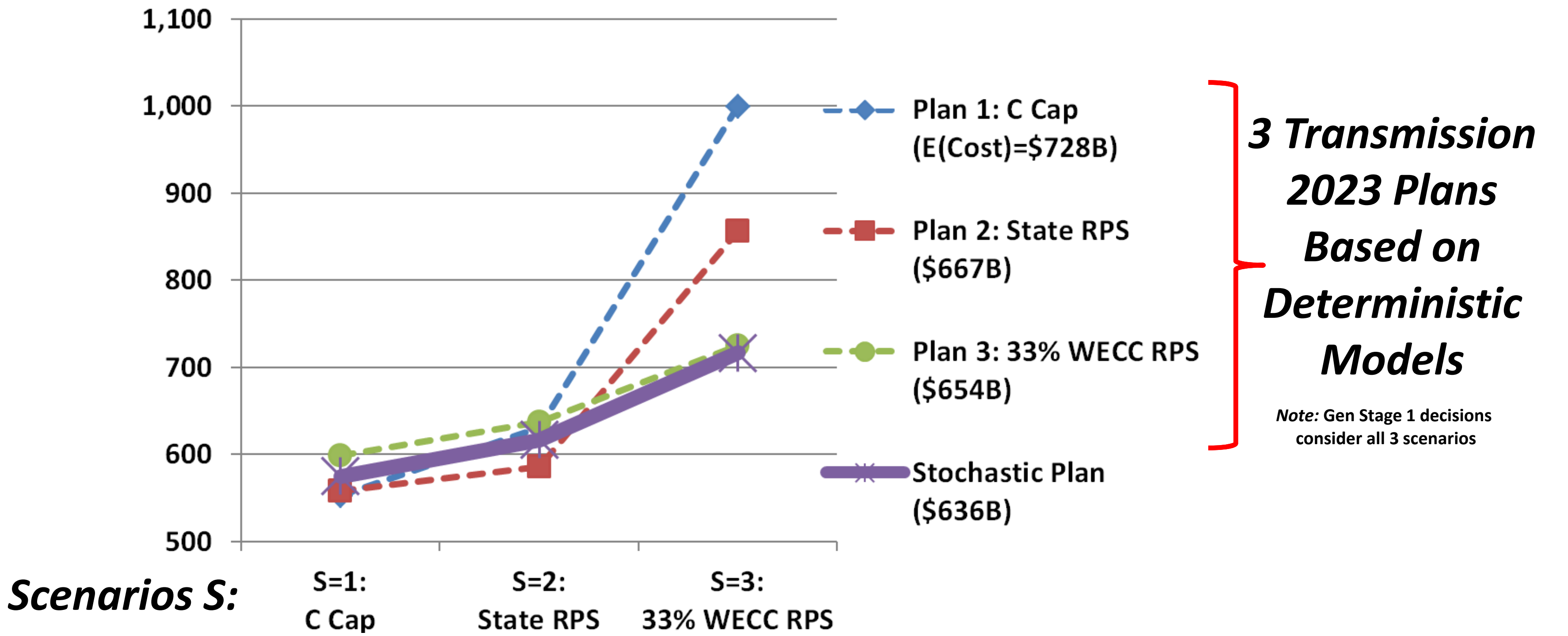




- High renewables
  - *Generation closer to California*
- **Unique stochastic lines**

3.7 Costs of Stage 1 Transmission Plan

Costs of Alternative 2023 Transmission Plans Under Each of 3 Scenarios



- **"Value of Stochastic Solution"**

  = Reduction in E(Cost) from stochastic planning ~ $47B
- **Cf. WECC 10-Year Regional Transmission Plan:**
  - ~$20B in transmission to meet 2020 demand & renewable targets

Outline

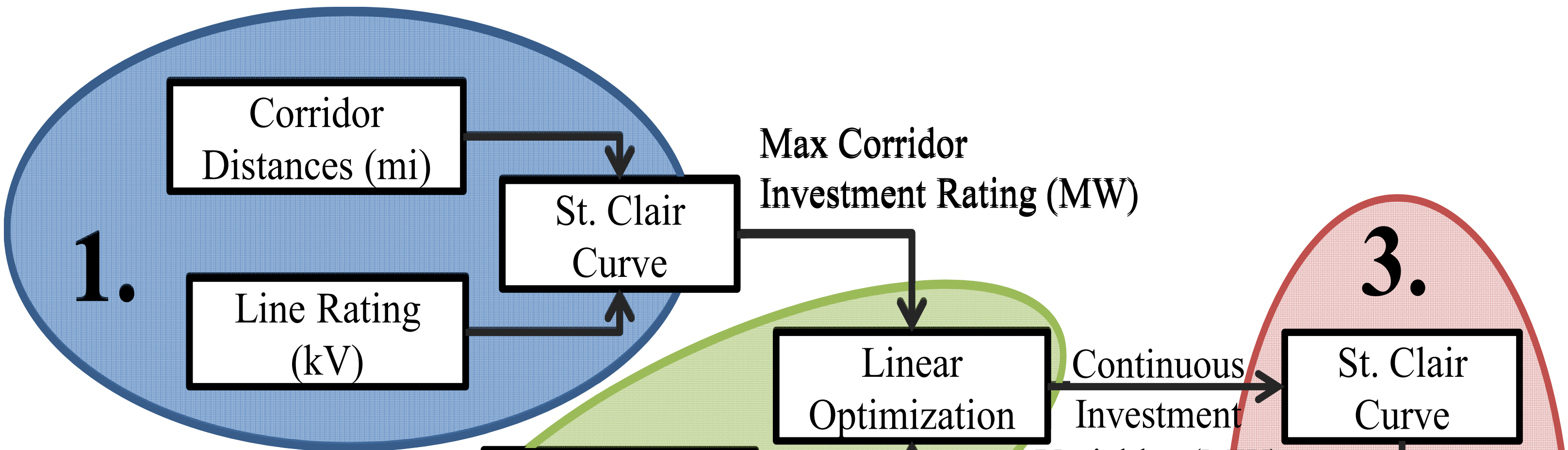
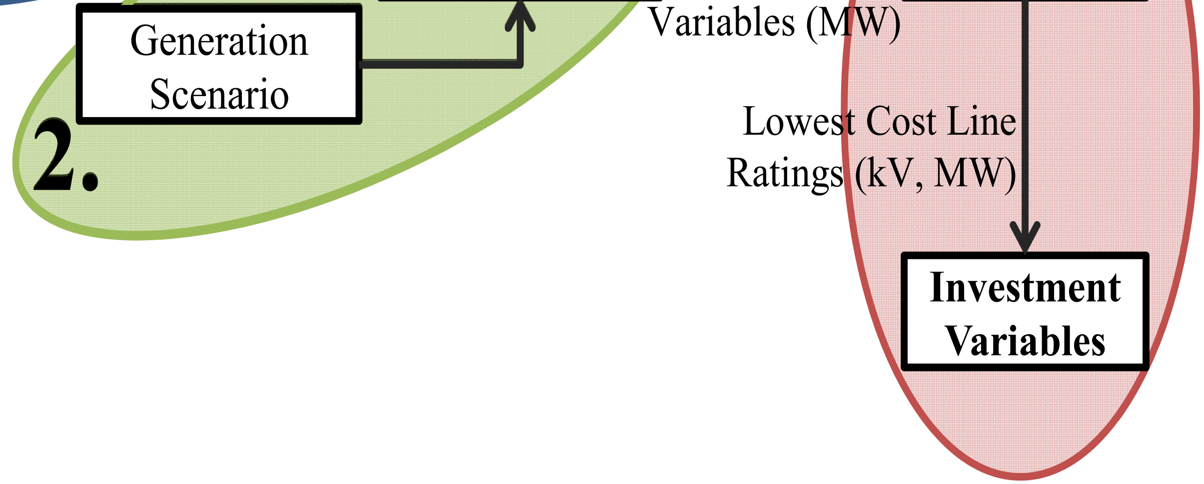
1. Introduction
2. Model Overview, Realistic Test-Case: WECC 240
3. Results
4. Dealing with Large Problems
5. Conclusions

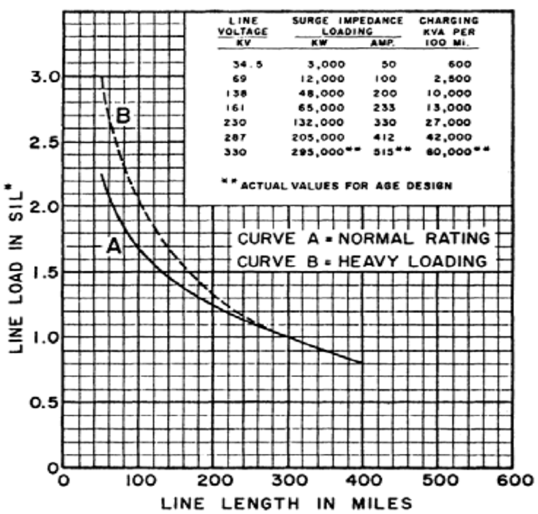
4.1 Dealing with Large Problems

- Good LP approximations of Unit Commitment MILPs
- Pre-screening of Transmission Alternatives
- Decomposition Approaches

4.2 A Problem: Too Many Options

A Solution: Reduce # Options with St. Clair Screening Model

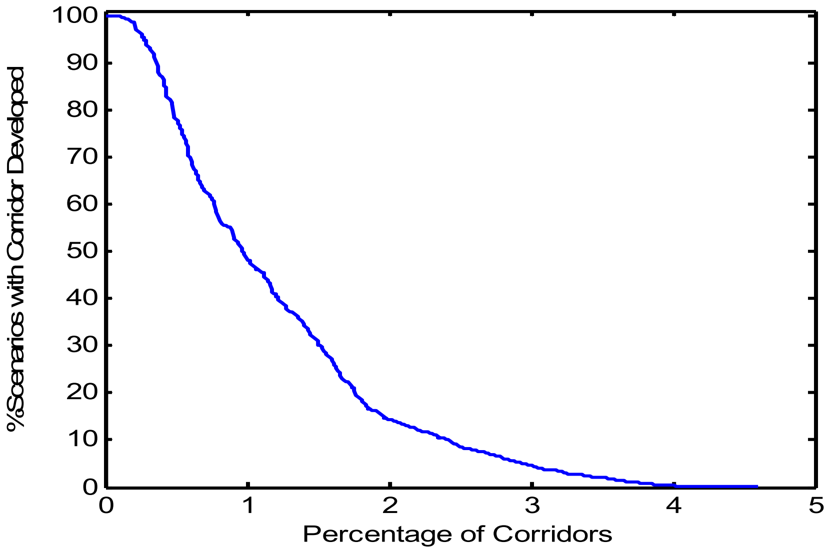


LINE VOLTAGE KV	SURGE IMPEDANCE LOADING KW	SURGE IMPEDANCE LOADING AMP.	CHARGING KVA PER 100 MI.
34.5	3,000	50	600
69	12,000	100	2,500
138	48,000	200	10,000
161	65,000	233	13,000
230	132,000	330	27,000
287	205,000	412	42,000
330	295,000**	515**	80,000**

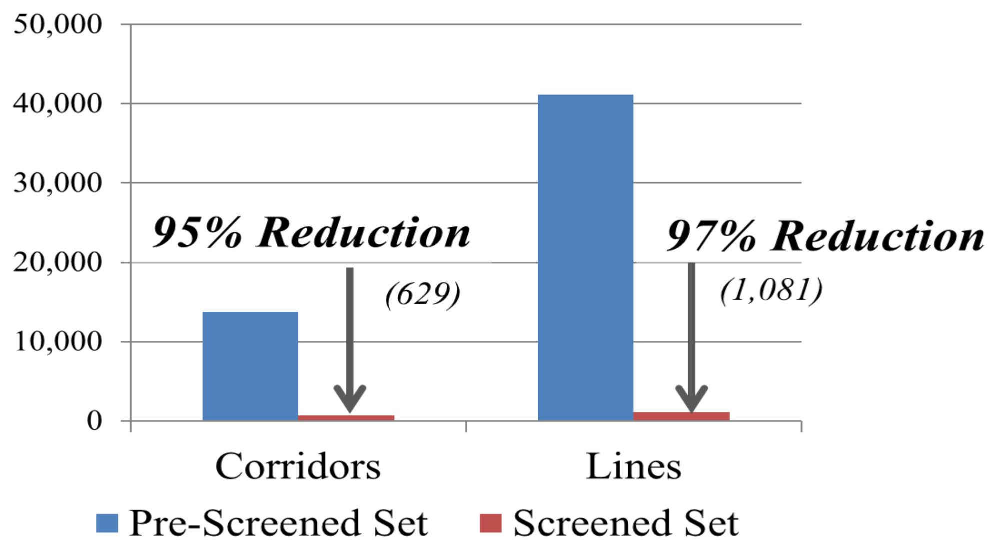
** ACTUAL VALUES FOR AGE DESIGN

(P. Donohoo, MIT Ph.D. Thesis; Donohoo, Webster, Perez-Arriaga, *PES General Meeting*, 2013)

4.3 Screening Model: Reduced # Options



- **Across 1500 runs of the WECC 240 bus LP model, only <5% of corridors are <u>ever</u> chosen**
- **Safely ignore the other 95%?**



4.4 Another Problem: Too Many Operating & Long-Run Scenarios

E.g., WECC 240 with 100 scenarios: No feasible solution after 1 day

A Solution: Decomposition

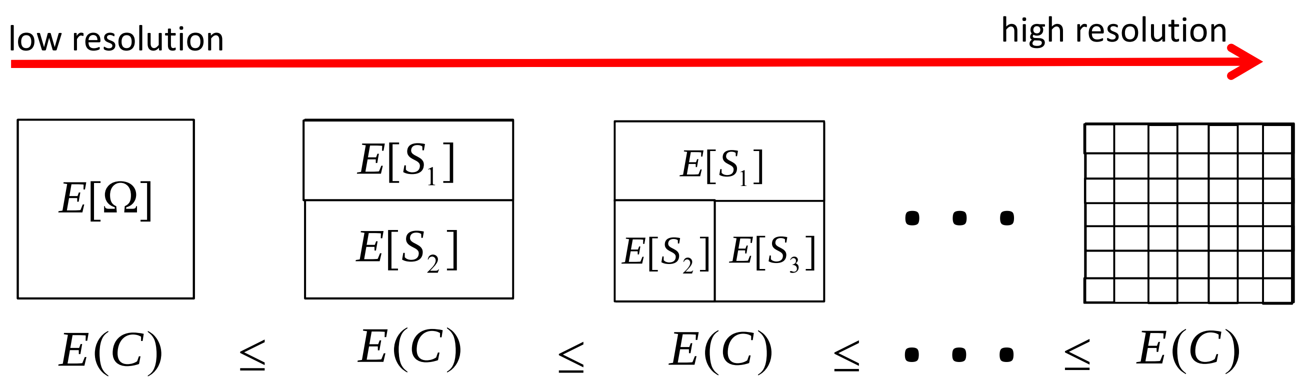
Benders Decomposition: Alternate between:

- "Master" design problem (gives lower bound)
- Operations simulation (gives upper bound)

Iteration tightens bounds, converges (eventually....) to optimum

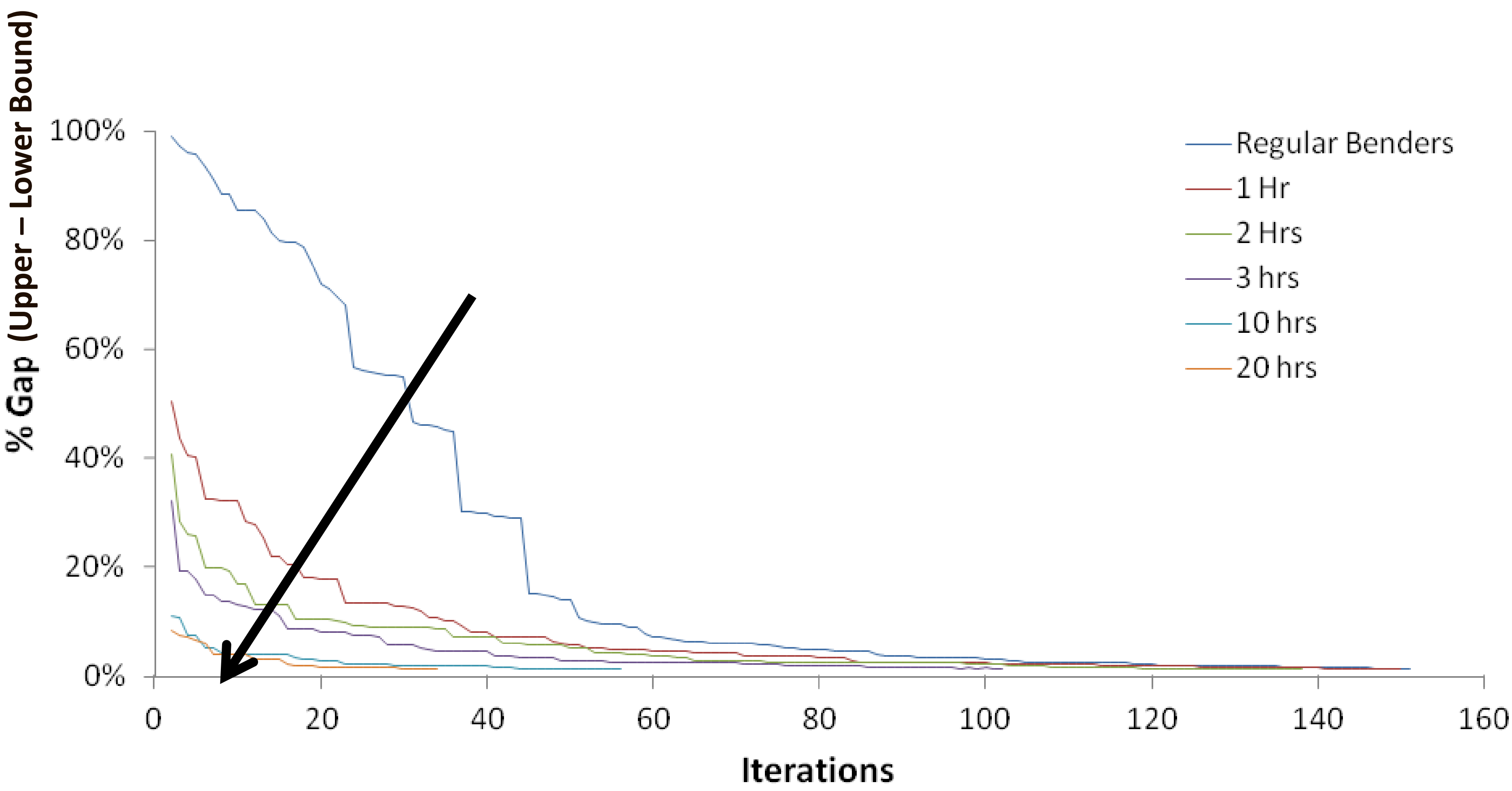
Accelerate Benders by Tightening Master Problem Lower Bound:

1) Create k partitions of space of load/VER realizations space **Ω**
2) Add ***deterministic operating problem*** for each partition to Benders master problem
3) Iterate in usual Benders fashion



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

4.5 Faster Benders Convergence with New Constraints (17 Bus Problem)



4.6 Decomposition by Progressive Hedging (F. Munoz/J.-P. Watson)

Sandia National Laboratories

Subproblem 1 | Subproblem 2 | Subproblem 3

Investments Scenario 1	Investments Scenario 2	…	Investments Scenario N
Operations Scenario 1	Operations Scenario 2	…	Operations Scenario N

→ Progressive Hedging enforces non-anticipativity constraints

↓

One 1st Stage investment plan for all scenarios

Progressive Hedging (Rockafellar/Wets):

- Converges if problem convex, good heuristic for mixed-integer problems
- Available: PySP package of Pyomo (Sandia NL)
- Used to solve large stochastic Unit Commitment problems

Improvements:

- Accelerate convergence through variable fixing and/or slamming , e.g.:
  - Fix variable if line is needed in all scenarios
  - All alternatives considered only in first iterations
- New lower bounds from dual decomposition (S. Ryan, Iowa State)

In Practice:

- WECC-240 and 100 scenarios: CPLEX → No feasible solution after 1 day of CPU time
  PH → 20 iterations/15 min yields 1.5% optimality gap

4.7 Goals of Sandia Effort

Sandia National Laboratories

- Execute stochastic transmission and generation expansion planning **at scale**, **on real-world data sets**

  - Stochastic models are needed,
  - But no commercial software available for stochastic investment planning

- Produce solutions in **tractable run-times**, **with bounds**

- Develop scenario selection algorithms for execution on **commodity workstations**, not just supercomputers

Outline

1. Introduction
2. Model Overview, Realistic Test-Case: WECC 240
3. Results
4. Dealing with Large Problems
5. Conclusions

5 Conclusions

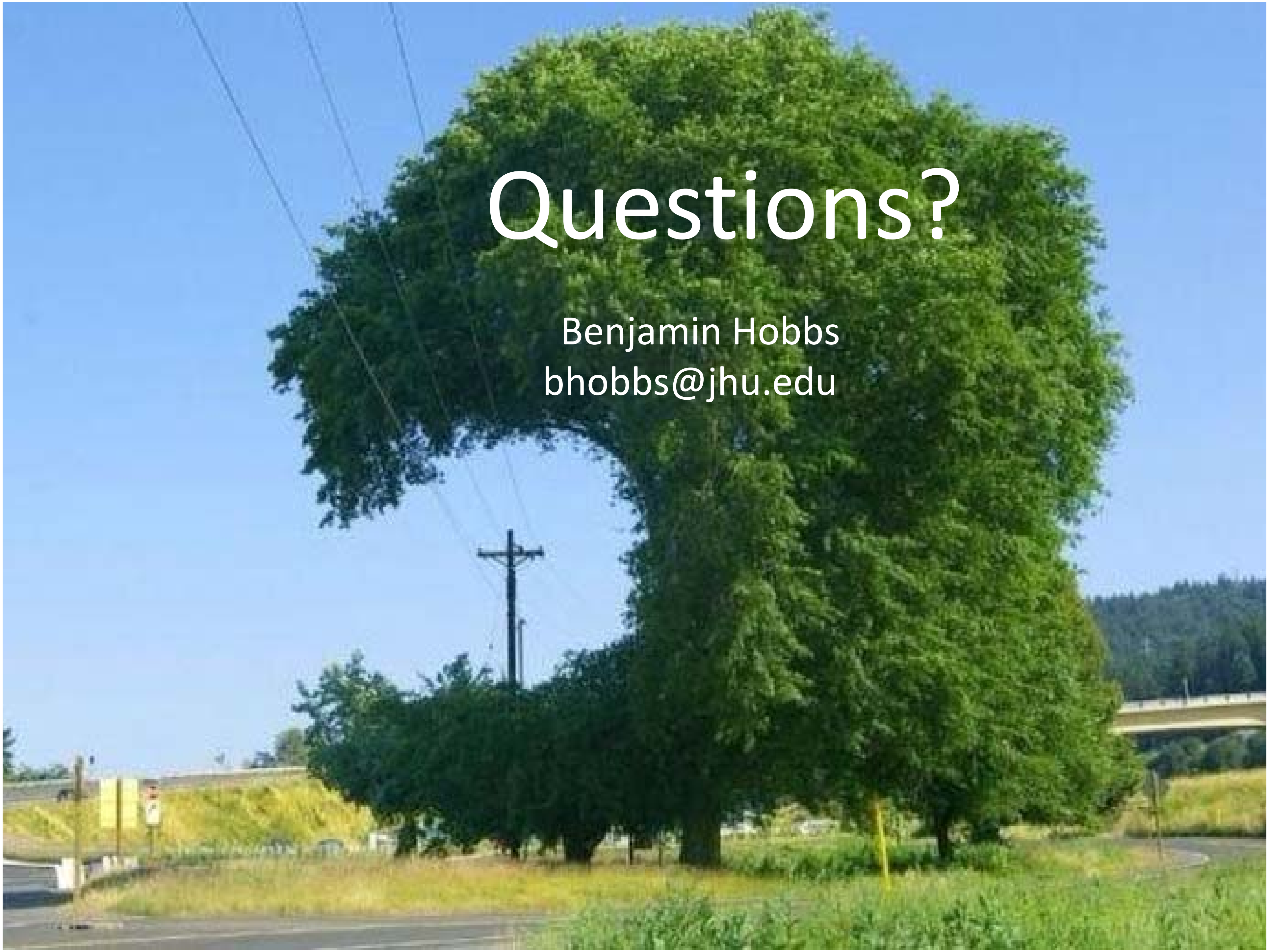
- Scenario Planning has a major shortcoming:
  Deterministic plans don't account for flexibility

- Heuristic planning rules can perform <u>worse</u> than myopic deterministic plans

- Value of Stochastic Solution can be ~2X the cost of transmission

- Can solve very large problems (e.g., more scenarios, operating conditions) with
  → screening
  → bounding/decomposition

- *Next:* Demos for WECC and other systems with realistic data


Questions?
Benjamin Hobbs
bhobbs@jhu.edu

References

AESO, "**AESO Long-term Transmission Plan**," Alberta Electric System Operator, June 2012. www.aeso.ca

M. Awad, K.E. Casey, A.S. Geevarghese, J.C. Miller, A.F. Rahimi, A.Y. Sheffrin, M. Zhang, E. Toolson, G. Drayton, B.F. Hobbs, and F.A. Wolak, **"Economic Assessment of Transmission Upgrades: Application of the California ISO Approach"**, Ch. 7, in X.-P. Zhang, Restructured Electric Power Systems: Analysis of Electricity Markets with Equilibrium Models, Power Engineering Series, J. Wiley & Sons/IEEE Press, July 2010, 241-270.

CAISO, "**2011-2012 Transmission Plan**," California ISO, March 2012. www.caiso.com

FERC Order 1000 - Transmission Planning and Cost Allocation.

A. Liu, B.F. Hobbs, J. Ho, J. McCalley, V. Krishnan, M. Shahidehpour, and Q. Zheng, **Co-optimization of Transmission and Other Supply Resources**, Prepared for the Eastern Interconnection States' Planning Council, NARUC, Dec. 2013, naruc.org/Grants/Documents/Co-optimization-White-paper_Final_rv1.pdf

B. F. Hobbs and Y. Ji, "**Stochastic Programming-Based Bounding of Expected Production Costs for Multiarea Electric Power Systems**," Operations Research, 97 (6), 836-848, 1999.

MISO, "**Regional Generation Outlet Study**," Midwest ISO, November 2010. www.midwestiso.org

F.D. Munoz, B.F. Hobbs, and S. Kasina, An Engineering-Economic Approach to Transmission Planning Under Market and Regulatory Uncertainties: WECC Case Study, IEEE Transactions on Power Systems, 29(1), January 2014, 307-317.

J.P. Pfeifenberger and D. Hou, "**Transmission's True Value: Adding up the Benefits of Infrastructure Investments,**" Public Utilities Fortnightly, February 2012, 44-50.

J.E. Price and J. Goodin, "**Reduced Network Modeling of WECC as a Market Design Prototype**, IEEE PES GM, 2011.

R. P. O'Neill, E. A. Krall, K. W. Hedman, and S. S. Oren, "**A Model and Approach for Optimal Power Systems Planning and Investment**," Mathematical Programming, 2012.

R.T. Rockafellar and R.J.B. Wets, "**Scenarios and Policy Aggregation under Uncertainty**," Mathematics of Operations Research, 1991, 119-147.

A.H. van der Weijde and B.F. Hobbs, "**The Economics of Planning Electricity Transmission to Accommodate Renewables: Using Two-Stage Optimisation to Evaluate Flexibility and the Cost of Disregarding Uncertainty**, Energy Economics, 34(5), Sept. 2012, 2089-2101.