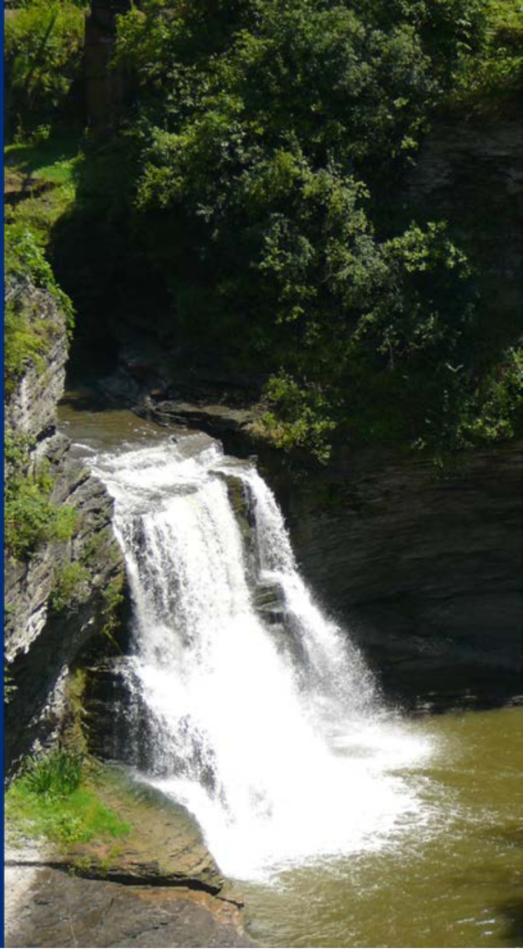
The Johns Hopkins University
Environment, Energy, Sustainability & Health Institute

The Value of Better Transmission Planning Models: *Long-run Stochastic Planning, DC Load Flow, Unit Commitment, & More Hours*



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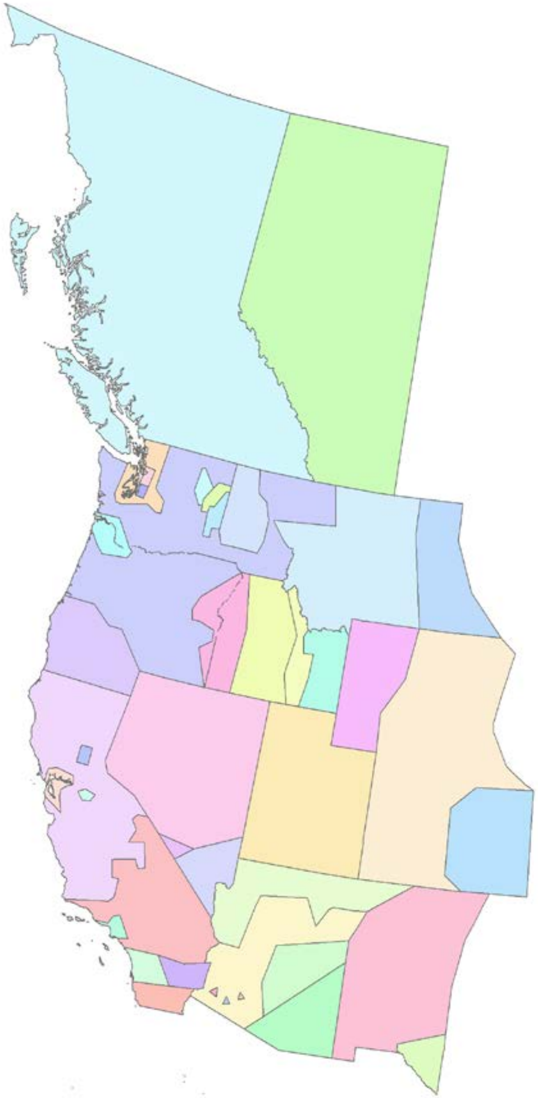
Results are hypothetical; opinions expressed don't necessarily represent the position of the funding agencies or any of the above individuals; the authors are solely responsible for any opinions or errors.

Agenda

- **Motivation**
- Methodology
- Results
- Conclusions

Western Electricity Coordinating Council



Motivation

- Why long-term?
  - Line construction is **slow & costly**
    → potential for large regret
- Why proactive planning (co-optimize trans & gen)? [Sauma & Oren '06; Liu et al. '13]
  - Transmission routing affects generation **siting**
- Why uncertainty?
  - Long run: Uncertain **fuel prices, load growth, policy (renewable & carbon)**
  - Short run: Load and renewable **variability**
- Why stochastic programming? [van der Weijde & H '12; Munoz et al. '14]
  - To find a solution that adapts well to several possible futures **in a single run**

Motivation: WECC 2013 Plan

Plan's recommendations:

#1,5 Quantify uncertainty in planning studies, especially beyond 2020

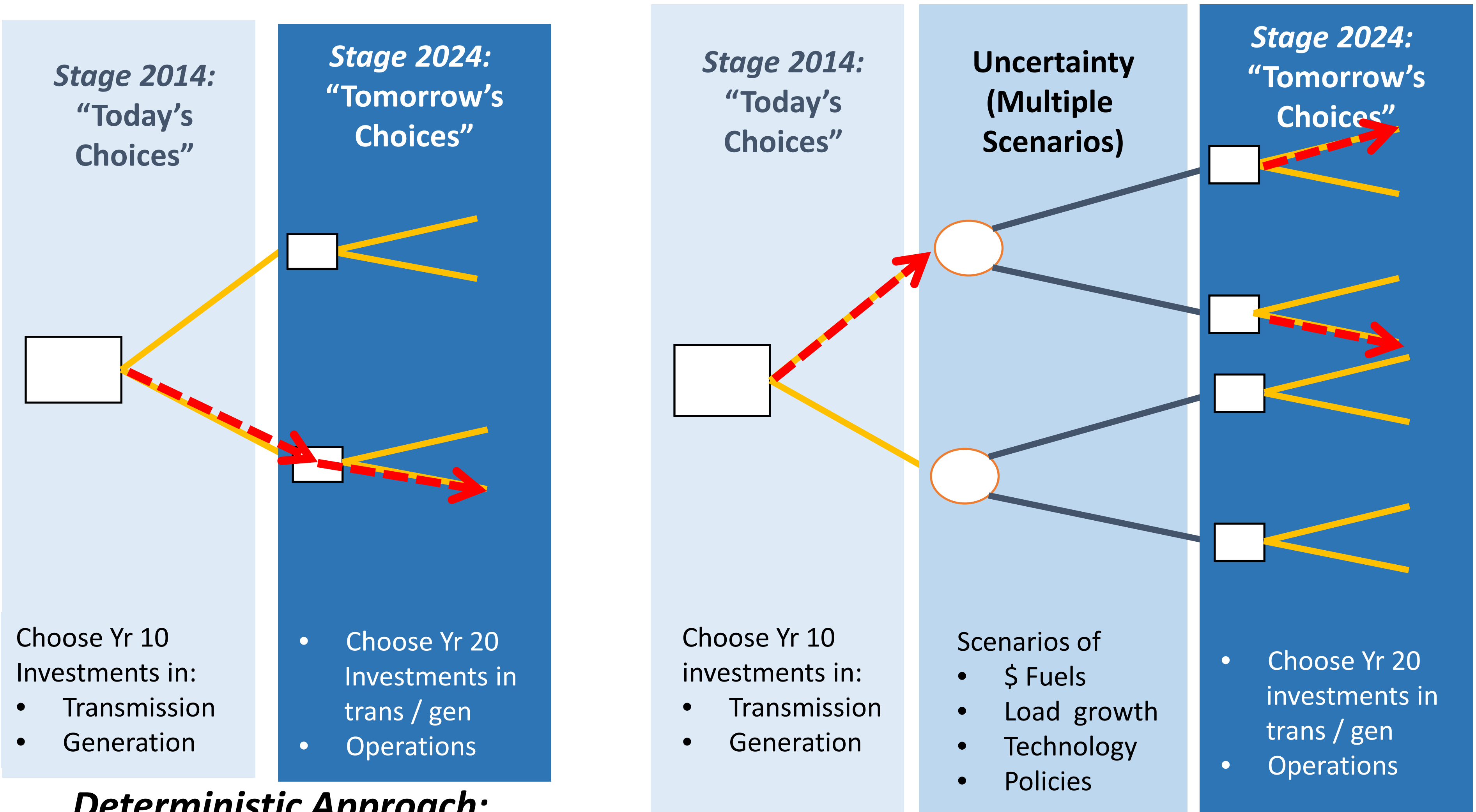
#3 Assess operational & infrastructure investment approaches to providing operational flexibility

#9 Acknowledge uncertainty around construction of 10-yr study transmission

Contents

- Motivation
- **Methodology**
  - JHSMINE
  - Scenario development
  - WECC network model
- Results
- Conclusions

JHU Stochastic Multistage Integrated Network Expansion (JHSMINE): *A Stochastic Program*



Deterministic Approach: One model for each study case

JHSMINE: Solve all cases at once in one model

JHSMINE formulation: Stochastic MILP

Optimize the objective:

Minimize (probability-weighted, present worth) of cost over 40 yrs

By choosing values of decision variables:

- Transmission investment (0-1)
  - 10 yr "portal" lines (in addition to Common Case lines)
  - 20 yr lines
- Gen investment & dispatch *(co-optimized)*

Respecting constraints:

- Kirchhoff's laws (linear OPF) by hour
- Generator operating constraints
  - Variable renewable availability by hour
  - Unit commitment linearization
- RPS
- Siting restrictions

Accounting for uncertainties:

- load/renewable conditions (hourly variability)
- *IN STOCHASTIC MODEL:* long-run scenarios

Long Run (30 year) Scenarios

Low Value
Base Case Value
High Value

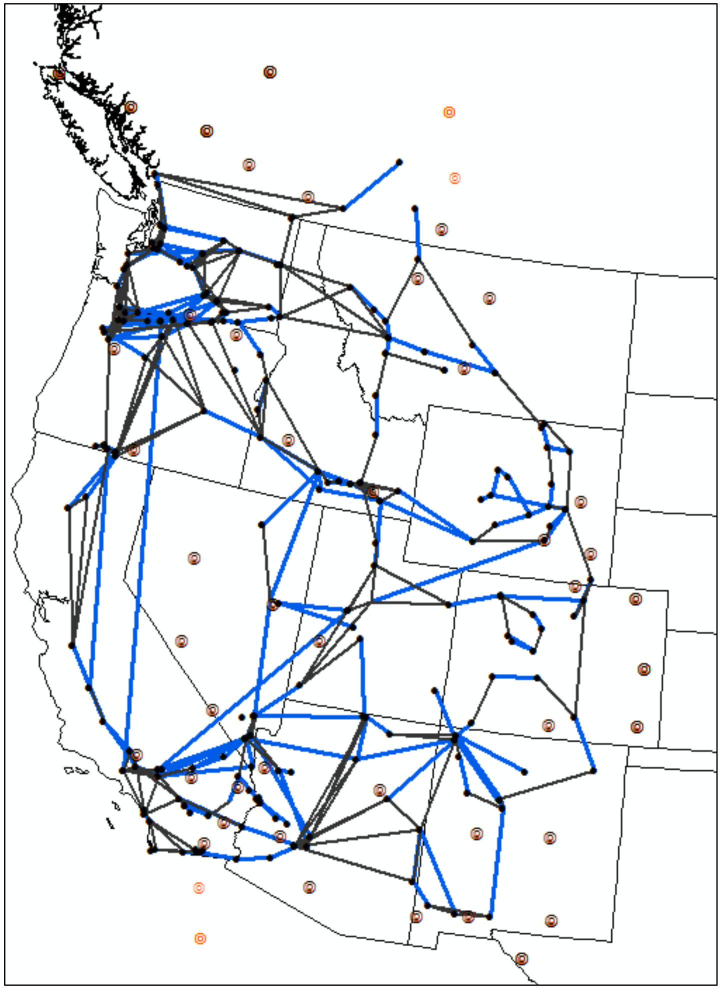
5 Example Scenarios predefined by WECC

Variable: / **Scenario**	*Gas Price*	*Carbon Price*	*Load Growth*	*State RPS*	*Federal RPS*	*DG*	*Wind Cap. Cost*	*Geo Cap. Cost*	*Solar Cap. Cost*	*DR*	*Storage*	*Peak Growth*	*Instate RPS*	*Coal Price*	*IGCC w/ CCS Cap. Cost*
Base Case	Base	Base	Base	Base	Base	Base	Base	Base	Base	Base	Base	Base	Base	Base	Base
WECC 1: Econ. Recovery	High	Base	High	Base	Base	Base	High	Base	Base	Base	Base	High	Base	Base	Base
WECC 2: Clean Energy	Base	High	High	High	High	Base	Low	Low	Low	Base	Base	High	Low	Base	Low
WECC 3: Short-Term Consumer Costs	Base	Low	Low	Low	Base	Base	High	Base	High	Base	Base	Low	Base	Base	Base
WECC 4: Long-Term Societal Costs	Low	High	Low	High	High	Base	Low	Base	Base	Base	Base	Low	High	Base	Base

Probabilities:

Equiprobable; Moment-matching assignment

WECC 300 Bus Network



300-bus network
(developed by JHU, with help of ASU):
Pipes & Bubbles or Linearized DC OPF (KCL/KVL)

- –Preserve WECC paths between regions
- –244 preserved monitored lines
- –282 equivalenced unmonitored lines
- –26 hubs for new thermal plants
- –WREZs for renewable development

Contents

- Motivation
- Methodology
- Results: 4 Sets of Questions:
  1. Is stochastic planning ***practical***?
  2. Are the plans ***better***?
  3. Are stochastic solutions ***sensitive*** to:
     - # or probabilities of the scenarios?
  4. What is the ***economic value*** of other model features?
     - # hours, unit commitment, network
- Conclusions

These are hypothetical runs based the JHU database and don't represent official WECC assumptions, policy, or results

1. Is stochastic programming practical for transmission planning?

Answer: Yes*

	21 Zone		
# Scenarios	Base (1)	WECC 5	WECC 5
Load flow model	KCL	KCL	KCL
Operations model	Dispatch	Dispatch	Unit commitment
# Load hours	24	24	72
MIP gap	0.01%	0.01%	0.10%
# Variables/Constraints	60K/68K	340K/300K	3.4M/2.2M
Solution times	5 sec	56 sec	2 hrs

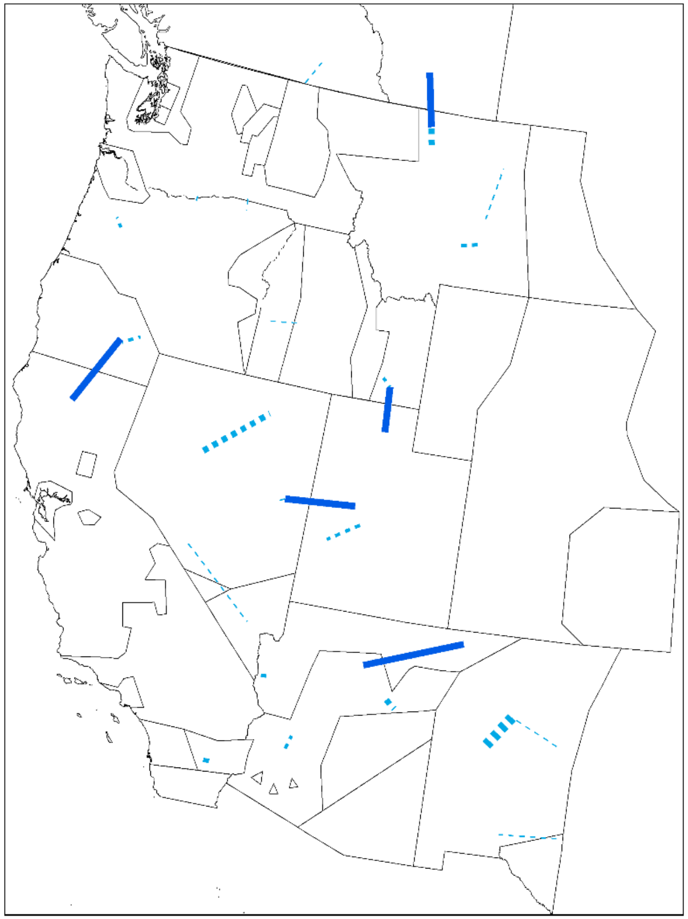
*Tradeoff:

If you simplify the network (KCL) and operations (dispatch, no UC)

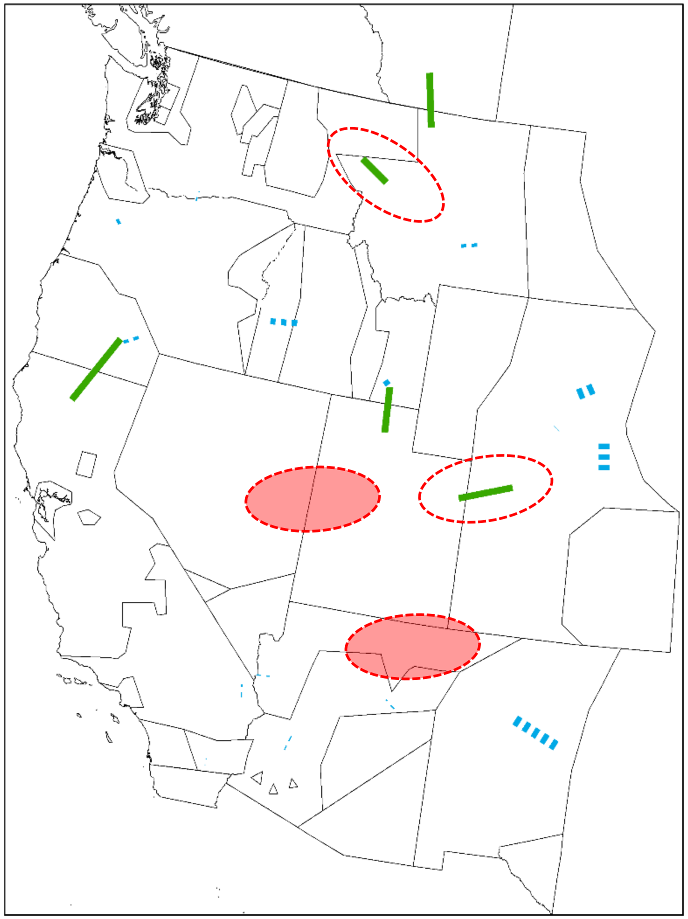
→ *then you can have more scenarios & hours*

2. Do stochastic and deterministic plans differ?

Answer: Yes*;* stochastic model identifies lines that enhance robustness but that the deterministic approach misses



300-bus model, Base Case,
1st stage decisions



300-bus model, 5 Scenario Differentiated Probability,
1st stage decisions

2. Are stochastic solutions better?

- If you build "Base Case" 1st stage transmission lines rather than the optimal stochastic lines in 300 bus model, then E(cost penalty) =

    - *$1.0B-$6.5B (depending on probabilities)*
    - *= "Value of Stochastic Solution"*

  Cf.

    - *~$10B of variable 1st stage transmission investment*
    - *$48B net value (PW) of adding transmission in WECC*

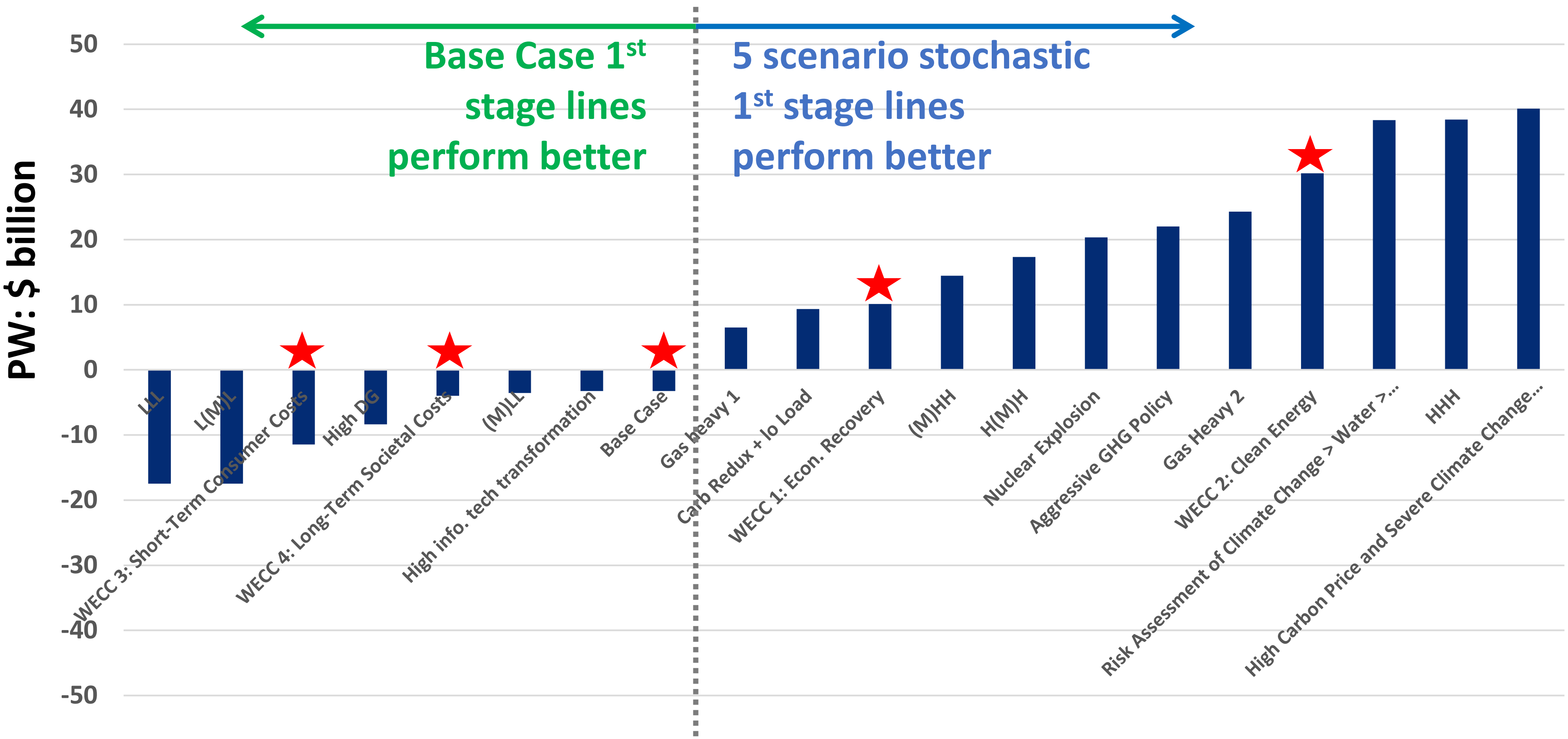
- Deterministic plans based on other scenarios have $1.3B-$29.7B penalty (300 bus) (average = $8.3B)

2. Are stochastic solutions better?

Are they more robust against scenarios not considered?

Answer: Yes, the 5 Scenario 1st stage lines perform better against the withheld 15 scenarios than the base case (deterministic) 1st stage lines

Base Case *minus* 5 Scenario Stochastic (with Equal Probabilities, 300 bus model)

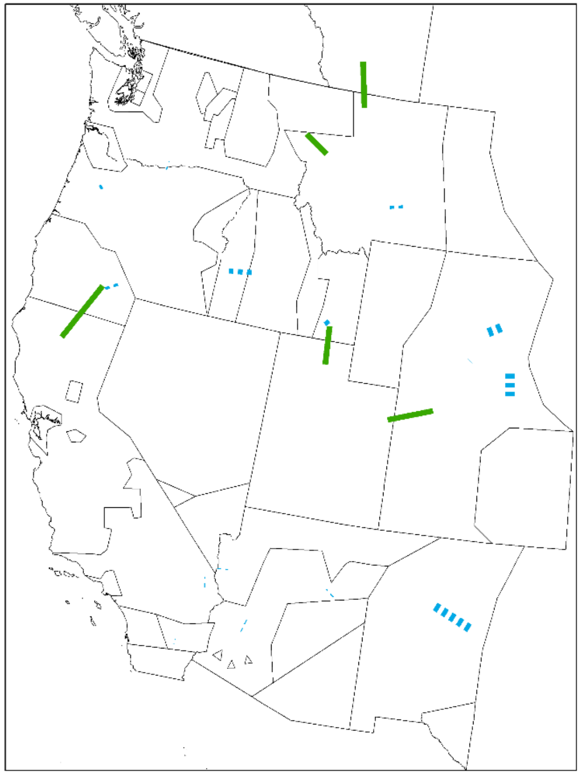


★ *Included in 5 Scenario Model; other 15 scenarios not in model*

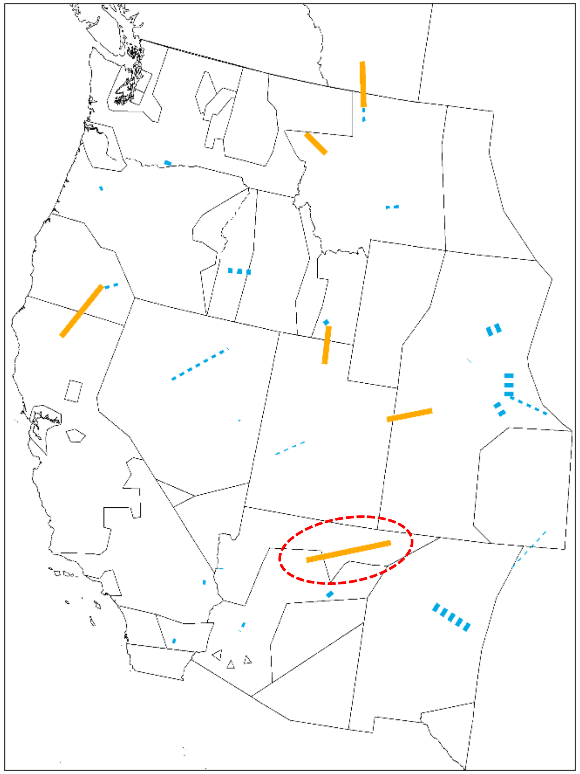
3. Are stochastic solutions sensitive to probabilities?

Answer: Not much for 300 bus case's 1st stage lines

Differentiated Probabilities



Even Probabilities



Possible explanation: **As long as scenarios span the possibilities,** decisions will not change significantly

4. What's the value of other model features? *E.g., "Dispatch" vs. "Unit Commitment Modeling"*

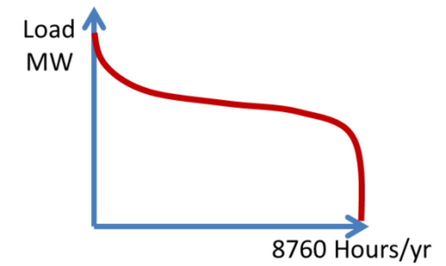
Simple "load duration curve" method

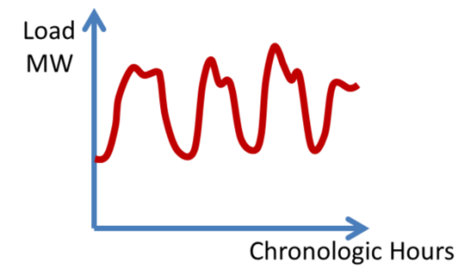
(assumes infinite flexibility)

versus

Unit commitment (UC) approximation

(captures flexibility limits)

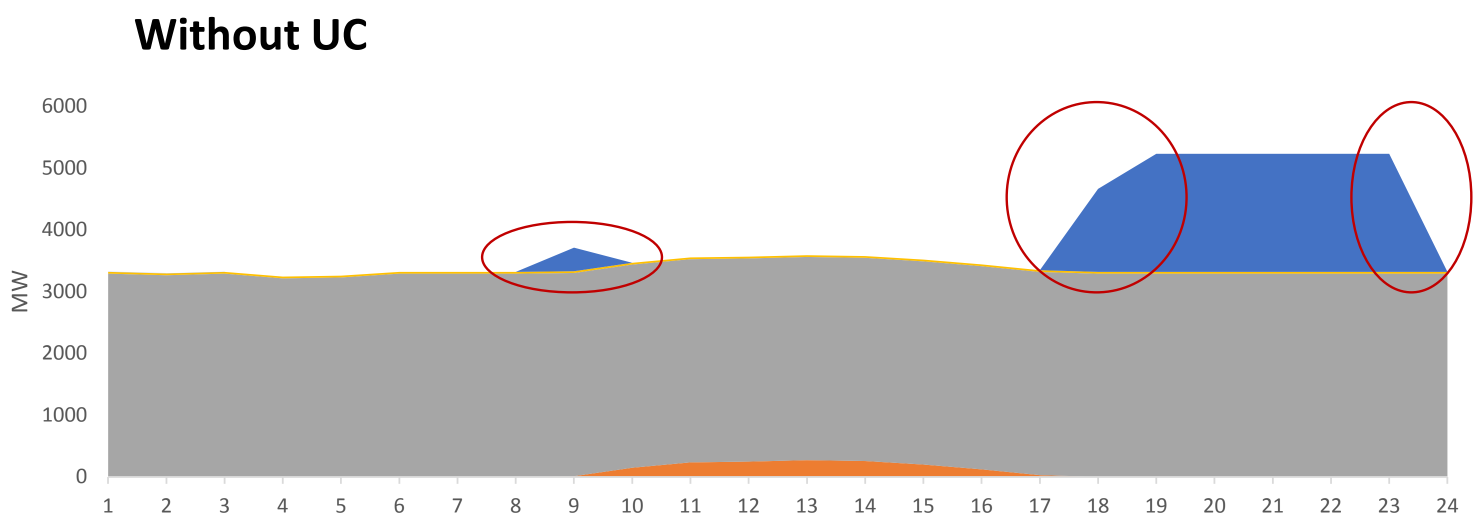


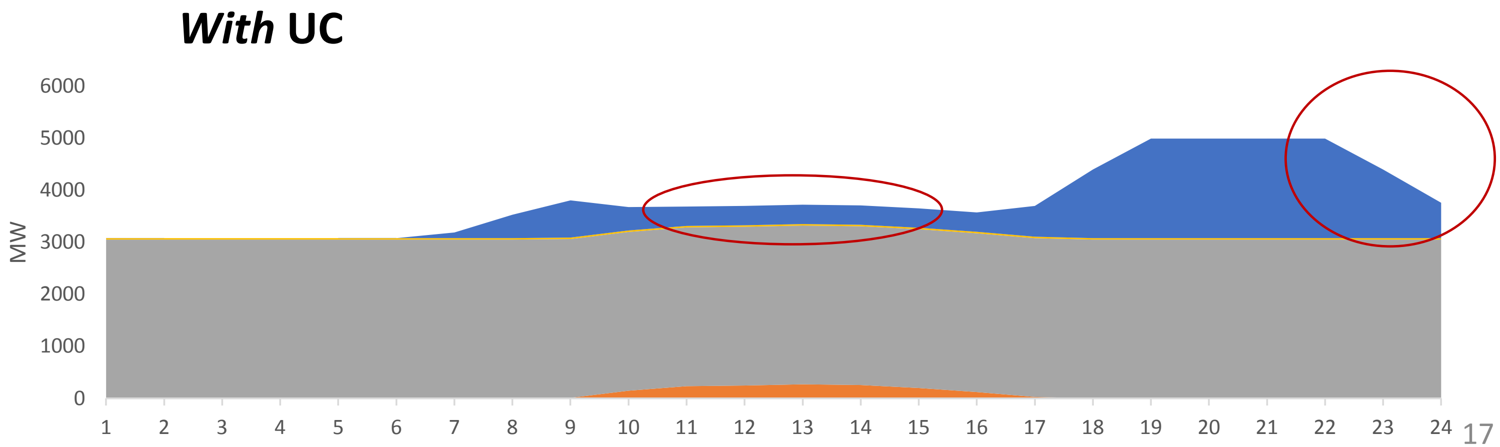


- Simplified "relaxed" UC, which preserves computational efficiency of LP
  - Ramp limits
  - Approximation of start-up costs, Pmin constraints

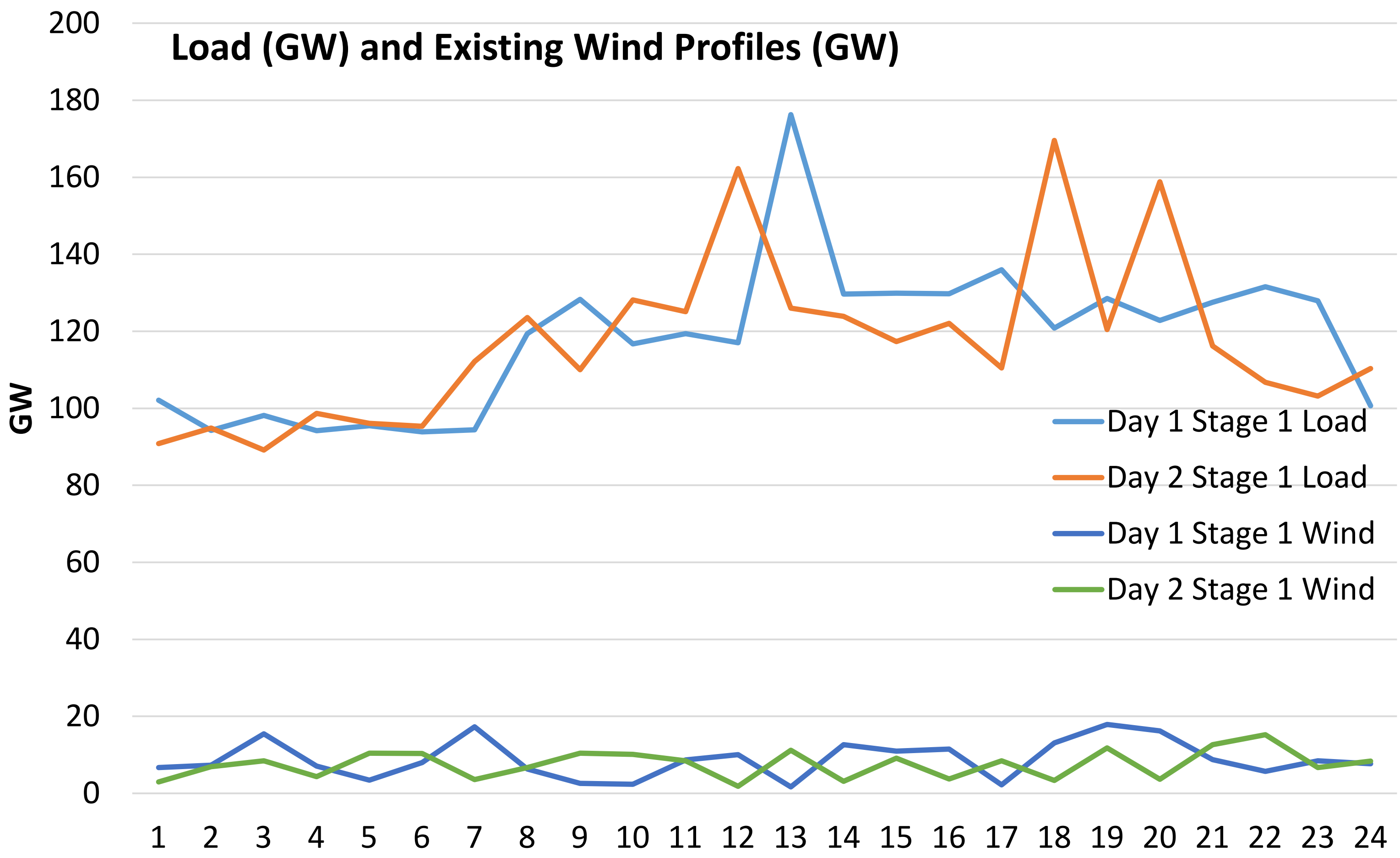
4. Value of other model features?

Answer for UC: Yes, in some cases with high coal





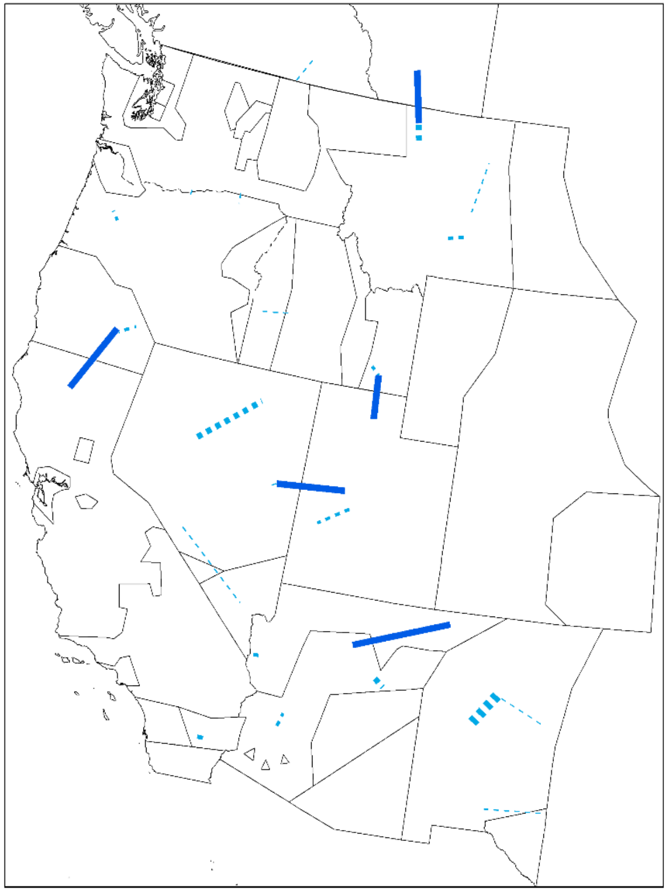
4. Value of other model features?
E.g., 24 vs. 48 hours per year



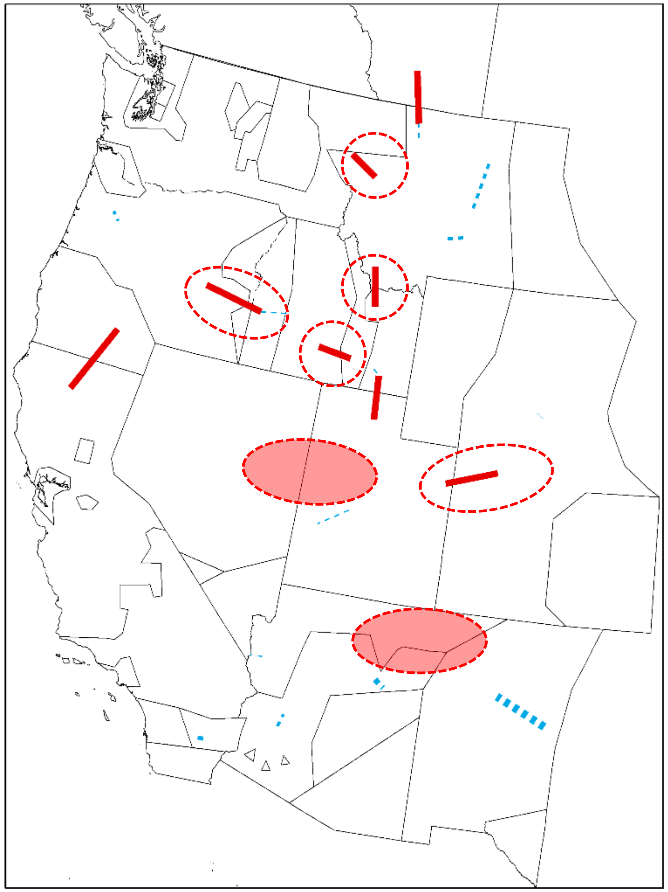
4. Does a more complex model change the plan?
Comparison of 2024 additions, Deterministic Base Case

Answer: Yes

"Pipes and Bubbles", Dispatch Only, 24 hours



"DC Linear," Unit Commitment, 48 hours



4. Which model feature most improves solutions?

- Modeling choices:
  - *Network representation* ("pipes-and-bubbles" vs. DC OPF)
  - *Generator unit commitment* (dispatch only vs. linearized start-up costs/Pmin constraints/ramp rates)
  - *Hour resolution* (24 hrs/yr vs. 48 hrs/yr)
  - *Uncertainties* (1 long run scenario vs. stochastic programming with 5 scenarios)

- "Value of Model Sophistication" (VoMS): Compare performance under full model of:
  - Transmission solution from model *without feature*
  - Transmission solution from model *with feature*
  - Compare that to cost of transmission (~$10B 2015-2024) or value of adding transmission (~$48B 2015-2034)

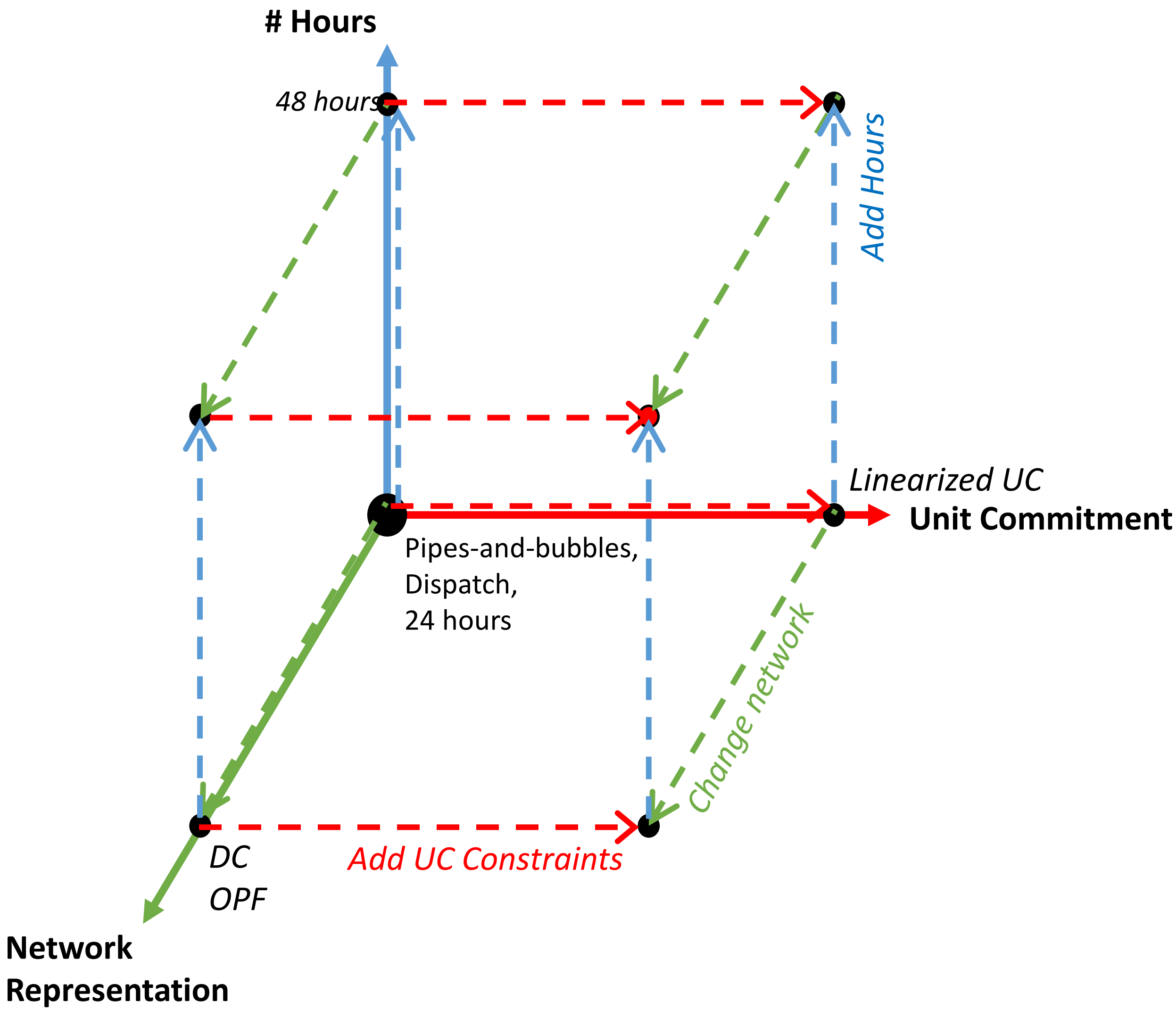
4. VoMS is useful

- Limited computation power→ we must choose which feature to include
  - Which one?

- Value of Model Sophistication (VoMS):
  - How much would you pay to add this feature to the model?
  - Analogous to decision analysis' "value of information"

4. Does a more complex model change the plan?

Hours Resolution



Solve models with different features

↓ Plans

Test Plans against market simulation (the most complicated model)

↓ System Costs

Compare the costs, and calculate VoSM (benefit of adding feature)

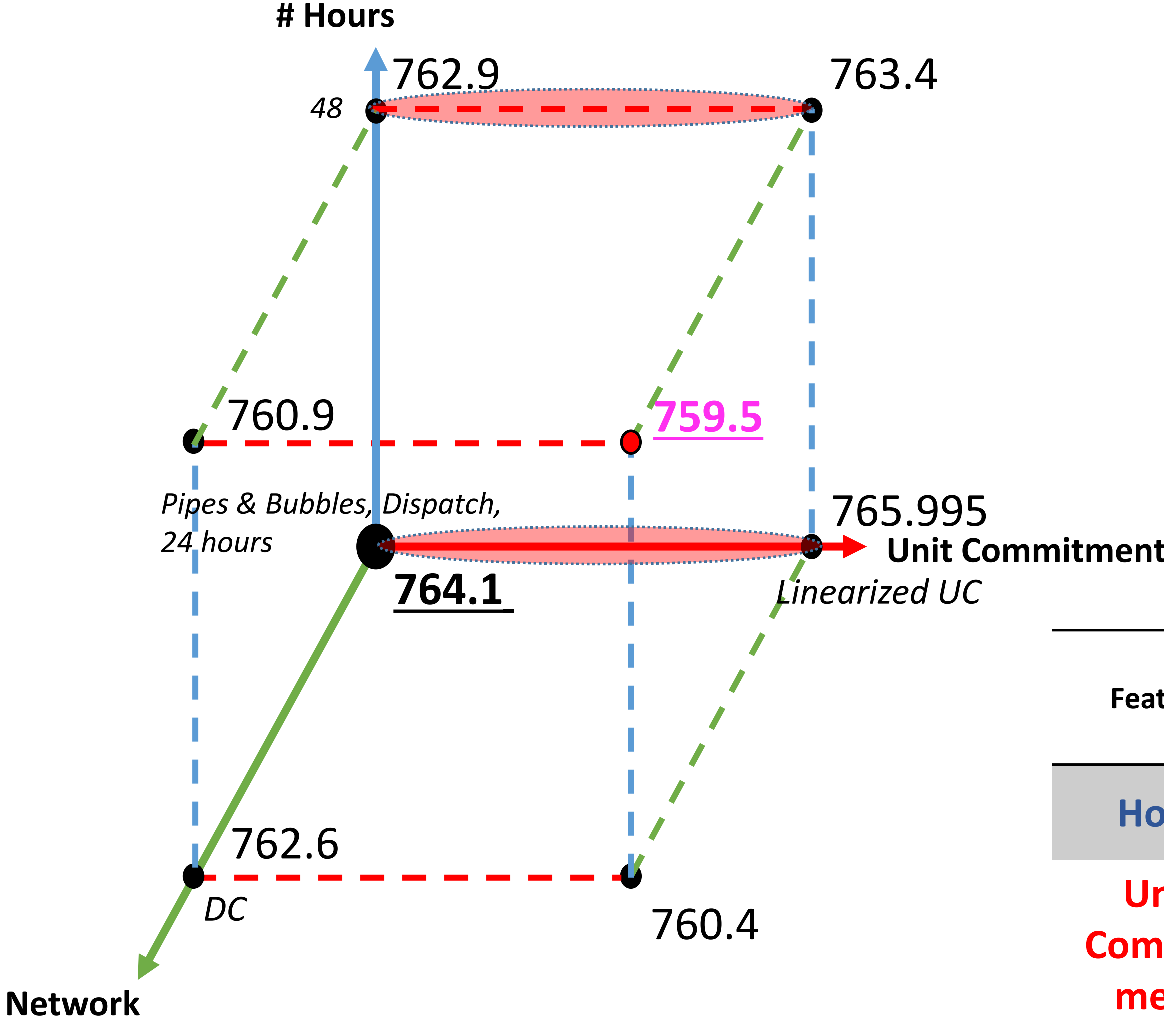
For example, VoSM of unit commitment is the average of red differences

4. Overview of models

	Deterministic								Stochastic
Generator Commit-ment	w/o UC	Linearized UC	w/o UC	Linearized UC	w/o UC	Linearized UC	w/o UC	Linearized UC	w/o UC
Network	P&B	P&B	DC OPF	DC OPF	P&B	P&B	DC OPF	DC OPF	P&B
Hour Resolution per Stage	24	24	24	24	48	48	48	48	24
Scenarios	Base Case	Base Case	Base Case	Base Case	Base Case	Base Case	Base Case	Base Case	5 Scenario
# Constraints	230185	988585	257641	1016041	459865	1976665	514777	2031577	1150921
# Variables	181361 (30 binary)	465761 (30)	193313 (30)	477713 (30)	361649 (30)	930449 (30)	385553 (30)	954353 (30)	904637 (90)
Solving Time	23	109	2876	21188	68	455	14714	105683	332

*All (MILP) models were solved to less than 1e-7 convergence gap to get accurate solutions

4. Results: Hours vs. Unit Commitment vs. Network? $Billion (PW) for WECC



Feature	Min Benefit (billion $)	Max Benefit (billion $)	Mean VoMS (billion $)
Hour	0.9	2.6	1.6
Unit Commit-ment	-1.9	2.1	0.3
Network	1.5	5.6	3.2

4. VOMS

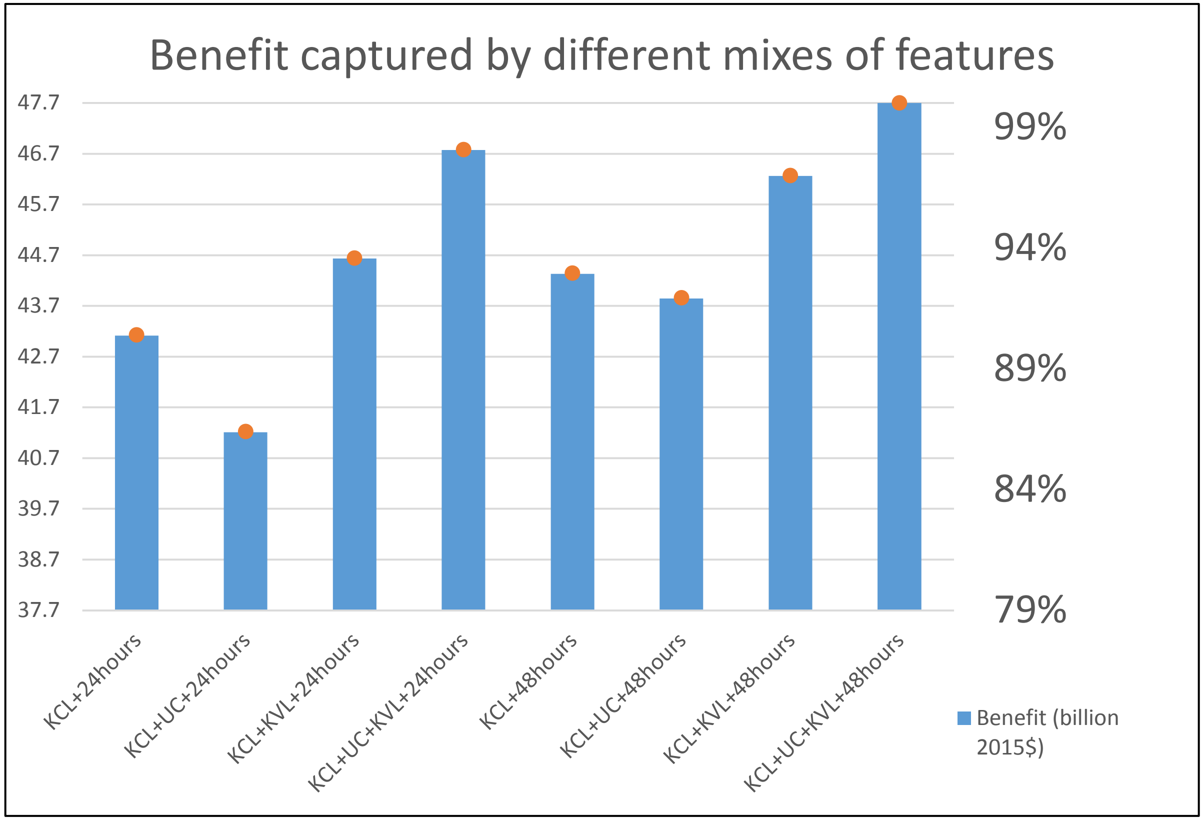
4. How much of the benefit of transmission additions is captured?

➢ Benefit of transmission:

= PW system cost with no transmission expansion

— PW System cost with optimal plans

= $47.7B in base case



- Basic model (no UC/few hours/“pipes & bubbles”) captures >90% of benefits
- Adding a feature (e.g., UC) doesn’t necessarily improve the plan

Contents

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Conclusions

- Stochastic programming is **practical** for WECC planning
- Stochastic transmission plans **differ** from deterministic plans. They are **more robust** to scenarios not considered
  - $ cost of ignoring uncertainty = ~size of investments themselves
- We can use **fewer scenarios** to characterize majority of the uncertainty
  - 5 vs 20 scenario results very similar
- Load flow model and multiple scenarios **strongly** affect 1st stage lines
  - Their VoMS/VSS ~$3Billion
  - Probabilities, UC representation, & # Hours less important
- **Limitations**:
  - Curse of dimensionality
    - # hours, scenarios
    - # candidate lines (binaries)
  - KVL and unit commitment also slow the model


Questions?
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