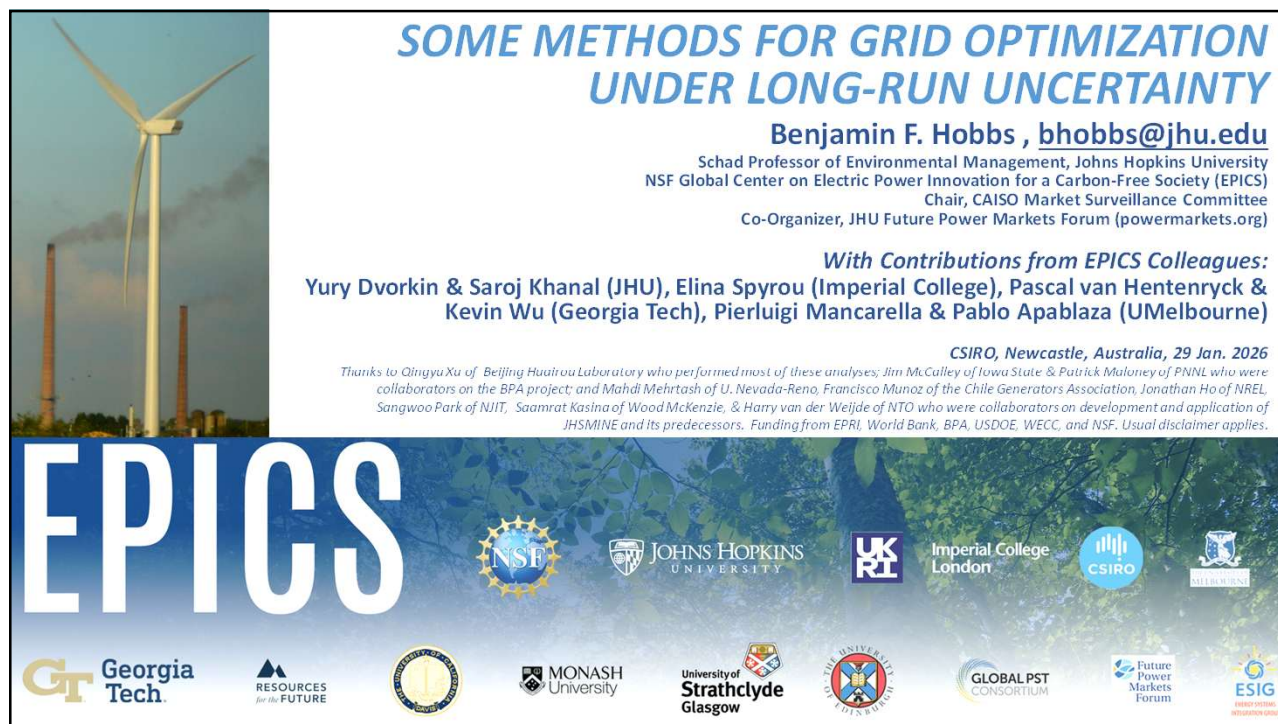


First half of presentation (on uncertainty):



SOME METHODS FOR GRID OPTIMIZATION UNDER LONG-RUN UNCERTAINTY

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 Chair, CAISO Market Surveillance Committee
 Co-Organizer, JHU Future Power Markets Forum (powermarkets.org)

With Contributions from EPICS Colleagues:
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CSIRO, Newcastle, Australia, 29 Jan. 2026

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EPICS

NSF | JOHNS HOPKINS UNIVERSITY | UKRI | Imperial College London | CSIRO | MELBOURNE


Georgia Tech | RESOURCES for the FUTURE | MONASH University | University of Strathclyde Glasgow | GLOBAL PST CONSORTIUM | Future Power Markets Forum | ESIG

1

Overview

JOHNS HOPKINS
SCHOOL OF ENVIRONMENT & PLANNING
ENERGY INSTITUTE

- I. Uncertainty-aware planning: Why?
- II. Stochastic Programming
- III. Robust Programming
- IV. Results for BPA & WECC-wide analyses
 - Q1: Do stochastic grid plans *differ*?**
 - Q2: Are stochastic plans *better*?**
 - Q3: What is *benefit of SP* compared to other model enhancements?**
 (more hours, DC load flow, unit commitment?)
- V. Decomposition & AI to enhance computability



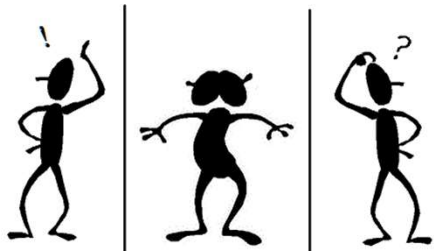
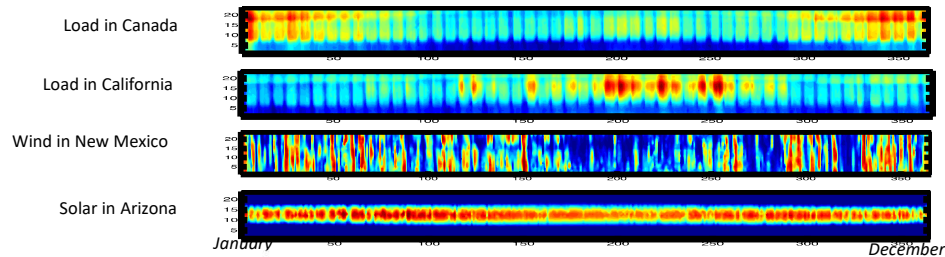
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2

I. Why Uncertainty-Aware Planning?

Two challenges:

1. Operating Variability (over hours):



Certainty

Risk

Uncertainty

2. Deep uncertainty (over decades):

- Fuel Costs
- Demand Growth
- Technology Costs
- Carbon Policy
- DR
- PEV
- RPS
- Distributed Generation
- Coal Retirements

3

3

What Can We Learn from Uncertainty-Aware Planning?

1. Do risks of some projects justify “wait & see”?

- Given stranded asset risks, defer until need clearer?
- “Option value” of delay should be quantified

→ **Might build less under uncertainty**

2. Do some projects have a “flexibility” or “insurance” value that justifies their upfront costs?

- Create options to deal with multiple possible futures?
- Enhance trade that hedges risks?
- Insure against extreme scenarios?

→ **Might build more under uncertainty**

4

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How to assess uncertainty-aware planning frameworks?

(Xu & Hobbs, 2019, 2020; Spyrou, Hobbs et al. 2024)



How much \$ can we save by explicitly considering risks?

1. Methodological capability Models' ability to capture: possible consequences of multiple uncertainties of concern • options & corrective actions				3. Manager & stakeholder acceptance Readily understood criteria for decision. Transparency, easy sensitivity analyses	
Criterion 1: Methodological capability				Criterion 3: Contribution to decision making and stakeholder acceptance	
Theme	How the methodological framework considers:			Engagement goal	Number of views
Uncertainty	Space of possible states	Probabilities of states	Chronological evolution	For each theme in the 1 st column, which goal could the framework serve: to inform, to consult, or to collaborate?	For each theme in the 1 st column, can the framework consider multiple views and how?
Plans	Feasible set	Asset-temporal-spatial resolution	Future updates to plans		
Consequences: Attributes	Types (e.g., reliability, cost)	Resolution	Precision		
Consequences: Assessment	Different types of criteria (e.g., min-max)	Updates to criteria for assessment of plans	Process to elicit preferences		
2. Practical applicability Criterion 2: Practical applicability					
<ul style="list-style-type: none"> • Computational resources • Software 					

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Overview




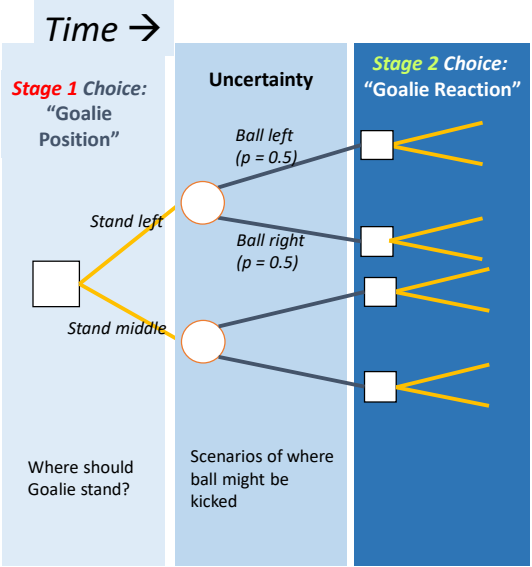
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II. How does Stochastic Programming (SP) work? Uncertainty & Adaptation as a "Decision Tree"





➤ The optimum for **Stage 1** considers:

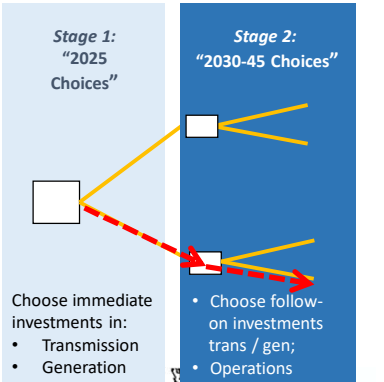
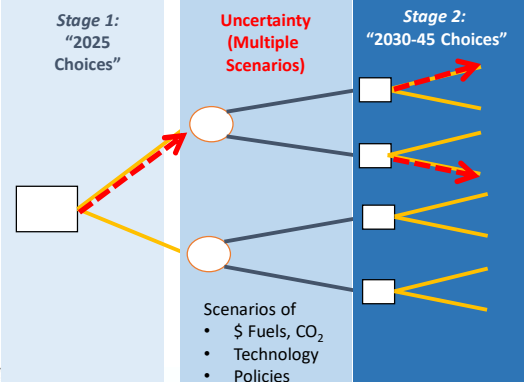
- Each scenario's probability
- How you'd adapt in **Stage 2**, given:
 - ✓ the scenario
 - ✓ options left open by **Stage 1** decisions

➤ **Stage 1's** optimum might not be best for any individual scenario
 → Must evaluate flexibility provided by **Stage 1** choice under **all** scenarios at once


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Multistage (Adaptive) Grid Planning: Single Scenario (Deterministic) vs. Multiscenario

Example Results (BPA System)
 (Maloney, Xu, McCalley, Hobbs, 2018)



1st Stage Transmission, *Deterministic*



1st Stage Transmission, *Stochastic Five Scenarios*

Stage 1 Decisions: "PUT OFF CHOICE" (not "INVEST MORE: INSURE & DIVERSIFY")

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SP's Math Formulation: MILP

(van der Weijde, Hobbs, *Energy Economics*, 2012; Munoz, Hobbs et al., *IEEE TPWRS*; Xu, Hobbs in *Transmission Investment in Liberalized Markets*, 2020)

"Here-&Now"

□

Uncertainty

○

○

"Wait-&-See"

□

□

□

□

$$\text{MIN NPV Cost} = C_1 X_1 + \sum_{\text{scenarios } S} (P_S * C_2 X_{2,S})$$

Subject to:

$$\begin{cases} A_{1,1} X_1 \\ \{A_{2,1,S} X_1\} \end{cases} + A_{2,2,S} X_{2,S} \leq \begin{cases} B_1 \\ B_{2,S} \end{cases}, \quad \forall S$$

- **Decision variables X 's include:**
 - **Investments:** transmission (and if "cooptimize": gen, DSM, storage)
 - **Operations:** generator, storage, DR dispatch, phase shifter settings... (production costing or short-run market simulation)
- **Constraints include:**
 - Kirchhoff's Laws
 - Generator and transmission capacity / operating restrictions
 - Siting restrictions
 - Emissions caps, renewable portfolio standards

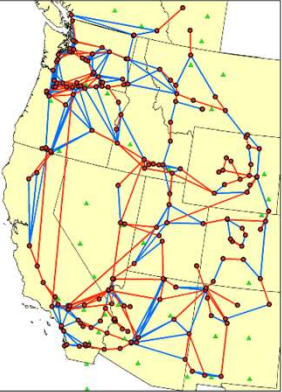
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Our Hypothetical BPA Implementation of JHSMINE

(Johns Hopkins Stochastic Multistage Integrated Network Evaluation)

- BPA/WECC Stochastic Programming model (JHU):
 - Here-&-now: Decide 2018, online 2024
 - Wait-&-see: Decide 2024, online 2030
 - 8 Scenarios, 11 Uncertain variables
- ~10¹ load blocks per year (so could solve many times)
- Investment variables:
 - All WECC lines
 - New unannounced resource mix & sites: assume competitive generators respond to LMPs

- Preserved Bus
- Renewable Candidates
- Preserved Lines
- Equivalent Lines
- States/Provinces



Example 300-bus network

(developed by JHU for WECC analyses, with help of ASU)

Pipes & Bubbles or Linearized DC OPF (KCL/KVL)

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Uncertainties considered in hypothetical BPA/WECC study



	Uncertainty	Hi (3)	Lo (1)	Medium
1	Carbon Cost Years Implement	2020	Never	2026
2	Wind Build cost decay rate	6 times base case decay rate	0.75 times base case decay rate	Defined by NREL ATB Rate varies by Year
3	Solar Build cost decay rate	2 times base case decay rate	0.75 times base case decay rate	Defined by NREL ATB Rate varies by Year
4	Fuel Price	2% APR	0.25% APR	1.125% (average of 2% and 0.25%)
5	Base Demand Growth (Each area demand growth determined by base + Area specific demand growth)	1.92% (1.5 times base value)	0.565% (Half base value)	1.13%
6	base Peak Demand (Each area peak growth determined by base + Area specific demand growth)	1.7% APR (1.5 times base value)	0.64% APR (Half base value)	1.28% APR
7	Hydro CF	1.35 x base values	0.65 x base values	1 x base values
8	Initial Line Multiplier	1.25 x base costs	1.25 x base costs	1.25 x base costs
9	Late Line Multiplier	1.5 x base costs	1 x base costs	1.25 x base costs
10	Total Solar subgrid Init Penetration	0.10%	0.10%	0.10%
11	Total Solar subgrid linear AGR	0.60%	0.20%	0.4% (average of 0.6% and 0.2%)
12	DER Solar subgrid Init Penetration	0.10%	0.10%	0.10%
13	DER Solar subgrid linear AGR	0.22%	0.05%	0.0135% (average of 0.22% and 0.05%)
14	Solar SW Init Penetration	2.00%	2.00%	2.00%
15	Solar SW linear AGR	0.80%	0.50%	0.65% (average of 0.8% and 0.5%)

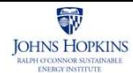
Scenario #	Probability	Scenario String
1	0.125	33331113333
2	0.125	33131113111
3	0.125	31313333333
4	0.125	31111131111
5	0.125	13333313333
6	0.125	13133313111
7	0.125	11311131333
8	0.125	11113333111

By far the most impact on investments.
Especially on:

- BPA & non-BPA lines
- PV build (non-BPA)

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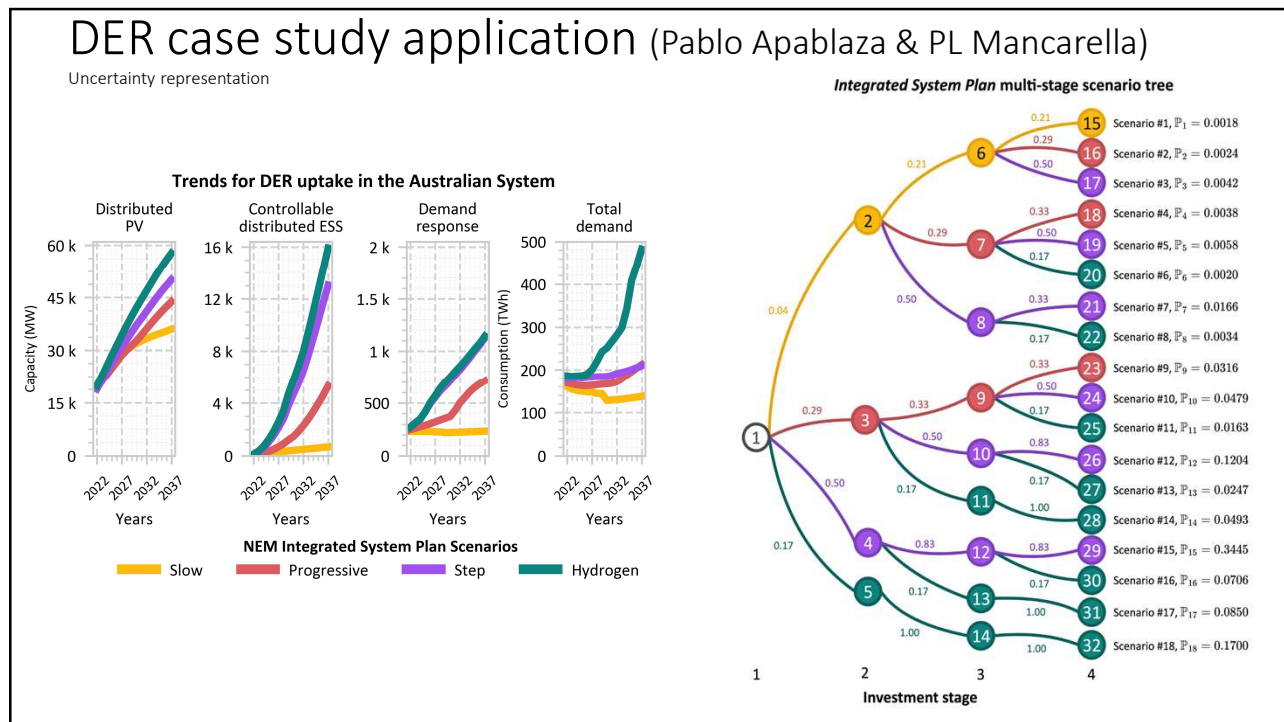
Summary: Introduction to SP



- SP asks: what choices *now* minimize P-weighted cost—balance first-costs vs. later robustness/adaptability, considering:
 - Impacts over all scenarios of “here-&-now” choices
 - *Later* “wait-&-see”/recourse/adapt decisions, after learning what scenario will occur
- SP widely used in power systems (see refs.)
 - $\geq 100M$ variables handled in gen-trans planning problems using decomposition (Munoz, Watson, Hobbs, 2016)
- Elaborate versions consider > 2 stages
 - E.g., AEMO Integrated System plan (Figure next page thanks to Pierluigi & Pablo, UMelbourne)

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Summary: Introduction to SP



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- Elaborate versions consider > 2 stages
 - E.g., AEMO Integrated System plan
- But: **Curse of dimensionality!**
 - # variables, computational time

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III. Another Approach: Robustness-Based Methods

➤ **Scenarios + Probabilities** → **Uncertainty Set**

- ✓ Either a Set of Scenarios or Continuous Range of Possible Futures
- ✓ Object: Maximize Robustness: Minimize {worst outcome among all scenarios/possible outcomes}
- ✓ **3 well-known "Robustness" methods:**

(1) **"Robust Optimization": Choose plan to MIN worst outcome over infinite set of possible futures** (Malcolm, Zenios 1994)

- ✓ Highly challenging for large problems, especially if later "adaptation" (wait-and-see recourse)

(2) **"Robust Decision Making": (a) Define set of candidate plans,**

(b) evaluate each under each scenario,

(c) choose plan to MIN worst outcome over scenarios (Cervigni et al. 2015)

- ✓ Computationally practical, but no recourse/adaptation

(3) **"Adaptive Robust DM": (a) Define set of candidate *base* plans,**

(b) under each scenario, "*adapt*" plan under scenarios where it does badly,

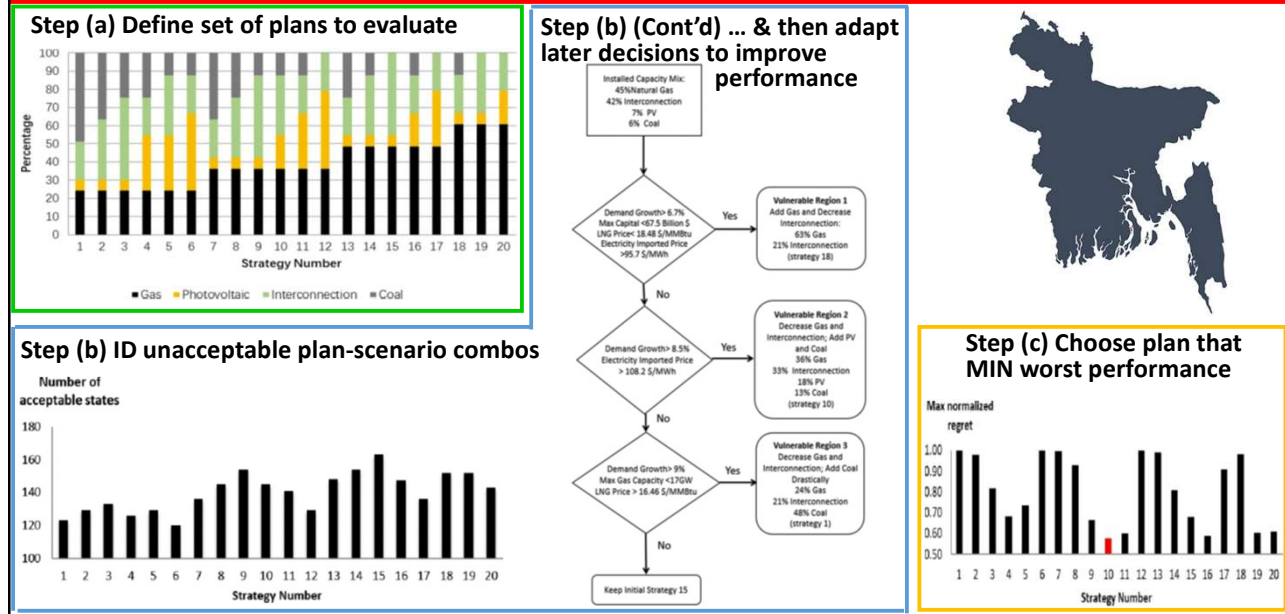
(c) choose plan to MIN worst "*adapted*" outcome over scenarios (Moreira et al. 2016)

- ✓ There are many methods to identify plan/scenario combinations that need adaptation (Step (b)); then apply heuristics or optimization for Step (c)

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Adaptive RDM for Bangladesh Power Sector (World Bank)

(Jiang, Vogt-Schilb, Spyrou, Hobbs, 2025)



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IV. SP vs. Single-Scenario (“Deterministic”) Model

- Deterministic provides best plan for 1 scenario
 - gives insight into other scenarios only through laborious sensitivity analysis

- The “cost” to use SP is:
 - Time/effort to characterize uncertainties
 - ➔ Need to automate this process
 - Computational intensity
 - ➔ Deploy decomposition with HPC

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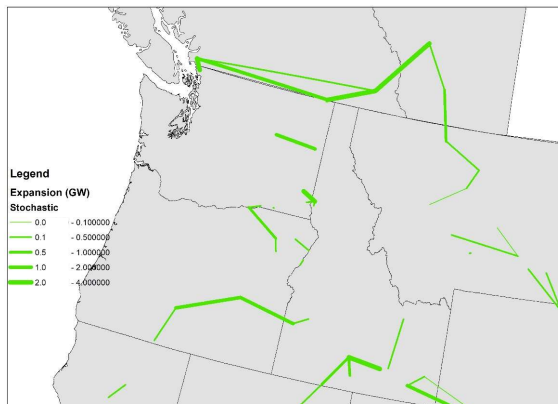
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Q1: How do SP vs. deterministic grid plans differ: 1st Stage Grid Investments

(Xu, Maloney, McCalley, Hobbs analyses)

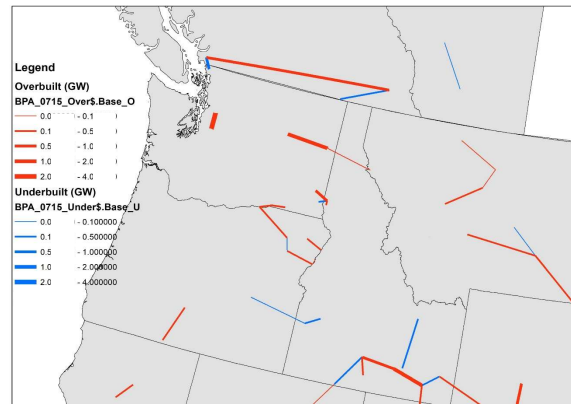
1st Stage Solution (decide in 2018, online in 2024 in all scenarios)

➔ *Uncertainty-aware optimization delays some investments (“wait for information”); but expands others (as “insurance”)*



Stochastic Programming

1st stage transmission expansion Cost:
WECC-wide: \$5240M; BPA: \$706M



Single Scenario Solution (All “Medium”): *Changes relative to SP*
(Blue is underbuilt; Red is overbuilt compared to SP solution)

1st stage transmission investment:
WECC-wide: \$5310M, BPA \$934M

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Q2: Are stochastic plans better?

- Benefit of including uncertainty for planning 1st stage **BPA** internal & intertie lines: **\$320M** (Expected present worth\$)
- ... And for planning 1st stage **WECC** internal & intertie lines : **\$1675M**



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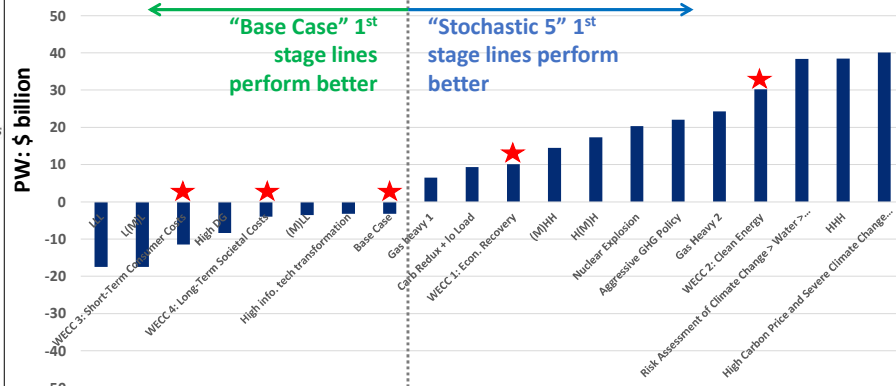
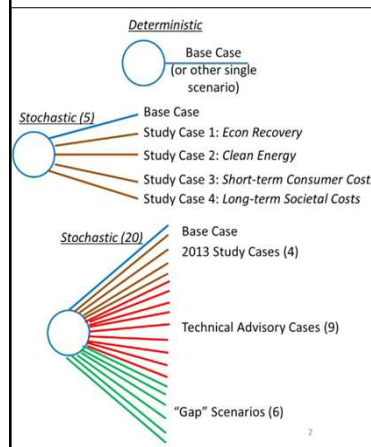
Q2': Are stochastic solutions better for unconsidered scenarios?

(Xu, Hobbs et al., 2016)

Are they more robust against scenarios not considered?

Answer for WECC-wide analysis: Yes, the “Stochastic 5” 1st stage lines perform better against the withheld 15 scenarios than the “Base Case” (1 scenario) 1st stage lines

Cost increase by scenario for “Base Case” vs. “Stochastic 5” plan
(equal probabilities, 300 bus model, “wait-&-see” decisions optimized by scenario)



★ Included in “Stochastic 5” Model; other 15 scenarios not in model

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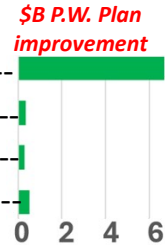
Q3: Benefits of SP vs. Other Model Enhancements

(Xu, Hobbs, 2019)

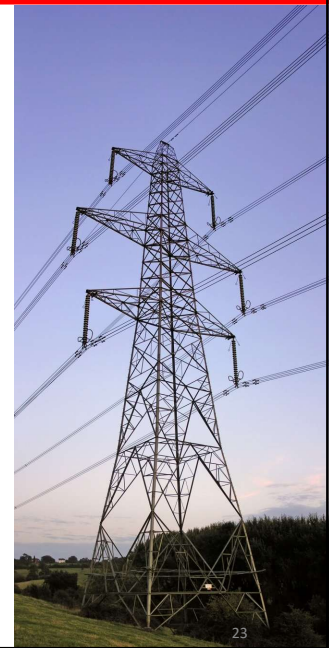
What is the economic value of improving realism of transmission planning models?

Compare for WECC:

- Multiple scenarios (stochastic programming)-----
- Enhance Network model (KCL v. KCL/KVL v. hybrid)---
- More hours (wind, solar, load variability)-----
- Including unit commitment constraints & costs-----



(Compared to \$26B net benefit for base plan)



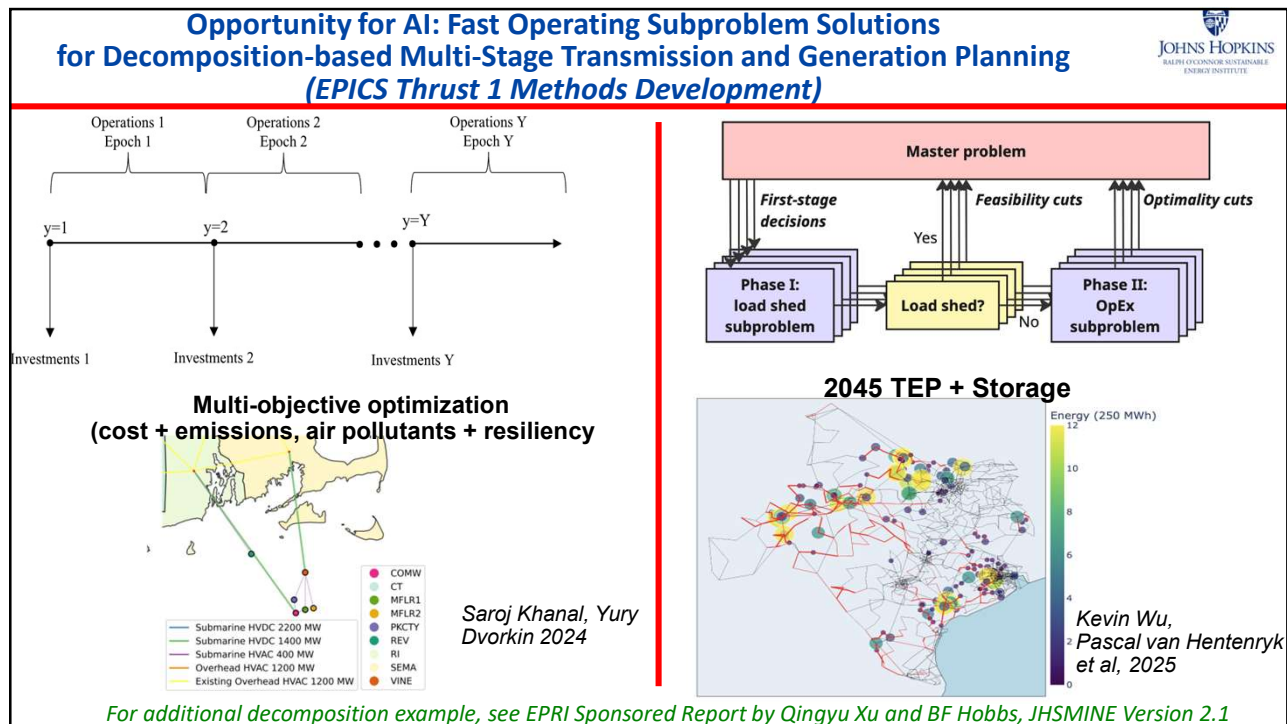
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Conclusion: Questions for EPICS

- Uncertainty-aware planning with many long-run scenarios is *practical* using SP or RDM ... and it matters (impacts decisions & benefits)!
 - So: what's needed to move this to practice?
- Apply to more issues where there are big bets?
 - Multifuel (H2)
 - Offshore grids
 - SMR, Fusion
- Use methods to quantify decision-relevant indices: value of information, options, flexibility/adaptability, enhanced methods
- Address curse of dimensionality with decomposition & AI?

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Bulk Market Operations & Battery Storage Conundrums

Benjamin F. Hobbs

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Global Director, NSF Global Center on Electric Power Innovation for a Carbon-Free Society
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CSIRO, Newcastle, Australia, 29 Jan. 2026

Thanks to my collaborators, especially Qiwei Zhang of NREL, Bolun Xu of Columbia University, and Jim Bushnell & Scott Harvey, CAISO MSC, and to the ISO staff. Funding from USDOE & NSF, with the usual disclaimer



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How do combinations of:
• *short-run price uncertainties &*
• *market software simplifications*
lead to inefficiencies in using battery storage?
AND HOW CAN WE DO BETTER?

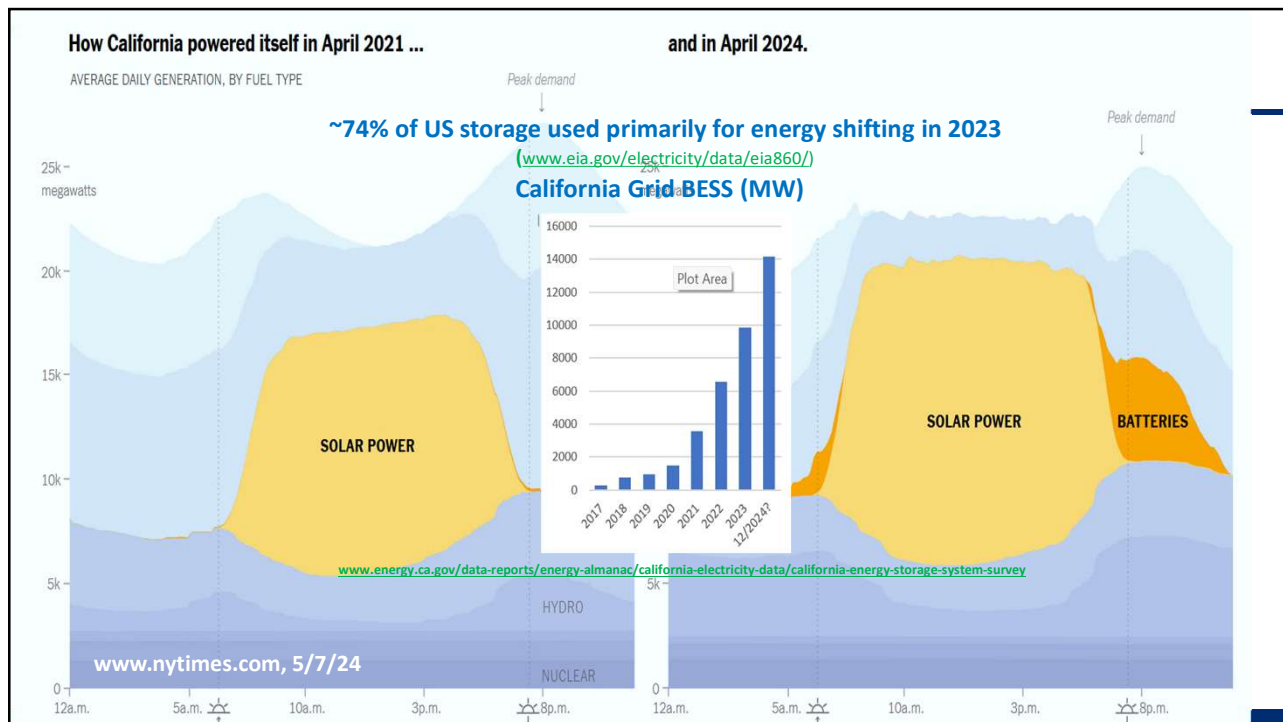
Outline

- I. Storage growth → opportunity-cost dominated prices
- II. Two ways to include opportunity costs:
optimize system (market software) vs. *internalize* (offers)
- III. Uncertainty compounds market design limitations
- IV. Correcting specific market design issues:
 - A. Market power mitigation
 - B. Price distortions
 - C. SOC uncertainty when provide both A/S & energy

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I. Storage → opportunity-cost based prices

➤ In thermal dominated systems, spot price = ~fuel cost of marginal units

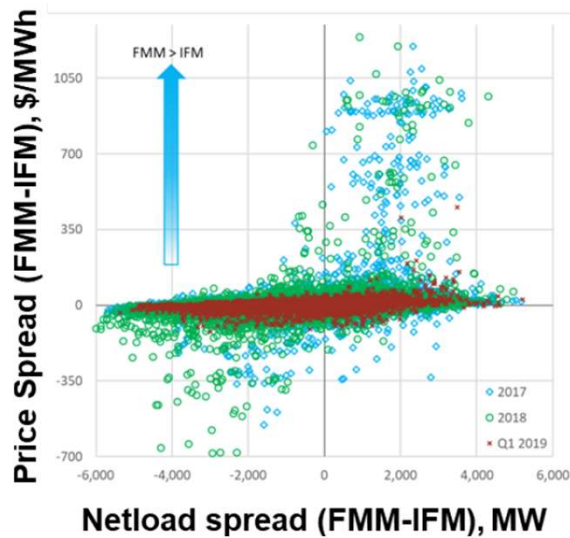
- **With exceptions:**
 - Unit commitment / ramp rates complexities
 - Reserve requirements
 - Demand willingness-to-pay (thanks to Fred Schweppe!)

➤ But for storage, “variable cost” = loss of *later* revenue if generate *now* (“opportunity cost”)

- Tied to either *later* consumer willingness-to-pay or later cost of thermal generation
 - Or cost of battery degradation/life reduction (thanks to Bolun Xu!)

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Real-time prices-- thus opportunity costs-- are highly uncertain



- Real time (15 minute)-Day ahead price spread (CAISO) versus RT net load imbalance, 2017-2019, CAISO

Source: M. Blonsky (NREL), E. Spyrou (Imperial College), Q. Zhang, B. Hobbs (JHU) et al., "An Integrated Paradigm for the Management of Delivery Risk in Electricity Markets— From Batteries to Insurance and Beyond" Final Report, June 2024

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II. Two ways to include opportunity costs



Fred Schweppe

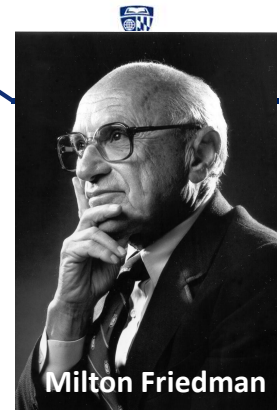
V.L. statue,
Fremont, Seattle

➤ Central dispatch by ISO

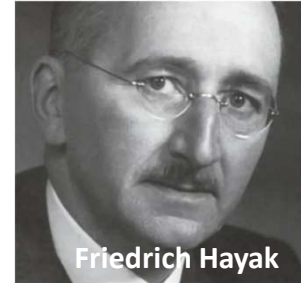
- Multiperiod gen schedule optimization
- Include state-of-charge, capacity, efficiency, other storage parameters; hydro: other water uses, including environmental
- Bidders submit technical parameters (and O&M and degradation costs per MWh)
 - Optimization's duals then automatically reflect opportunity costs

➤ Internalized by owners in offers

- Each resource owner provides future prices and their own schedules
- Under competition
 - Offer to buy based on future revenue
 - Offer to sell based on future opportunity cost



Milton Friedman



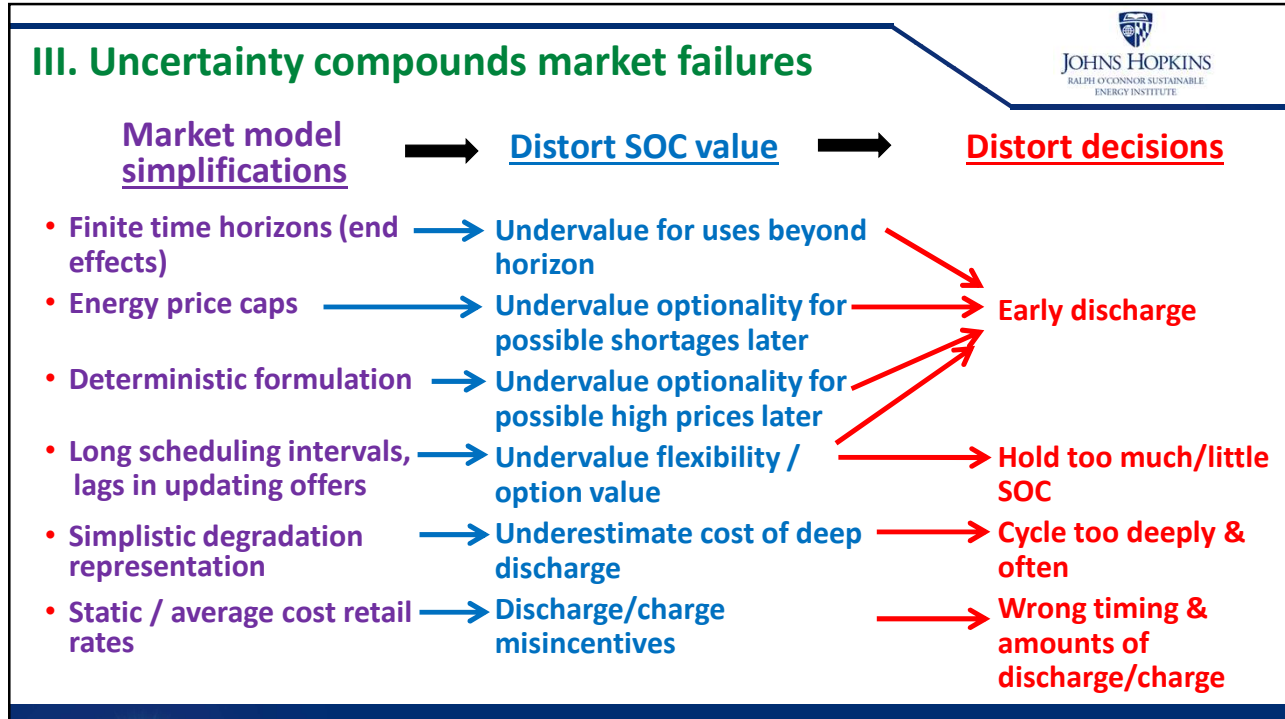
Friedrich Hayek

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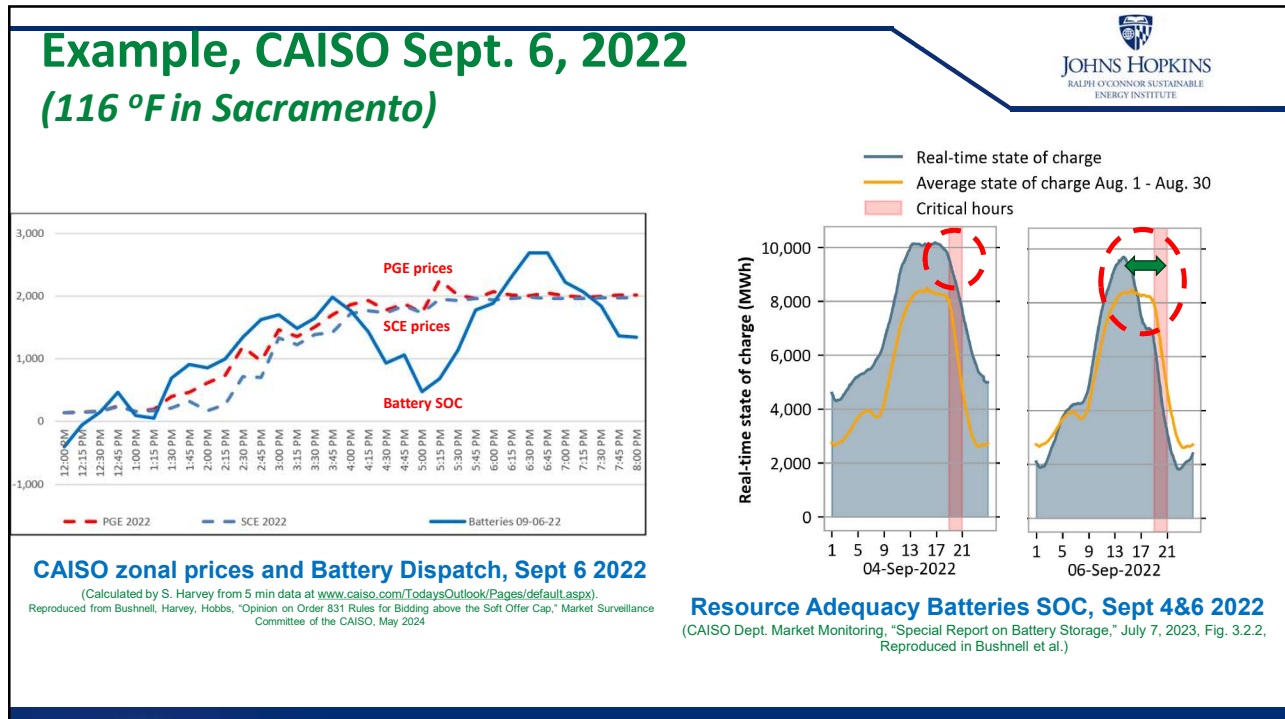
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IV. Specific market design issues

California ISO

Stakeholder center Policy initiatives Recurring processes Commenting tool

INITIATIVE:
Energy storage and distributed energy resources

Started: Aug 27, 2015


The focus of this initiative is on enhancing the ability of ISO connected and distribution-connected resources to participate in the ISO market, including rooftop solar, energy storage, plug-in electric vehicles, and demand response. These resources represent an increasingly important part of the future resource mix and will help lower carbon emissions and provide operational benefits.

INITIATIVE:
Storage design and modeling

Started: Nov 25, 2024

This initiative explores enhancements to energy storage market design, modeling, and processes. Efforts are organized into four topic groups: Outage Management, Uplift and Default Energy Bids, State-of-Charge Management Topics, and Mixed-Fuel & Distribution-Level Resources.

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Correcting market failures

<h3 style="color: purple;">Market/Software Simplifications</h3> <ul style="list-style-type: none"> • Finite time horizons (end effects) • Energy price caps • Deterministic formulation • Long scheduling intervals, lags in updating offers • Simplistic degradation representation • Static / average cost retail rates 	<p>→</p> <p>→</p> <p>→</p> <p>→</p> <p>→</p> <p>→</p>	<h3 style="color: blue;">Market/Software Fix?</h3> <ul style="list-style-type: none"> • Price or constrain ending SOC <ul style="list-style-type: none"> ○ Constraint could be relaxed at specified price • Lengthen time horizon • Raise caps • ISO intervention/SOC auction • Multiple scenarios to ensure robustness • Intraday markets • Smaller intervals • Better degradation modeling • Dynamic pricing / utility or aggregator control
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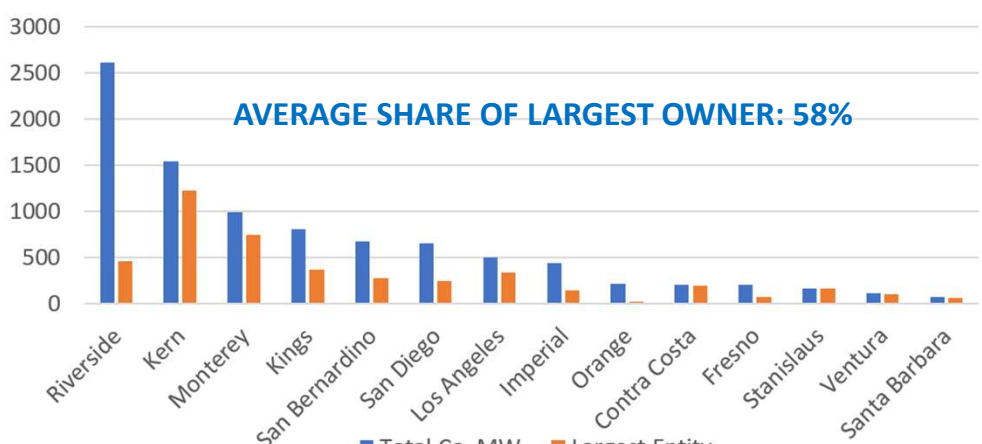
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A. Local market power mitigation

Local Market Concentration (California Counties, 2024)



County	Total Co. MW	Largest Entity
Riverside	2600	450
Kern	1500	1200
Monterey	1000	750
Kings	800	400
San Bernardino	700	300
San Diego	650	250
Los Angeles	500	350
Imperial	450	150
Orange	250	100
Contra Costa	200	200
Fresno	200	100
Stanislaus	150	150
Ventura	100	100
Santa Barbara	50	50

AVERAGE SHARE OF LARGEST OWNER: 58%

Author calculations. Date from: www.eia.gov/electricity/data/eia860m/

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A. Local market power mitigation

➤ US (e.g., California) *ex ante* style. Two steps:

1. “Pivotal supplier test” for key constraints; if fail, then...
2. ...Mitigate offers (to “Default Energy Bid” (DEB) = ~%110 variable cost)
 - Best when based on transparent fuel price indices—unlike opportunity costs
 - E.g., for thermal units: registered heat rate * fuel cost

➤ Battery storage’s challenges

- High concentration in liquid markets
 - Only local resource dispatchable in RT?
 - Mitigation ineffective, only introducing more competition might work?
- Uncertainty → No transparent indices for LMPs reflecting latest conditions
 - CAISO proposes using day-ahead prices for RT opportunity costs
 - But under stressful conditions: RT price forecasts may be >> DA
→ mitigating RT offers down to low DA opportunity costs causes premature discharge
- Given prices, opportunity cost for discharge energy depends on SOC
- In theory, market power can also be exercised when charging:
 - By reducing purchases or decreasing bids to charge

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B. Ways to Avoid Premature Dispatch

➤ CAISO: “Exceptional Dispatch” by operators

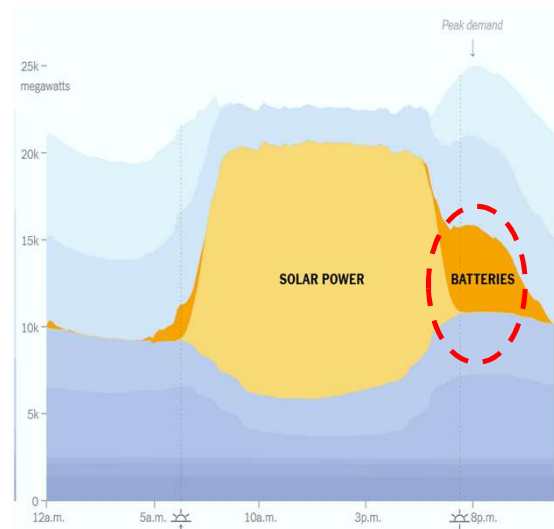
- Impose end-of-hour min SOC for individual batteries so enough “gas in tank” for critical period, e.g., 5-8pm
 - CAISO, www.nytimes.com, May 7, 2024
- Difficult to juggle 100’s of battery plants

➤ Optimize? Considered (*not adopted*) by CAISO: SOC procurement auction

- Operator forecasts MWh of SOC needed (e.g., Dvorkin, Tapia EPICS/ERCOT/GPST methodology)
- Solicit offers, yielding a MWh SOC clearing price
 - Provides extra revenue to discourage premature discharge

➤ Issues

- Unfair & inefficient to give revenue to a class of resource just because it is inferior (i.e., energy constrained)
 - and pay less to unconstrained resources (e.g., turbines)?
- If not locational, might inefficiently procure SOC at nodes with lower energy value (LMPs), not where most needed
- Adds market complexity



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C. SOC uncertainty when provide both energy & A/S

➤ Envelope Method

stakeholdercenter.caiso.com/initiatedocuments/workshop-paper-energy-storage-enhancements-state-of-charge-implementation-update-oct-2-2023.pdf

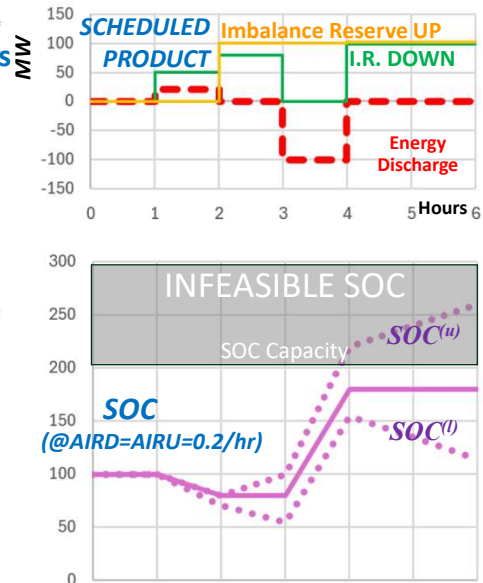
- **PROBLEM:** SOC may “bleed” if battery supplies reserves
 - Lose SOC if provide “imbalance reserve_up” (“IRU”)
 - Gain SOC if provide “imbalance reserve_down” (“IRD”)
- **SOLUTION?** Constrain SOC under two worst outcomes:
 - Upper worst case calculated as if only IRD bleeds
 - Lower worst case as if only IRU bleeds

$$SOC_{i,t}^{(u)} = SOC_{i,t-1}^{(u)} - EN_{i,t}^{(+)} - \eta_i EN_{i,t}^{(-)} \leq \overline{SOC}_{i,t}$$

$$SOC_{i,t}^{(l)} = SOC_{i,t-1}^{(l)} - EN_{i,t}^{(+)} - \eta_i EN_{i,t}^{(-)} \geq \underline{SOC}_{i,t}$$

➤ Challenges

- A role for stochastic programming?
- What risks of insufficient SOC should we tolerate?
- Are random AIRD/AIRU more uncertain & correlated with battery use for energy when system is stressed?



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Conclusion, & Questions for EPICS

➤ Battery storage fundamentally changes the market

- **Couples scheduling decisions & costs across intervals**
 - Long time horizons, complex (perhaps stochastic) optimizations
 - e.g., see R. Green, & Y. Dvorkin & T. Tapas, methods
 - Prices increasingly = opportunity costs, not fuel costs
- **Big challenge: How to correct/account for market failures in market designs & software?**
 - E.g., better retail-bulk market incentives for efficiently using BTM storage
- **Especially: Market power mitigation may need to emphasize market structure, not ex ante mitigation**
 - More liquidity and transparency: intraday markets & more settlements?
 - Decrease ownership concentration?
 - Increase market sizes through more transmission?

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