JOHNS HOPKINS
RALPH O'CONNOR SUSTAINABLE ENERGY INSTITUTE

# Risk Management and Clean Energy Transition

Yury Dvorkin

EPICS

Energy at Hopkins

# What Matters for Efficient Risk Management?

## Make Better Decisions with Less

**Better:**
- Cost, reliability, emissions
- Physics-informed models
- Market suitable
- Fast computations
- Insight discovery

**Less:**
- Data requirements
- Computational costs
- Malfunction
- Distrust

# A Typical Decision-Making Pipeline

Consider a decision-making problem (SCUC/SCED): $\min_{x \in \mathcal{X}(\omega)} C(x, \omega)$

$C(\cdot)$ objective (cost) function

$\mathcal{X}$ feasible solution space

$x$ vector of decision variables

$\omega \in \Omega$ vector of uncertain parameters

Bottlenecks for risk management :

- Scenario generation
- Accelerated computations
- Risk representation

Concerns:

- Do we have enough data?
- What about guarantees and solution accuracy?
- Do we target the right risk?
- Who will use it?

Current markets:

- No differentiation between extreme and normal reserve
- No direct interface for risk management (VB, CfD, etc)

If extremes are not considered , why should producers care?

# How to Fit Risk Into This Pipeline?

Consider a decision-making problem (SCUC/SCED): $\min_{x \in \mathcal{X}(\omega)} C(x, \omega)$

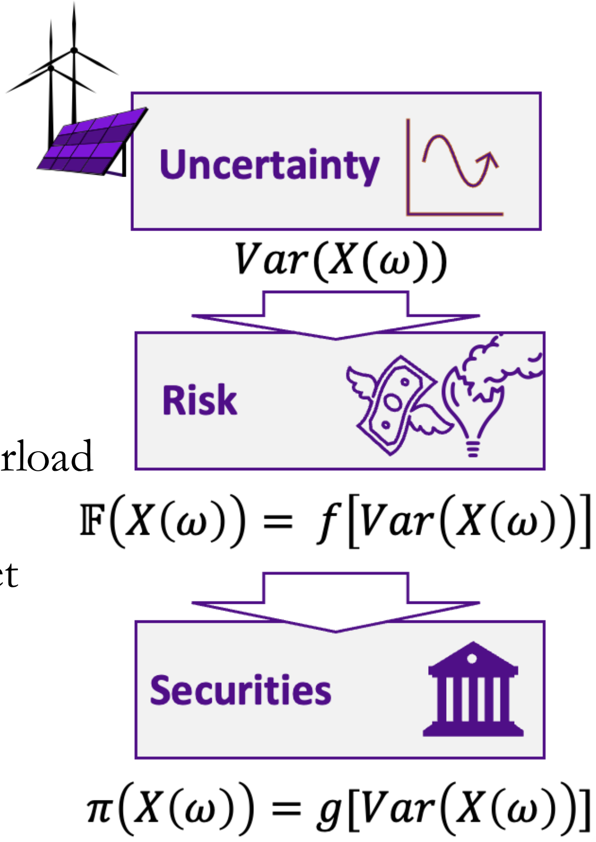
| | | | |
|---|---|---|---|
| $C(\cdot)$ | objective (cost) function | $\mathcal{X}$ | feasible solution space |
| $x$ | vector of decision variables | $\omega \in \Omega$ | vector of uncertain parameters |

**Uncertainty** arises from

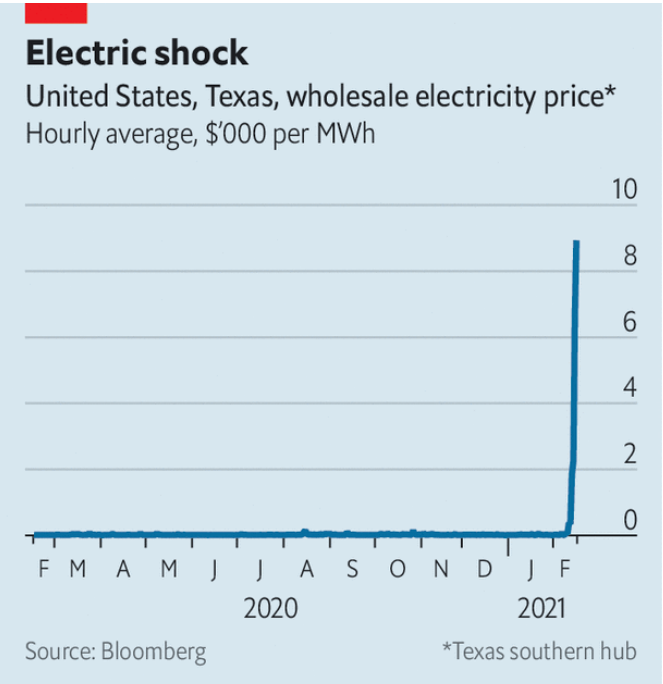
- Forecast errors (renewables and demand)
- Sudden unavailability of resources, full or partial
- *Complex* events

**Risk** arises from uncertainty, regardless of its source

- Physical risk (e.g. constraint violation or operational infeasibility – overload or power mismatch)
- Financial risk (e.g. shortfall from physical risk – profit, liquidity, market losses)
- Risk = Probability × Consequence
- Various risk metrics exist (CVaR, VaR, CoVaR, etc)

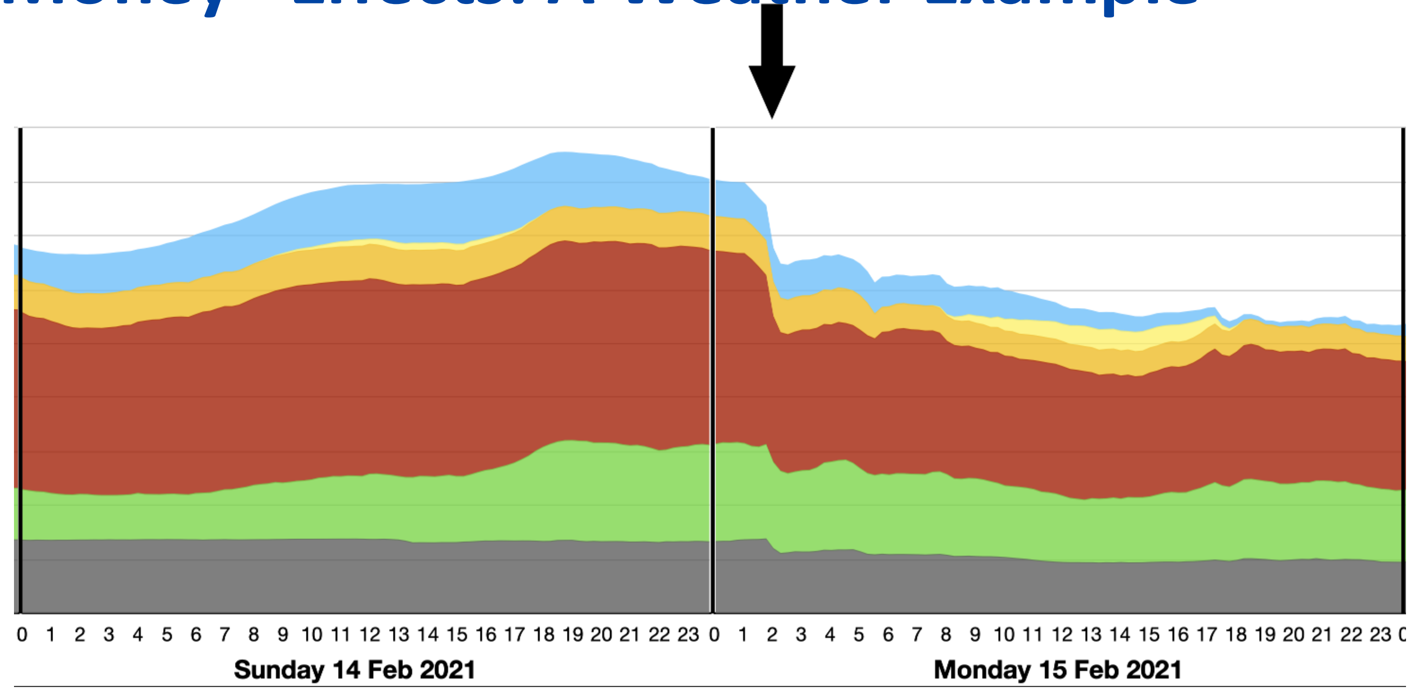


# Bottlenecks Cause "Missing Money" Effects: A Weather Example




The Economist

Low availability led to high prices




Commodities

## Texas cuts $9,000 power price cap after February freeze

**Reuters**

December 3, 2021 11:53 AM EST · Updated 2 years ago

Aa

# Bottlenecks Cause "Missing Money" Effects: A Weather Example

**Texas did the wrong thing (once again), it is obvious:**

- Reduced prices cap led to less incentives to improve availability and participate in the market, especially for high-stake hours
  - High demand
  - Low availability of supply
  - A combination of both

**The important and overlooked argument is that market prices didn't help**

- Let's discuss ideal-world prices

$$\lambda_{i:j} = \lambda_{i:j}^{e} \cdot \pi^{0} + (\lambda_{i:j}^{max} - \lambda_{i:j}^{e}) \cdot (1 - \pi^{0})$$

"ideal" price → $\lambda_{i:j}$

price cap → $\lambda_{i:j}^{max}$

marginal price of energy → $\lambda_{i:j}^{e}$

probability of normal operations → $\pi^{0}$

probability of an "oops" → $(1 - \pi^{0})$

# Out of Market Interventions Can be Much Worse

**What is the spot market for wholesale electricity, and how will AEMO's decision to suspend it affect consumers?**

By Tobias Jurss-Lewis

Energy Industry

Wed 15 Jun 2022

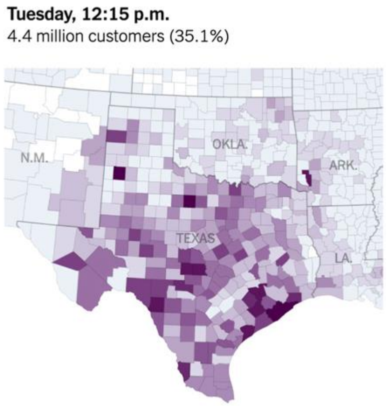
STATE

**Texas Supreme Court sides with state regulators on $16 billion winter storm overcharges**

Several important "market" limitations:

- Limited demand elasticity + shielded consumption
- No incentives to stay in the market, especially during critical hours
  - High demand
  - Low availability of supply
  - A combination of both

- Self-commitment is always an option




$1B+ in losses/hr

**1GW producer lost opportunity of ~$100K/hr**

# "Missing Money" as a Problem Statement

Private risk evaluation of "firm" agent *i*

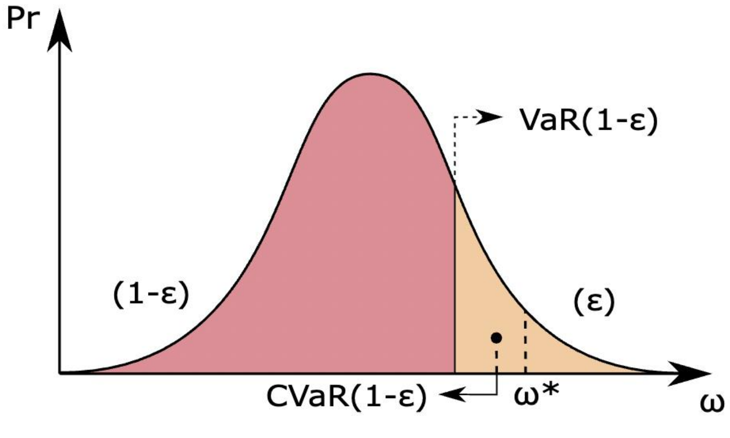
$$\max_{\alpha_i, p_{G,i}} \mathbb{R}_i \left[ \lambda_i p_{G,i}(\omega) + \chi_i \alpha_i \right]$$
$$p_{G,i}(\omega), \alpha_i \in \mathcal{O}_i$$

Private risk evaluation of "variable" agent *j*

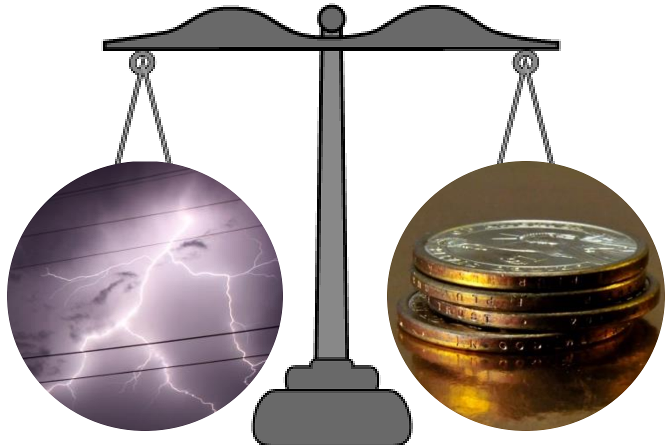
$$\max_{\alpha_j, p_{U,j}} \mathbb{R}_j \left[ \lambda_{i:j} p_{U,j}(\omega) - \chi_{i:j} \alpha_j \right]$$
$$p_{U,j}(\omega), \alpha_j \in \mathcal{O}_j$$

Social risk evaluation

$$p_{U,j:i} + p_{G,i} = p_{D,i} \qquad :(\lambda_i)$$
$$\sum_{i:j} \alpha_{i:j} = 1 \qquad :(\chi_{i:j})$$




What is "worst-case" $\omega^*$ and "optimal" $\epsilon$?

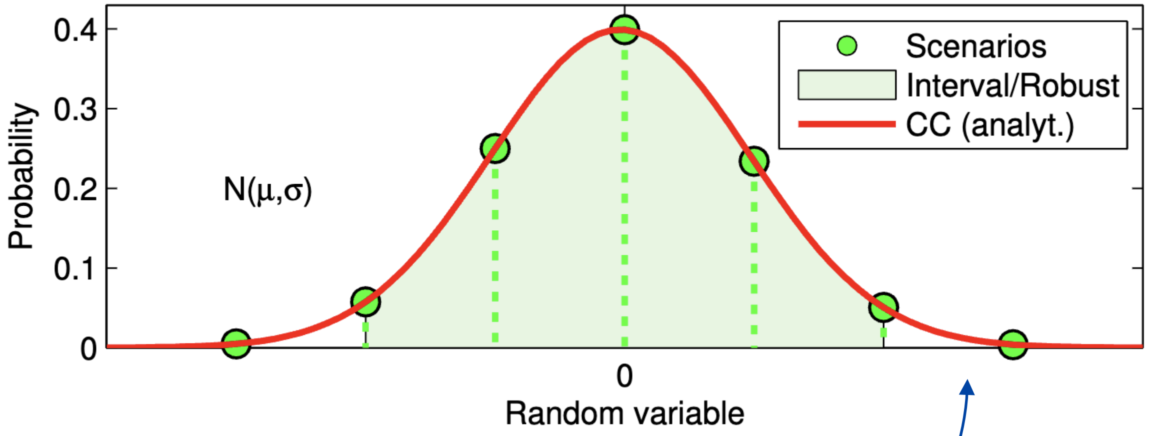


**Two missing parts: (i) extremes and (ii) volatility**

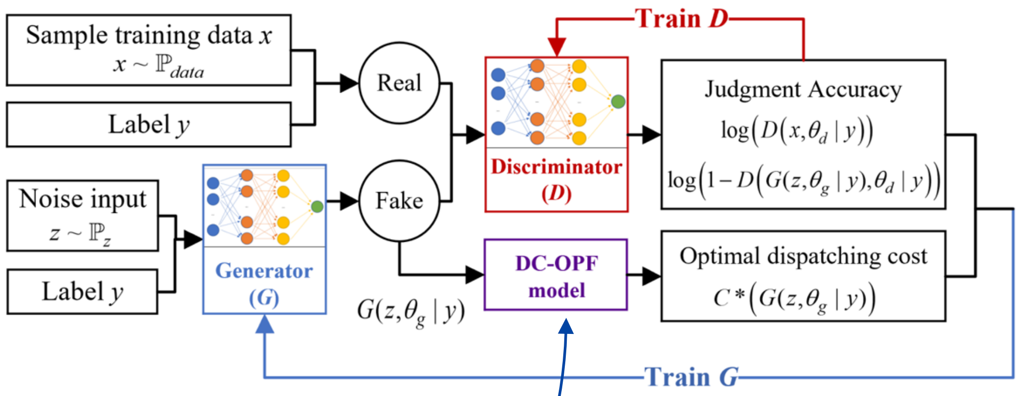
# What is Needed  to Overcome “Missing Money” Effects?

**Risk management** requires thinking across three dimensions of representation of risks – (i) **modeling extreme outcomes and variability**, (ii) **endogenizing them into decision support tools** and (iii) **alignment of incentives and risk management goals.**

# Aligning Private and Social Risks: Represent Extreme Outcomes




Hard to sample extreme events




Hard to implement physics of extreme events

**Risk modeling is largely informed by financial engineering, benefiting from:**

- Lack of physical complexity
- Randomness
- Rather “smooth” jumps

$$C = N(d_1)S_t - N(d_2)Ke^{-rt}$$

$$\text{where } d_1 = \frac{\ln\frac{S_t}{K} + (r + \frac{\sigma^2}{2})t}{\sigma\sqrt{t}}$$

$$\text{and } d_2 = d_1 - \sigma\sqrt{t}$$

# Aligning Private and Social Risks: Endogenize Extreme Outcomes

More generic and nuanced approaches to sample *less-likely* events is needed

$$\underset{u \in \mathcal{U}}{\text{minimize}} \quad J(u)$$
$$\text{subject to} \quad \mathbb{P}\left(F(u,\xi) \geq z\right) \leq \alpha, \quad \text{where } \alpha \ll 1.$$

Traditional risk constraints

$$\mathbb{P}(F(u,\xi) \geq z)$$
$$\xi^\star \in \underset{\xi \in \Xi}{\text{argmin}} \left\{ I(\xi) : F(u,\xi) \geq z \right\}$$

Risk constraints with large-deviation theory

Challenges:

- Depend on the indicator function $I(\cdot)$
- Includes inner minimization for $\xi^*$
- Not clear how to compute the optimal solution
- Likely to be extremely conservative

# Aligning Private and Social Risks: Endogenize Extreme Outcomes

$$
\begin{aligned}
\underset{u \in \mathcal{U}}{\text{minimize}} \quad & J(u) \\
\text{subject to} \quad & P_k(u, z, \xi^\star) \leq \alpha \\
& \xi^\star \in \underset{\xi \in \Xi}{\text{argmin}} \left\{ I(\xi) : F(u, \xi) \geq z \right\}
\end{aligned}
$$

Employ a three-step strategy:

- Reformulate the inner level using first-order conditions
- Postulate the indicator function
- Obtain single-level approximation

# Aligning Private and Social Risks: Endogenize Extreme Outcomes

$$
\begin{aligned}
\underset{u \in \mathcal{U}}{\text{minimize}} \quad & J(u) \\
\text{subject to} \quad & P_k(u, z, \xi^\star) \leq \alpha \\
& \xi^\star \in \underset{\xi \in \Xi}{\text{argmin}} \{ I(\xi) : F(u, \xi) \geq z \}
\end{aligned}
$$

Cannot be solved at scale and efficiently

$$
\begin{aligned}
\underset{u, \xi^\star, \lambda}{\text{minimize}} \quad & J(u) \\
\text{subject to} \quad & u \in \mathcal{U},\ \xi^\star \in \Xi,\ \lambda \in \mathbb{R}_+ \\
& P_k(u, z, \xi^\star) \leq \alpha, \\
& F(u, \xi^\star) = z, \\
& \nabla I(\xi^\star) = \lambda \nabla_\xi F(u, \xi^\star).
\end{aligned}
$$

Note that $\geq$ is replaced with $=$

- No convexity of $F(\cdot)$ is required
- Indicator function is low

$$
\begin{aligned}
\underset{u, \xi^\star, \eta^\star, \lambda}{\text{minimize}} \quad & J(u) \\
\text{subject to} \quad & u \in \mathcal{U},\ \xi^\star \in \Xi,\ \eta^\star \in \mathbb{R}^n,\ \lambda \in \mathbb{R}_+ \\
& P_k(u, z, \xi^\star) \leq \alpha, \\
& F(u, \xi^\star) = z, \\
& \eta^\star = \lambda \nabla_\xi F(u, \xi^\star), \\
& \xi^\star = \nabla S(\eta^\star).
\end{aligned}
$$

Single-level approximation

- Ensures convexity
- Provides guarantees
- Captures extreme cases
- Can be used for pricing

# Aligning Private and Social Risks: Endogenize Extreme Outcomes

$$\begin{aligned} \underset{u \in \mathcal{U}}{\text{minimize}} \quad & J(u) \\ \text{subject to} \quad & P_k(u, z, \xi^\star) \leq \alpha \\ & \xi^\star \in \underset{\xi \in \Xi}{\text{argmin}} \{ I(\xi) : F(u, \xi) \geq z \} \end{aligned}$$

Cannot be solved at scale and efficiently

$$\begin{aligned} \underset{u, \xi^\star, \lambda}{\text{minimize}} \quad & J(u) \\ \text{subject to} \quad & u \in \mathcal{U},\ \xi^\star \in \Xi,\ \lambda \in \mathbb{R}_+ \\ & P_k(u, z, \xi^\star) \leq \alpha, \\ & F(u, \xi^\star) = z, \\ & \nabla I(\xi^\star) = \lambda \nabla_\xi F(u, \xi^\star). \end{aligned}$$

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$$\begin{aligned} \underset{u, \xi^\star, \eta^\star, \lambda}{\text{minimize}} \quad & J(u) \\ \text{subject to} \quad & u \in \mathcal{U},\ \xi^\star \in \Xi,\ \eta^\star \in \mathbb{R}^n,\ \lambda \in \mathbb{R}_+ \\ & P_k(u, z, \xi^\star) \leq \alpha, \\ & F(u, \xi^\star) = z, \\ & \eta^\star = \lambda \nabla_\xi F(u, \xi^\star), \\ & \xi^\star = \nabla S(\eta^\star). \end{aligned}$$

Treatment of risk via Taylor's expansion

$$P_1(u, z, \xi^\star) = \Phi(-\sqrt{2I(\xi^\star)}) = \Phi(-\|\xi^\star - \mu\|_{\Sigma^{-1}}).$$

or

$$P_2(u, z, \xi^\star) \approx \Phi(-\|\xi^\star - \mu\|_{\Sigma^{-1}}) \det{}_{\perp \hat{n}}(H)^{-\frac{1}{2}}$$

# Aligning Private and Social Risks: Example

Chance-constrained ED

$$
\begin{aligned}
\min_{\Xi}\ & \mathbb{E}_\omega\Big[\sum_{n\in\mathcal{G}} C_n(p_n(\Omega))\Big] \\
s.t.\ & \sum_{n\in\mathcal{G}} p_n + \hat{W} - d = 0 \\
& p_n(\Omega) = p_n + \delta_n(\Omega) && \forall n \\
& \mathbb{P}_\omega\big[p_n^{min} \le p_n(\Omega) \le p_n^{max}\big] \ge 1-\epsilon && \forall n \\
& \sum_{n\in\mathcal{G}} \delta_n(\Omega) - \Omega = 0
\end{aligned}
$$

LDT-constrained ED

$$
\begin{aligned}
\min_{p,\alpha,\beta}\ & \mathbb{E}_\omega\big[\sum_n C_n(p_n,\alpha_n,\beta_n)\big] \\
s.t.\ & \alpha_n,\ \beta_n,\ p_n \ge 0 && \forall n \\
& \mathbb{P}_\omega[p_n^{min} \le p_n - \alpha_n\omega \\
& \qquad \le p_n^{max},\ \forall n] \ge 1-\epsilon \\
& \mathbb{P}_\omega[p_n^{min} \le p_n - \alpha_n\omega - \beta_n\omega \\
& \qquad \le p_n^{max},\ \forall n] \ge 1-\epsilon^{ext} \\
& \sum_n p_n + \hat{W} - d = 0 \\
& \sum_n \alpha_n = 1 \\
& \sum_n \beta_n = 1
\end{aligned}
$$

$$
\begin{aligned}
& P_k(p_n,\alpha_n,\beta_n) \le 1-\epsilon^{ext} && \forall n \\
& \omega^* \in \arg\min_\omega\{I(\omega) : p_n^{min} \le \\
& \qquad p_n - (\alpha_n+\beta_n)\,\omega \le p_n^{max}\}
\end{aligned}
$$

# Aligning Private and Social Risks: Example

Single-level LDT-constrained ED

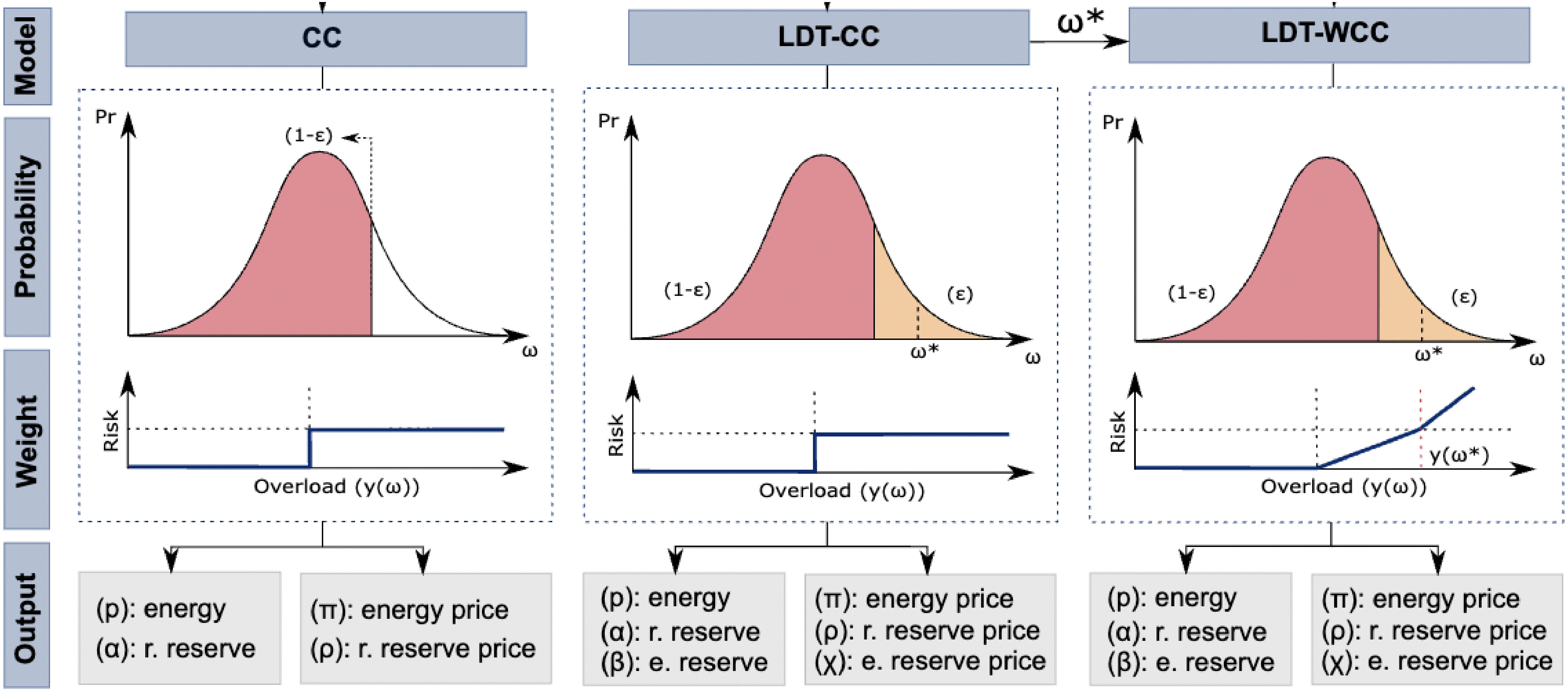
$$
\begin{aligned}
\min_{p,\alpha,\beta,\omega^*,\lambda^*} \quad & \mathbb{E}_\omega\Big[\sum_n C_n(p_n, \alpha_n, \beta_n)\Big] & \\
s.t. \quad & \alpha_n, \beta_n, p_n \geq 0, \lambda^* > 0 & \forall n \\
(\delta_n^+): \quad & p_n - p_n^{max} + \alpha_n \hat{\sigma}_n \leq 0 & \forall n \\
(\mu_n^+): \quad & -p_n^{max} + p_n - (\alpha_n + \beta_n)\ \omega^* = 0 & \forall n \\
(\nu): \quad & \Sigma^{-1/2}\omega^* + \Phi^{-1}(\epsilon^{ext}) \leq 0 & \\
(\xi_n): \quad & \Sigma^{-1}\omega^* - (\alpha_n + \beta_n)\lambda^* = 0 & \forall n \\
(\pi): \quad & \sum_n p_n + \hat{w} - d = 0 & \\
(\rho): \quad & \sum_n \alpha_n - 1 = 0 & \\
(\chi): \quad & \sum_n \beta_n - 1 = 0 &
\end{aligned}
$$

Extremely conservative!

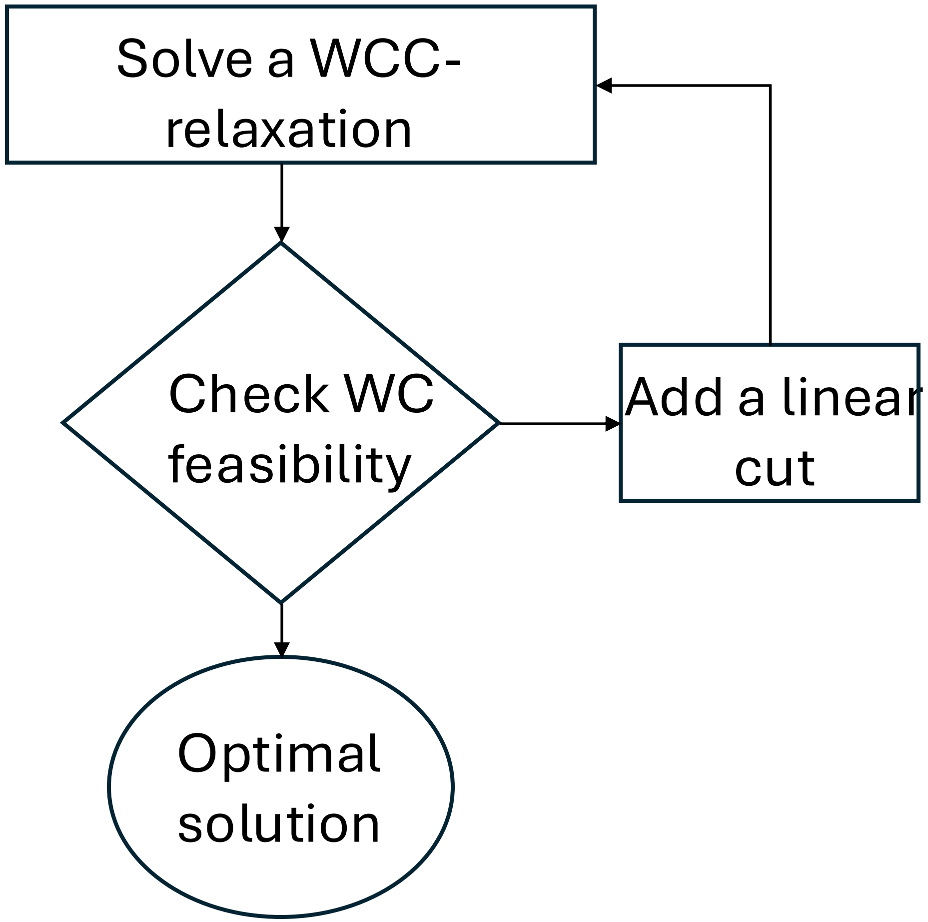
Here is an idea: use weighted chance constraints to alleviate conservatism!

# Aligning Private and Social Risks: Example

Weighted chance constraints to avoid conservatism by regulating your rate of response (risk)



# Aligning  Private and Social Risks: Computable Equilibrium!



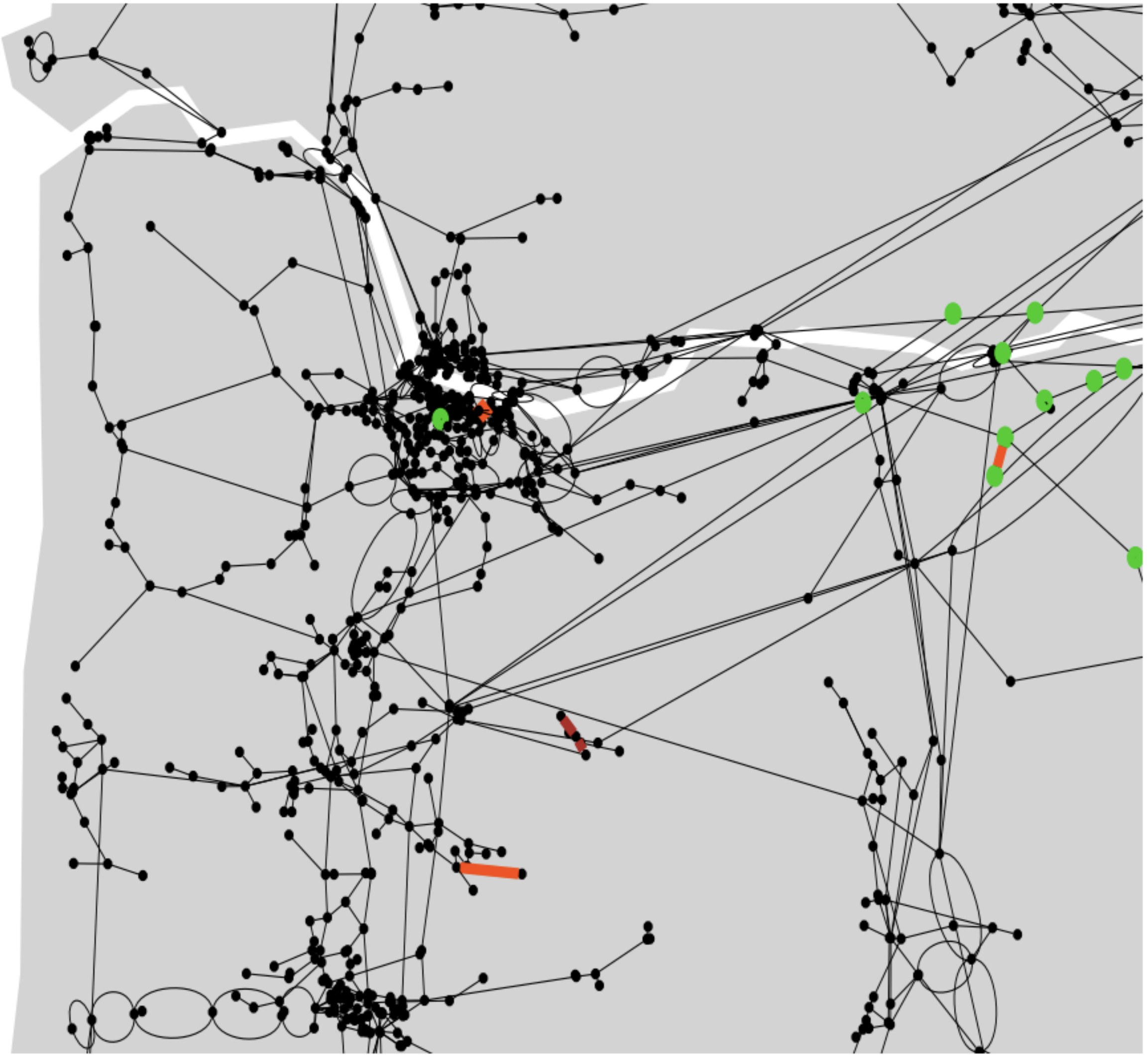

*1) Theorem 1: Equilibrium payments:* Lets $\{p_n^*, \alpha_n^*, \beta_n^*, \omega^*, \lambda^*\}$ be the optimal solution of the problem [ref] and let $\{\pi, \rho, \chi\}$ be the dual variables. Then. $\{p_n^*, \alpha_n^*, \beta_n^* \forall n\}, \omega^*, \lambda^*, \pi, \rho, \chi\}$ constitutes a market equilibrium.

- The marker clears at $\sum p_n - \hat{W} = d$, $\sum \alpha_n = 1$, and $\sum \beta_n = 1$
- Each producer maximize its profit under the payment $\Gamma_n = \pi p_n + \rho \alpha_n + \chi \beta_n$

First given a $(\omega^*, \lambda)$ if $\{p_n^*, \alpha_n^*, \beta_n^* \forall n\}$ is feasible and solved to optimality, optimal values $\{p^*, \alpha^*, \beta^* \forall n\}$ must satisfy equality constraints. And as the result $\sum p_n^* - \hat{w} = d$, $\sum \alpha_n^* = 1$, and $\sum \beta_n^* = 1$

**Important**: completes market with risk, while ensuring cost recovery and revenue adequacy.

# Aligning  Private and Social Risks: Results



Solvable for a realistically large instance:

- 2209 nodes
- 2866 nodes
- June 2022 data set

Solver: Gurobi

One instance w/out cutting planes: 19.4 s
One instance w/cutting planes: 3.7 s

Cost savings (relative to non-WCC case) – 3.9%

# Aligning Private and Social Risks: Results

**Considering extreme events does change <u>dispatch</u> and <u>reserve</u> allocation**

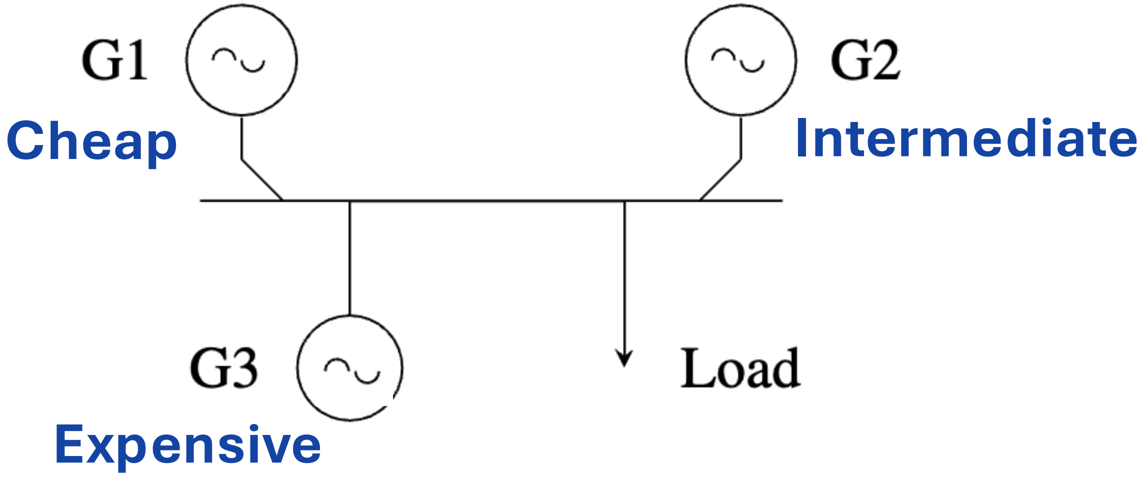



TABLE I: Optimal primal results

| Model | Energy ($p$) & Reserves ($\alpha, \beta$) dispatch Variables | G1 | G2 | G3 |
|---|---|---|---|---|
| CC | $p^*$ [MW] | 40 | 45 | 30 |
| | $\alpha^*$ [%] | 0 | 0 | 1 |
| LDT-WCC | $p^*$ [MW] | 40 | 36.05 | 38.95 |
| | $\alpha^*$ [%] | 0 | 0.04 | 0.96 |
| | $\beta^*$ [%] | 0 | 1 | 0 |
| LDT-CC | $p^*$ [MW] | 40 | 36.45 | 38.55 |
| | $\alpha^*$ [%] | 0 | 0 | 1 |
| | $\beta^*$ [%] | 0 | 0.68 | 0.32 |

The most diversified reserve portfolio

**Considering extreme events does change <u>reserve, not energy prices</u>**

TABLE II: Optimal dual results and total cost

| Model | Energy ($\pi$) & Reserves ($\rho, \chi$) prices $\pi^*$ [$/MW] | $\rho^*$ [$/MW] | $\chi^*$ [$/MW] | T. Cost [$] |
|---|---|---|---|---|
| CC | 35.30 | 89.99 | - | 3502.18 |
| LDT-WCC | 35.46 | 80.42 | 100.75 | 3591.03 |
| LDT-CC | 35.41 | 90.55 | 120.00 | 3621.31 |

# Aligning Private and Social Risks: Larger Instances

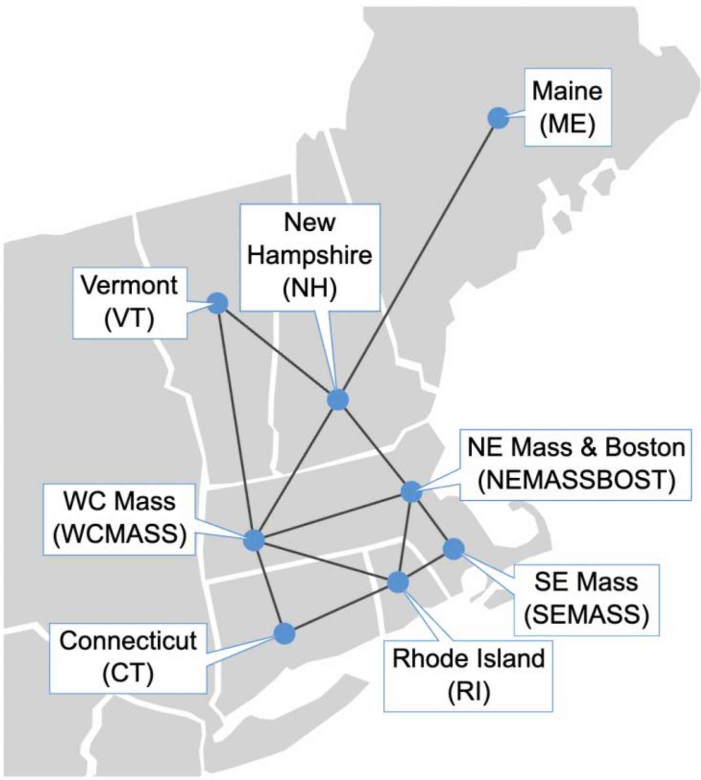



TABLE IV: Optimal dual results [$/MW]

| | Price | CC | LDT-WCC | LDT-CC |
|---|---|---|---|---|
| Energy | $\pi^*_{CT}$ | 55.84 | 56.44 | 56.18 |
| | $\pi^*_{ME}$ | 125.61 | 126.29 | 126.01 |
| | $\pi^*_{NEMASSB}$ | 141.93 | 142.98 | 142.32 |
| | $\pi^*_{NH}$ | 125.61 | 126.29 | 126.01 |
| | $\pi^*_{RI}$ | 51.50 | 52.19 | 51.90 |
| | $\pi^*_{SEMASS}$ | 207.02 | 207.63 | 207.39 |
| | $\pi^*_{VT}$ | 118.08 | 118.77 | 118.48 |
| | $\pi^*_{WCMASS}$ | 106.78 | 107.48 | 107.19 |
| Reg. Res | $\rho^*$ | 280 | 850 | 1049.22 |
| Ext. Res | $\chi^*$ | - | 1500 | 1699.224 |

Pay more upfront to avoid being sorry

Consistent zonal energy prices and monotonic (to risk) reserve prices.

## So What?

- Let's discuss ideal-world prices:

$$\boldsymbol{\lambda_{i:j} = \lambda^{e}_{i:j} \cdot \pi^{0}} + (\boldsymbol{\lambda^{max}_{i:j} - \lambda^{e}_{i:j}}) \cdot (\mathbf{1} - \boldsymbol{\pi^{0}})$$

- We found the best proxy by introducing an additional (extreme) reserve product and completing market design with risk:

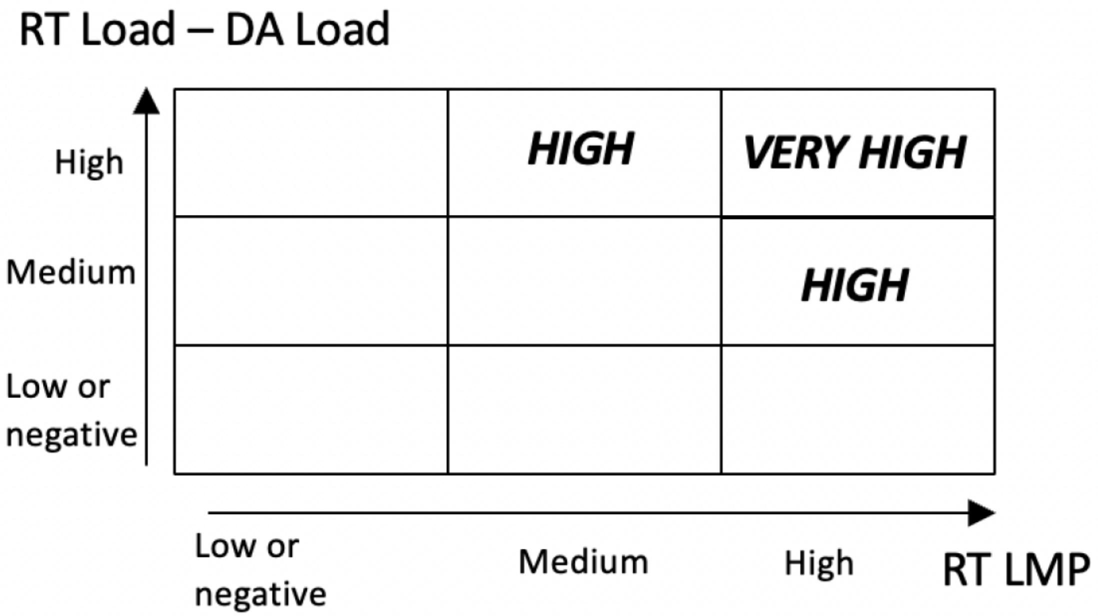
$$\boldsymbol{\lambda_{i:j} = \lambda^{e}_{i:j} \cdot \pi^{0}}$$
$$\boldsymbol{\chi \sim \mathbf{E}_{\pi^{0}}[(\lambda^{max}_{i:j} - \lambda^{e}_{i:j}(\pi^{0}) \cdot (1 - \pi^{0})]}$$

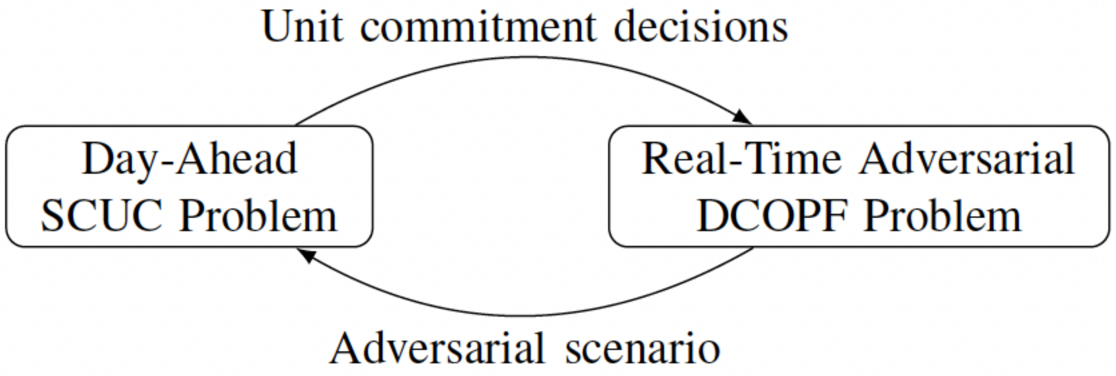
- Still, it doesn't solve the problem of price volatility

# Price Volatility

Price volatility drives consumer's risk exposure (recall largely inelastic demand):

- Volatile prices can still be efficient though
- Hedges against volatility exists (e.g., VB)
- Important point: we do <u>not</u> seek to eliminate volatility
- Goal: Complete markets with information about volatility



# Price Volatility

Adversarial problem can come in a variety of forms, but there are two conditions:

- Must be internalized with current market designs
- Must be "computable"
- Must be "priceable"

$$\min \sum_{t\in\mathcal{T}^{\text{DA}}} \left( \sum_{g\in\mathcal{G}} \left(h_{gt} + C_g^{\text{Start}} v_{gt} + C_g^{\text{Down}} w_{gt}\right) + \sum_{i\in\mathcal{N}} C^{\text{VOLL}} p_{it}^{\text{Unmet}} \right) + \rho \hat{V}(\mathbf{y})$$

Typical SCUC/SCED constraints

$$\hat{V}(\mathbf{y}) = \max_{\boldsymbol{\omega}\in\Omega} \frac{1}{N^{\text{tp}}} \sum_{t\in\mathcal{T}^{\text{RT}}} \sum_{i\in\mathcal{N}} \lambda_{it}(\mathbf{y},\boldsymbol{\omega}) (d_{it}^{\text{RT}} - \bar{D}_{it})^{+}$$

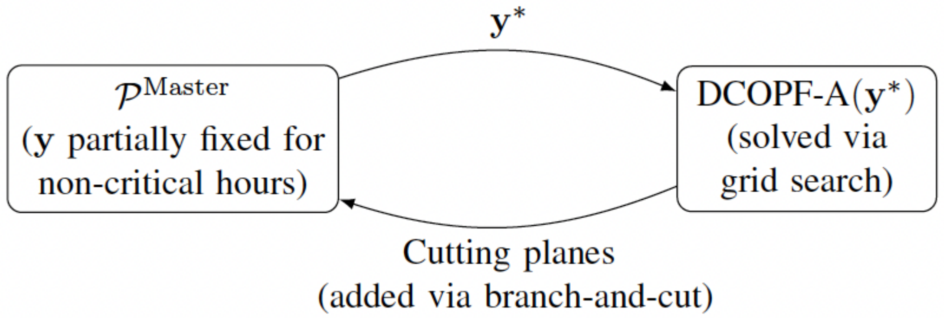
Proxy for consumer risk exposure

RT price

Power mismatch

Decomposable problem:

- No-good, L-shaped, LBBD cuts
- Solves as quick as SCUC

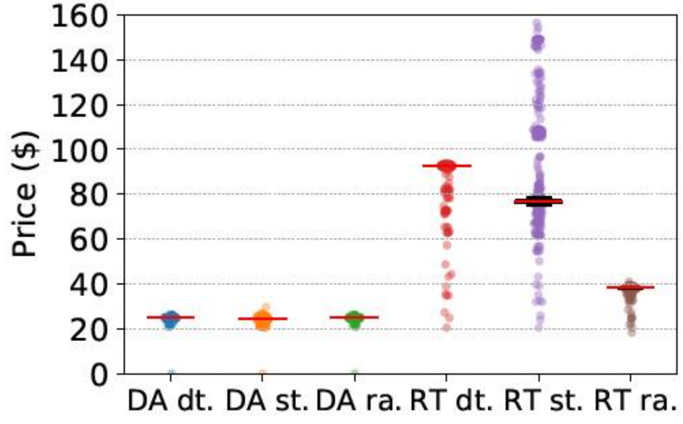


# Price Volatility

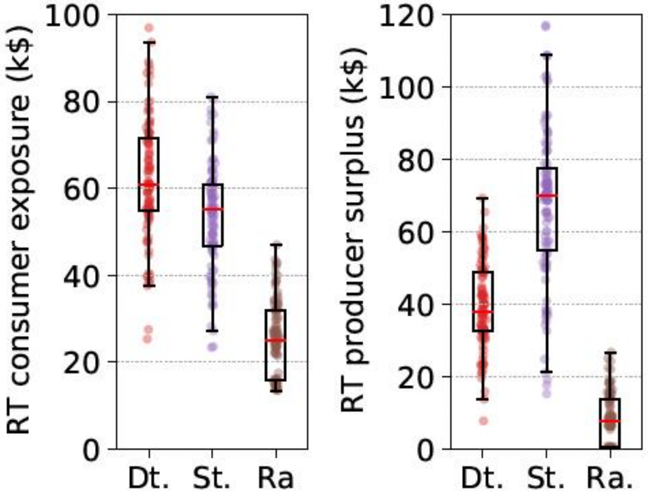
TABLE I: COMPARISON OF RISK-AWARE AND DETERMINISTIC SCUC PROBLEMS FOR $\rho = 1$

| $R^d$ | $R^w$ | Save (k$) | Deter. cost (M$) | Cost red. (%) | DA cost diff ($) | Consr. exp. (k$) |
|---|---|---|---|---|---|---|
| 0.1 | 0.2 | 0.00 | 5.37 | 0.00 | 0.00 | 8.53 |
| 0.1 | 0.4 | 0.12 | 5.37 | 0.00 | 116.16 | 8.53 |
| 0.1 | 0.6 | 0.00 | 5.37 | 0.00 | 0.00 | 8.89 |
| 0.1 | 0.8 | 42.29 | 5.41 | 0.78 | 116.16 | 8.89 |
| 0.1 | 1.0 | 42.28 | 5.41 | 0.78 | 123.50 | 8.89 |
| 0.2 | 0.2 | 114.71 | 5.50 | 2.09 | 116.16 | 17.78 |
| *0.2 | 0.4 | 114.14 | 5.50 | 2.08 | 688.03 | 17.78 |
| 0.2 | 0.6 | 115.74 | 5.50 | 2.11 | 1446.22 | 16.76 |
| 0.2 | 0.8 | 108.58 | 5.50 | 1.98 | 8130.20 | 17.78 |
| *0.2 | 1.0 | 115.64 | 5.50 | 2.10 | 1072.06 | 17.78 |

* Instance solved with 3 root cuts.




(a)




- Consumer risk exposure is reduced at no expense to the system efficiency.
- Risk management is not orthogonal to efficiency.
- Dramatic reduction in consumer exposure

# Concluding Thoughts

- Risk management scales to realistically large networks
- Extreme outcomes and volatility are considered endogenously and without computationally intensive sampling
- We provide a robust pricing framework that captures option-value of resiliency
- This framework can be adapted to other applications

## Thank you! Questions? Suggestions? Feedback?

- We are constantly looking for Ph.D. applicants
- Reach out to us at ydvorki1@jhu.edu

- Collaborators: