Wholesale electricity market design under uncertainty

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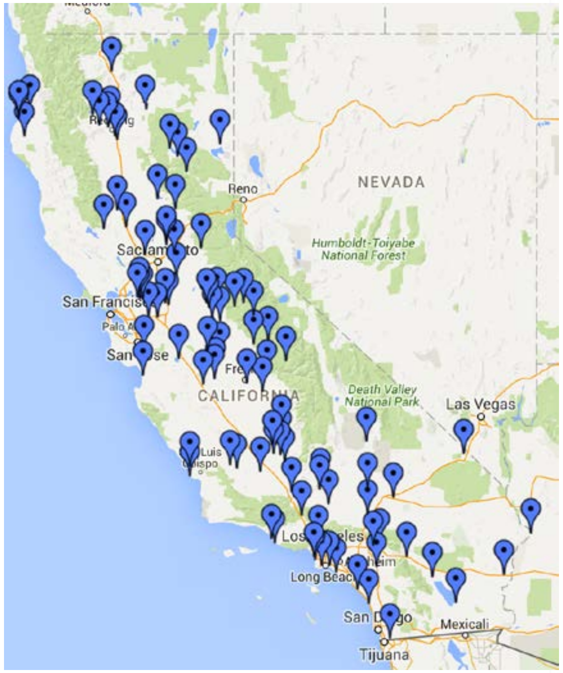
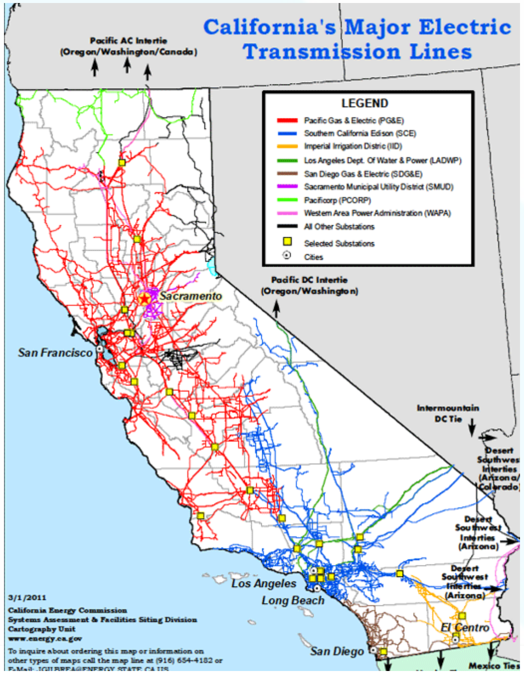
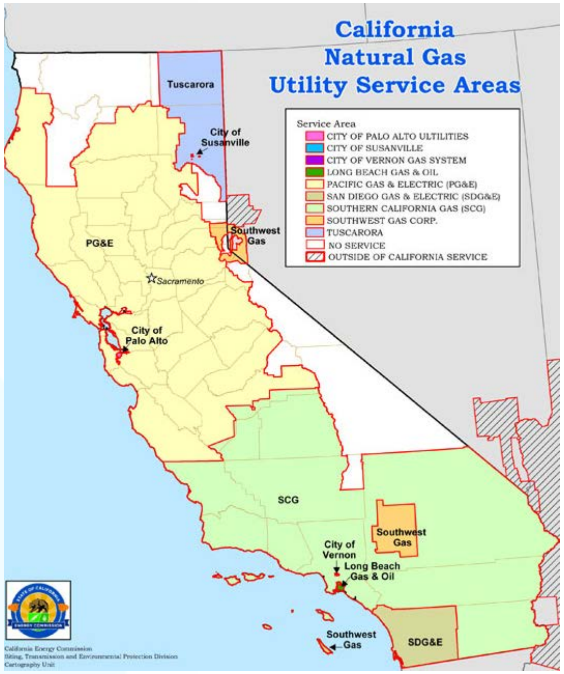
Wholesale electricity markets

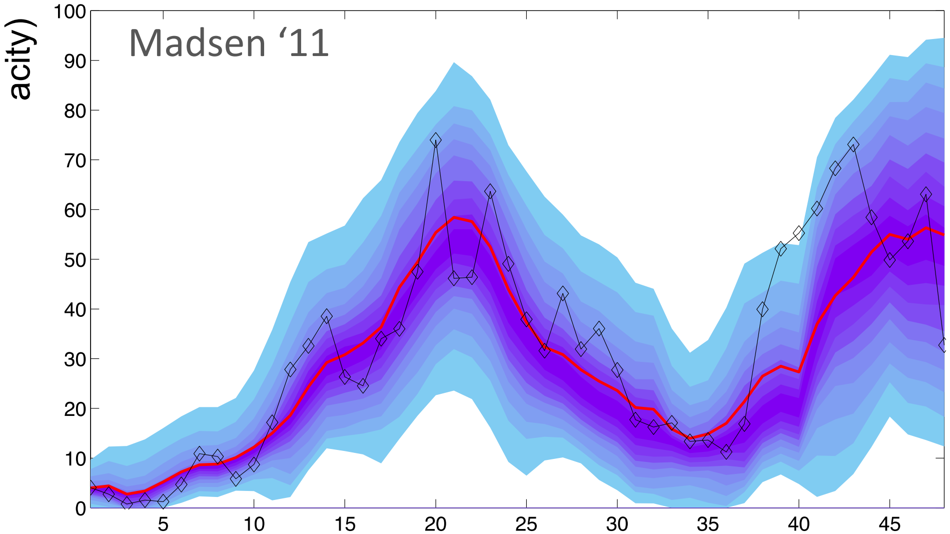
California ISO
Your Link to Power







Do market structures need to change with deepening penetration of variable renewable supply?



Uncertain

Intermittent

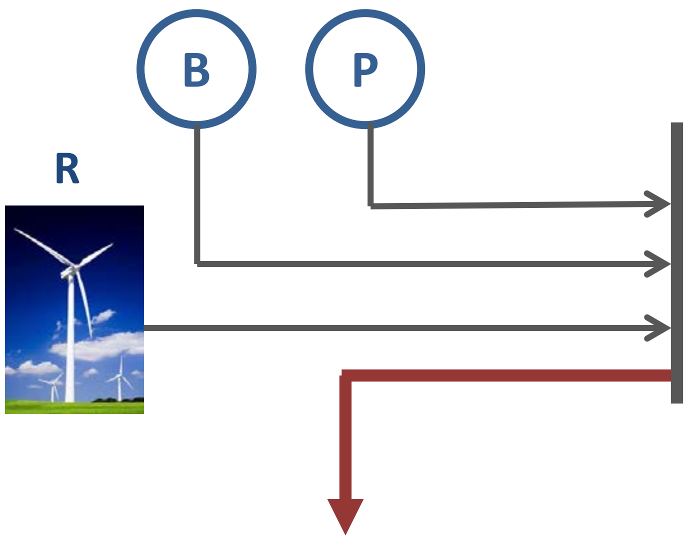
Non-dispatchable

Q1. *Do we need to change the forward market design?*

Q2. *How can we design instruments to mitigate financial risks?*

A copperplate power system

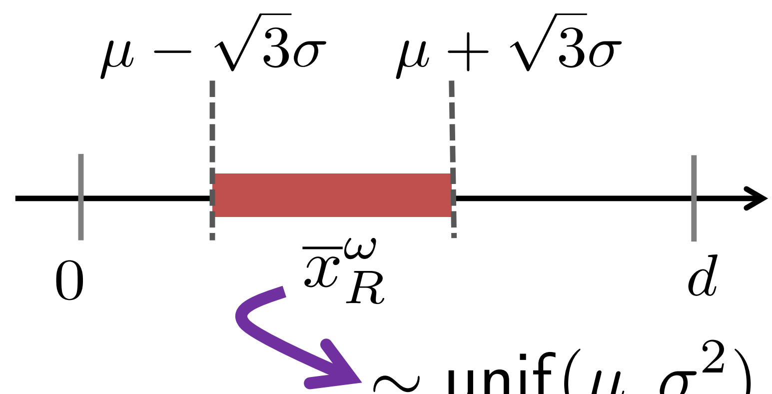
$\Omega =$ Scenarios of available renewable supply



$d > 0$

Uncontrollable but predictable demand

Renewable power producer



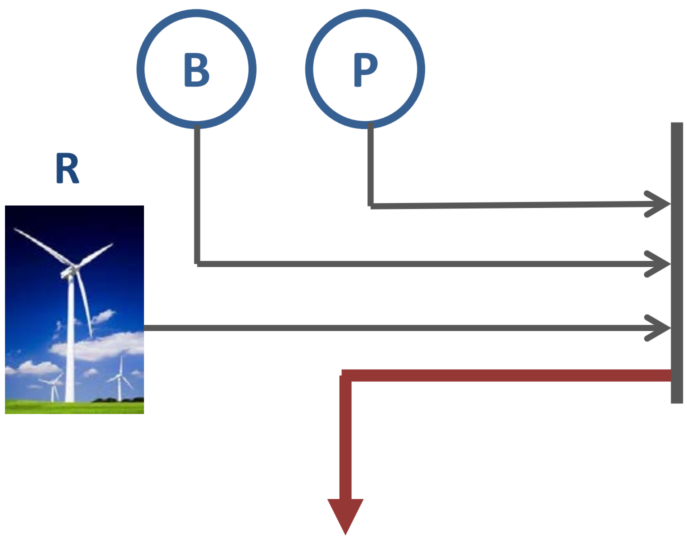
$\sim$ unif(μ, σ^2)

$$0 \leq x_R^\omega \leq \overline{x}_R^\omega$$

cost $= 0.$

A copperplate power system

$\Omega =$ Scenarios of available renewable supply



$d > 0$

Uncontrollable but predictable demand

B **Baseload generator**

$$0 \leq x_B^\omega \leq \infty$$

$$|x_B^\omega - X_B| = 0$$

cost $= x_B^\omega$

Forward set point

$\rho > 1$

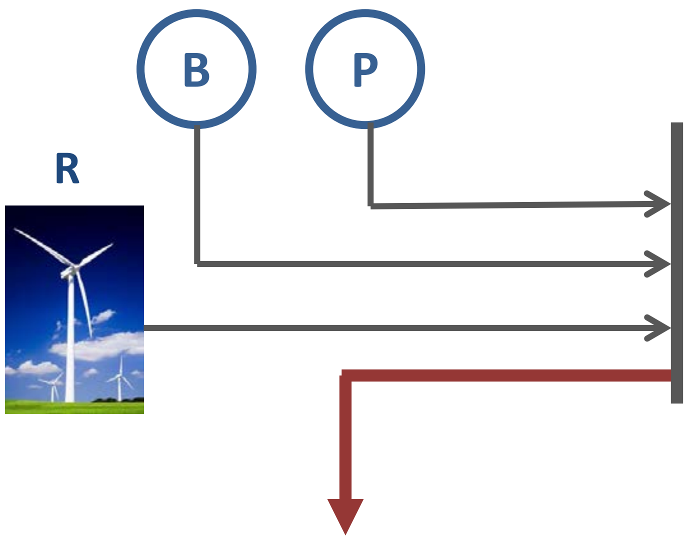
P **Peaker power plant**

$$0 \leq x_P^\omega \leq \infty$$

$$|x_P^\omega - X_P| \leq \infty$$

cost $= \rho x_P^\omega$

A copperplate power system



$$d > 0$$

Uncontrollable but predictable demand

A certainty-equivalent based forward dispatch

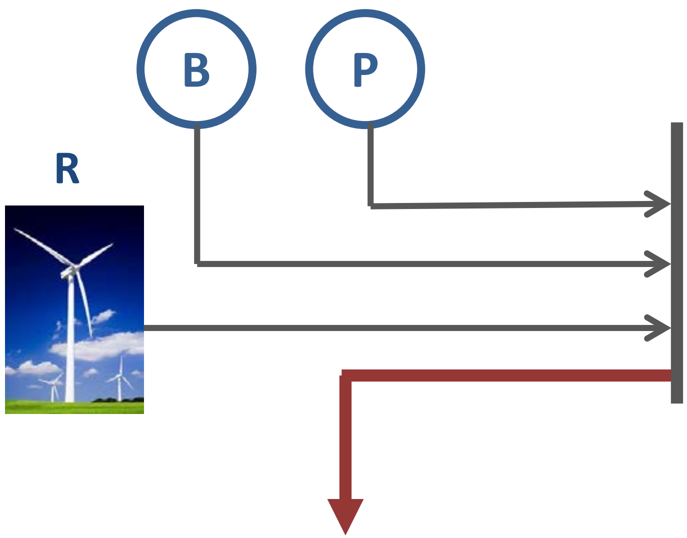
$$\begin{aligned}
\underset{X_B, X_P, X_R}{\text{minimize}} \quad & 1 \cdot X_B + \rho \cdot X_P + 0 \cdot X_R, \\
\text{subject to} \quad & X_B + X_P + X_R = d, \\
& X_B \geq 0, X_P \geq 0, \\
& 0 \leq X_R \leq \mu.
\end{aligned}$$

Forward price = optimal Lagrange multiplier P^*

Summary of forward market clearing:

$$\begin{aligned}
X_B^* &= d - \mu, \\
X_P^* &= 0, \\
X_R^* &= \mu, \\
P^* &= 1.
\end{aligned}$$

A copperplate power system



$$d > 0$$

Uncontrollable but predictable demand

Real-time balancing, given forward dispatch

$$\begin{aligned} \underset{x_B^\omega, x_P^\omega, x_R^\omega}{\text{minimize}} \quad & 1 \cdot x_B^\omega + \rho \cdot x_P^\omega + 0 \cdot x_R^\omega, \\ \text{subject to} \quad & x_B^\omega + x_P^\omega + x_R^\omega = d, \\ & |x_B^\omega - X_B| = 0, \\ & x_P^\omega \geq 0, \\ & 0 \leq x_R^\omega \leq \overline{x}_R^\omega. \end{aligned}$$

Summary of real-time market clearing:

$$x_B^{\square,!} = d - \mu,$$

$$x_P^{\square,!} = (\mu - !)^+,$$

$$x_R^{\square,!} = \min\{!, \mu\},$$

$$p^{\square,!} = \square \cdot \mathbb{1}_{\{! < \mu\}}.$$

More generally, for a power network…

Dispatch model + **Payment scheme**

Certainty equivalent dispatch

Locational marginal pricing

- Forecast uncertain variables
- Dispatch forward against that forecast
- Re-dispatch to balance attending deviation in real-time

Problems with the certainty equivalent approach

Forward market clearing process is agnostic to the real-time balancing costs.

Expected total costs: $$d - \mu + \frac{\sqrt{3}}{4}\rho\sigma$$

cost of "waiting" (ρ)

measure of "uncertainty" (σ)

What do forward prices mean?

Does it allow the forward market-participants to hedge their financial risks?

What prices are deemed meaningful?

System operator decides the allocation (quantities, prices) through a centralized market clearing process.

Suppose each generator reflects its true marginal cost to the system operator in its supply offer. Then, she should be willing to produce the prescribed dispatch quantity, when it is paid at the prescribed price. Further, if the generator is a price-taker, it should reflect its true marginal cost to the system operator.

(Quantities, prices) constitute an efficient competitive equilibrium.

A stochastic economic dispatch model

$$\begin{aligned} \underset{x_B^\omega, X_B, x_P^\omega, x_R^\omega}{\text{minimize}} \quad & \mathbb{E}_{\mathbf{P}}\left[1 \cdot x_B^\omega + \rho \cdot x_P^\omega + 0 \cdot x_R^\omega\right], \\ \text{subject to} \quad & \left.\begin{aligned} & x_B^\omega + x_P^\omega + x_R^\omega = d, \\ & |x_B^\omega - X_B| = 0, \\ & x_P^\omega \geq 0, \\ & 0 \leq x_R^\omega \leq \overline{x}_R^\omega. \end{aligned}\right\} \mathbf{P}\text{- a.s.} \end{aligned}$$

Assume common knowledge.

What really constitutes a forward dispatch? Forward prices?

Introduce extra dispatch quantities X_P, X_R, and impose demand-supply balance constraint among X_B, X_P, X_R, d. Pritchard '10.

Other schemes: Galiana '05, Wong '07, Bouffard '08, Morales '09, '12.

A stochastic economic dispatch model

- Enforce forward balance constraint among ***non-physical*** variables, and price such a constraint.
- Can be ***revenue inadequate*** for certain realizations of available renewable supply.

What really constitutes a forward dispatch? Forward prices?

Introduce extra dispatch quantities X_P, X_R, and impose demand-supply balance constraint among X_B, X_P, X_R, d. Pritchard '10.

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Contingent pricing approach

Dispatch model + **Payment scheme**

Stochastic economic dispatch

- Defines a dispatch policy

Locational marginal pricing

Defines a pricing policy

Contingent pricing for stochastic economic dispatch

$$\begin{aligned} \underset{x_B^\omega, X_B, x_P^\omega, x_R^\omega}{\text{minimize}} \quad & \mathbb{E}_{\mathbf{P}}\left[1 \cdot x_B^\omega + \rho \cdot x_P^\omega + 0 \cdot x_R^\omega\right], \\ \text{subject to} \quad & \left.\begin{aligned} & x_B^\omega + x_P^\omega + x_R^\omega = d, \\ & |x_B^\omega - X_B| = 0, \\ & x_P^\omega \geq 0, \\ & 0 \leq x_R^\omega \leq \overline{x}_R^\omega. \end{aligned}\right\} \mathbf{P}\text{- a.s.} \end{aligned}$$

Market outcome: $x_B^{*,\omega}, x_P^{*,\omega}, x_R^{*,\omega}, p^{*,\omega}$ for each $\omega \in \Omega$.

Contingent pricing for stochastic economic dispatch

- At the forward stage:
  - The system operator solves the stochastic economic dispatch problem
  - Announces the dispatch policy, and the pricing policy $x_B^{*,\omega}, x_P^{*,\omega}, x_R^{*,\omega}, p^{*,\omega}$
- In real-time:
  - Enforce the computed dispatch policy
  - Pay according to the pricing policy

Contingent pricing for stochastic economic dispatch

Advantages:

- Supports an efficient competitive equilibrium
- Revenue adequate over a network in all scenarios

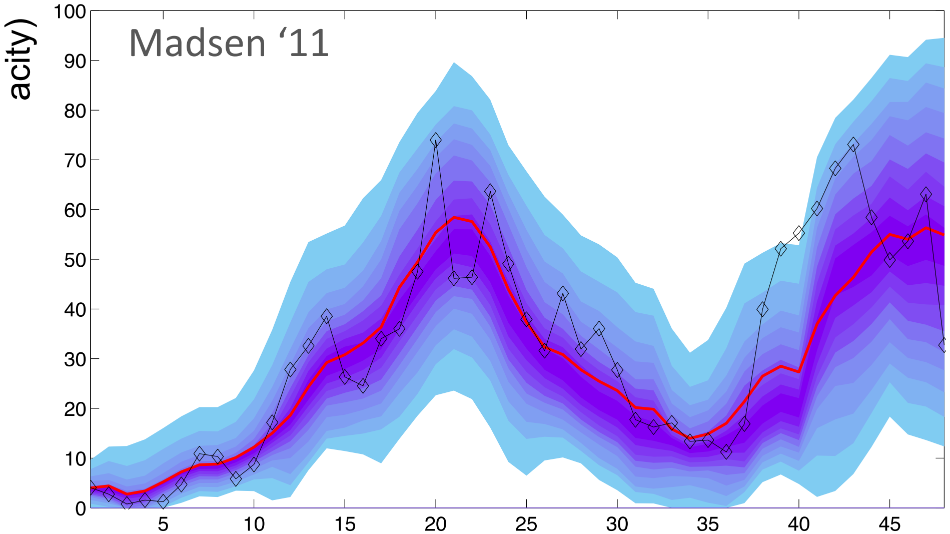
Limitations:

- Communicating a "policy" can be challenging
- Takes away the ability of forward markets to hedge against volatility in real-time markets

"On the design of wholesale electricity markets under uncertainty", S. Bose. Proceedings of the 53rd Annual Allerton Conference, 2015.

"Contingent pricing approach to wholesale electricity markets under uncertainty", S. Bose and E. Bitar. In preparation.

Do market structures need to change with deepening penetration of variable renewable supply?



Uncertain

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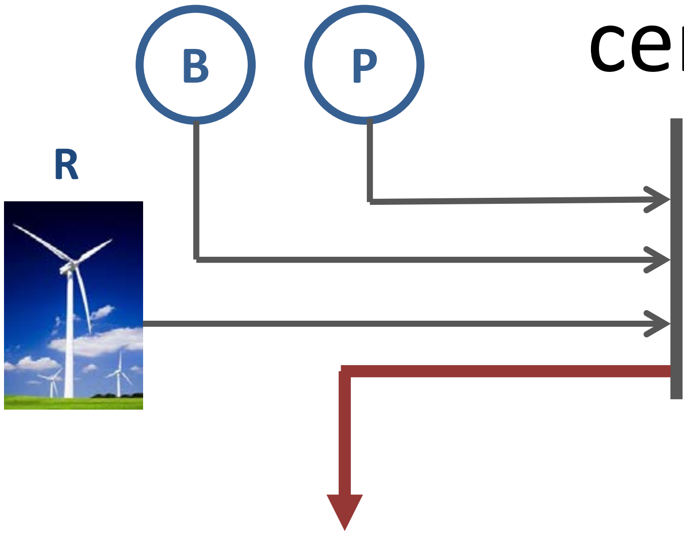
Volatility of payments from certainty equivalent approach



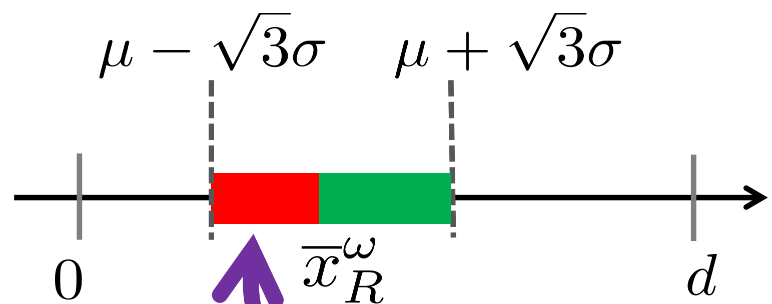
$$d > 0$$

Payments to market participants:

$$\pi_B^\omega = d - \mu,$$
$$\pi_P^\omega = \rho(\mu - \omega)^+,$$
$$\pi_R^\omega = \mu - \rho(\mu - \omega)^+.$$

$\text{var}\left[\pi^\omega\right]$: a measure of volatility

Q1. Can we reduce this volatility?



Set over which R gets negative payments
$\left[\mu - \sqrt{3}\sigma, \mu(1 - 1/\rho)\right)$

Q2. Can we shrink this set?

A partial remedy: *bilateral* cash-settled call option

Assume that players are risk-neutral, and have correct price conjectures.

R

option buyer

Δ

option quantity

(q, K)

(option price, strike price)

P

option seller

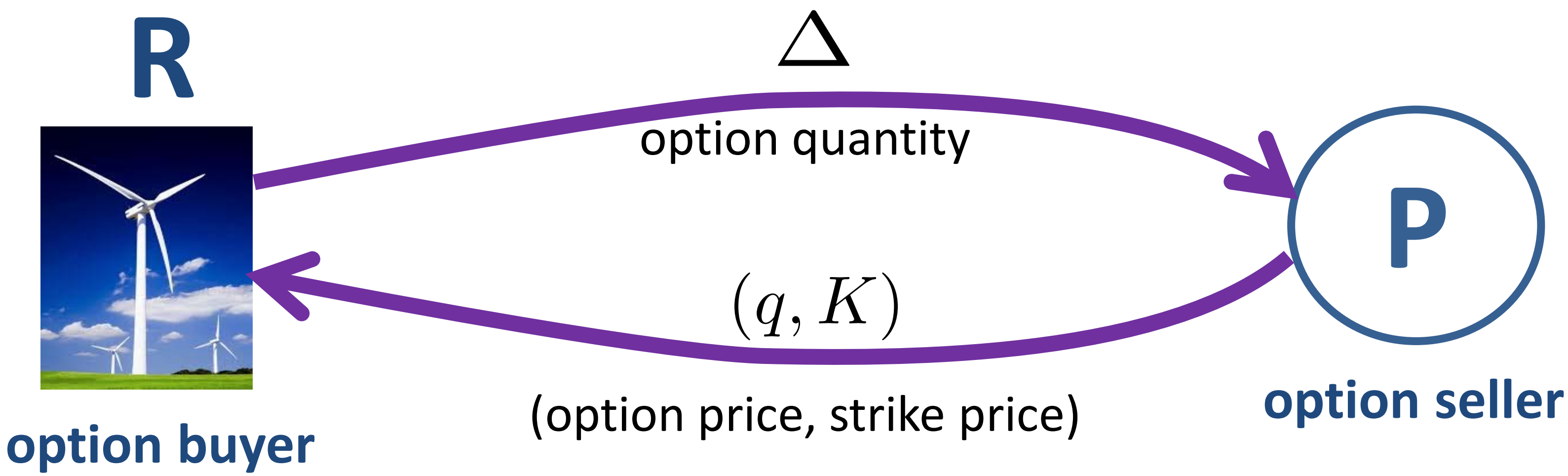
$$\Pi_R^\omega(q, K, \Delta) := \pi_R^\omega - q\Delta + (p^{\omega,*} - K)^+ \Delta,$$

$$\Pi_P^\omega(q, K, \Delta) := \underbrace{\pi_P^\omega}_{\text{Payment from electricity market}} + \underbrace{q\Delta - (p^{\omega,*} - K)^+ \Delta}_{\text{Payment from option trade}}.$$

Payment from electricity market

Payment from option trade

Outcomes identified as Stackelberg equilibria



Definition. $(q^*, K^*, \Delta^*) \in \mathbb{R}_+^2 \times \mathbb{R}_+^2 \to [0, \sqrt{3}\sigma]$ constitutes a Stackelberg equilibrium, if

$$\mathbb{E}\left[\Pi_P^\omega(q^*, K^*, \Delta^*(q^*, K^*))\right] \geq \mathbb{E}\left[\Pi_P^\omega(q, K, \Delta^*(q, K))\right],$$
$$\mathbb{E}\left[\Pi_R^\omega(q, K, \Delta^*(q, K))\right] \geq \mathbb{E}\left[\Pi_R^\omega(q, K, \Delta(q, K))\right],$$

for any $(q, K, \Delta) \in \mathbb{R}_+^2 \times \mathbb{R}_+^2 \to [0, \sqrt{3}\sigma]$.

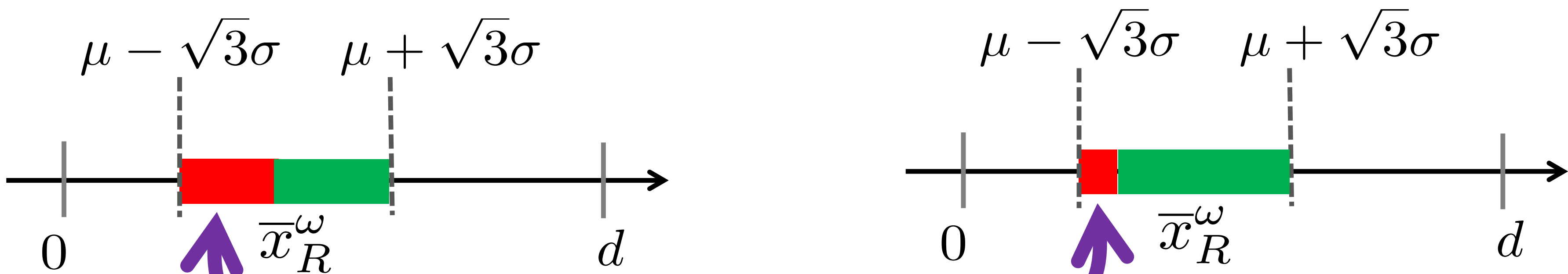
Proposition. The nontrivial Stackelberg equilibria are given by

$$\mathcal{N} = \left\{ (q, K, \Delta) \mid (q, K) \in \mathbb{R}_+^2,\ \Delta : \mathbb{R}_+^2 \to [0, \sqrt{3}\sigma],\ 2q + K = \rho \right\}.$$

For $i \in \{R, P\}$ and any $(q^*, K^*, \Delta^*(q^*, K^*) = \sqrt{3}\sigma) \in \mathcal{N}$, we have

$$\text{var}\left[\Pi_i^\omega(q^*, K^*, \Delta^*(q^*, K^*))\right] - \text{var}\left[\pi_i^\omega\right] = -3K^*\sigma^2/2 < 0.$$

measure of "uncertainty"



Set over which R gets negative payments

$\left[\mu - \sqrt{3}\sigma, \mu(1 - 1/\rho)\right)$ shrinks to $\left[\mu - \sqrt{3}\sigma, \mu(1 - 1/\rho) - \sqrt{3}q^*\sigma/\rho\right)$

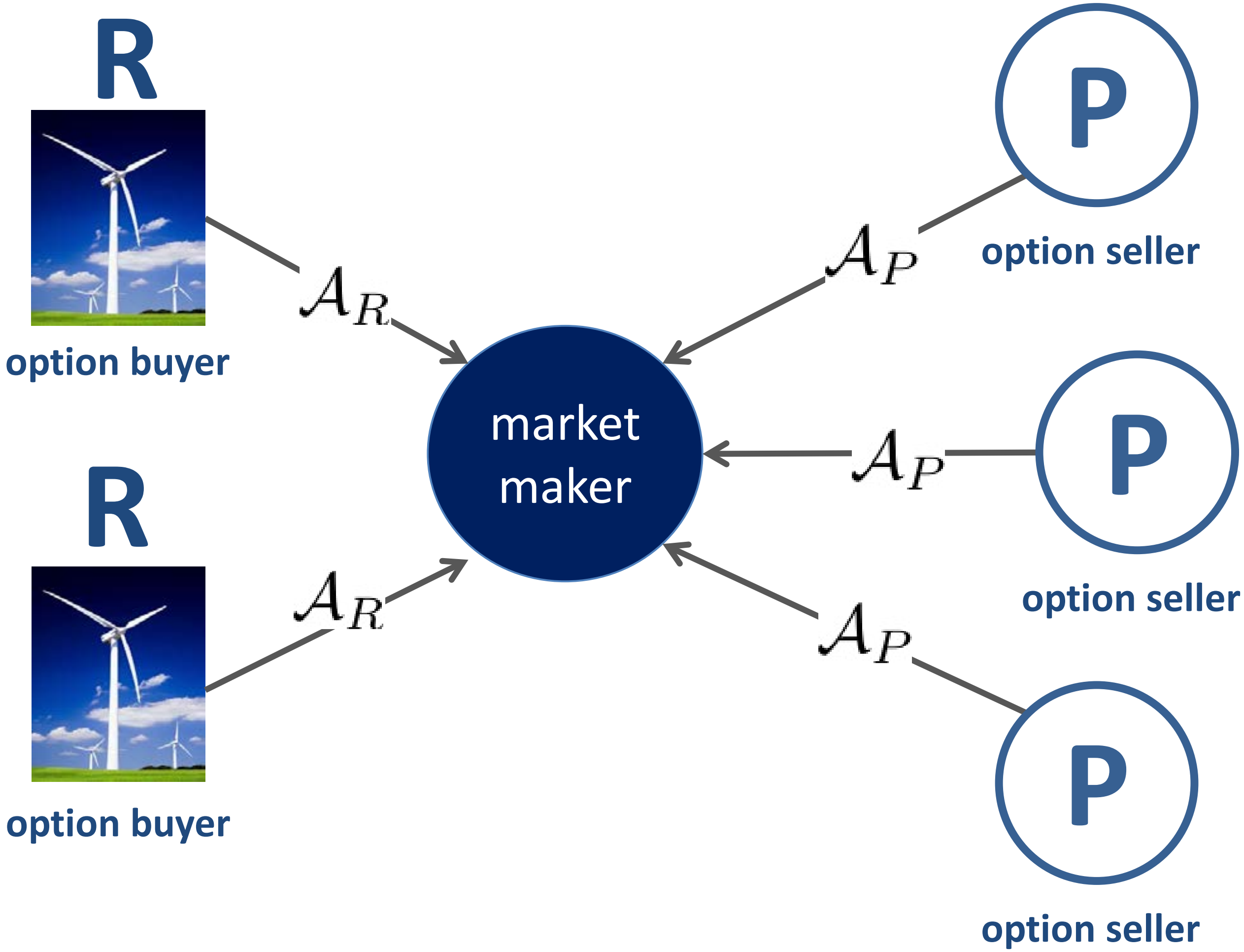
A partial remedy: *bilateral* cash-settled call option

Needs multiple such trades with a collection of dispatchable and renewable power producers

Key idea: introduce an intermediary we call the market maker

"Cash-settled options for wholesale electricity markets", K. Alshehri, S. Bose, and T. Başar. To appear in the proceedings of the 20th IFAC World Congress, 2017.

Market maker buys from option sellers and sells them to option buyers



$\mathcal{A}$ defines the set of acceptable trades (q, K, Δ) for each participant.

Market maker buys from option sellers and sells them to option buyers

…a centralized option trading mechanism

…generalizes the bilateral trade case

Option market clearing via stochastic optimization:

$$
\begin{aligned}
\text{maximize} \quad & \mathbb{E}[\mathrm{MS}^{\omega}], \\
\text{subject to} \quad & \sum_{P \in \mathfrak{P}} \Delta_P = \sum_{R \in \mathfrak{R}} \Delta_R, \\
& (q_P, K_P, \Delta_P) \in A_P, \ (q_R, K_R, \Delta_R) \in A_R, \\
& \delta_P^{\omega} \in [0, \Delta_P], \\
& \sum_{P \in \mathfrak{P}} \delta_P^{\omega} = \sum_{R \in \mathfrak{R}} \Delta_R \mathbb{1}_{\{p^{\omega,*} \geq K_R\}} \\
& \text{for each } P \in \mathfrak{P}, \ R \in \mathfrak{R}, \ \omega \in \Omega
\end{aligned}
$$

Market maker may have a different objective.

Can encode risk aversion in the set of acceptable trades.

$$
\mathrm{MS}^{\omega} := \sum_{R \in \mathfrak{R}} \left[q_R \Delta_R - (p^{\omega,*} - K_R)^{+} \Delta_R \right] - \sum_{P \in \mathfrak{P}} \left[q_P \Delta_P - (p^{\omega,*} - K_P)^{+} \delta_P^{\omega} \right].
$$

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Thank you!