Capacity Markets and the Energy Transition

PSERC Webinar

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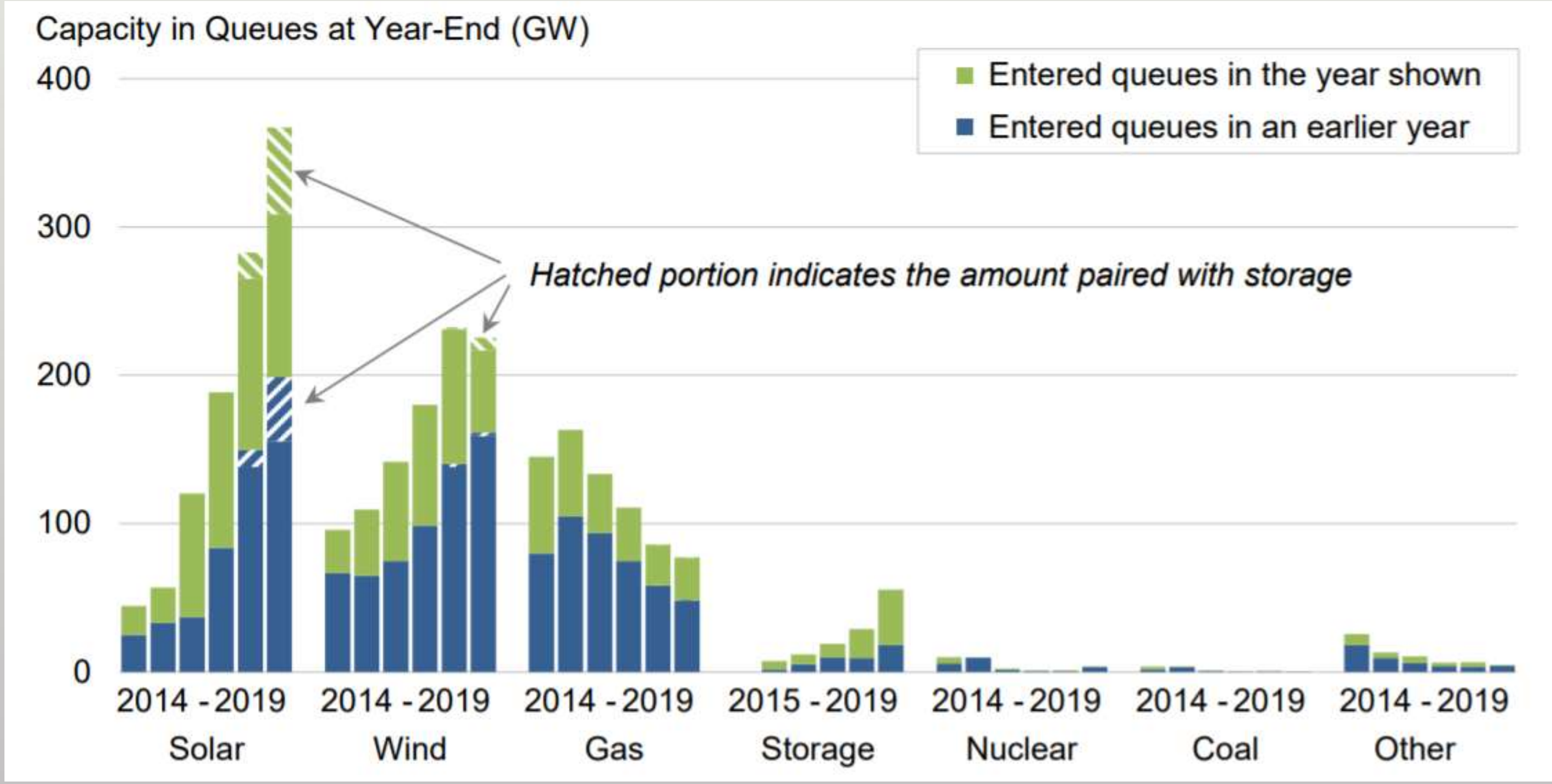
What is getting built?

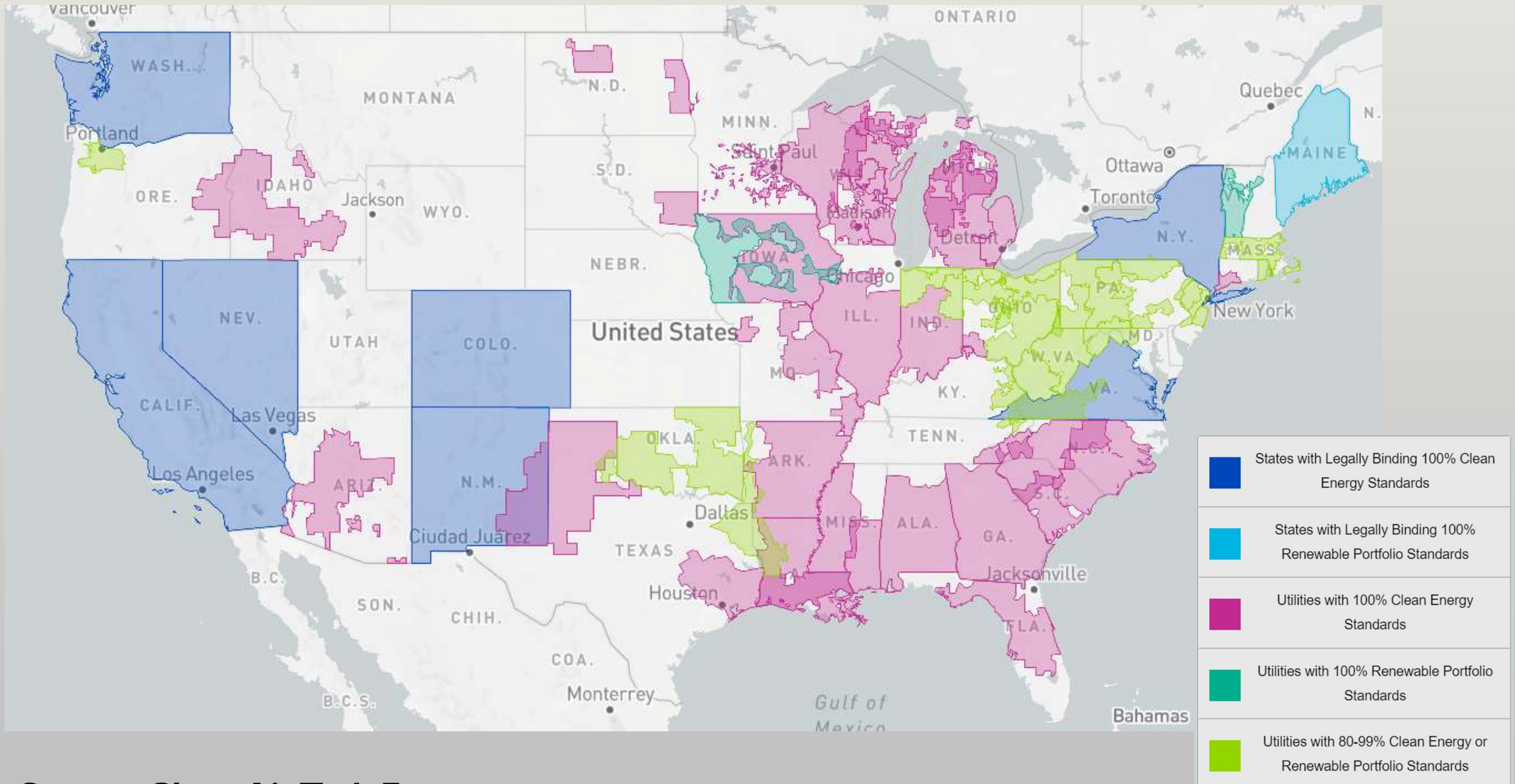
Interconnection queues are dominated by wind and solar, even in areas without decarbonization goals



Source: https://emp.lbl.gov/sites/default/files/2020_utility-scale_solar_data_update.pdf

Electricity sector commitments

State and utility clean-energy commitments entail 80–100% reductions in carbon emissions



Source: Clean Air Task Force

Can today's markets support a transition?

greentechmedia:

How Wind and Solar Will Blow Up Power Markets

According to Ben Paulos, in the long run, the main zero-carbon energy sources are not compatible with conventional market design.

- **Variability and zero marginal cost are putting stress on current market designs**

Capacity markets at a crossroads

FERC

“We should be taking a hard look at whether a mandatory capacity market remains a just and reasonable resource adequacy construct in today’s rapidly evolving electricity sector.”

-Richard Glick, 12/19/2019 (dissent on PJM MOPR)

Market design philosophy

Principle of competitive markets:

Transparent & Complete Price Signals → **Efficient Investment and Operation**

- **Theory behind competitive markets does not change due to variability or zero marginal cost**

What needs to change?

Principle of competitive markets:

Transparent & Complete Price Signals → **Efficient Investment and Operation**

- **In practice, price signals and markets are incomplete in important ways**

Claims

This talk hopes to convince you of two things:

1. **Current capacity markets may not adequately compensate flexible resources needed to complement wind and solar**

2. **Current capacity markets preferentially facilitate financing of high-marginal-cost technologies**

What's missing?

1. Missing Money
2. Missing Incentives
3. Missing Markets

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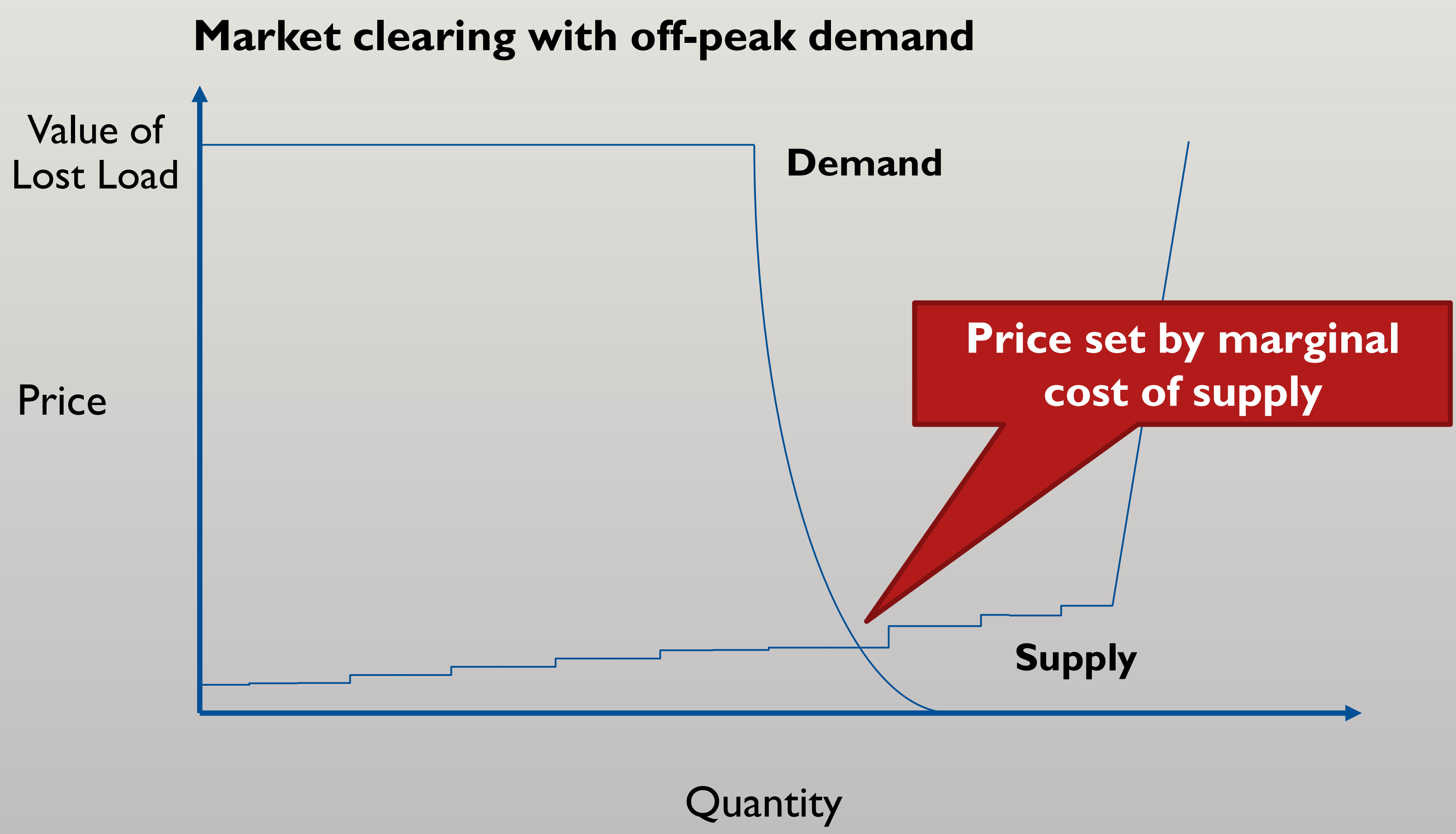
1. **Missing Money**
2. Missing Incentives
3. Missing Markets

Energy-only markets

In textbook, energy-only markets, all revenue is derived from the sale of energy and ancillary services



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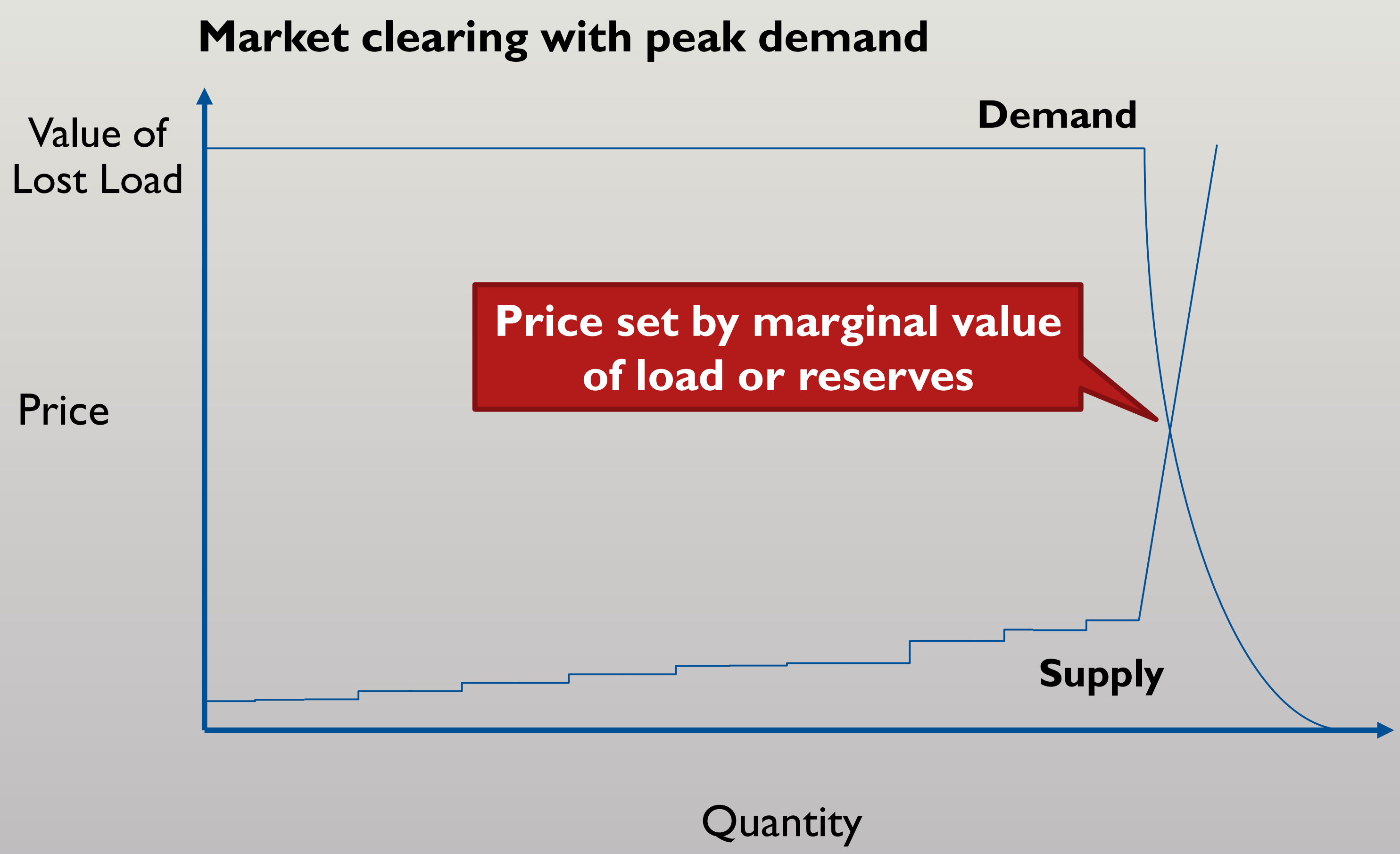

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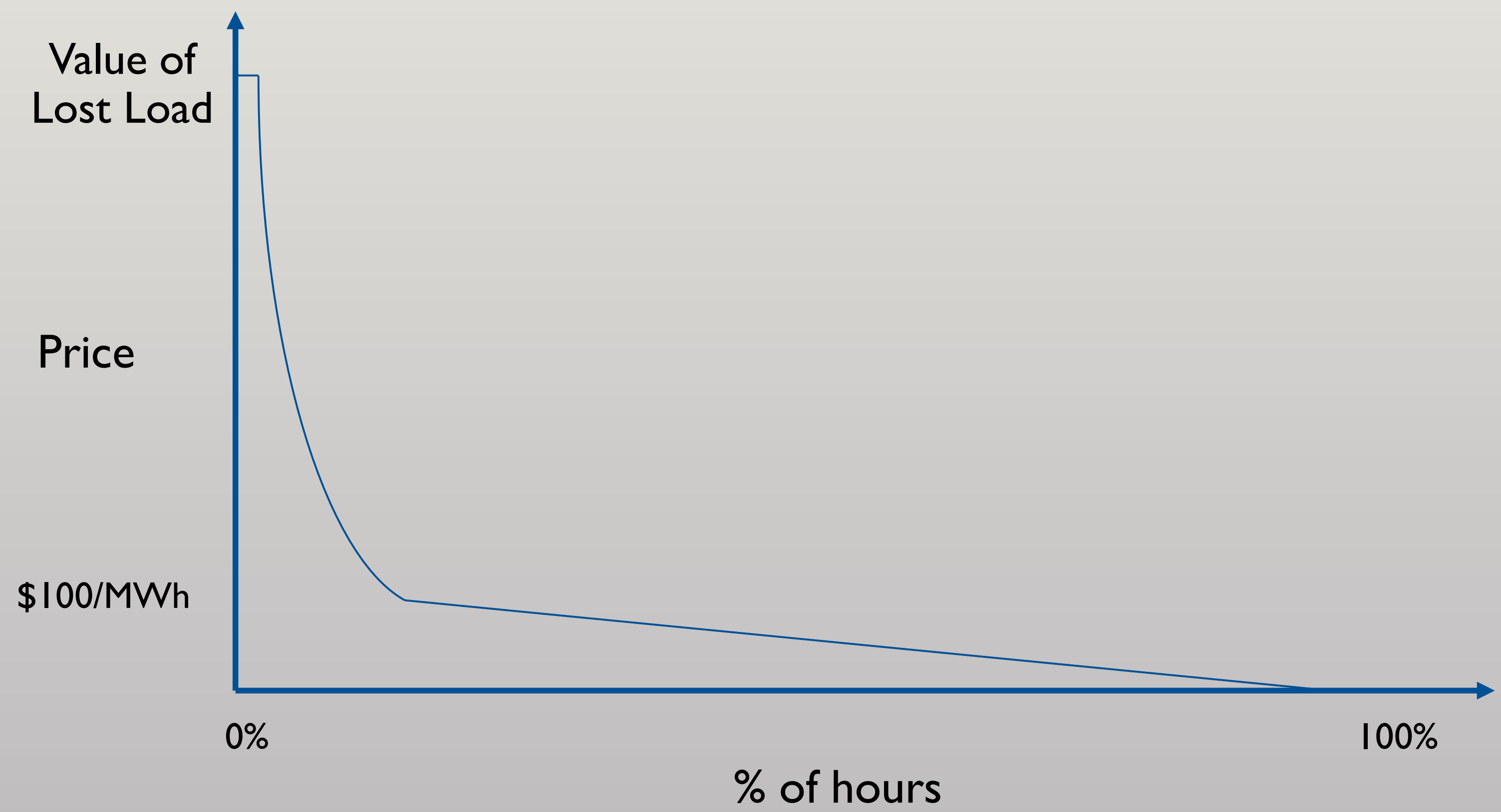
Energy-only markets

Prices are typically high variance, with a large portion of operating profits coming in a few scarcity hours

Wholesale price duration curve



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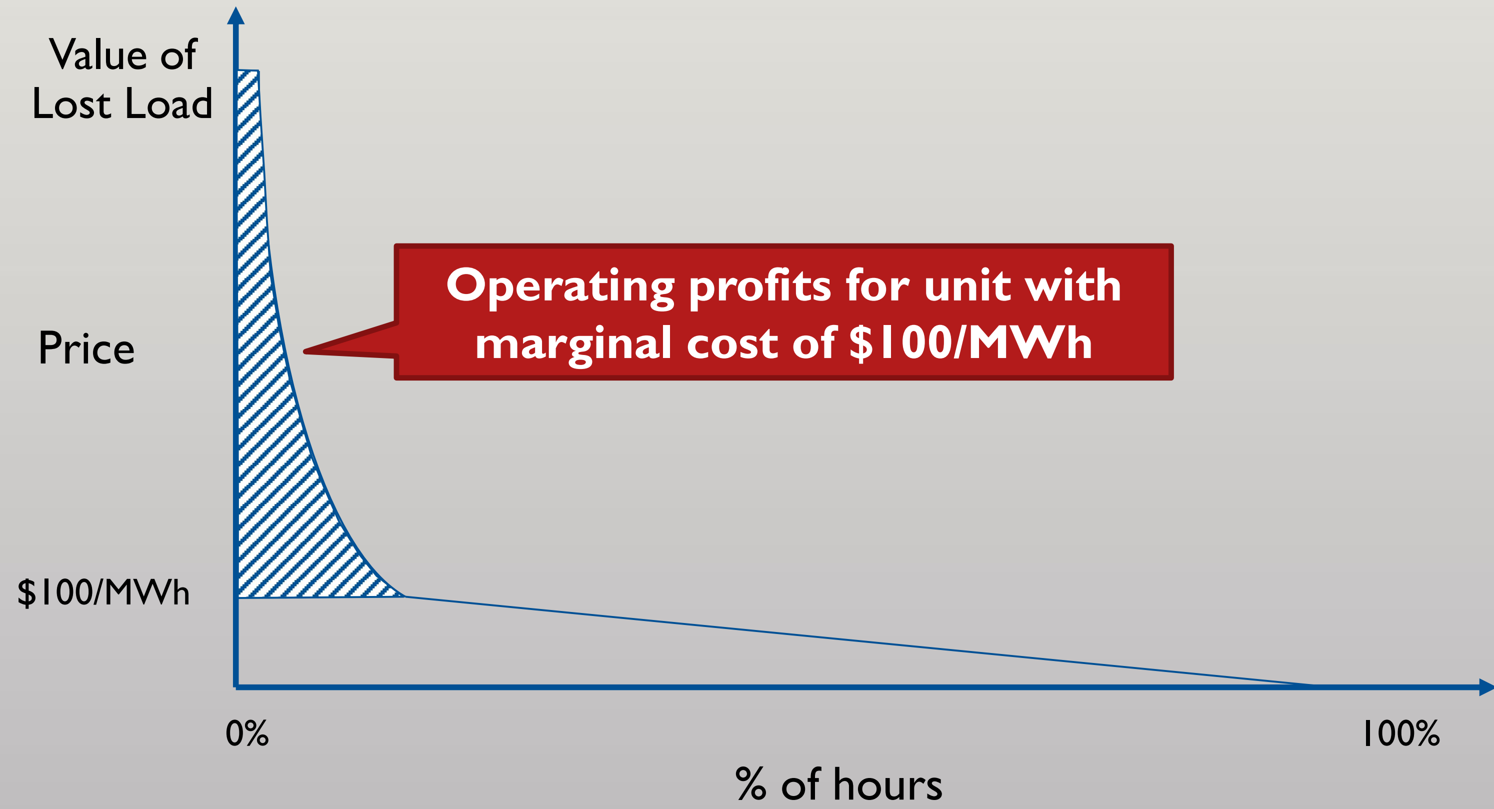
Operating profits

Units earn operating profits when the price goes above their marginal cost of production

Wholesale price duration curve



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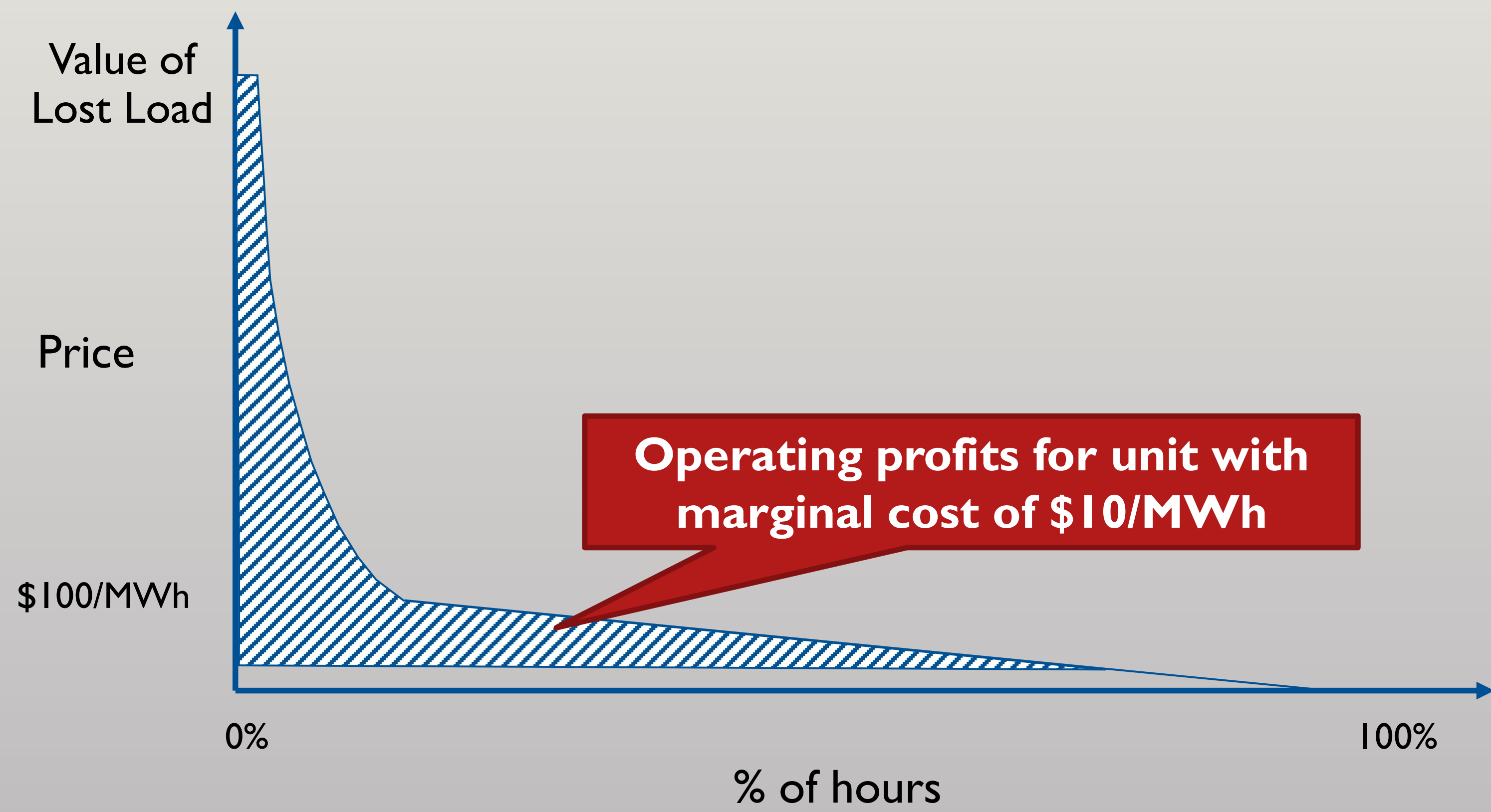

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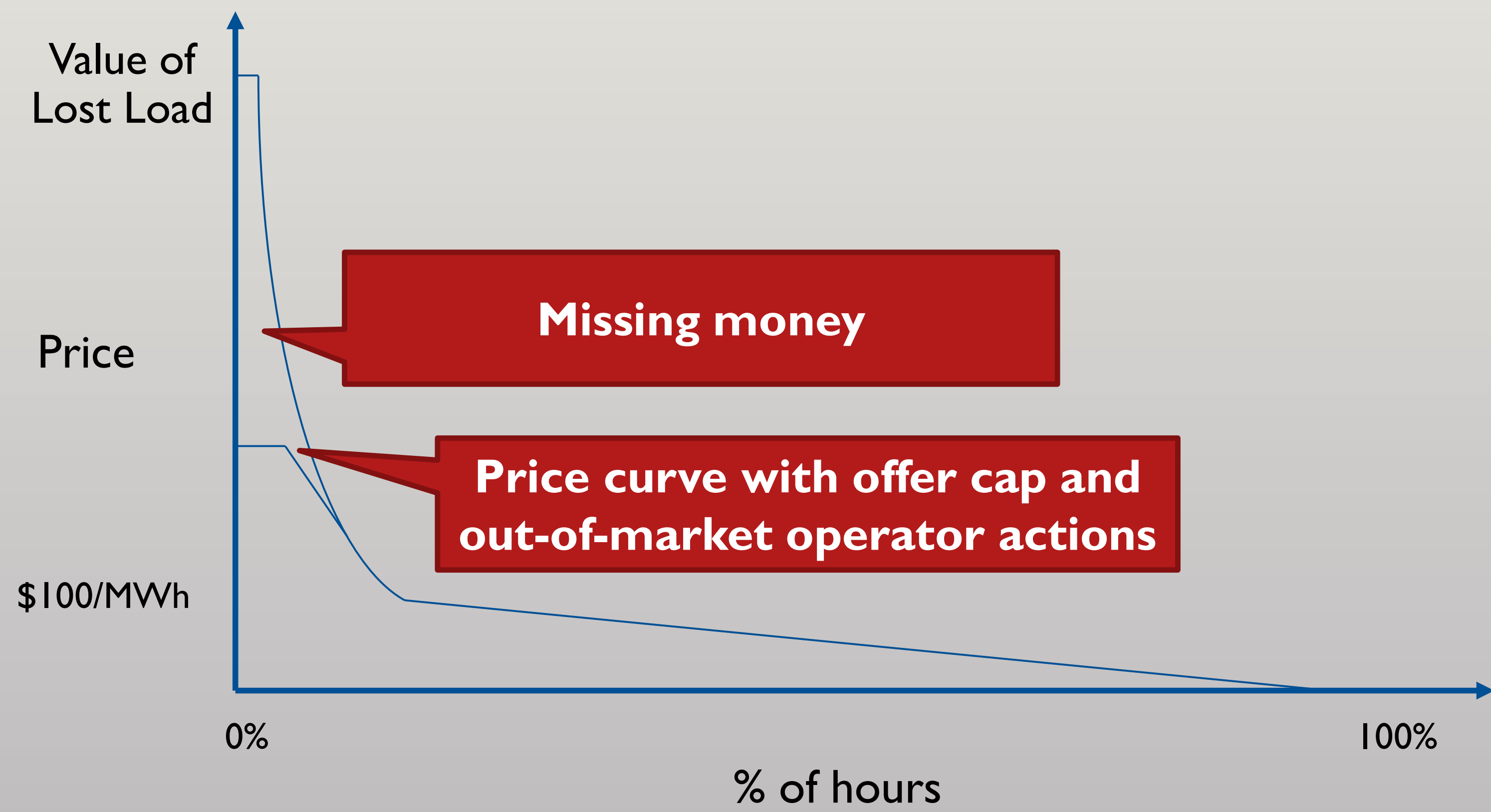
Missing money

Suppression of prices during scarcity is primary driver of the “missing money” problem

Wholesale price duration curve



Capacity payments in theory

- **Idea: pay generators for capacity to solve missing money problem**
- **Goal: on average, recreate the revenue that they would have received in an ideal, energy-only market**
- **Result: a stable revenue stream that replaces volatile scarcity rents**

Intent is to create the same revenues and thus the same capacity mix as an ideal energy-only market

Capacity payments in practice

This talk hopes to convince you of two things:

1. **Current capacity markets may not adequately compensate flexible resources needed to complement wind and solar**

2. Current capacity markets preferentially facilitate financing of high-marginal-cost technologies

What's missing?

1. Missing Money
2. **Missing Incentives**
3. Missing Markets

Capacity expansion

Long-term goal is to find a collection of investments that maximizes value of operating the system minus the upfront cost

$$\max_{x} \quad -\sum_{g \in G} C_g^{inv} x_g + \mathrm{E}[V_1(x;\xi)]$$

Investment cost

Expected surplus from operations given uncertainty

Example system

Suppose we have two technologies available:

Resource	Investment Cost ($/MW)	Energy Cost ($/MWh)	Ramp Capability (MW/MW)
Fast	80	25	0.6
Slow	40	30	0.2

Operating period consists of two hour-long periods:

- **Demand $D_1 \sim U(80, 120)$, $D_2 \sim U(50, 150)$**
- **In first hour, system operator can predict decile of demand in second hour**
- **Operator dispatches in first hour given conditional distribution of D_2 and ramping constraints**

Value of lost load = overgeneration penalty = $10k

First operating hour

Problem at time $t = 1$ is to dispatch system given ramping constraints and uncertain demand D_2

$$V_1(x;\xi_1) = \max_{p_1,d_1,o_1} \underbrace{bd_1 - co_1 - \sum_{g\in G} C_g^{EN} p_{g1}}_{\text{Surplus in } t=1} + \underbrace{\mathrm{E}[V_2(x,p_1;\xi_2)|\xi_1]}_{\text{Expected surplus in } t=2}$$

Surplus in $t = 1$

Expected surplus in $t = 2$

$$s.t. \quad d_1 + o_1 - \sum_{g\in G} p_{g1} = 0$$

Power balance

Resource limits

$$\left\{\begin{array}{ll} d_1 \le D_1 & \\ p_{g1} \le x_g & \forall g \in G \\ p_{g1} \ge 0 & \forall g \in G \\ o_1, d_1 \ge 0 & \end{array}\right.$$

Second operating hour

Problem at time $t = 2$ is to dispatch system given ramping constraints and decisions x and p_1

$$V_2(x, p_1; \xi_2) = \max_{p_2, d_2, o_2} \quad bd_2 - co_2 - \sum_{g \in G} C_g^{EN} p_{g2}$$

$$\text{s.t.} \quad d_2 + o_2 - \sum_{g \in G} p_{g2} = 0$$

$$d_2 \le D_2$$

$$p_{g2} \le x_g \qquad \forall g \in G$$

$$p_{g2} - p_{g1} \le r_g x_g \qquad \forall g \in G$$

$$p_{g1} - p_{g2} \le r_g x_g \qquad \forall g \in G$$

$$p_{g2} \ge 0 \qquad \forall g \in G$$

$$o_2, d_2 \ge 0$$

Clearing prices are the duals to power balance constraints

Add ramping constraints dependent on decision at $t = 1$

Optimal capacity mix

Optimal capacity mix for example system:

Resource	Capacity (MW)	Ramp Capability (MW)
Fast	86.3	51.8
Slow	63.4	12.7
Total	149.7	64.5

- **Optimal to shed load whenever demand D_2 exceeds 149.7 or the ramp $D_2 - D_1$ exceeds 64.5**

In idealized system, prices reflect ramping constraints and support optimal mix

Ramp event

- **Optimal mix:**

Resource	Capacity (MW)	Ramp Capability (MW)
Fast	86.3	51.8
Slow	63.4	12.7
Total	149.7	64.5

- **Suppose at $t = 1$ we have demand $D_1 = 80.5$ and we forecast $D_2 \sim U(140, 150)$**
- **Have enough capacity to serve up to 149.7,**
- **Only enough ramp capability to serve up to $80.5 + 64.5 = 145.0$**

➤ **50% chance that we will need to shed load, at a cost of $10,000/MWh**

Pricing outcomes

Efficient prices include the possibility of power balance violation at time $t = 2$

Period	Demand (MW)	Fast Gen Output (MW)	Slow Gen Output (MW)	Price ($/MWh)
1	$D_t = 80.5$	34.5	46.0	$-4{,}955$
2	$D_t < 145.0$	86.3	$D_2 - 86.3$	30
	$D_t \geq 145.0$	86.3	58.7	$10{,}000$

Average price of $30/MWh across both periods and all realizations of D_2

- **Both generators profitable in expectation due to higher output in t_2**

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Profit impacts of price cap and floor

Suppose market has a price floor of -$150/MWh and a cap of $1,000/MWh

Expected profit per unit capacity

Tech	Without Cap and Floor	With Cap and Floor	Missing Money
Fast	$\$3008/MW$	$\$430/MW$	$\$2{,}578/MW$
Slow	$\$1019/MW$	$\$340/MW$	$\$679/MW$

- **Making up the Missing Money with a uniform payment will either overcompensate the Slow resource or undercompensate the Fast one**

Claim 1

This talk hopes to convince you of two things:

1. **Current capacity markets may not adequately compensate flexible resources needed to complement wind and solar**

2. Current capacity markets preferentially facilitate financing of high-marginal-cost technologies

Uniform capacity payments contribute to this inadequate compensation

What's missing?

1. Missing Money
2. Missing Incentives
3. **Missing Markets**

Missing markets

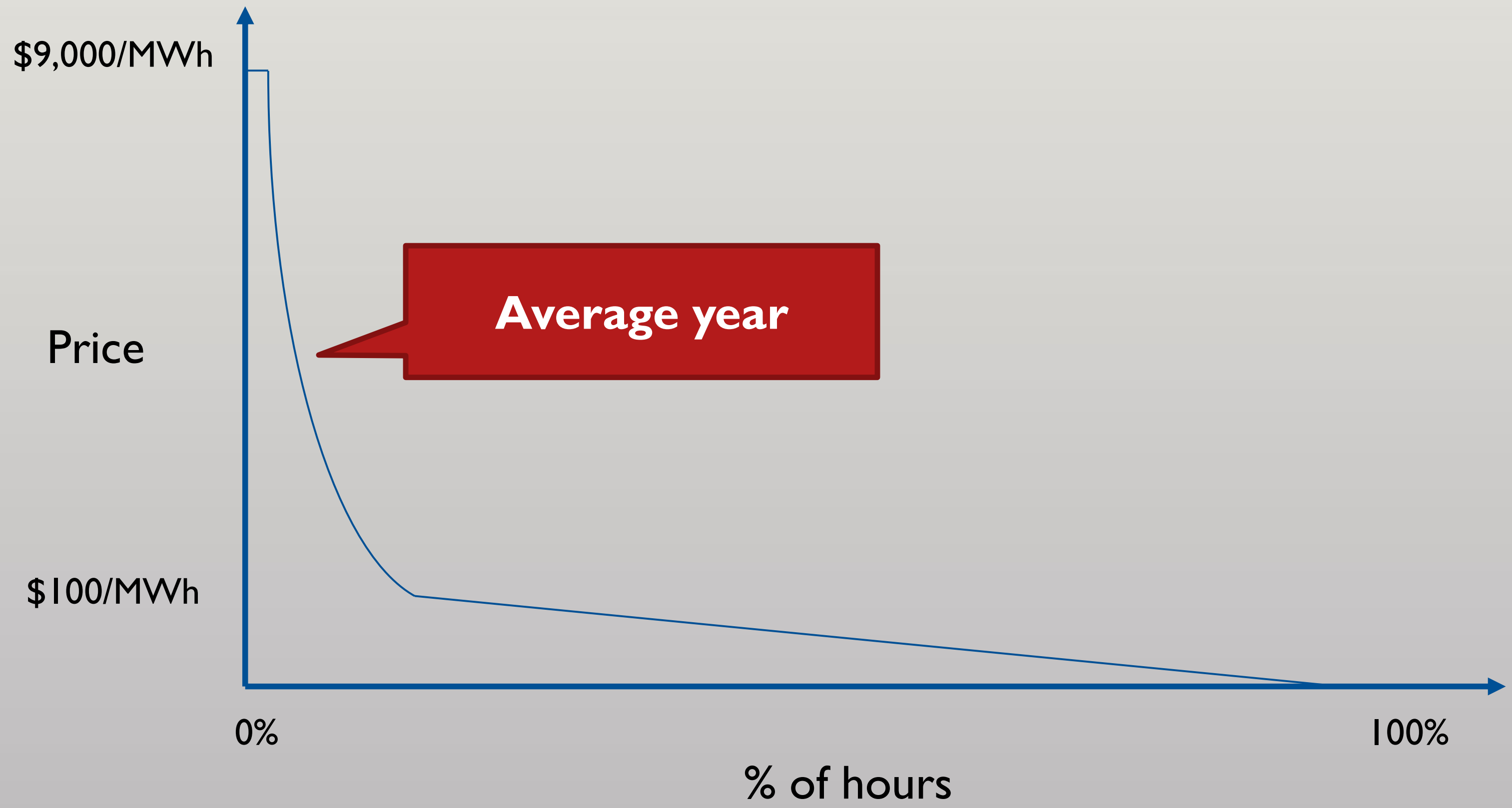
Liberalized electricity systems are generally thought to have insufficient long-term risk sharing

Theory	Practice
• Market participants project future revenues based on consistent market model • Participants trade risk through a variety of mechanisms	• Difficult to project future revenues due to changing market rules and market conditions • Demand side much less willing and able to sign long-term contracts than supply side

Investment risk

Investors in generation look at a range of potential future operating conditions

Wholesale price duration curve



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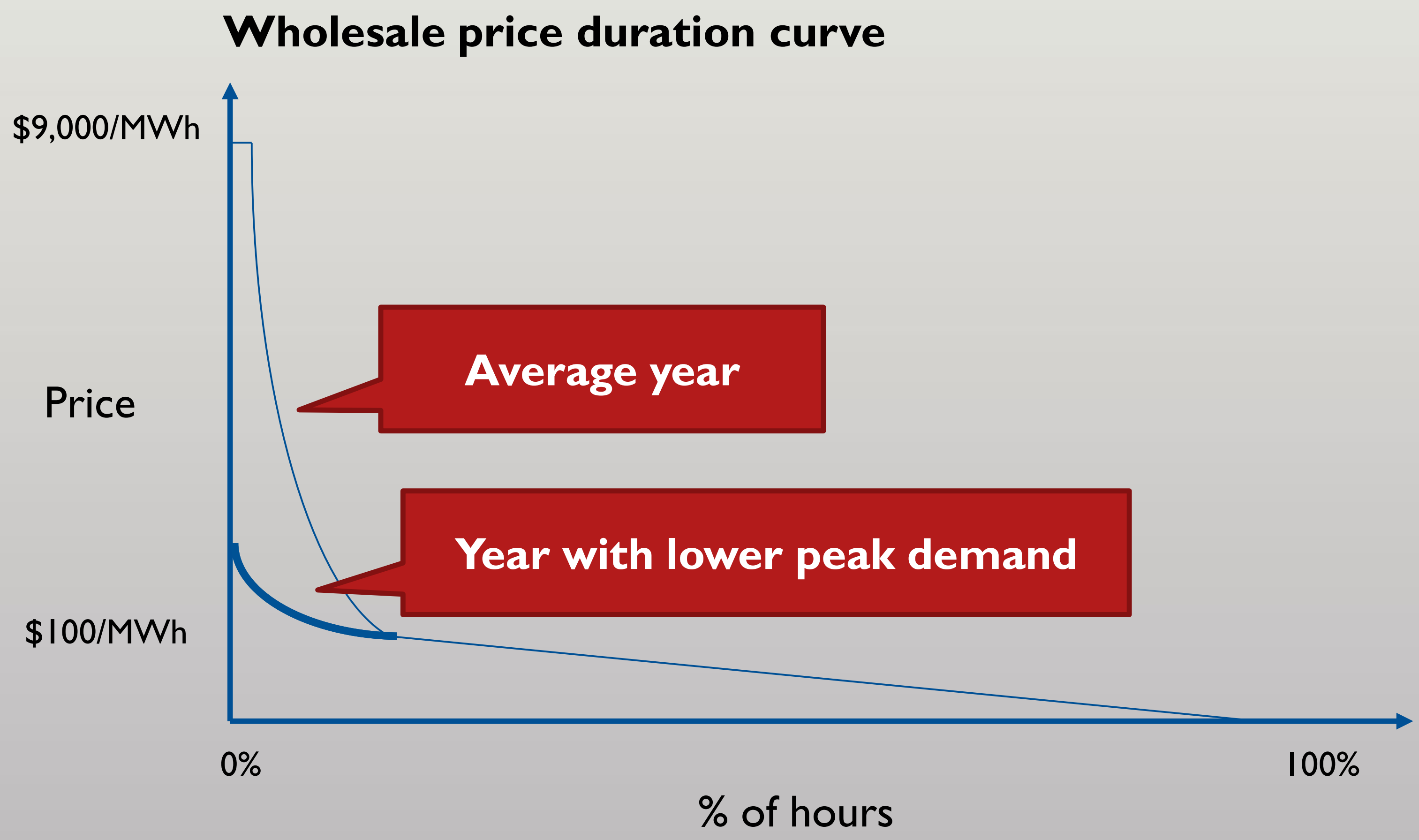

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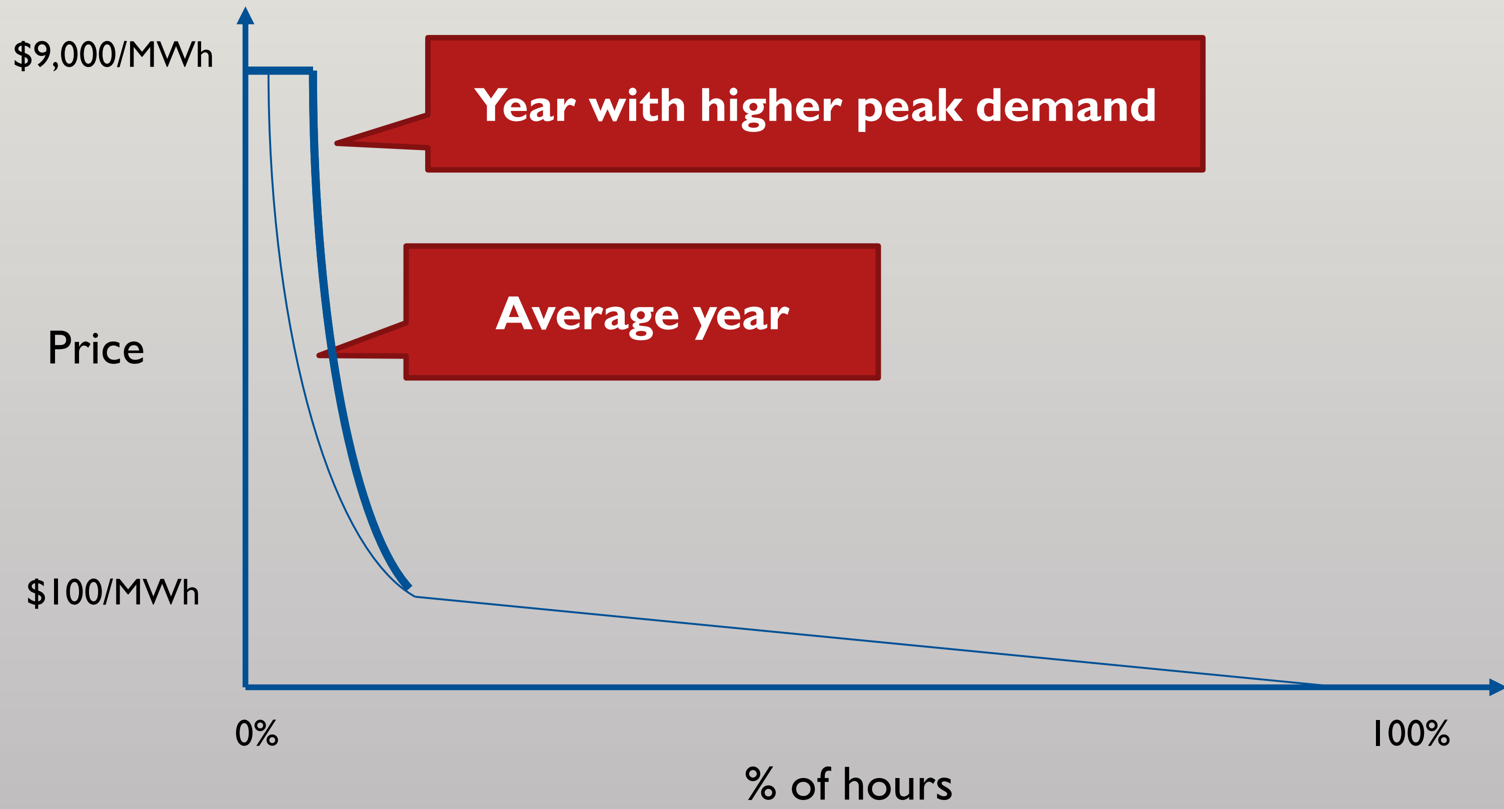

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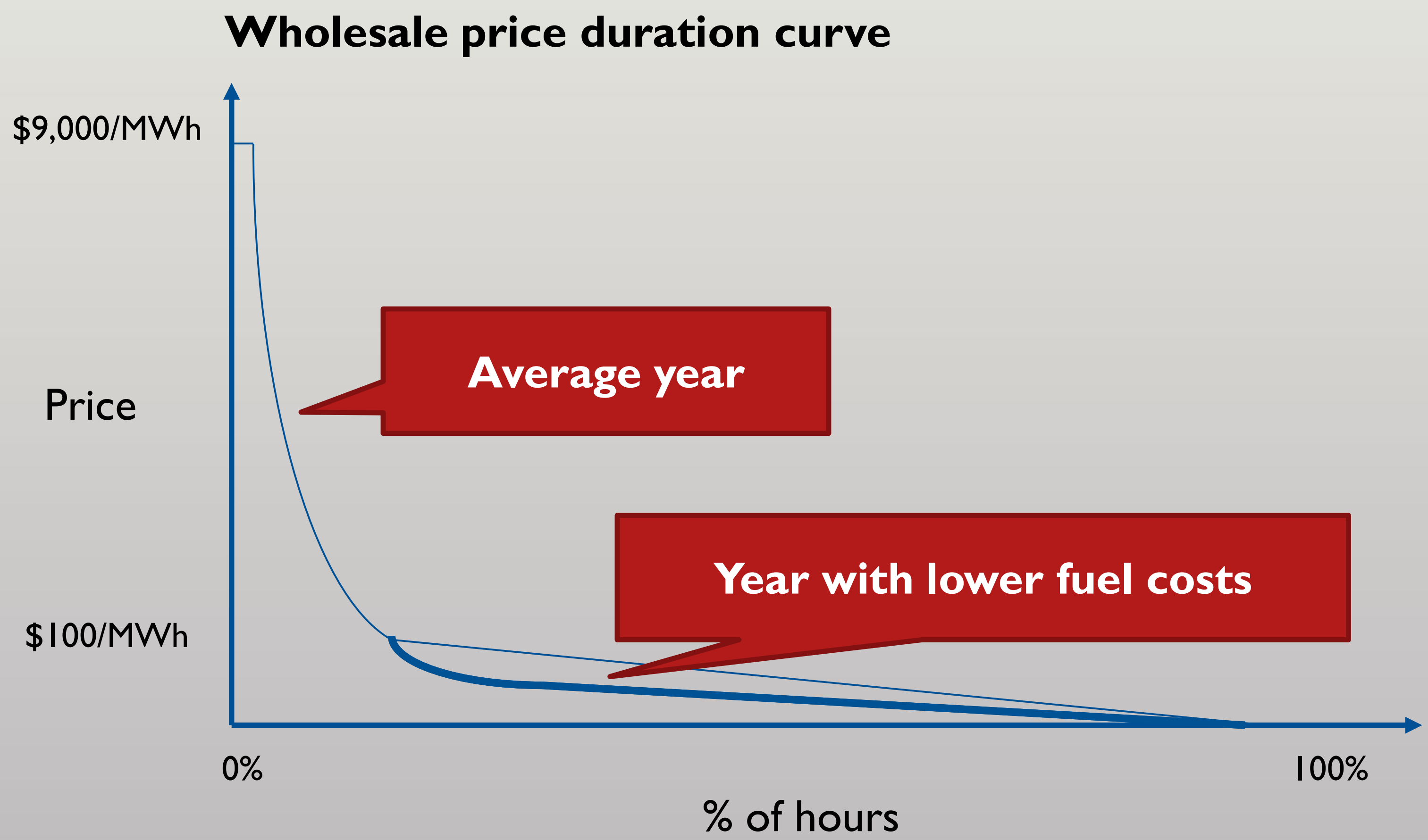

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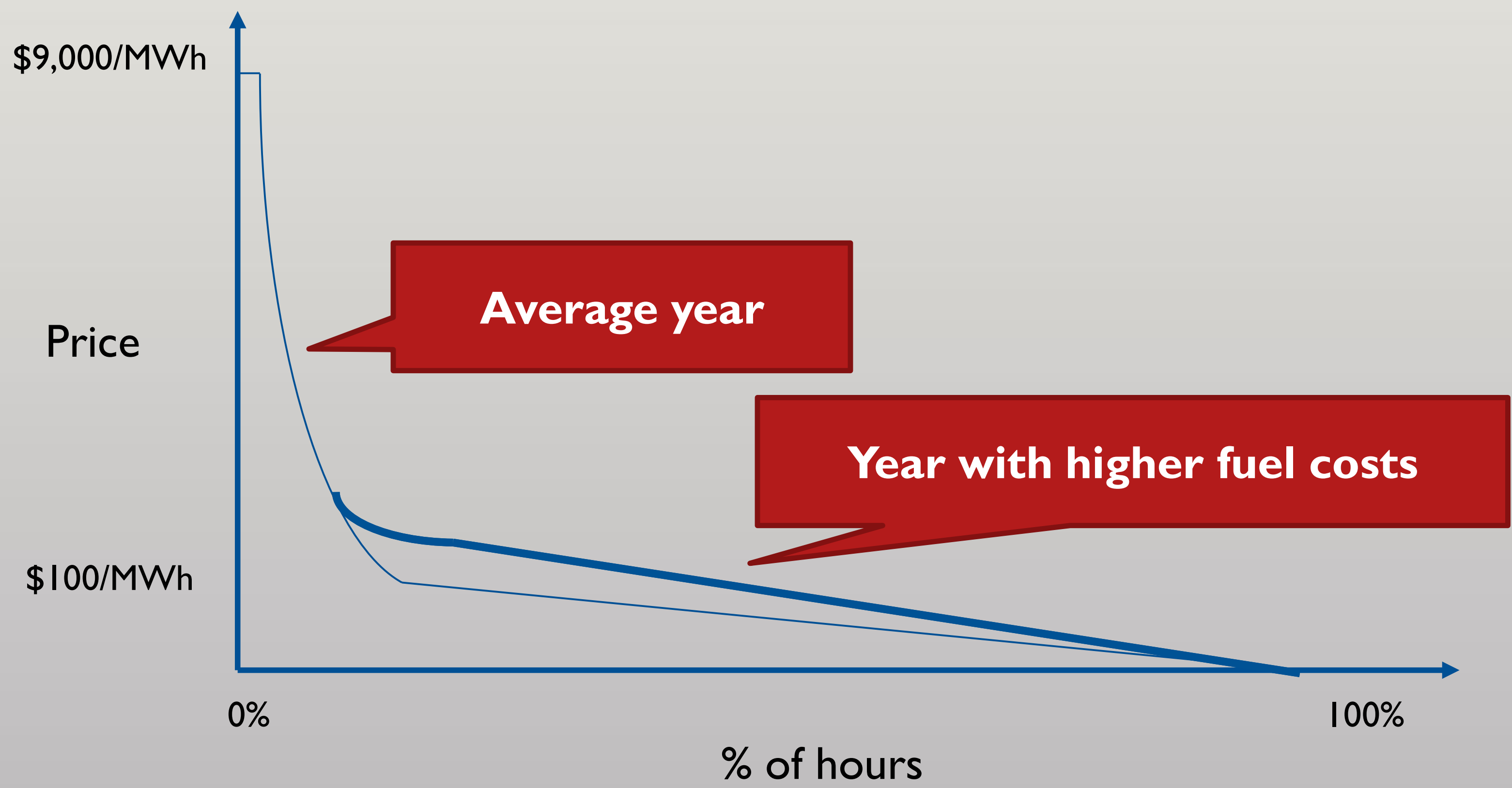

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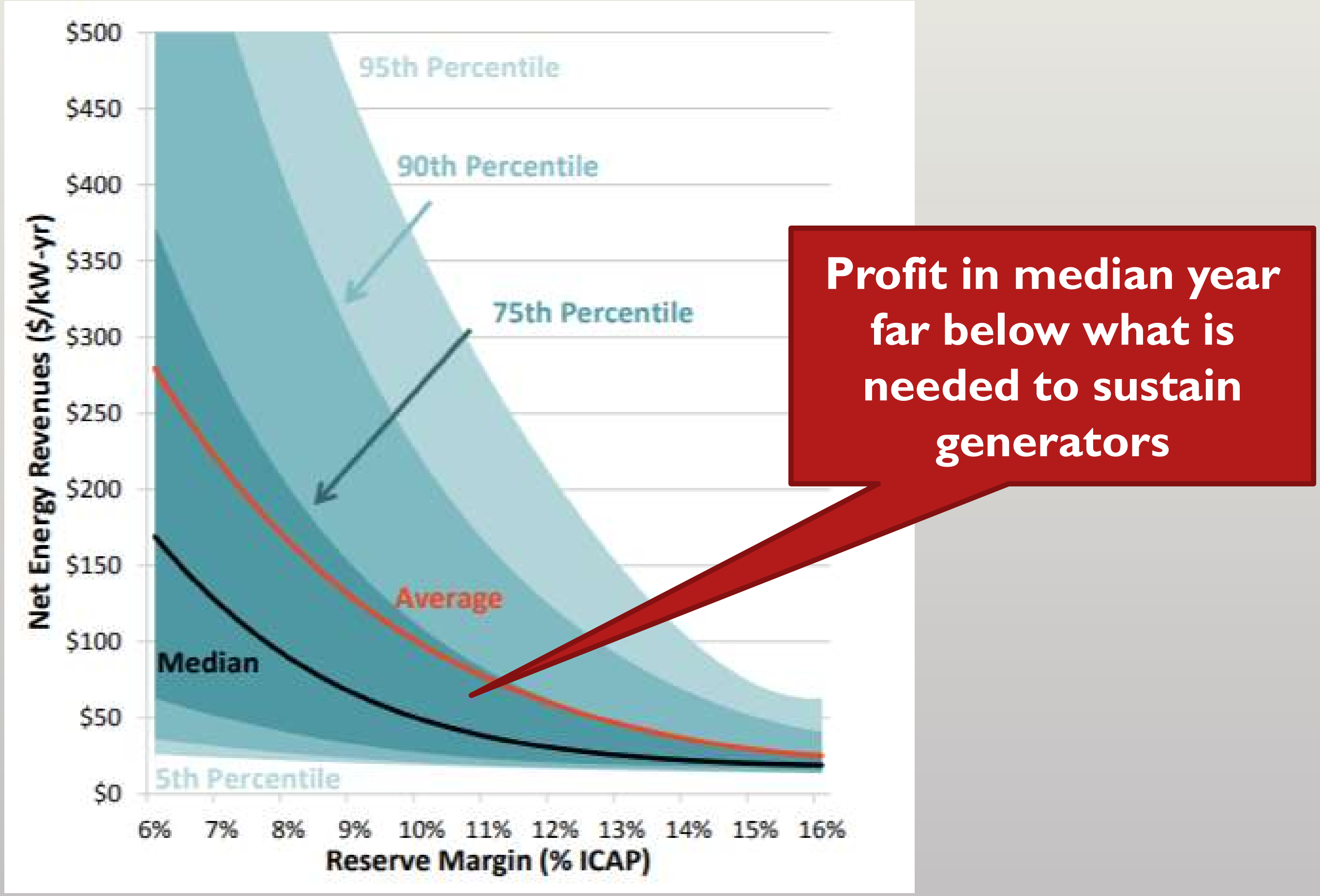
Investment risk

Distribution of operating profits in ERCOT



Source: Estimation of the Market Equilibrium and Economically Optimal Reserve Margins for the ERCOT Region (The Brattle Group)

Risk hedging

Capacity markets play an important role in reducing risk given volatility in fundamental value

> ***"Lenders size at 1.15x revenue from the capacity price … Sometimes we are open to giving credit on a conservative merchant energy revenue forecast. We would probably use a 2.0x to 2.5x debt service coverage ratio.***
>
> ***-Ralph Cho, Investec***

- **Presence of capacity market shifts risk back to customers and partially fills void left by missing markets for long-term risk sharing**

Source: Cost of capital: 2020 Outlook (Norton Rose Fulbright)

Sources of operating profit

The missing money replaced by capacity markets aligns with operating profits for higher-cost units

Split of PJM operating profits between energy and capacity

Marginal Cost	% profits from energy market	% profits from capacity market
$10/MWh	83%	17%
$100/MWh	10%	90%

- **Facilitates financing of high-marginal cost units relative to low-marginal cost units**

Note: Calculation assumes energy sales in the Day-Ahead Market at the PJM pricing node whenever the LMP is above marginal cost and capacity sales in the Base Residual Auction at the RTO-wide clearing price for delivery years 2014/15–2017/18

Claim 2

This talk hopes to convince you of two things:

1. Current capacity markets may not adequately compensate flexible resources needed to complement wind and solar

2. **Current capacity markets preferentially facilitate financing of high-marginal-cost technologies**

Modeling the effect of risk trading

Traditional optimization framework for capacity expansion has exogenous risk embedded in investment cost for each resource

Investment cost annualized according to a weighted average cost of capital

$$\max_{x} \quad -\sum_{g \in G} C_g^{inv} x_g + \sum_{\omega \in \Omega} p^{\omega} H(x; \xi^{\omega})$$

$$\text{s.t.} \quad x \geq 0$$

Risk neutral with respect to a nominal probability distribution describing operating conditions over many years

Equilibrium conditions

- **With exogenous risk, solving social optimization problem gives competitive equilibrium**
- **Equilibrium conditions imply zero expected profit for each installed technology**

$$0 \leq x_g \perp \sum_{\omega \in \Omega} p^{\omega} \pi_g(x; \xi^{\omega}) - C_g^{inv} \geq 0 \qquad \forall g \in G$$

Operating profit for generator in each scenario with the chosen capacity mix

Introducing a capacity market changes the distribution of π_g but does not change the sum

Endogenizing risk

To endogenize risk, replace expected value with an averse risk measure and form equilibrium problem

$$0 \leq x_g \perp \mathcal{R}_g\left(\pi_g(x;\xi)\right) - C_g^{inv} \geq 0 \qquad \forall g \in G$$

Averse risk measure for operating profit of generator

Investment cost annualized at risk-free rate

- **Introducing a capacity market changes the distribution of π_g and therefore the capacity mix**

Equilibrium model sketch

Instead of an optimization problem, we solve an equilibrium problem requiring simultaneous solution of several simple mathematical programs:

- **Dispatch problem for many time periods / scenarios**
- **Generators maximize risk-averse profit**
- **Load optimizes risk-averse consumption**
- **Financial markets clear**
- **Generator entry/exit decisions**

Risk aversion

Risk aversion can push the capacity mix in any direction, depending on:

1. **Which types of risk market participants are most concerned about**
2. **What kinds of hedging mechanisms are available to trade risk between market participants**

We focus on three risks and three trades, corresponding to three archetypal technologies

Risk trades

Risks, risk trades, and corresponding technologies

Technology	Risk	Trade
Baseload	Fuel costs	Forward/future/PPA
Variable	Availability	Unit contingent PPA
Peaker	Demand level	Option

- **With a strike price near typical offer caps, option contract resembles a capacity mechanism**

Equilibrium model sketch

- Two-stage model:
  - Capacity and financial trading decisions made in first stage
  - Many potential operating scenarios in second
- Both entry and dispatch are perfectly competitive
- Investors in generation make entry/exit decisions according to a coherent risk measure on profit
- All market participants share the same nominal distribution of second-stage operating scenarios, but not necessarily the same risk measure

Complete markets

- **"Complete" markets in risk would allow market participants to trade against every possible future scenario**
- **Under this assumption, equilibrium problem can be reformulated as optimization problem**
- **We use the results of this optimization problem to assess impact of incomplete markets**

Numerical example

- **Nominal demand based on PJM in 2017**
- **Technologies:**
  - **Baseload**
  - **Peaker**
  - **Variable**
- **Sources of uncertainty:**
  - **Demand (10 realizations)**
  - **Peaking technology fuel cost (10 realizations)**
  - **Availability of variable tech (4 realizations)**
- **Eight possibilities for trades**
  - **All subsets of futures, options, and unit contingent contracts**

Example results

Equilibrium capacity with zero or one trades

Capacity (GW)	No Trading
Baseload	38.7
Peaker	97.6
Variable	118.1

Example results

Equilibrium capacity with zero or one trades

Capacity (GW)	No Trading	Unit Only
Baseload	38.7	1.9
Peaker	97.6	121.3
Variable	**118.1**	**195.1**

- **Introduction of unit contingent contract shifts resource mix toward variable technology**

Example results

Equilibrium capacity with zero or one trades

Capacity (GW)	No Trading	Unit Only	Option Only
Baseload	38.7	1.9	0.0
Peaker	97.6	121.3	131.0
Variable	118.1	195.1	167.7

- **Introduction of capacity mechanism forces baseload technology out of the system**

Example results

Equilibrium capacity with zero or one trades

Capacity (GW)	No Trading	Unit Only	Option Only	Future Only
Baseload	**38.7**	1.9	0.0	**70.9**
Peaker	97.6	121.3	131.0	79.9
Variable	118.1	195.1	167.7	48.9

- **Introduction of future pushes mix toward baseload technology**

Example results

Equilibrium capacity with zero or one trades

Capacity (GW)	No Trading	Unit Only	Option Only	Future Only
Baseload	38.7	1.9	0.0	70.9
Peaker	97.6	121.3	131.0	79.9
Variable	118.1	195.1	167.7	48.9

Welfare relative to social optimum (complete trading)

$/yr	-$17.6B	-$13.1B	-$6.0B	-$3.6B

Example results

Equilibrium capacity with two or three trades

Capacity (GW)	All Contracts
Baseload	42.5
Peaker	96.6
Variable	120.4

Example results

Equilibrium capacity with two or three trades

Capacity (GW)	Future + Unit	All Contracts
Baseload	70.9	42.5
Peaker	79.9	96.6
Variable	48.9	120.4

- **Removing option contract pushes mix away from peaking technology**

Example results

Equilibrium capacity with two or three trades

Capacity (GW)	Future + Unit	Option + Unit
Baseload	70.9	0.0
Peaker	79.9	126.9
Variable	48.9	195.7

All Contracts
42.5
96.6
120.4

- **Removing futures contract pushes mix away from baseload technology**

Example results

Equilibrium capacity with two or three trades

Capacity (GW)	Future + Unit	Option + Unit	Option + Future	All Contracts
Baseload	70.9	0.0	68.2	42.5
Peaker	79.9	126.9	81.3	96.6
Variable	48.9	195.7	**56.8**	**120.4**

- **Removing unit contingent contract pushes mix away from variable technology**

Example results

Equilibrium capacity with two or three trades

Capacity (GW)	Future + Unit	Option + Unit	Option + Future	All Contracts
Baseload	70.9	0.0	68.2	42.5
Peaker	79.9	126.9	81.3	96.6
Variable	48.9	195.7	56.8	120.4

Welfare relative to social optimum (complete trading)

$/yr	-$3.6B	-$1.0B	-$0.9B	-$0.6B

- **Best results are achieved with all trades available**

Preferred trades

When all trades are available, technologies prefer to trade the contract best adapted to its risk profile

Trade Volume (GW)

	Future	Option	Unit
Baseload	38.5	1.5	0.0
Peaker	0.9	96.7	0.0
Variable	12.8	0.0	91.8

Claim 2

This talk hopes to convince you of two things:

1. Current capacity markets may not adequately compensate flexible resources needed to complement wind and solar

2. **Current capacity markets preferentially facilitate financing of high-marginal-cost technologies**

- **Capacity payments are particularly well suited to the risk profile of these resources**

Can today's markets support a transition?

greentechmedia:

How Wind and Solar Will Blow Up Power Markets

According to Ben Paulos, in the long run, the main zero-carbon energy sources are not compatible with conventional market design.

- **Need reforms to both short-term price formation and long-term resource adequacy mechanisms to facilitate efficient adoption of new technologies**

Additional reading

Mays, J., Missing incentives for flexibility in wholesale electricity markets, Energy Policy (in press).
https://doi.org/10.1016/j.enpol.2020.112010

Mays, J., Morton, D.P. & O'Neill, R.P. Asymmetric risk and fuel neutrality in electricity capacity markets. Nature Energy 4, 948–956 (2019).
https://doi.org/10.1038/s41560-019-0476-1