Can We Get Market and Regulatory Designs 'Right' for Energy Storage?

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Outline

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What is Energy Storage?

Thermal

- Ice storage
- Phase-change materials
- Molten salts

Chemical

- Hydrogen
- Supercapacitors
- Batteries

Mechanical

- Pumped hydroelectric storage
- Compressed-air energy storage
- Flywheels
- Superconducting magnetic energy storage

Demand Response

- Building thermal mass
- Electric-vehicle charging or other flexible loads

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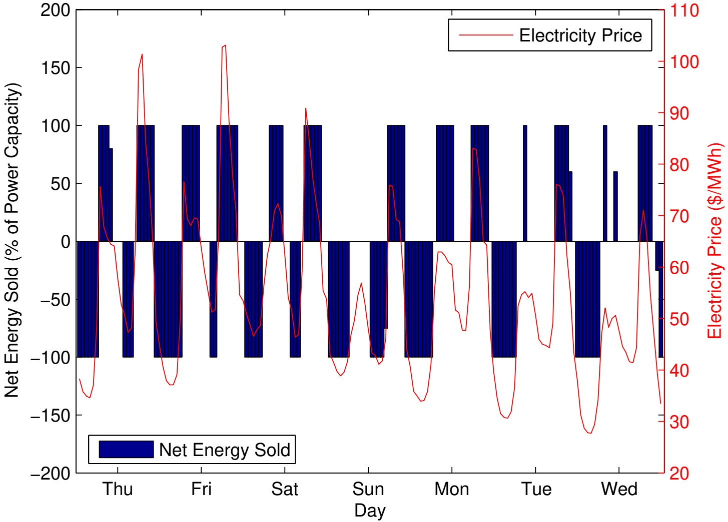
What Can We Do With Energy Storage?

1. Energy arbitrage/shifting
2. Capacity deferral
   1. Generation
   2. Transmission
   3. Distribution
3. Ancillary services
4. End-user applications
   1. Tariff management
   2. Power quality
   3. Backup energy

Energy Arbitrage/Shifting



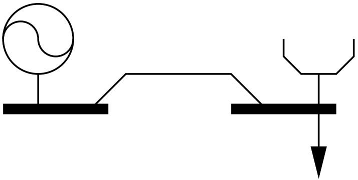
[Sioshansi et al., 2009]

Capacity Deferral

Generation-Capacity Deferral

- Charge during low-load hours
- Discharge during high-load hours

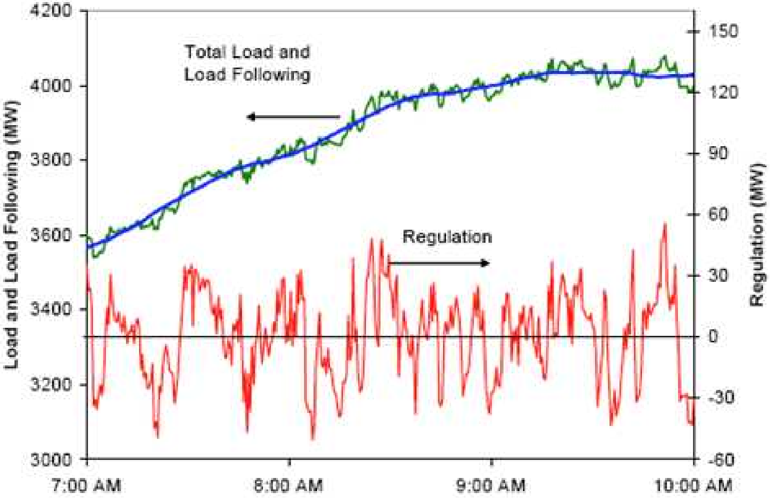
Transmission and Distribution Deferral



Transmission/Distribution System with Storage

- Site storage on the constrained end of a line
- Store energy when line is loaded lightly
- Discharge when line is constrained

Ancillary Services



[Kirby, 2004]

End-User Applications

Tariff Management

- Time-variant pricing
- Demand charges

Power Quality and Backup Energy

- Improve power quality (*e.g.*, voltage, frequency, harmonics)
- Backup during a service disruption

Value Stacking

	Operating Profits [cents/week]			
Case	Arbitrage	Regulation	Avoided Load Curtailment	Total
Arbitrage	42.84			42.84
Outage	41.61		4.62	46.23
Distribution Deferral	34.31		144.48	178.79
Frequency Regulation	39.07	296.04		335.11

Table : Illustrative case studies [Xi et al., 2014, Xi and Sioshansi, 2016]

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Hybrid Market Designs

Market-Priced Services

- Energy
- Ancillary services
- Generation capacity

Regulated Services

- Transmission capacity
- Distribution capacity
- Power quality
- Service reliability

Different Regulatory Treatments of Assets

- Energy is priced in the market $\Longrightarrow$ generators recover costs through wholesale prices
- Distribution and transmission are regulated $\Longrightarrow$ recover costs through the ratebase
- Assets are barred from crossing these lines, for important market-design reasons

What Can We Do With Energy Storage?

1. Energy arbitrage/shifting $\Longleftarrow$ market-priced
2. Capacity deferral
   1. Generation $\Longleftarrow$ market-priced
   2. Transmission $\Longleftarrow$ market-priced/regulated
   3. Distribution $\Longleftarrow$ regulated
3. Ancillary services $\Longleftarrow$ market-priced/regulated
4. End-user applications
   1. Tariff management $\Longleftarrow$ market-priced
   2. Power quality $\Longleftarrow$ regulated
   3. Backup energy $\Longleftarrow$ regulated

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Value Stacking

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Would This Be Legal?

	Operating Profits [cents/week]			
Case	Arbitrage	Regulation	Avoided Load Curtailment	Total
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- Leave $\approx$ 20% of potential value on the table?

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Demonstrative Example: Texas

- Oncor (a T&D utility) proposed building 5 GW of distributed batteries in its Texas service territory
- State law bars T&D utilities from owning assets that participate in the wholesale market, which is good from a market-design perspective [Sioshansi, 2010]
- The impasse:
  - The batteries are not worth the investment cost on the basis of regulated distribution-deferral and voltage-support benefits *only*
  - They would be economically prudent if they could participate also in the wholesale energy and frequency-reserve markets [Chang et al., 2014]

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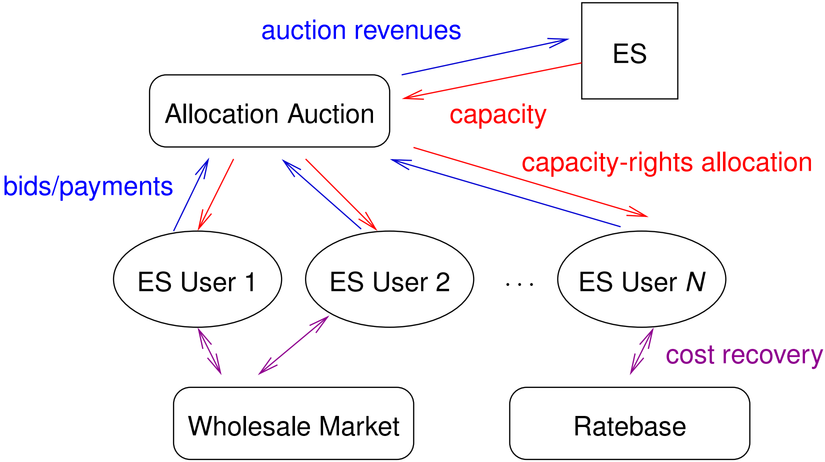
Fundamental Issue

- Mixing market-contingent and unpriced value streams
- Not harm market design through rate-based/customer-subsidized energy-storage assets participating in the wholesale market

Outline

Illustration

[He et al., 2011, Sioshansi, 2017]



Concept

1. Storage owner auctions storage-capacity rights to third parties wanting to use storage
2. Cost recovery of storage-capacity rights by third parties based on their intended use, *e.g.*:
   - Wind generator buys rights to shift wind production to a higher-priced period, cost recovered through wholesale transactions
   - T&D utility buys rights for service reliability, cost recovered through ratebase
3. Different third parties compete for rights for different purposes, thus the full asset value can be captured

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Defining Storage-Capacity Rights

- To a first-order approximation (*e.g.*, neglecting degradation and nonlinearities), storage use has two governing constraints
  1. power
  2. energy
- Depending on intended use, power and/or energy constraints are impacted, *e.g.*:
  - Wind Generator
    - buys rights to shift wind production to a higher-priced period
    - cares only about charging/discharging power at specific times
    - not what happens to the energy during the intervening periods
  - T&D Utility
    - buys rights for service reliability
    - wants to charge/discharge power at certain times
    - cares that the energy is available during the intervening periods

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Illustrative Storage-Capacity Rights

- Power-Capacity Right: Entitles the holder to inject energy into or withdraw energy from storage at a given point in time
- Energy-Capacity Right: Entitles the holder to inject energy into and withdraw energy from storage at given points in time *and* keep the energy in storage during the intervening time

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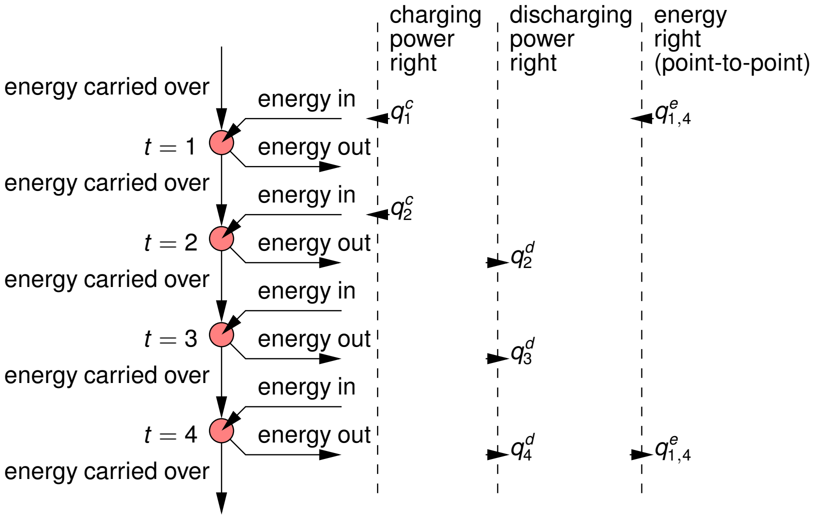
Illustration of Storage-Capacity Rights



Auction Model

- Key: Simultaneous feasibility (*e.g.*, allocating 15 MW of storage capacity among wind generator and T&D utility wanting to use 10 MW each)

$$\max_{q,s} \sum_{t=1}^{T} \sum_{n \in N_t} (\pi^d_{t,n} q^d_{t,n} - \pi^c_{t,n} q^c_{t,n}) + \sum_{t=1}^{T} \sum_{t'=t+1}^{T} \sum_{m \in M_{t,t'}} \pi^e_{t,t',m} q^e_{t,t',m}$$

$$\text{s.t. } s_t = \eta^s s_{t-1} + \sum_{n \in N_t} (\eta^c q^c_{t,n} - q^d_{t,n}) + \sum_{t'=t+1}^{T} \sum_{m \in M_{t,t'}} \eta^c q^e_{t,t',m} - \sum_{t'=1}^{t-1} \sum_{m \in M_{t',t}} q^e_{t',t,m} \quad \forall t \quad (\lambda_t)$$

$$\sum_{t'=1}^{t} \sum_{t''=t+1}^{T} \sum_{m \in M_{t',t''}} q^e_{t',t'',m} \le s_t \le H \cdot \bar{R} \quad \forall t \quad (\sigma^-_t, \sigma^+_t)$$

$$-\bar{R} \le \sum_{n \in N_t} (\eta^c q^c_{t,n} - q^d_{t,n}) + \sum_{t'=t+1}^{T} \sum_{m \in M_{t,t'}} \eta^c q^e_{t,t',m} - \sum_{t'=1}^{t-1} \sum_{m \in M_{t',t}} q^e_{t',t,m} \le \bar{R} \quad \forall t \quad (\gamma^-_t, \gamma^+_t)$$

$$0 \le q^c_{t,n} \le Q^c_{t,n} \quad \forall t, n$$

$$0 \le q^d_{t,n} \le Q^d_{t,n} \quad \forall t, n$$

$$0 \le q^e_{t,t',m} \le Q^e_{t,t',m} \quad \forall t, t' > t, m$$

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Pricing Rules

- Lagrange multipliers associated with power limits for power-capacity rights
- Lagrange multipliers associated with power and energy limits for energy-capacity rights
- Analogue to locational marginal pricing, except we're paying to move energy around in time, not space

Detailed Pricing Rules

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Auction Properties

Proposition

The allocation and prices are equilibrium-supporting.

Proposition

The storage-device owner earns non-negative revenues from the allocation of storage-capacity rights. Moreover, the net revenues earned by the storage-device owner equals its imputed marginal value.

Implementation Details

- Who runs the auction?
- Timing of the auction/long-term contracting
- Imperfect competition?

Outline

To Conclude

- Energy storage breaks the traditional classification of assets from the perspective of regulation and cost recovery
- This has hampered storage investment or has/will give rise to price distortions, especially with distributed energy storage
- Storage-capacity rights can overcome this cost-recovery hurdle

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Thank you!

Appendix

Pricing Rule

Hour-t power-capacity charging rights priced at:

$$-\eta^c \lambda_t - \eta^c \cdot (\gamma_t^- - \gamma_t^+)$$

Hour-t power-capacity discharging rights priced at:

$$-\lambda_t - (\gamma_t^- - \gamma_t^+)$$

Energy-capacity rights consisting of an hour-t injection and hour-t' withdrawal priced at:

$$\eta^c \lambda_t - \lambda_{t'} - \sum_{\tau=t}^{t'-1} \sigma_\tau^- + \eta^c \cdot (\gamma_t^- - \gamma_t^+) - (\gamma_{t'}^- - \gamma_{t'}^+)$$

Pricing Overview

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