Arbitrage Strategies for Energy Storage

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Storage: Questions

- Why do we want/need energy storage
  - system services
  - shifting forward in time
- Is energy storage economically viable
  - expected revenue streams
  - risk management
- Are there market design/institutional obstructions
  - market failures
  - fossil vs digital world
Storage: Time Shifts

- Arbitrage
  - buy cheap, sell dear

- Time scale
  - years
  - months
  - week(s)
  - day(s)
  - hour(s)
  - minute(s)
Motivation

- Integrating stored/pumped hydro w/wind
- Integrating batteries w/wind and/or solar
  - reliability
  - risk-management
  - proconsumers
- Batteries are cool — but (almost) useless and a waste of money
Outline

1. Background
2. Arbitrage Strategies
3. Flexibility and Swing Options
4. Conclusion
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Price Variability

- Price variability is the key
- Seasonal/diurnal patterns
- Stochastic component
- Stochastic production
Prices in Oslo and Sweden (2010/17)

Spot Prices in NO and SE

Spot Price (EUR/MWh)

Hour of the week
Prices in Denmark

Distribution of Hourly Spot Prices

Spot Price (EUR/MWh)

Hour

1 3 6 9 12 15 18 21 24
Prices in Denmark (seasonally adjusted)
Arbitrage in Bidding Markets

- Conceptual framework
  - Selling/buying one unit in each period
  - Offering buy/sell bids
- Storage $X_t \in \{0, 1, \ldots, X_{\text{max}}\}$
- Buy bid $0 \leq b_t$
- Sell bid $s_t \leq \bar{p}$.
- Beliefs/expectations about bid distribution $F(p)$
Stochastic Dynamic Programming

\[ V(X_t) = \max_{b_t, s_t} \left( -F_t(b_t) \int_0^{b_t} p dF_t(p) + (1 - F_t(s_t)) \int_{s_t}^{\bar{p}} p dF_t(p) \right) \]

\[ + \beta \left( F_t(b_t) V(X_{t+1}) + (F_t(s_t) - F_t(b_t)) V(X_t) + (1 - F_t(s_t)) V(X_{t-1}) \right) \]  \hspace{1cm} (1)

- Solve numerically (Judd)
  - Infinite time horizon
  - Optimal bidding strategy
  - Value function \( V(X) \)
- Repeated single period
- Repeated sequential 24-hour period
Day-Ahead Market Auction

- Need to bid for each hour simultaneously
- Cannot condition bids sequentially
- How much to bid: $b_{ht}$ and $s_{ht}$
- Which hours to participate $\delta^b_{ht}, \delta^s_{ht} \in \{0, 1\}$

$$V(X_t) = \max_{b_{ht}, s_{ht}, \delta^b_{ht}, \delta^s_{ht}} \sum_h \left(-\delta^b_{ht} F_{ht}(b_{ht}) \int_0^{b_{ht}} p dF_{ht}(p) + \delta^s_{ht} \cdots \right)$$

subject to $\sum_h \delta^s_{ht} \leq X_t$ and $X_t + \sum_h \delta^b_{ht} \leq X_{max}$. 
Feasible Method

- SDP is a feasible method
  - easy for day ahead auction
  - arbitrage across hours/days

- Bid/price distribution
  - forecast (systematic component)
  - bid stack

- Need to select hours
Arbitrage in Denmark

Expected Utilization (6 unit storage)

Hour of the day
Market Design

- Basic version of day-ahead market
  - submit bids before gate closure
  - need excess capacity
  - timing and frequency of closure

- Basic version of intra-day market
  - continuous trading
  - market clearing at specific times

- Real I-SAM design
  - very flexible
  - read the manual (!)
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Increased Flexibility

- Increase demand/supply flexibility
- Buy/sell at the right time
- Swing options for buy/sell units
- Options called by market operator when desired
- Energy storage can offer such options
- The SDP model for pricing such contracts
Trading Exotic Options

- I-SAM and the EUPHEMIA algorithm
  - market clearing and market coupling
  - allows great flexibility in orders

- Complex orders
- Block orders
- Flexible hourly orders
  - sell/buy $x$ units at price $s$
  - flexible wrt which hour
  - allocated to the best period
  - paid market price (not bid price)
Swing Arbitrage in Denmark

Expected Daily Arbitrage Returns)

Year


0 10 20 30 40 50
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Conclusions

- Arbitrage value may justify storage
- SDP modeling of bidding behavior in auction markets
- Market design in place for (commercial) storage
  - arbitrage across days/hours
  - swing options for arbitrage and flexibility
  - gate closure times and frequency
- Detailed case studies next...
Thank you for your attention.

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