Dispatch Auction Designs and Arbitrage Strategies for Energy Storage Units

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Storage: Questions

- Why do we want/need energy storage
  - system services
  - shifting energy forward in time
- Is energy storage economically viable
  - expected revenue streams (arbitrage)
  - risk management
- Are there market design/institutional obstructions
  - market failures
  - fossile vs digital world

Storage: Time Shifts

- Arbitrage
  - buy cheap, sell dear
- Time scale
  - year(s)
  - month(s)
  - 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
- Arbitrage value of storage
- Market auction design and quirks

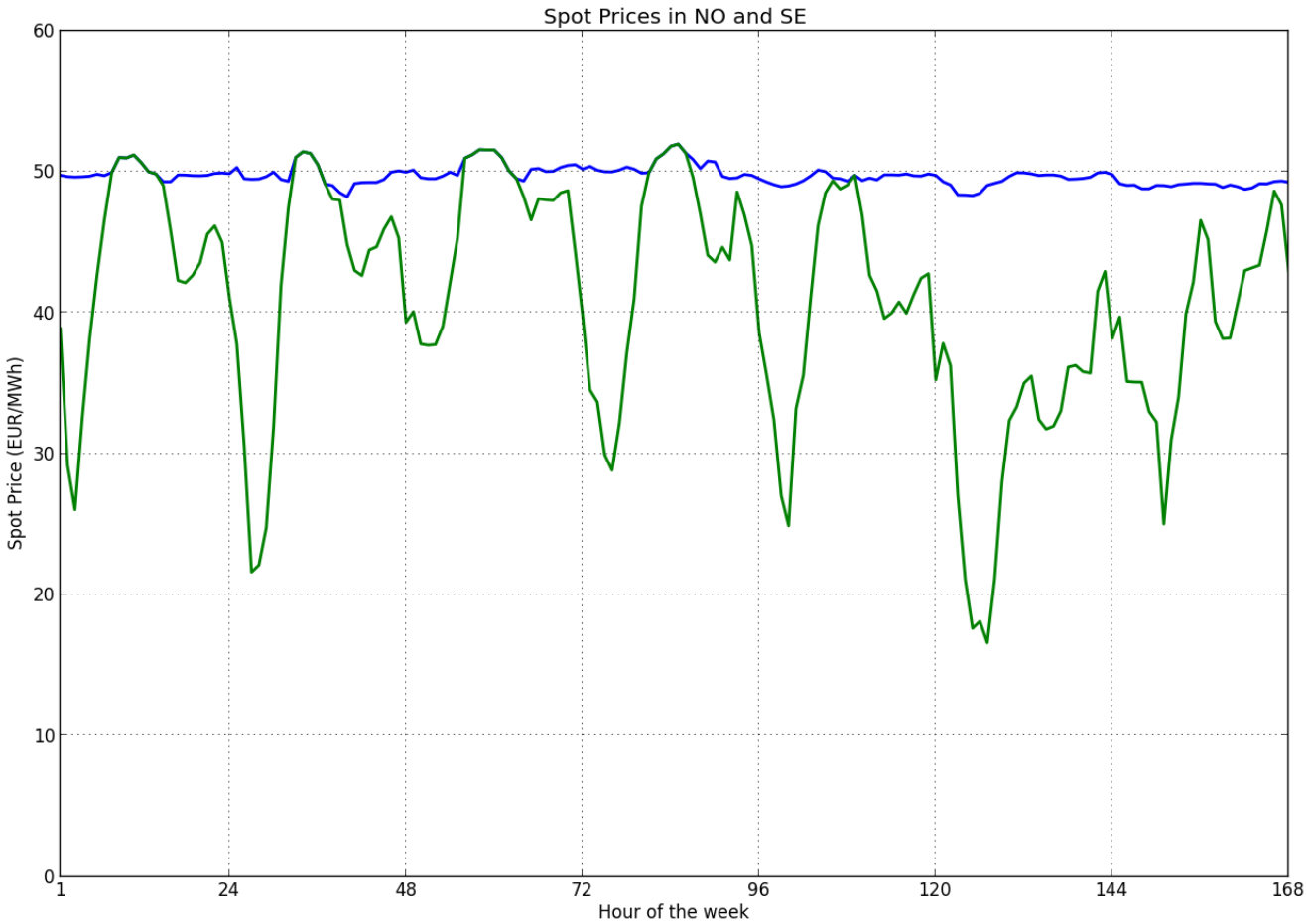
Outline

Outline

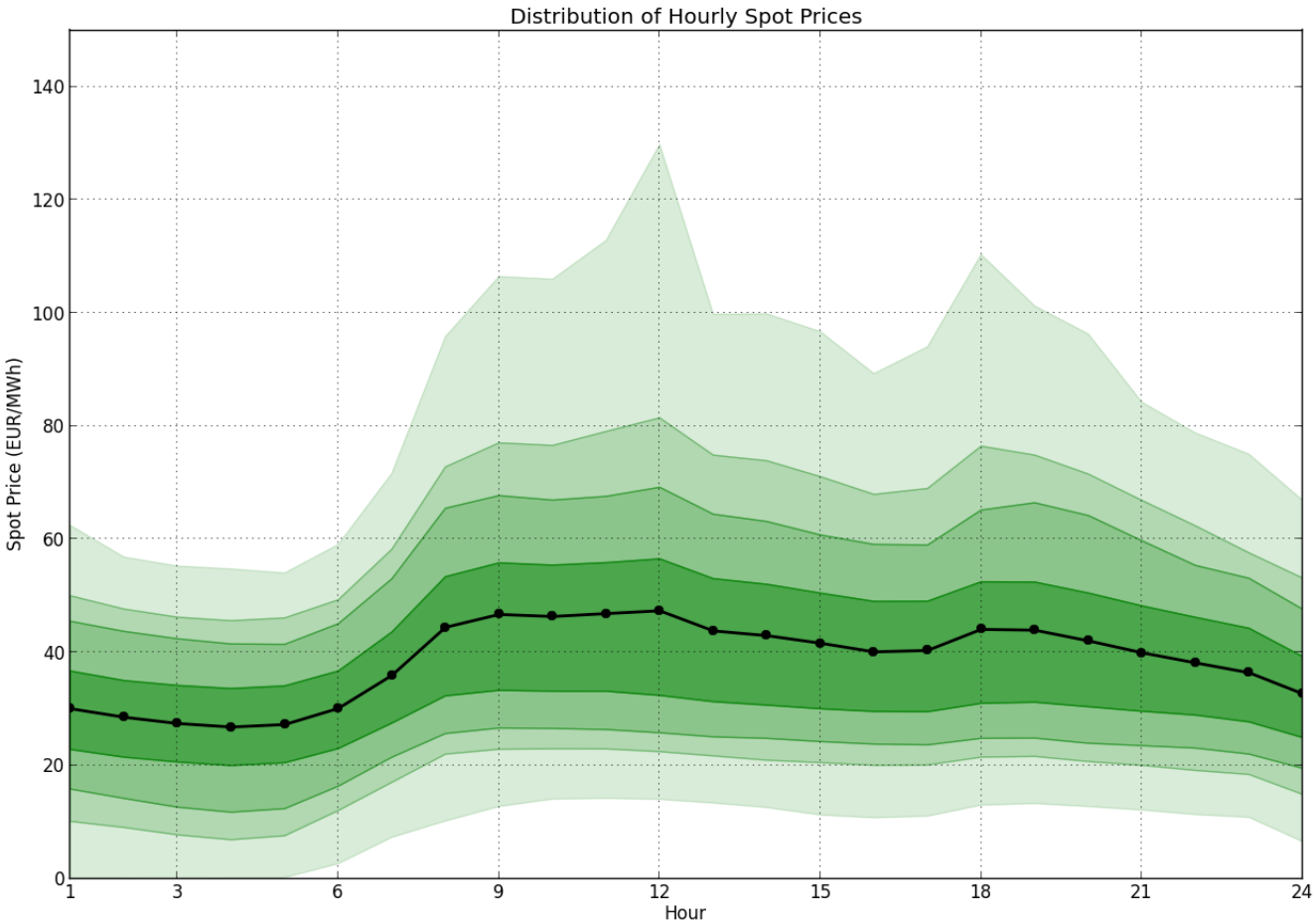
Price Variability

- Price variability is the key
- Seasonal/dinural patterns
- Stochastic component
- Stochastic production

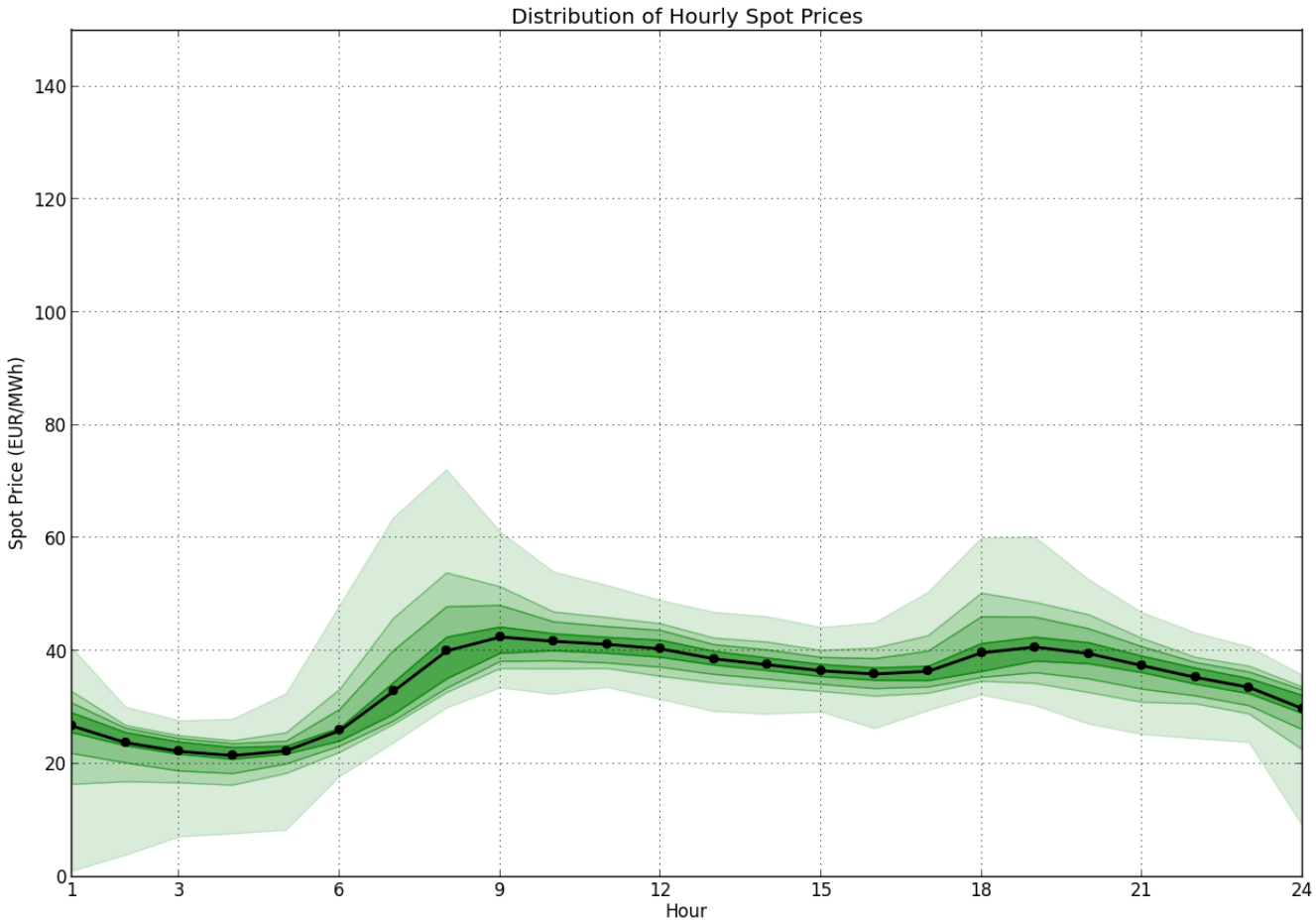
Prices in NO (Oslo) and SE (2010/17)



Prices in Denmark



Prices Seasonally Adjusted



Arbitrage in Bidding Markets

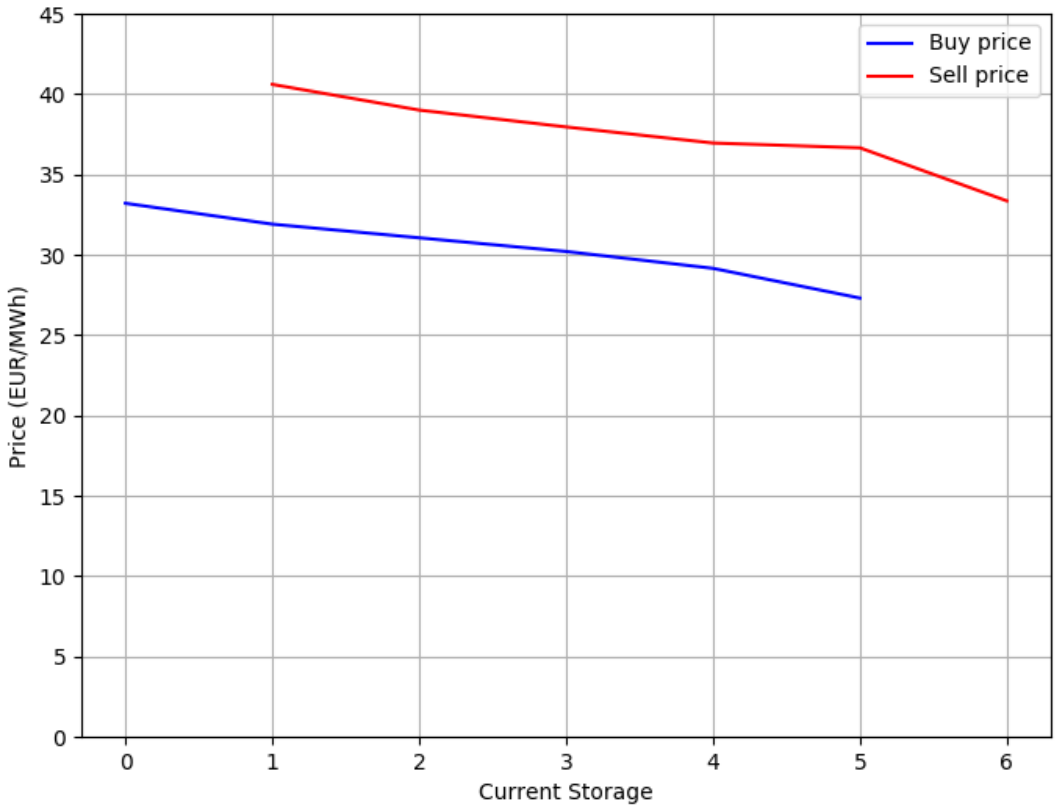
- Conceptual framework
  - Selling/buying one unit in each period
  - Offering buy/sell bids
- Storage $X_t \in \{0, 1, \ldots, X_{max}\}$
- Buy bid $0 \leq b_t$
- Sell bid $s_t \leq \bar{p}$.
- Beliefs/expectations about bid distribution $F(p)$

Stochastic Dynamic Programming

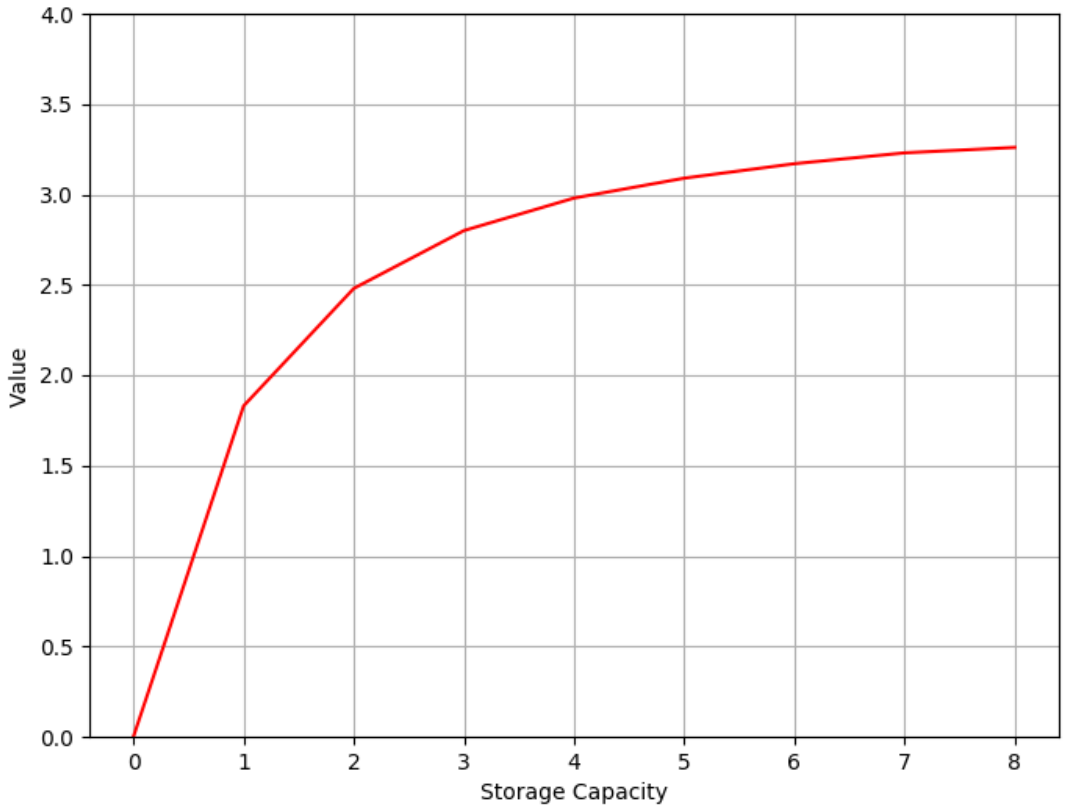
$$V(X_t) = \max_{b_t, s_t} \left(-(1+\gamma_b) F_t(b_t) \int_0^{b_t} p dF_t(p) + (1-\gamma_s)(1-F_t(s_t)) \int_{s_t}^{\bar{p}} p dF_t(p) \right)$$
$$+ \beta \left(F_t(b_t) V(X_t+1) + (F_t(s_t) - F_t(b_t)) V(X_t) + (1-F_t(s_t)) V(X_t-1) \right) \quad (1)$$

- Solve numerically (Judd)
  - Infinite time horizon
  - Optimal bidding strategy
  - Value function $V(X)$
- Repeated single period
- Repeated sequential 24-hour period

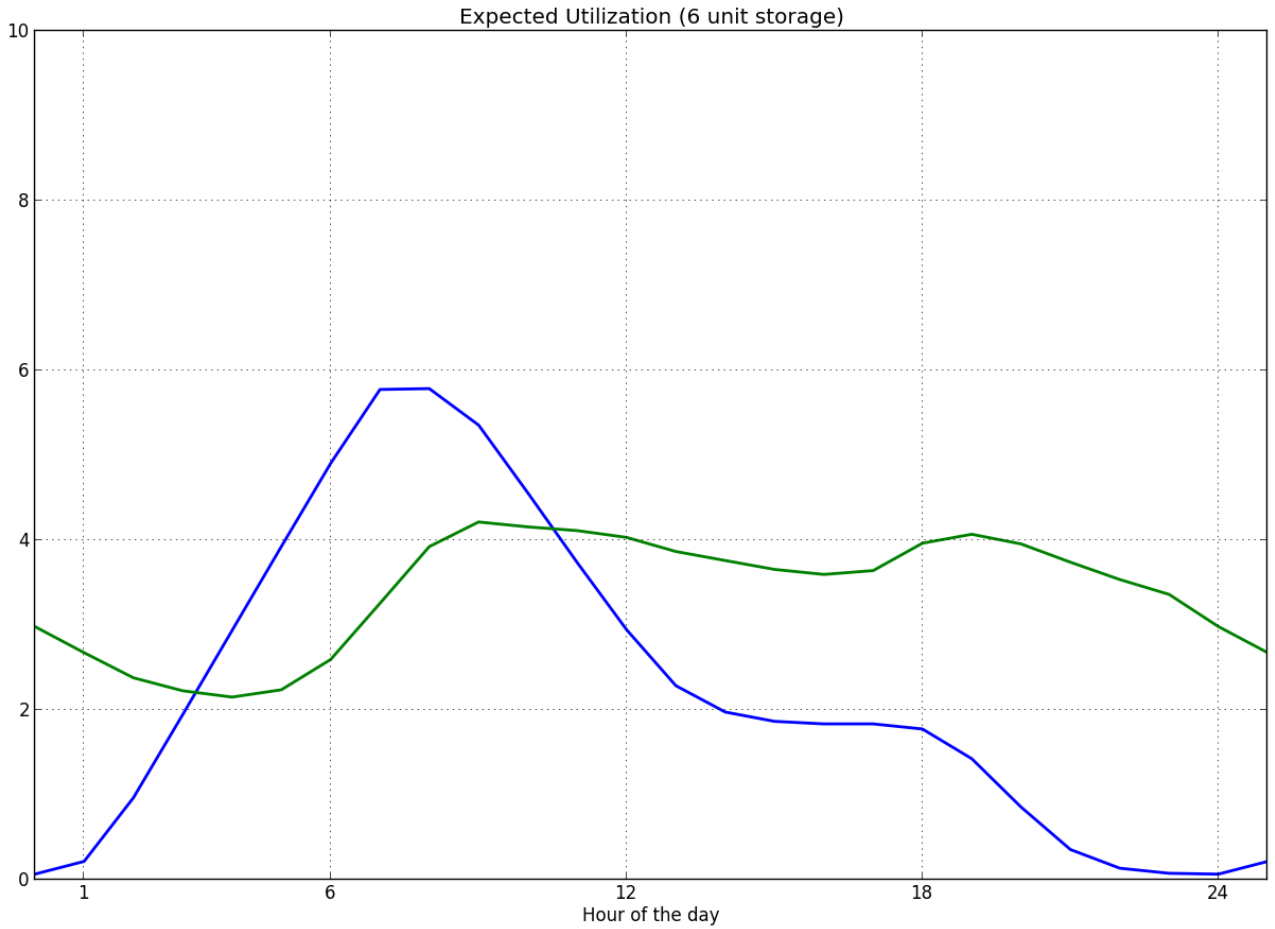
Optimal Bid Strategies



Value of Storage Capacity



Daily Utilization of Storage Denmark



Day-Ahead Market Auction I

- Currently 24 market periods (hours)
- Need to bid for each hour simultaneously
- Cannot condition bids sequentially
- How much to bid: b_{ht} and s_{ht}
- Which hours to participate $\delta^b_{ht}, \delta^b_{ht} \in \{0, 1\}$

Day-Ahead Market Auction II

$$V(X_t) = \max_{b_{ht}, s_{ht}, \delta^b_{ht}, \delta^b_{ht}} \sum_h \left(-\delta^b_{ht}(1+\gamma_b) F_{ht}(b_{ht}) \int_0^{b_{ht}} p dF_{ht}(p) + \delta^s_{ht} \cdots \right) + \beta \cdots$$

subject to

$$\sum_h \delta^s_{ht} \leq X_t$$

and

$$X_t + \sum_h \delta^b_{ht} \leq X_{max}.$$

Evaluating Value of Storage

- SDP is a feasible method
  - easy for intraday auctions
  - day-ahead auction with selected hours
  - arbitrage value across hours/days
- Bid/price distribution
  - parameteric/non-parameteric
  - forecast (systematic component)
- Marginal value
  - applies only to small storage
  - embedd in structural demand/supply model

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
- Forward market
  - arbitrage across multiple days
  - requires functioning forward markets

Outline

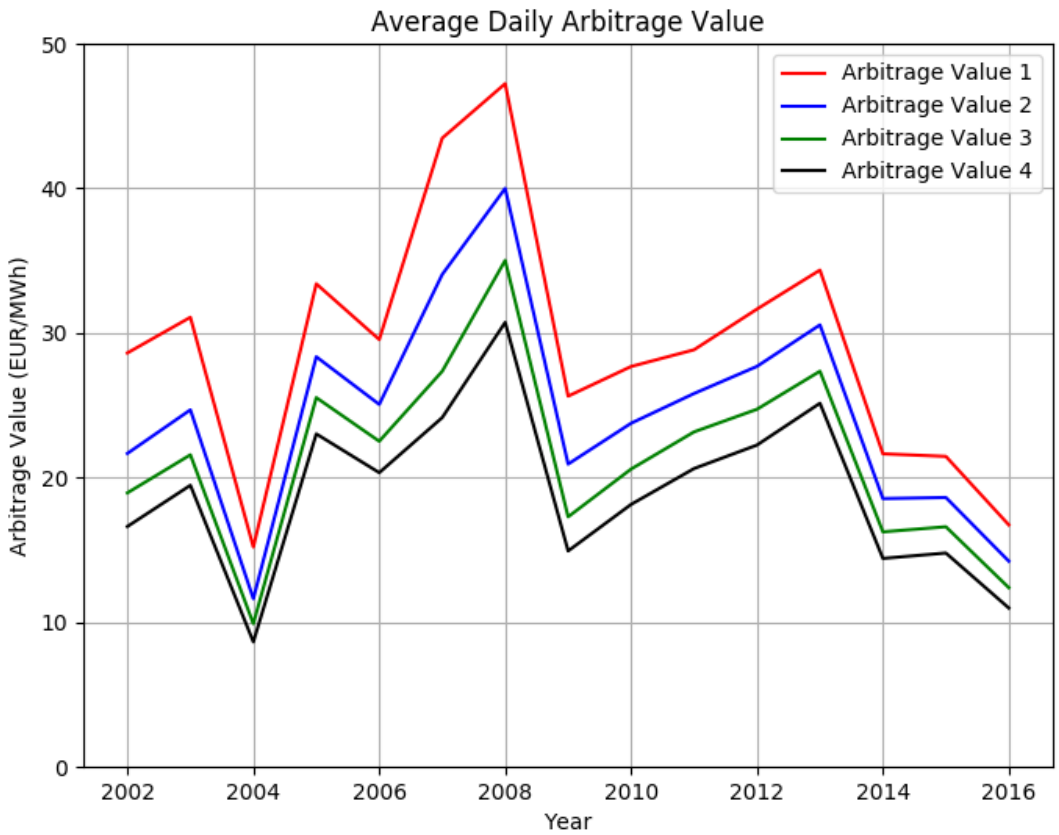
Increased Flexibility

- 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

- 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

Swing Arbitrage in Denmark



Outline

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
- Missing functioning forward markets

Thank you for your attention.

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