Outline

1. Coordinated day-ahead and intraday market bidding

2. Weather based trading strategies on intraday markets

3. Liquidity of intraday markets
Outline


Motivation

Goal

Optimal non-anticipative trading strategies on short-term markets.
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Goal

Optimal non-anticipative trading strategies on short-term markets.

We deal with the following setting

- European market design
- No long-term future markets
- No bidding on reserve markets
- Special focus on continuous intraday trading
- Take perspective of single players that
  - are not acting strategically
  - recognize that the market is not efficient
Short-Term Power Markets

- Day-ahead market: auction one day ahead of delivery
- Intraday market: continuous, trades until shortly before delivery
- Balancing market
  - auction one day before delivery
  - remuneration for power and energy
  - continuous calls-offs by the TSO
Prices are random
Demands and production are random

market 

Market prices often do not reflect true values
Decisions: Problems & Complications

- Prices are random
- Demands and production are random
- Hard technical constraints, demands have to be fulfilled
- High temporal resolution
- Products *seize to exist* (electricity is a *service*)
Decisions: Problems & Complications

- Prices are random
- Demands and production are random
- Hard technical constraints, demands have to be fulfilled
- High temporal resolution
- Products *seize to exist* (electricity is a *service*)
- Illiquid markets
- Interaction between markets is non-trivial
  - Market prices often do not reflect true values

\[ \text{reBAP}_t = \beta_0 + \beta_1 \text{ID1}_t + \varepsilon_t \]
Liquidity

- Day-ahead market: high volumes, auction
- Intraday: smaller volumes, trading *spread out*

Source: EPEX, 2018
Liquidity

- Day-ahead market: high volumes, auction
- Intraday: smaller volumes, trading *spread out*
- Liquidity costs on intraday markets are still substantial
Liquidity

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<table>
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Liquidity

- Day-ahead market: high volumes, auction

- Intraday: smaller volumes, trading *spread out*

- Liquidity costs on intraday markets are still substantial

- Continuous trading tends to increase (liquidity) cost
  - Schwartz (2012)
  - Budish et al. (2015)
  - Du and Zhu (2017)
  - Deutsche Börse Group (2018)
Setting

Market an energy storage on the day-ahead and intraday market.
### Setting
Market an energy storage on the day-ahead and intraday market.

<table>
<thead>
<tr>
<th>Question I</th>
<th>Why not exclusively trade on the day-ahead market?</th>
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<tr>
<td>Question II</td>
<td>Why not exclusively trade on the intraday market?</td>
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<tr>
<td>Question III</td>
<td>Why not trade on both markets and decide independently?</td>
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Setting
Market an energy storage on the day-ahead and intraday market.

Question I
Why not exclusively trade on the day-ahead market?

Question II
Why not exclusively trade on the intraday market?

Question III
Why not trade on both markets and decide independently?

Assumptions

- Maximize expected profits of an electricity storage
- Bid for two time periods
  - $t = 0$: Bid on day-ahead market for delivery in $t = 1, 2$
  - $t = 1$: Intraday market trading for period 1
  - $t = 2$: Intraday market trading for period 2
- Start with empty storage
- Linear price response $\beta$ for intraday market trading
- No price response for day-ahead trading
- $\mathbb{E}(P_t^I | P_t^D = p_t^D) = p_t^D$ for $t = 1, 2$
Day and Intraday: A Simple Model

Proposition

If intraday prices have a higher dispersion, then

- it is never optimal to use full capacity on the day-ahead market;
- there exists $\bar{\beta} > 0$ such that for $\beta \in [0, \bar{\beta}]$, it is optimal to only trade on the intraday market.

- Attractiveness of the intraday market: volatility & information
- Attractiveness of the day-ahead market: market depth
- Small and fast storages should focus on the intraday market
- Larger storages should focus on the day-ahead market
Value of Coordination: Case Study

- Day-ahead trading
- Hourly intraday trading
- Fit price processes from data (order book) data
- Calculate LB on value of coordination using scenario trees
- UB by information relaxation

Three types of assets
- Small battery storage: 10MW / 10 MWh, efficiency of 95%
- Pumped hydro storage: 1000 MW / 8000 MWh, efficiency of 75%
- Seasonal hydro: 100 MW, no pump, 50 MW continuous inflow
## Numerical Results

<table>
<thead>
<tr>
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<th>Market</th>
<th>Avg Profit (EUR)</th>
<th>Avg Volume (MWh)</th>
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Problem with Decisions

Challenge

Finding (globally) optimal intraday trading strategies is hard!

- Decisions are single buy and sell decisions for a random price
  - Intraday market: continuous trading based on a limit order book

- Order book dynamics
  - evolve at short time scale
  - changes happen at random points in time
  - order book consists of bid and offer curves

- Need another layer of modeling to make trading decisions
Order Book Dynamics

Sell Stack

200€, 50 MW
80€, 2 MW
45€, 12 MW
37€, 22 MW

Bid-Ask Spread

Buy Stack

35€, 17 MW
32€, 97 MW
22€, 12 MW
-20€, 42 MW
Order Book Dynamics

New price tick at T=2: 45€
<table>
<thead>
<tr>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-anticipative trading strategy for intraday-only <em>arbitrage trading</em>.</td>
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</tbody>
</table>
## Intraday Trading

### Goal

Non-anticipative trading strategy for intraday-only *arbitrage trading*.

- No assets, no demand
- Accurate processing of order level data
- Policy should prescribe directly implementable trading decisions
- Decision should be computable in real time
- Positive *out-of-sample profits*

Intraday Trading

Goal

Non-anticipative trading strategy for intraday-only *arbitrage trading*.

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Intraday Trading: Literature

- Most papers on intraday trading consider asset backed trading

- Most papers do not consider exact order book dynamics
  - Exception: Bertrand and Papavasiliou (2019)

- Some related recent literature
  - Kath and Ziel (2018): Day-ahead vs intraday based on forecasts
  - Maciejowska et al. (2019): Day-ahead vs intraday arbitrage
  - Bertrand and Papavasiliou (2019): Storage optimization
  - Monteiro et al. (2020): Arbitrage trading with futures
  - Wozabal and Rameseder (2020): Auction based intraday trading
  - Kath and Ziel (2020): Optimal order execution
Interlude: Milliseconds & Microwaves

High frequency trading on financial markets (Budish et al., 2015).

- Trading on *signals* indicating changes in asset values
- The proceeds of HFT strategies go to fastest trader
- *Arms race for speed*
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### Ping Time New York-Chicago

- Telecommunication line between NY and Chicago: 16 ms
- *Spread Networks.* *Straight* cable for $300 Mio.: 13 ms
- Since then: microwave towers reducing time to 8 ms
- Speed limit: 4 ms (speed of light)
Interlude: Milliseconds & Microwaves

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- Similar races take place in other areas
  - Computing: code held in the L1-cache of processors
  - Ping times within the exchange: distance to clearing server
- Earnings from ES vs SPY arbitrage alone: $75 Mio/year
Sniping Stale Quotes

Fundamental Value: 36€
Sniping Stale Quotes

Fundamental Value: 75€
Sniping Stale Quotes

Stale Quotes

<table>
<thead>
<tr>
<th>T= 1</th>
<th>T= 2</th>
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<tbody>
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<td>200€, 50 MW</td>
<td>200€, 50 MW</td>
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<td>80€, 2 MW</td>
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<td>37€, 22 MW</td>
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<td>35€, 17 MW</td>
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</tr>
<tr>
<td>22€, 12 MW</td>
<td>22€, 12 MW</td>
</tr>
<tr>
<td>-20€, 42 MW</td>
<td>-20€, 42 MW</td>
</tr>
</tbody>
</table>
Sniping Stale Quotes

Strategy: Snipe Stale Quotes

Buy
- 12 MW for 45€
- 22 MW for 37€

Sell
- 36 MW for 70€

Profit
- 1166€
Trading Strategy: Intuition

Renewables and intraday prices

- German market has a significant fraction of renewable energy
- Day-ahead market trading based day-ahead weather forecasts
- Forecast errors trigger supply/demand shocks and price changes at the intraday market
  - Kiesel and Paraschiv (2017)
  - Kremer et al. (2020a,b)
  - Kulakov and Ziel (2019)
Trading Strategy: Intuition

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Strategy

Trade based on superior (early) forecasts of *day-ahead forecast errors* anticipating future intraday price changes.
Traditional Weather Forecasting

Traditional weather forecasting produces infrequent forecasts with a coarse temporal resolution.

- Based on *expensive* data (satellite images, weather balloons)
- Only 4 – 6 updates a day

VRES expansion prompted the development of specialized forecasts

- Feedback from real time production data
- Forecasting relevant parameters (wind speeds, cloud cover)
- New providers
  - Enfor, ConWX, Gnarum, enercast, weathernews, windsim, Meteologica
Forecasts: VRES Production

Hourly forecast-errors of intraday updates for wind and pv

Day-Ahead at 11:00
offset=8 hours
offset=5 hours
offset=3 hours
best intraday forecast

MWh

Quarter-hourly forecast-errors of intraday updates for wind and pv

Day-Ahead at 11:00
offset=8 hours
offset=5 hours
offset=3 hours
best intraday forecast

MWh

\times 10^4
A Parametric Policy

- Trade contract with delivery at $t$ based on forecast from $s < t$
  \[ \varepsilon_t^s = f_t^{DA} - f_t^s \]

- Trade (up to) quantity $V$

- Build up position in $[t_1, t_2]$ and unwind in $[t_3, t_4]$
Define thresholds $\Delta^+$ and $\Delta^-$ for signal strength.

Calculate trading decision $x_{t_1}$ as

$$x_{t_1} = \begin{cases} 
V^+, & \text{if } \varepsilon_t^s > \Delta^+ \\
-V^-, & \text{if } \varepsilon_t^s < -\Delta^- \\
0, & \text{otherwise.}
\end{cases}$$
Patience is key?

Modes of Trading

Two ways of interfacing with the continuous market:

1. Accepting existing limit orders
2. Placing limit/market orders

Impatient Strategy
Build up position with immediate-or-cancel market order at \( t_1 \)
Unwind position with immediate-or-cancel market order at \( t_4 \)
Clear imbalance for reBAP

Patient Strategy
Build up position placing limit order on top of bid/offer stack at \( t_1 \)
Make sure that order stays on the top until either \( V \) is traded or \( t_2 \)
Unwind position in the same manner in \([t_3, t_4]\) Immediate-or-cancel market order at \( t_4 \) for remaining position
Clear imbalance for reBAP
Patience is key?

Modes of Trading

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- *Immediate-or-cancel* market order at $t_4$ for remaining position
- Clear imbalance for reBAP
Optimizing the Strategy

Parameter Choice

Fix timing and use a simple grid search on a discrete policy space.

Fix timing

- Use forecast 8 hours before delivery and choose $t_1 = t - 8h$
  - 8 hour forecast allows to react early

- $t_2 = t - 3h$, i.e., we choose a long first trading period
  - Ensures enough time to build up position, when liquidity is limited

- Choose $[t_3, t_4] = [t - 65m, t - 35m]$ to unwind the position
  - Better liquidity close to delivery
  - 5 remaining minutes used for market orders to close positions
    (patient strategy)
Optimizing the Strategy

Parameter Choice

Fix timing and use a simple grid search on a discrete policy space.

Grid search to determine $V^\pm$ and $\Delta^\pm$

- Using historical training data on days $d \in D_1$
- Define set of thresholds $L = \{100 \cdot i : 0 \leq i \leq 20\} \subseteq \mathbb{N}$
- Define set of volumes

\[
V = \{1, 5\} \cup \{10 \cdot i : 1 \leq i \leq 30\} \subseteq \mathbb{N} \quad \text{for hourly products}
\]
\[
V = \{1, 2, 3, 4\} \cup \{5 \cdot i : 1 \leq i \leq 6\} \subseteq \mathbb{N} \quad \text{for 1/4-hourly products}
\]

- Define $\Pi_d(\Delta^\pm, V^\pm)$ as trading profits on day $d$ and solve

\[
(\bar{\Delta}^\pm, \bar{V}^\pm) \in \arg\max \left\{ \sum_{d \in D_1} \Pi_d(\Delta^\pm, V^\pm) : V^\pm \in V, \Delta^\pm \in L \right\}.
\]
In-Sample Evaluation

- Training data $D_1$: 01.07.2017 to 31.12.2018
  - 58.6 million orders for hourly products
  - 131 million orders for quarter-hourly products
In-Sample Evaluation

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  - Evaluate against detailed order book data
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- Take transaction costs into account
  - Trading fees: 0.125\(\text{€}/\text{MWh}\)
  - No fees for changes of limit order
  - *Order-to-trade ratio* (OTR), should stay below 100
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- **Use** $\varepsilon^8_t$ as well as $\varepsilon^0_t$ for the strategy
  - $\varepsilon^8_t$ can be used to assess profits using early forecast
  - $\varepsilon^0_t$ yields an upper bound for the value of a weather forecast
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  - $\varepsilon_t^8$ can be used to assess profits using early forecast
  - $\varepsilon_t^0$ yields an upper bound for the value of a weather forecast

- Test patient trading strategy against impatient strategy

- Define a sensible range for parameter values
### Results

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<thead>
<tr>
<th>Actual ($\varepsilon^0_t$)</th>
<th>Positive</th>
<th>Negative</th>
<th>Overall</th>
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<tbody>
<tr>
<td>Patient</td>
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<td>1 000</td>
<td>1 600</td>
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<table>
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<th>Negative</th>
<th>Overall</th>
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<tr>
<td>H</td>
<td>1 000</td>
<td>2 000</td>
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</tbody>
</table>

- Patient strategy clearly outperforms impatient strategy
- $\varepsilon^0_t$ generates 5-10 more profits than $\varepsilon^8_t$
- QH products permit less volume and generate less profit
Optimal Parameters ($\varepsilon_t^0$)

Hourly products $\varepsilon_t^0 > 0$

Profit for hourly products $\varepsilon_t^0 < 0$

Quarter-hourly products $\varepsilon_t^0 > 0$

Profit for quarter-hourly products $\varepsilon_t^0 < 0$
Optimal Parameters ($\varepsilon^8_t$)

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**Profit for hourly products $\varepsilon^8_t < 0$**

**Quarter-hourly products $\varepsilon^8_t > 0$**

**Profit for quarter-hourly products $\varepsilon^8_t < 0$**
Out-of-Sample

Goal

Train non-anticipative strategy.

- Evaluation period: 01.01.2018 until 31.12.2018
- Results for $\varepsilon_t^0$ and $\varepsilon_t^8$
- Only test patient strategy
- Rolling window setting
  - Retrain strategy every day based on the last 180 days of data
- Evaluate on detailed order book data
- Take transaction costs into account
Out-of-Sample: Hourly Products

- True forecast yield profits one order of magnitude larger
- Profits positive overall, but many products with losses
- Large volumes are being traded
- Smaller volumes and open positions
- Less volatility in daily profits
### Out-of-Sample: Statistics

<table>
<thead>
<tr>
<th></th>
<th>Hour $\varepsilon_t^8$</th>
<th>Hour $\varepsilon_t^0$</th>
<th>Quarter Hour $\varepsilon_t^8$</th>
<th>Quarter Hour $\varepsilon_t^0$</th>
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<td>136 863</td>
<td>311 802</td>
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</table>

- Profit for hourly products larger than for quarter hourly products
- Profits for perfect forecast 5-10 larger than for $\varepsilon_t^8$
### Out-of-Sample: Statistics

<table>
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- No significant balancing costs
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- All profits are significantly positive
### Out-of-Sample: Statistics

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- Higher risk (dispersion) for $\varepsilon^0_t$ and for hourly products
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- Only a fraction of products is actually traded
- Strategy generates a substantial amount of limit orders
Conclusion

- Coordination between day-ahead and intraday markets
  - Coordinated bidding is optimal
  - Finding optimal trading decisions is hard
Conclusion

- Coordination between day-ahead and intraday markets
  - Coordinated bidding is optimal
  - Finding optimal trading decisions is hard

- Profitable weather based trading strategies exist
  - Intraday market is not (semi)-strong efficient
  - Potential for considerable improvement with better forecasts
  - Potential for better strategies
  - Potential for more sophisticated learning
Conclusion

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  - Coordinated bidding is optimal
  - Finding optimal trading decisions is hard

- Profitable weather based trading strategies exist
  - Intraday market is not (semi)-strong efficient
  - Potential for considerable improvement with better forecasts
  - Potential for better strategies
  - Potential for more sophisticated learning

- Liquidity cost on the intraday market is substantial
  - Impatient strategies based on market orders are unprofitable
  - Day-ahead market is still attractive


## Capital Requirements (Insample)

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