Stochastic Multi-Stage Optimization for Battery Energy Storage in Power Grids

Energy Innovation Summit, Berlin, 2025-06-24

Sara Frimodig, PhD, Head of Optimization

Agenda

- Background
- Optimization Problem
- Results
- Take aways & Next steps

Agenda

Background

Optimization Problem

Results

Take aways & Next steps

We are in an energy revolution

ELECTRIFICATION & INCREASED POWER DEMAND

x2 electricity demand (2050 vs 2023, Europe)

BUILD OUT OF INTERMITTENT, RENEWABLE ENERGY

From conventional and dispatchable to intermittent, creating more volatility

DECENTRALIZATION OF THE ENERGY SYSTEM

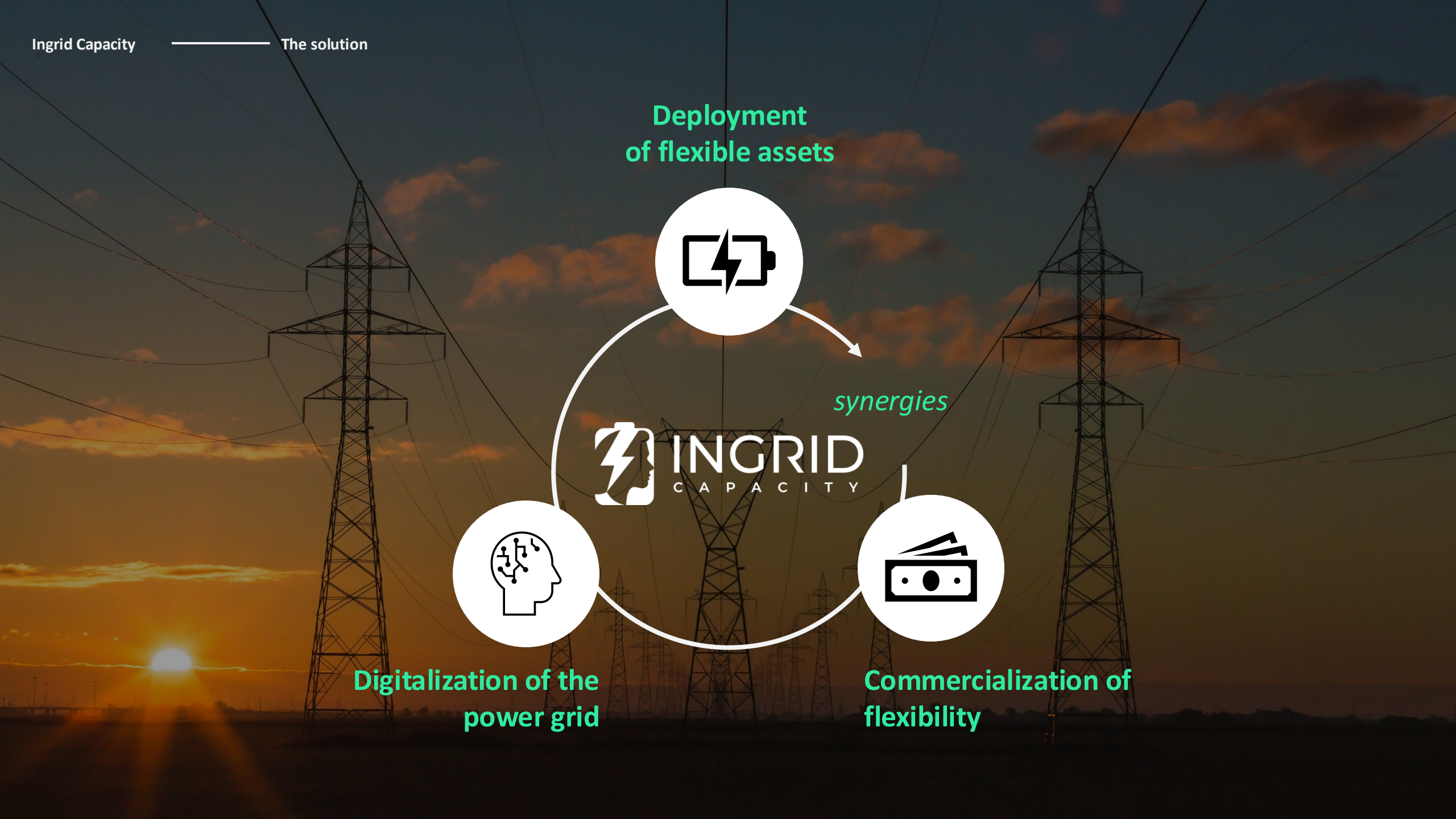
Adding more complexity to the system

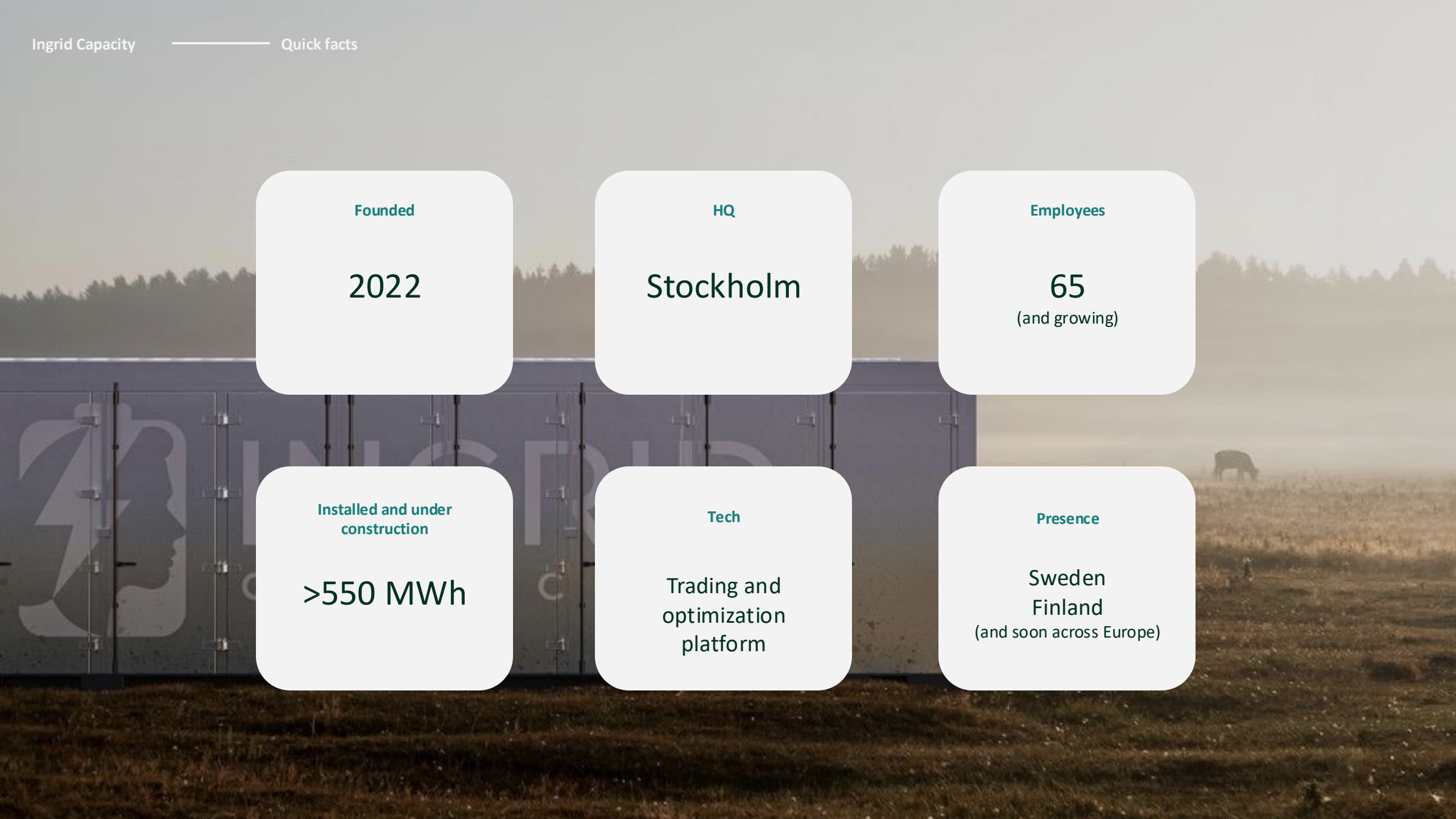
UPGRADING AN OLD TRANSMISSION GRID

Need of major transmission upgrades and ramp-up of new infrastructure deployment

Need for a more flexible and smart energy system

INGRID CAPACITY


Deployment
of flexible assets
synergies
INGRID
CAPACITY
Digitalization of the
power grid
Commercialization of
flexibility



Founded

2022

HQ

Stockholm

Employees

65
(and growing)

Installed and under construction

>550 MWh

Tech

Trading and optimization platform

Presence

Sweden
Finland
(and soon across Europe)

Agenda

- Background
- **Optimization Problem**
- Results
- Take aways & Next steps

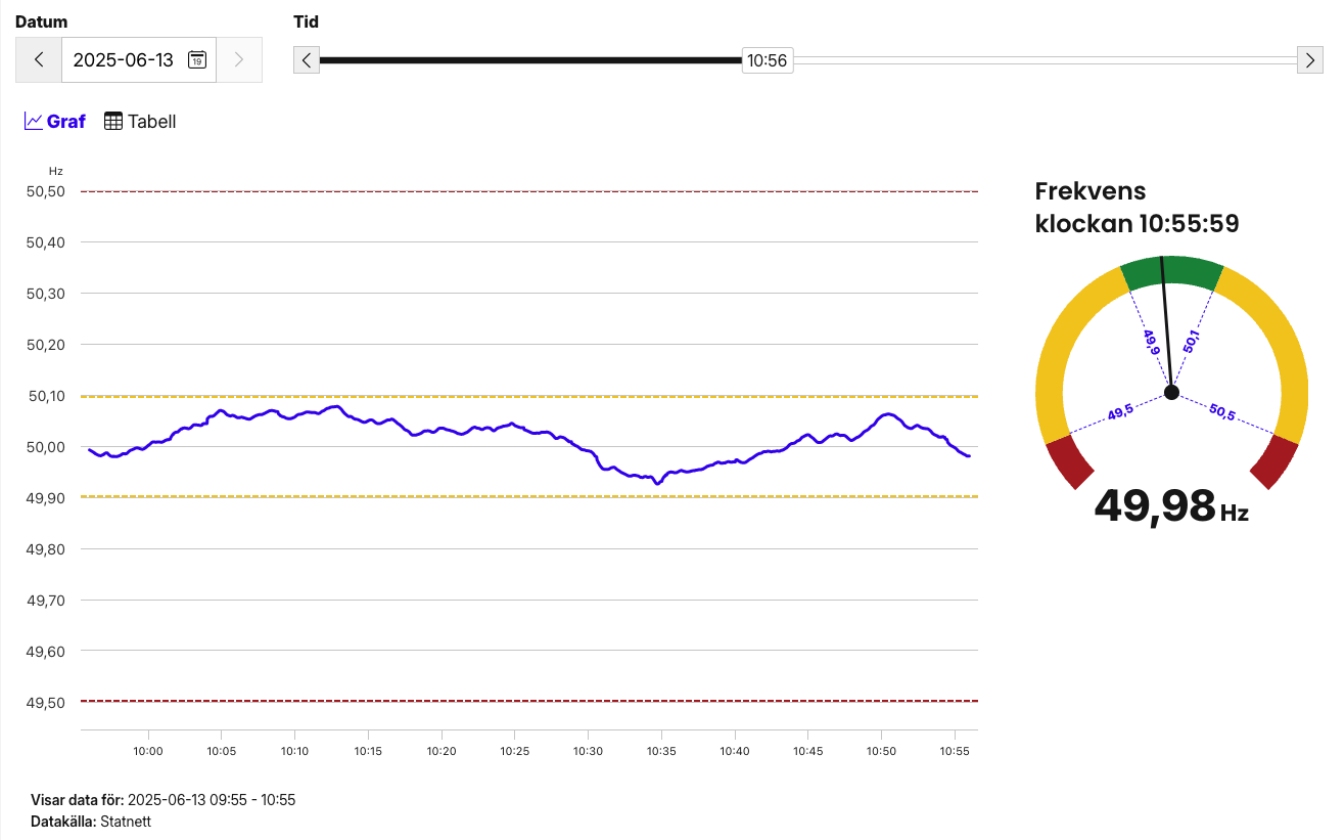
Using BESS to Stabilize the Grid

Ancillary services – sold to TSO

- FFR
- FCR-N
- FCR-D Down
- FCR-D Up
- aFRR
- mFRR

Electricity market – trading at Nord Pool

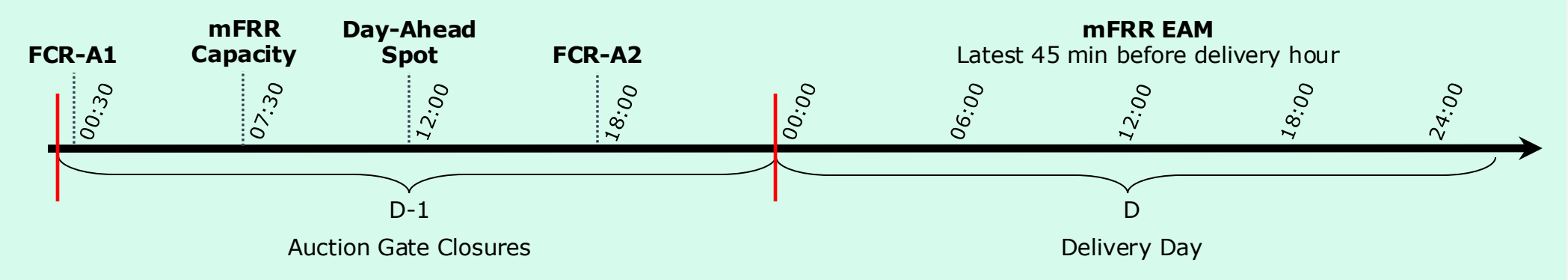
- Day-ahead spot
- Intra-day



Optimizing Battery Usage

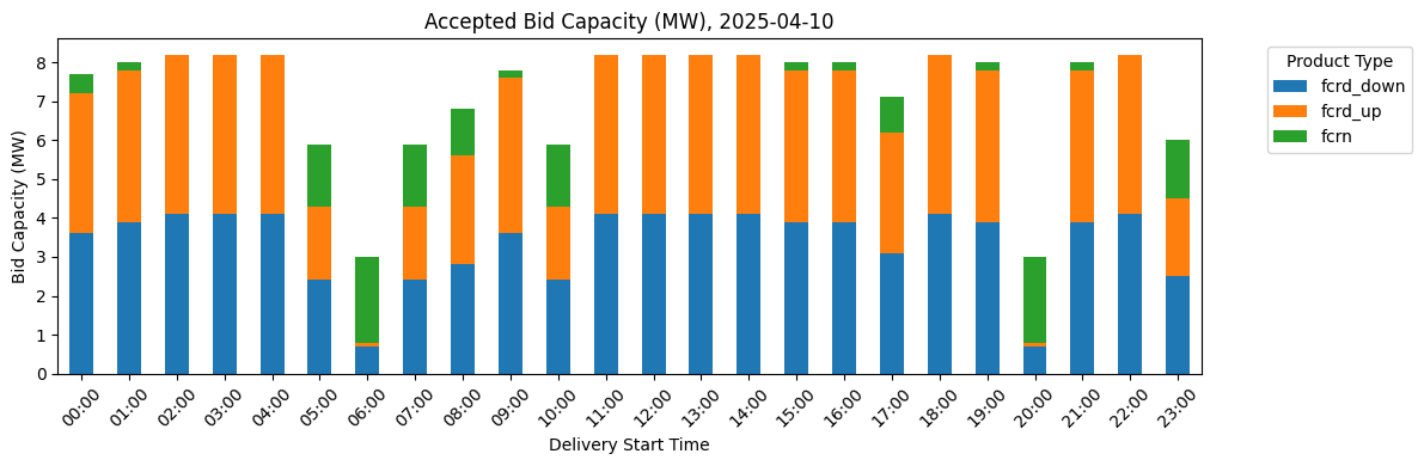
Goal: Optimize battery usage over the day's 24 hours

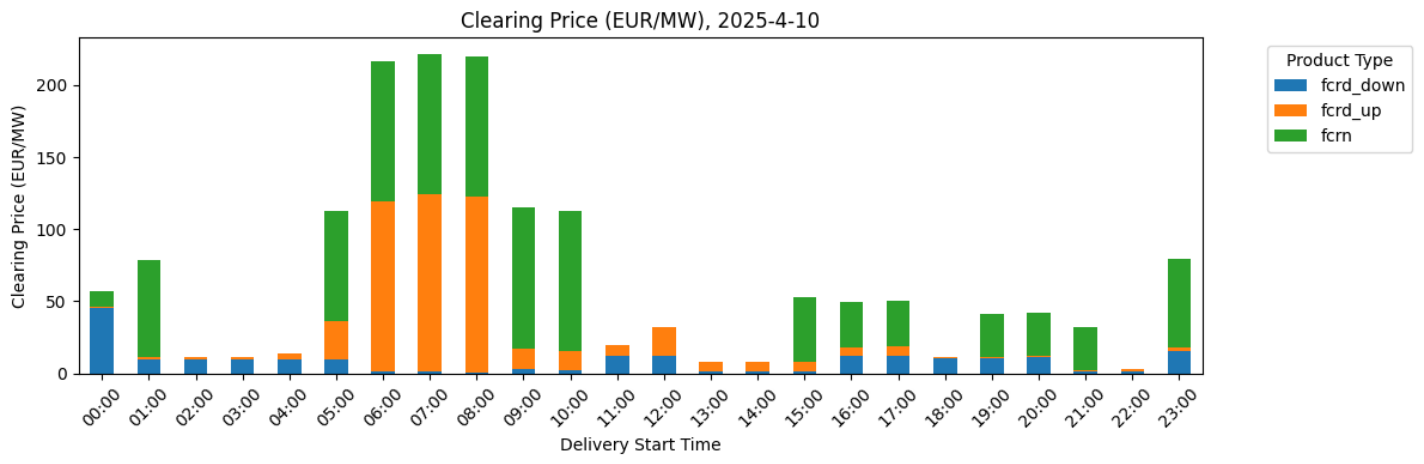
- There are multiple different auctions every day with different closure times
- For each hour of the day, how much of the battery capacity (MW) should we allocate to the different services, and to what price?
- How much should we sell **now**, and how much capacity should we save for **future auctions**?



Bidding Schedule for Products and Hours

- For each product, create a bid with a **volume** (MW) and **price** for each hour of the delivery day
- What we trade for one hour affects what we can do the next hour
- For ancillary services – uncertainty in activation of service

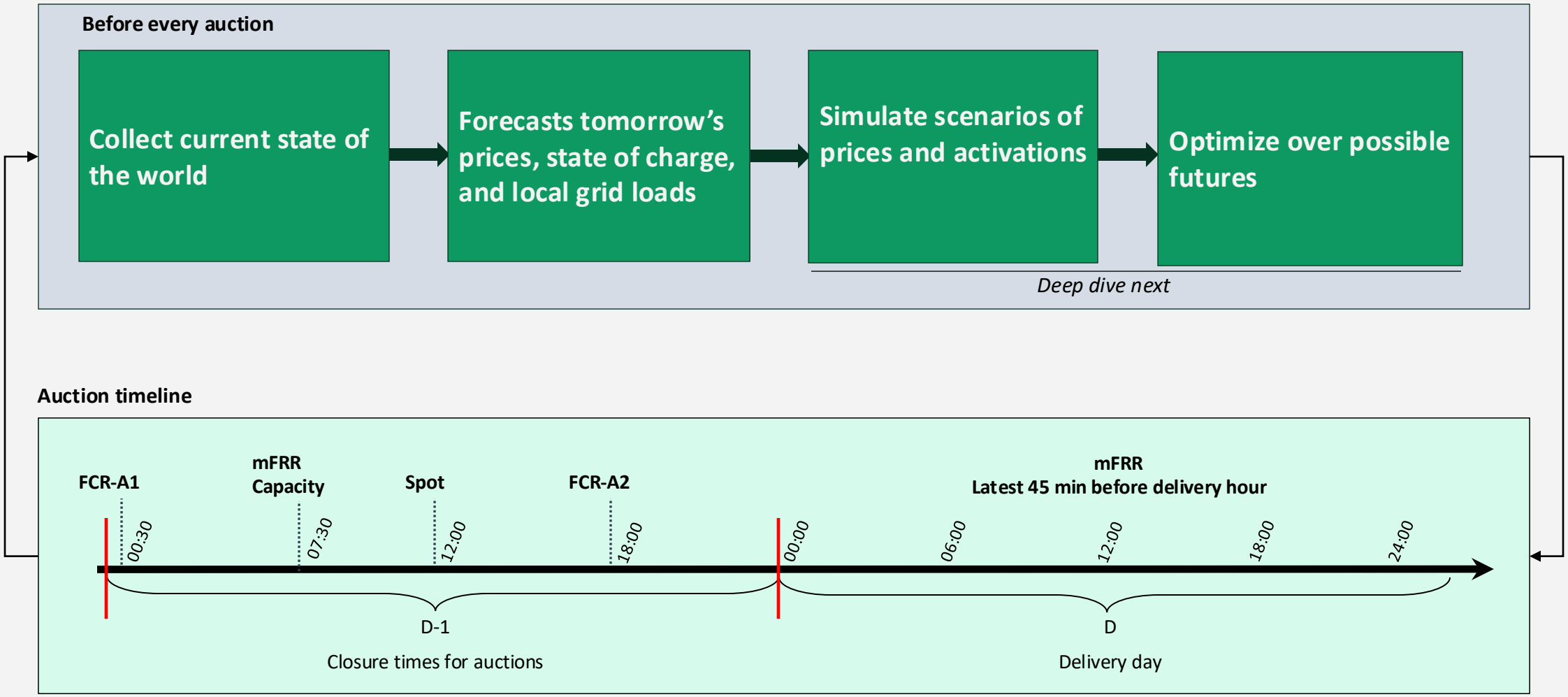




Formulating the Optimization Problem

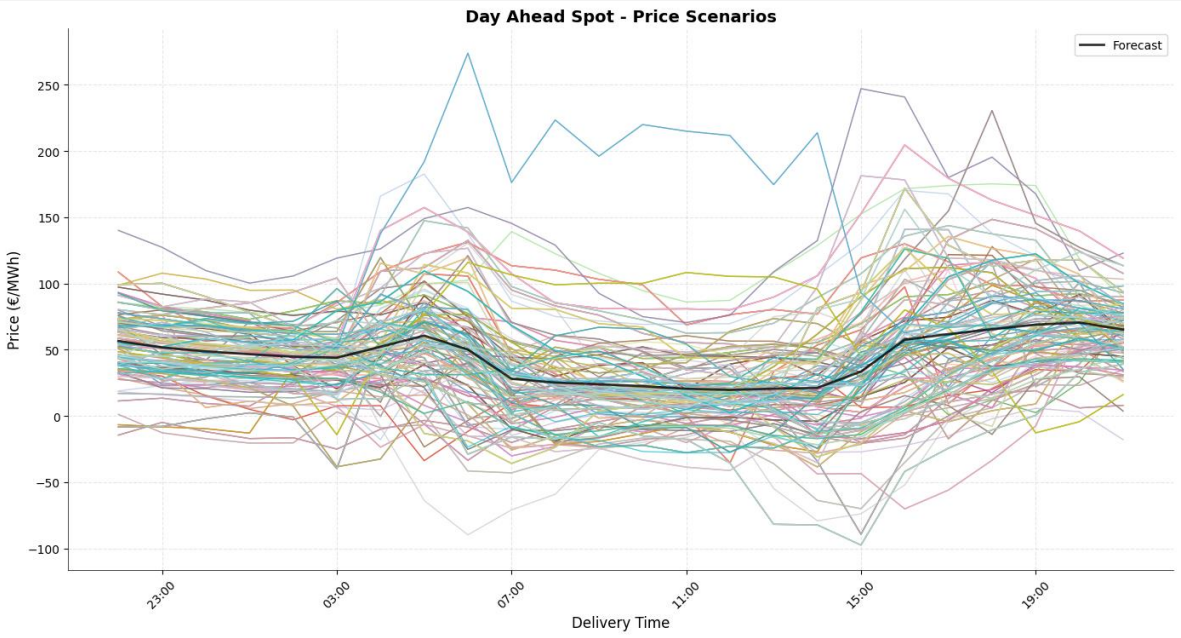
- Accurately balance what is possible now, versus what could be the future potential if it were to wait
- Realistic usage of the physical battery & state of charge
- Respect grid limitations and local grid agreements
- Modeling of all rules & regulations both from Nord Pool and Svenska Kraftnät
- Consciously controlling how risk averse the bids are
- Solve the problem sufficiently fast

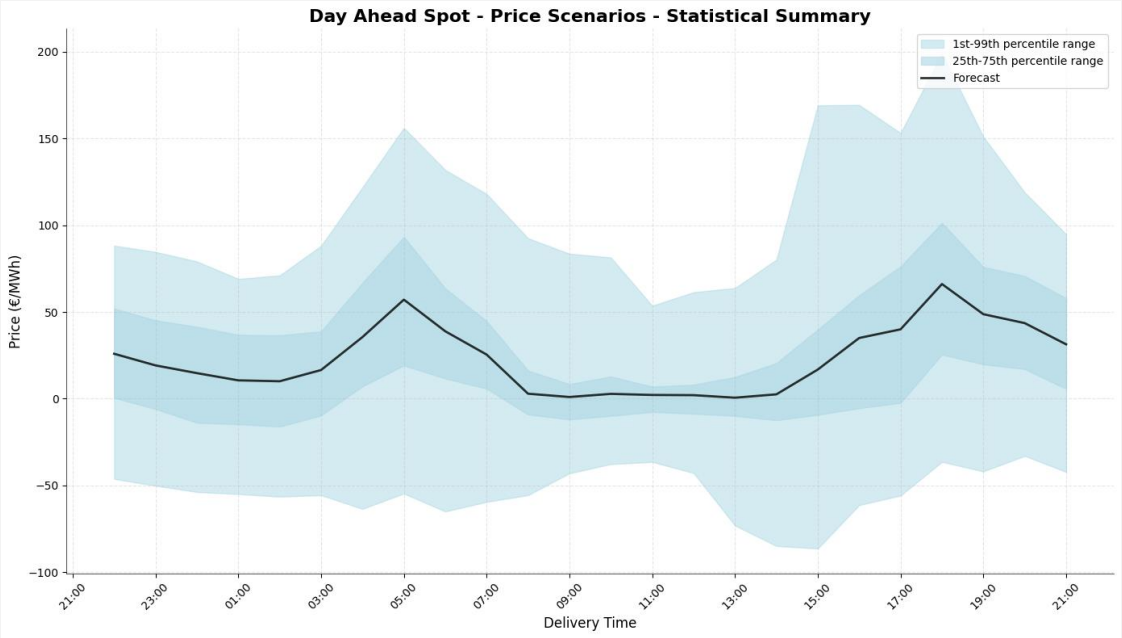
How it works: Stochastic scenario-based MILP optimization, run for each asset before each auction

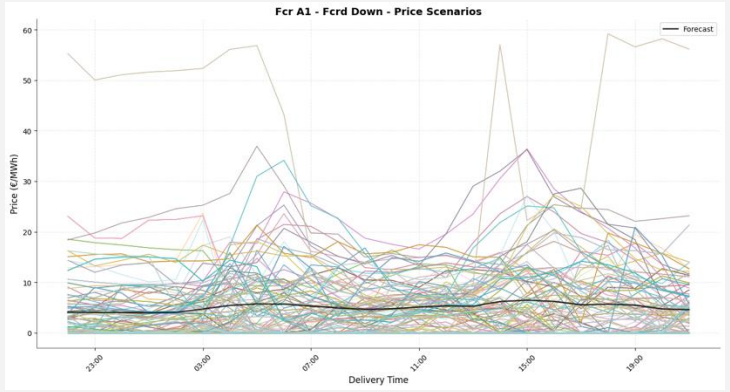


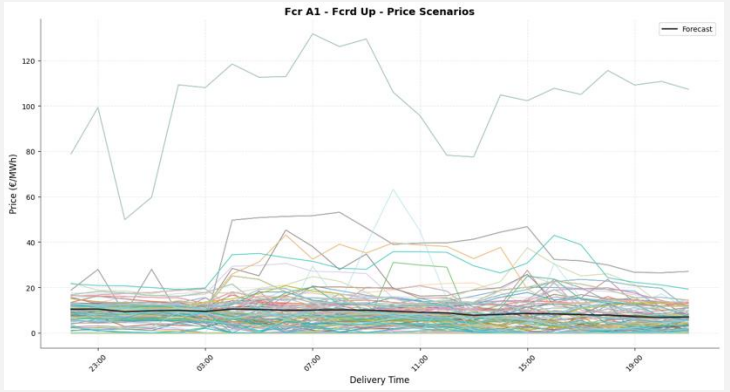
Scenarios for possible future prices and activations

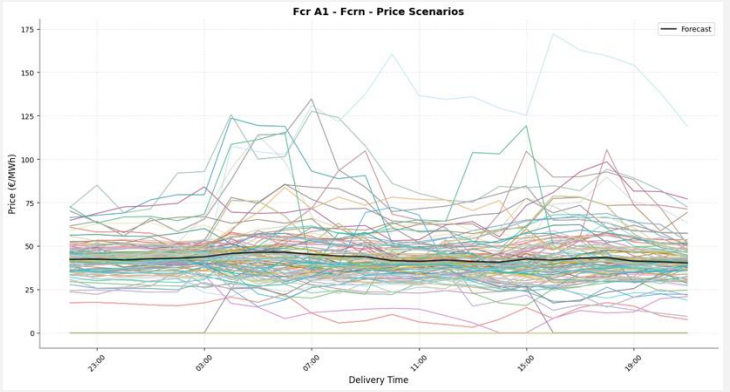
For each market, we generate 300 possible scenarios based on forecasts and historical deviations to forecasts (residual errors)

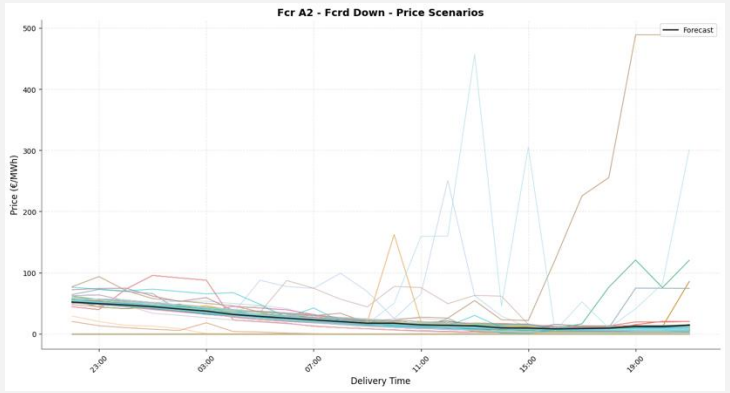


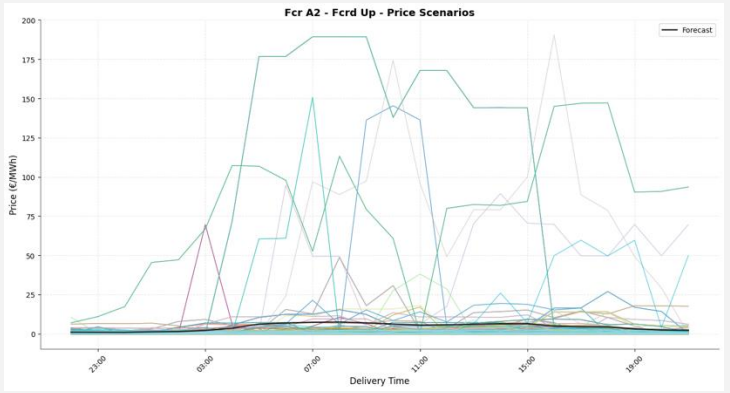


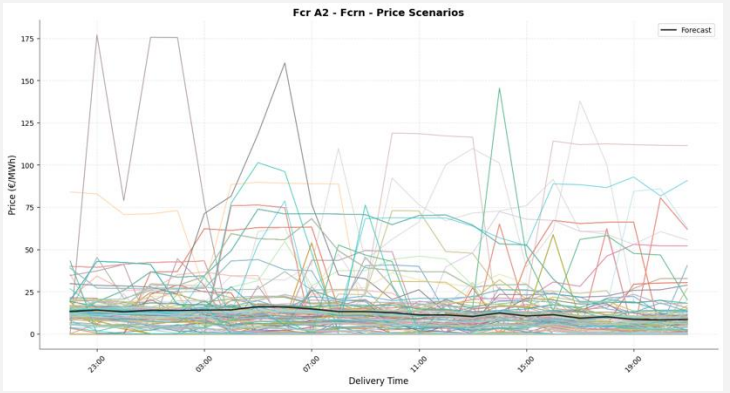

Fcr A1 - Fcrd Down - Price Scenarios
Forecast
Price (€/MWh)
Delivery Time

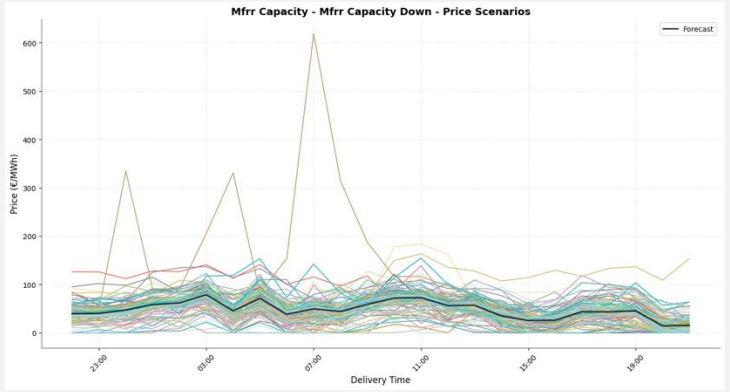

Fcr A1 - Fcrd Up - Price Scenarios
Forecast
Price (€/MWh)
Delivery Time

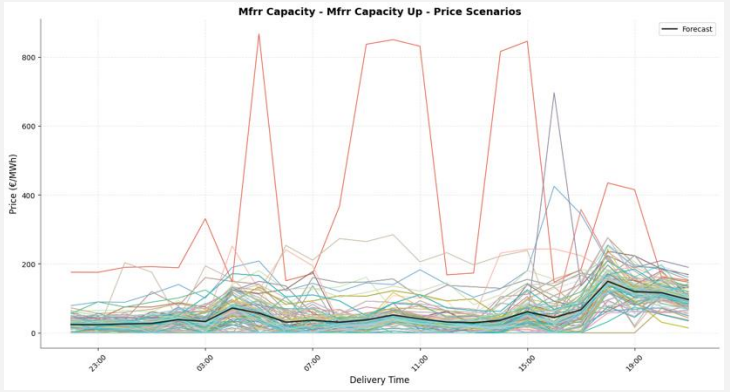

Fcr A1 - Fcrn - Price Scenarios
Forecast
Price (€/MWh)
Delivery Time

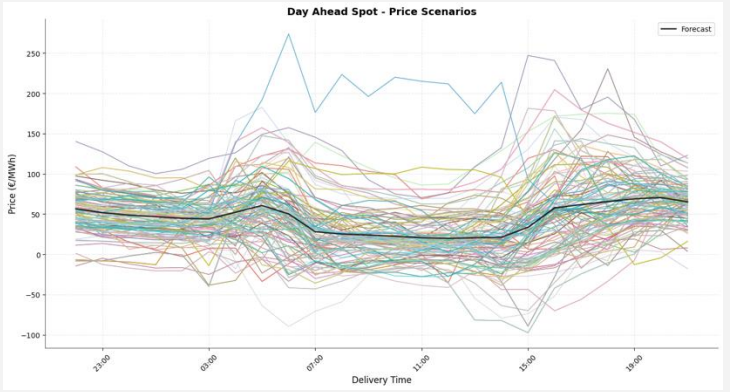

Fcr A2 - Fcrd Down - Price Scenarios
Forecast
Price (€/MWh)
Delivery Time


Fcr A2 - Fcrd Up - Price Scenarios
Forecast
Price (€/MWh)
Delivery Time


Fcr A2 - Fcrn - Price Scenarios
Forecast
Price (€/MWh)
Delivery Time


Mfrr Capacity - Mfrr Capacity Down - Price Scenarios
Forecast
Price (€/MWh)
Delivery Time


Mfrr Capacity - Mfrr Capacity Up - Price Scenarios
Forecast
Price (€/MWh)
Delivery Time


Day Ahead Spot - Price Scenarios
Forecast
Price (€/MWh)
Delivery Time

Formulating the Optimization Problem

Objective: Maximize the expected income across all future scenarios

The objective function is then to maximize the total revenue minus the imbalance fees, minus the tariffs, plus the end-of-day state-of-charge, over all scenarios and hours

$$\text{maximize} \sum_{s \in S} \pi_s \left(\sum_{h \in H} \left(\text{revenue}_h^{\text{past}} + revenue_{sh}^{\text{current}} + revenue_{sh}^{\text{future}} - imb_{sh} - gat_{sh} \right) + eod_s - \text{power\_tariff}_s \right),$$

where π_s is the weight of scenario s and power_tariff_s is the power tariff caused by the bids in scenario s.

Subject to

- Battery limitations
- Grid limitations
- Ancillary services regulations and limitations (Svenska Kraftnät, Nord Pool)
- And more…

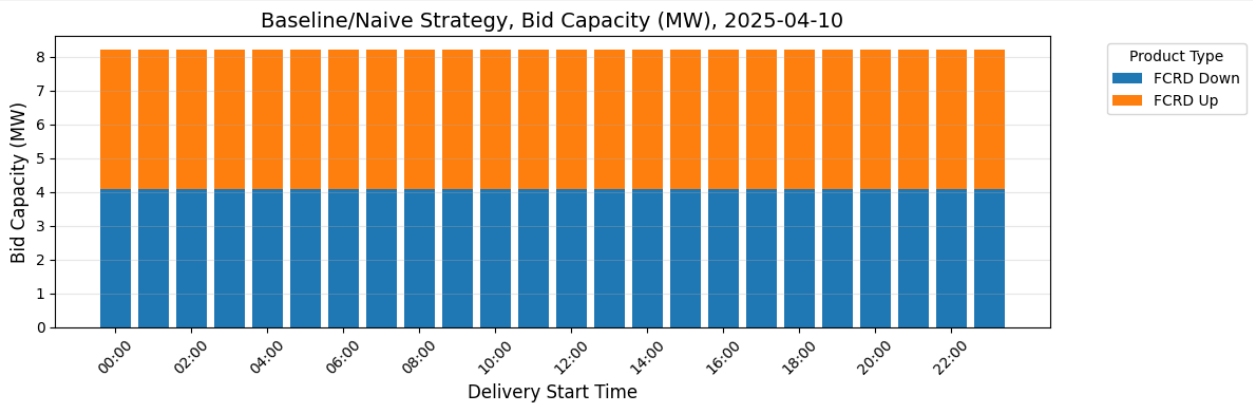
Agenda

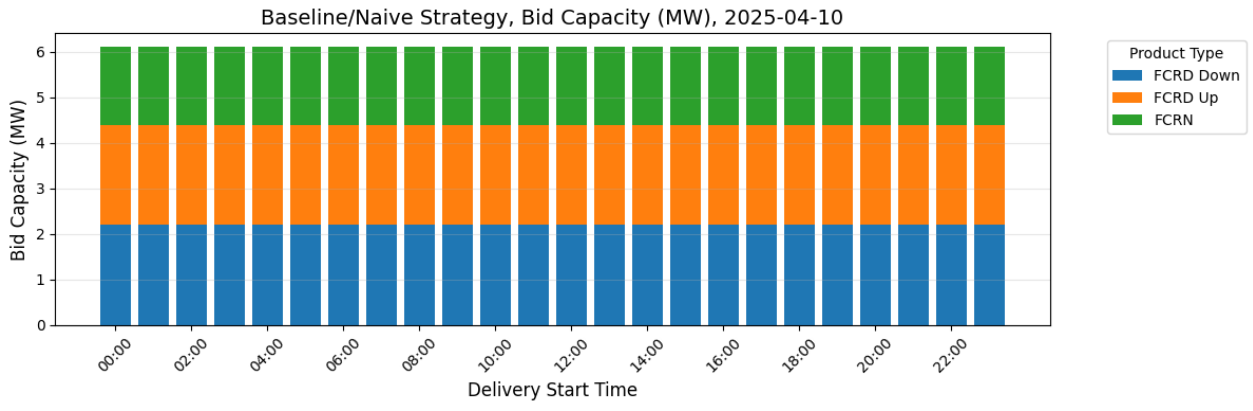
- Background
- Optimization Problem
- **Results**
- Take aways & Next steps

Evaluation: What are we comparing against?

Baseline Strategy:

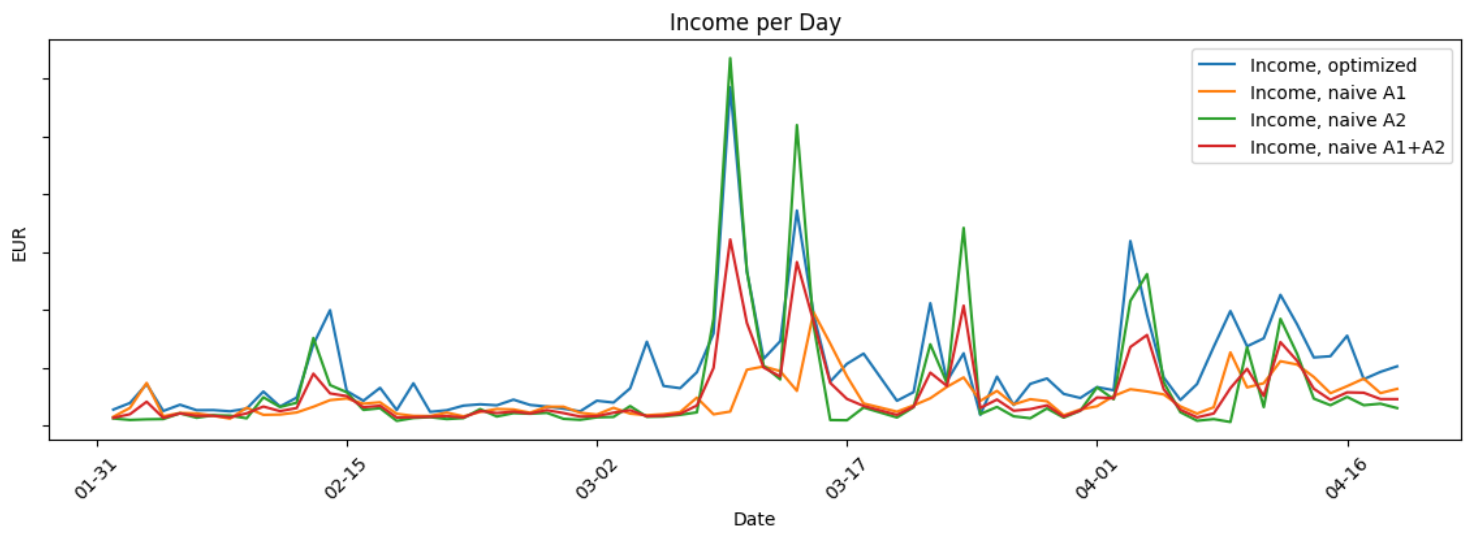
- Every hour, every day, bid maximum in both directions to lowest possible price:
  - FCR-D Down, FCR-D Up
  - FCR-D Down, FCR-D Up, FCR-N
- Naive strategy has worked well historically

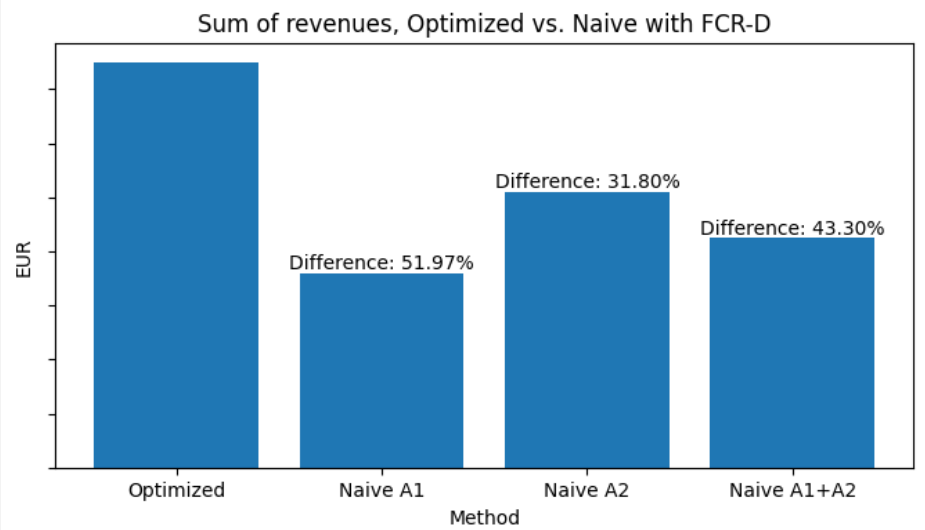




Optimized vs. Baseline FCR-D

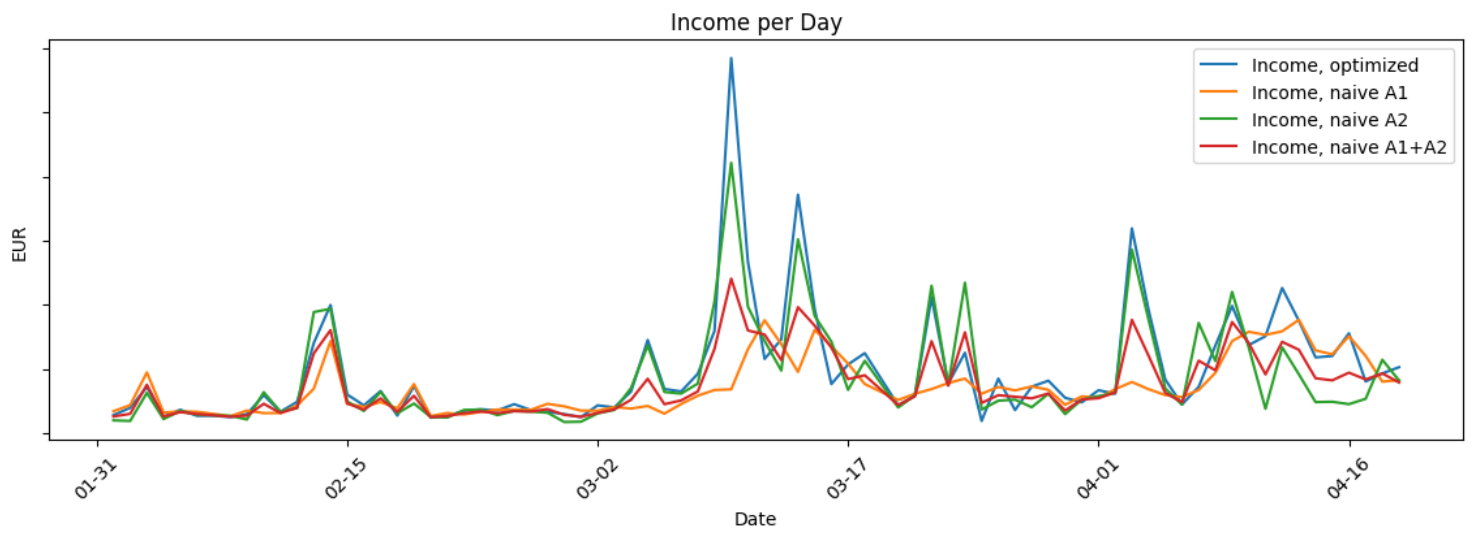
- Backtest over 2.5 months for an asset from our portfolio
- Compare optimized FCR-D and FCR-N bids to naive baseline strategy with only FCR-D
  - Place all volume on FCR-A1 (first FCR auction)
  - Place all volume on FCR-A2 (second FCR auction)
  - Divide volume evenly between A1 and A2

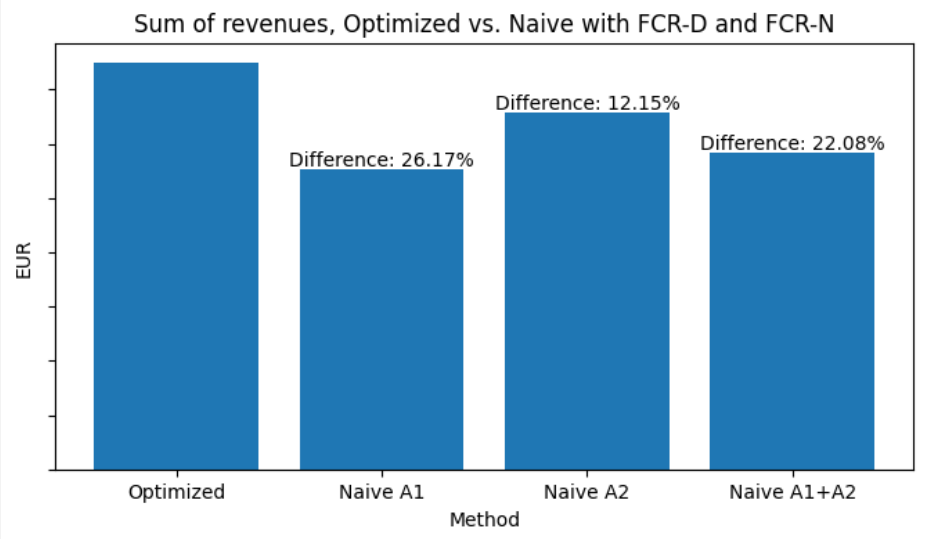




Optimized vs. Baseline FCR-D & FCR-N

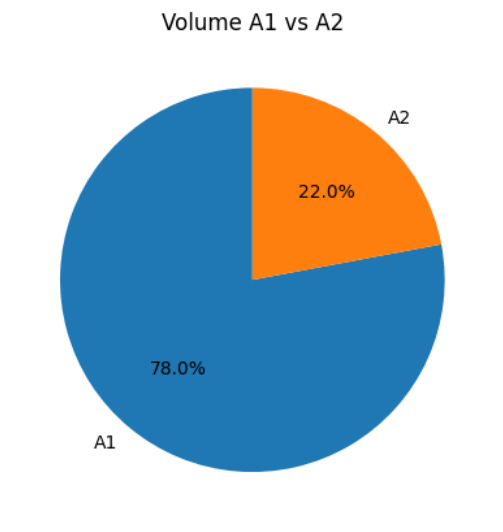
- Backtest over 2.5 months for an asset from our portfolio
- Compare optimized FCR-D and FCR-N bids to naive baseline strategy with FCR-D and FCR-N
  - Place all volume on FCR-A1 (first FCR auction)
  - Place all volume on FCR-A2 (second FCR auction)
  - Divide volume evenly between A1 and A2

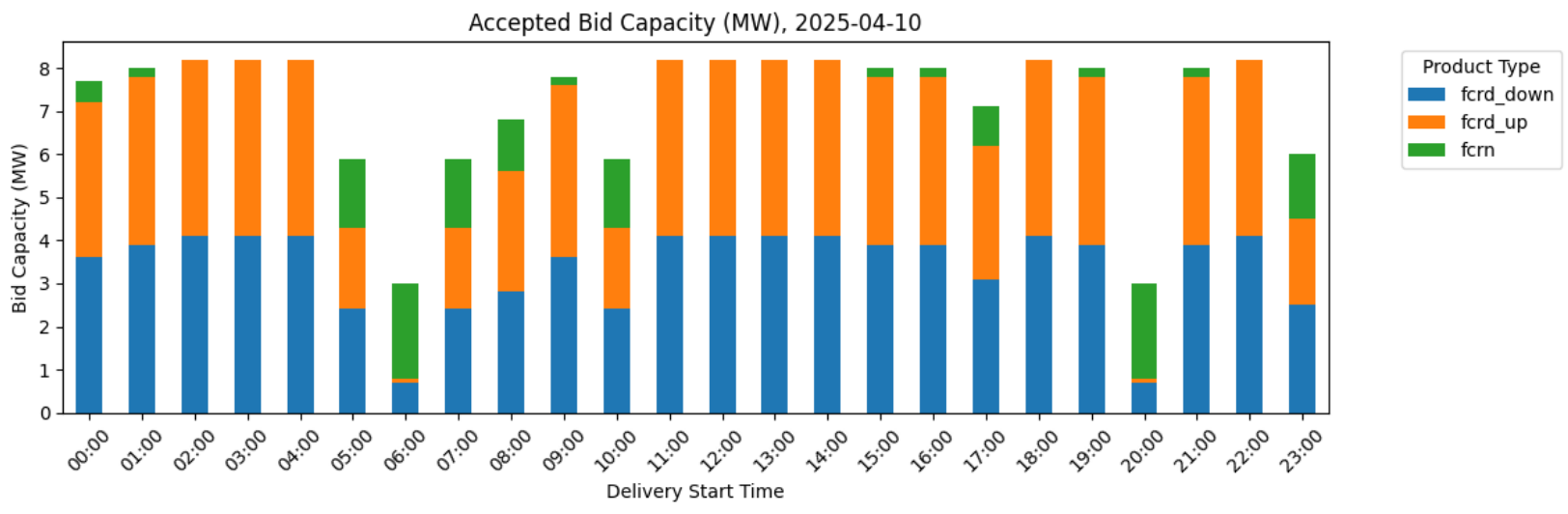


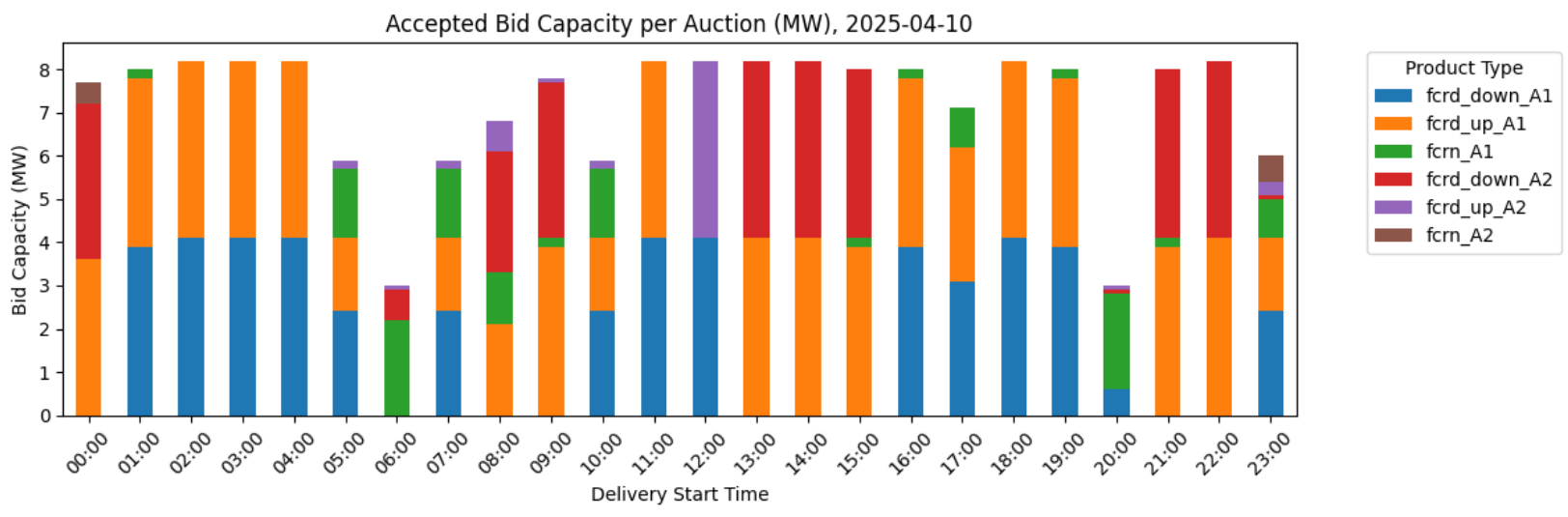


Optimized Plans Leverage Information About the Future

Results for a random date



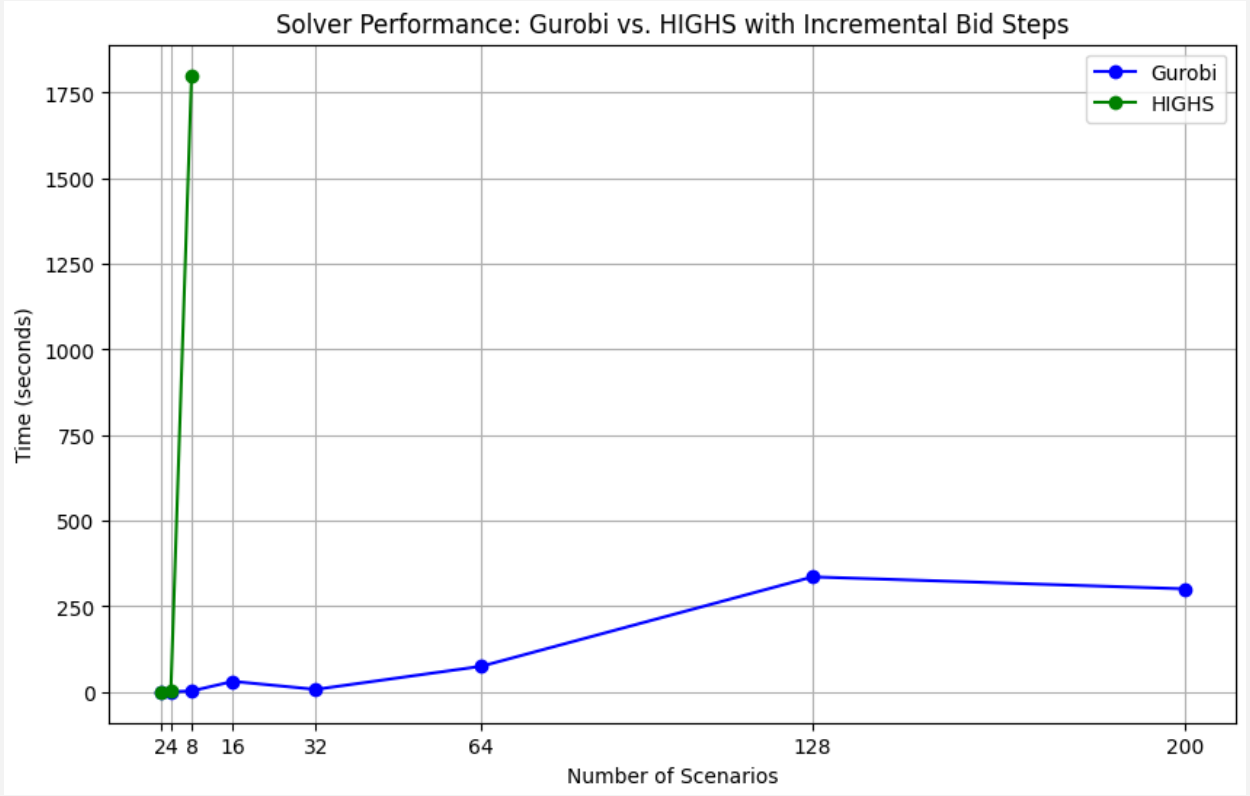




Incremental bid size

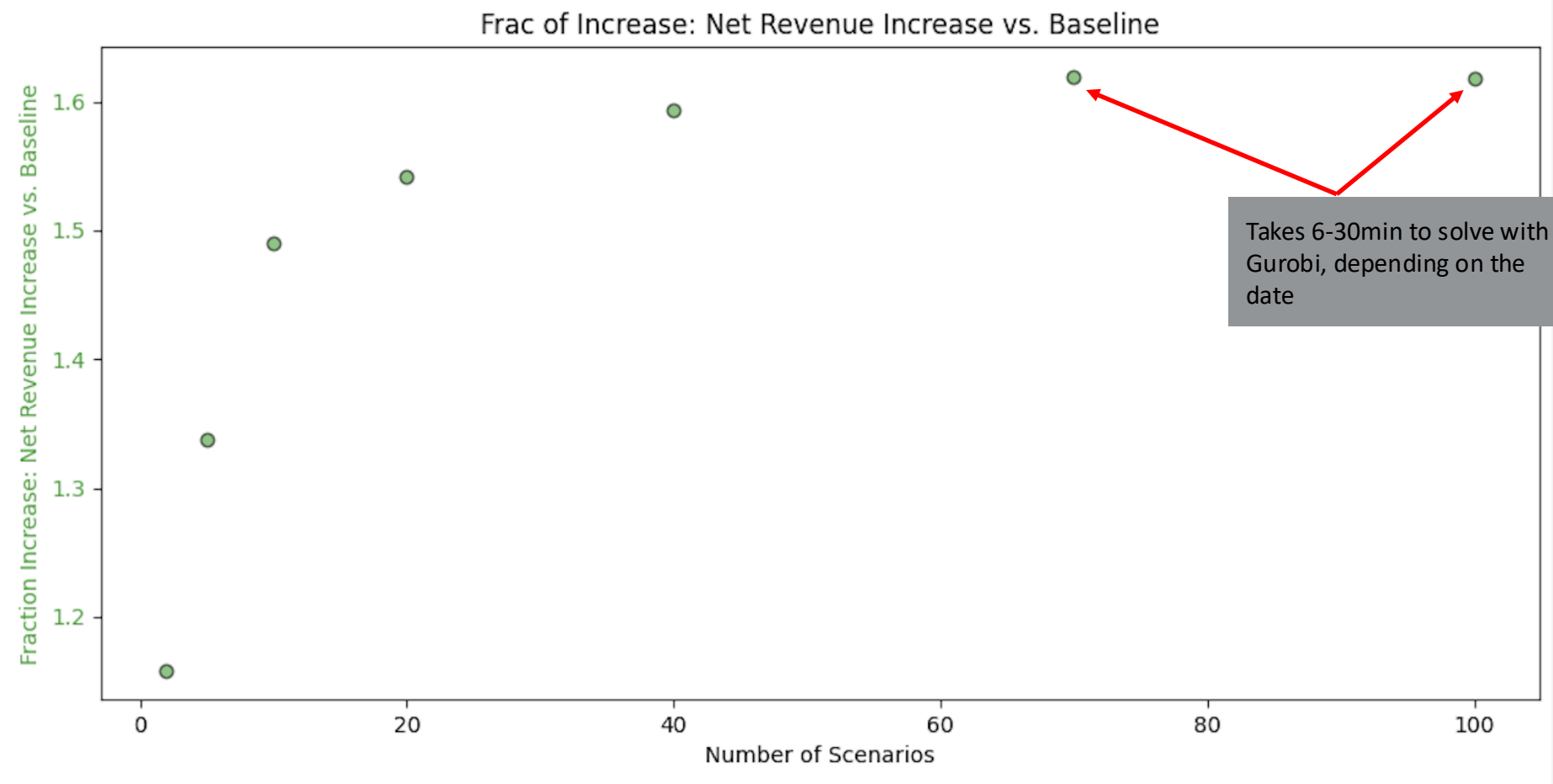
- Bids must be in increments of 0.1 MW
- Can postprocess (16.67 -> 16.6)
  - Suboptimal
  - Technically tedious, since we have to guarantee feasibility
- We also have lots of ”if”-constraints modeled with binary variables and big M-constraints

Gurobi can handle this (in contrast to HiGHS), but the solver times increase 5-10x compared to solving the continuous problem



Value of Number Scenarios

On average, we make 5% more revenue using 100 scenarios instead of 20



Agenda

Background

Optimization Problem

Results

Take aways & Next steps

Take Aways

Optimizing the usage of the battery over 24 hours includes answering the questions

- For each hour of the day, how much of the battery capacity (MW) should we allocate to the different services, and to what price?
- How much should we sell **now**, and how much capacity should we save for **future auctions**?

We model this as a stochastic multi-stage mixed-integer linear program (MILP) problem with sampled scenarios

Thank you!

Our mission is to power a sustainable future by revolutionizing the way we store and harness energy.

2022	550+	65
Founded	MWh installed and under construction	Team members

careers.ingridcapacity.com