Department of Wind and Energy Systems

Mathematical Programming for the Market Integration of Power-to-X Hybrid Power Plants

The Case of a Plant in Denmark

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PowerWeb Annual Conference, TU Delft
September 27, 2023

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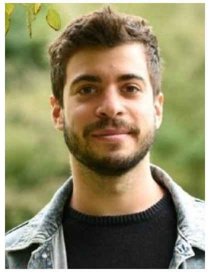

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DTU

DTU SIEMENS Gamesa RENEWABLE ENERGY EUDP

HOMEY project

Towards H_2-driven business model: Portfolio management of a multi-energy system under uncertainty

Outline

Preliminaries

- Why Power-to-X
- An Overview of TSO Services
- Challenges

Physical Modeling of Electrolyzers

Value of Ancillary Services for Electrolyzers

Portfolio Management Problem: Distributionally Robust Optimization

Preliminaries:

Why Power-to-X?

P2X strategy in Denmark: New electrolyzers to be installed

Nordjylland

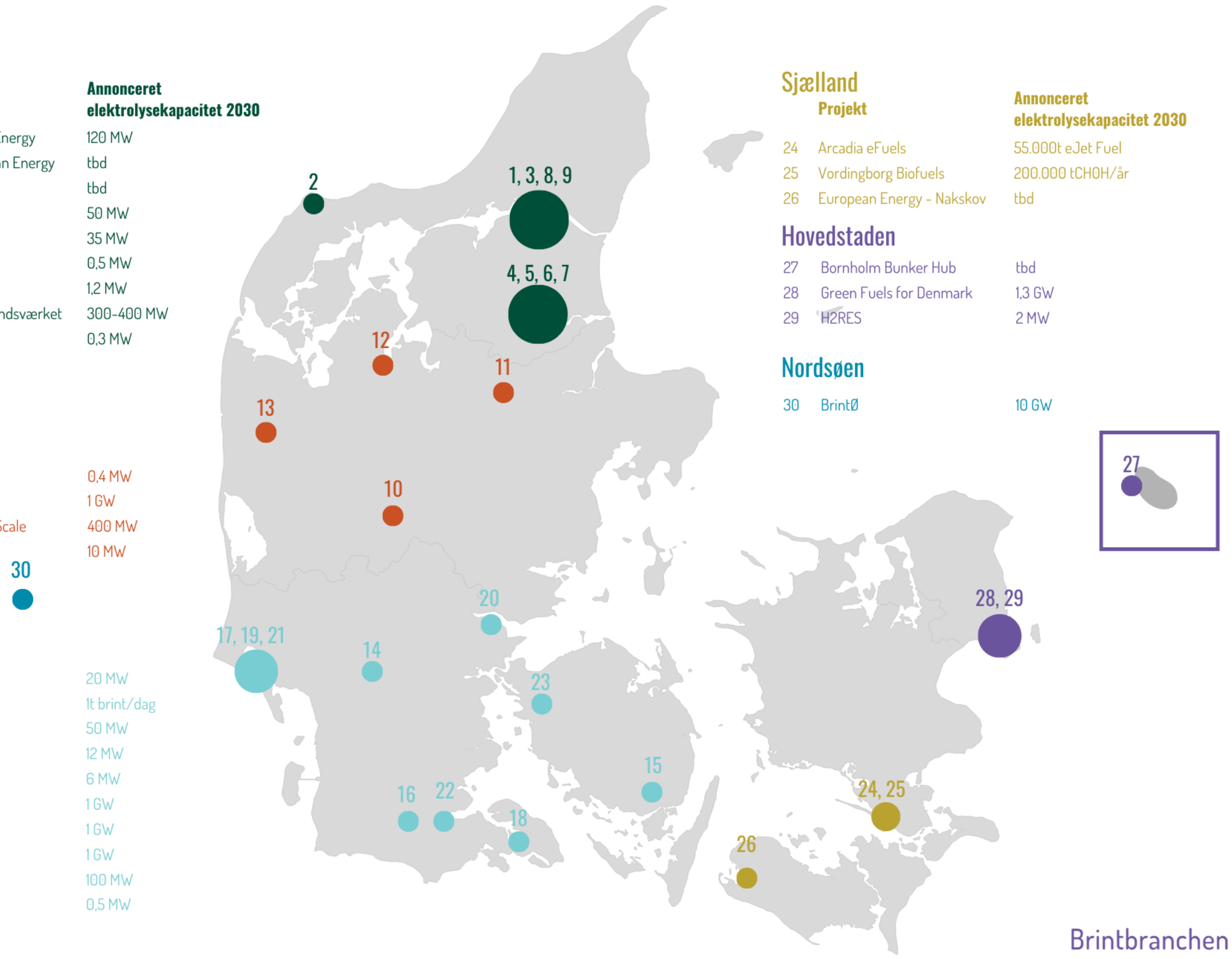
	Projekt	Annonceret elektrolysekapacitet 2030
1	Aalborg Havn - European Energy	120 MW
2	Hanstholm Havn - European Energy	tbd
3	Green Hub CCU Aalborg	tbd
4	Handest	50 MW
5	Hejring	35 MW
6	HFC Marine	0,5 MW
7	HyBalance	1,2 MW
8	Metanolprojekt v. Nordjyllandsværket	300-400 MW
9	Power2Met	0,3 MW

Midtjylland

10	Brande - Flø Hydrogen	0,4 MW
11	Green Hydrogen Hub	1 GW
12	Greenlab Skive - GreenHyScale	400 MW
13	REDDAP	10 MW

Syddanmark

14	Biogas Holsted	20 MW
15	Estech	1t brint/dag
16	European Energy v. Kassø	50 MW
17	European Energy v. Måde	12 MW
18	Glansager	6 MW
19	H2 Energy Europe	1 GW
20	HySynergy	1 GW
21	HØST	1 GW
22	Linde - Aabenraa Havn	100 MW
23	Strandmøllen	0,5 MW



Sjælland

	Projekt	Annonceret elektrolysekapacitet 2030
24	Arcadia eFuels	55.000t eJet Fuel
25	Vordingborg Biofuels	200.000 tCH3OH/år
26	European Energy - Nakskov	tbd

Hovedstaden

27	Bornholm Bunker Hub	tbd
28	Green Fuels for Denmark	1,3 GW
29	H2RES	2 MW

Nordsøen

30	BrintØ	10 GW

Brintbranchen

- **4-6 GW** of electrolyzers by **2030**
- **1.25 billion DKK** in support
- CO_2 emission reduction: **2.5-4.0 million tons**

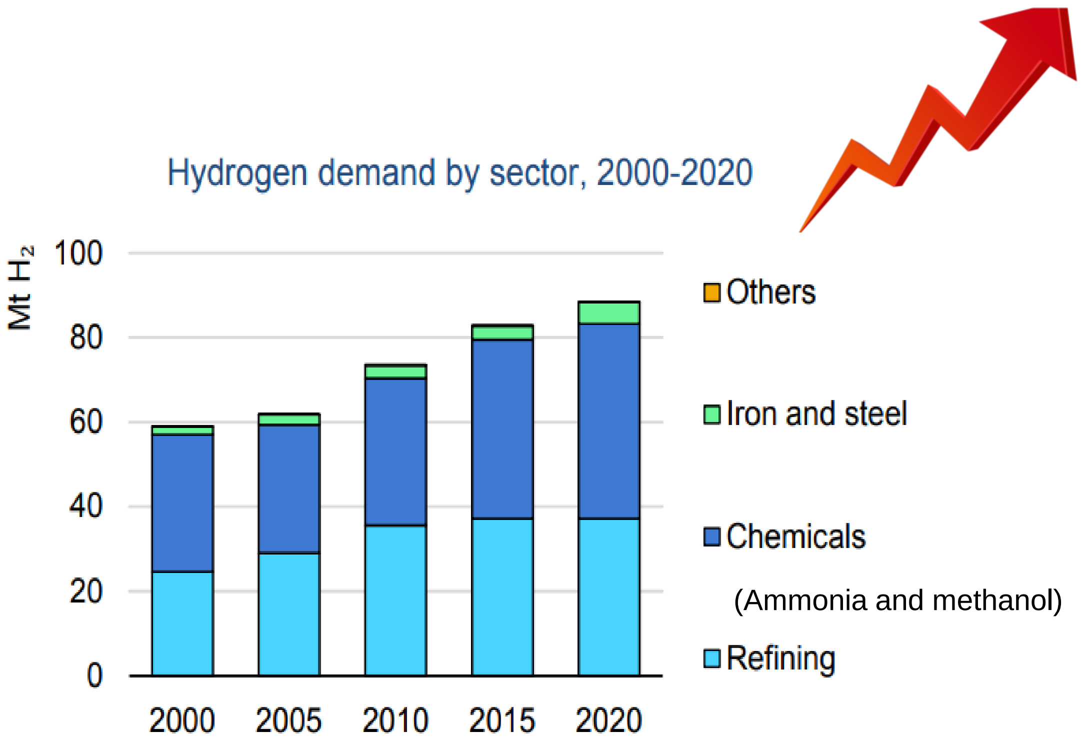
Why Power-to-X?

1. Current **hydrogen demand**
   - **90 Mt** of H2 in 2020
   - Only **0.03%** from water electrolysis

2. **Indirect electrification** and decarbonization of
   - Heavy **transport** (heavy-duty vehicles, aviation and shipping
   - **Industry**

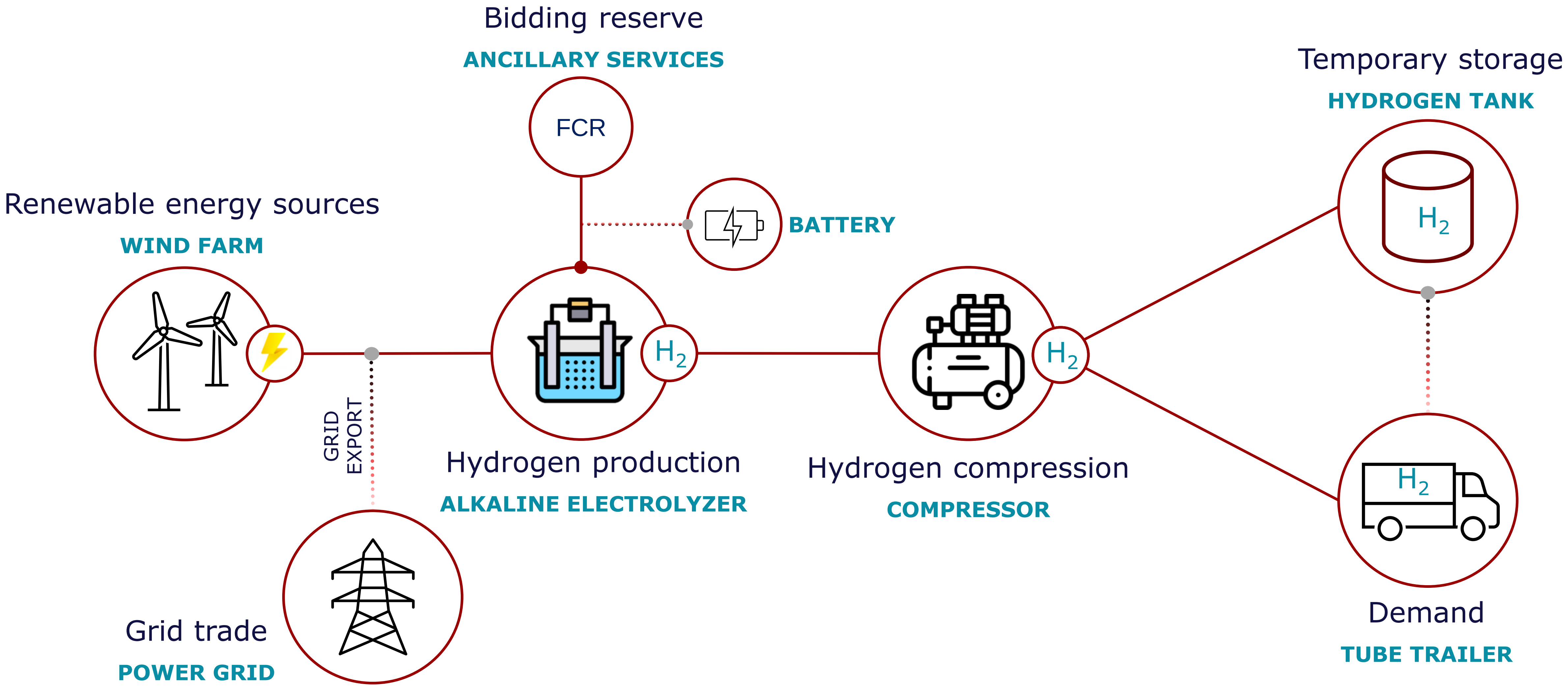
3. Added value to the **power system:**
   - Higher **utilization** of renewables in the grid (reduce curtailment)
   - **Ancillary services** provision (high ramping rates)

530 Mt in 2050 in IEA's Net Zero Emissions scenario



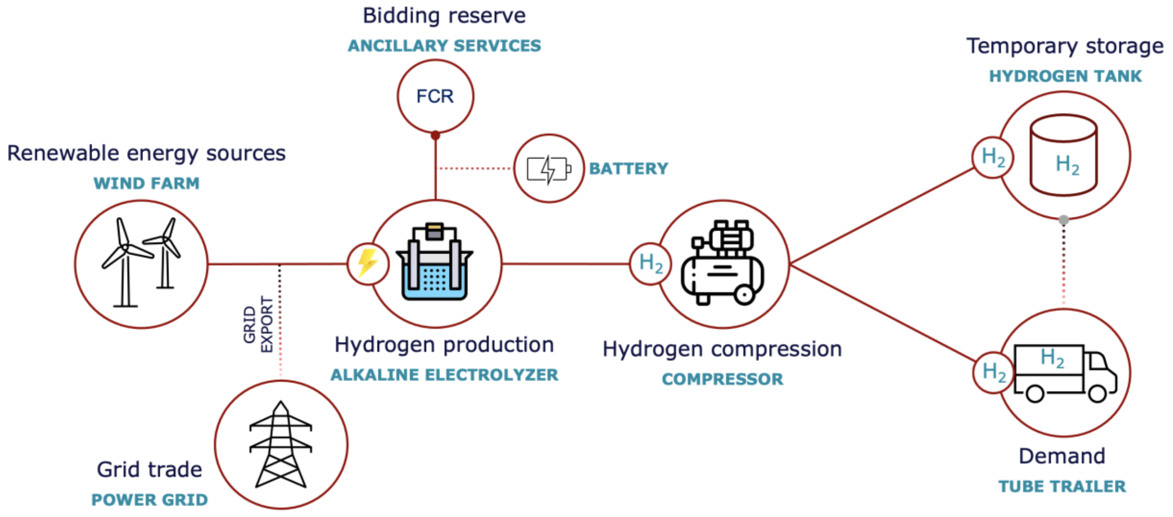
Source: IEA, 2021

Hybrid Power Plant



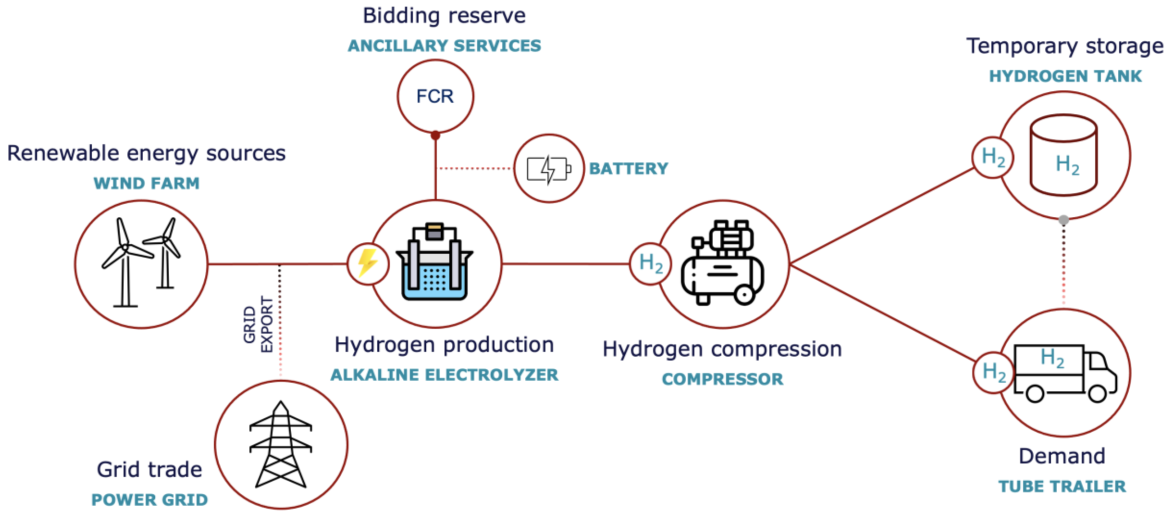
Credit: Marco Saretta

Hybrid Power Plant



What are the products of the hybrid power plant?

Hybrid Power Plant



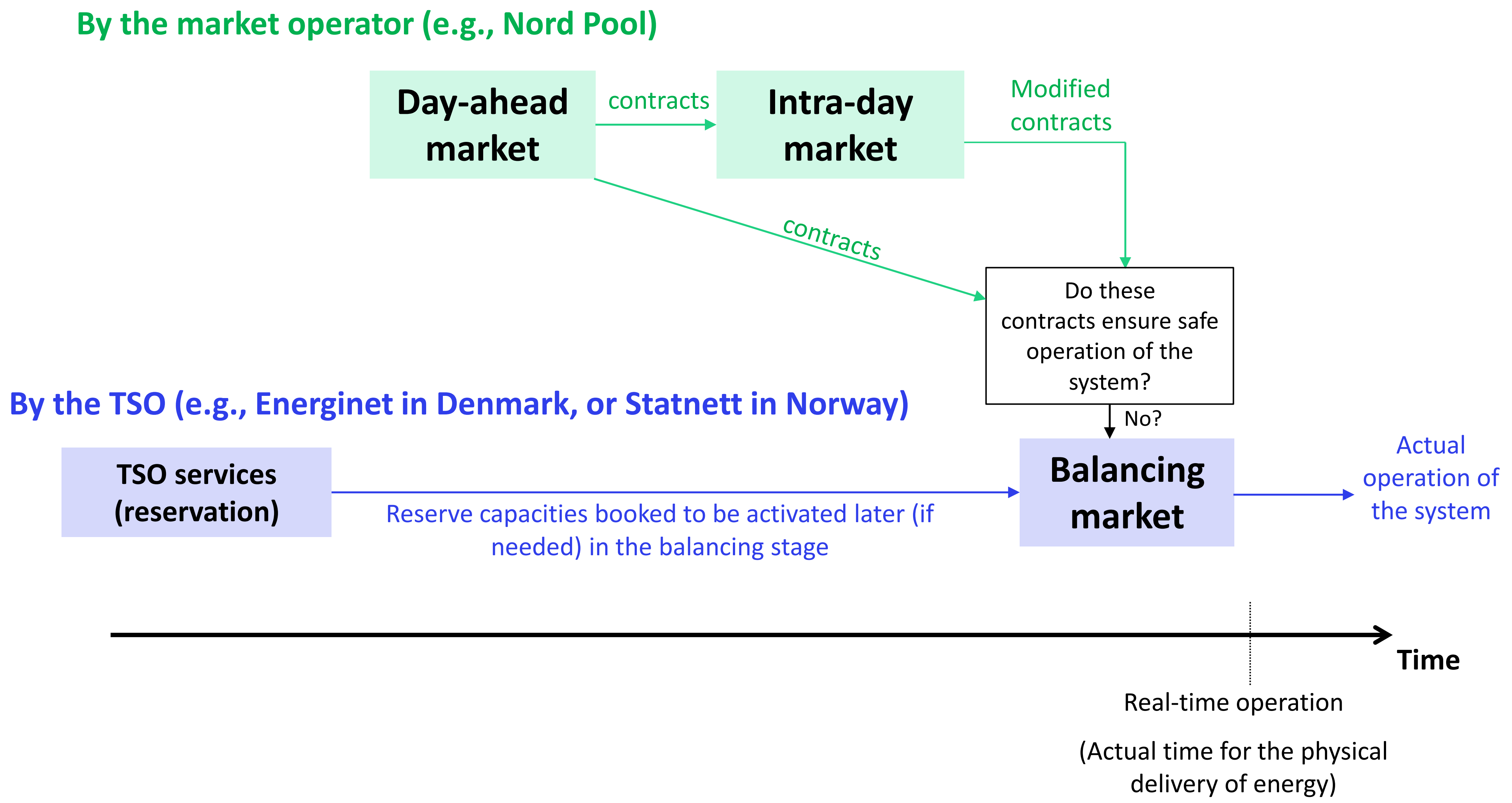
Portfolio of products:

- **Power** (to be sold in various trading floors)
- **Hydrogen** (fixed price)
- **TSO services** such as frequency-based ancillary services (electrolyzers are fast flexible demands!)
- **DSO services** (if the plant is connected to a distribution grid) such as grid congestion services

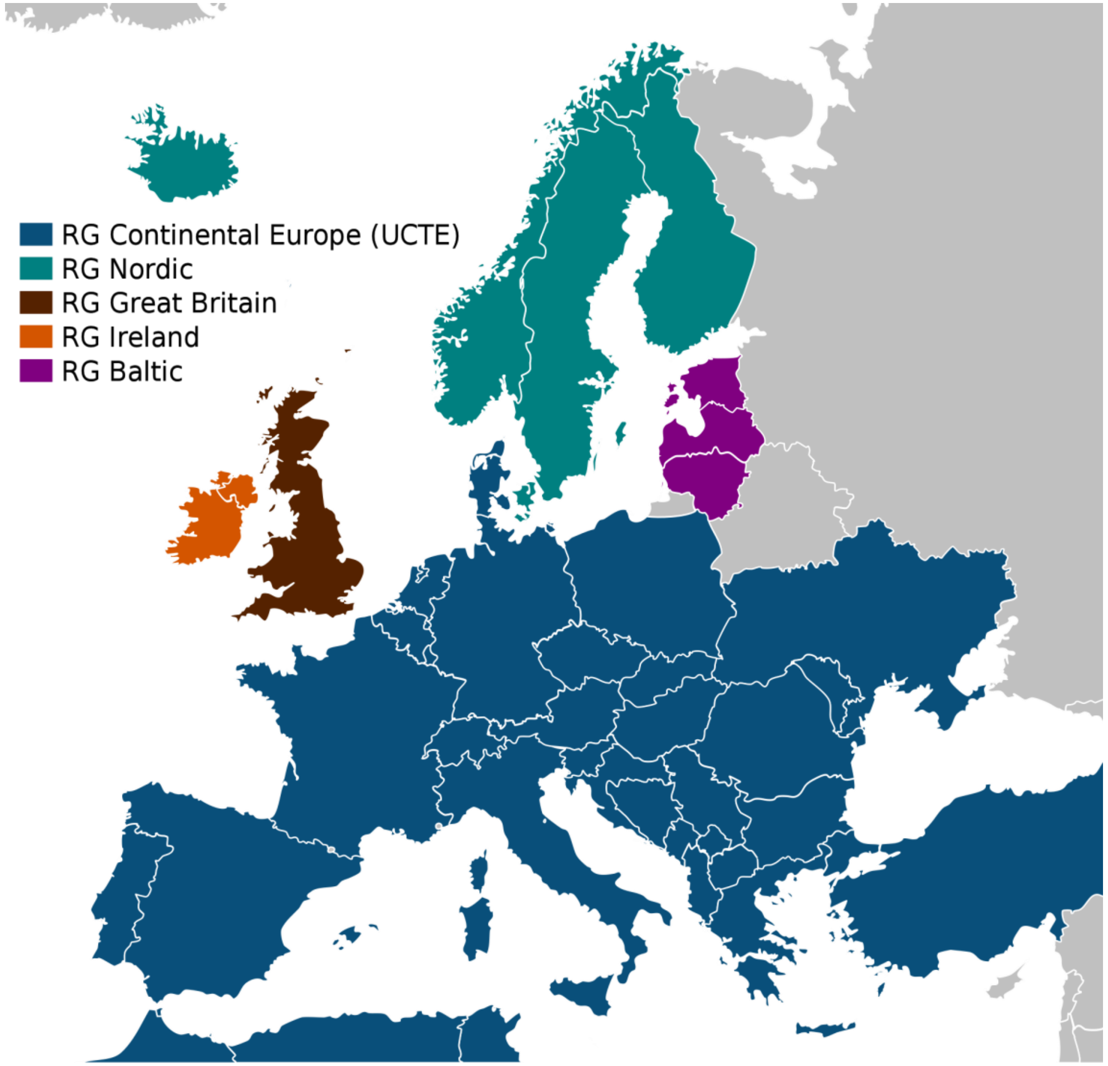
Preliminaries:

An Overview of TSO Services

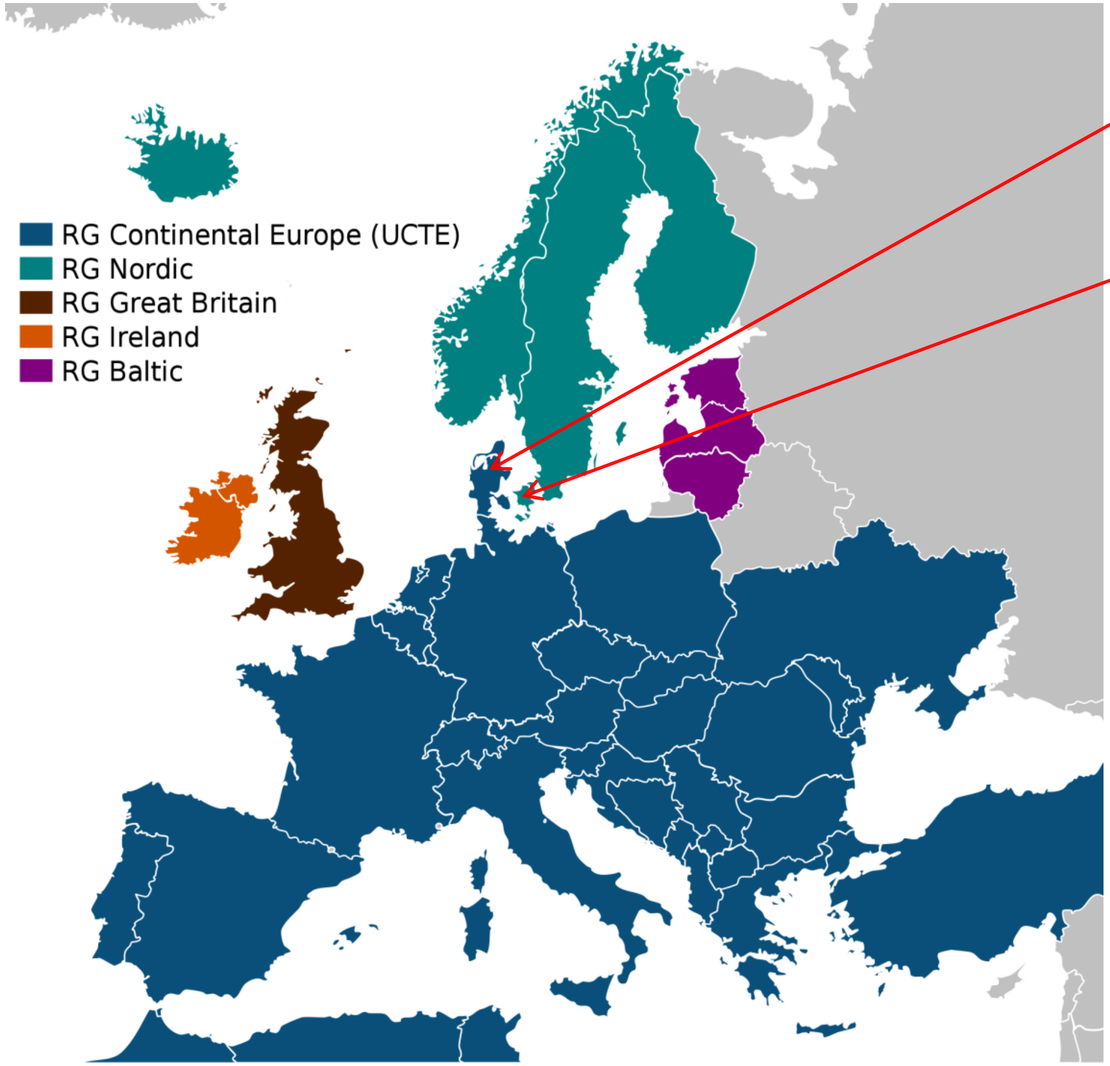
Recall: Who clears what market (European setup)?



Synchronous Grid Areas in Europe



Synchronous Grid Areas in Europe

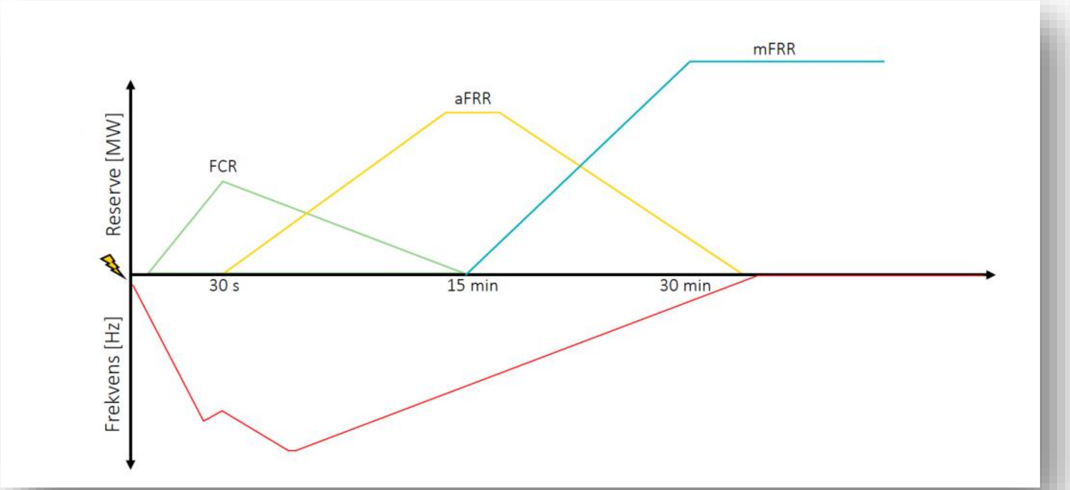


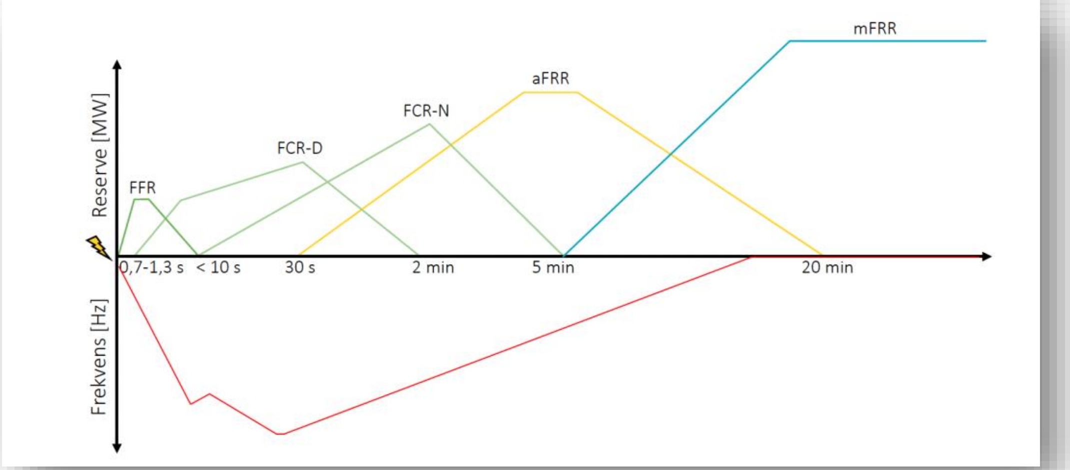
DK1 (part of UCTE)

DK2 (part of Nordic)

Energinet is operating the Danish power system in two areas → different ancillary services exist in DK1 and DK2

Frequency-based Ancillary Services in DK1 and DK2





Ancillary services in DK1 (as part of the continental area)

- FCR (frequency containment reserve)
- aFRR (automatic frequency restoration reserve)
- mFRR (manual frequency restoration reserve)

Ancillary services in DK2 (as part of the Nordic area)

- FFR (fast frequency reserve)
- FCR-D (D stands for disturbance)
- FCR-N (N stands for normal)
- aFRR
- mFRR

Source: *Energinet (Gennemgang af Nuværende Systemydelse Markeder)*

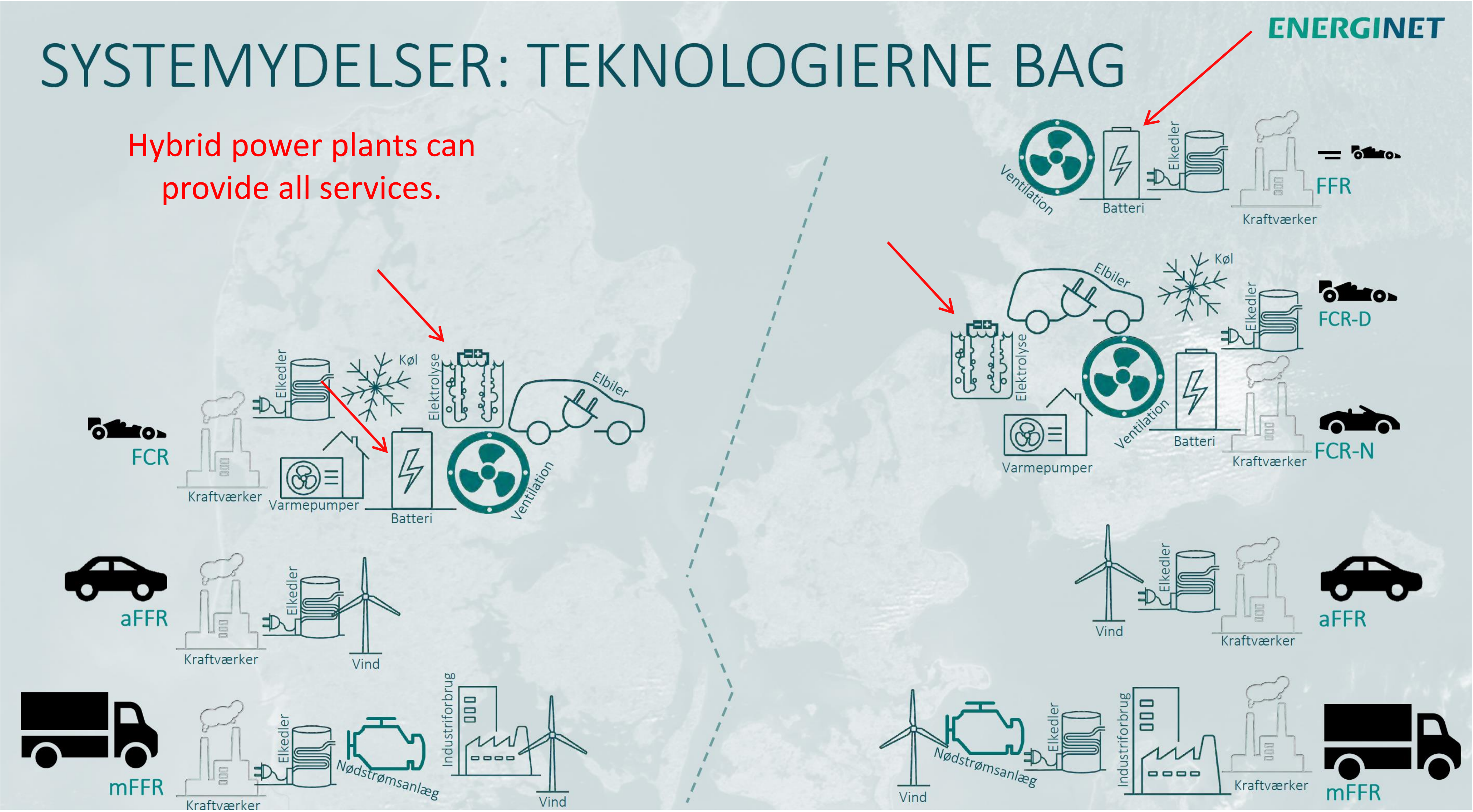
Specifics of Ancillary Services in DK1 and DK2

Source: *Energinet (Gennemgang af Nuværende Systemydelse Markeder)*

Potential Service Providers in DK1 and DK2

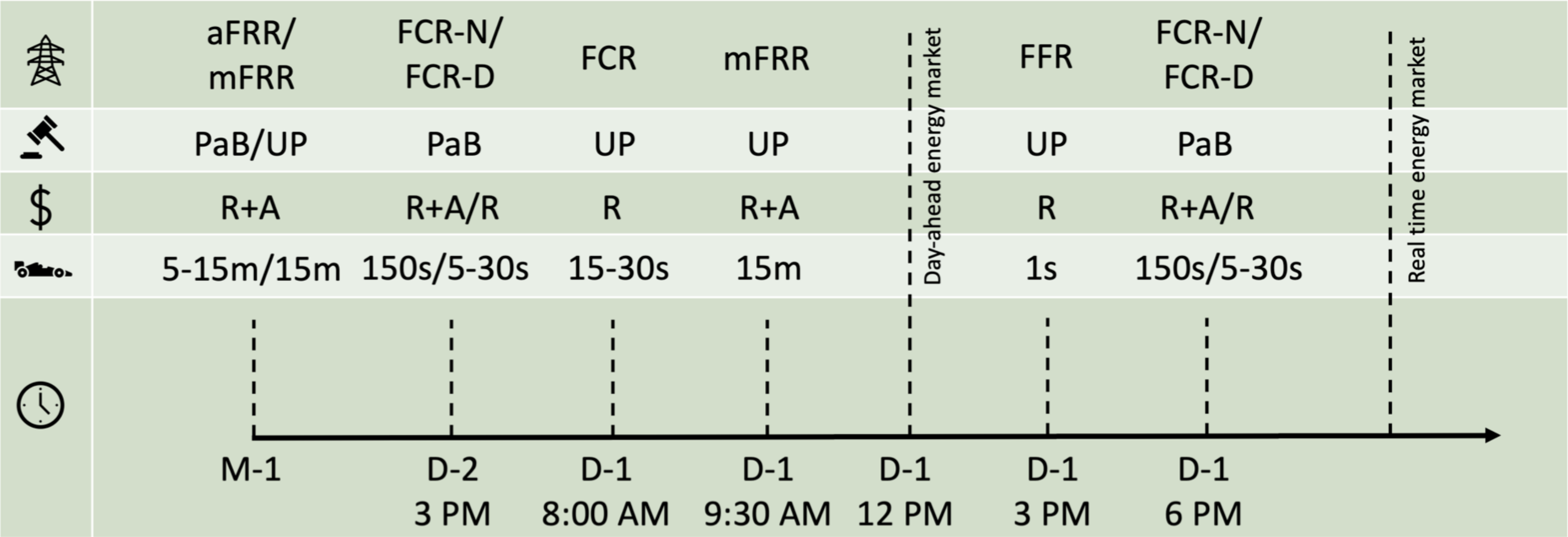
Source: *Energinet (Gennemgang af Nuværende Systemydelse Markeder)*

Potential Service Providers in DK1 and DK2



Source: *Energinet (Gennemgang af Nuværende Systemydelse Markeder)*

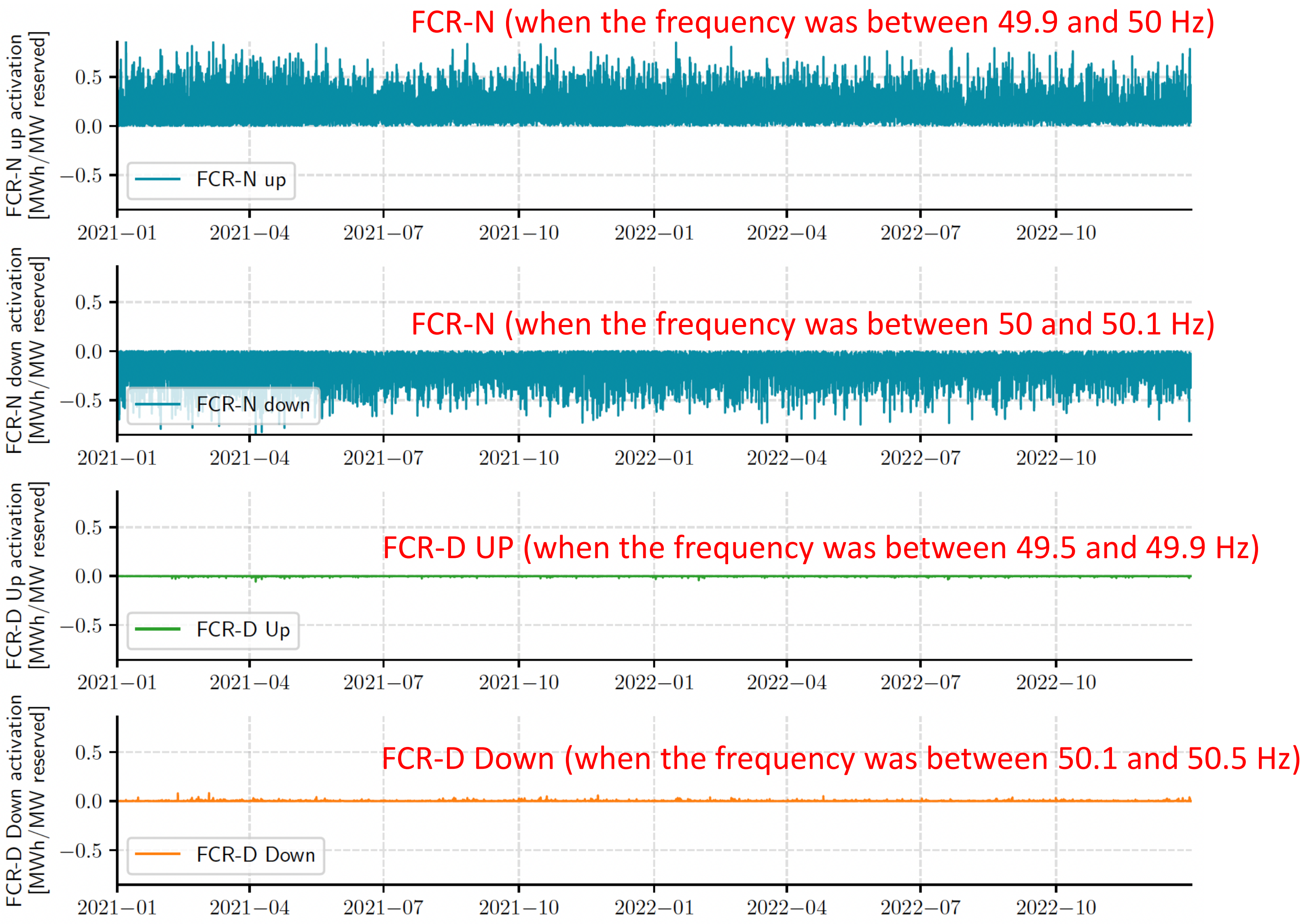
Ancillary Service Markets in DK1 and DK2



Timeline for reservation auctions for all ancillary services in Denmark
Service mFRR has monthly and daily auctions. Both FCR-N and FCR-D have two auctions, running two days and one day before delivery. The auction scheme is shown together with the origin of payment (third row) and the speed of full response (fourth row). For aFRR, the speed of full response is 15 min in DK1 and 5 minutes in DK2, and will be 5 min in DK1 from 2024. *Abbreviations:* PaB: pay-as-bid. UP: uniform pricing. R: reservation payment. A: activation payment. M: month. D: day. m: minutes. s: seconds.

Source: Peter A. V. Gade, Trygve Skjøtskift, Henrik W. Bindner, and JK, "Ecosystem for demand-side flexibility revisited: The Danish solution", *The Electricity Journal*, vol. 35, no. 9, Article no. 107206, November 2022 [link | arXiv]

Historical data: Activated FCR-D and FCR-N in DK2 (2021-2022)



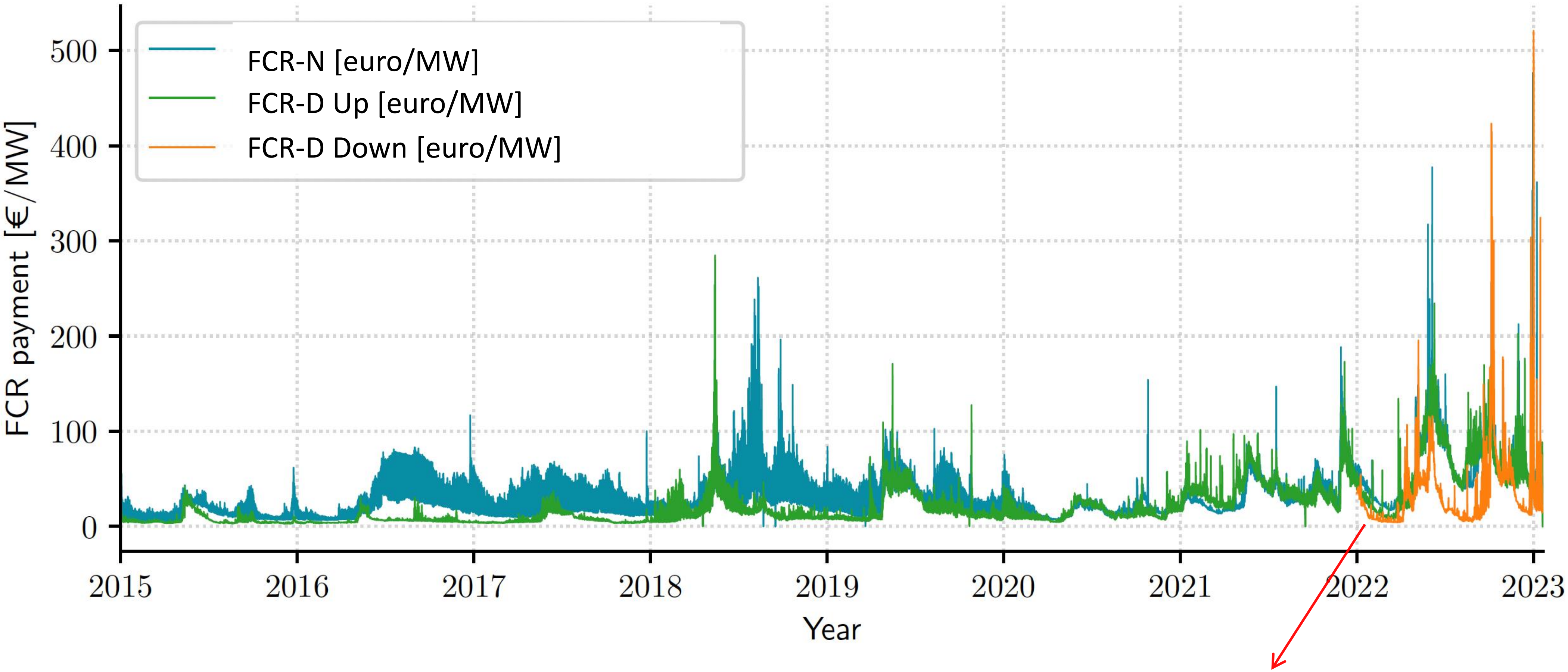
Credit: Marco Saretta

Historical data: Activated FCR-D and FCR-N in DK2 (2021-2022)

FCR-D was very rarely activated! Service providers received payments due to capacity reservation but were activated very rarely!

Credit: Marco Saretta

Historical data: FCR-D and FCR-N prices in DK2 (2015-2022)



FCR-D Down (a service when frequency is between 50.1 and 50.5 Hz) started in January 2022

Credit: Marco Saretta

Challenges

Portfolio Management Problem of the Hybrid Power Plant

Input data

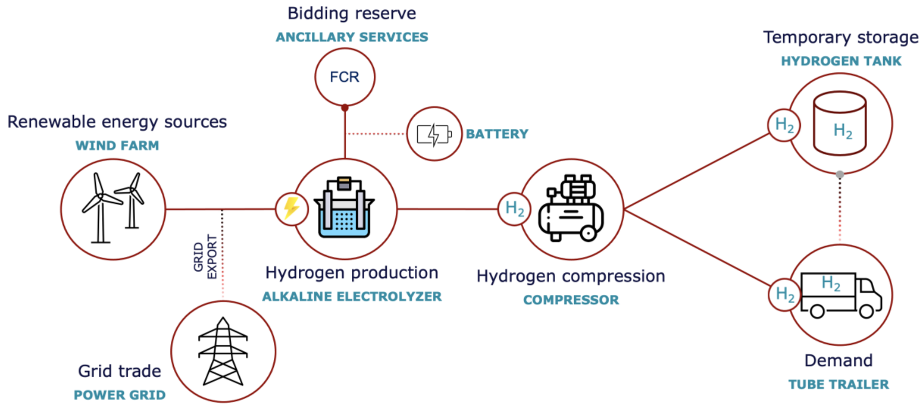
Electricity
- Day-ahead price forecast
- Balancing price forecast
- Wind power forecast

Ancillary services
- FCR/aFRR/mFRR reservation price forecast
- Forecast of activation for each service

Hydrogen
- Hydrogen price
- Minimum hydrogen demand (e.g., over a day)
- Tube trailer availability (e.g., over the next day)

Other technical data

Maximize (expected) profit
Subject to physical and bidding constraints



Scheduling (bidding) decisions

Portfolio Management Problem of the Hybrid Power Plant

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Maximize (expected) profit
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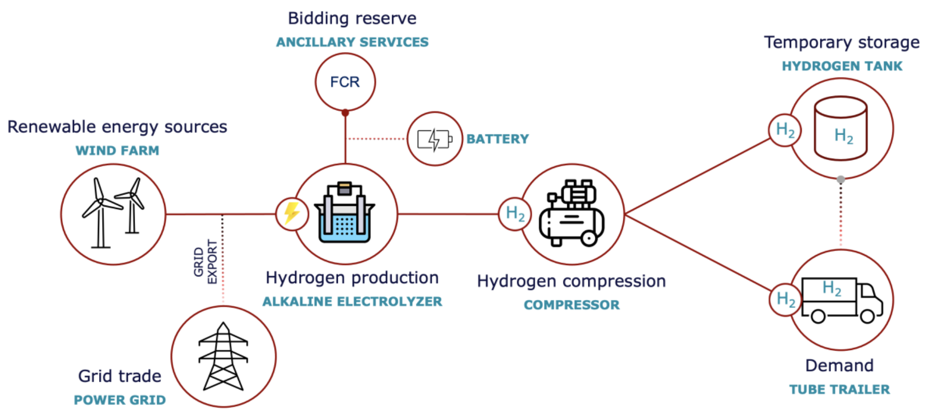

Electricity (uncertain)
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- Balancing price forecast
- Wind power forecast

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Other technical data (certain)

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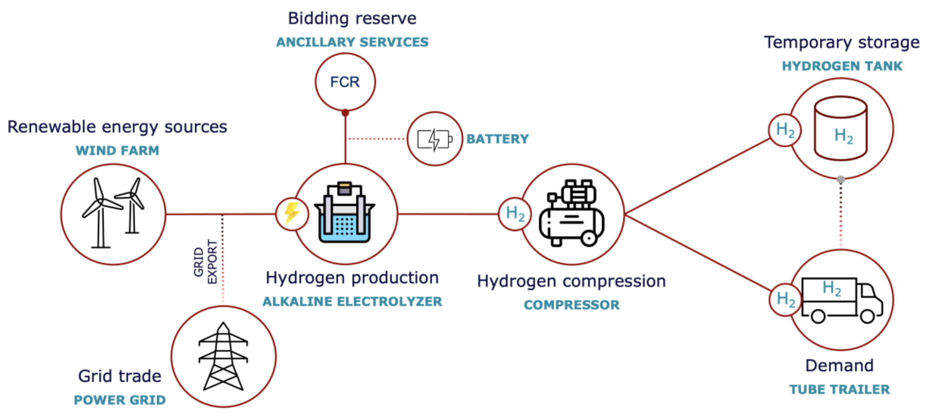

Any challenge?

Scheduling (bidding) decisions

Portfolio Management Problem

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Electricity (uncertain)
- ○ Day-ahead price forecast
- ○ Balancing price forecast
- ○ Wind power forecast

Ancillary services (uncertain)
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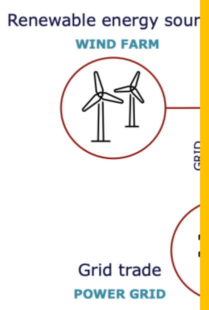
Other technical data (certain)

Maximiz
Subject t



How to properly model uncertainty?

High dimensionality
- ○ Many (potentially correlated) sources of uncertainty

Non-stationarity
- ○ The analysis of historical data suggests our stochastic environment is not necessarily stationary!

Lack of enough historical data
- ○ Example 1: FCR-D down market has been recently established
- ○ Example 2: Denmark has recently switched to a 1-price balancing scheme (before it was 2-price)

Conditionality
- ○ The distribution of forecast error depends on the point forecast.

etc

Portfolio Management Problem of the Hybrid Power Plant

Input data

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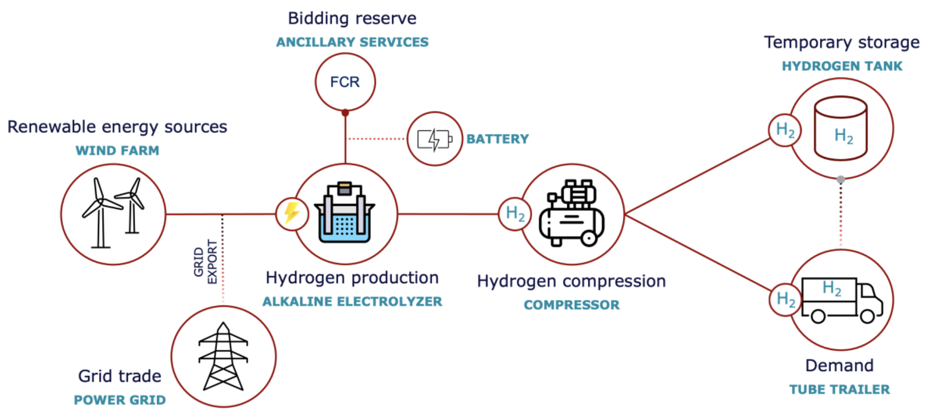

Any other challenge related to modeling the physics of the plant?

Scheduling (bidding) decisions

Portfolio Management Problem

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Electricity (uncertain)
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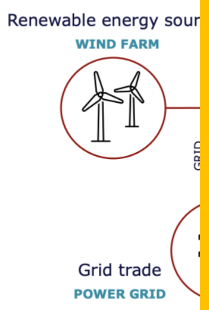
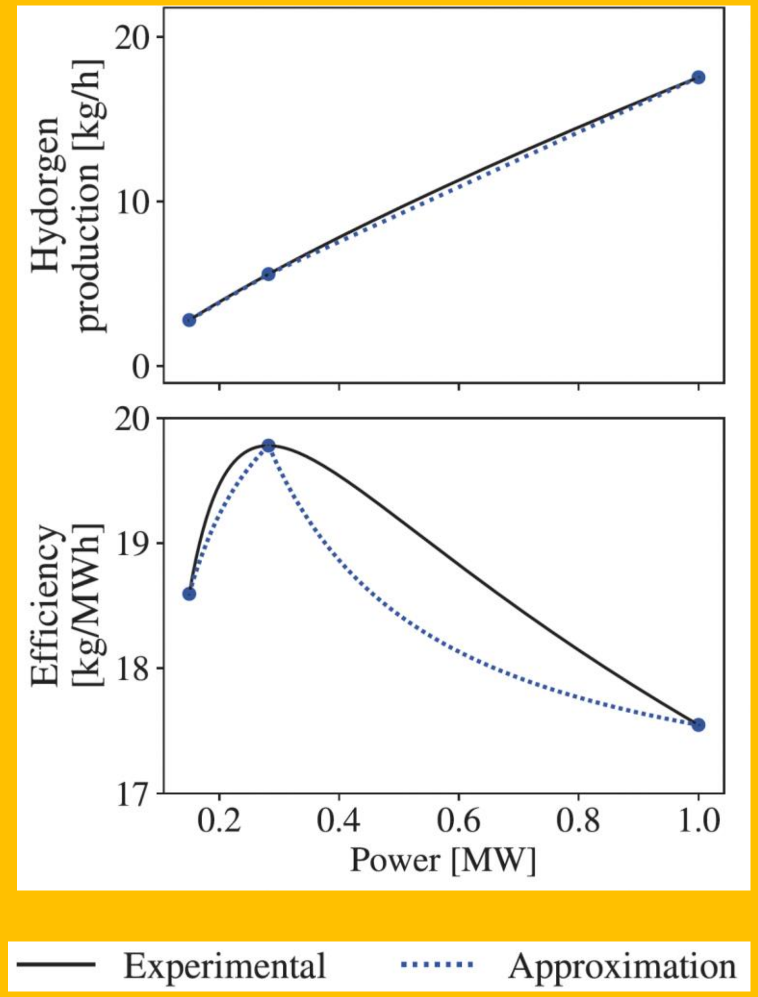


Electrolyzers are non-linear assets:



Several stakeholders in DK are interested in different aspects of such a portfolio management problem

EUROPEAN ENERGY

SIEMENS Gamesa RENEWABLE ENERGY

Danfoss

HYBRID GREENTECH Energy Storage Intelligence

Ørsted

Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping

ENERGINET

CIP Copenhagen Infrastructure Partners

RAMBØLL

TotalEnergies

Ea Energy Analyses

Example hybrid power plant

Site in Flø, Brande, belonging to Siemens Gamesa

Physical Modeling of Electrolyzers:

Piece-wise Linear Approximation

Question: To what extent does it matter to model the physics of electrolyzers in a detailed manner?

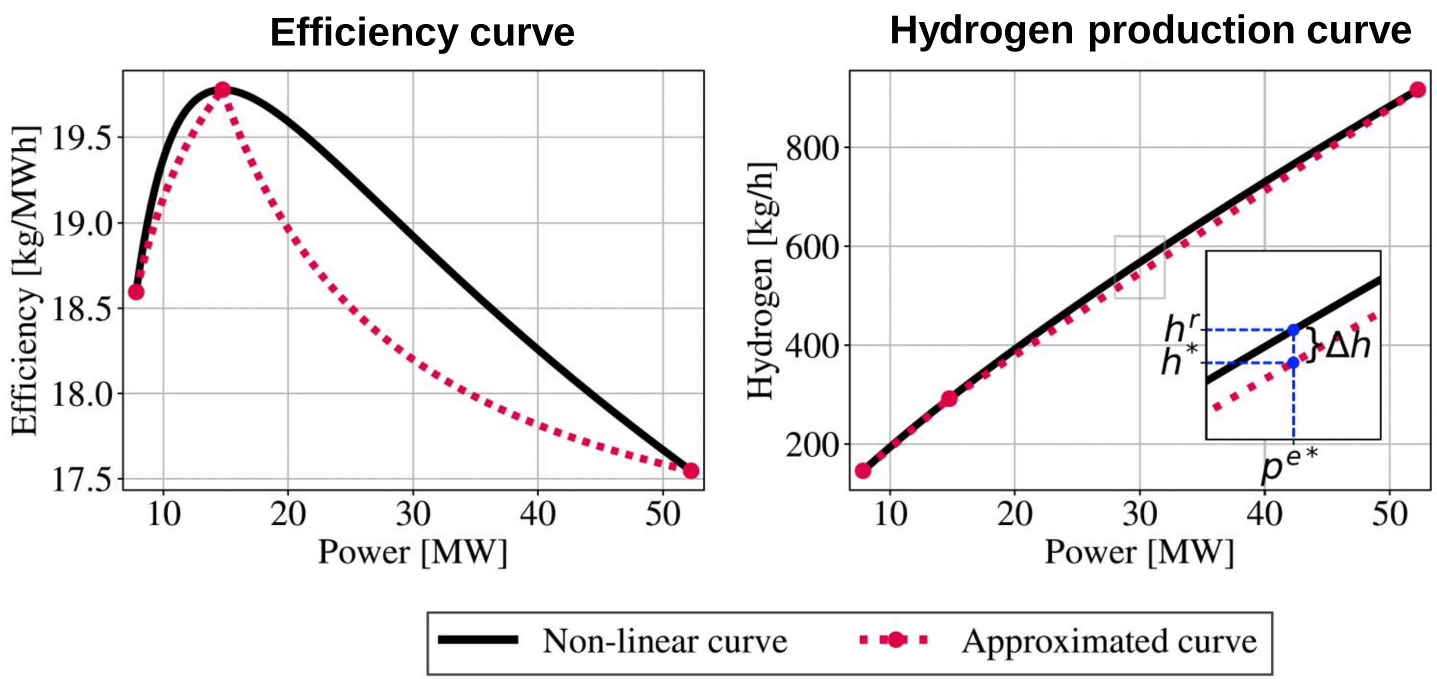
M. T. Baumhof, E. Raheli, A. Gloppen Johnsen, and JK, "Optimization of hybrid power plants: When is a detailed electrolyzer model necessary?," IEEE Belgrade PowerTech 2023. https://arxiv.org/abs/2301.05310

Codes: https://github.com/mtba-dtu/detailed-electrolyzer-model



Hydrogen Production and Efficiency Curves

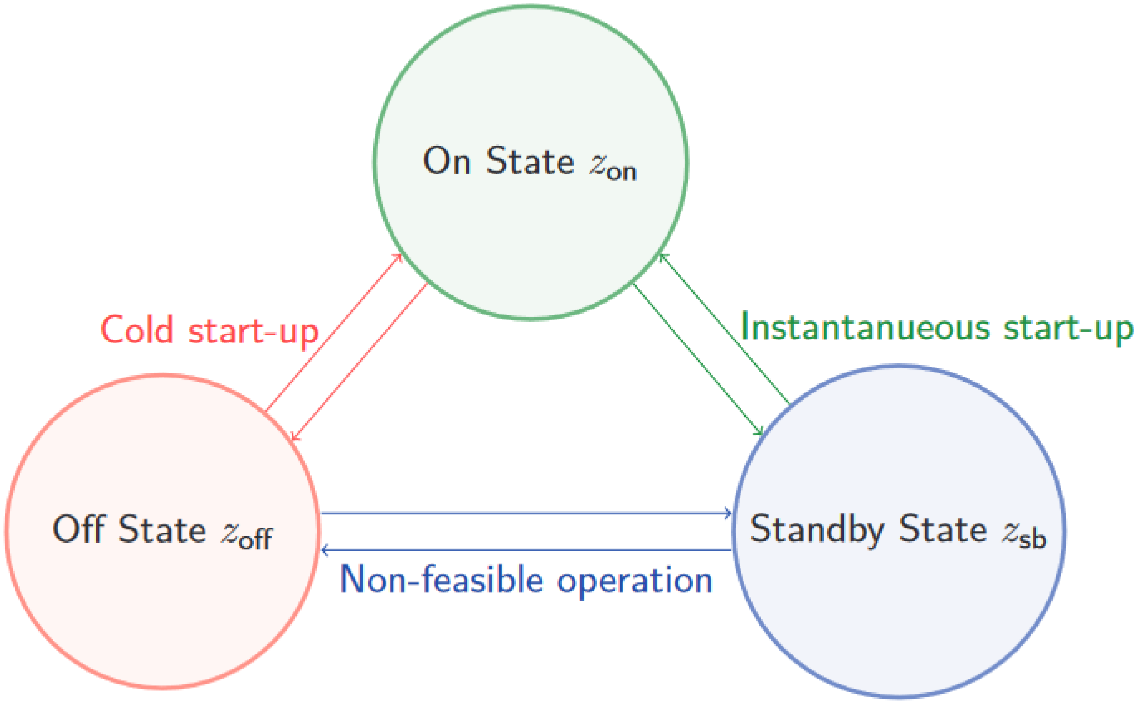
Consider a 52.25-MW alkaline electrolyzer, working at 90 °C and 30 bar.



A simple idea:

- Hydrogen production curve is linearized by a couple of red segments (each segment: *Ax*+*B*) → resulting model: MILP
- The approximate efficiency curve (red) is still nonlinear due to the intercept *B*, but this curve will not be used in our optimization model.

Operating States of Electrolyzers



Online

- Power conumption active
- Hydrogen production

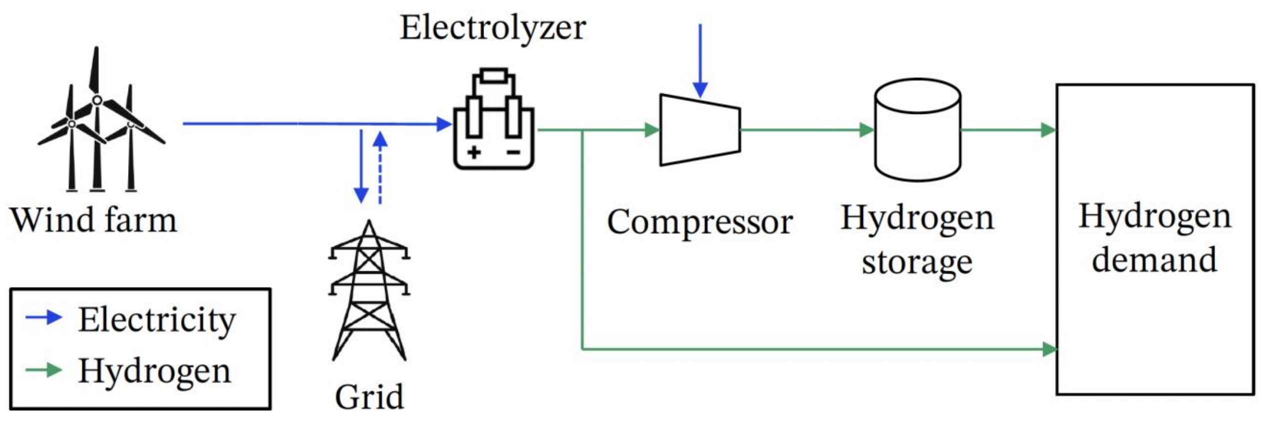
Offline

- No power consumption
- No hydrogen production
- When transitions from *Offline* to *Online*, pay the cold startup cost

Standby

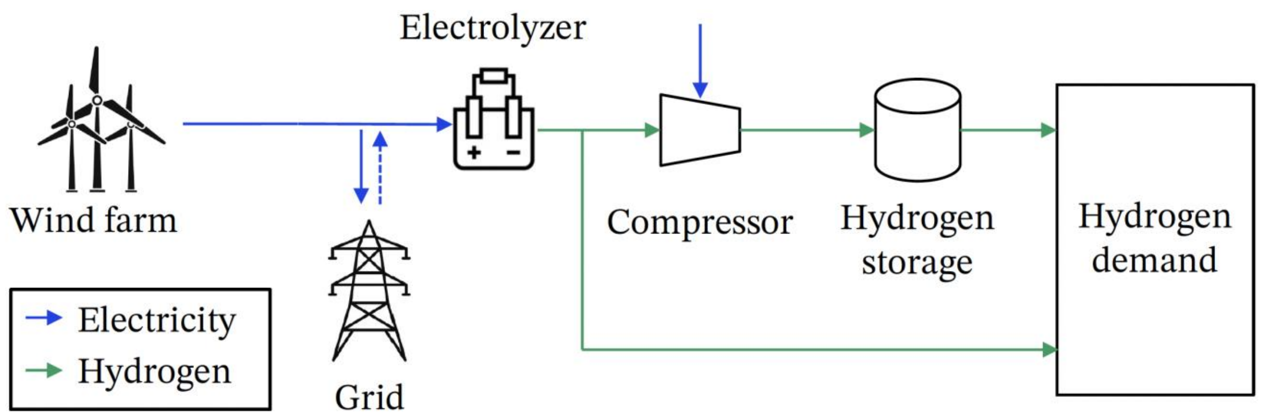
- No hydrogen production
- Power consumption reduced, to keep the electrolyzer hot and pressurized
- No cold start cost when transitions from *Standby* to *Online*

Case Study



- Only electricity and hydrogen (no ancillary services)
- One year simulation (8760 hours)
- Deterministic (known wind power and price profiles)

Case Study



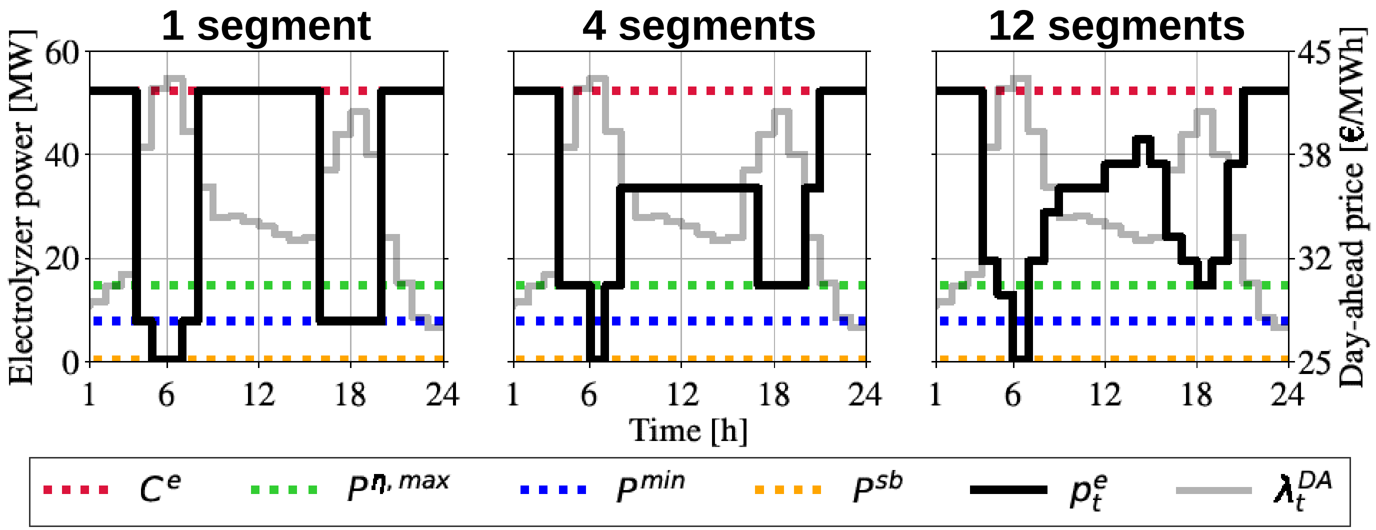
Wind farm	Capacity	104.5	MW
Electrolyzer	Capacity	52.25	MW
	Standby load	0.523	MW
	Minimum load	7.838	MW
	Pressure	30	bar
	Temperature	90	°C
	Maximum current density	5,000	A/m^2
	Startup cost	50	€/MW
	TSO tariff	15.06	€/MWh
Storage	Capacity	22,000	kg
	Input/Output	912.13	kg/h
Compressor	Inlet temperature	40	°C
	Inlet pressure	30	bar
	Outlet pressure	200	bar
	Mechanical efficiency	75%	
Hydrogen	Price	2.10	€/kg
	Minimum demand	2,750	kg/d

- Only electricity and hydrogen (no ancillary services)
- One year simulation (8760 hours)
- Deterministic (known wind power and price profiles)

Results: Impact of the number of segments 1/2

(Number of states fixed)

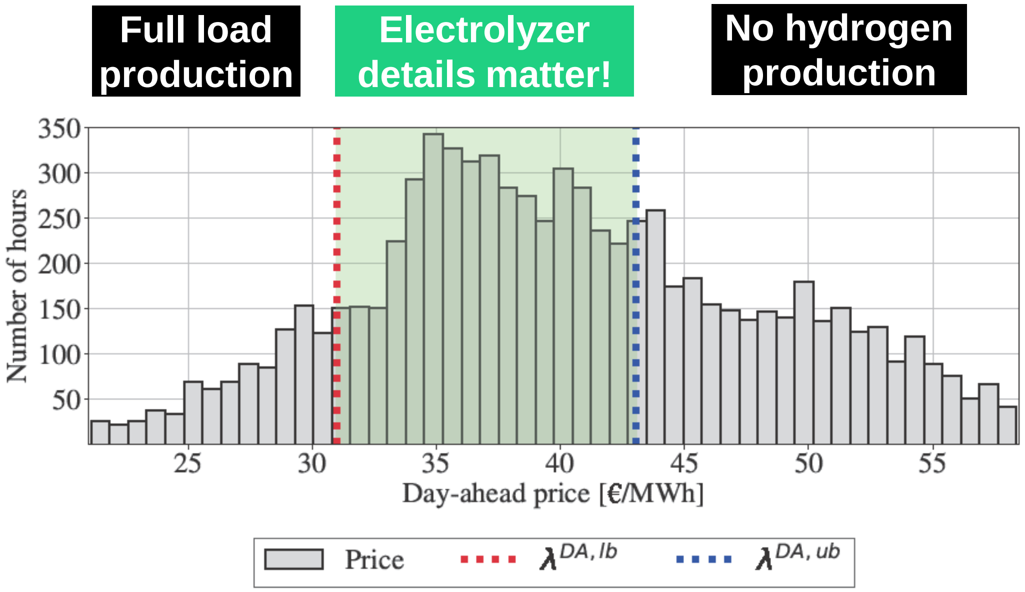
Power consumption schedule of the electrolyzer in an example high-wind day



- By adding more segments, the electrolyzer consumes power more **dynamically** (following the day-ahead price signal)
- This happens within a specific **price range**

Results: Impact of the number of segments 2/2

Histogram of the day-ahead hourly prices in 2019



$$\lambda^{\mathrm{DA,ub}} = \frac{\lambda^{\mathrm{h}} \eta^{\max} P^{\eta,\max}}{P^{\eta,\max} - P^{\mathrm{sb}}}.$$

$$\lambda^{\mathrm{DA,lb}} = \lambda^{\mathrm{h}} (\eta^{\mathrm{fl}} + C^{\mathrm{e}} \eta'(x)|_{x=C^{\mathrm{e}}})$$

$\lambda^{DA,ub}$ and $\lambda^{DA,lb}$ depends only on:

- electrolyzer efficiency curve
- standby power consumption
- hydrogen price

Based on the **range of day-ahead prices**, we know "***a priori***" whether adding more segments matter

Physical Modeling of Electrolyzers:

Conic Relaxation

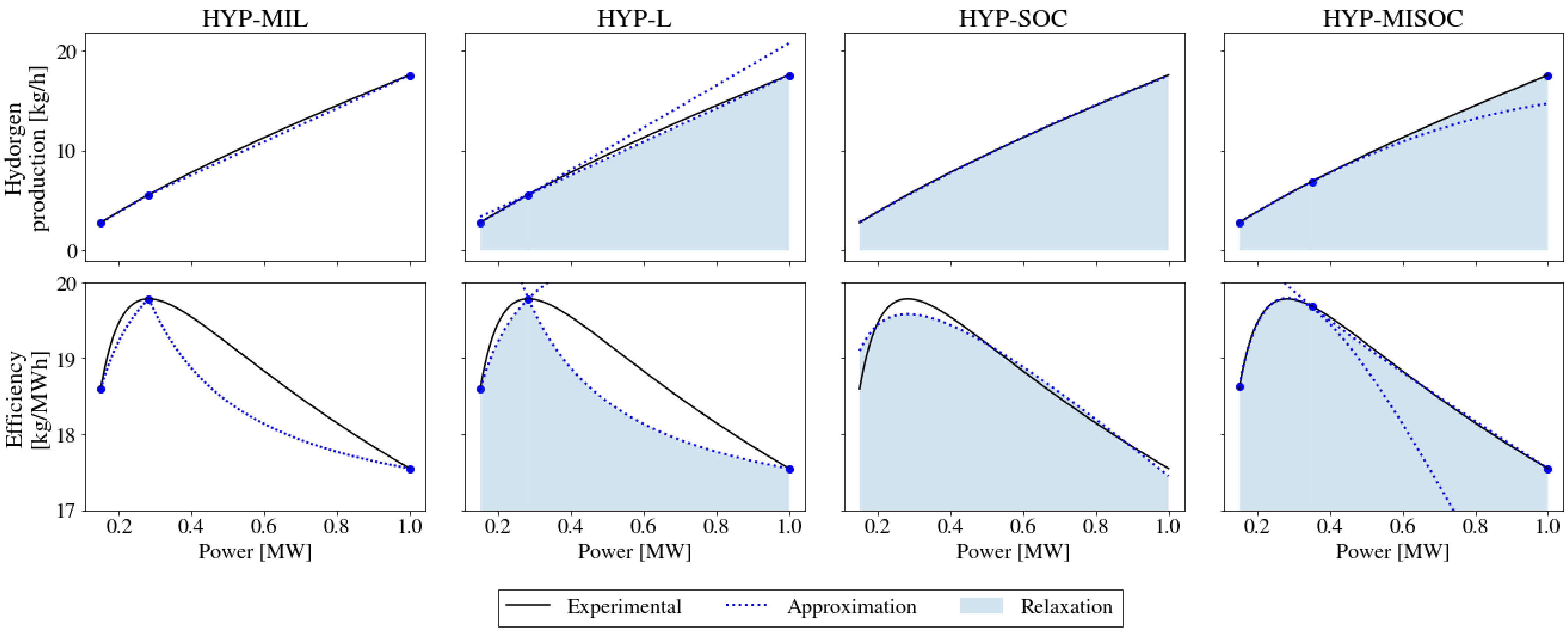
E. Raheli, Y. Werner, and JK, “A conic model for electrolyzer scheduling,” https://arxiv.org/abs/2306.10951

Codes: https://github.com/ELMA-Github/conic_electrolyzer_paper

Potential Solutions for Convexification of the Curve

Hydrogen production curves (convexified and then to be used in the model)

Efficiency curves (not to be used in the model)



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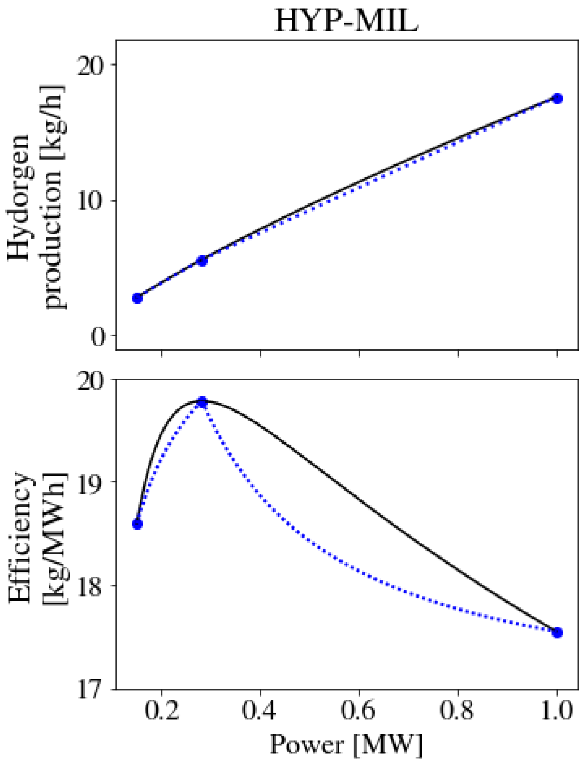
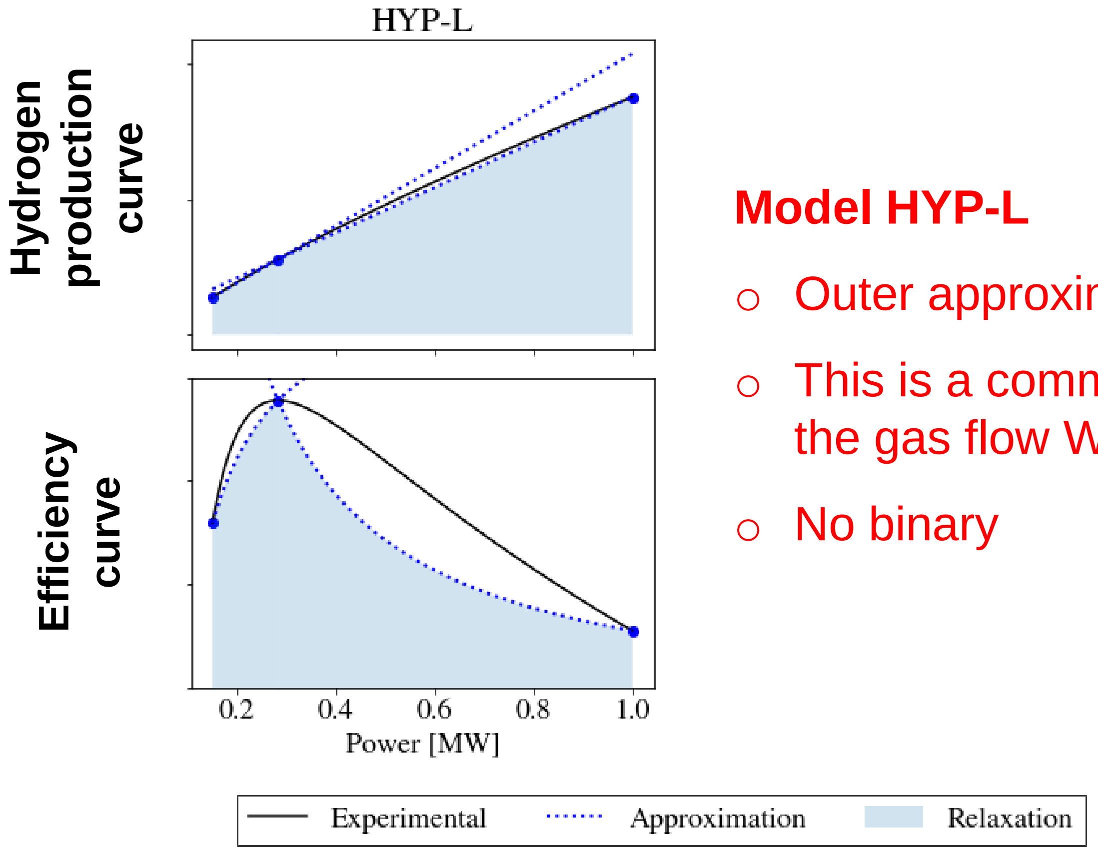


Model HYP-MIL

- Piece-wise linear approximation of the hydrogen production curve
- One binary per segment

Potential Solutions for Convexification of the Curve



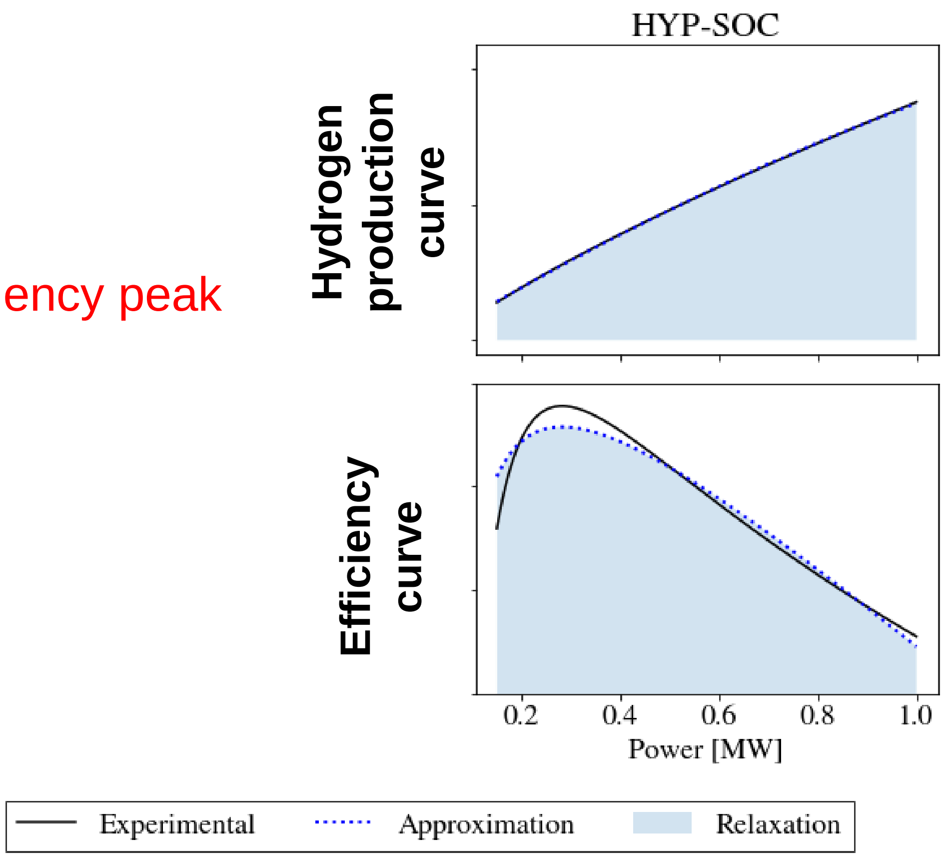
Model HYP-L

- Outer approximation (relaxation)
- This is a common approach to convexify the gas flow Weymouth equations.
- No binary

Potential Solutions for Convexification of the Curve

Model HYP-SOC

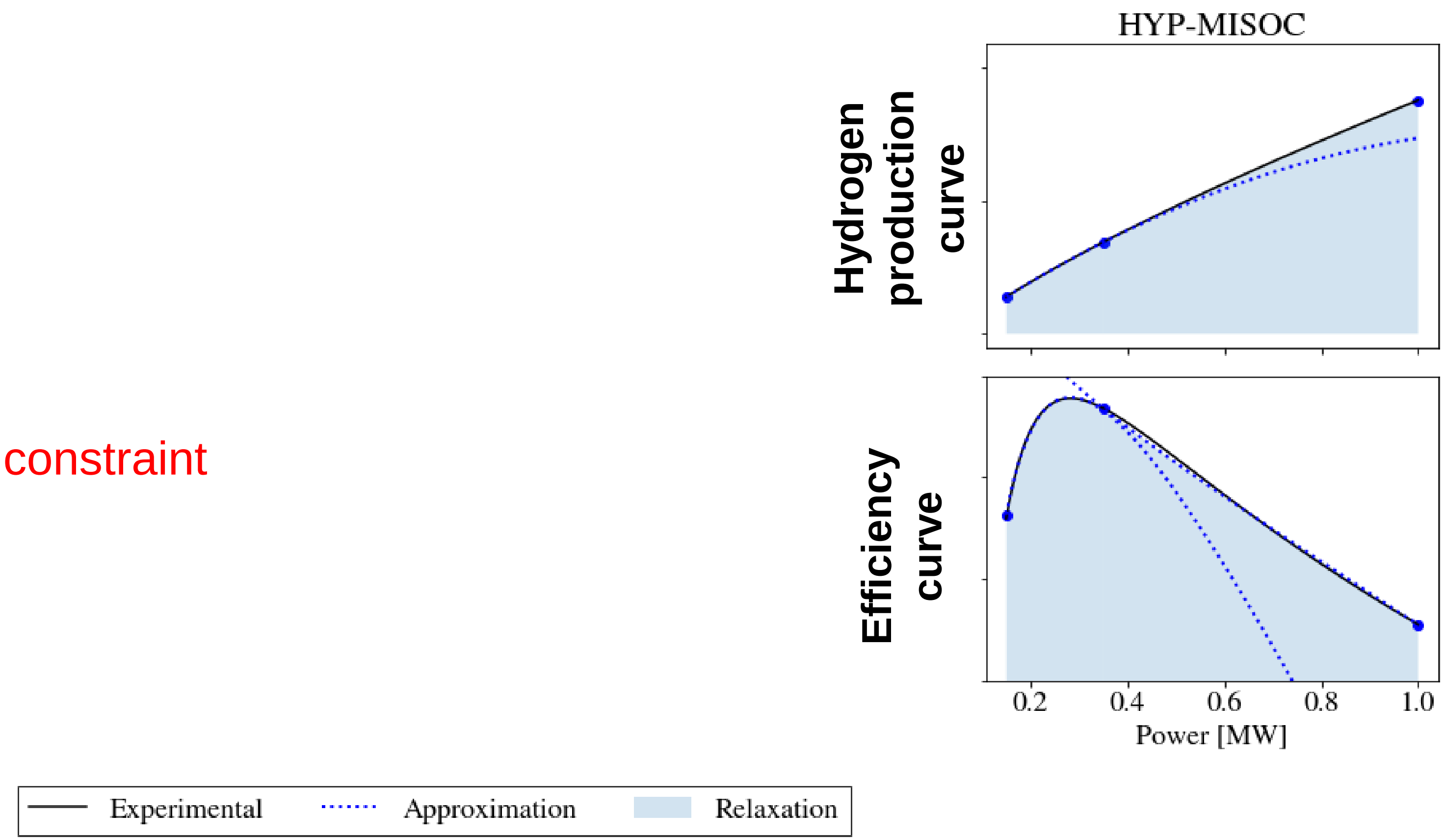
- Fitting a conic equation, with the same efficiency peak
- Conic relaxation
- No binary



Potential Solutions for Convexification of the Curve

Model HYP-MISOC

- Fitting two conic equations
- Conic relaxation
- One binary only to choose the active conic constraint



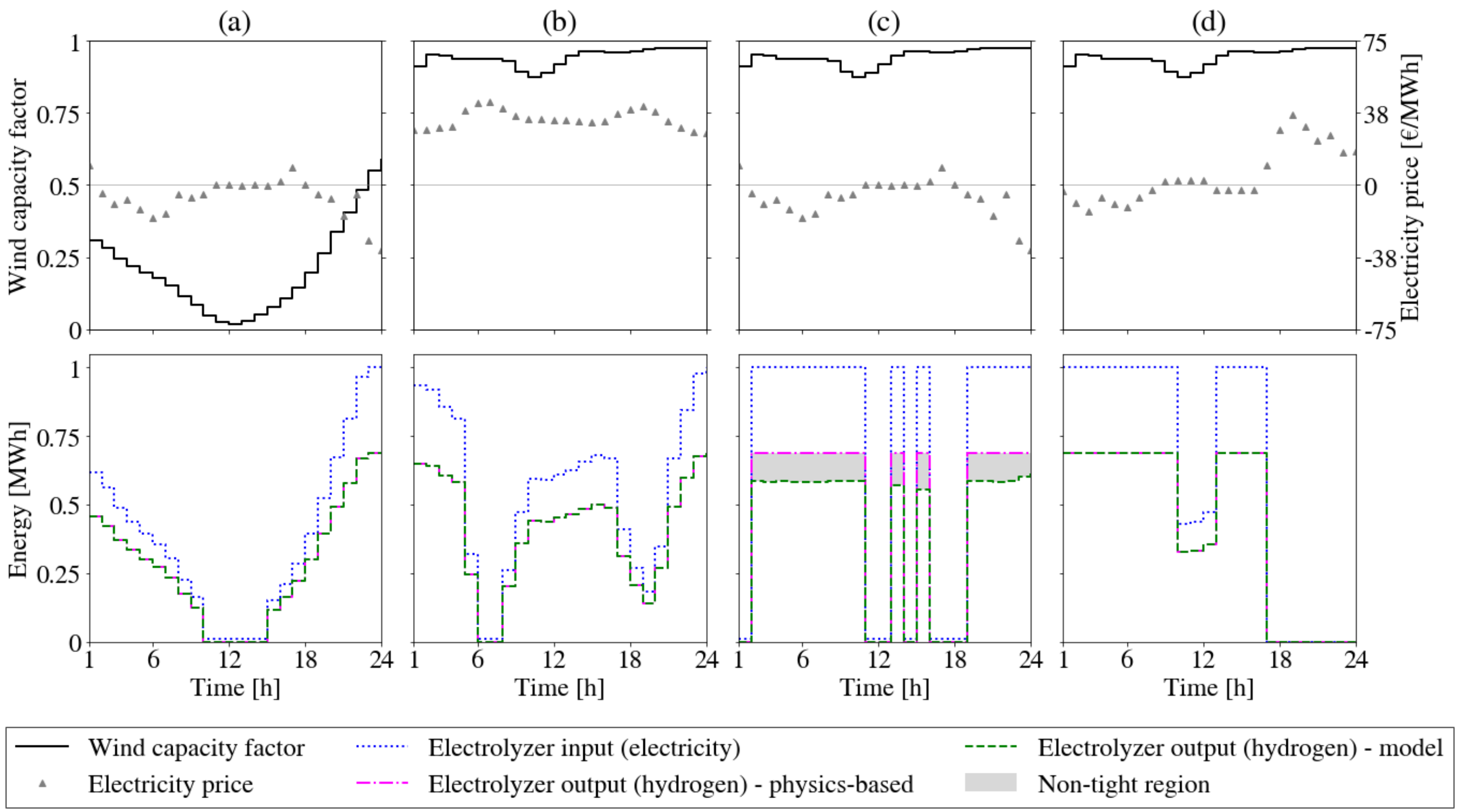
Case Study: Tightness of the Relaxation

HYP-SOC model (identical observations for other models)

Day	Minimum daily hydrogen demand constraint	Electricity prices	Wind	Tightness
a	Not binding	Most of hours: negative prices	Low wind	**Exact**
b	Binding	All hours: positive prices	High wind	**Exact**
c	Binding	Most of hours: negative prices	High wind	**Inexact**
d	Binding	Most of hours: positive prices	High wind	**Exact**

This is a real case study (17/03/2019)

Case Study: Tightness of the Relaxation



Some observations

- Day (a): if the demand constraint is not binding, the relaxation is always **exact.**
- Day (b): if the demand constraint is binding but prices are positive, the relaxation is always **exact.**
- Day (c): if the demand constraint is binding and there are many negative prices → relaxation is **inexact.**
- Day (d): if the demand constraint is binding and there are a few negative prices → the relaxation is **exact.**

- *Mathematical proofs of the **exactness** of the conic relaxation under (prevalent) operational circumstances are available in the paper.*

Value of Ancillary Services for Electrolyzers

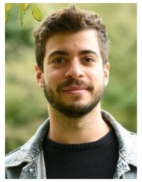
M. Saretta, E. Raheli, and JK, “Electrolyzer scheduling for Nordic FCR services," IEEE SmartGridComm 2023, Glasgow, Scotland, November 2023. https://arxiv.org/abs/2306.10962

Codes: https://github.com/marco-srtt/electrolyzer_nordic_FCR

A. Gloppen Johnsen, L. Mitridati, D. Zarrilli, and JK, “Value of ancillary services for electrolyzers," soon to be shared

Codes: TBD






Hybrid Power Plant in Ancillary Service Markets

Let's consider a subset of existing services in DK1, including mFRR (up and down) and FCR. There are minimum bid size and bid time length constraints.

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mFRR up:

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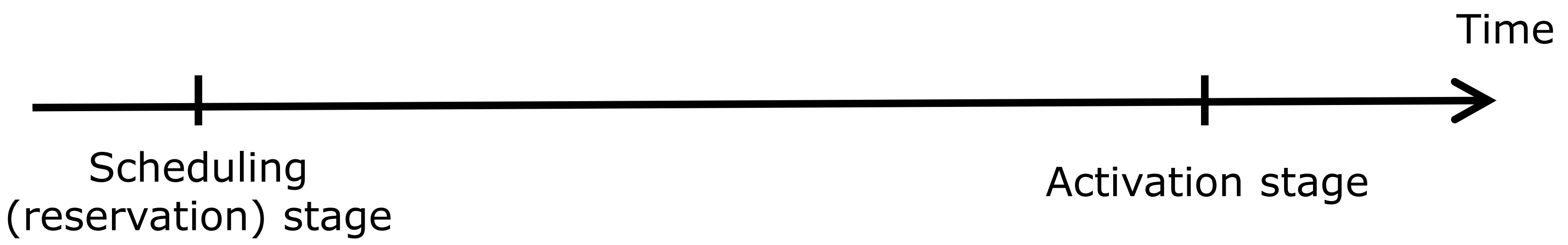
- If activated (partial or full), the plant is paid at the balancing price for the energy not consumed. Meanwhile, the plant will produce less hydrogen due to less electric energy consumption.



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Hybrid Power Plant in Ancillary Service Markets

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mFRR down:

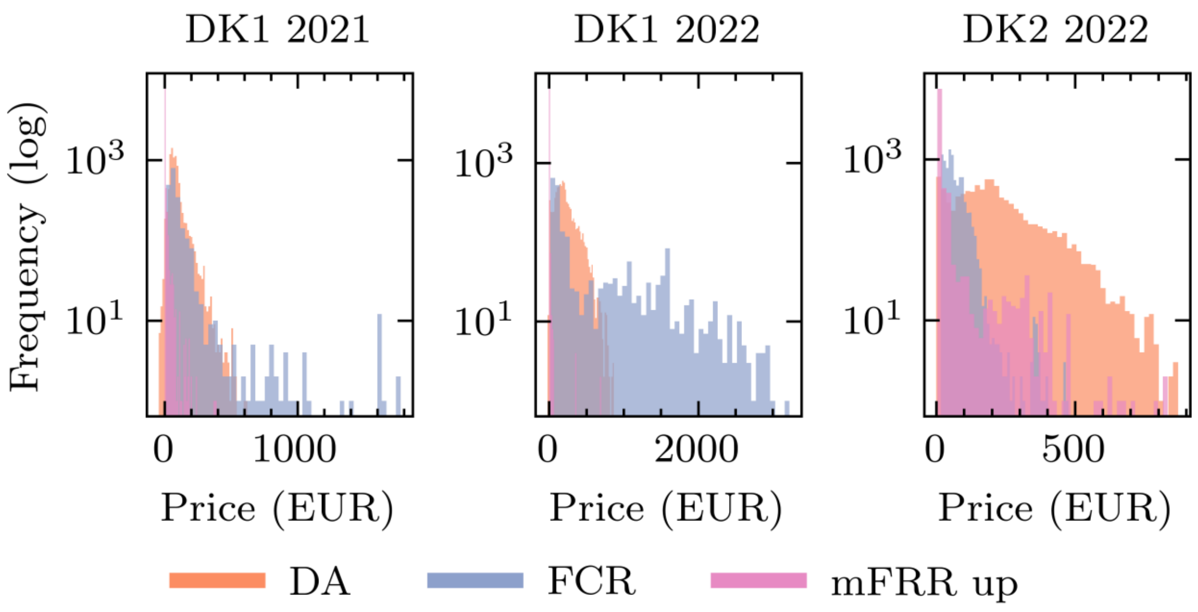
- The hybrid power plant is paid for the reservation sold based on mFRR down market price.
- If activated (partial or full), the plant pays at the balancing price for the additional energy consumed. Meanwhile, the plant will produce more hydrogen due to extra electric energy consumption.

FCR:

- The hybrid power plant is paid for the reservation sold based on FCR market price.
- No payment/cost in the balancing stage for the activation. Not an energy-intense service. The activation is automatic based on frequency deviations between 49.9 and 50.1 Hz, which is quite symmetric over a time period, so one can imagine FCR up and down activations cancel out each other.

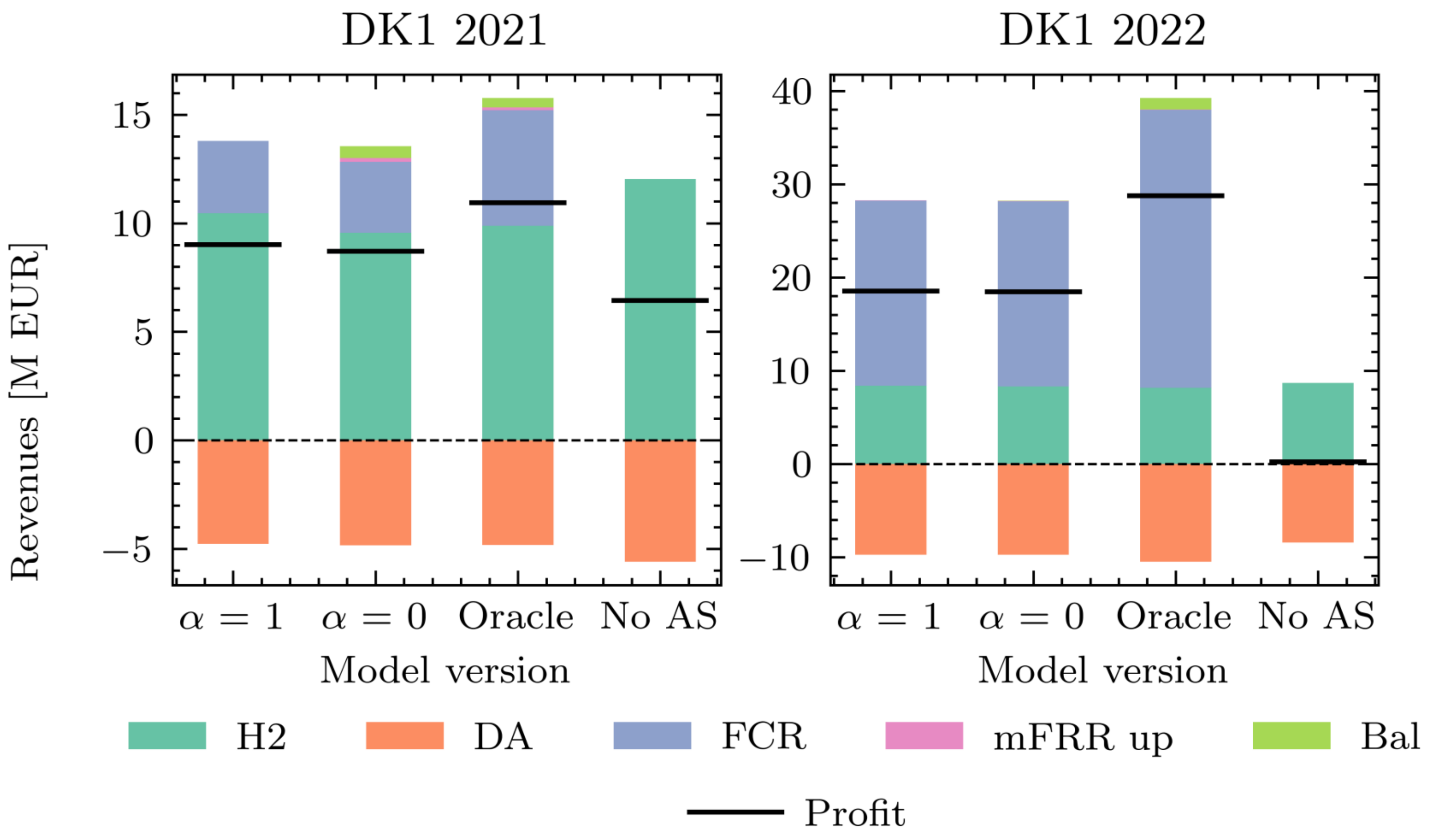
Hybrid Power Plant in Ancillary Service Markets

- We use realized prices in DK1 in 2021 and 2022 (ideal benchmark to obtain the highest potential value of services).
- Deterministic model

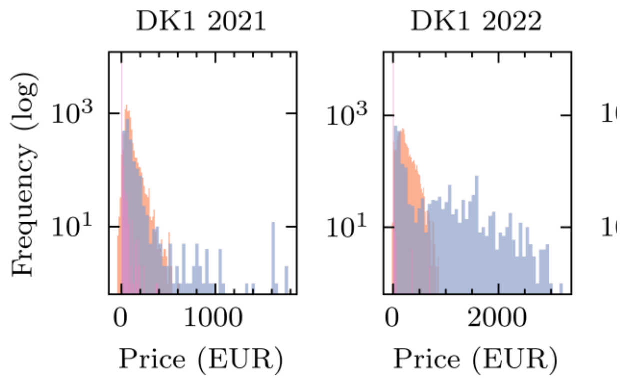


Hybrid Power Plant in Ancillary Service Markets

Revenues

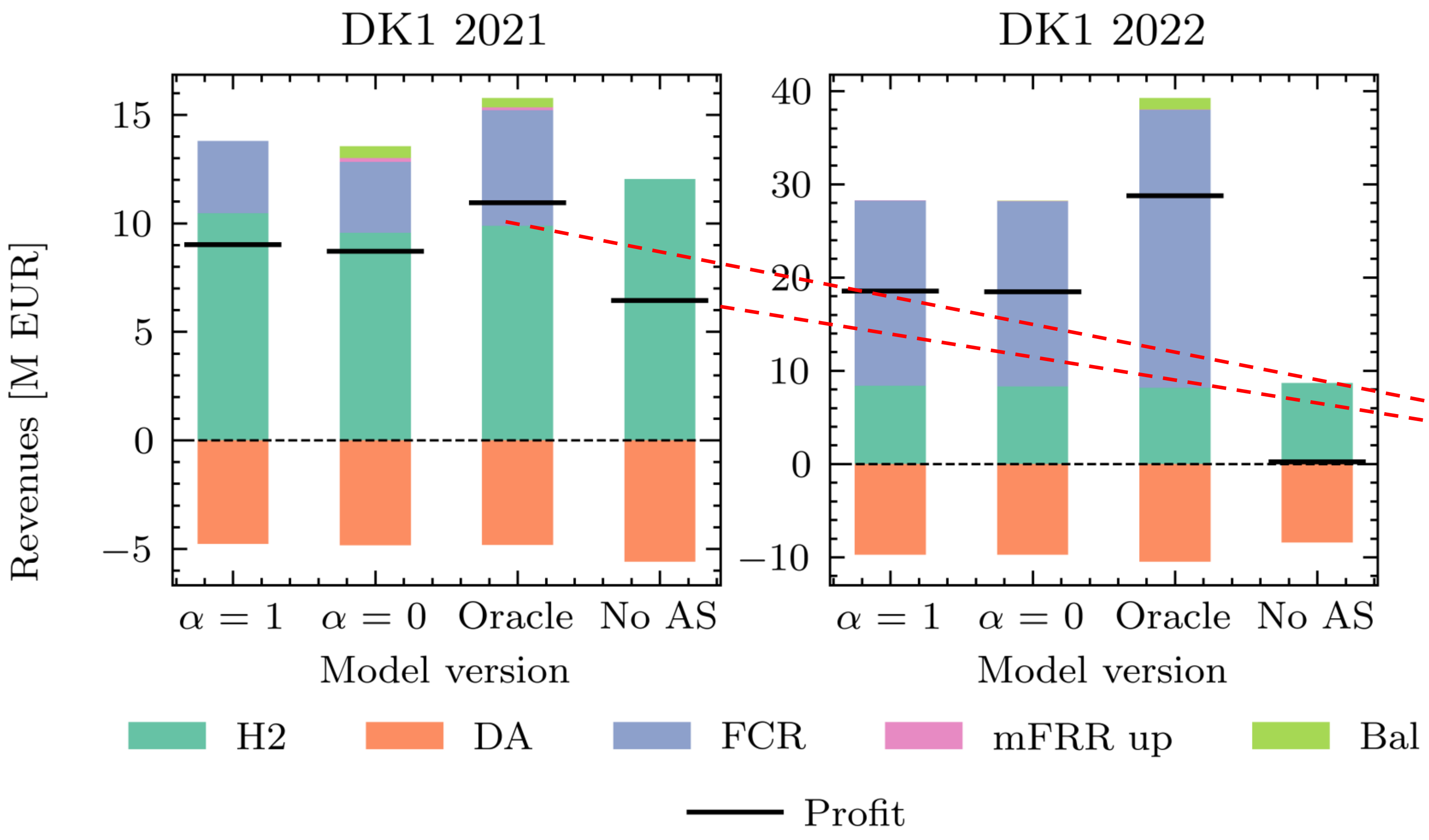


Prices

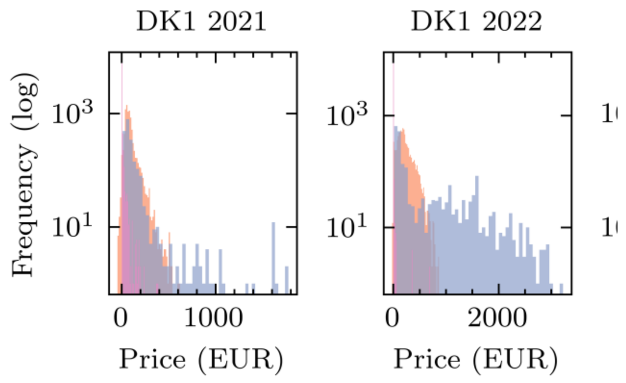


Hybrid Power Plant in Ancillary Service Markets

Revenues



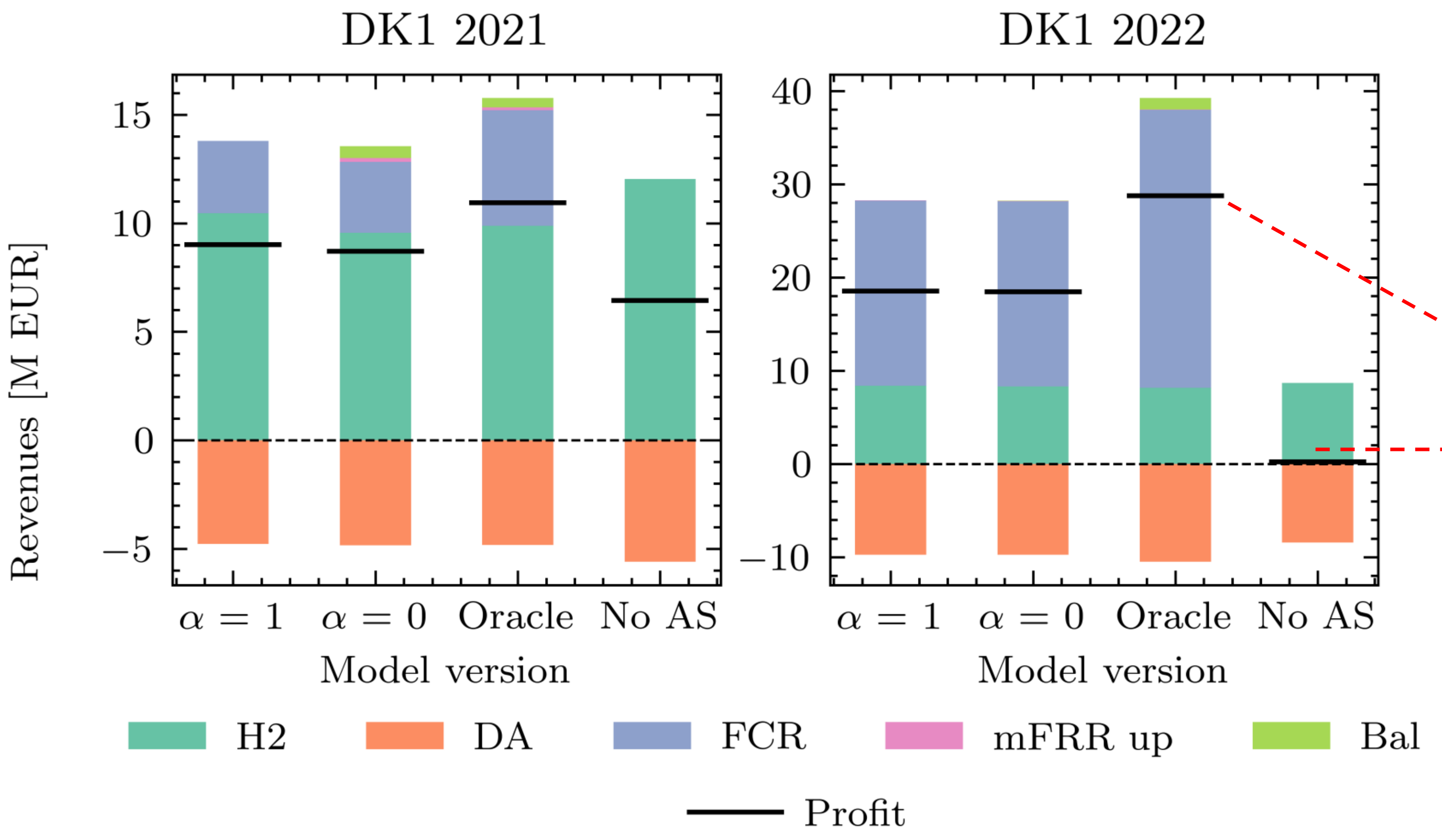
Prices



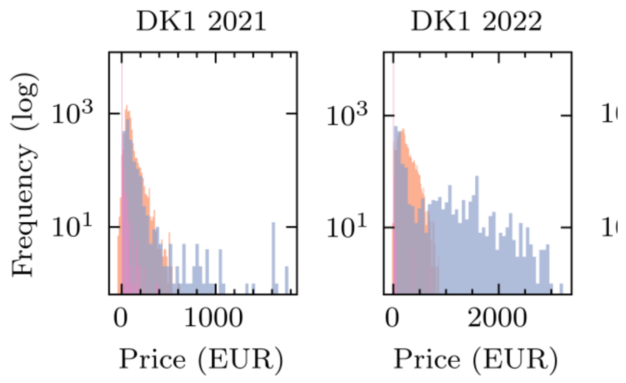
In DK1 (2021), an electrolyzer had a maximum potential to increase its profit by by **50%** providing FCR and mFRR services!

Hybrid Power Plant in Ancillary Service Markets

Revenues



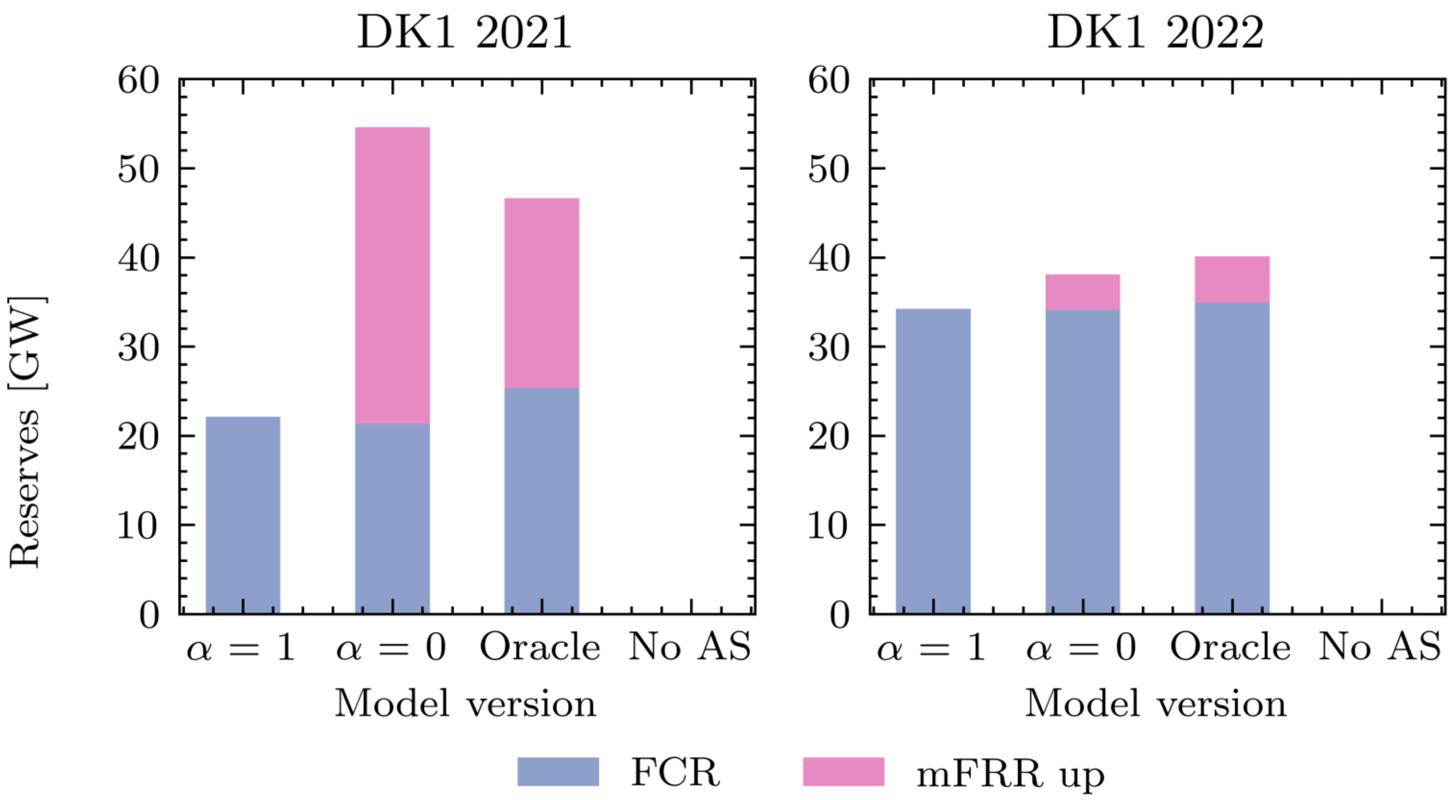
Prices



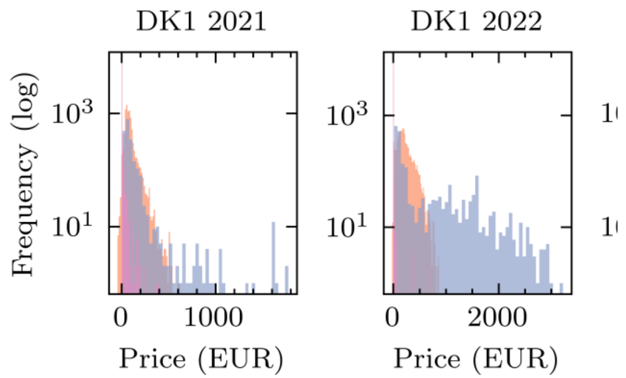
In DK1 (2022), there was a HUGE potential!

Hybrid Power Plant in Ancillary Service Markets

Quantities



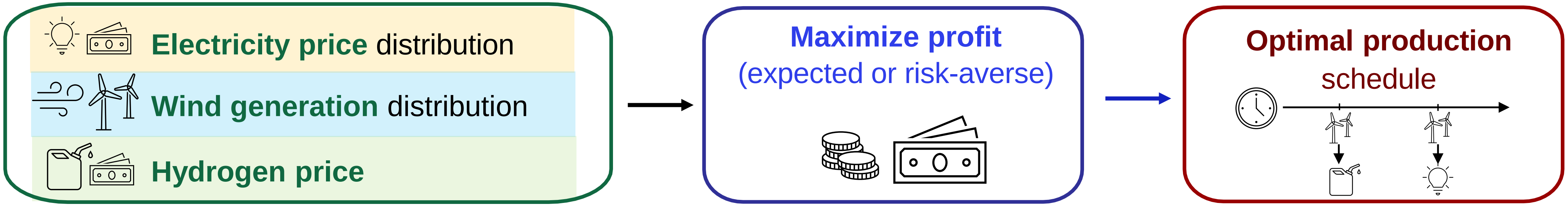
Prices



Portfolio Management Problem: Distributionally Robust Optimization




Concept



Electricity price distribution
Wind generation distribution
Hydrogen price
Maximize profit
(expected or risk-averse)
Optimal production
schedule

Concept

Electricity price distribution

Wind generation distribution

Hydrogen price

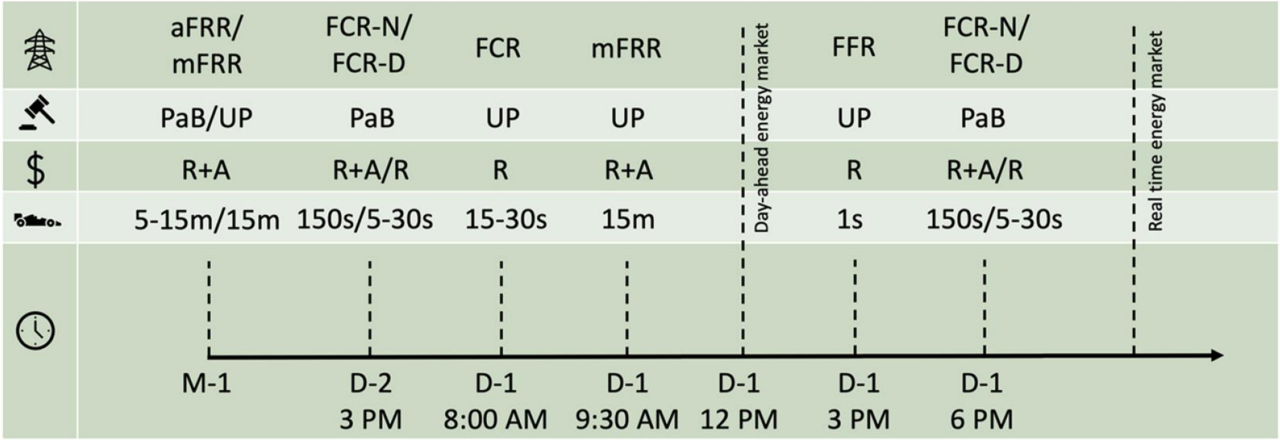
→

Maximize profit
(expected or risk-averse)

→

Optimal production
schedule

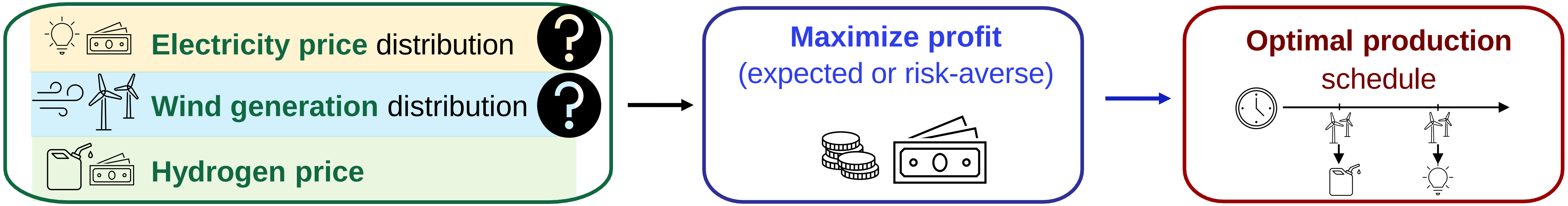
Also **Ancillary service market prices (FCR, aFRR, mFRR)**



Timeline of clearing ancillary service markets in Denmark

Reference: P. V. Gade et al., "Ecosystem for demand-side flexibility revisited: The Danish solution," *The Electricity Journal,* 2022

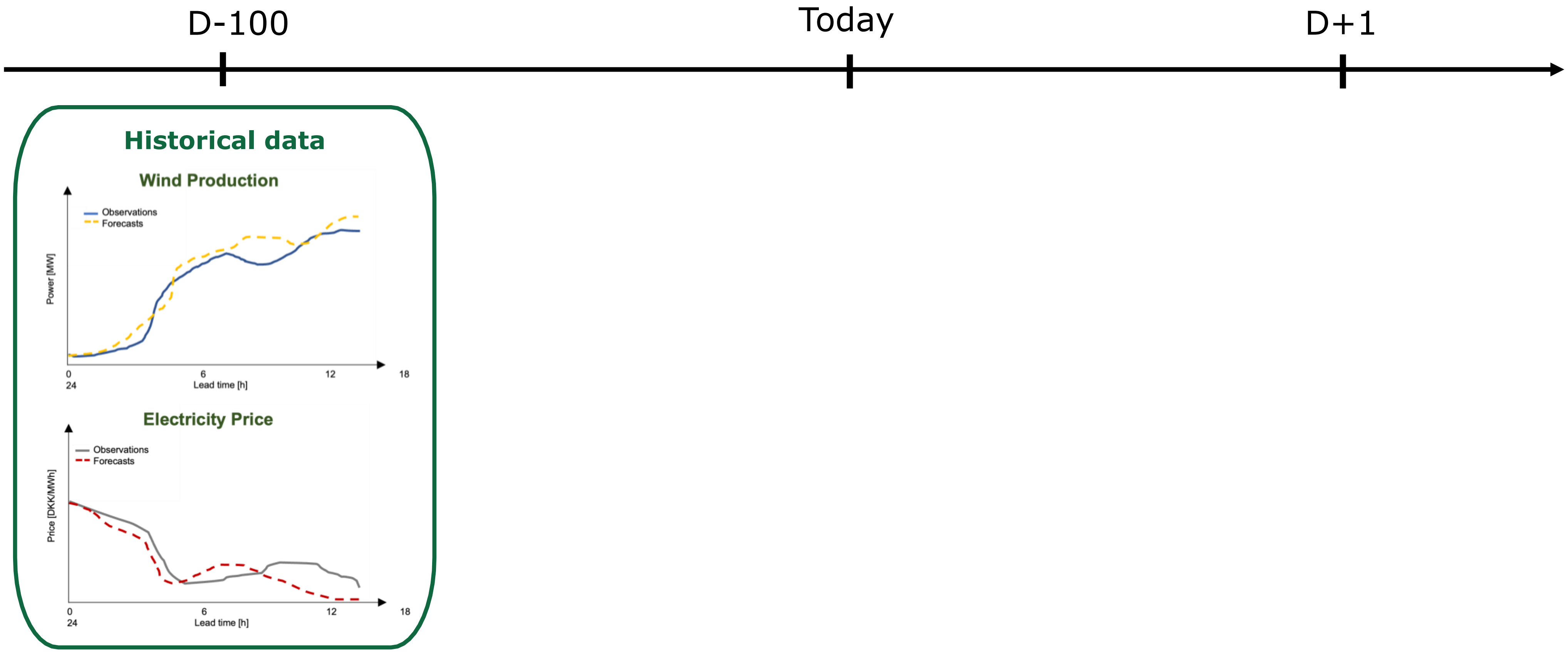
Concept



Main challenges:

- Model **uncertainty** sources accurately
- Model and **mitigate risk** of decisions

Concept


D-100
Today
D+1
Historical data
Wind Production
Observations
Forecasts
Power [MW]
0
24
6
12
18
Lead time [h]
Electricity Price
Observations
Forecasts
Price [DKK/MWh]
0
24
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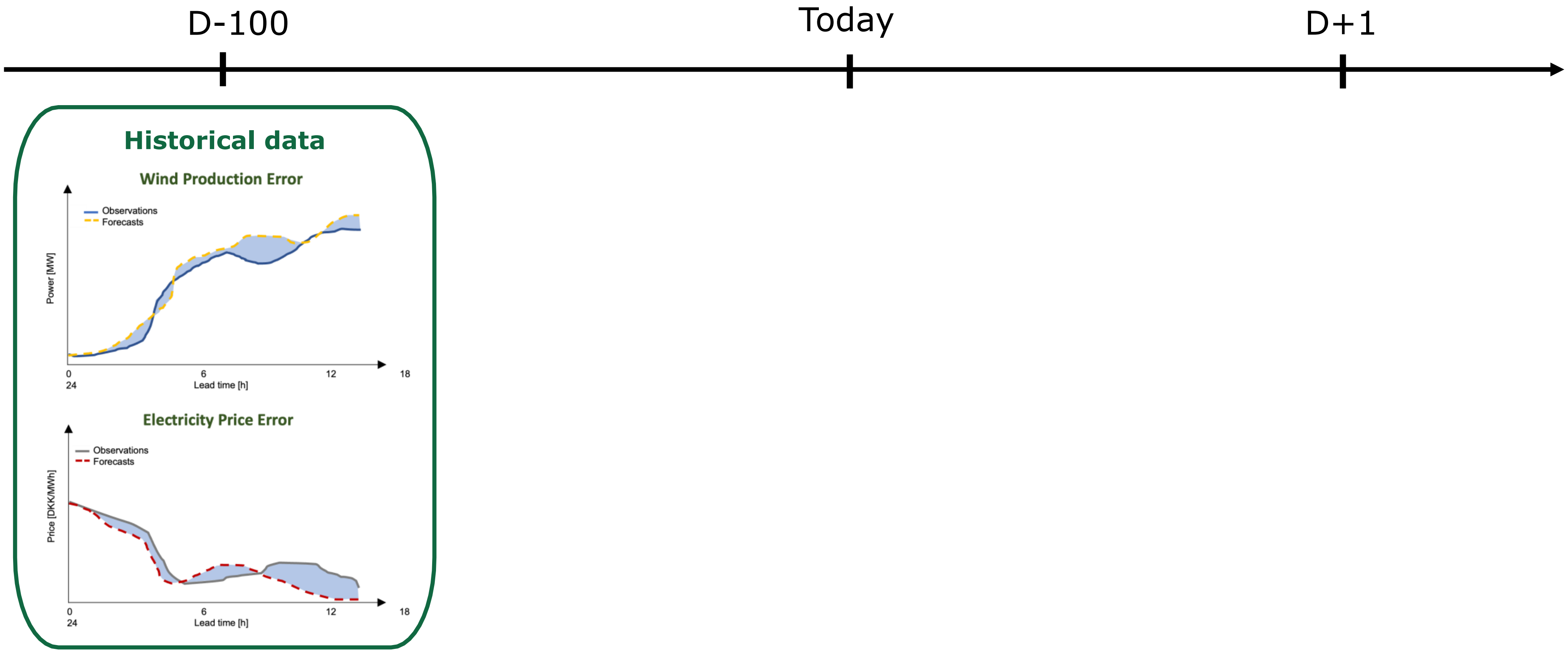
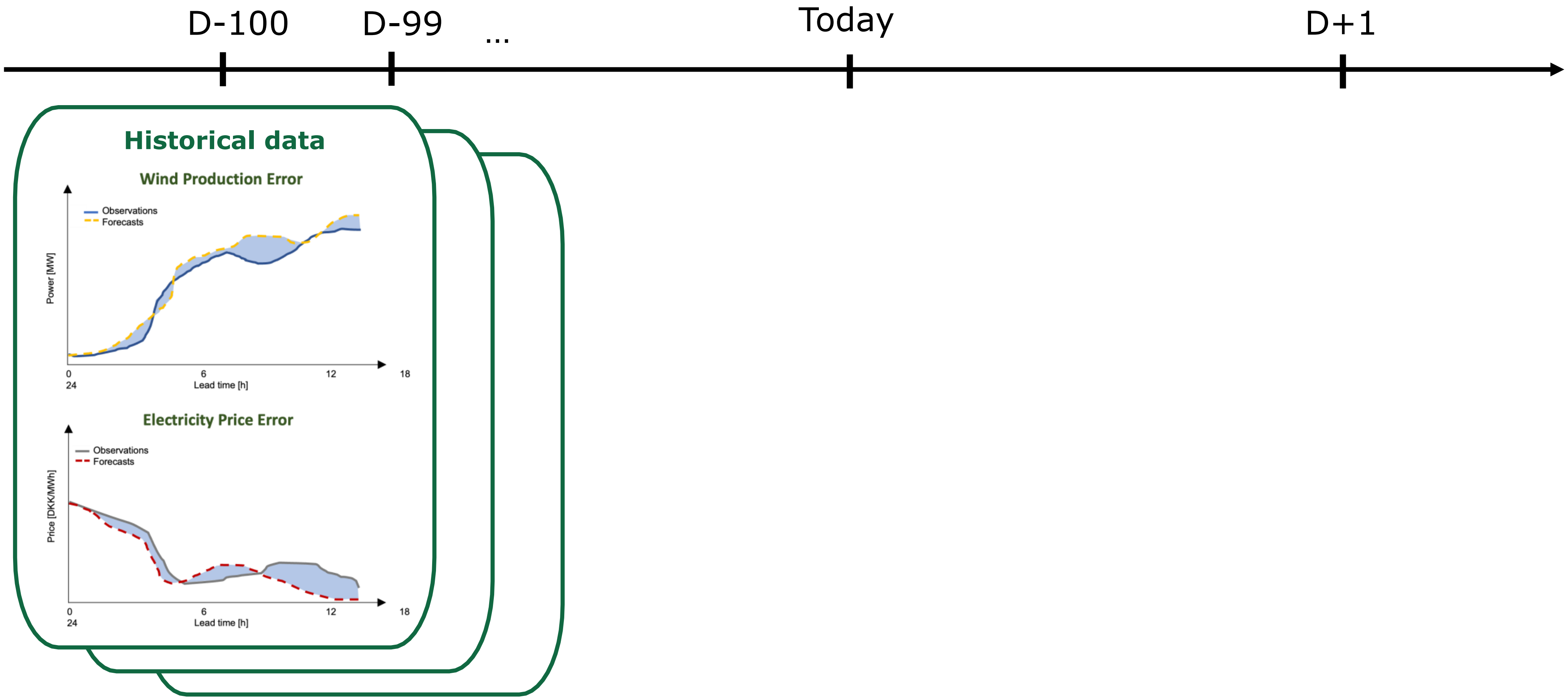
Concept



Historical forecasting error
= Forecast – Observation

Concept



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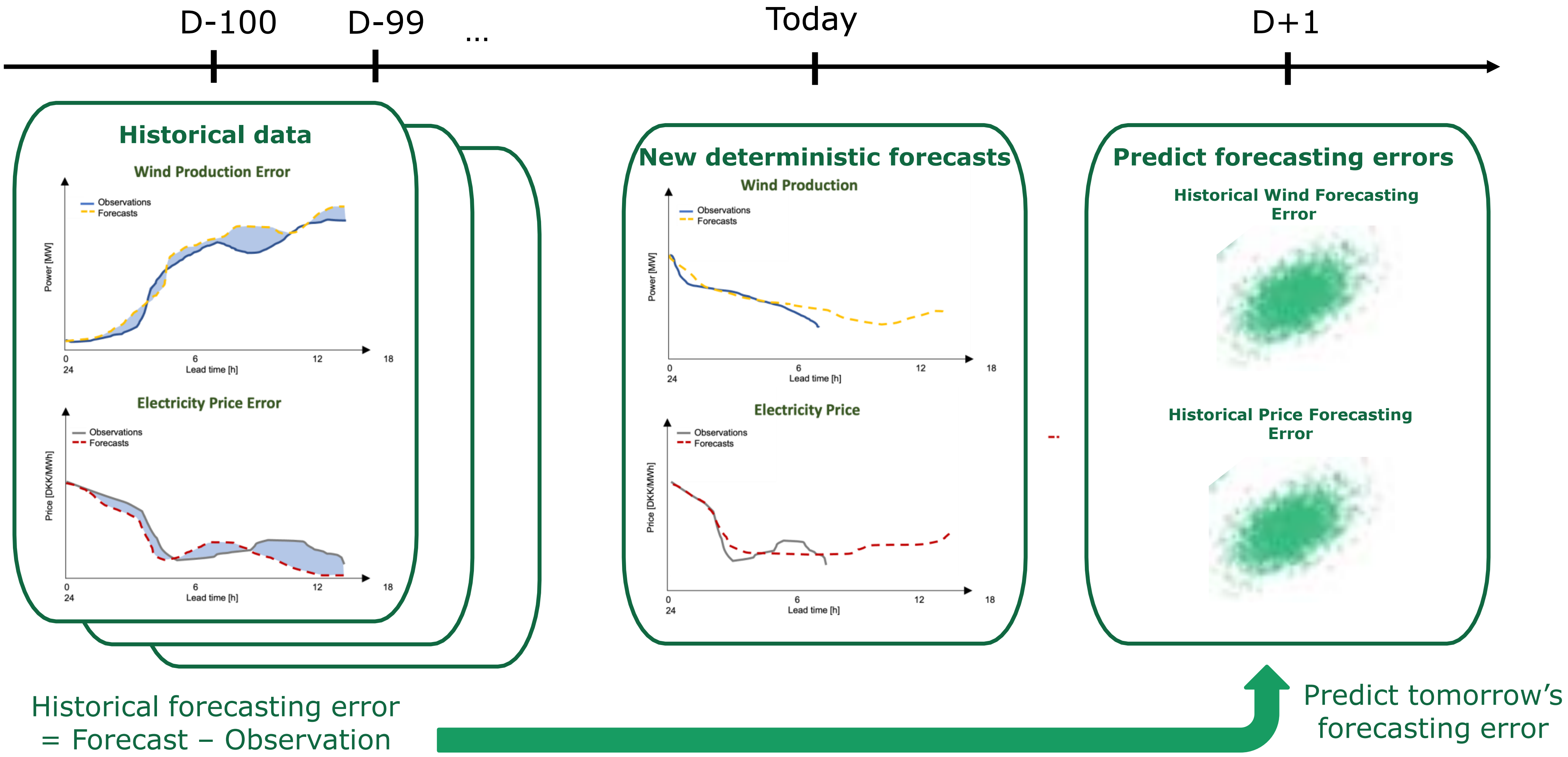
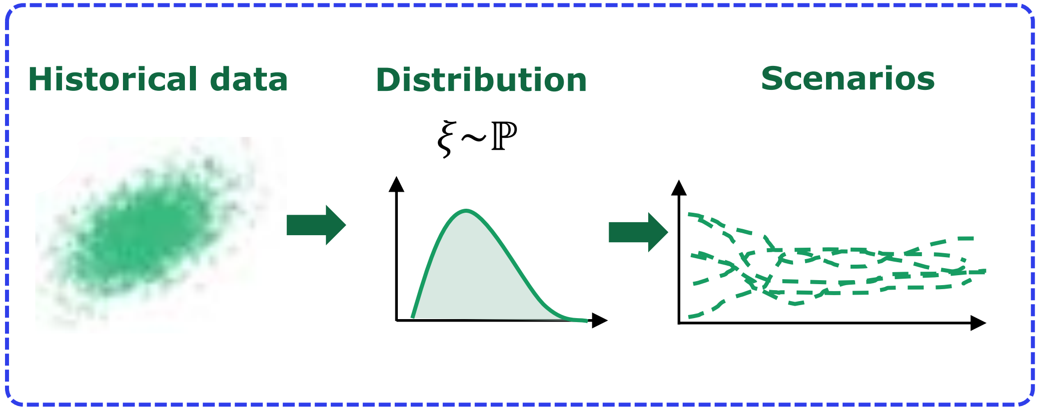

D-100
D-99
...
Today
D+1
Historical data
Wind Production Error
Observations
Forecasts
Power [MW]
Lead time [h]
Electricity Price Error
Price [DKK/MWh]
New deterministic forecasts
Wind Production
Electricity Price
Predict forecasting errors
Historical Wind Forecasting Error
Historical Price Forecasting Error
Historical forecasting error
= Forecast − Observation
Predict tomorrow's
forecasting error

Concept

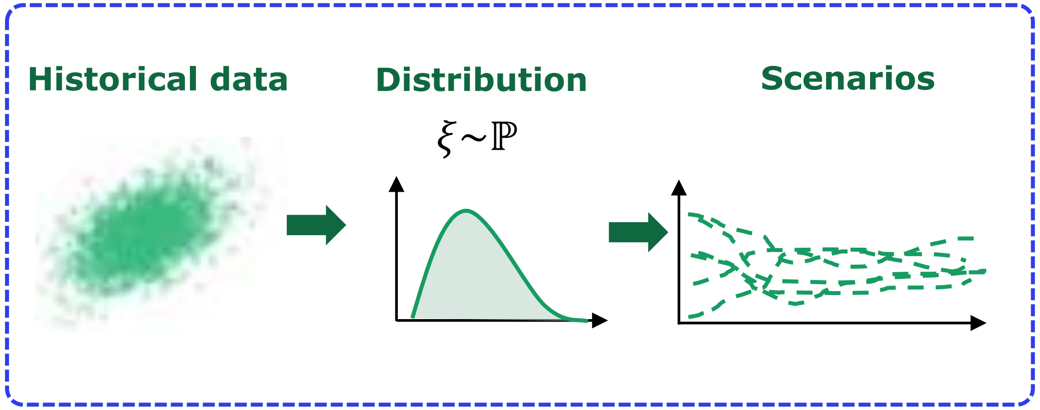
Scenario-Based Stochastic Optimization



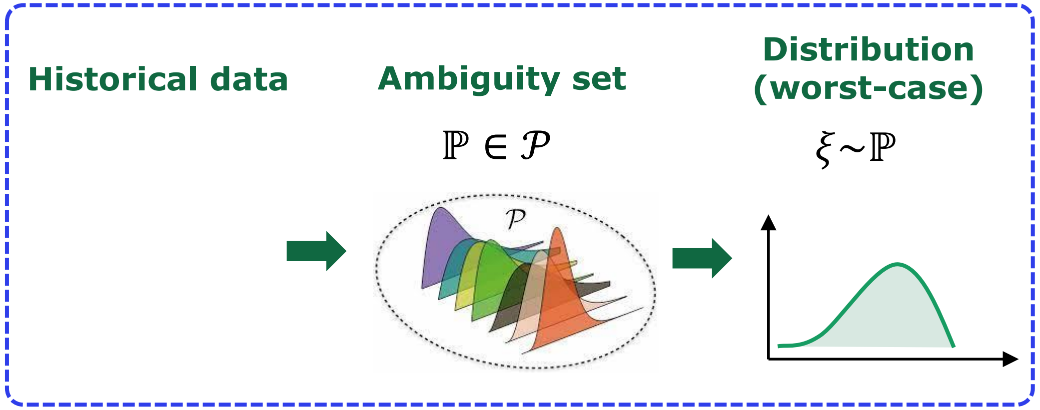
- **Aim:** Max. expected profit for **given distribution**
- **Challenge: Data-intensive** to estimate probability distribution $\mathbb{P}$

Concept

Scenario-Based Stochastic Optimization



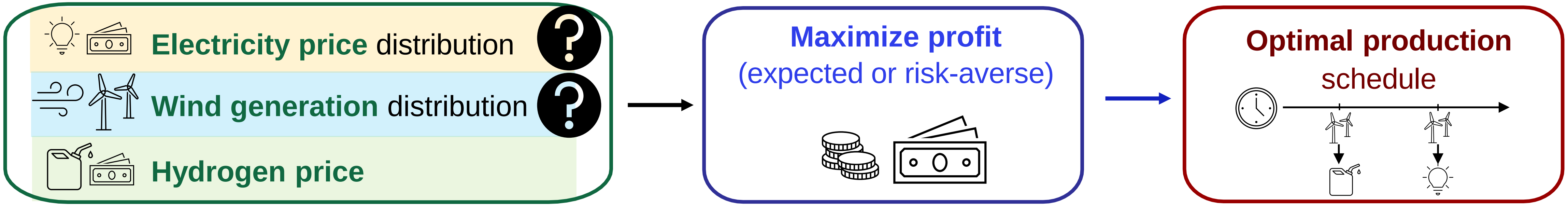
Distributionally Robust Optimization



- **Aim:** Max. expected profit for **given distribution**
- **Challenge: Data-intensive** to estimate probability distribution $\mathbb{P}$

- **Aim:** Max. expected profit for **worst-case distribution** in ambiguity set
- **Benefit: Data-driven** approach

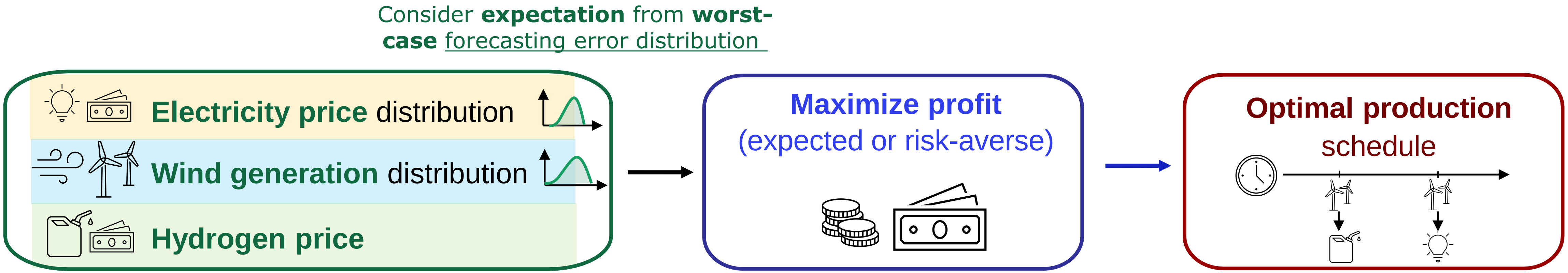
Concept



Main challenges:

- Model **uncertainty** sources accurately
- Model and **mitigate risk** of decisions

Concept



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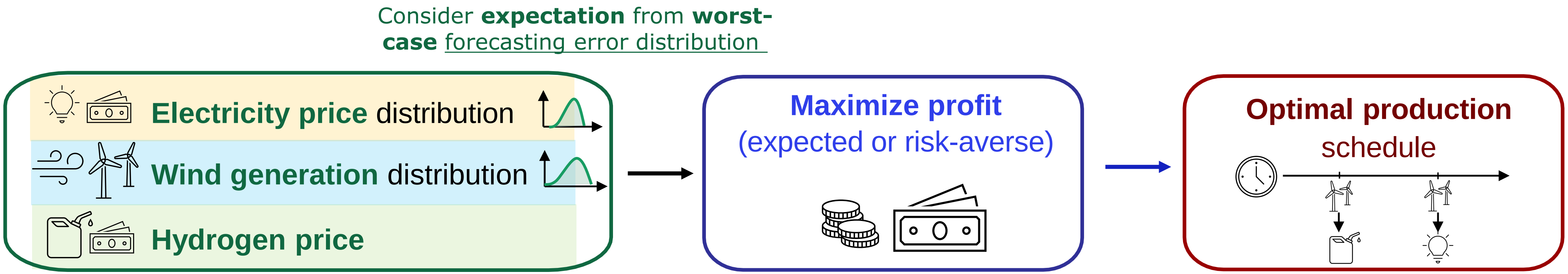

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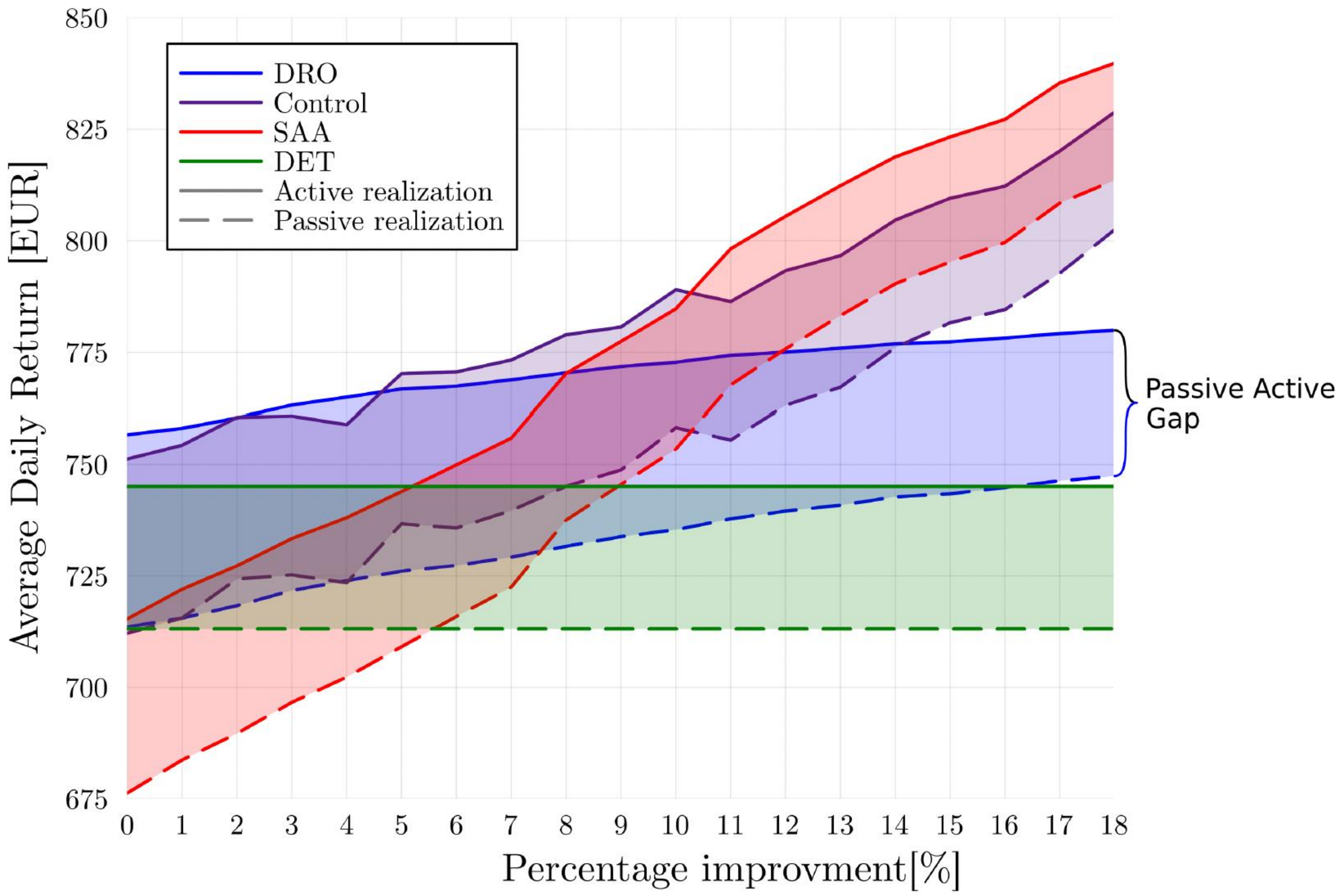
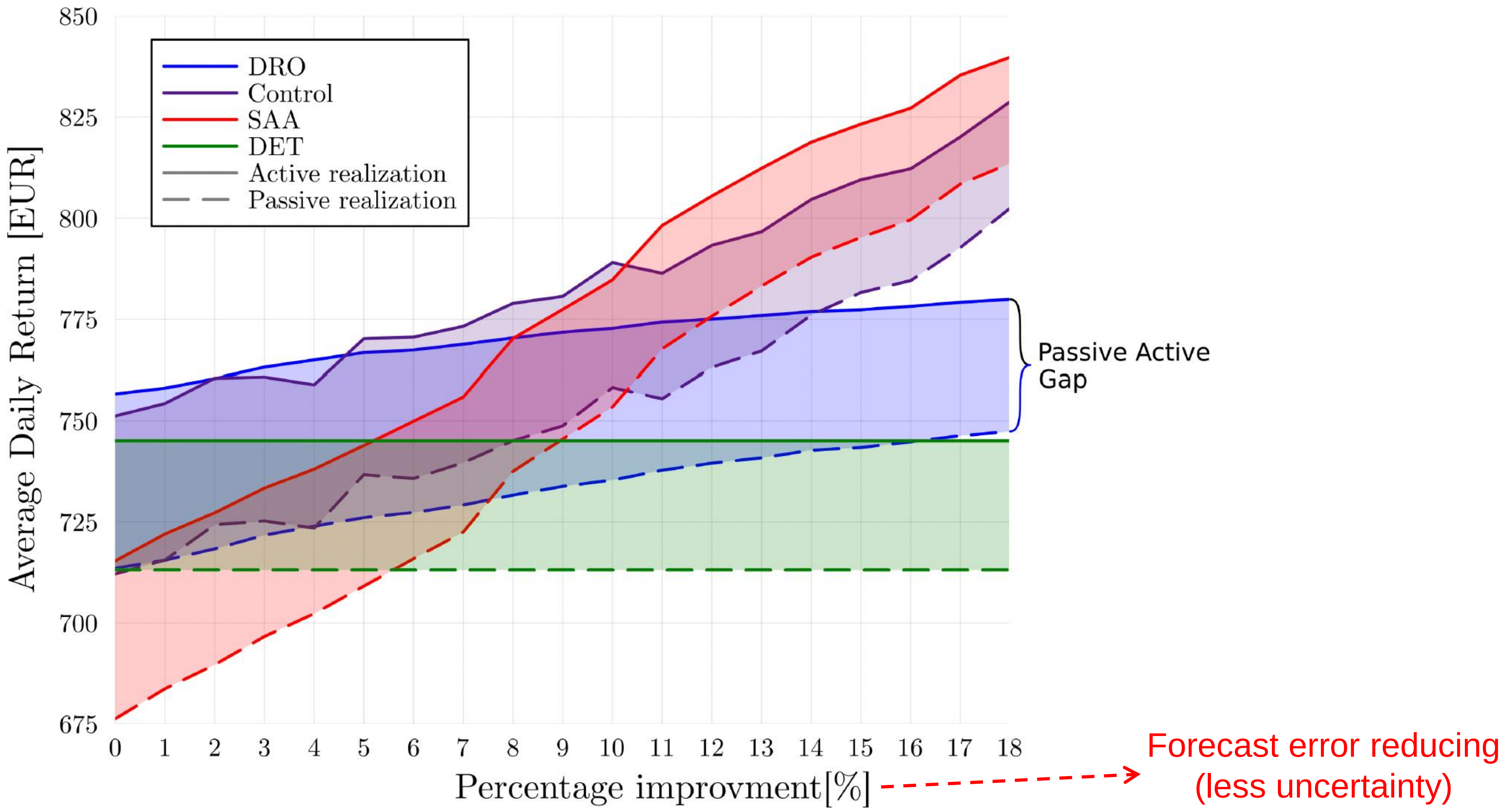
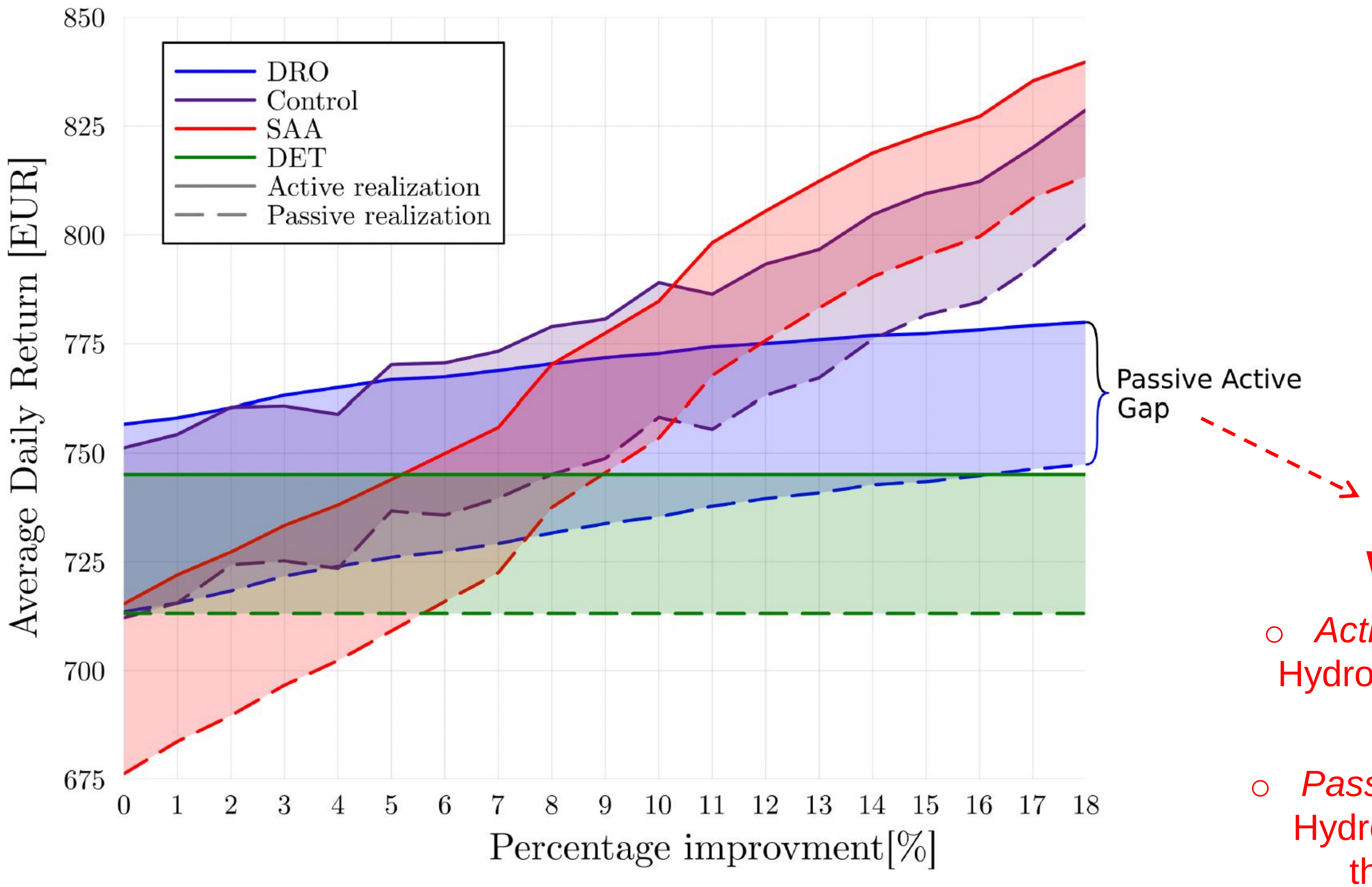
Out-of-Sample Results



Out-of-Sample Results



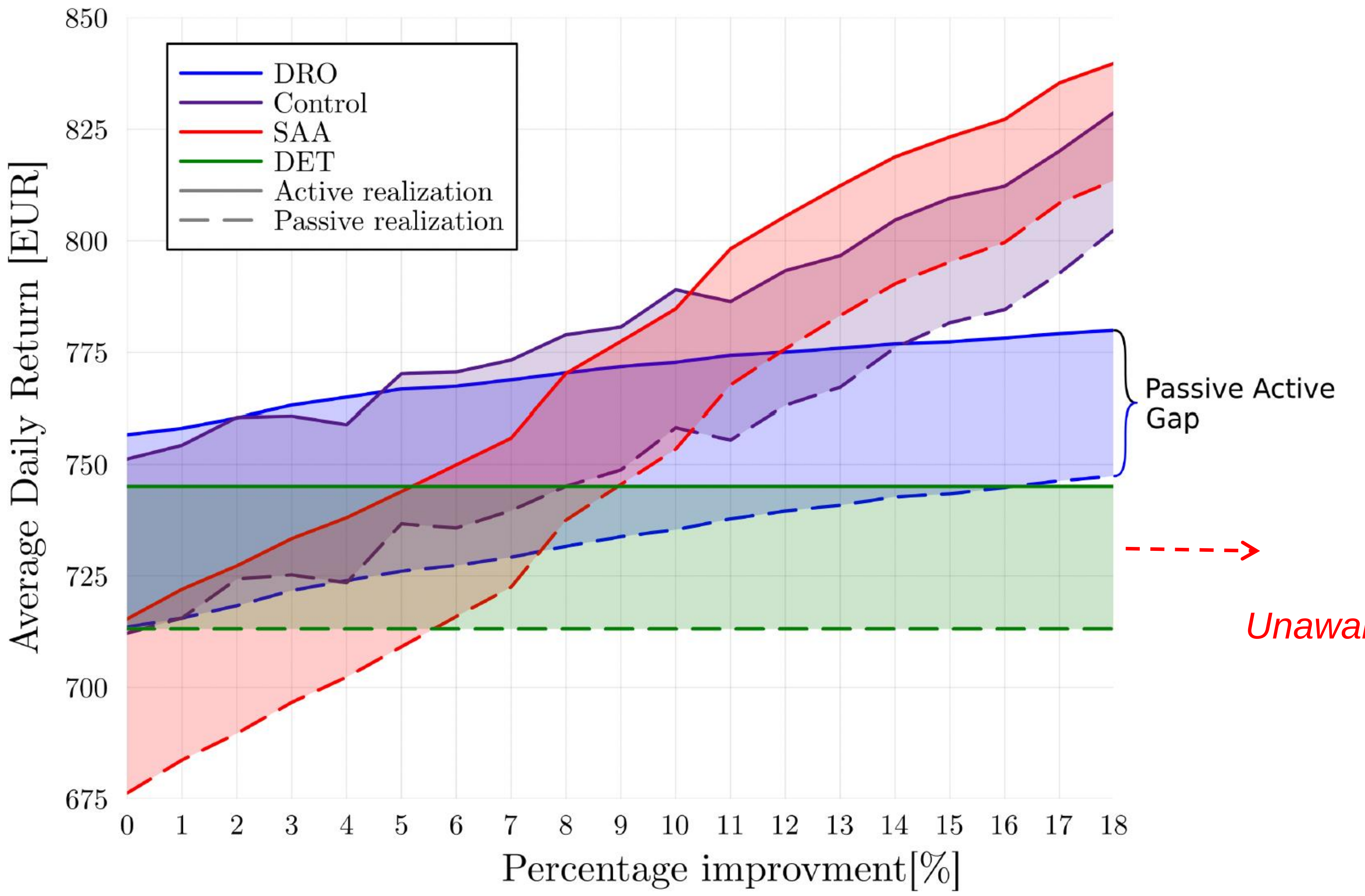
Out-of-Sample Results



Wasserstein DRO

- *Active model (upper bound):* Hydrogen production can be fully adjusted in real time
- *Passive model (upper bound):* Hydrogen production is fixed to the day-ahead schedule

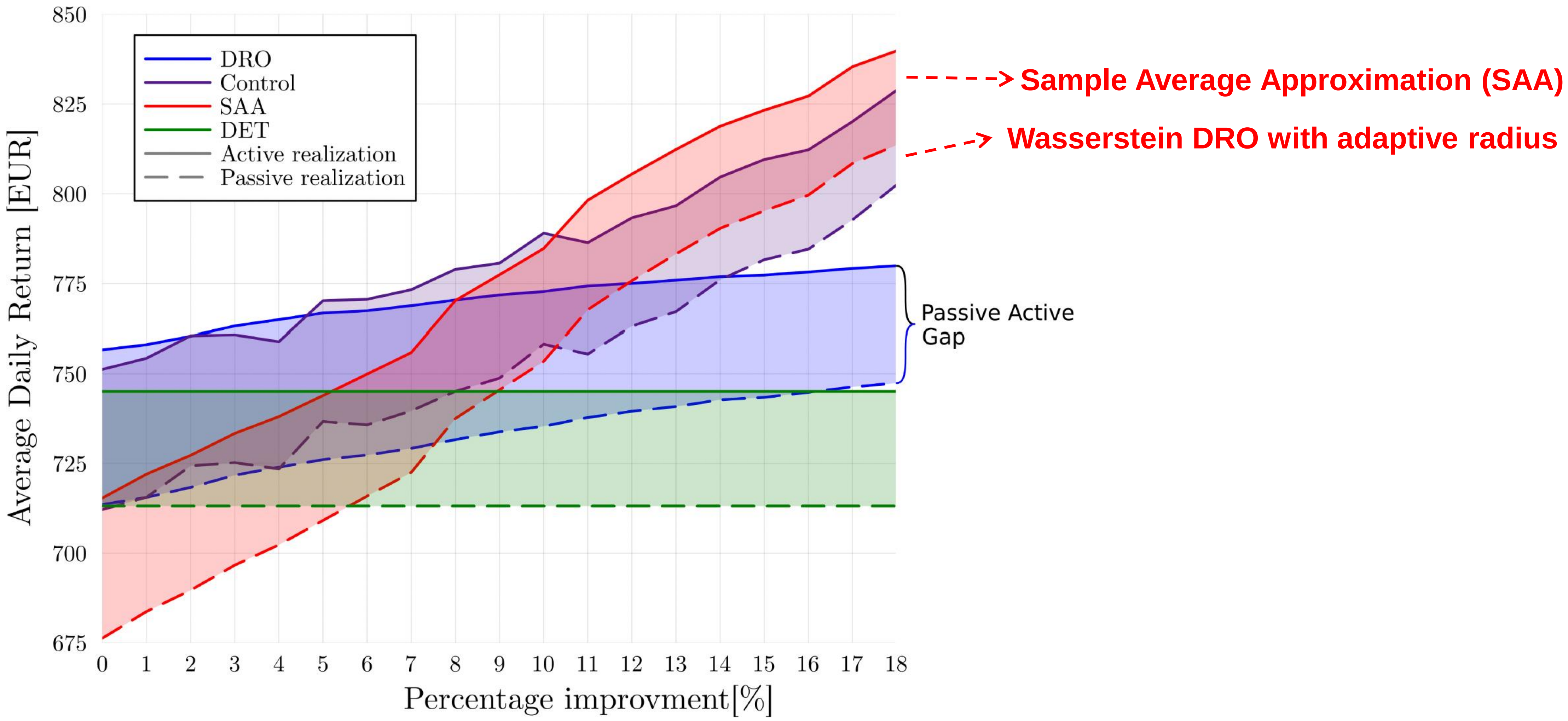
Out-of-Sample Results



Deterministic

Unaware of historical forecast error data

Out-of-Sample Results



Takeaways

- **Operational details** of P2X assets are important for the scheduling of the system.

- This is a **multi-market** decision-making problem:
  - Day-ahead and balancing electricity markets
  - Ancillary service (FCR, aFRR, mFRR) markets
  - Hydrogen

- Modeling **uncertainty** is key, while there might be lack of sufficient historical data to accurately characterize underlying probability distributions!

Thank you!

Jalal Kazempour

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