Renewable Hybrid Power Plants

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A utility-scale wind-solar-battery hybrid power plant is a crucial component of a larger, interconnected energy ecosystem, where renewable energy sources interact with market dynamics, weather conditions, and various energy sectors to meet the evolving needs of society.

OpenAI. (2024). ChatGPT (3.5) [Large language model]. https://chat.openai.com

OpenAI. (2024). ChatGPT [Large language model]. /g/g-pmuQfob8d-image-generator

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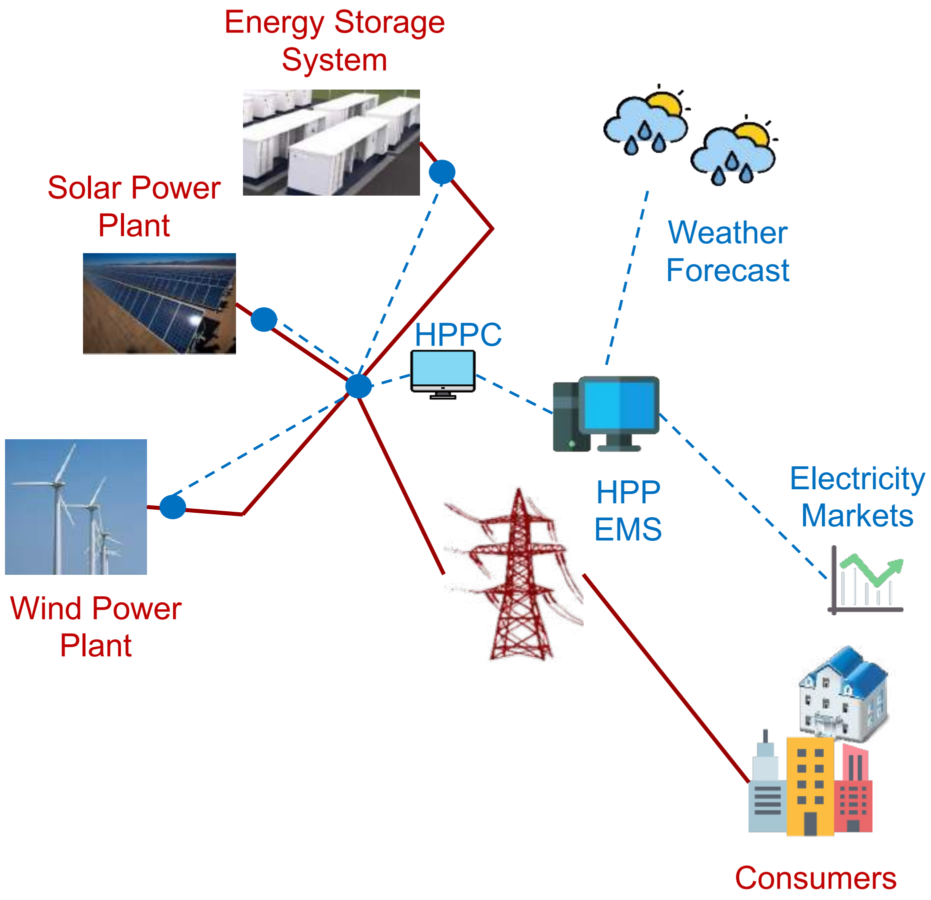
Hybrid Power Plant – Utility scale co-located grid connected



General Features	More than one generation sources involved
	All assets are owned by same company so higher controllability
	More RES integration with same grid connection

Motivation	To reduce cost/ maximize revenue from different energy markets
	One common energy management system
	Reduced curtailment means more value of RE
	Optimal utilization of land
	More flexibility allows for decommissioning of fossil fuel-based generators

Motivations for HPP – System Operators/Society

- Delayed requirement for transmission infrastructure reinforcement
- More RES integration with the same grid connection
- Optimal utilization of land
- Improved grid stability and security
- More flexibility allows for decommissioning of fossil fuel-based generators
- Increased capacity factor
- Reduced curtailment means more value from renewable energy

Motivations for HPP – Owners / Developers

- **Cost reduction and Revenue increase**
  - Infrastructure
    - Reduction in land cost
    - Optimal use of electrical infrastructure and other infrastructure (e.g. access roads) saves costs
  - Project Development
    - Joint permitting process reduces risks and costs
    - Shared resources reduce internal costs
    - Joint site development reduces costs for e.g. soil investigations & weather measurements
  - Park Performance
    - Less fluctuating production increases electrical infrastructure utilization
    - Storage increases flexibility and number of accessible markets (Energy market, ancillary services market)
    - Reduction of forecast error using storage

Reduction in variability

Increase in availability

Increase in capacity factor

Reduction in cost

Increase in revenue

Increase in ancillary service capability

Increase of lifetime of the wind turbine

Paulina Asbeck, "Next-Gen Generation System: The symbiotic relationship of solar, wind & storage hybrid power plants", 17th Wind Integration Workshop, 2018

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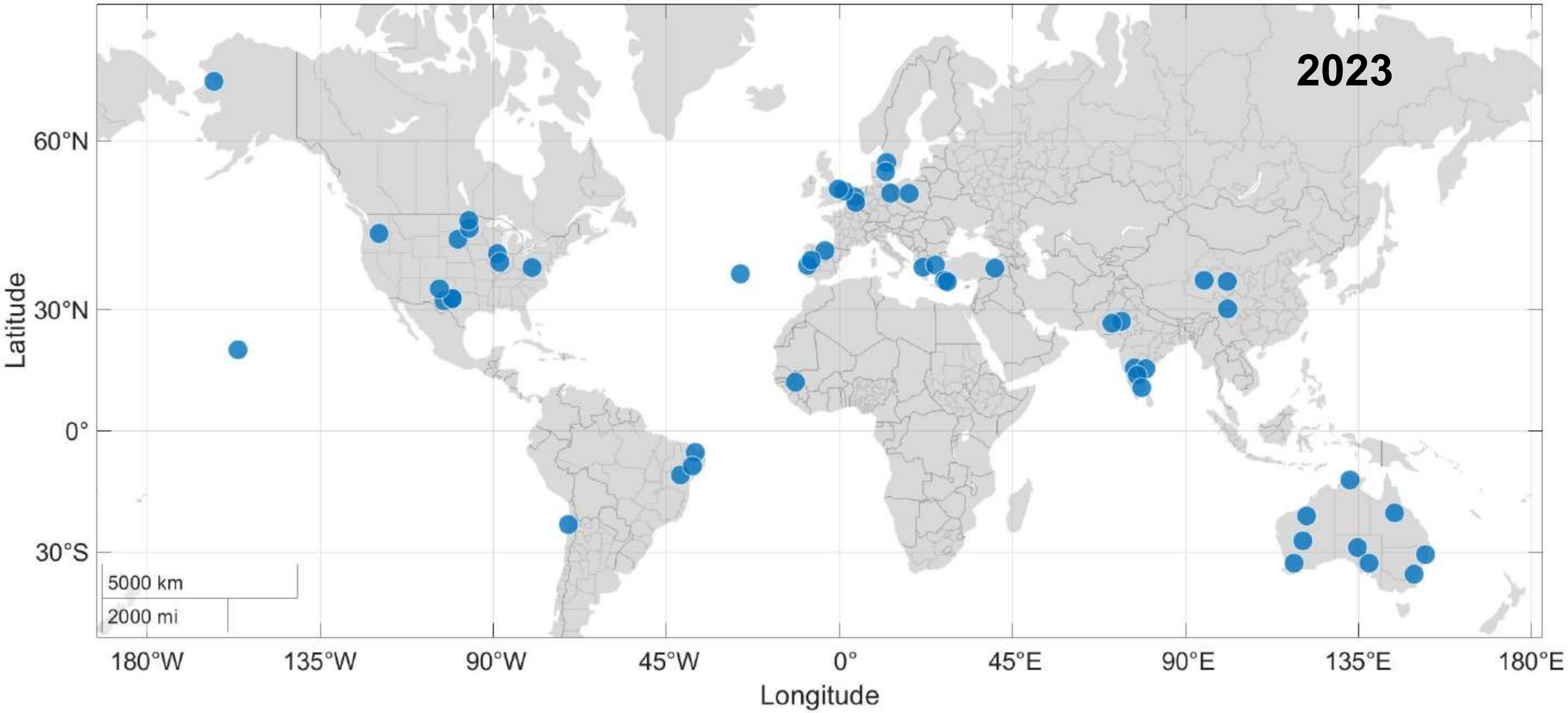
Utility-scale Hybrid Power Plants around the world



Rujie Zhu, "Optimal Energy Management of Hybrid Power Plants in Electricity Markets", PhD Thesis, DTU, 2023

Modelling the environment

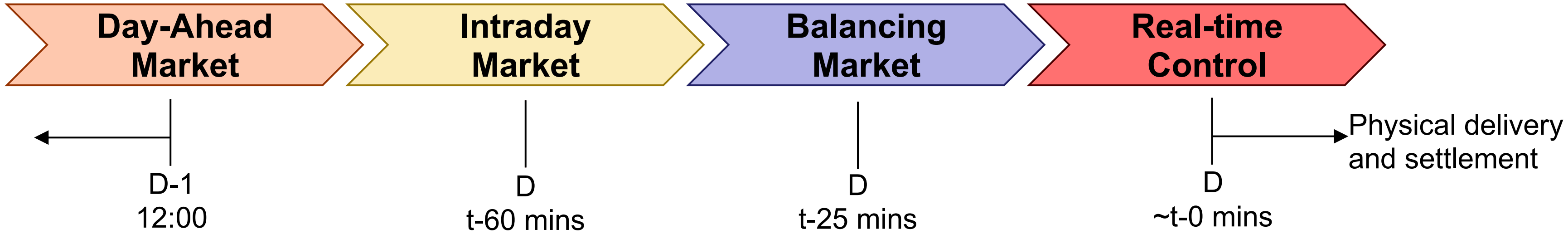
- DTU's Balancing Tool Chain

Basics of balancing

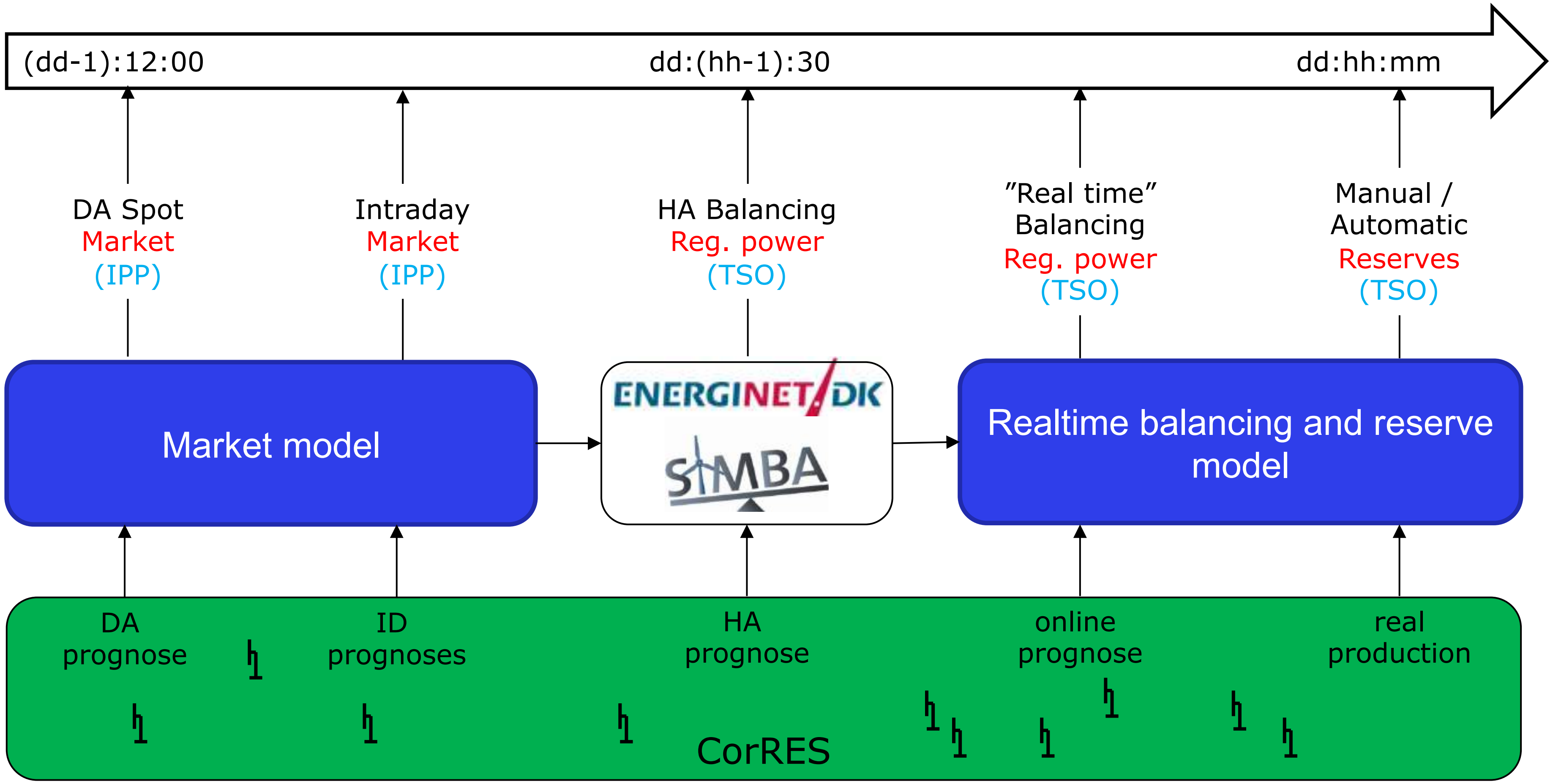
- **Principle - Electricity production must always match the demand**

- **Evolving Dynamics**
  1. Surge in VRE integration introducing variability and forecast uncertainty
  2. Gradual phase-out of controllable generation sources.
  3. Shifting consumption patterns and amplified uncertainties.
- **Market Dynamics**
  1. Majority of VRE is transacted in day-ahead markets.
  2. Gate closures can be 12 to 36 hours before actual power delivery.
  3. Considerable temporal separation results in forecast deviations.

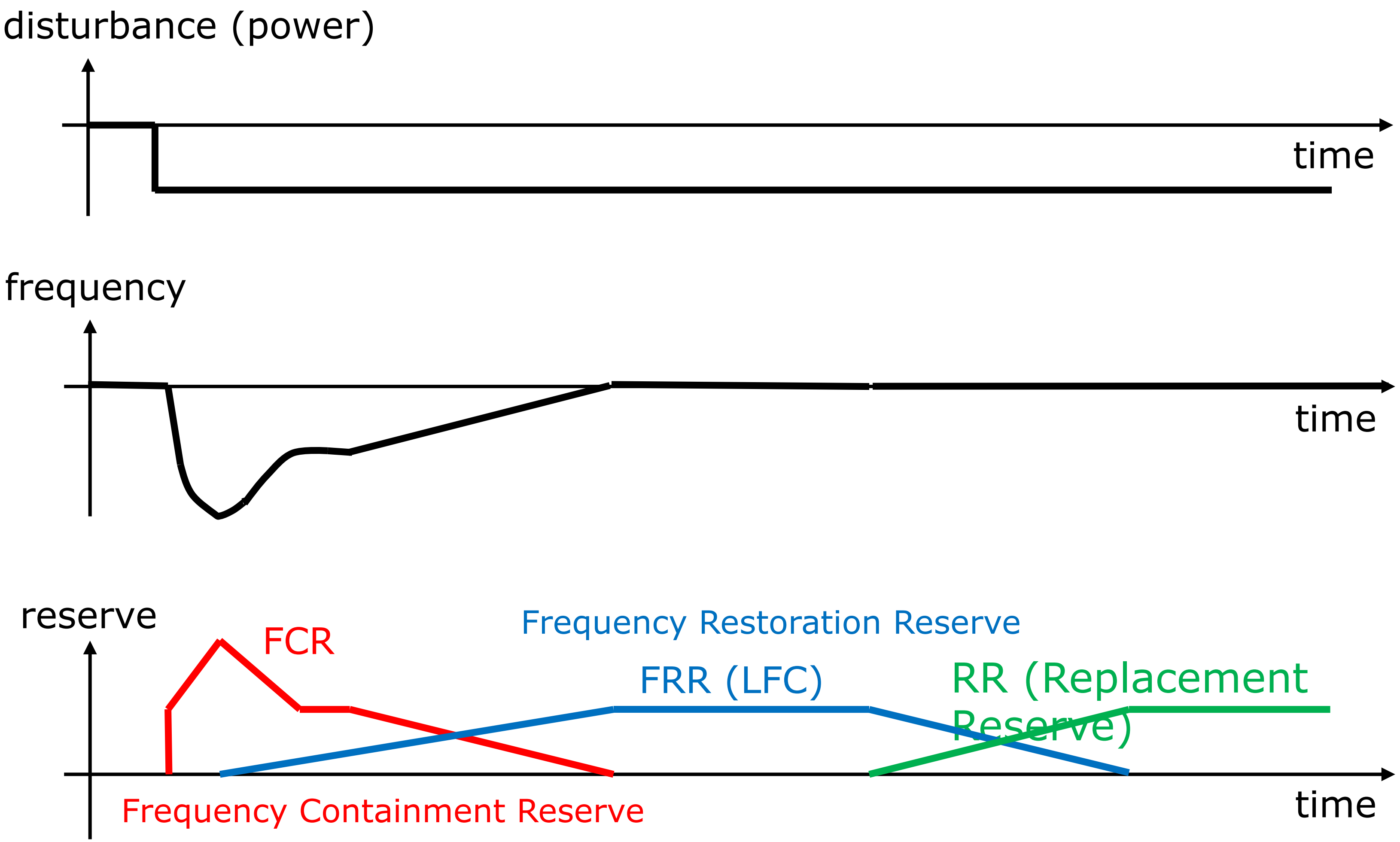
- Generators and utilities meet the deviations (+/-) anticipated after the DA markets in the succeeding markets



Balancing wind power forecast errors
(Danish system example)

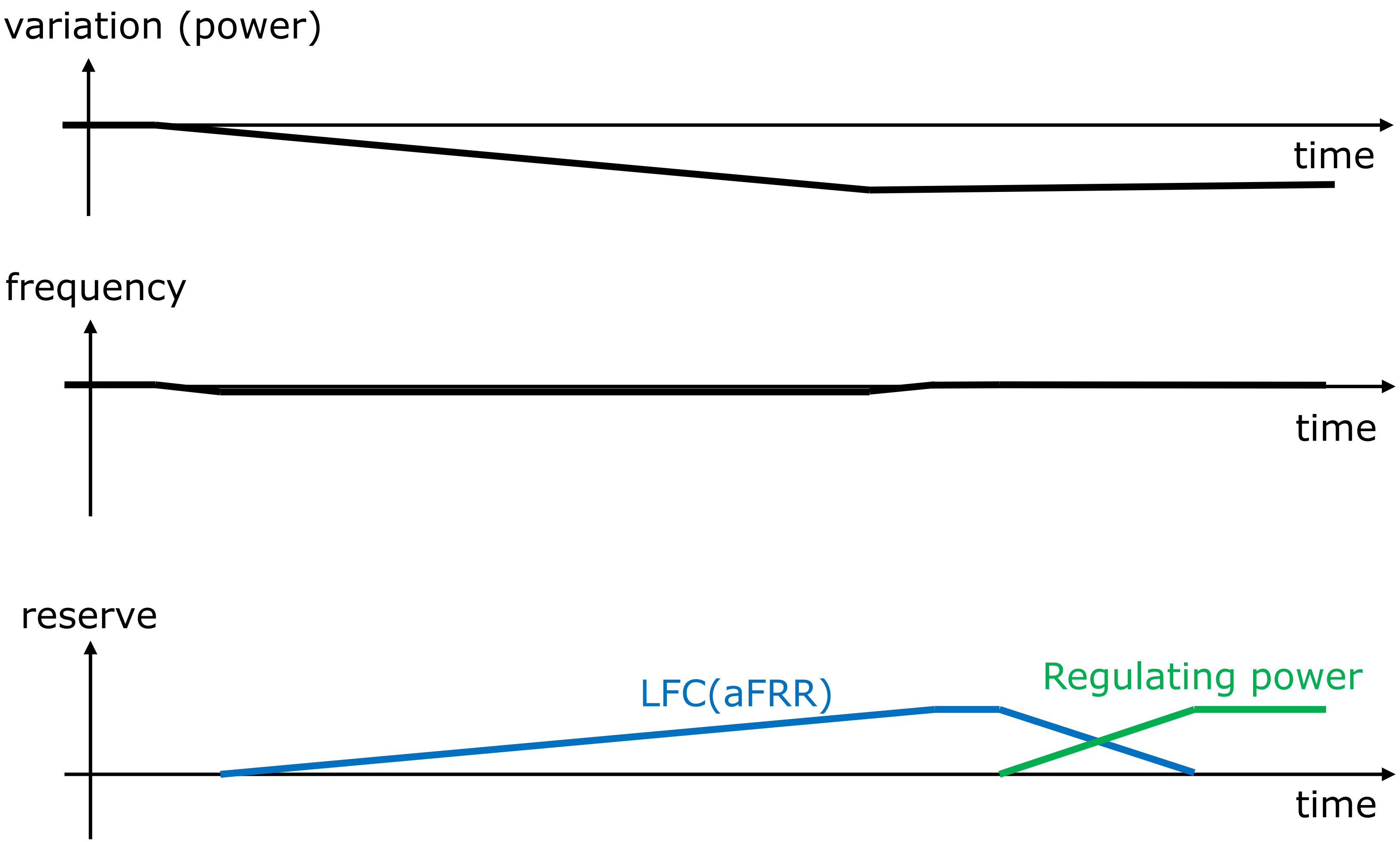


Use of reserves
Contigency/disturbance



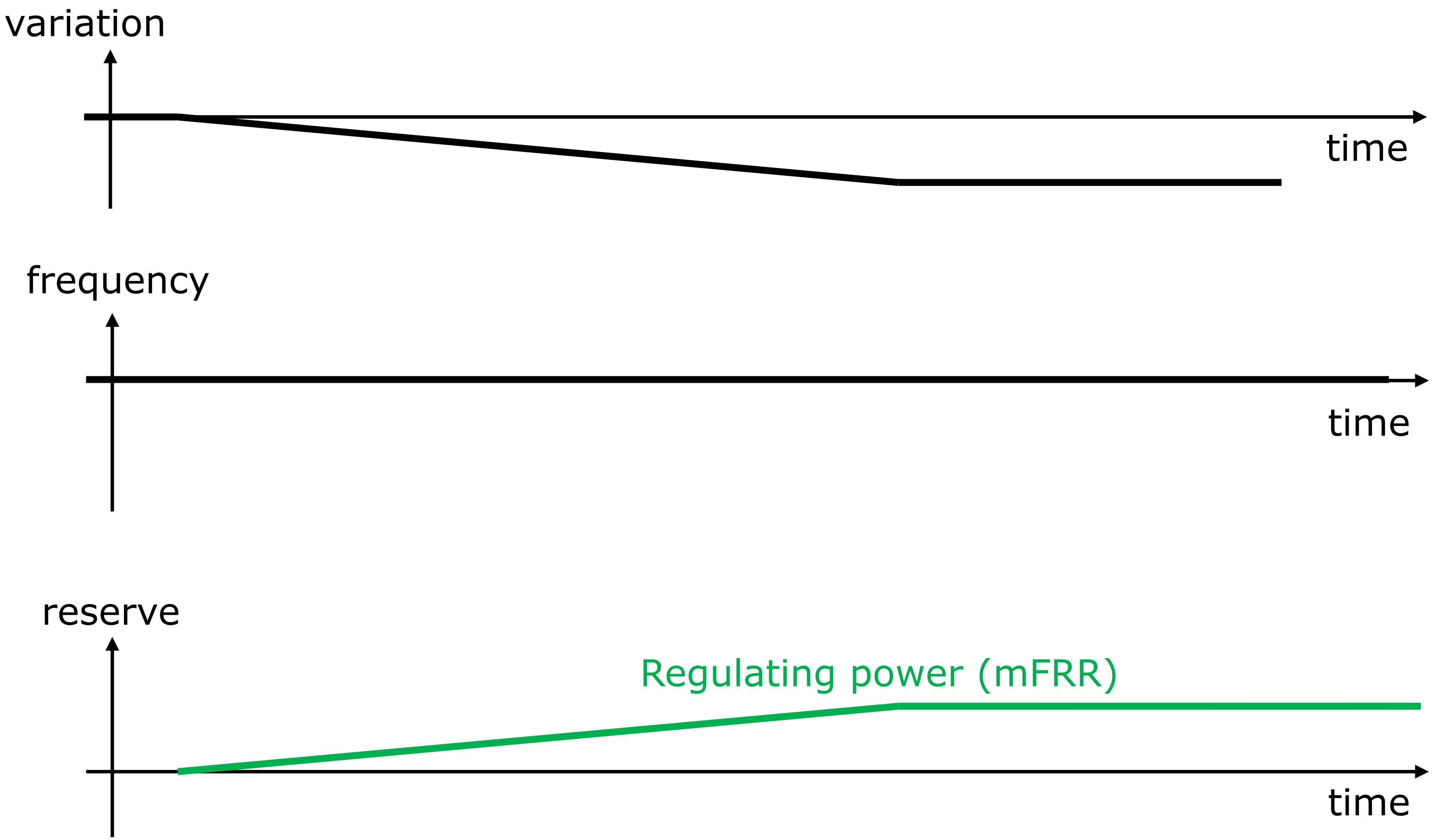
Use of reserves

Slow variations due to forecast errors



Load or wind variability

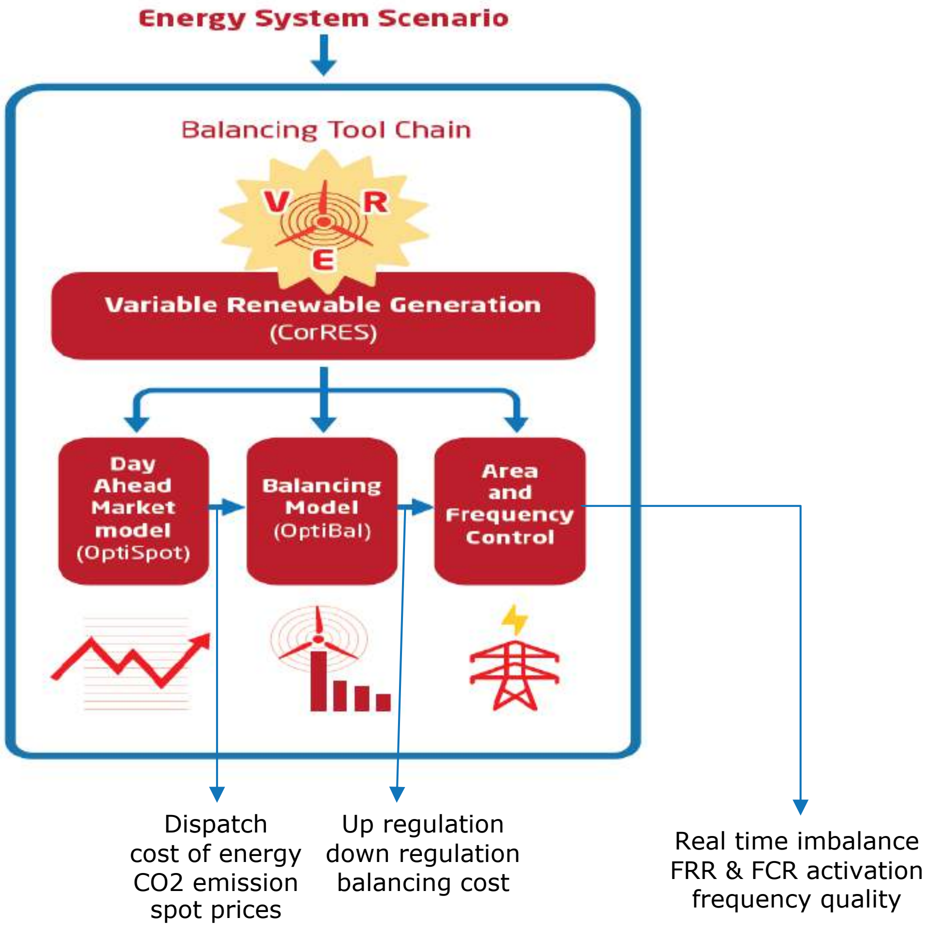
DA forecast error and perfect HA plan



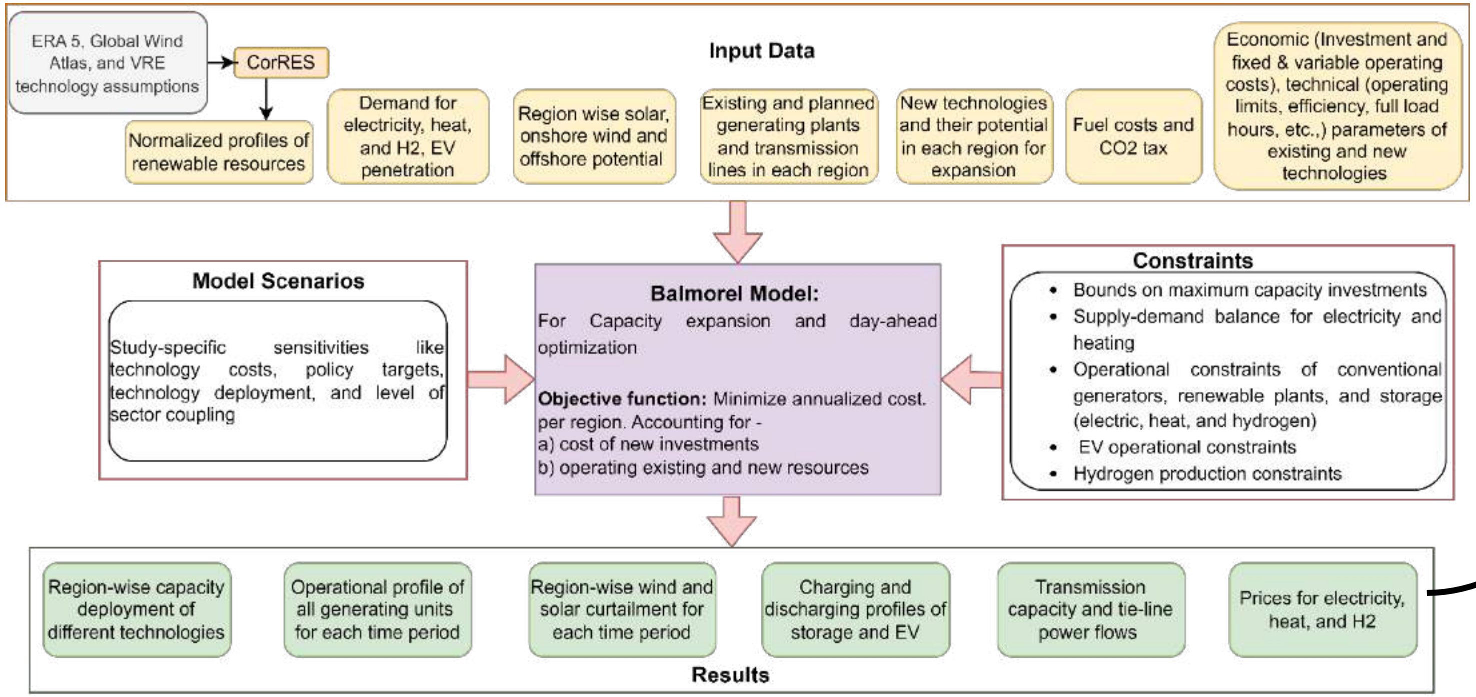
Balancing Tool Chain to capture all market dynamics

- **On top of Balmorel investment runs**
  - Or other scenarios

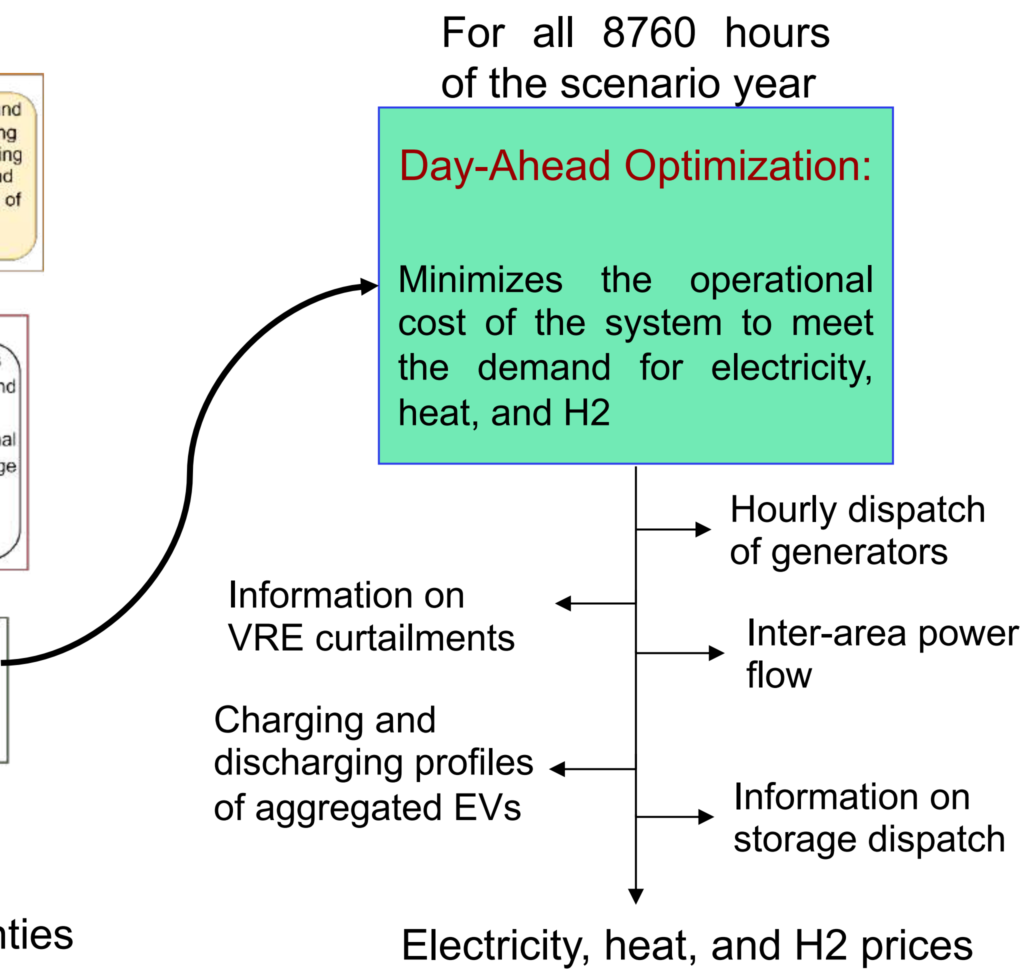
- Unit commitment and dispatch (spot market)
- Society cost of energy
- Balancing volume and costs (balancing model)
- **Real time imbalance**
- **Frequency quality**



A quick look at the preceding steps



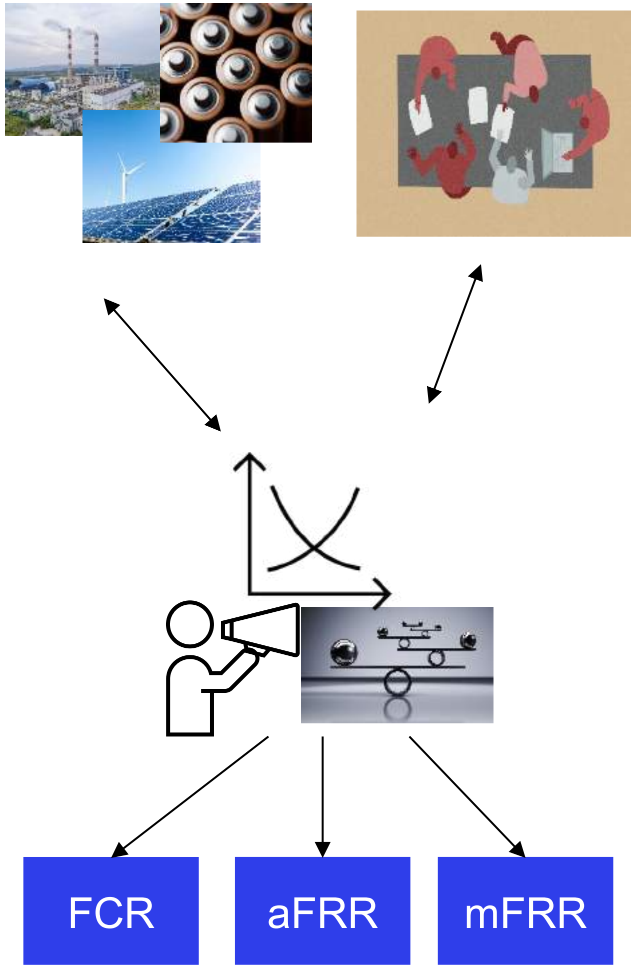
Capacity Expansion – with limited temporal resolution



- The two stages are deterministic and do not account for VRE uncertainties
- The volume of VRE forecast errors is increasing with their integration
- Balancing is going to play a crucial role in the future

Key Terms

Balancing market	entirety of institutional, commercial and operational arrangements that establish market-based management of balancing
Balance service provider	a market participant with reserve-providing units or reserve-providing groups able to provide balancing services to TSOs
Balance responsible party	a market participant or its chosen representative responsible for its imbalances (or) company that can and may handle the balance responsibility for production and consumption units and/or trades actual electricity.
Frequency Containment Reserves	active power reserves available to contain system frequency after the occurrence of an imbalance.
Automatic Frequency restoration reserve (aFRR)	FRR that can be activated by an automatic control device
manual Frequency restoration reserve (mFRR)	Frequency Restoration Reserves with manual activation



Q. What kind of balancing principles to be employed for future power and energy systems?

- **Three focal points: Types of reserves, procurement, and sources**

Reserves/services:

Traditional: Relied heavily on inertia and AGC control from large and controllable generators

Transition: Services targeting frequency regulation and containment, such as Dynamic services, Fast Reserve service, Frequency Control Ancillary Services (FCAS), and FCRs for more precise and real-time frequency adjustments.

Balancing Markets:

Traditional: Centralized dispatch mechanisms, based on merit-order lists, day-ahead markets, or bilateral contracts

Transition: Dynamic and intraday market mechanisms for balancing energy procurement like Dynamic reserve markets (DRM), cross-border markets, FCR Markets

Reserves Capacity (sources):

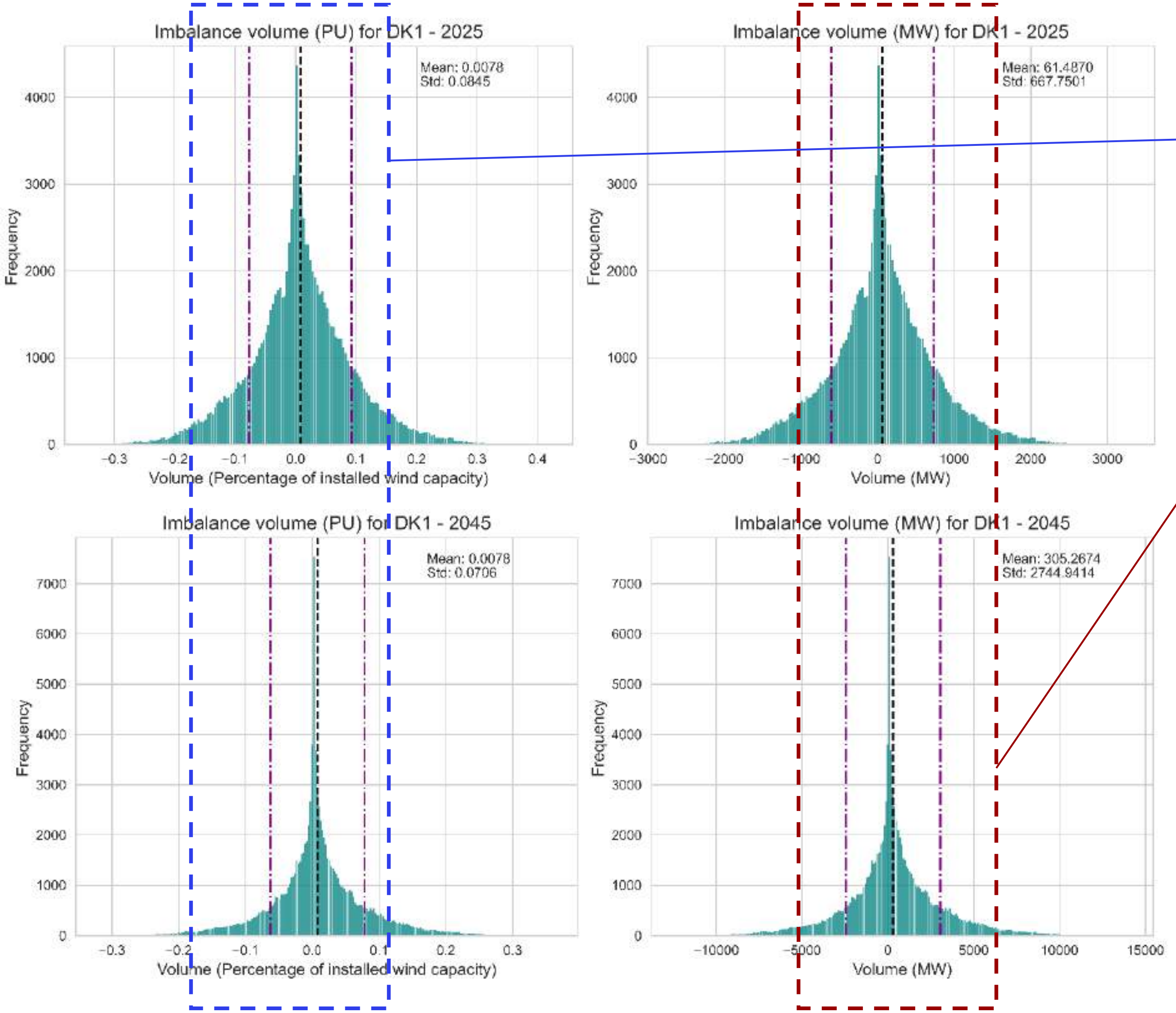
Traditional: Dependent on large centralized power plants and occasionally industrial consumers for reserves, ensuring grid reliability during unforeseen events

Transition: Diversification of resources contributing to reserves – Virtual and hybrid power plants, DERs, energy storage, demand response, VRE technologies.

Q. What kind of balancing principles to be employed for future power and energy systems?

TSO	Country	Traditional/Existing Balancing Approach	New Balancing Approach	Ref.
National Grid	UK	Firm frequency response (FFR) – static and dynamic, monthly tender process	Dynamic Containment (DC), Dynamic Moderation (DM), and Dynamic Regulation (DR) from automatic activation of generators, energy storage, or demand response	[1]
Terna	Italy	Procured through auctions	Fast Reserve service for frequency regulation, **technology-neutral** (can be standalone or aggregated) with required technical specifications	[2]
50Hertz	Germany	Primary Control Reserve (PCR) and Secondary Control Reserve (SCR) from pre-qualified balancing service providers	Pan-European balancing markets: FCR, aFRR, mFRR from pre-qualified BSPs	[3]
RTE	France	manual frequency restoration and replacement reserves from BSPs qualified through annual tenders	Operational member of TERRE for replacement reserves, non-operational member for MARI and PICASSO	[4]
Elia	Belgium	aFRR, mFRR, and FCR markets from pre-qualified Balancing responsible parties (BRPs)	Non-operational member of all pan-European balancing markets	[5]
Energinet	Denmark	Procured via auctions (qualification of BSPs). FFR capacity markets, FCR-D and FCR-N with Sweden, common Nordic aFRR and mFRR markets	Non-operational member for MARI and PICASSO	[6]

Q. What volume of operating reserve will future power systems require?

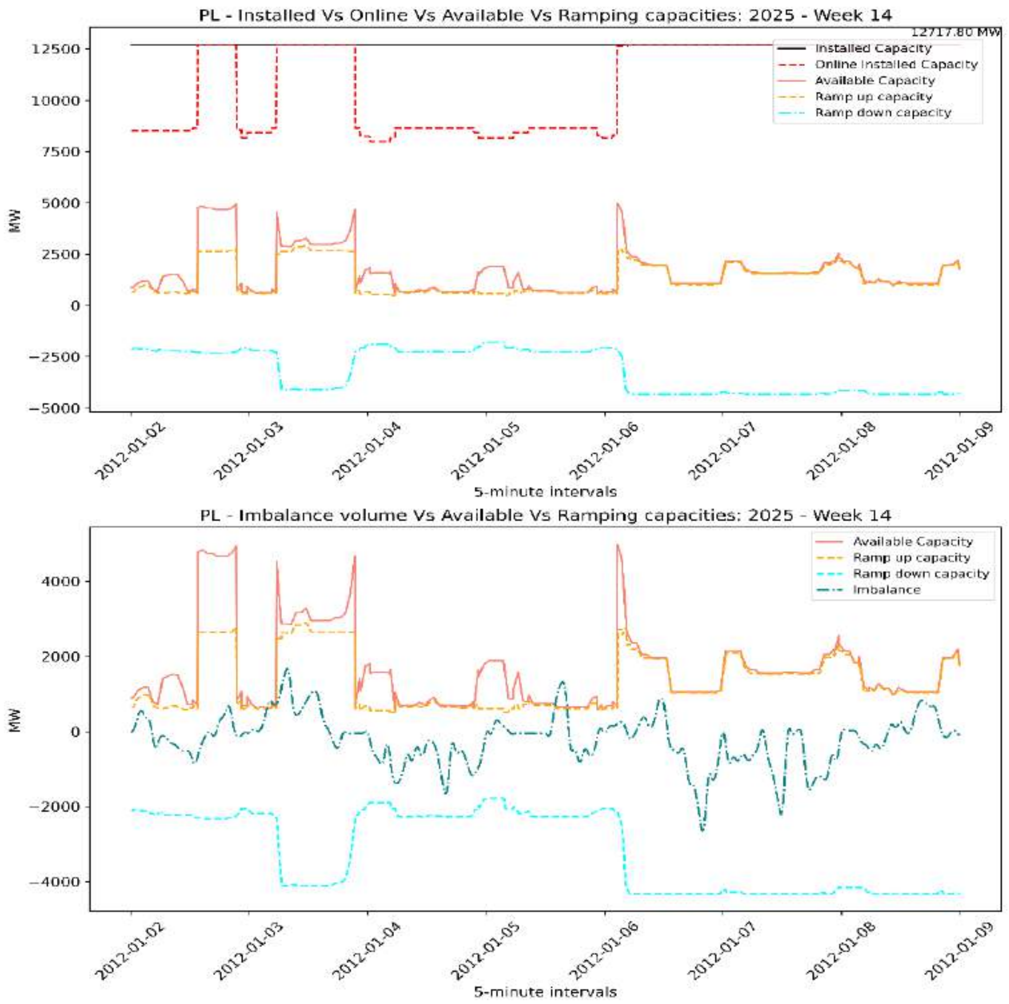


- the standard deviation of imbalances is less than 10% of the wind installed capacity for the respective years

- However, the magnitude of imbalances and standard deviation increase four-fold by 2045 from 2025 baseline – driven by VRE integration

- A similar trend is observed for most of the balancing areas, with imbalance volumes increasing at least by a factor of 02

Q. How much can the available generation fleet support the balancing reserve requirements?



- **Determining Factors:** Reserve sufficiency depends on the share & DA commitment of flexible generators and VRE forecast errors in a specific region.
- **Current Operations:** Generators recognized as "Balancing Service Providers" are predominantly held in standby or operate below their maximum potential (part load).
- **Look-Ahead:** With imbalance volumes predicted to surge by 4x, sustaining the current approach becomes economically untenable.
- **Modeling Insight:** Our study underscores that energy system planning models, even with assumed perfect foresight, might not deliver the required reserve precision.
- **Strategies for the Future:**
  1. Amplify the inclusion of flexible generators.
  2. Consider reserve sharing arrangements with adjacent regions.

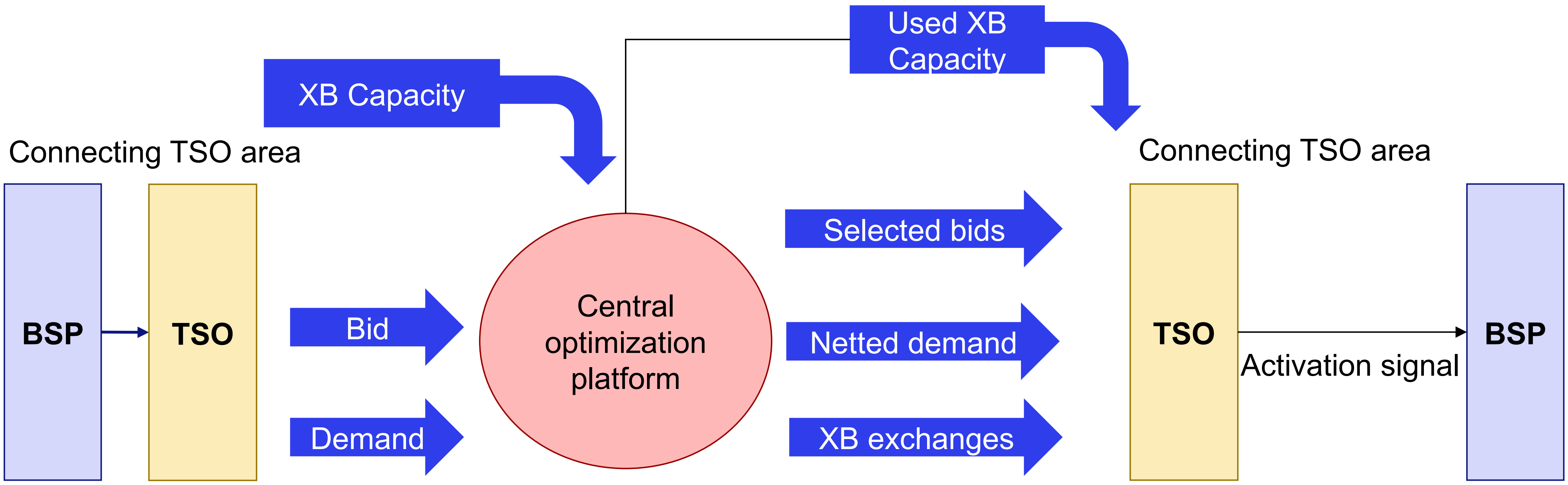
Q. How international cooperation can support the system requirements for balancing?

- In 2017, the European Agency for the Cooperation of Energy Regulators (ACER) and the European Network of Transmission System Operators for Electricity (ENTSO-E) issued guidelines to harmonize electricity balancing across European countries commonly referred as **EBGL**
- EBGL sets out a common framework for the procurement and activation of balancing services across the EU, with a focus on:
  - ➢ The definition of balancing services and the different types of balancing services that are available
  - ➢ The roles and responsibilities of the different actors involved in the balancing market, such as transmission system operators (TSOs), balancing responsible parties (BRPs), and balancing service providers (BSPs)
  - ➢ The rules for procuring and activating balancing services
  - ➢ The financial settlement of balancing services
- **Key Initiatives: Development of platforms for**
  - ➢ Manual Frequency Restoration Reserve (mFRR) - MARI
  - ➢ Automatic Frequency Restoration Reserve (aFRR) – PICASSO
  - ➢ Replacement Reserves (RR) – TERRE
  - ➢ Imbalance Netting (IN) - IGCC
- The initiatives increase efficiency, reduce cost, and improve the security of supply

MARI (Manual Frequency Restoration Reserve)

- MARI is a centralized platform to optimize mFRR energy exchange between European TSOs
- Brought into operation on October 5, 2022.
- Four German TSOs, ČEPS (Czechia), and APG (Austria) in operation, and further TSOs are expected to join in 2024.
- mFRR is a balancing service activated to restore grid frequency to its nominal value
- Once activated, BSPs must reach full capacity within 12.5 minutes and sustain for the subsequent 5 minutes
- Bidding Mechanism:
  - Supports both upward and downward mFRR
  - Gate closure: T-25 mins for BSPs and T-10 for TSOs
- Clearing & Settlement:
  - Gate closure auction model, constantly optimizing for current offers and bids, while accounting for the constraints
  - Implements "pay-as-cleared" pricing, creating a transparent market equilibrium price
- Optimization constraints:
  - Cross-border transmission capacities, current system imbalances, type of bids, Divisibility, and Activation type

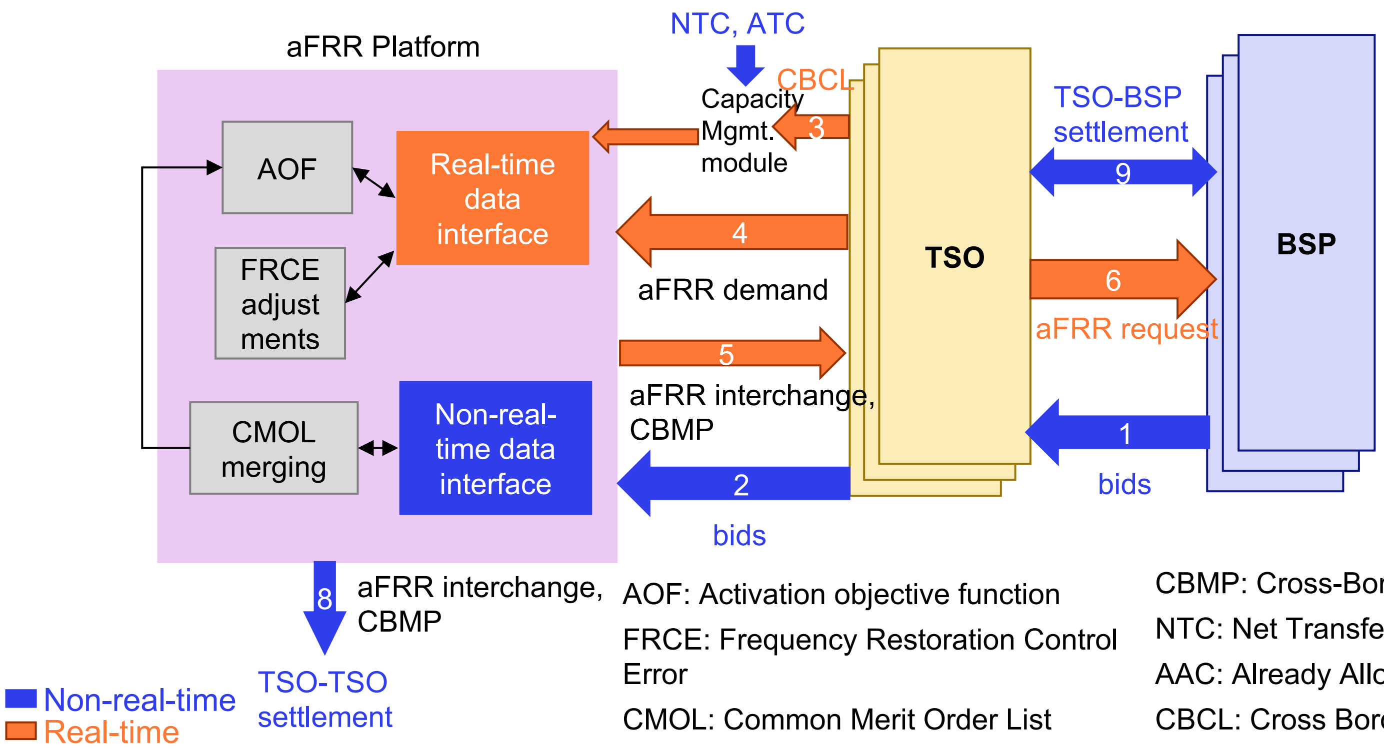
Information flow in MARI



Operation	Gate closure
BSPs providing their bids to the respective TSO → mFRR platform	T-25 mins
TSO demand and CZC → mFRR platform	T-10 mins
Communication on Selected bids to TSOs	T-7.5 mins
BSPs full dispatch	T+5 mins

PICASSO

- PICASSO is The Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation
- Facilitates the exchange of FRR with automatic activation on the European level
- aFRR is a secondary reserve that helps to maintain grid frequency
- Operational from June 2022, with 07 operational TSOs, others to join by July 2024



1. TSO receives bids from BSPs in their LFC area
2. TSO forwards standard aFRR balancing bids to platform
3. TSOs communicate Cross Border Capacity Limits to Platform
4. TSOs communicate aFRR demands to platform
5. Communication of clearing results to TSO
6. Communication of aFRR request from each LFC to BSP
7. Data Publication
8. TSO-TSO settlement process and invoicing
9. TSO-BSP settlement process and invoicing

AOF: Activation objective function

FRCE: Frequency Restoration Control Error

CMOL: Common Merit Order List

CBMP: Cross-Border Marginal Price

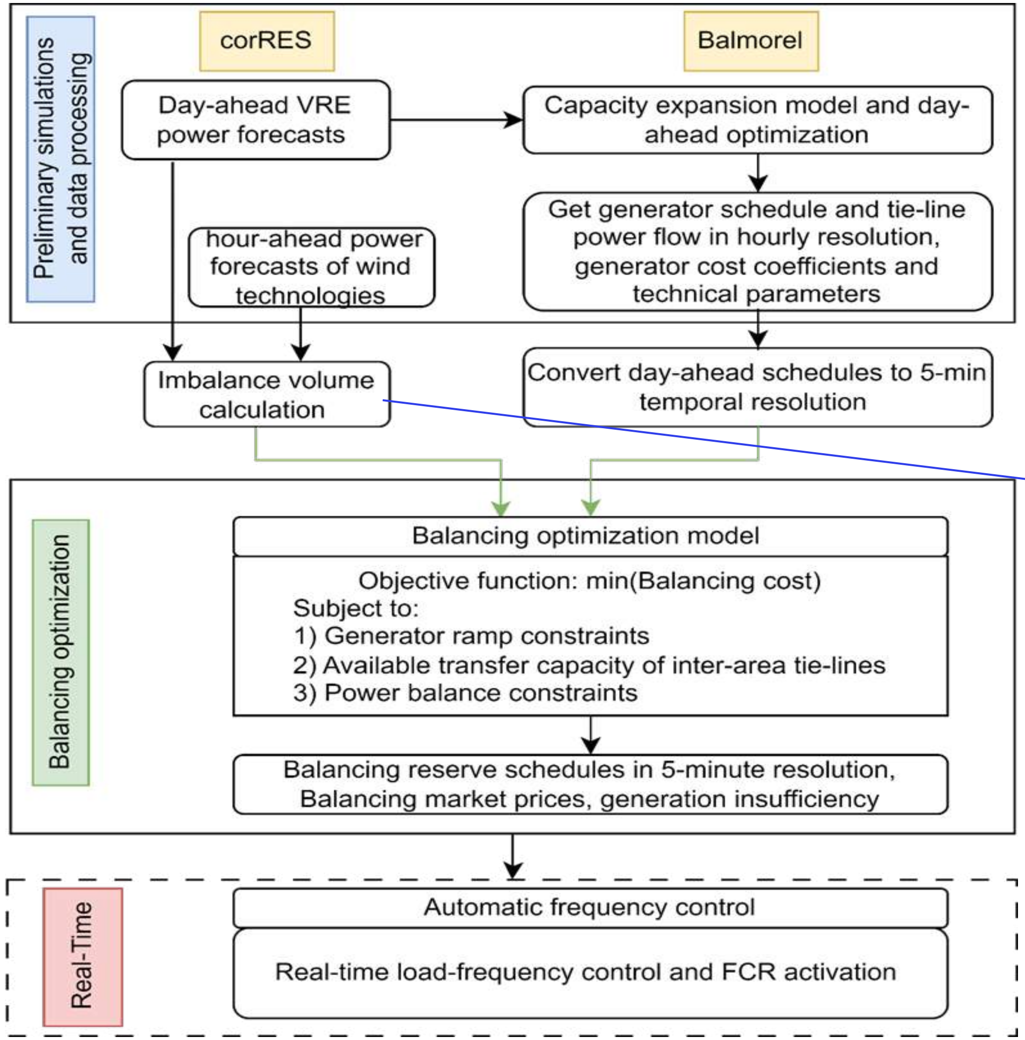
NTC: Net Transfer Capacity

AAC: Already Allocated Capacities

CBCL: Cross Border Capacity Limits

Implementation of Balancing principles

Q. How will evolving balancing methodologies affect market dynamics – prices, operational strategies, etc.?



- Understanding the significance of Balancing markets and their avenues require inputs from capacity expansion studies, VRE timeseries, power flows / transmission expansion, and day-ahead schedules
- BTC connects all the requisites – starting from Capacity expansion to real-time operations.

$$imbal^{+}_{a,m} = max(0, P^{DA}_{a,m} - P^{HA}_{a,m})$$

$$imbal^{-}_{a,m} = max(0, P^{HA}_{a,m} - P^{DA}_{a,m})$$

Imbalance volumes for each balancing area *a* and time *m*

- Positive imbalances (DA forecast >HA forecast) → Up-regulation requirements
- Negative imbalances (HA forecast >DA forecast) → Down-regulation requirements

Balancing Optimization Model

$$Obj: \quad min(\sum_{a,m} FRR_{a,m}^{up\_cost} + \sum_{a,m} FRR_{a,m}^{dn\_cost} + \sum_{a,m} FRR_{a,m}^{Insuff})$$

$$FRR_{a,m}^{up\_cost} = \sum_i P_{a,m,i}^{up\_reg} c_i$$

$$FRR_{a,m}^{dn\_cost} = \sum_i P_{a,m,i}^{dn\_reg} c_i$$

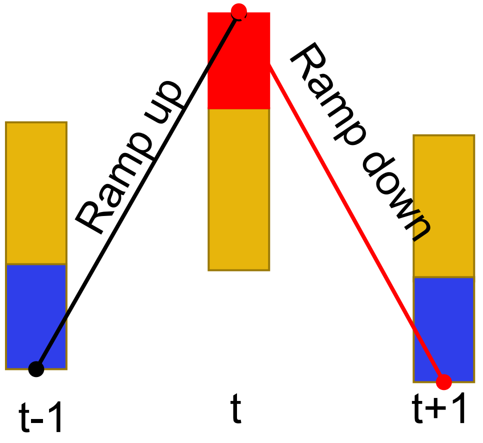
$$FRR_{a,m}^{Insuff} = P_{a,m}^{Insuff} c_{penalty} \qquad \forall i \in a_i$$

Minimizes the FRR procurement cost and penalty for its insufficiency

$$(P_{a,m,i}^{DA} + P_{a,m,i}^{up\_reg}) - (P_{a,m-1,i}^{DA} - P_{a,m-1,i}^{dn\_reg}) \le r_i^{up}$$

$$(P_{a,m,i}^{DA} + P_{a,m,i}^{up\_reg}) - (P_{a,m+1,i}^{DA} - P_{a,m+1,i}^{dn\_reg}) \le r_i^{dn}$$

Ramping constraints

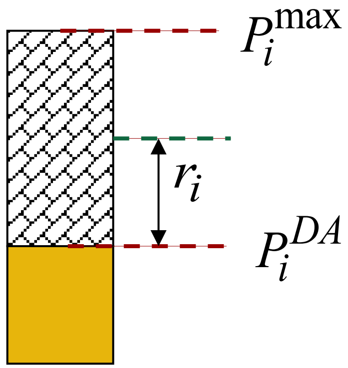


$$P_{a,m,i}^{up\_reg} \le Ava.Cap_{a,m,i}^{up}$$

$$P_{a,m,i}^{dn\_reg} \le Ava.Cap_{a,m,i}^{dn}$$

$$Ava.Cap_{a,m,i}^{up} = \left[\min(r_i^{up}, P_i^{\max} - P_{a,m-1,i}^{DA}) - \min(0, P_{a,m,i}^{DA} - P_{a,m-1,i}^{DA})\right] * u_{a,m,i}^{DA}$$

$$Ava.Cap_{a,m,i}^{dn} = \left[\min(r_i^{dn}, P_{a,m-1,i}^{DA} - P_i^{\min}) - \min(0, P_{a,m-1,i}^{DA} - P_{a,m,i}^{DA})\right] * u_{a,m-1,i}^{DA}$$



Schedules are subject to ATC: line limit-DA power flow

Q. What is the value of flexibility from various technologies for balancing services?

Test cases:

Balancing requirements for future European power systems

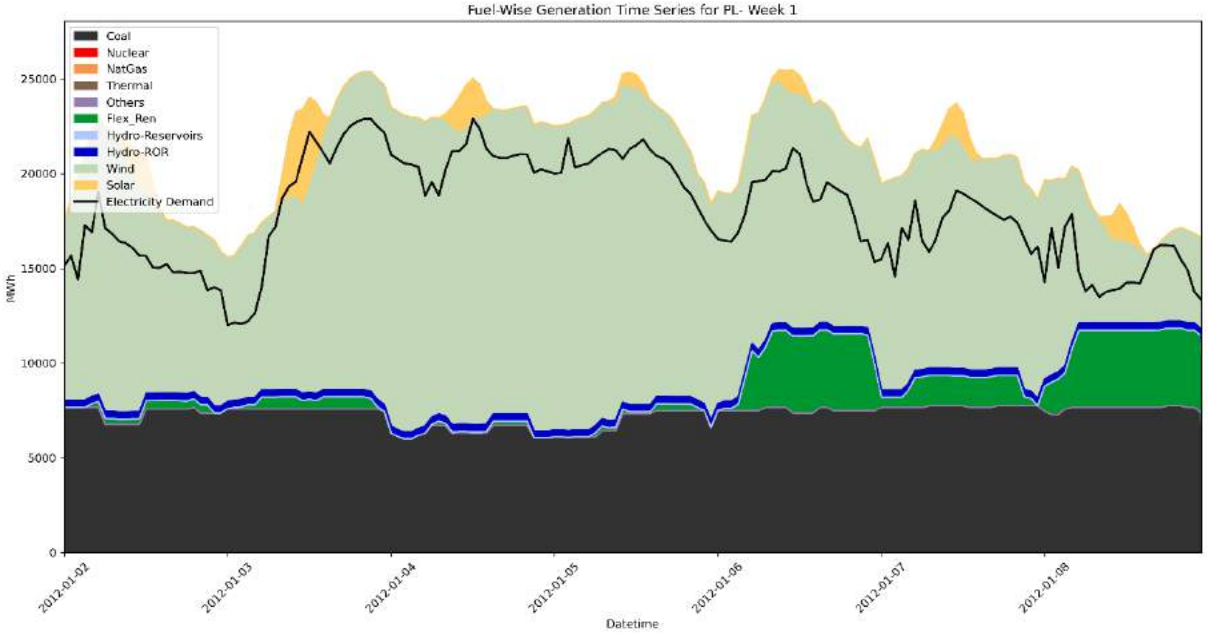
Operation of Hybrid Power Plants in Europe in 2030

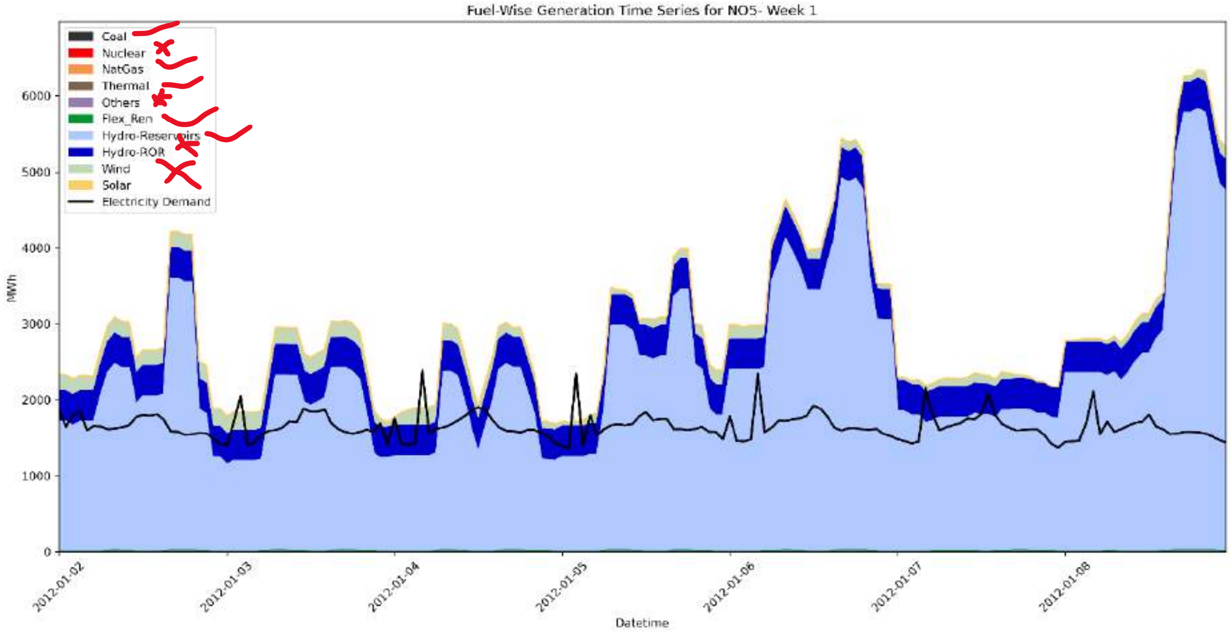
Balancing requirements for future European power systems

Areas under study

- All scenario years (2025, 2035, and 2045) will have a VRE time series based on the weather year 2012.
- Imbalance volumes are determined solely based on wind power forecast
- Controllable (flexible) generators, excluding nuclear, that are cleared in day-ahead market are only eligible to provide balancing reserves. *(partially relieved)*
- Netting of imbalances is only limited to respective bidding zones (or) balancing areas
- Balancing areas (or areas) considered in this work represent the current bidding zones of countries being studied, except for Germany.
- Germany is classified into 04 balancing areas to highlight the intra-regional transmission bottlenecks.

Day-Ahead market results





- Day-ahead schedules are in hourly resolution
- Flexible generators can participate in balancing markets
- Hourly schedules are converted into 5-minute temporal
- Net Transfer Capacity = Transmission capacity – DA power flow

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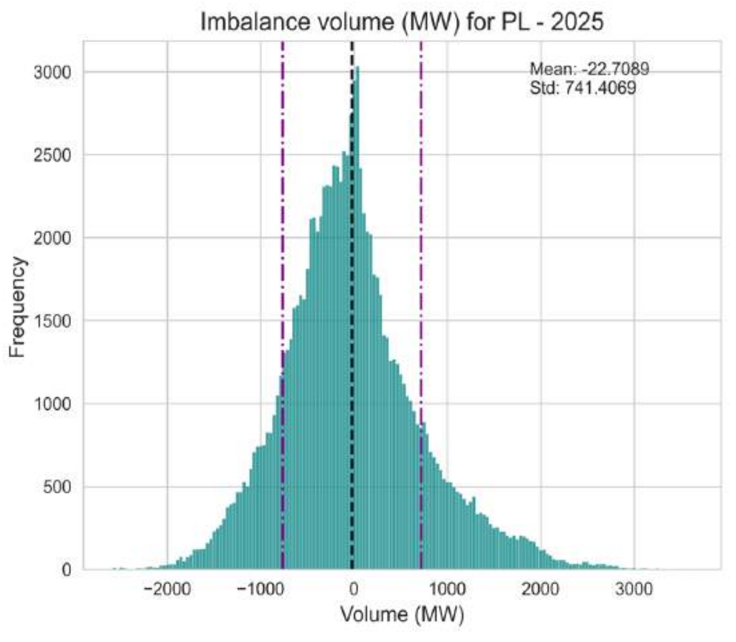
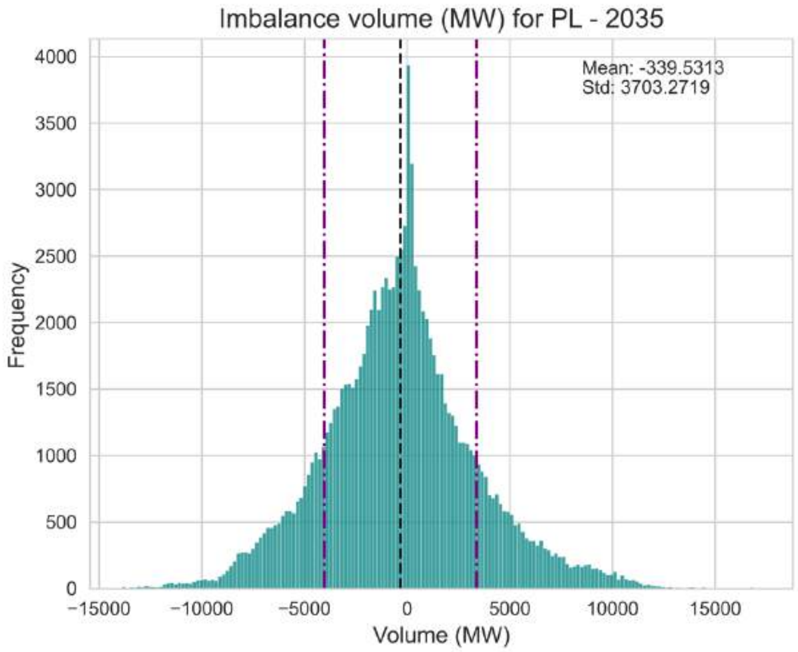
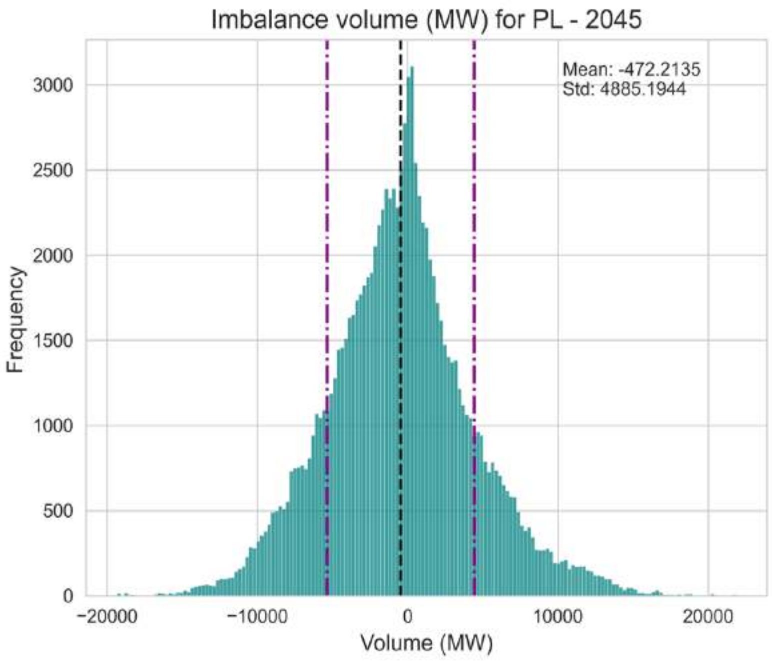
Wind Power Forecast Error



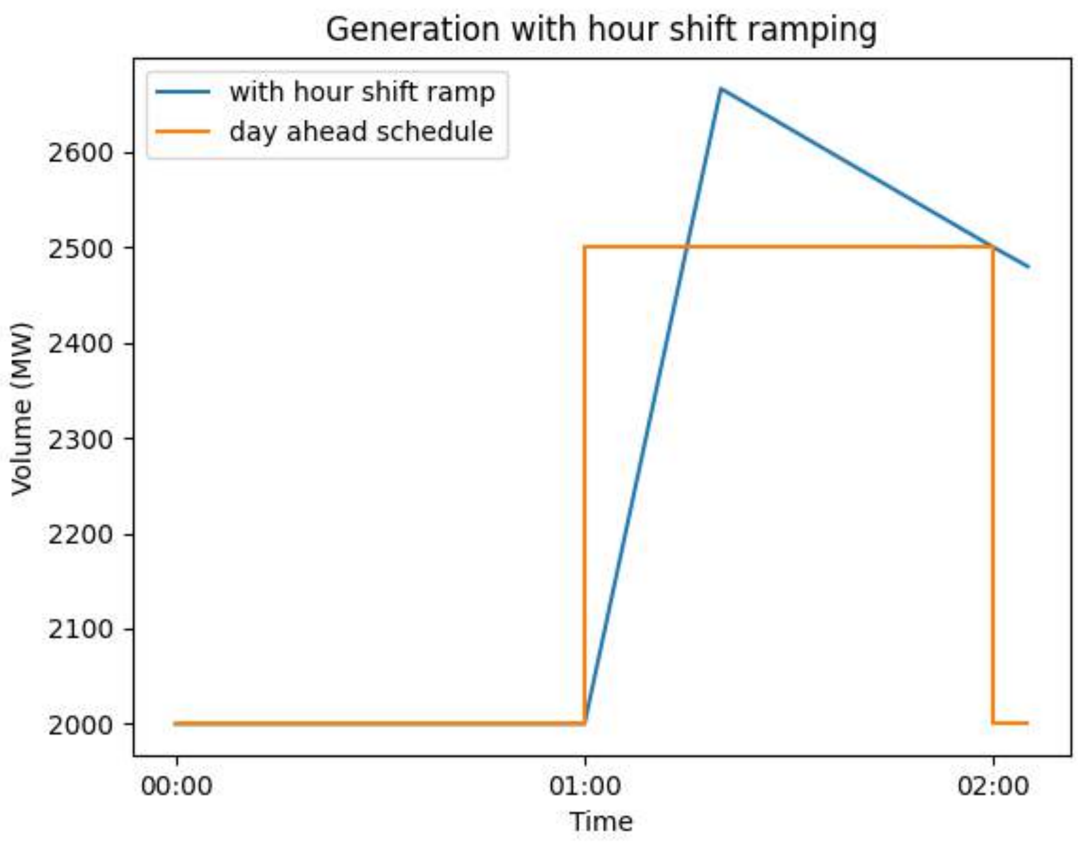




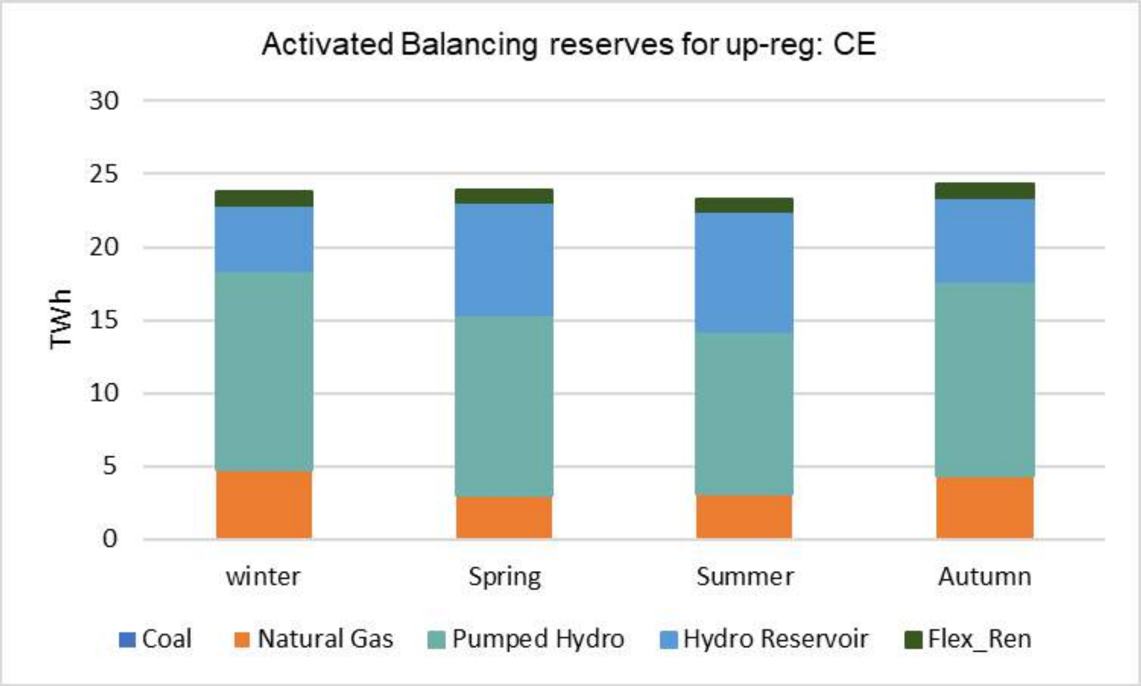
- There is a substantial increase in wind power forecast error towards 2050 as compared to the 2025 values.
- Long tails depict that there can be very high forecast errors for very few hours of the year which pose additional challenges for power system balancing.

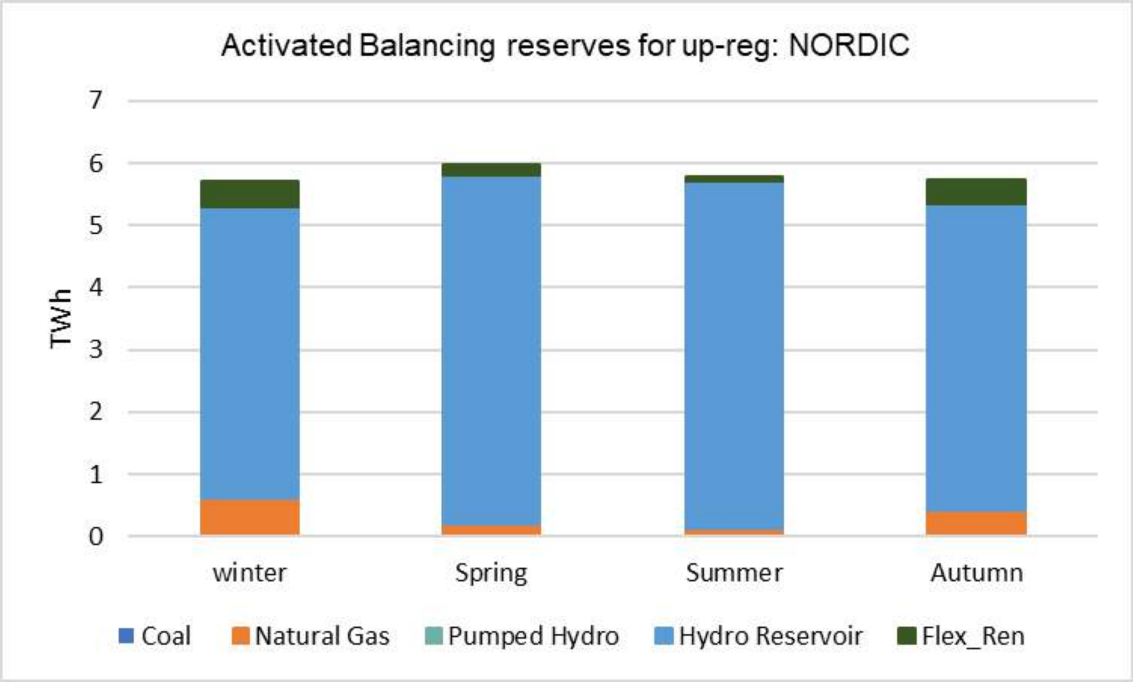
Error due to hour shifting

- Imbalances can also occur due to hour shift
- DA commitments tend to meet energy obligations
- Ramp between two scheduling intervals may lead to imbalances in BA
- Lower triangle → up-regulation requirement
- Upper triangle → down-regulation requirement



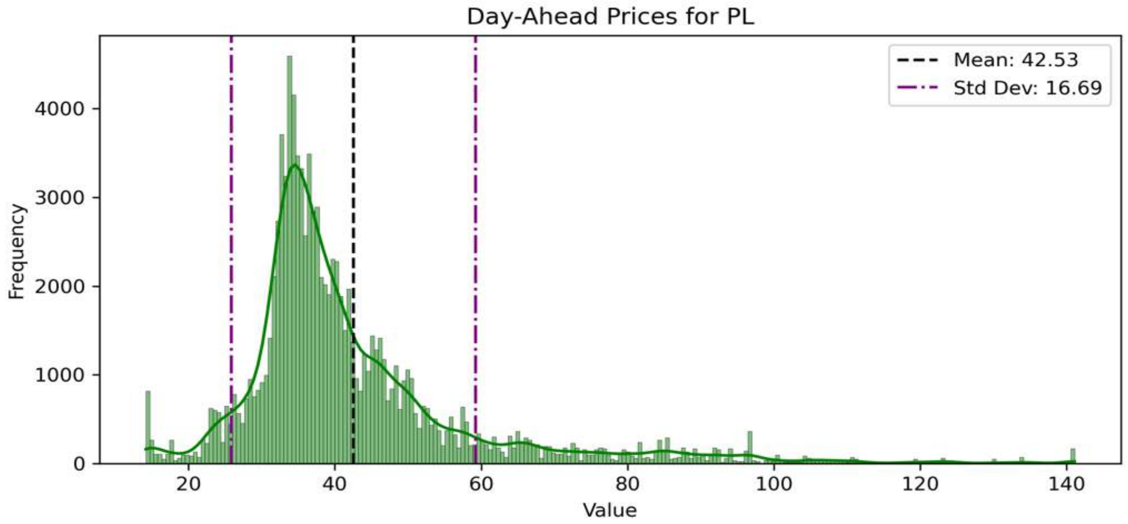
Activated balancing reserves - Up Regulation

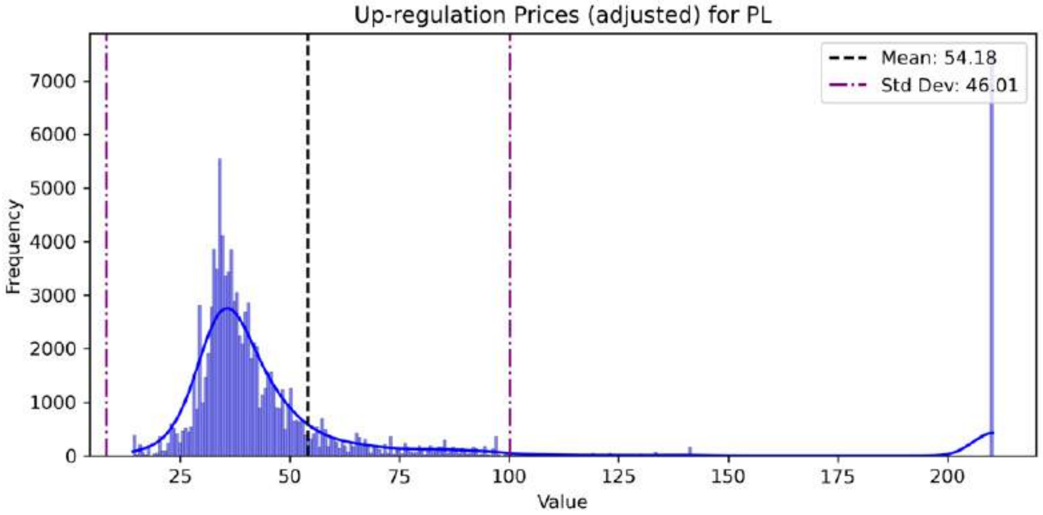


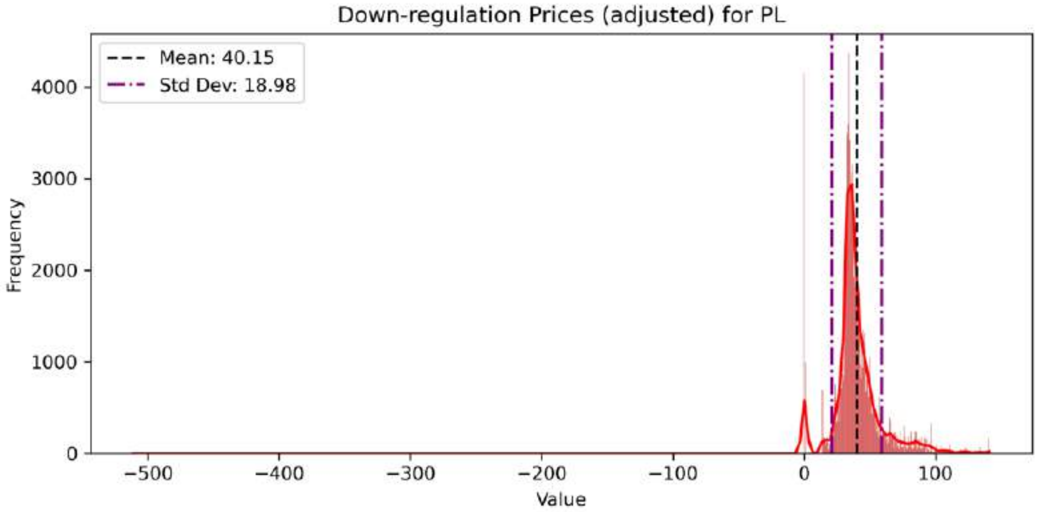


- In CE, the imbalances are mainly counteracted using Natural gas and Pumped storage hydro
- In Nordic, the imbalances are mainly counteracted using Hydro
- Wind technologies are also used for up-regulation if they are being curtailed in the day-ahead schedule (imbalances for the durations of curtailment are considered to be zero)

Preliminary Balancing Prices

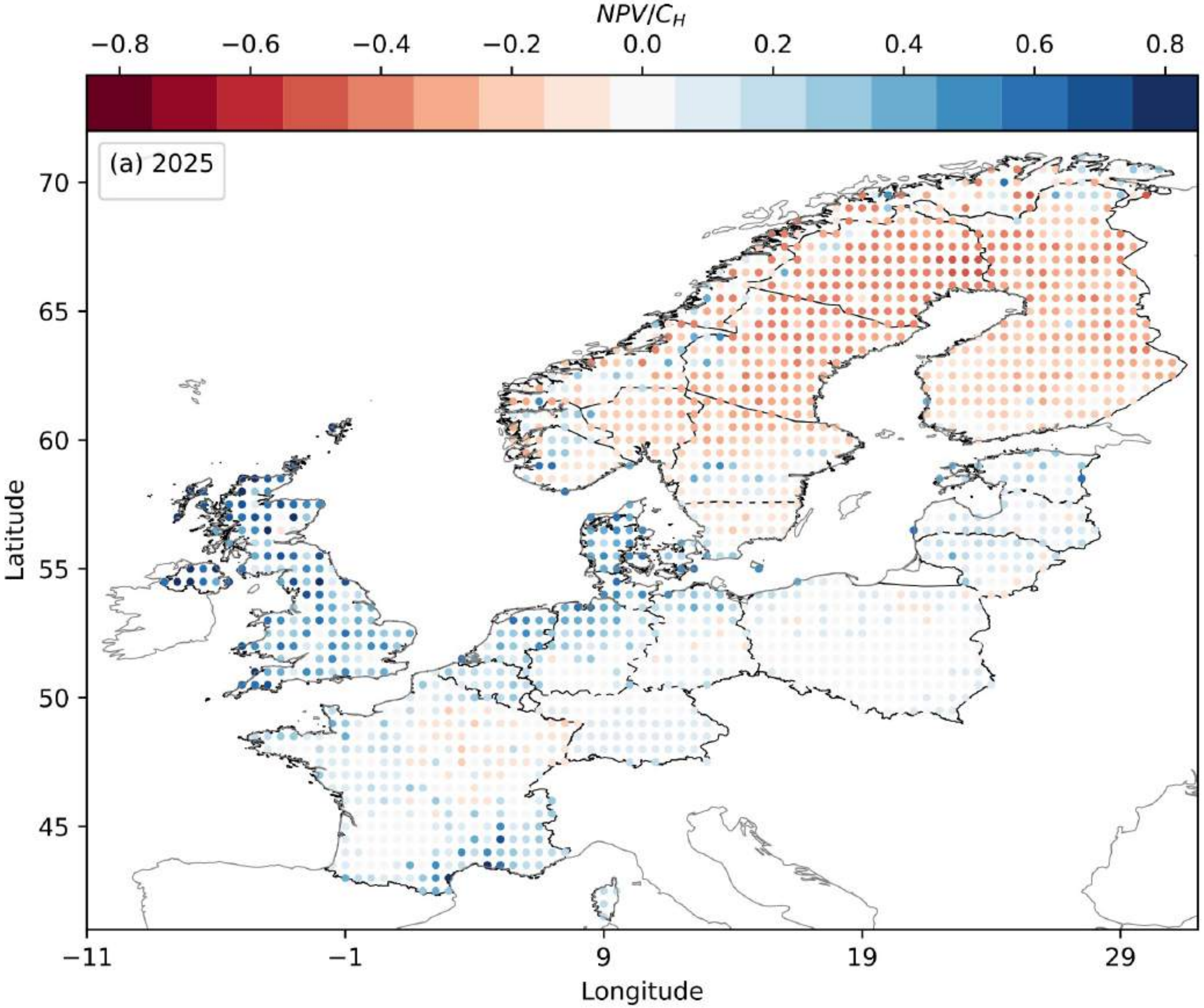




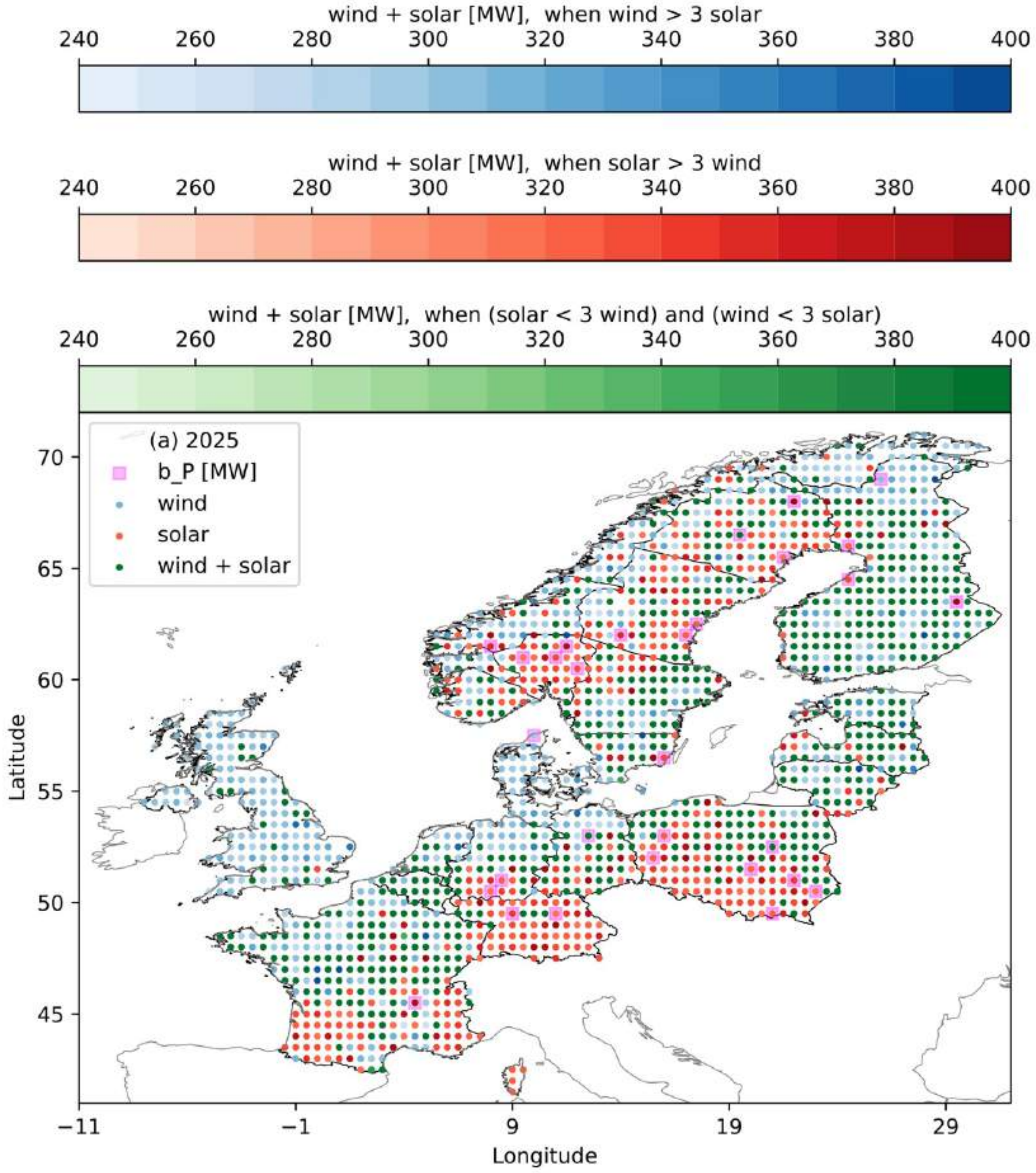


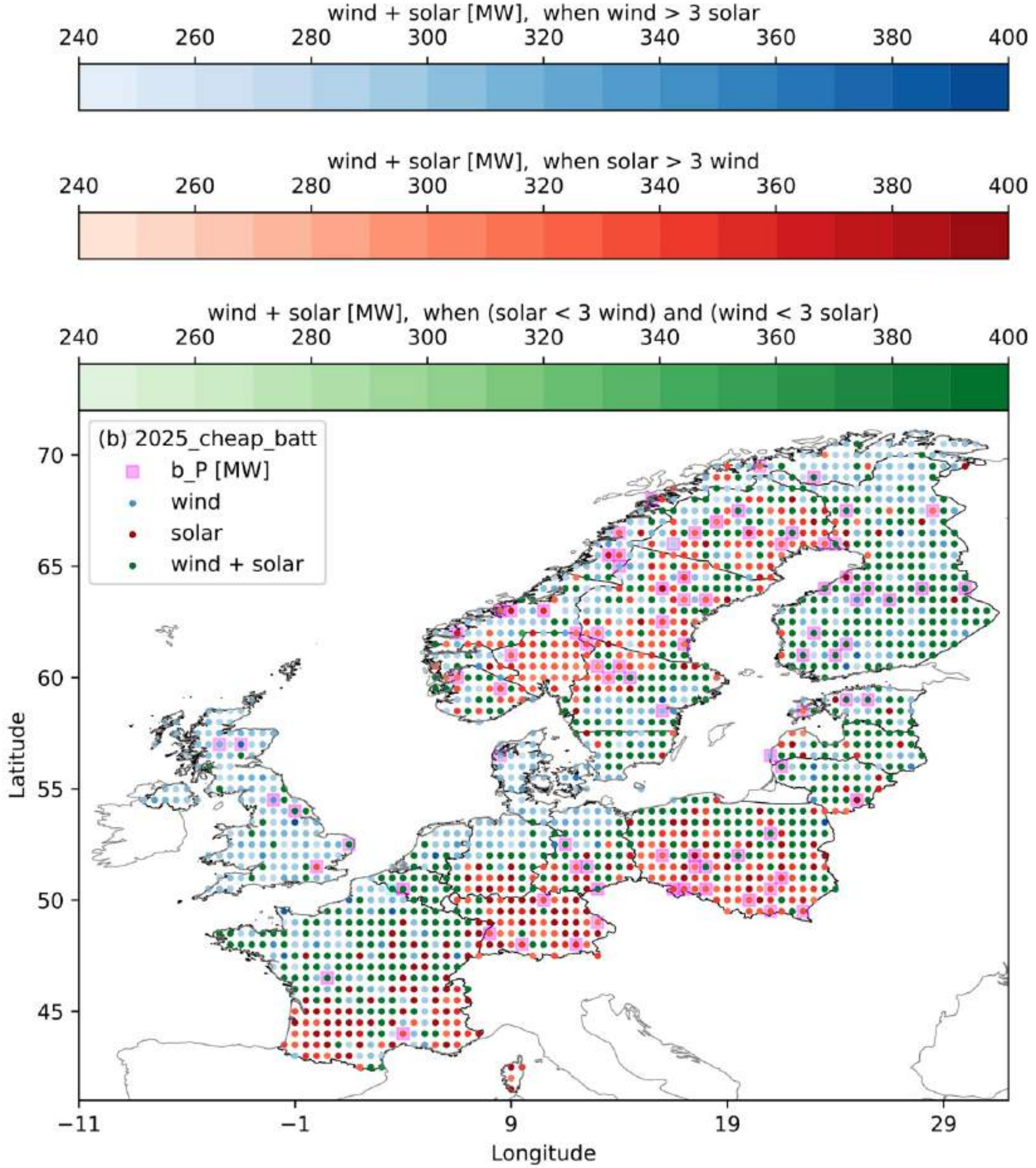
- Extreme levels of prices are determined by backup generators and penalties for VRE curtailments
- For the intervals with no up/down-regulation requirements, regulation prices = area's DA market clearing price
- Areas with more dependencies on neighboring areas (say DK) tend to have higher regulation prices
- Limited by cross-border XB availability and correlated imbalances

Wind Solar Battery HPP in Europe



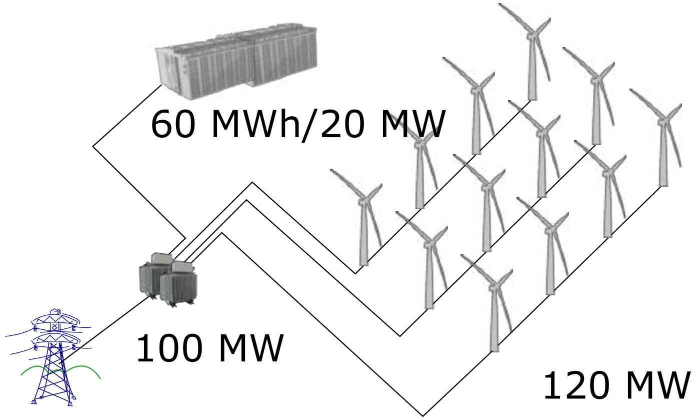
Juan Pablo Murcia Leon, Kaushik Das, “Profitability Of Hybrid Power Plants In Europe”, 22nd Wind and Solar Integration Workshop, 2023





Juan Pablo Murcia Leon, Kaushik Das, “Profitability Of Hybrid Power Plants In Europe”, 22nd Wind and Solar Integration Workshop, 2023

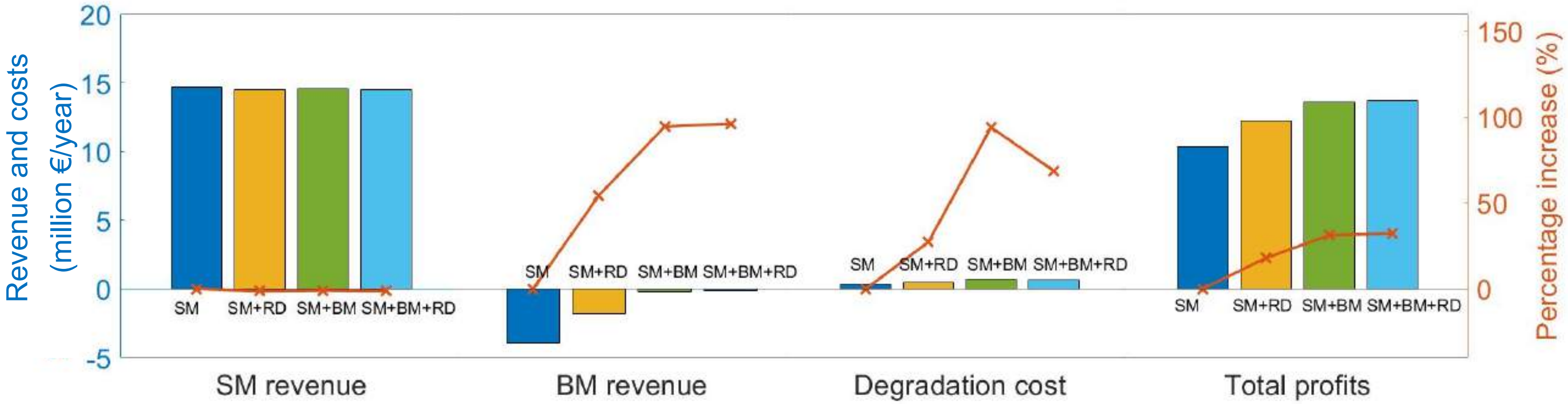
Energy Management System in Nordic System



Location: Western Denmark

- ✓ Spot revenues are similar
- ✓ Balancing revenues are increased
- ✓ Re-dispatch helps reduce battery degradation
- ✓ Total profits are increased
- ✓ There are benefits to participate in balancing markets

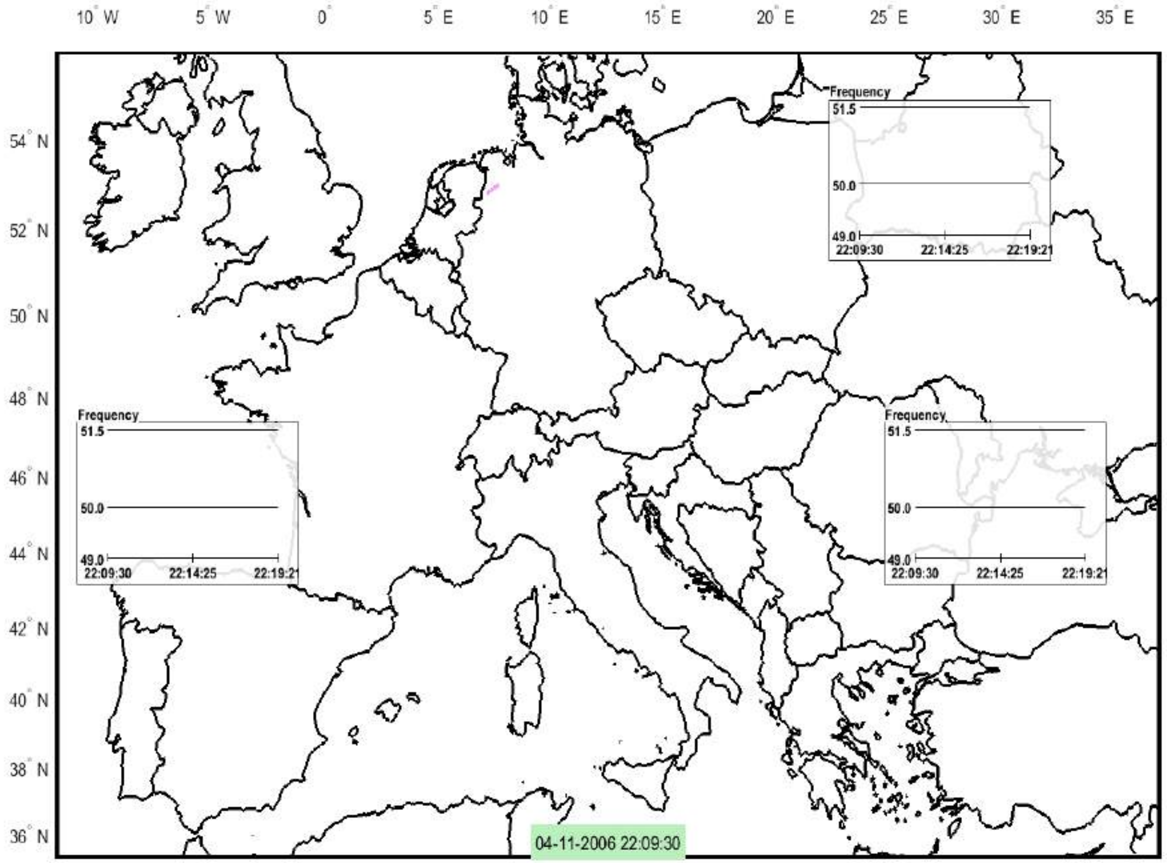
Operation strategy	Spot market	Balancing market	
	SMOpt	BMOpt	RDOpt
SM	✓		
SM+RD	✓		✓
SM+BM	✓	✓	
SM+BM+RD	✓	✓	✓



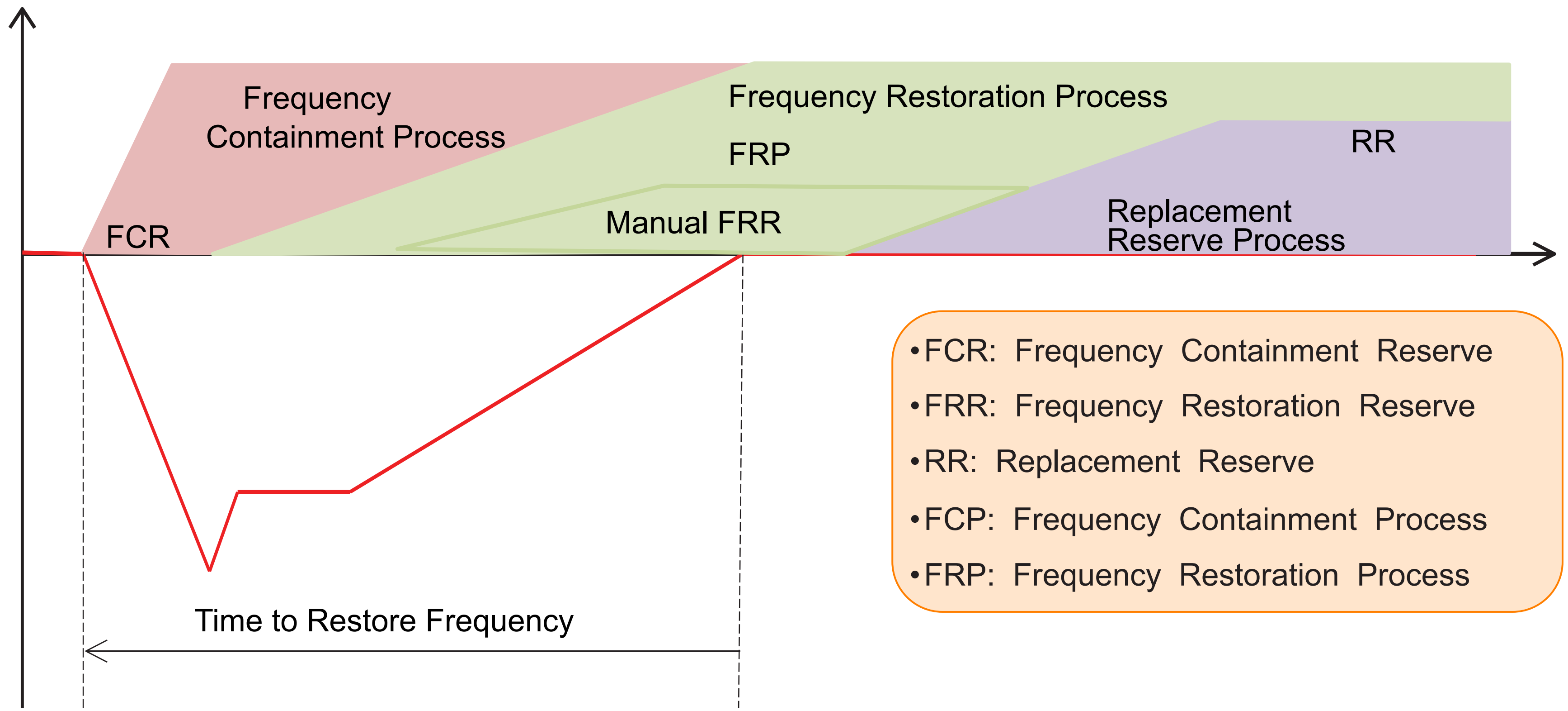
Area Control- Dynamic Model

Need for frequency containment reserves

- Imbalances between the electricity demand and generation in real-time (or close to real-time) determine the system frequency which is crucial for system stability
- Frequency containment and restoration processes restore frequency to the target levels, in Europe usually 50.00Hz.
- Frequency containment reserves (FCR) quickly counteract frequency deviations that occur when there is an imbalance between electricity generation and consumption.
- FCR are important because they help to prevent blackouts.
- With EB regulation, common market for procurement and exchange of FCR (FCR Cooperation) was formed



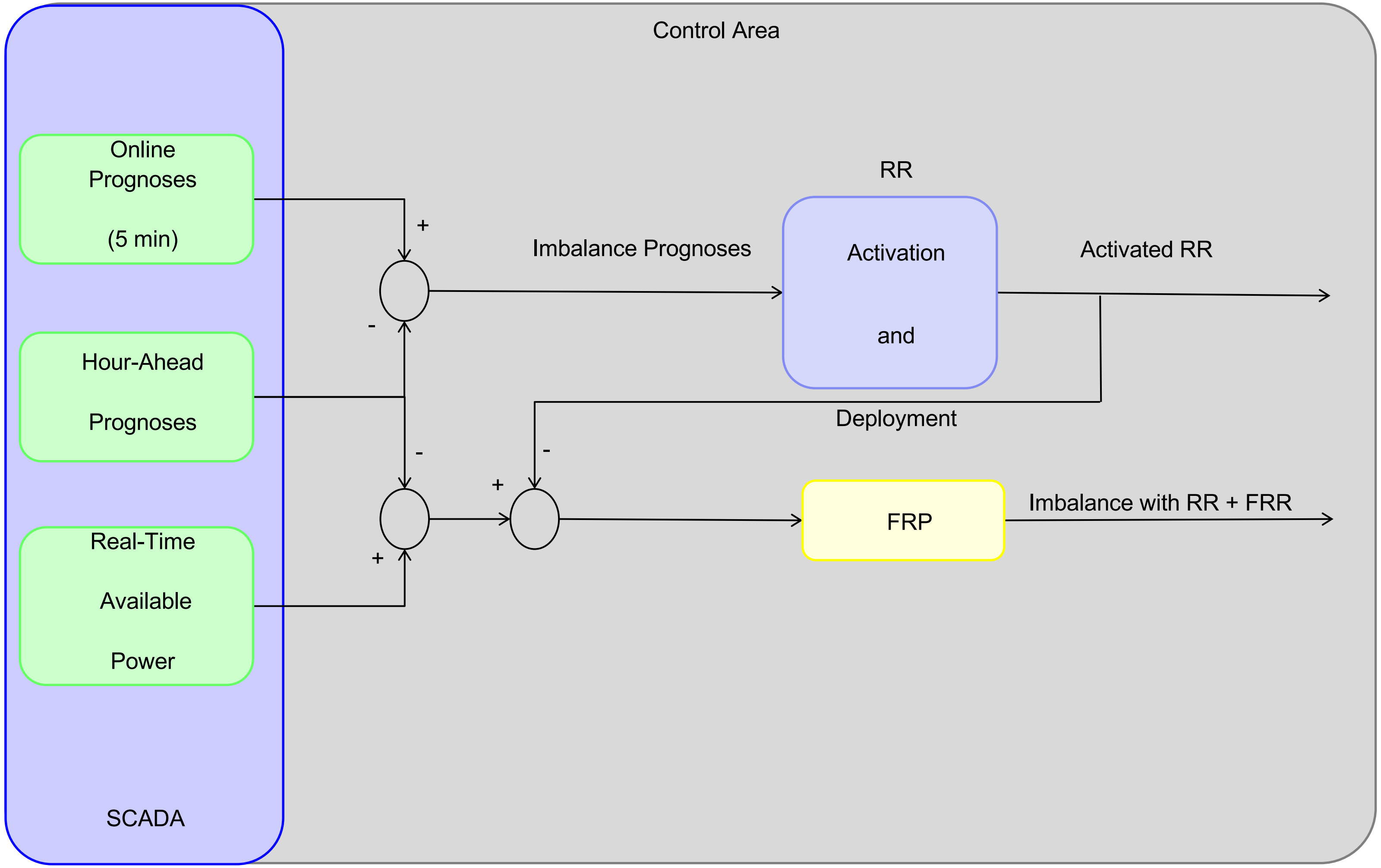
Operating frequency reserves



- FCR: Frequency Containment Reserve
- FRR: Frequency Restoration Reserve
- RR: Replacement Reserve
- FCP: Frequency Containment Process
- FRP: Frequency Restoration Process

- Frequency Containment Reserves (FCR) are used seconds or minutes after the occurrence of the imbalance for the containment of frequency.
- The Frequency Restoration Reserves (FRR) are utilized around 15 minutes after the event to return the frequency to its normal range (49.9 - 50.1 Hz) and to release FCR already deployed back into use.
- Lastly, the Replacement Reserves (RR) release activated FRR back to a state of readiness for use to counteract new imbalances

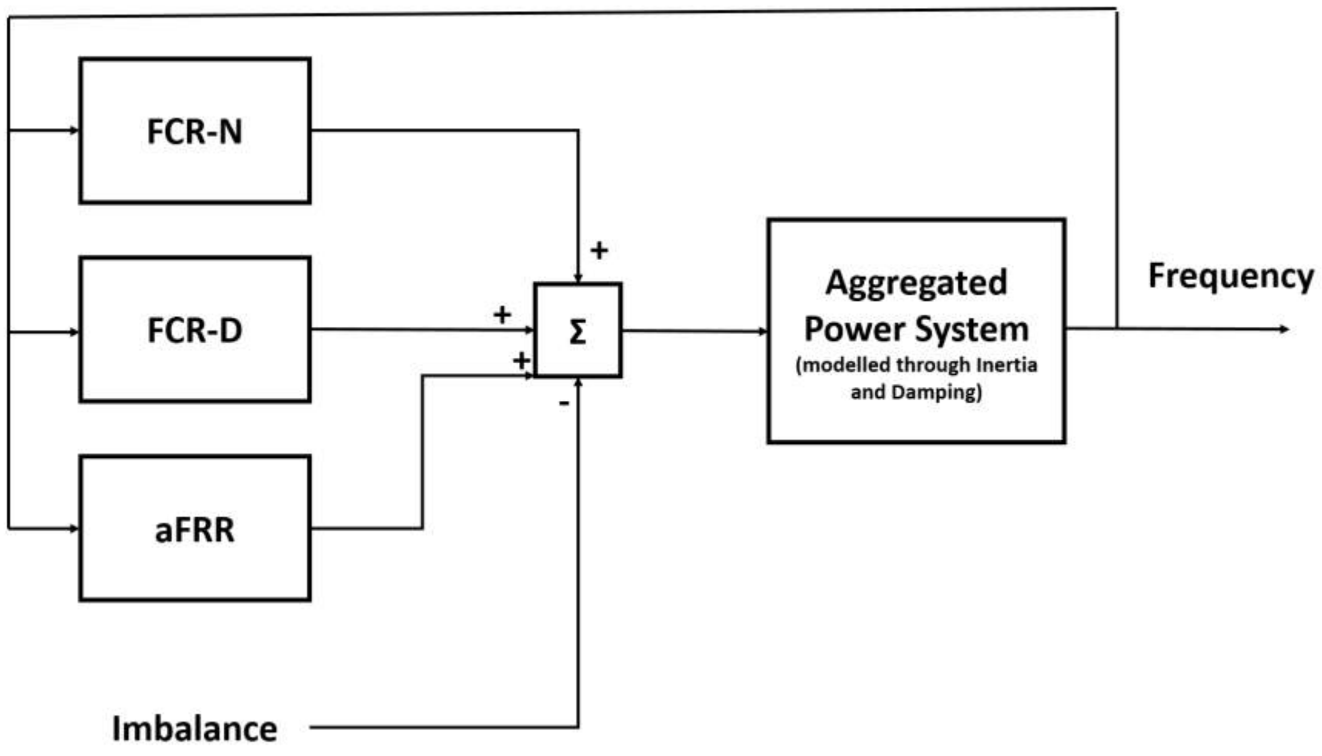
Operating frequency reserves



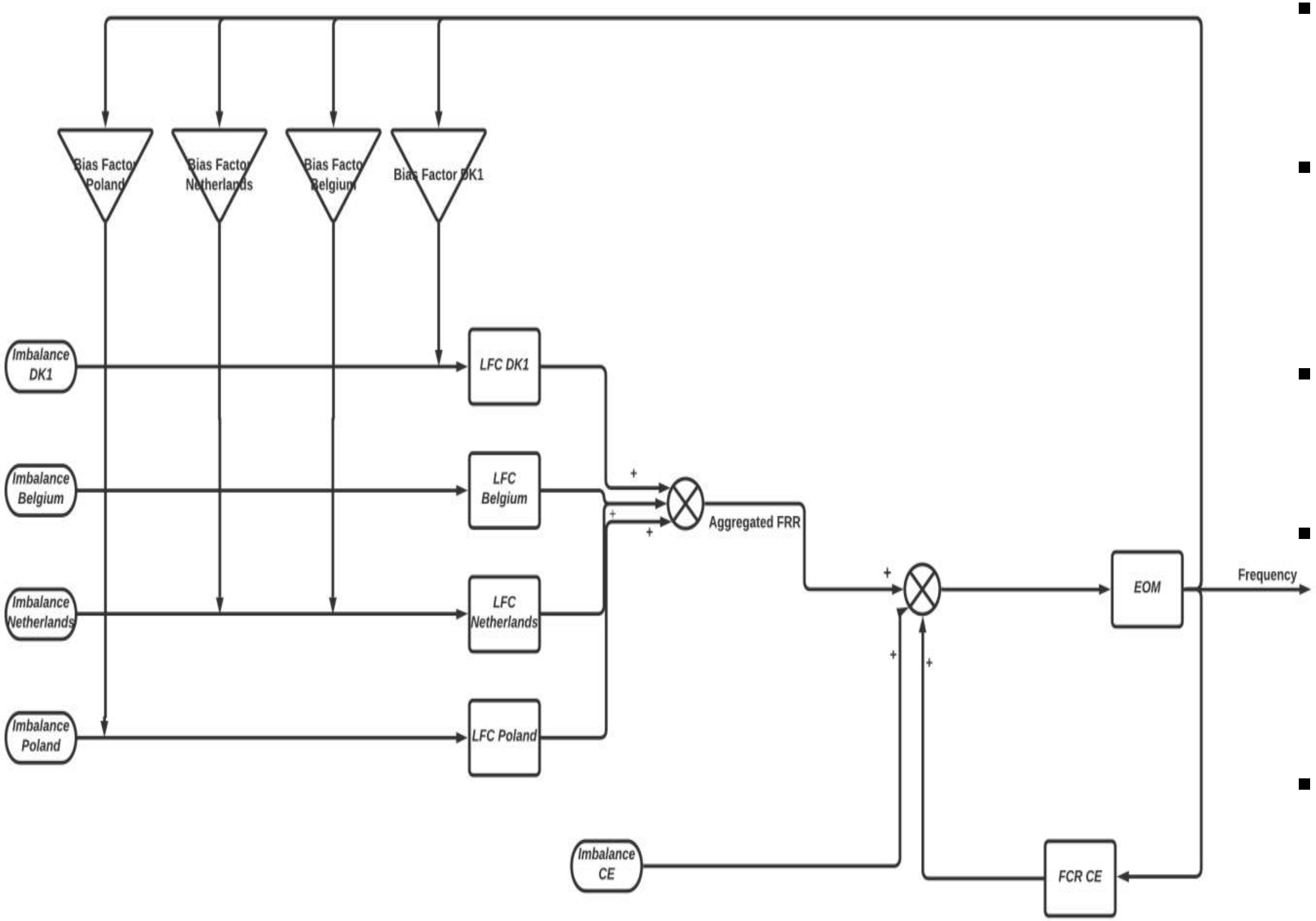
Frequency control

- Post mFRR deployment, the anticipated load-generation imbalances are taken care of by aFRR
- aFRR is automatically instructed by the central Load Frequency Controller (LF Controller) of the TSO and automatically activated at the aFRR provider.
- The central controller continuously sends the activation signals (typically every 4 to 10s) to the aFRR providers
- aFRR is provided by units that are ‘spinning’
- In the Nordic system (Finland, Sweden, Norway, and East Denmark), the TSOs have a common agreement to secure the obligated reserves for FCP and FRP. (they are in the process of integrating with Pan-European platforms)
- The balancing reserves products defined in the System Operation Agreement are namely the FCR-D, FCR-N , aFRR, and mFRR.
- The Frequency Containment Reserve for Normal operation (FCR-N) product is acting as a primary frequency control reserve and is used to balance the system within normal frequency band (49.9 - 50.1 Hz).
- In total, 600 MW of aggregated FCR-N are constantly maintained inside the Nordic area. Thus, the bias factor of the FCR-N is calculated as 600 MW/0.1Hz = 6000[MW/Hz]

Frequency control

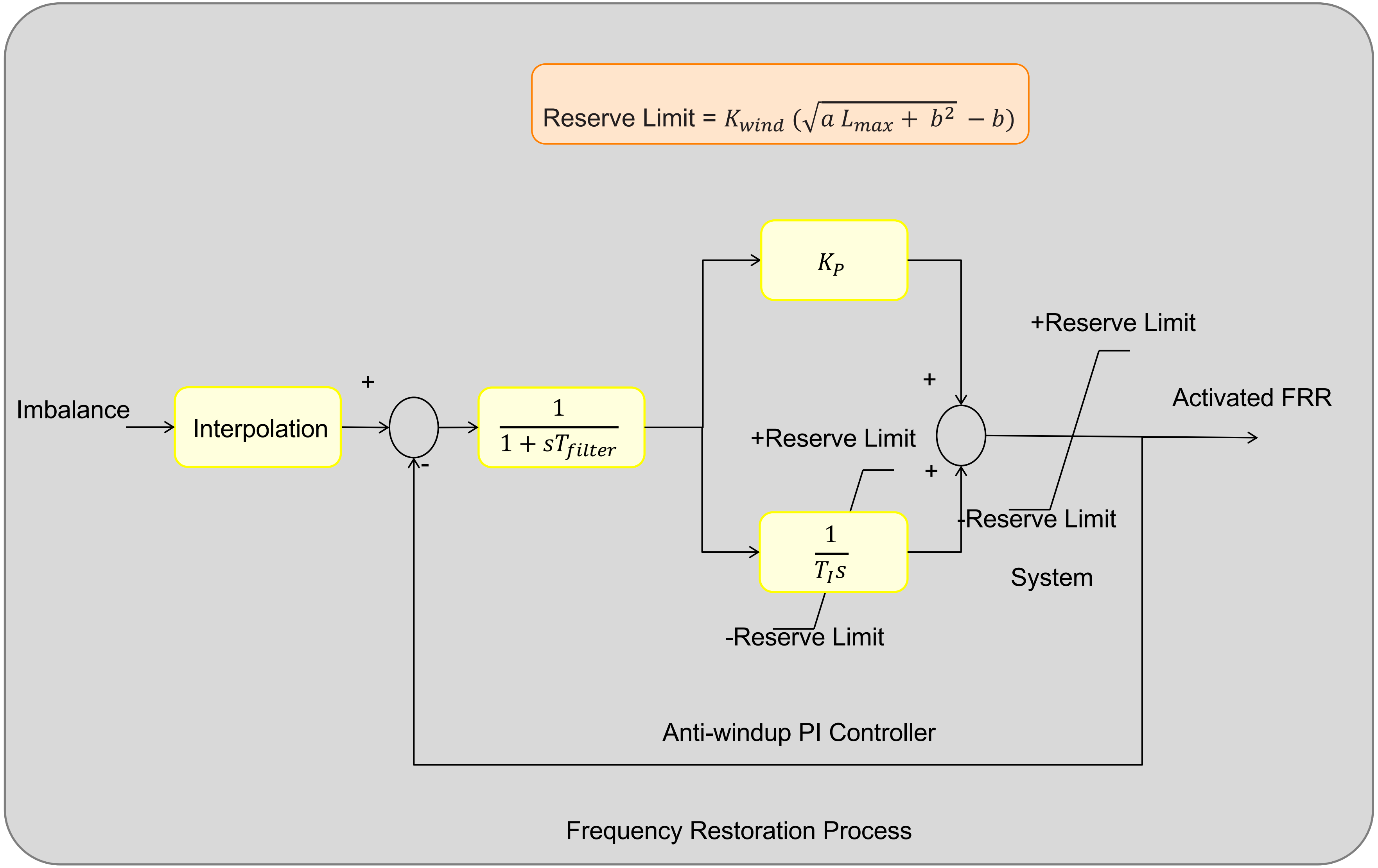


Dynamic modeling of Continental Europe



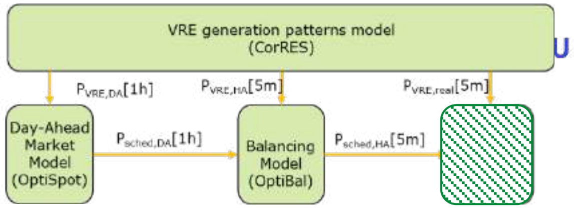
- Large synchronous areas such as Continental Europe use a multi-tiered approach to frequency control.
- First, the frequency containment is done locally by proportional control in order to ensure the avoidance of power oscillations in an abnormal operational state.
- Next, the frequency restoration takes place in order for the system to return to its pre-disturbance state.
- The frequency restoration, through Automatic Generation Control (AGC) or Load-Frequency Control (LFC), is done automatically and has proportional-integral control (or only integral control) characteristics.
- Decentralized feedback implemented by each control area contributes to the overall balance in the synchronous area.

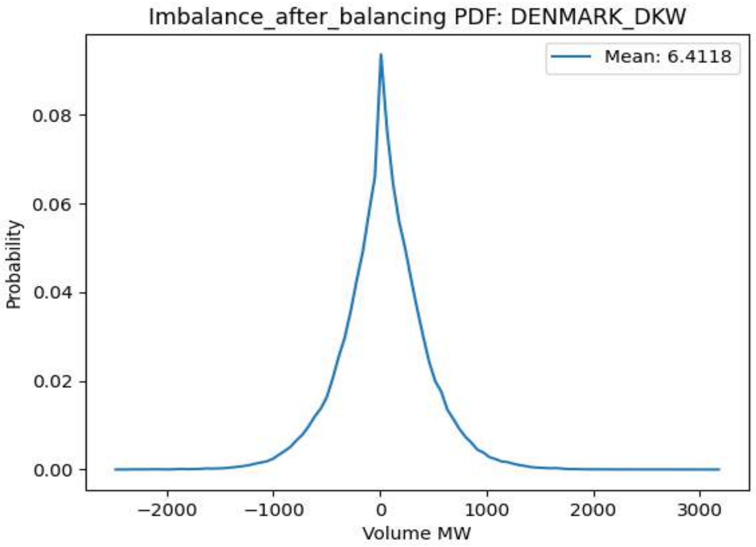
Load-Frequency control (LFC)

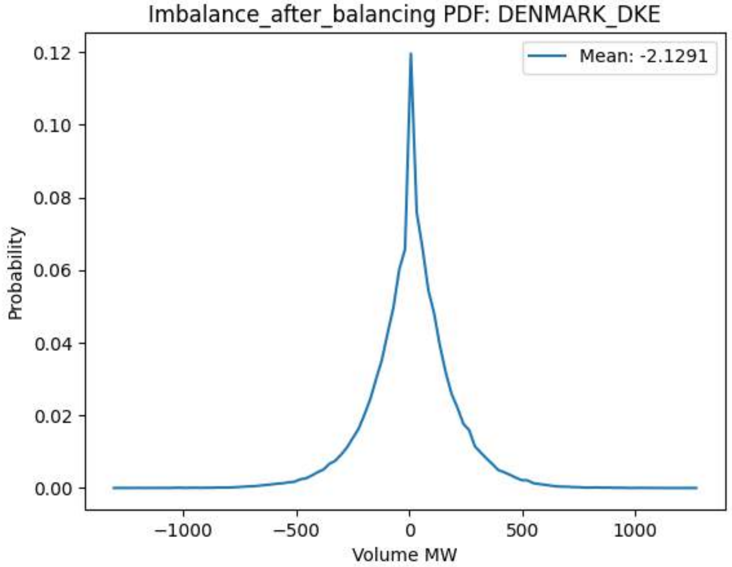


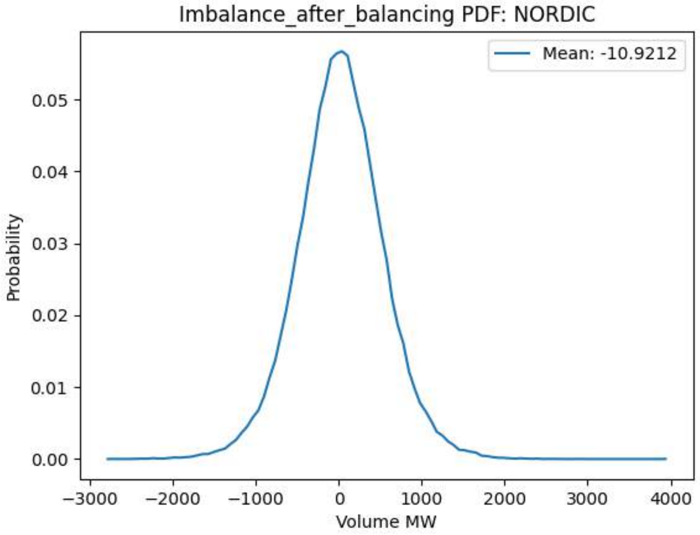
- The aFRR is considered to be deployed by automatic LFC.
- The LFC control is modeled with an anti-windup PI controller together with a measurement filter.

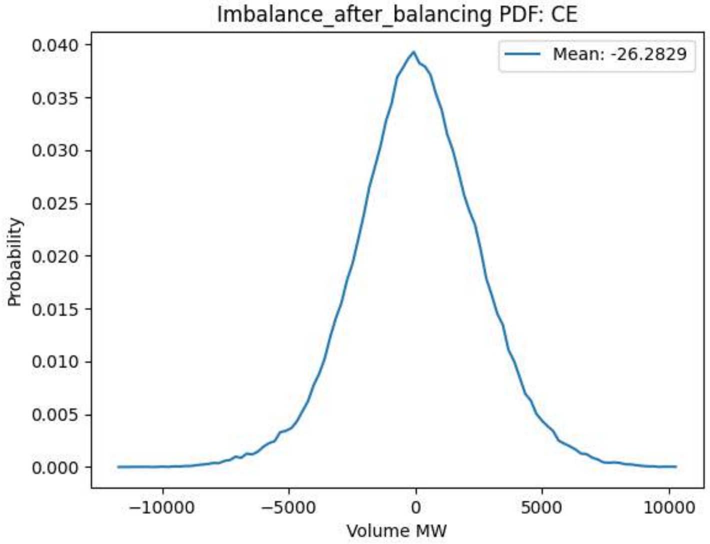
Real Time Imbalance

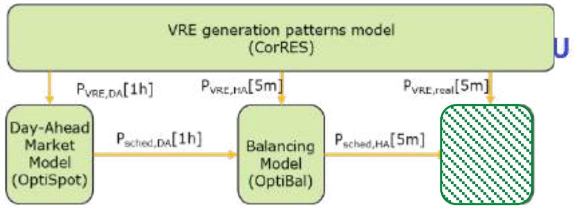










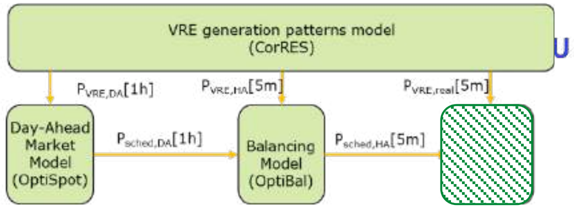


aFRR dimensioned

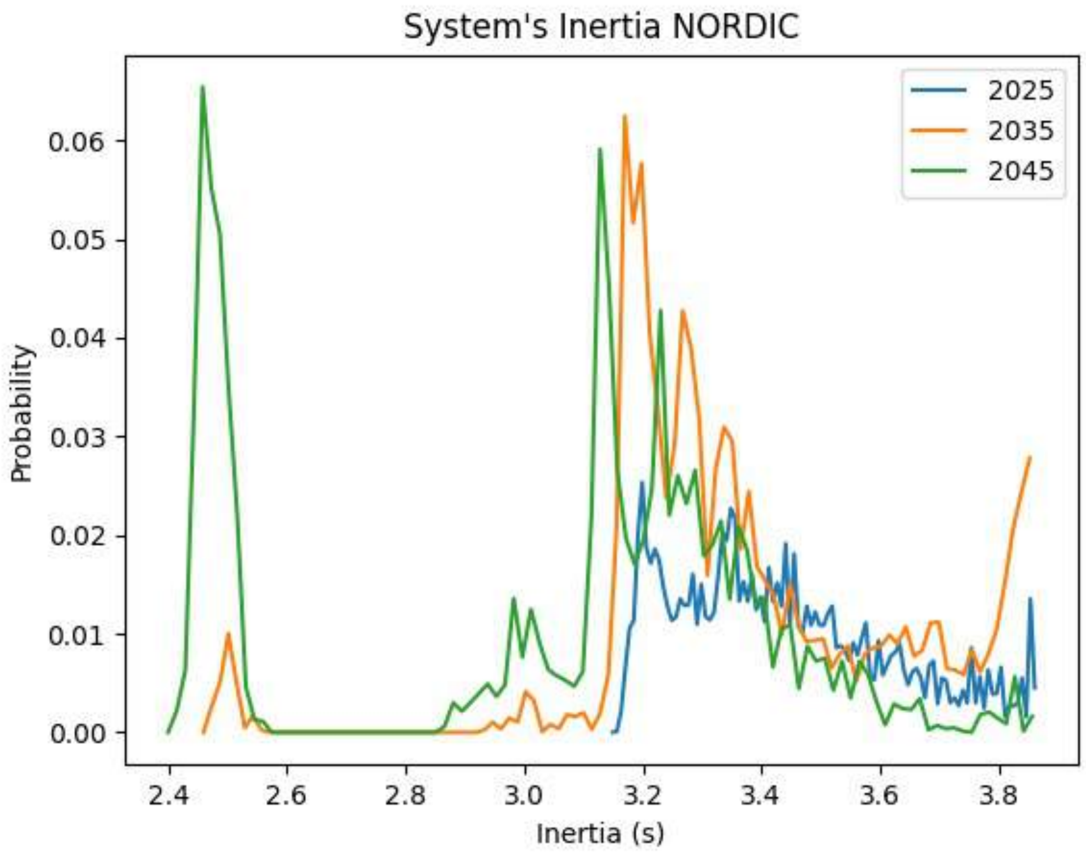
Control Areas	aFRR available 2025 (GW)
GERMANY	2.12
HOLLAND	1.18
DK1	0.66
BELGIUM	1.09
NORDIC	1.57

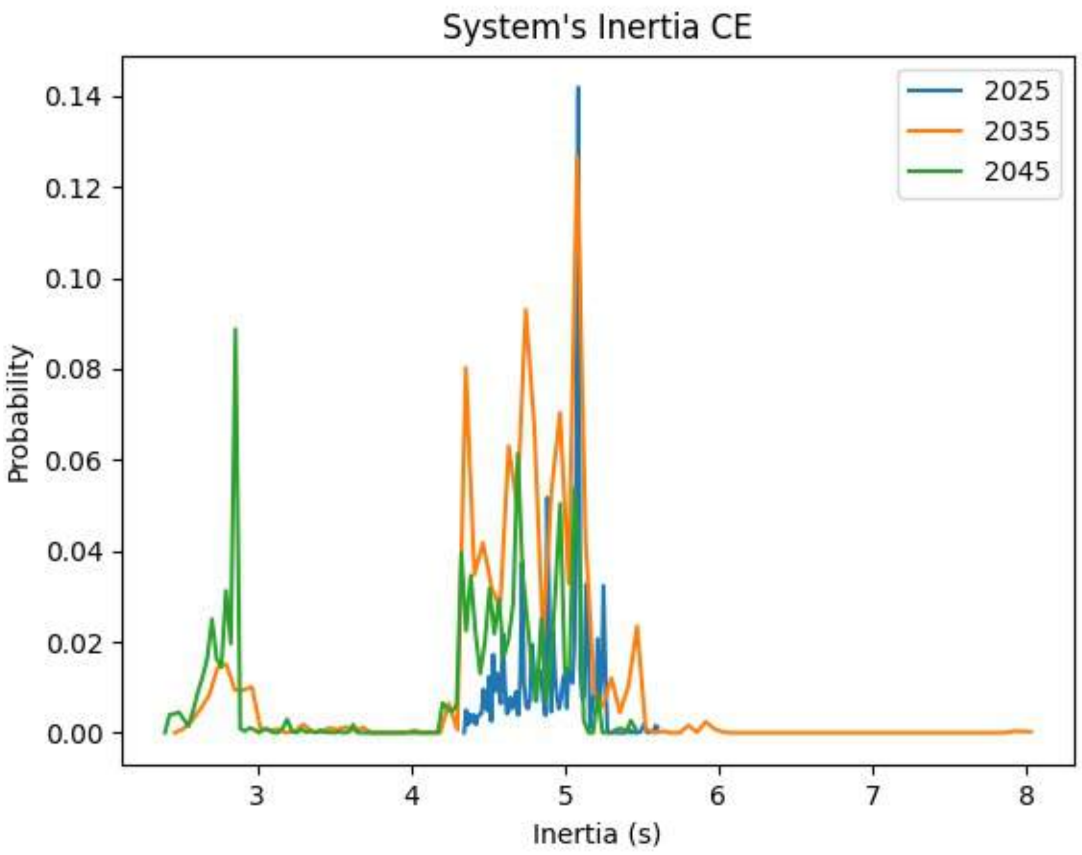
Dimensioned to handle 99% of the VRE forecast imbalance

DTU Wind Energy



System Inertia





Discussions

- Balancing is becoming more and more challenging

- The balancing principles varies in different countries
  - Depends on practices
  - Depends on capabilities and structure of power system
  - Depends on energy mix

- **Harmonization of balancing** in interconnected systems are becoming major issue

- Not considering wakes for balancing studies of future can cause substantial error in power systems operational planning in future

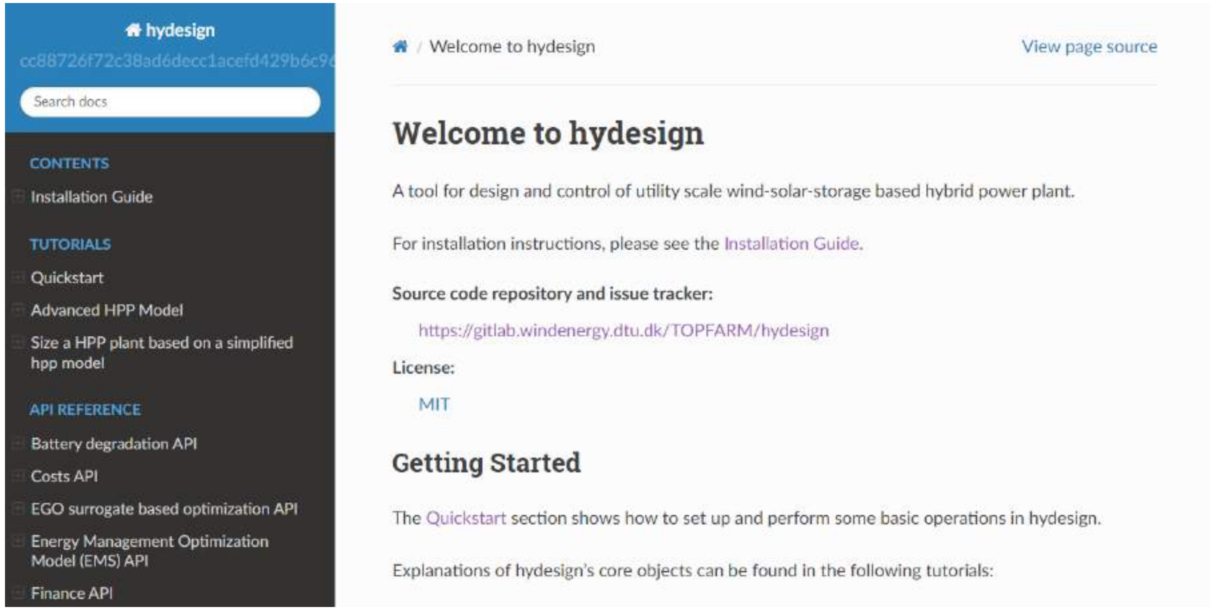
HyDesign

-- Sizing optimization of HPP

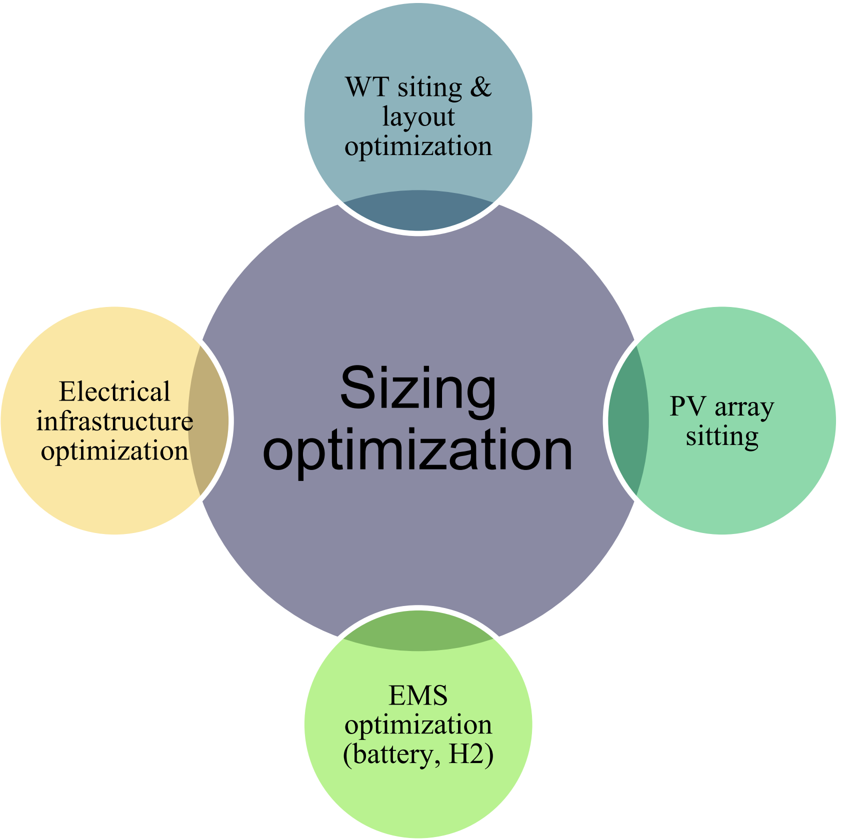
-- Evaluating different designs

HyDesign: Python-based open-source tool

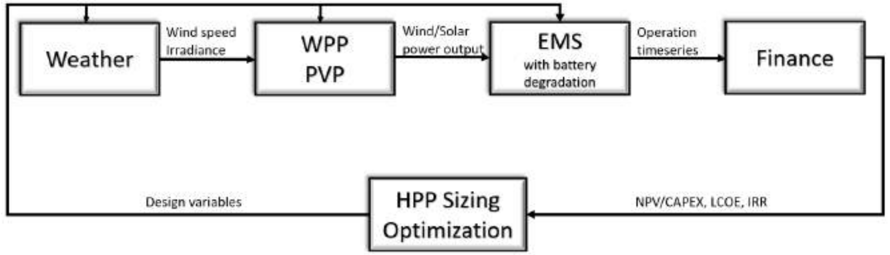
- HyDesign is a software platform for design and operation of utility-scale hybrid power plants
- Multi-disciplinary optimization problem implemented in OpenMDAO
- Can be used for sizing optimization of HPP or for evaluation of a specific plant design
- Objective function is user specified (min LCOE, max NPV/CAPEX…)
- Key components: wind, solar, battery, hydrogen, grid-connection

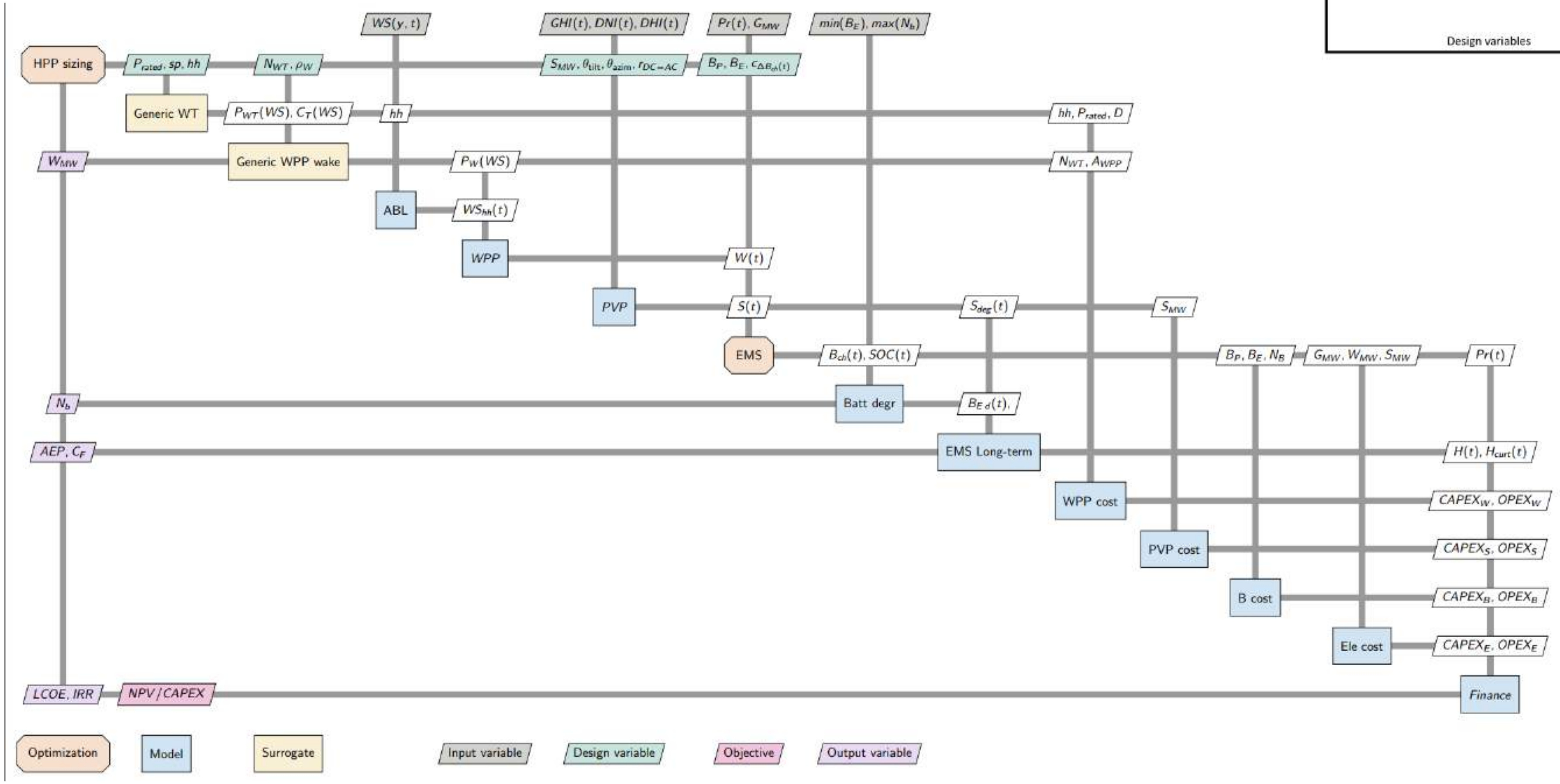


https://topfarm.pages.windenergy.dtu.dk/hydesign/



Workflow of HyDesign: HPP Sizing tool





Optimal sizing methodology of HPP

Inputs
- Electricity prices for SM and BM
- Site location for weather data
- Technologies cost

Sizing Optimization

Output (Design Variables)			Output
Wind	**Solar**	**Battery**	**Finance model**
Rotor diameter, hub height	AC power	Power rating	NPV/CAPEX
Area of land	Surface tilt angle	Energy storage Capacity	IRR
Rated power	Surface azimuth angle		LCOE
Number of wind turbines			AEP
Wind power density			Number of batteries

Optimal sizing methodology of HPP

Financial model of HPP

C_H: Total CAPEX

O_H: Total OPEX

$$C_H = C_W + C_S + C_B + C_E$$
$$O_H = O_W + O_S + O_b + O_E$$

Financial parameter calculation

Yearly income (R_y is revenue) → $I_y = (R_y - O_H)(1 - r_{tax})$

Annual Cashflow → $F_y = \begin{cases} -C_H \text{ for } y = 0 \\ I_y \text{ for } y > 0 \end{cases}$

Net present Value → $NPV = \sum_y F_y / (1 + \text{WACC}_{\text{tx}})^y$

Internal rate of return → $0 = \sum_y F_y / (1 + IRR)^y$

$C_L = \sum_y (O_H / (1 + \text{WACC}_{\text{tx}})^y) + C_H$

Annual energy production → $AEP_L = \sum_y (AEP_y / (1 + \text{WACC}_{\text{tx}})^y)$

Levelized cost of electricity → $LCoE = C_L / AEP_L$

DTU

Optimal sizing methodology of HPP

Sizing optimization results for 3 example sites in India with an objective function as:

- NPV/CAPEX
- LCoE

Key observations:

- Investments in PV plant or wind plant are dependent on the site location.
- With the objective function to minimize LCoE, investments in battery is not preferred.
- Positive NPV, and higher IRR indicates a good business case.

Site		Good solar		Good wind		Bad solar bad wind	
Design objective		$LCoE$	NPV/C_H	$LCoE$	NPV/C_H	$LCoE$	NPV/C_H
Design Variables	**Units**						
h_c	m	10	10	10	10	10	10
sp	W/m^2	200	200	360	360	200	200
P_{rated}	MW	1	1	8	4	1	1
N_{WT}	-	0	0	38	66	0	0
ρ_W	MW/km^2	5.0	5.0	7.8	7.4	5.0	7.5
S_{MW}	MW	322	400	0	54	328	400
θ_{tilt}	$deg.$	28.3	35.0	0.0	21.1	24.8	29.5
θ_{azim}	$deg.$	210	210	150	210	210	210
r_{AD}	-	1.5	1.6	1.0	1.7	1.7	1.9
B_P	MW	0	104	0	57	0	150
b_{Eh}	hours	1	7	4	4	1	7
C_{bfl}	-	0.0	0.0	16.0	0.7	26.7	0.0
Design Summary							
G	MW	300	300	300	300	300	300
W_{MW}	MW	0	0	304	264	0	0
S_{MW}	MW	322	400	0	54	328	400
B_P	MW	0	104	0	57	0	150
B_E	MWh	0	728	0	228	0	1050
N_B	-	0	2	0	3	0	2
D	m	-	-	168	119	-	-
hh	m	-	-	94	69	-	-
Outputs							
NPV/C_H	-	-0.264	0.747	0.996	1.042	-0.548	0.537
NPV	$MEuro$	-42.5	178.0	304.9	304.8	-96.0	151.5
IRR	-	-	0.128	0.145	0.151	-	0.110
$LCOE$	$Euro/MWh$	18.73	22.26	17.51	19.13	21.06	26.82
C_H	$MEuro$	160.9	238.3	306.2	292.6	175.1	282.3
O_H	$MEuro$	2.2	2.9	5.2	6.1	2.5	3.4
l_{life}	$MEuro$	372	3.8	99	41	417	2.9
AEP	GWh	732	927	1564	1441	712	918
AE_{curt}	GWh	4.5	1.3	0.9	0.0	7.2	2.3
GUF	-	0.28	0.35	0.60	0.55	0.27	0.35

Murcia Leon, Juan Pablo, Hajar Habbou, Mikkel Friis-Møller, Megha Gupta, Rujie Zhu, and Kaushik Das. "HyDesign: a tool for sizing optimization for grid-connected hybrid power plants including wind, solar photovoltaic, and Li-ion batteries." *Wind Energy Science Discussions* 2023 (2023): 1-22.

Energy management system optimization model (EMS): only Spot Market

$$\max \quad \sum_t (Pr(t) \times H(t)) - l_b$$
$$l_b = C_{bfl} \times \sum_t (|\Delta B(t)| \times (Pr_{\text{peak}} - Pr(t)))$$

Objective to maximize revenue

such that $\forall t$ $\quad H(t) = W(t) + S(t) + B(t) - P_{\text{curt}}(t)$

HPP power output

$$H(t) \leq G$$
$$E_{SoC}(t+1) = \begin{cases} E_{SoC}(t) - \eta_{\text{charge}} B(t)\, \Delta t & \text{if} \quad B(t) \leq 0 \\ E_{SoC}(t) - B(t)\, \Delta t / \eta_{\text{discharge}} & \text{if} \quad B(t) > 0 \end{cases}$$
$$E_{SoC}(t) \geq B_E \times (1 - B_{E\,\text{depth}})$$
$$E_{SoC}(t) \leq B_E$$
$$B(t) \leq B_P$$
$$B(t) \geq -B_P$$

Battery storage operation

Inputs

- WPP power time series
- PVP power time series
- SM electricity price time series
- Battery power capacity
- Battery energy storage capacity
- Grid capacity
- Battery parameters

EMS

- Maximize revenue of HPP subject to the system constraint
- Revenue is earned from selling electricity to the grid in SM

Outputs

- HPP power output
- Curtailed power
- Battery charging-discharging power
- Battery energy level

Energy management system optimization model (EMS): multiple energy markets

Inputs

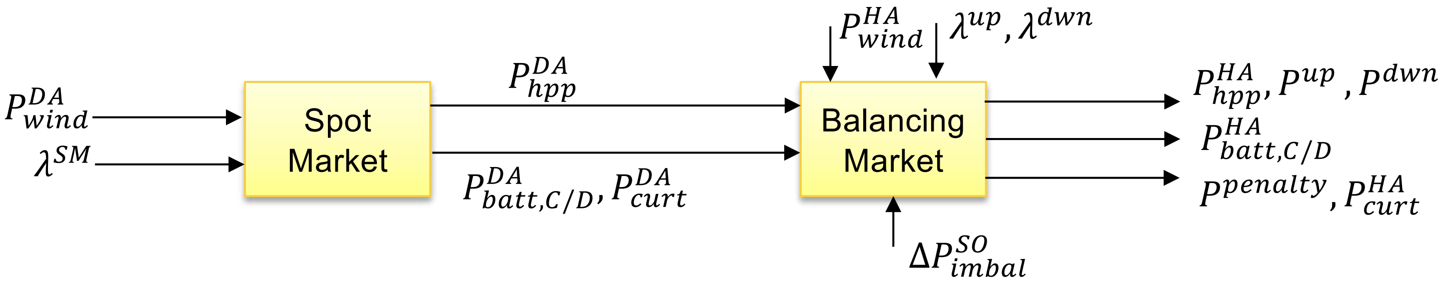
- WPP power time series in DA and HA
- PVP power time series in DA and HA
- SM electricity price time series
- BM prices
- System imbalance power
- Battery power capacity
- Battery energy storage capacity
- Grid capacity
- Battery parameters

EMS

- Maximize revenue of HPP subject to the system constraint
- Revenue is earned from selling electricity to the grid in SM and in intra-day markets

Outputs

- HPP power output in SM and balancing markets
- Curtailed power
- Battery charging-discharging power
- Battery energy level



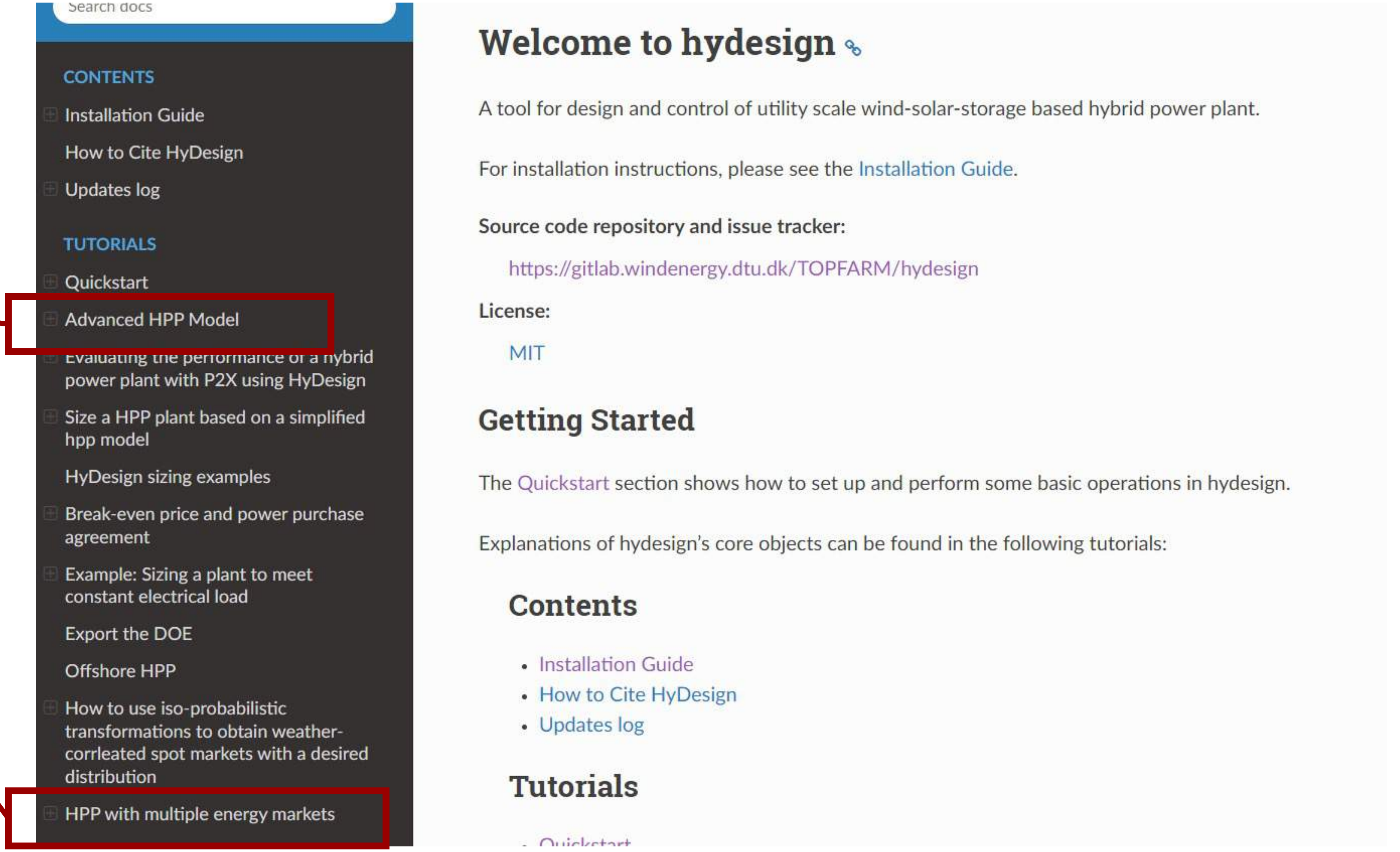
Let’s see how HyDesign looks, and how it works……..

- Gitlab repository: https://gitlab.windenergy.dtu.dk/TOPFARM/hydesign
- At the bottom -> link to documentation -> https://topfarm.pages.windenergy.dtu.dk/hydesign

Exercises:

Exercise 1: Advanced HPP Model -> HPP design evaluation

Exercise 2: HPP with multiple energy markets -> HPP design evaluation with SM and BM



Exercises:

Open the notebook in Google Colab

Advanced HPP Model   View page source

Open in Colab | Edit on Gitlab

Advanced HPP Model

Evaluating the performance of a hybrid power plant using HyDesign

- Run each cell
- Check for the list of example sites (select the test site).
- Change the site name accordingly.

	case	name	longitude	latitude	altitude	
0	India	Indian_site_good_wind	77.500226	8.334294	679.803454	
1	India	Indian_site_good_solar	68.542204	23.542099	29.883557	
2	India	Indian_site_bad_solar_bad_wind	77.916878	17.292316	627.424643	Indi
3	Europe	France_good_solar	4.229736	44.422011	204.000000	
4	Europe	France_good_wind	-0.864258	48.744116	302.000000	
5	Europe	France_bad_solar_n_wind	2.167969	47.428087	140.000000	
6	Europe	Germany_bad_solar_n_wind	10.766602	49.310798	442.000000	Eu
7	Europe	Germany_good_wind	7.873535	53.287111	5.000000	
8	Europe	Denmark_good_solar	11.813965	55.397760	42.000000	
9	Europe	Denmark_good_wind	8.594398	56.227322	85.000000	

```
[11] name = 'Denmark_good_wind'
ex_site = examples_sites.loc[examples_sites.name == name]

longitude = ex_site['longitude'].values[0]
latitude = ex_site['latitude'].values[0]
altitude = ex_site['altitude'].values[0]
```

Exercises:

- In this cell, the evaluation of a HPP design is done
- Select the size of HPP:
  - wind plant size in MW: Nwt * P_rated;
  - solar_MW;
  - battery size
    - b_P: battery power in MW
    - b_E_h: battery energy hours)

Evaluating the HPP model

```
[13] start = time.time()

     clearance = 10
     sp = 350
     p_rated = 5
     Nwt = 62
     wind_MW_per_km2 = 7
     solar_MW = 50
     surface_tilt = 50
     surface_azimuth = 180
     solar_DCAC = 1.5
     b_P = 20
     b_E_h  = 3
     cost_of_batt_degr = 5
```

Exercises:

The output of the HPP model evaluation:

Objective function: maximize NPV/CAPEX

NPV: Net present Value

IRR: Internal rate of return

LCOE: Levelized cost of electricity

CAPEX: Total capital expenditure

OPEX: Total operational expenditure

AEP: Annual energy production

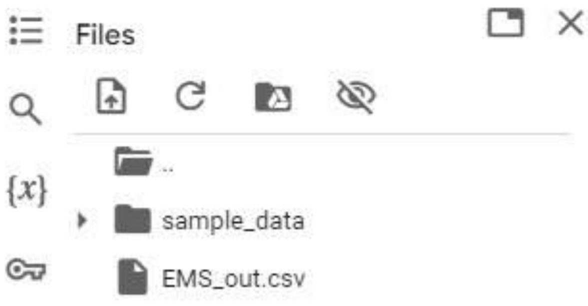
GUF: Grid utilization factor

Grid [MW]: grid capacity

```
NPV_over_CAPEX: 0.726
NPV [MEuro]: 230.293
IRR: 0.120
LCOE [Euro/MWh]: 22.151
CAPEX [MEuro]: 317.377
OPEX [MEuro]: 5.960
Wind CAPEX [MEuro]: 236.934
Wind OPEX [MEuro]: 5.622
PV CAPEX [MEuro]: 16.583
PV OPEX [MEuro]: 0.338
Batt CAPEX [MEuro]: 3.470
Batt OPEX [MEuro]: 0.000
Shared CAPEX [MEuro]: 60.390
Shared Opex [MEuro]: 0.000
penalty lifetime [MEuro]: 0.000
AEP [GWh]: 1321.424
GUF: 0.503
grid [MW]: 300.000
wind [MW]: 310.000
solar [MW]: 50.000
Battery Energy [MWh]: 60.000
Battery Power [MW]: 20.000
Total curtailment [GWh]: 417.558
Awpp [km2]: 44.286
Rotor diam [m]: 134.867
Hub height [m]: 77.434
Number_of_batteries: 1.000

exec. time [min]: 0.3864752968152364
```

Exercises: Download output files and plots

- The output files can be downloaded from here for further analysis. (Note: Remember to download and rename the file before starting the new simulation, the results won't get saved automatically)




```
df = pd.DataFrame(results_1year)
df.to_csv('EMS_out.csv')
```

```
design_df = design_df.transpose()
design_df.to_csv('output.csv')
```

- The output files can be renamed here.
- Re-run the evaluation function and check for the results.

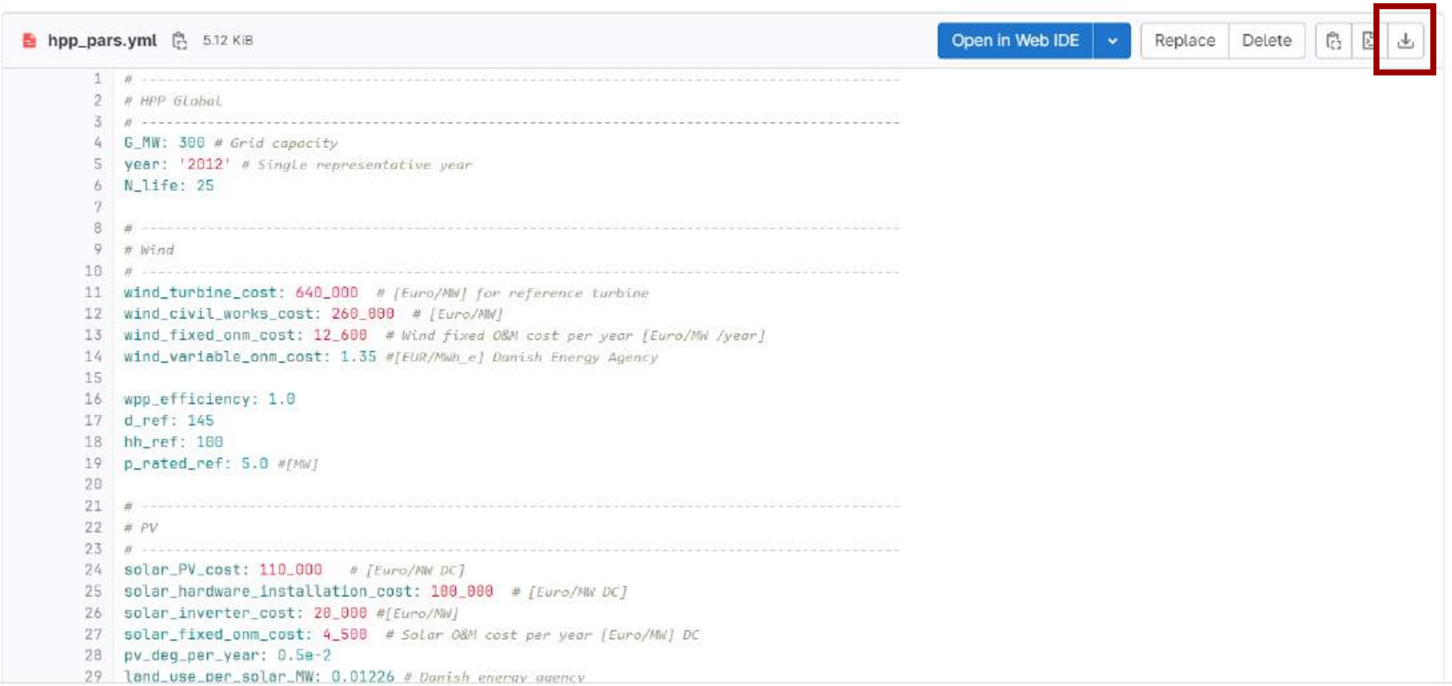
Exercises: Notes

- Select site (9): Denmark_good_wind
- First, run the exercise with only HPP participating in spot market and save results.
- Next, run the exercise with HPP participating in spot and balancing (Intra-day) markets both (It works only for Wind + Battery plants, make solar_MW =0).

- By default: there are some specific design given (Wind + Battery HPP): Wind-350 MW, Grid connection-300 MW, Battery: 100 MW/ 300 MWh
- Check for improvement in NPV, NPV/CAPEX, LCOE for HPP participating in SM and BM both.
- Change the size of battery and plot the sensitivity of NPV/CAPEX with the battery size.
- Comment on the impact of grid connection capacity (100/ 300 MW) on econometrics (with SM + BM).

Exercises: Changing input file data

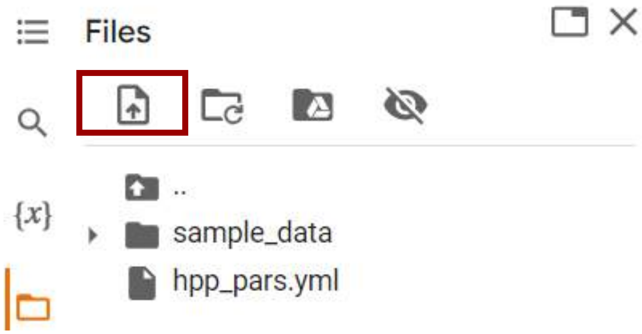
Download the input file ‘hpp_pars.yml’ -> contains technology (Wind, solar, battery, grid connection) costs value and other parameters
https://gitlab.windenergy.dtu.dk/TOPFARM/hydesign/-/blob/main/hydesign/examples/Europe/hpp_pars.yml

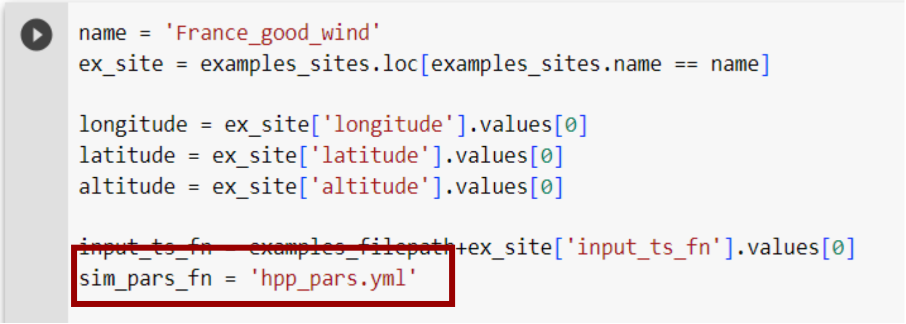



```yaml
# ------------------------------------------------------------------------------------------------
# HPP Global
# ------------------------------------------------------------------------------------------------
G_MW: 300 # Grid capacity
year: '2012' # Single representative year
N_life: 25

# ------------------------------------------------------------------------------------------------
# Wind
# ------------------------------------------------------------------------------------------------
wind_turbine_cost: 640_000  # [Euro/MW] for reference turbine
wind_civil_works_cost: 260_000  # [Euro/MW]
wind_fixed_onm_cost: 12_600  # Wind fixed O&M cost per year [Euro/MW /year]
wind_variable_onm_cost: 1.35 #[EUR/MWh_e] Danish Energy Agency

wpp_efficiency: 1.0
d_ref: 145
hh_ref: 100
p_rated_ref: 5.0 #[MW]

# ------------------------------------------------------------------------------------------------
# PV
# ------------------------------------------------------------------------------------------------
solar_PV_cost: 110_000   # [Euro/MW DC]
solar_hardware_installation_cost: 100_000  # [Euro/MW DC]
solar_inverter_cost: 20_000 #[Euro/MW]
solar_fixed_onm_cost: 4_500  # Solar O&M cost per year [Euro/MW] DC
pv_deg_per_year: 0.5e-2
land_use_per_solar_MW: 0.01226 # Danish energy agency
```

Exercises: Changing input file data

- Modify the input data in ‘hpp_pars.yml’ as desired. Upload the modified the input file ‘hpp_pars.yml’ in the current directory. (Note: The file name can be renamed as well)





- Rename the input file name in the notebook to point toward the modified set of inputs.
- Re-run the evaluation function and check for the results.

Tasks:

1. Change the size of wind plant/ battery/ grid capacity for example site 9 (check for just 2-3 different configurations) and compare change in values of
   a) NPV
   b) NPV/CAPEX
   c) LCOE
   d) AEP
   e) GUF
   f) Total curtailment
2. Perform any one set of HPP configurations (wind + battery) as in Exercise 1 with BM. Make comparison and analyze the results.
3. For HPP with BM, find optimal size of battery doing sensitivity analysis with an objective to maximize NPV/CAPEX

Sample template for results for one configuration			
S. No.	**Parameter**	**HPP with SM**	**HPP with SM and BM**
1	NPV		
2	NPV/CAPEX		
3	LCOE		
4	AEP		
5	GUF		
6	Total cutailment		

Learning Objectives:

- Impact of the size of a HPP on the econometrics such as NPV/CAPEX, LCOE.
- Improvement in curtailment and econometrics of HPP when participating in multiple energy markets.
- Impact of cost of various technologies in HPP on the econometrics.