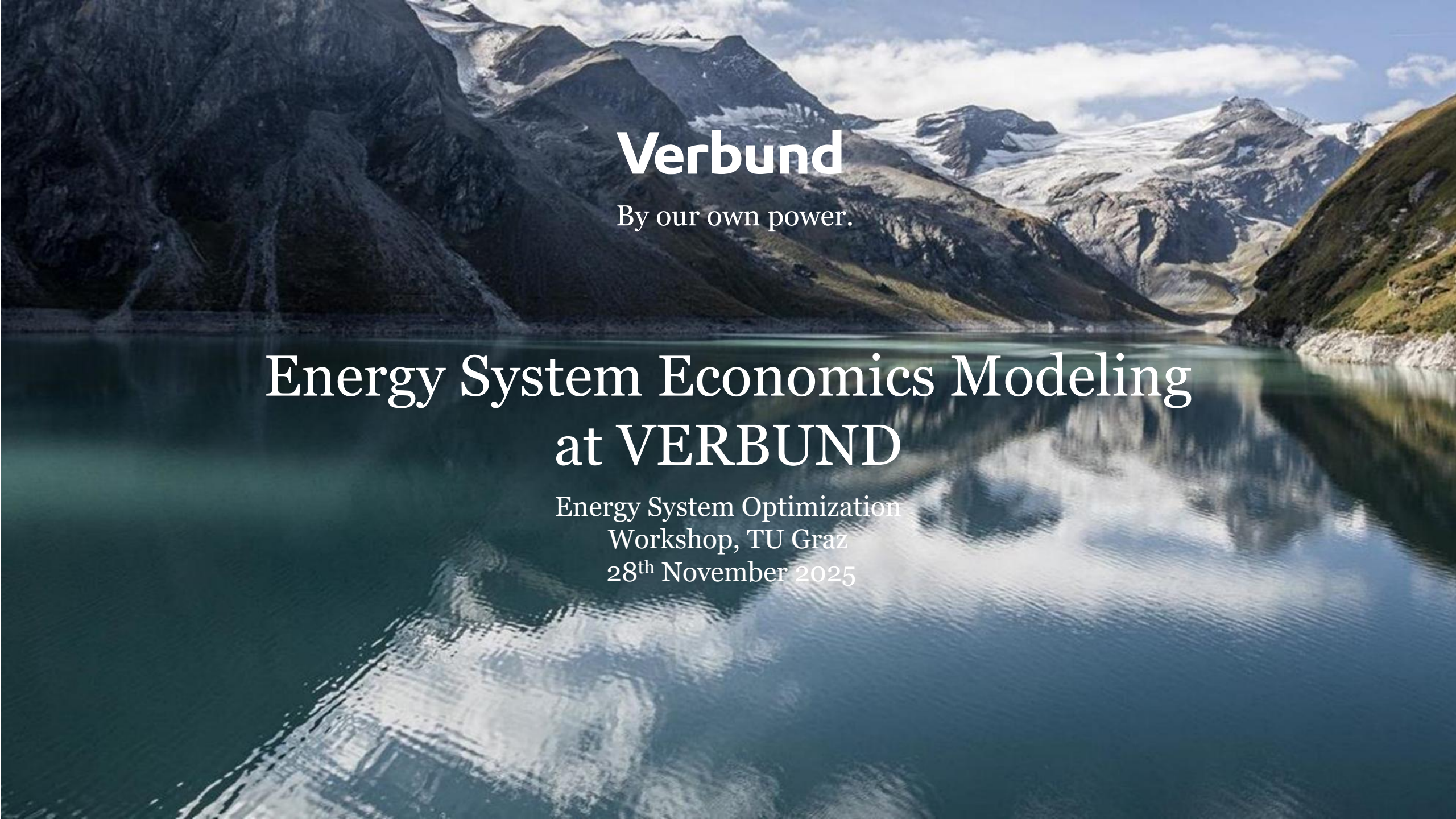


Verbund

By our own power.

Energy System Economics Modeling at VERBUND

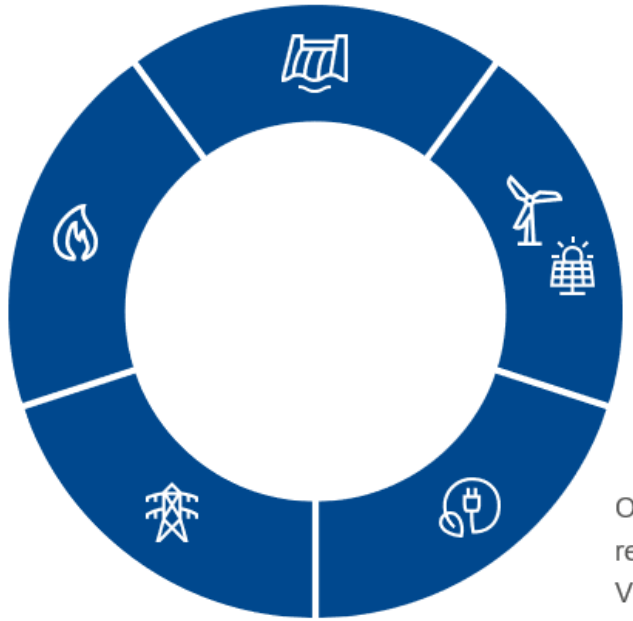
Energy System Optimization
Workshop, TU Graz
28th November 2025

VERBUND - Austria's largest electricity utility

132 VERBUND hydropower plants with over 8,400 MW output.

GCA's high-pressure natural gas pipeline network is around **900** kilometres long.

Up to **1/4** of our overall electricity generation will come from wind and solar power by 2030.



APG's transregional power grid extends over approx. **3,400** kilometres.

Over **490,000** residential customers relied on VERBUND in 2024.

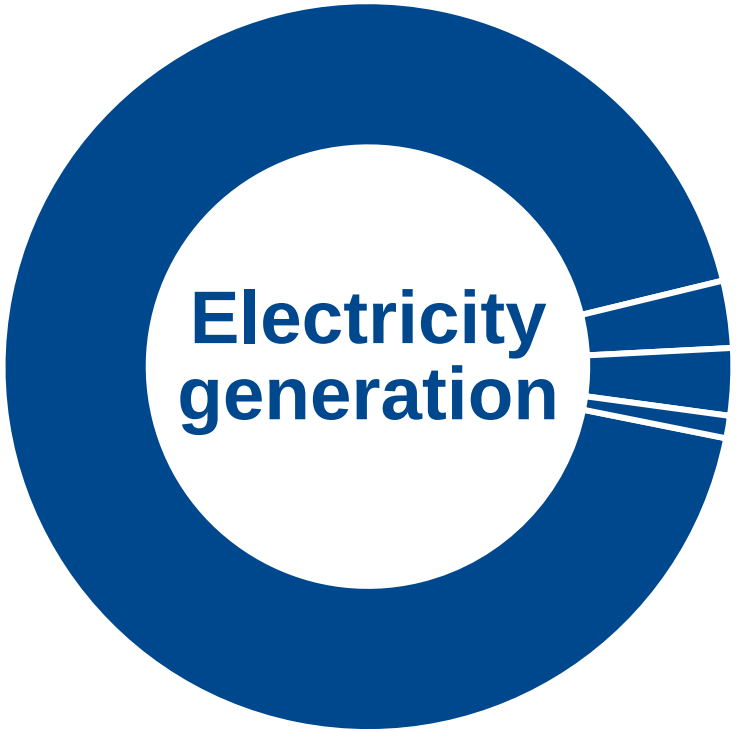






Sustainable energy future
~96% generation from renewable energy sources

Hydropower[1]
>90% of electricity generation
132 hydropower plants
33,448 GWh electricity



Wind power
<5% of electricity generation
342 wind power plants
1,818 GWh electricity

Solar power[2]
>1% of electricity generation
47 photovoltaic farms
446 GWh electricity

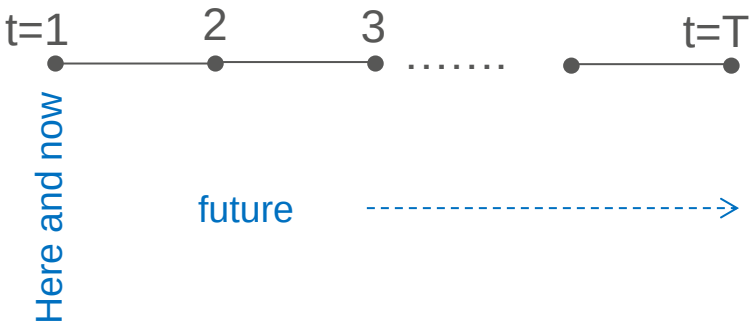
Thermal power
<4% of electricity generation
2 thermal power plants
1,300 GWh electricity

Battery storage
<1% of electricity generation
15 plants
44 GWh electricity

[1]including purchase rights; excluding non-fully-consolidated installations (Ashta 1&2 and Nussdorf)
[2]excluding leased/contracted installations
of which 27,989 GWh from run-of-river and 5,459 GWh from pumping/storage power plants
All figures ACTUAL production 2024

Energy Economic Optimization Models @ VERBUND

hourly or quarter-hourly time discretization (imposed by the market):

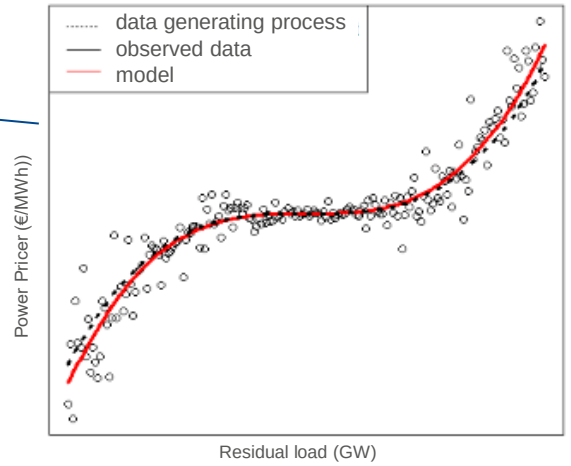


- **VERBUND Energy Market Model**
- Hydro Storage Optimization
- other models for other flexible assets
  (CHP CCGT Mellach/Graz, BESS, H_2 Electrolyzers, Demand Response, …)

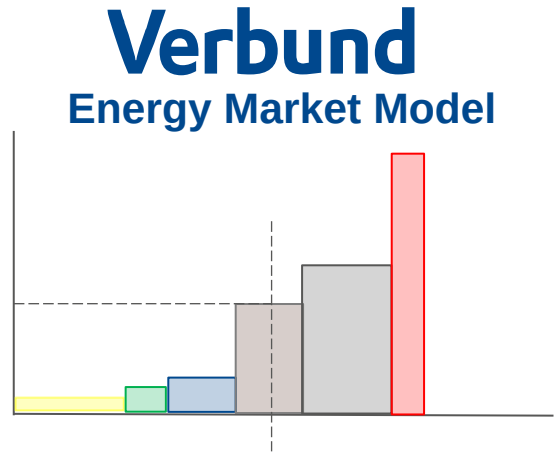
VERBUND Energy Market Model

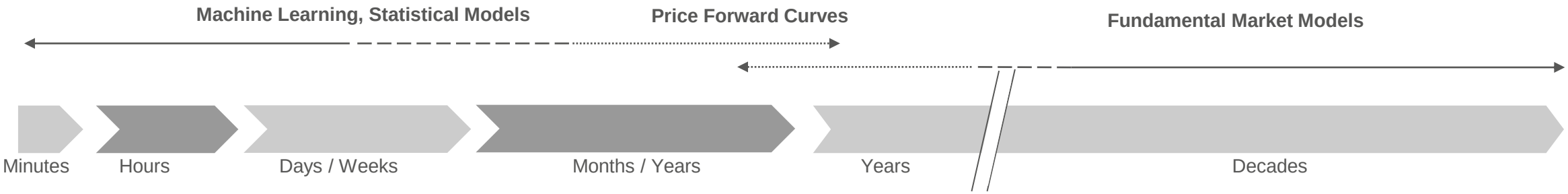
Electricity Price Models

Econometric Models / Machine Learning
- short-term horizon, models based on observed data
- point estimates / quantile estimates



Fundamental Market Models
- medium-term to long-term energy market models assuming perfect competition
- simulation of market and system components
  (demand, power plants, interconnectors, storages, flexibility providers)





VERBUND Energy Market Model

Verbund Energy Market Model (VEMM)

- Optimization Toolbox, which requires extensive assumption datasets for many countries
- The models evaluates future development of power generation fleets across Europe which are expected to meet defined demand requirements
- Most important outputs are power prices and underlying results (dispatch, generation mix, financial & technical key figures)
- Outputs are used for strategic decision making, planing & budgeting, investment project evaluation, impairment, …

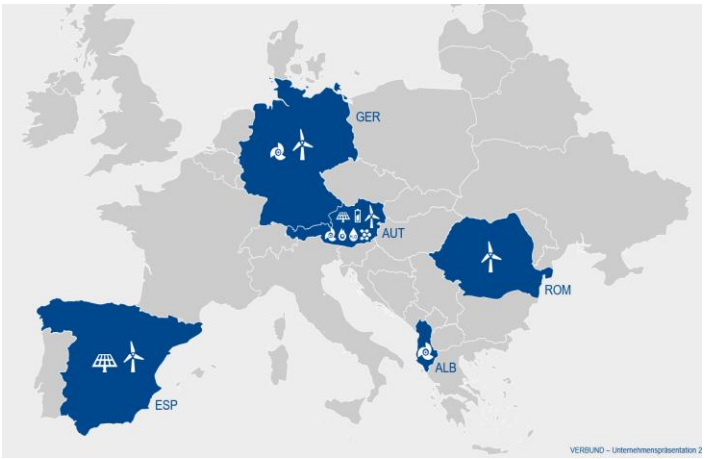
Definition of Scenarios & Input Data

- Fuel Prices
- CO_2 Prices
- Electricity Demand
- Flexibility Options
- Interconnectors

VEMM

Scenario Results

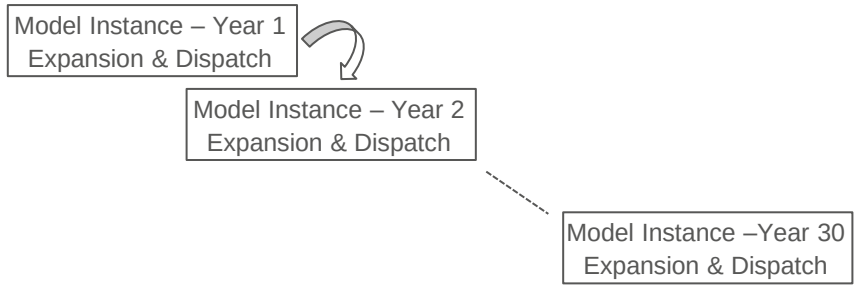
- Power Prices
- Capacities
- Generation
- Margins, Captured Prices, Spreads, …



VERBUND Energy Market Model

VEMM - Approach

- Linear cost minimization approach solving expansion planning and dispatch problems
- Sequential and hierarchical models
- Compression of input data to reduce calculation times
- Data, model build Up and result processing is carried out in R
- Optimization problems are formulated in GAMS and solved via CPLEX
- In House Servers and Cloud Servers



Minimizing Total System Cost:

$$TC = \sum_p \sum_t v\_gen(p,t) * p\_srmc(p,t) + \sum_p \sum_t v\_build(p,t) * p\_invest(p,t) + \ \ldots$$

considering various constraints in every time interval t, e.g.:

$$p\_load(t) = \sum_p v\_gen(p,t)$$

$$v\_gen(p,t) \leq p\_genmax(p) * p\_cap\_rating(p,t)$$

$$\vdots$$

$$v\_storage\_cont(p,t-1) + p\_inflow(p,t) - v\_gen(p,t) = v\_storage\_cont(p,t)$$

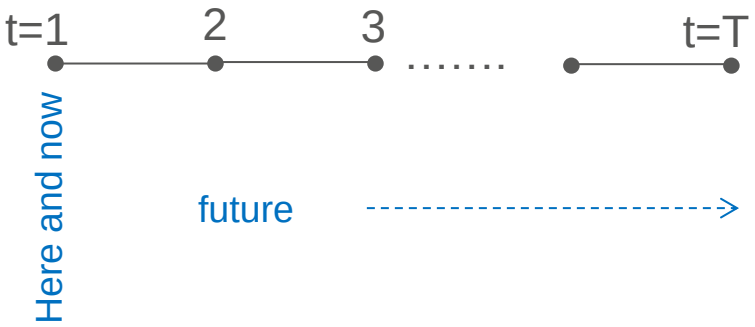
t … $Index\ Time$
p … $Index\ PowerPlant$

v_build … $Capacity\ Expansion$
v_gen … $Generation$
$v\_storage\_cont$ … $StorageLevel$
p_load … $Demand$
p_cap_rating … $CapacityRating$

p_srmc … $ProdutionCost$
p_genmax … $Maximum\ Production$
p_inflow … $Inflow\ in\ Storage$
p_invest … $InvestCost$

Energy Economic Optimization Models @ VERBUND

hourly or quarter-hourly time discretization (imposed by the market):



- VERBUND Energy Market Model
- **Hydro Storage Optimization**
- other models for other flexible assets
  (CHP CCGT Mellach/Graz, BESS, H_2 Electrolyzers, Demand Response, …)

Hydro Storage Optimization

VERBUND Hydro Power Plants in Austria (and Germany):
High mountain hydro storage power plants with big reservoirs → (yearly / seasonal storages)

coupeled with smaller ones (weekly / daily storages)

and with run-of-river plants ↓

Hydro Storage Optimization

Hydro storage plants: turbines, pumps, natural inflow

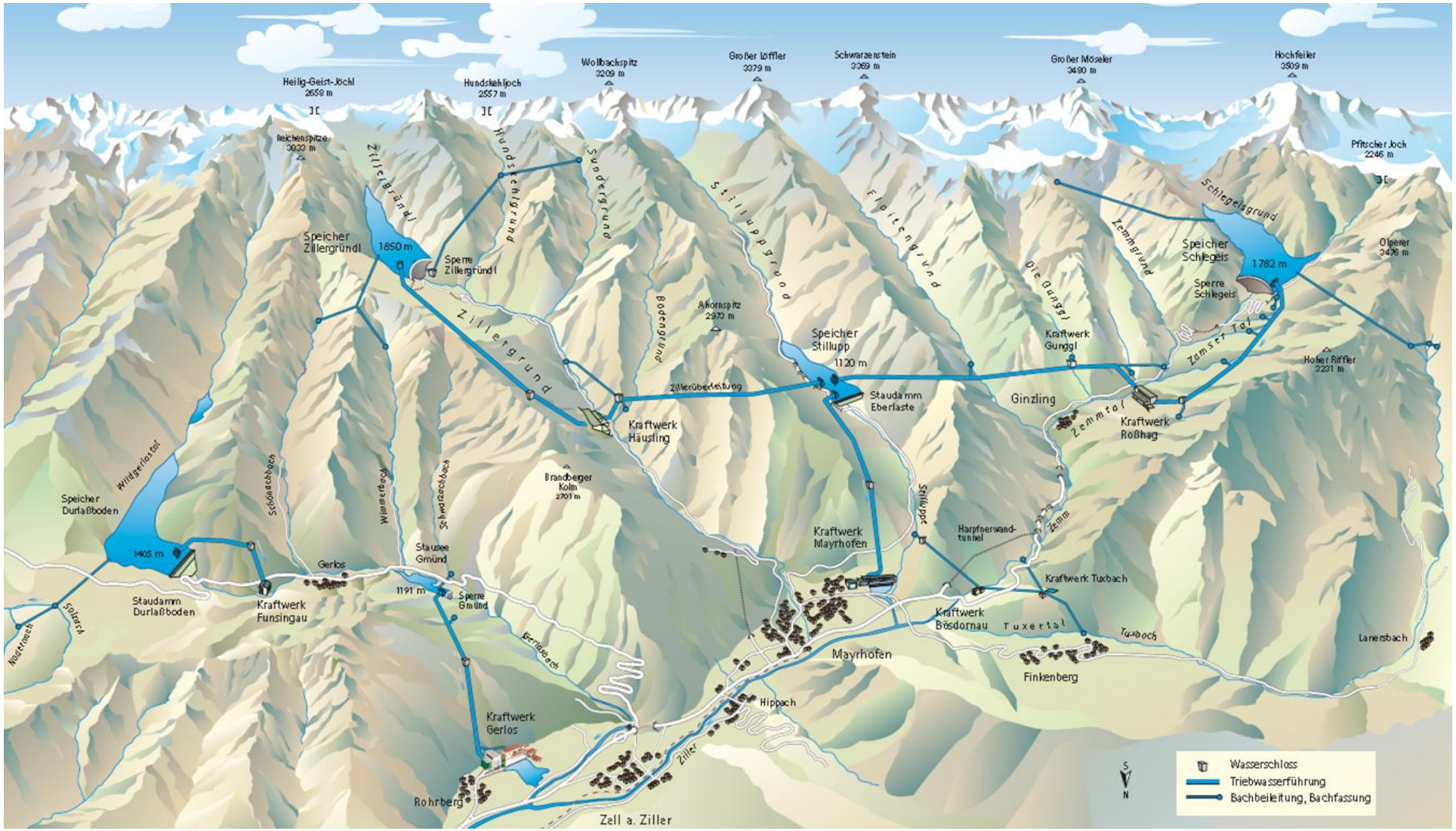
e.g.:
Group Zemm/Ziller → (Tyrol)

+ 2 other major groups:

- Kaprun (Salzburg)
- Malta/Reißeck (Carinthia)

connected

- hydrologically (by rivers)
- by reserve constraints

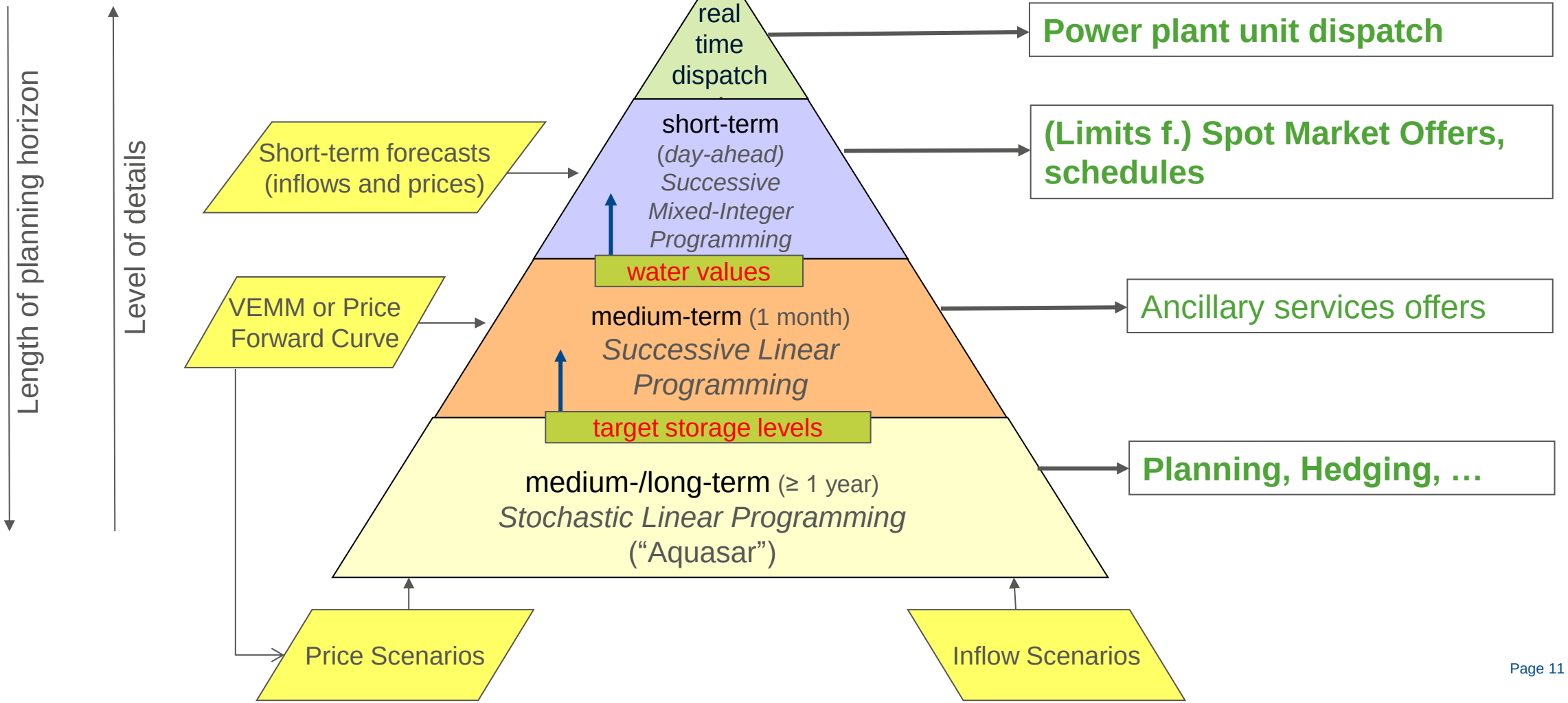


Hydro Storage Optimization

Optimization / Planning / Scheduling / Dispatch

Objective: long-term revenue maximization

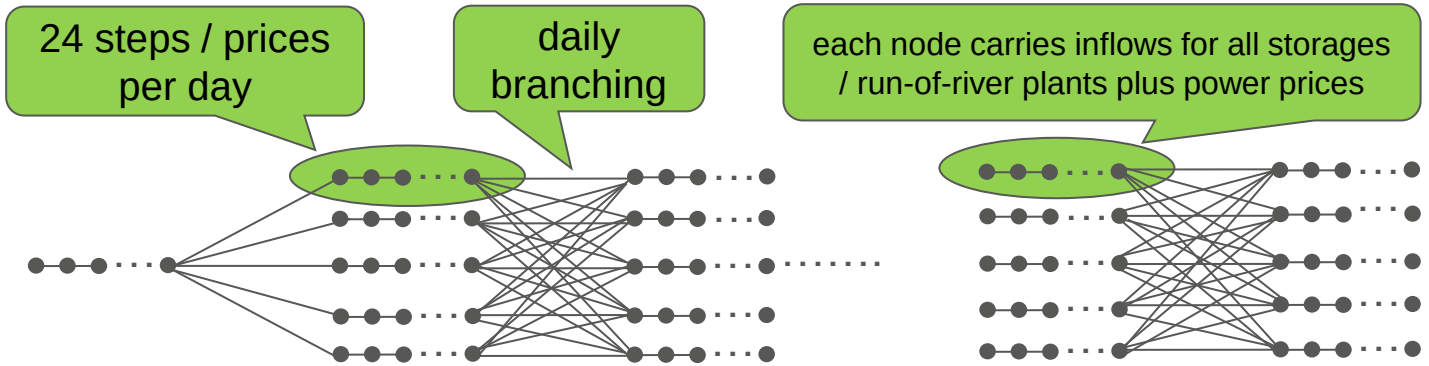
continuous re-optimization! (rolling horizon)

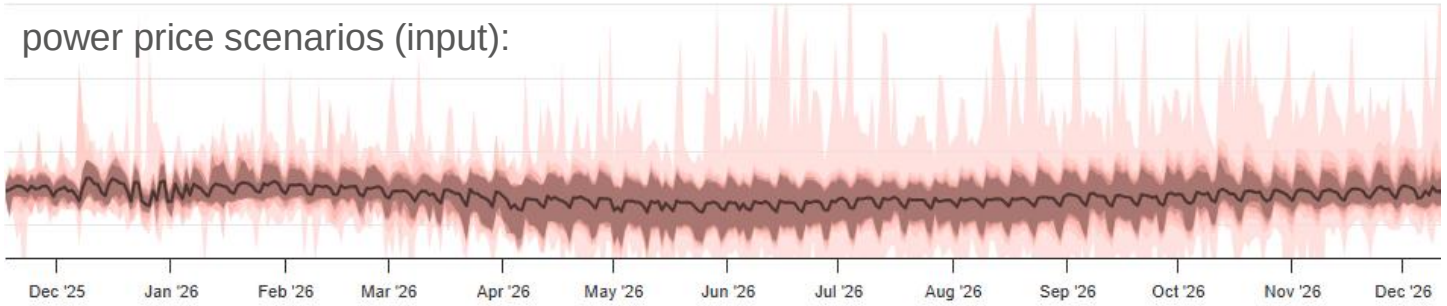


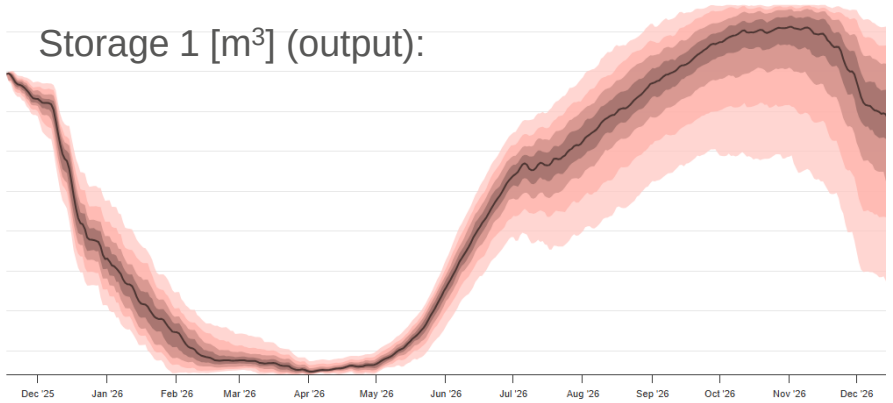
Hydro Storage Optimization

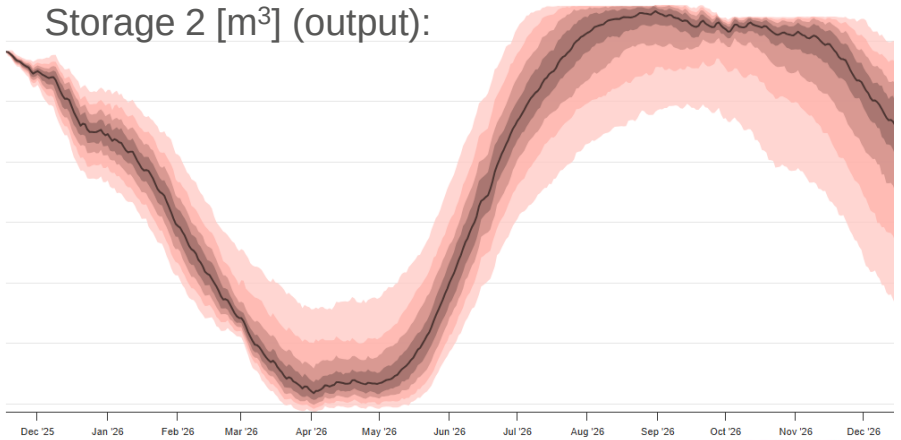
Medium-/Long-Term Stochastic Optimization:

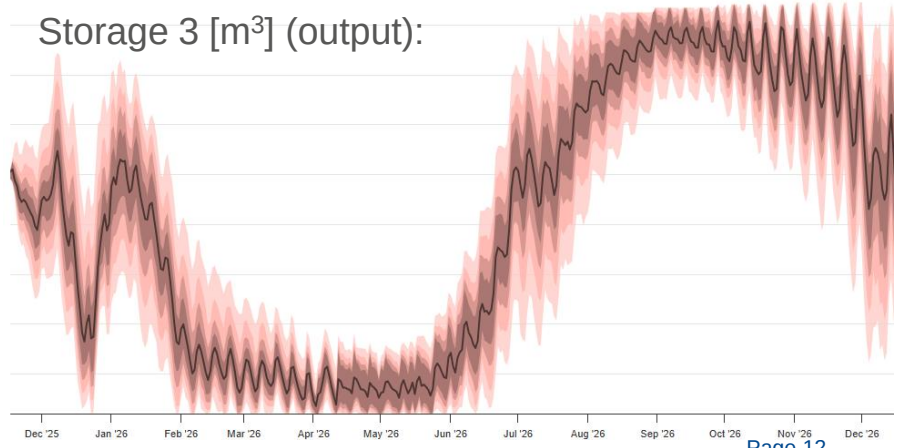
- SDDP/ADDP model based on the QUASAR Java API
- Planning horizon: 1 up to 3 years, hourly discretization
- everything has to be *linear* (i.e., piecewise linear convex)
- 1 power price per hour and scenario (i.e., only day-ahead prices)
- approximate modelling of effect of storages on run-of-river plants and flow times
- control reserve / ancillary services as fixed constraints
- uses recombining scenario trees (“lattices”):











Energy Economic Optimization Models @ VERBUND

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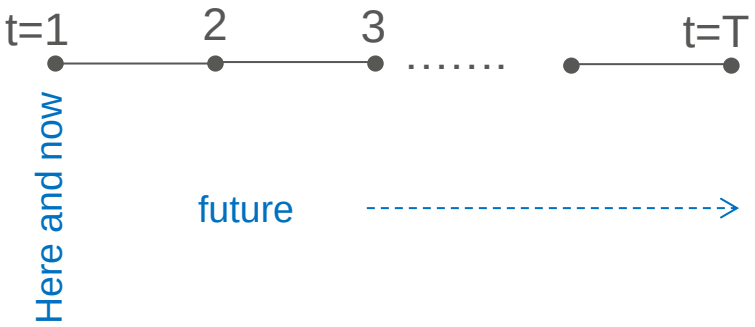

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- **other models for other flexible assets**
  (CHP CCGT Mellach/Graz, BESS, H_2 Electrolyzers, Demand Response, …)

  → directly incorporate day-ahead vs. intraday
  as well as control energy (FCR, aFRR, mFRR) into the optimization !

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