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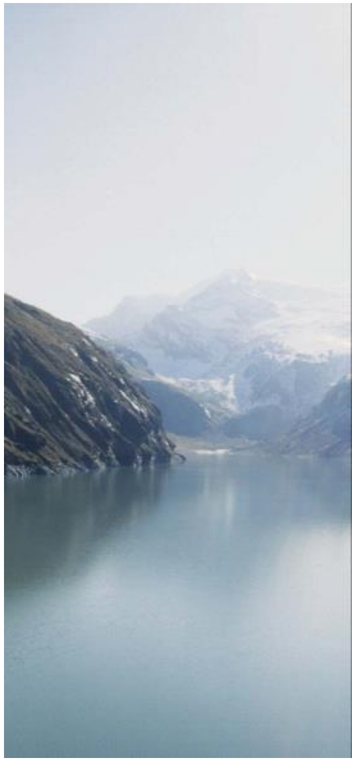
Medium-term planning for an Alpine hydro storage power system in a market environment using the QUASAR stochastic optimizer



Andreas Eichhorn, VERBUND Trading GmbH, Vienna, Austria
Nils Löhndorf, Vienna University of Economics and Business, Austria

Workshop on Hydro Scheduling, Trondheim, 17/09/2015

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The Company

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VERBUND at a glance

95% production from renewable energy sources

more than 300.000 residential customers – market leader in the industrial customer segment

approximately 3,000 employees

127 hydropower plants

No. 1 in fighting climate change among European powersupply companies

Austria‘s leading electricity company

Strategic focus on Austria an Germany

first green bond in German speaking Europe

51 % owned by the Republic of Austria

Largest hydropower producer in Bavaria

Austria-wide charging infrastructure for electric vehicles

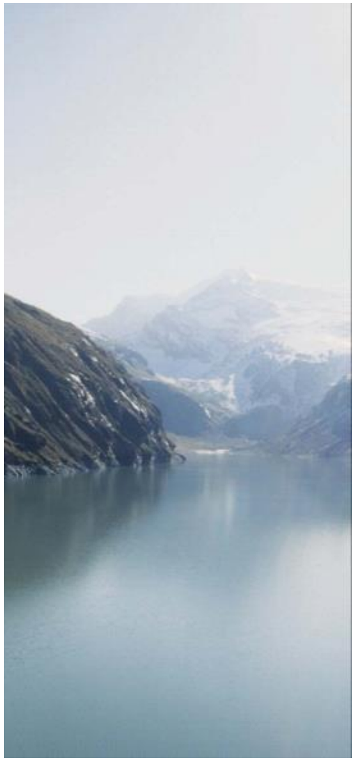
234 apprentices trained since 2009

Energy related products and services

Social responsibility: € 1.3 million support for „VERBUND-Stromhilfefonds“ of Caritas since 2009

Environmental management – top-10-position of 160 energy companies analyzed by oekom research

Environmental measures - € 186 million investment in fishways so far



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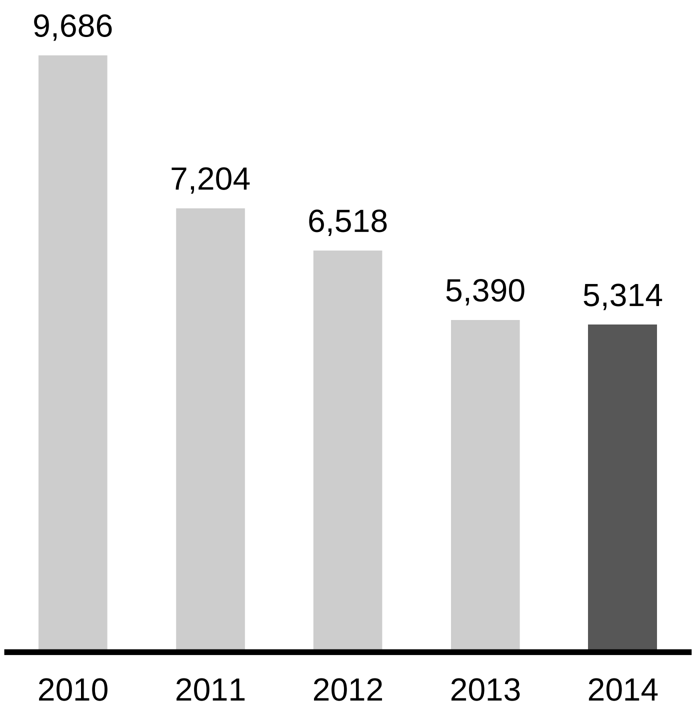
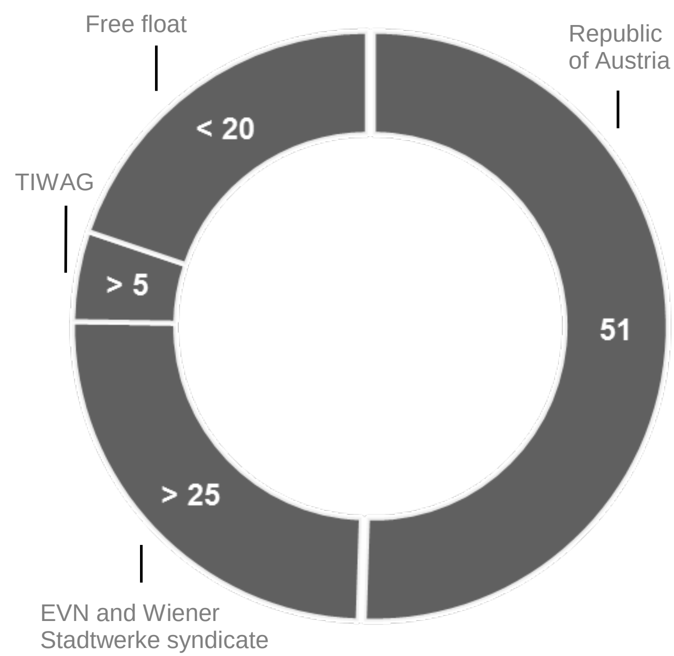
The Shares

Market Capitalisation (mio. €)



Shareholders’ Structure



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VERBUND Strategy:
Profitable Growth through EcoExcellence

EcoExcellence

At all value-added steps of electrical energy, we strive for economic and ecological excellence and are thereby creating added value for customers and other stakeholders.

Focus on **hydropower, wind power** and the **transmission grid**

Focus on **Austria** and **Germany**

Majorities in future, **strategic investments** in Austria and at international level

Innovative products & services Green electricity products, energy management, electric mobility, operations management

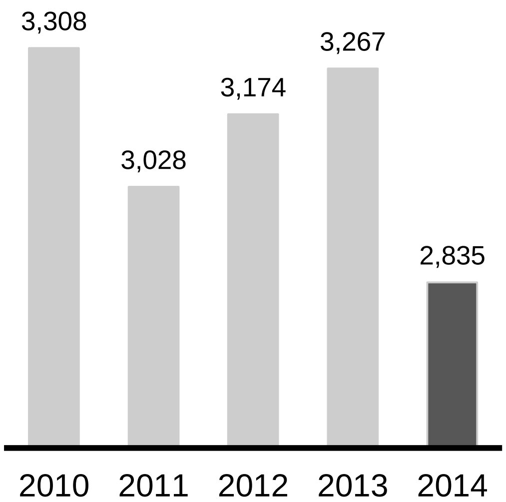
* Based on the current risk profile

Highlights

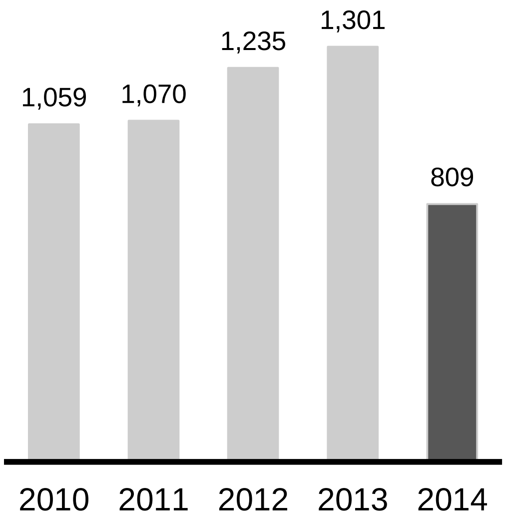
- Market capitalization ~ 5.3 billion Euro
- 151 power plants (incl. subscription rights) - capacity of ~ 9,700 MW
- ~ 34 billion kWh total production (2014)
- ~ 870 million Euro investments 2015 - 1017, especially in Austria and Germany (power grid and efficiency enhancement of existing hydropower plants)
- 119,9 TWh sales volume in 2014, active in 12 European countries
- ~ 9.5 TWh to consumers (industry and households), currently approx. 322,000 household customers in Austria (~7 % market share) and 20 % market share industrial customers
- ~ 3,500 km of line length of the Austrian transmission grid
- Innovation leader for electricity: e-mobility, energy management

Key Figures

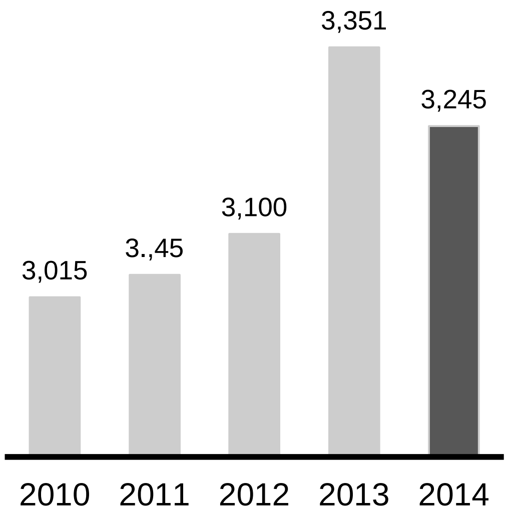
Sales Revenue (in mio EUR)



EBITDA (in mio EUR)

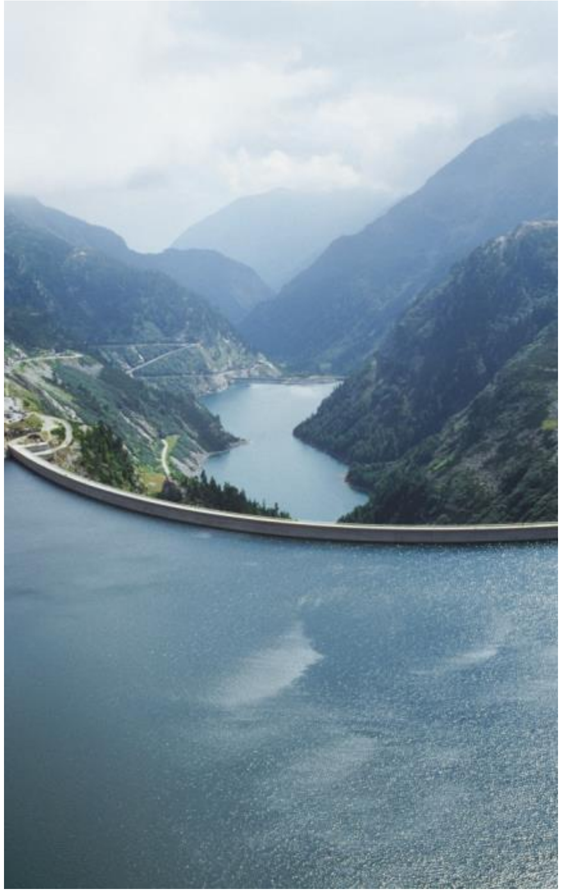


Number of Employees



Generation from renewable hydropower

- 127 hydropower plants
- 91 % capacity from hydropower plants (7,700 MW)
- global reputation as hydropower specialist with long-term experience in planning, constructing and operating hydropower plants
- high environmental standards, high social and cultural responsibility - the sustainable rating agency oekom research lists VERBUND as a “prime investment”.
- 30 % of the hydropower plant sites have been nominated nature conservation areas following construction of the power plant.



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Germany

- largest electricity market in Europe and VERBUND‘s most important market outside Austria
- 21 wind power stations with 86 MW in Rhineland-Palatinate
- 2 sales offices in Munich and Düsseldorf catering to industry-customers and distributors in Germany
- AQUANTO – joint venture of VERBUND and EnBW for distributing green electricity products and energy services

Europe

Romania

- Casimcea wind farm on the Black Sea coast
- total capacity of 226 MW

Albania

- 53 MW run-of-river power plant in Ashta -
- world largest power plant to feature matrix technology
- 50:50 joint venture of VERBUND and EVN

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Hydropower plants: Construction and Efficiency Measures

- Modernization of its existing hydropower plants to increase their efficiency
- pumped storage power plant Reisseck II
  to be finished in 2015
  430 MW, increase of capacity by ~ 40 %
- Modernization of Ybbs-Persenbeug, the oldest power plant along the Danube
  additional energy for 17.000 households
- Modernization of Töging Hydropower Plant in Bavaria
- continuing approval procedures for „Energiespeicher Riedl“ (pumped storage power plant along the Danube river in Bavaria)

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Environmental Measures

total investment in 2014: 47,2 million Euro

- improvement of continuity of water bodies
- improvement of fish habitats

LIFE+ Traisen:
- Austria‘s largest restoration project ever
- Redesign of the Traisen estuary at Altenwörth Power Plant
- 11 km new wetland area

„Fish Snail“ Retznei
- Innovative fish ladder for smaller power plants
- Austrian Patent
- Cost-effective and environmentally friendly

Wind power complements hydropower

Austria
- 37 wind power stations in Bruck / Leitha, Petronell-Carnuntum and Hollern
- total capacity of 85 MW
- Wind farm Bruck-Göttlesbrunn with 21 MW will be finished by 2015

Romania
- Casimcea windpark with 88 stations
- total capacity of 226 MW

Germany
- 21wind power stations in Rhineland-Palatinate
- total capacity of 86 MW

Trading and Retail

- VERBUND is one of Europe's most successful electricity traders in Austria and Europe
- Market Leader B2B in Austria and Germany (Big Businesses and Utilities).
- VERBUND's own electricity is marketed via stock exchanges, as well as directly to re-distributors and key accounts.
- Trade activities in more than 120 TWh of electric energy in 2014 in 12 European countries
- ~ 56 % of the electricity sales take place in Austria
 Germany is the second largest market for VERBUND
- Innovative Services and Solutions complete the VERBUND portfolio

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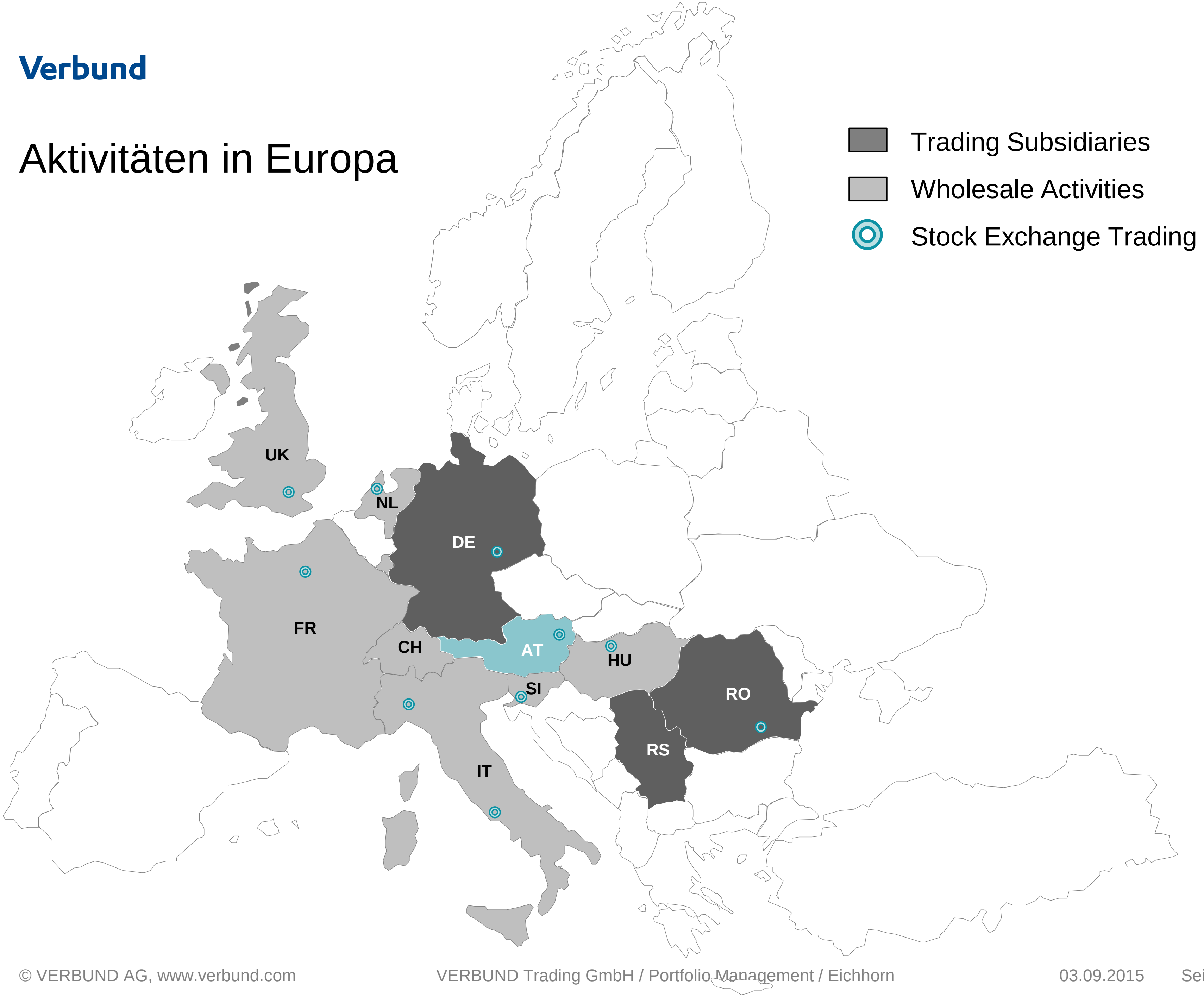
Aktivitäten in Europa



Hydro Storage Power Plants

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Hydro Power Plants in Austria and Germany

High mountains hydro power plants
with big reservoirs (yearly storages) →

coupeled with smaller ones
(weekly- / daily storages)

and run-of-river plants ↓

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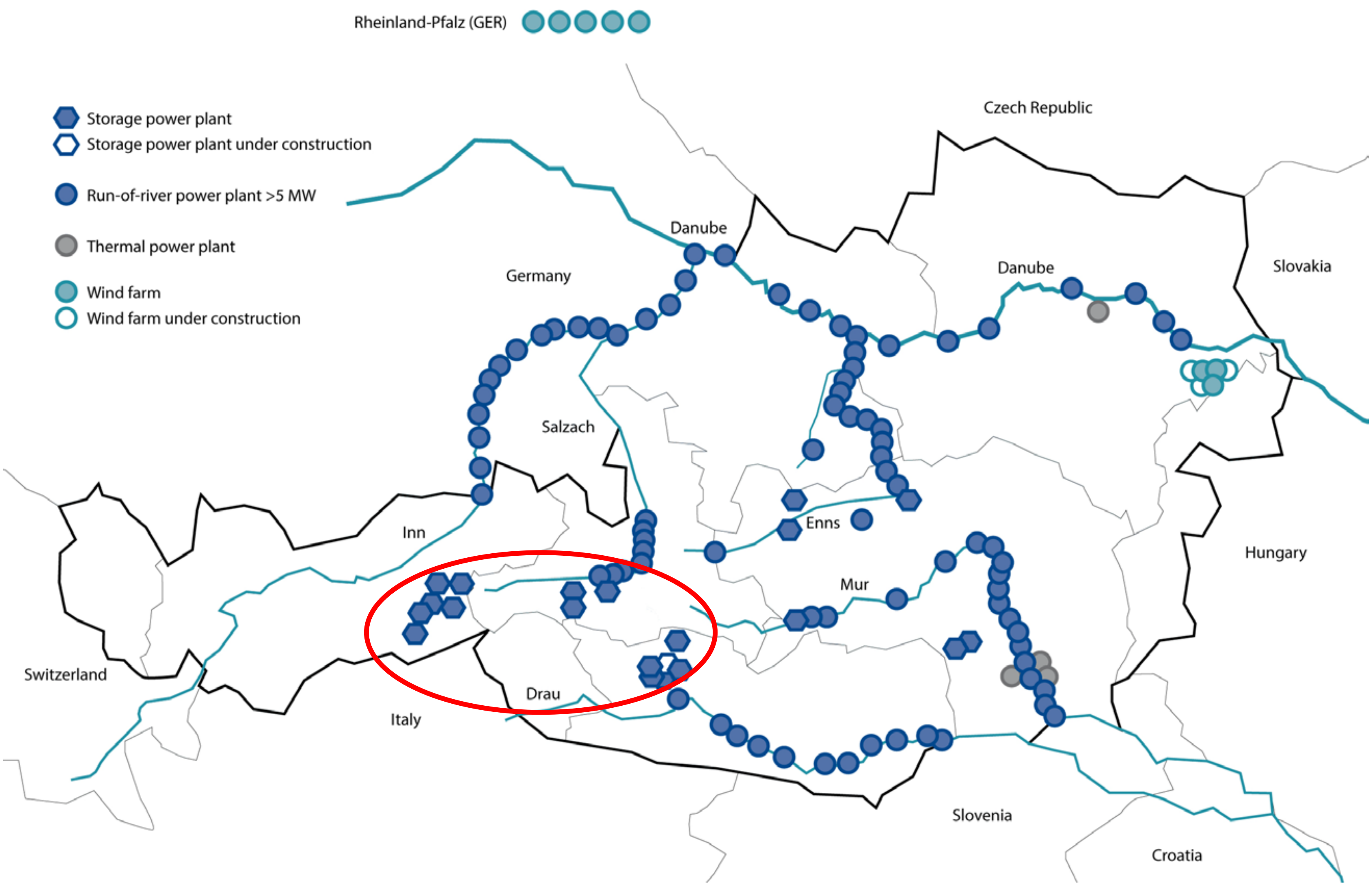
Power plants in Austria and Germany



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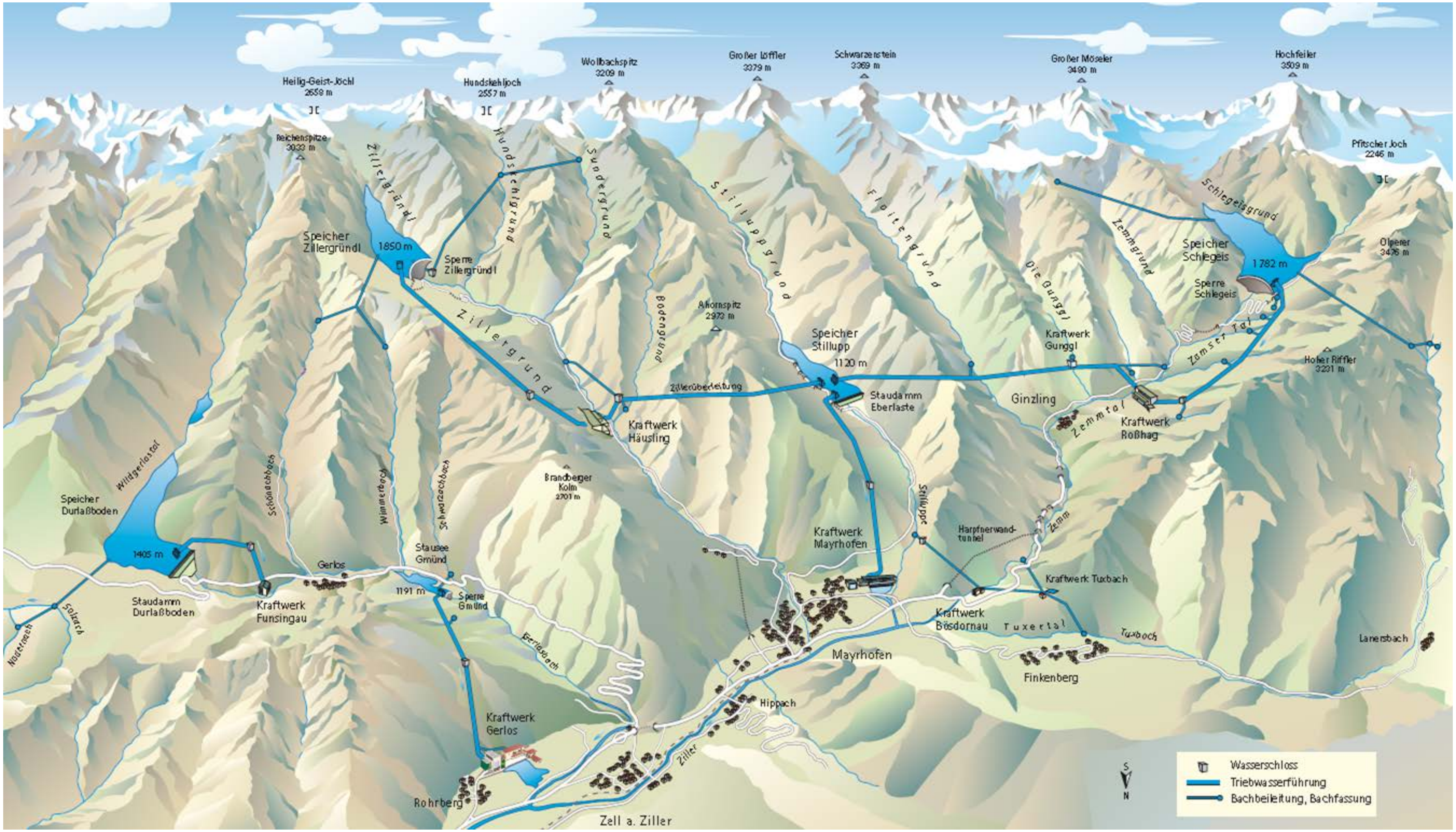
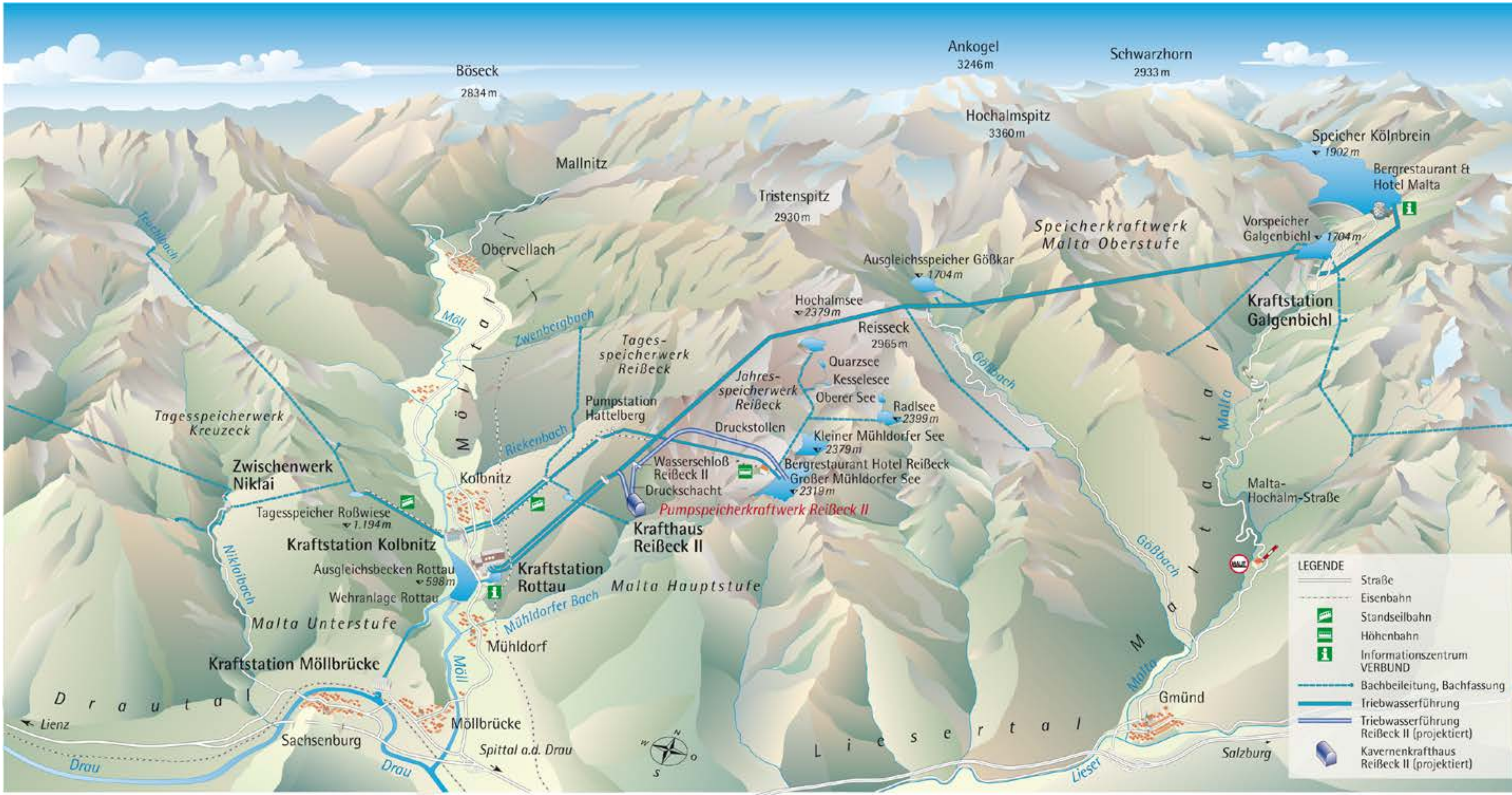
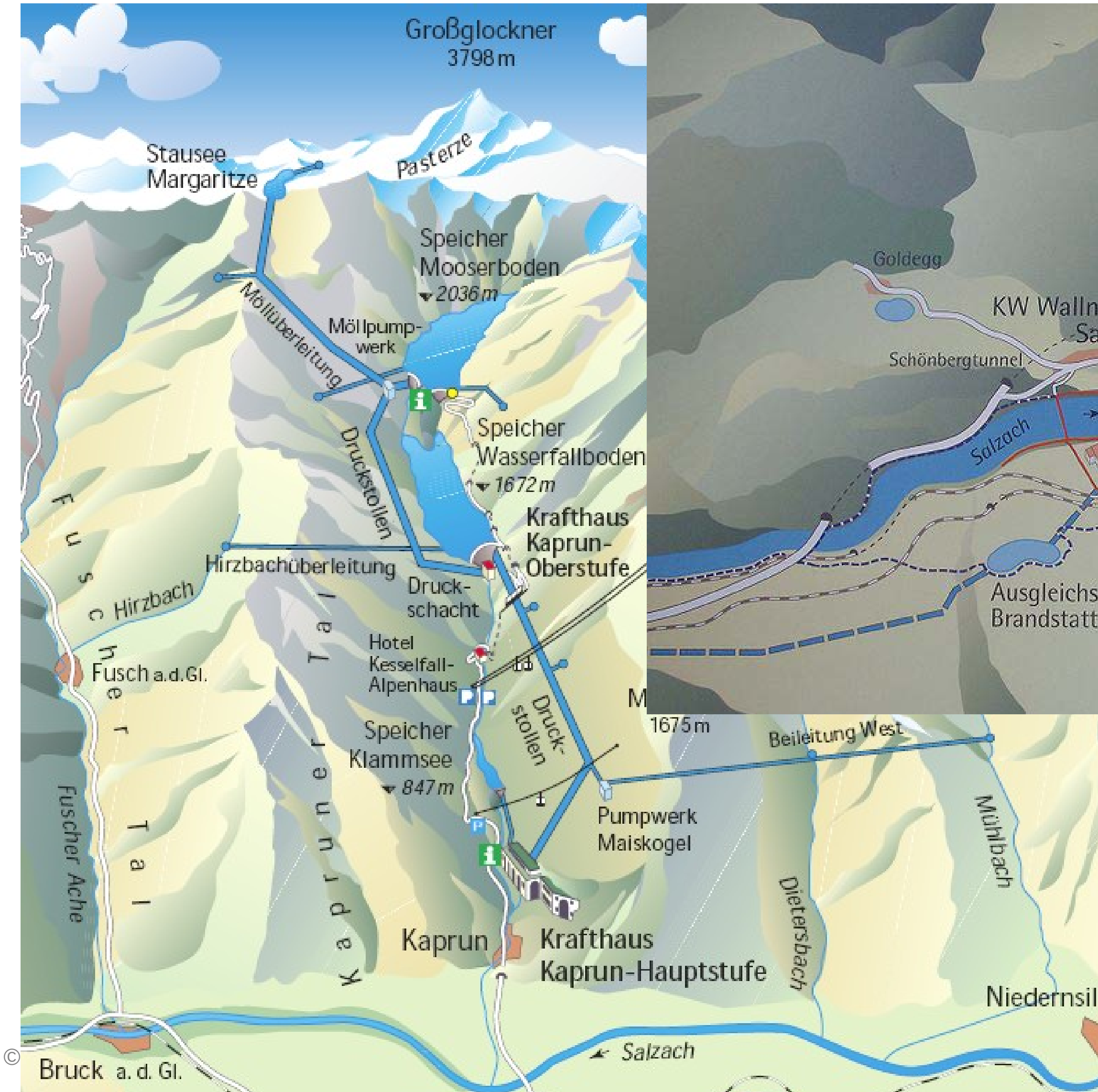
Storage Power plants in Austria: Group Zemm/Ziller (Tyrol)



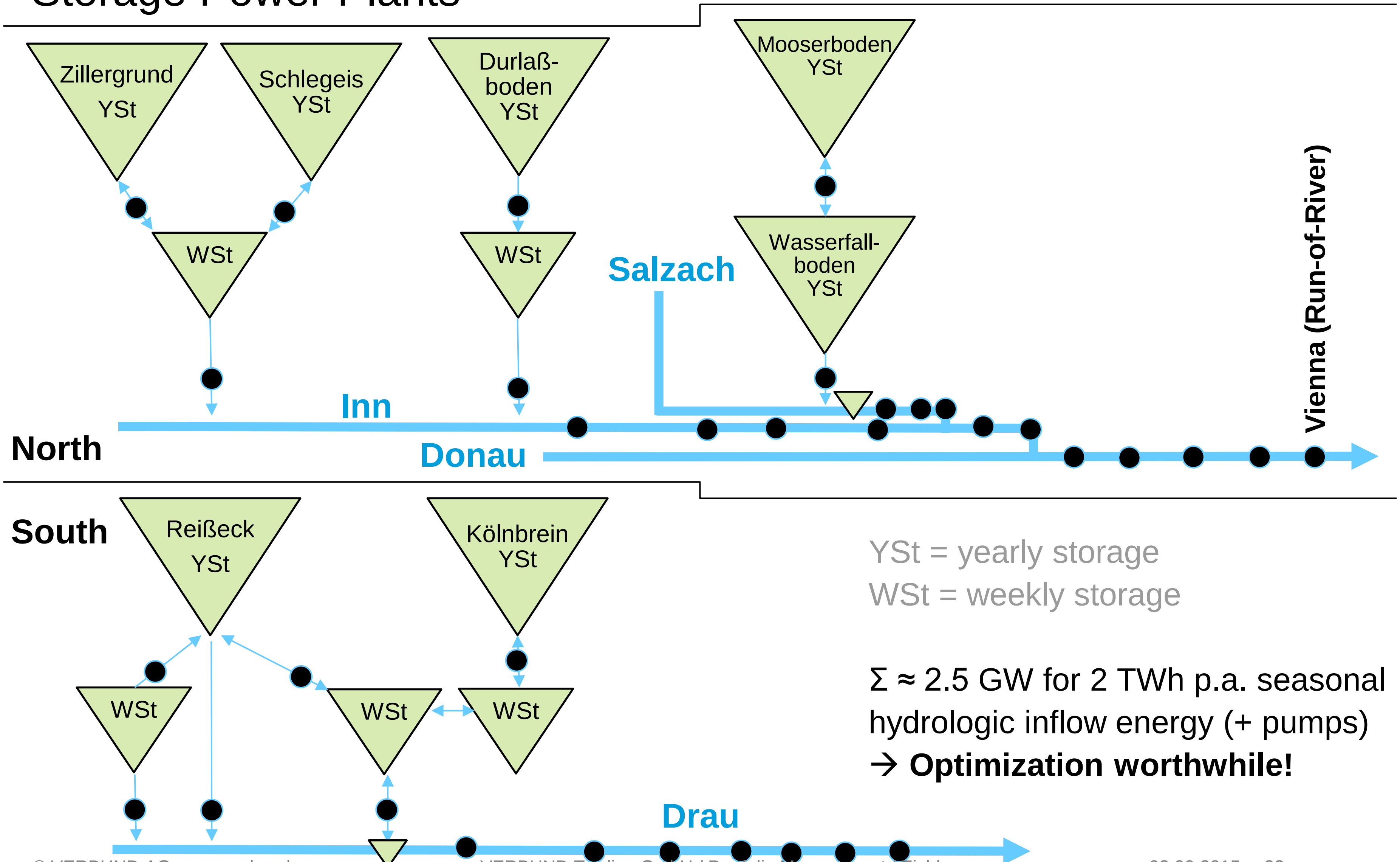
Storage Power plants in Austria: Group Malta/Reißeck (Carinthia)



Storage Power plants in Austria: Kaprun/Schwarzach (Salzburg)



Storage Power Plants



YSt = yearly storage
WSt = weekly storage

Σ ≈ 2.5 GW for 2 TWh p.a. seasonal hydrologic inflow energy (+ pumps)
→ **Optimization worthwhile!**

Yearly Cycle of a Typical VERBUND Mountain Hydro Reservoir

→ Seasonal inflow has to be distributed optimally over the year (plus: decide when to pump) subject to volume restrictions

Electricity Market Environment

Market Characteristics in Austria & Germany

Day-ahead spot market (auction) is a liquid market → most important market

→ Almost no volume risk, all positions (sales, Forwards) can be cleared here; *netting* with physical production
→ Physical production is scheduled *independently* of
- sales positions
- hedging / Forwards position

→ Physical production is mainly driven by day-ahead spot prices

Intra-day market (continuous trading) is less liquid, much more volatile

→ further opportunities for flexible plants / storages

Control reserve / ancillary service market: week-ahead auction, pay-as-bid

→ further opportunities for flexible plants / storages

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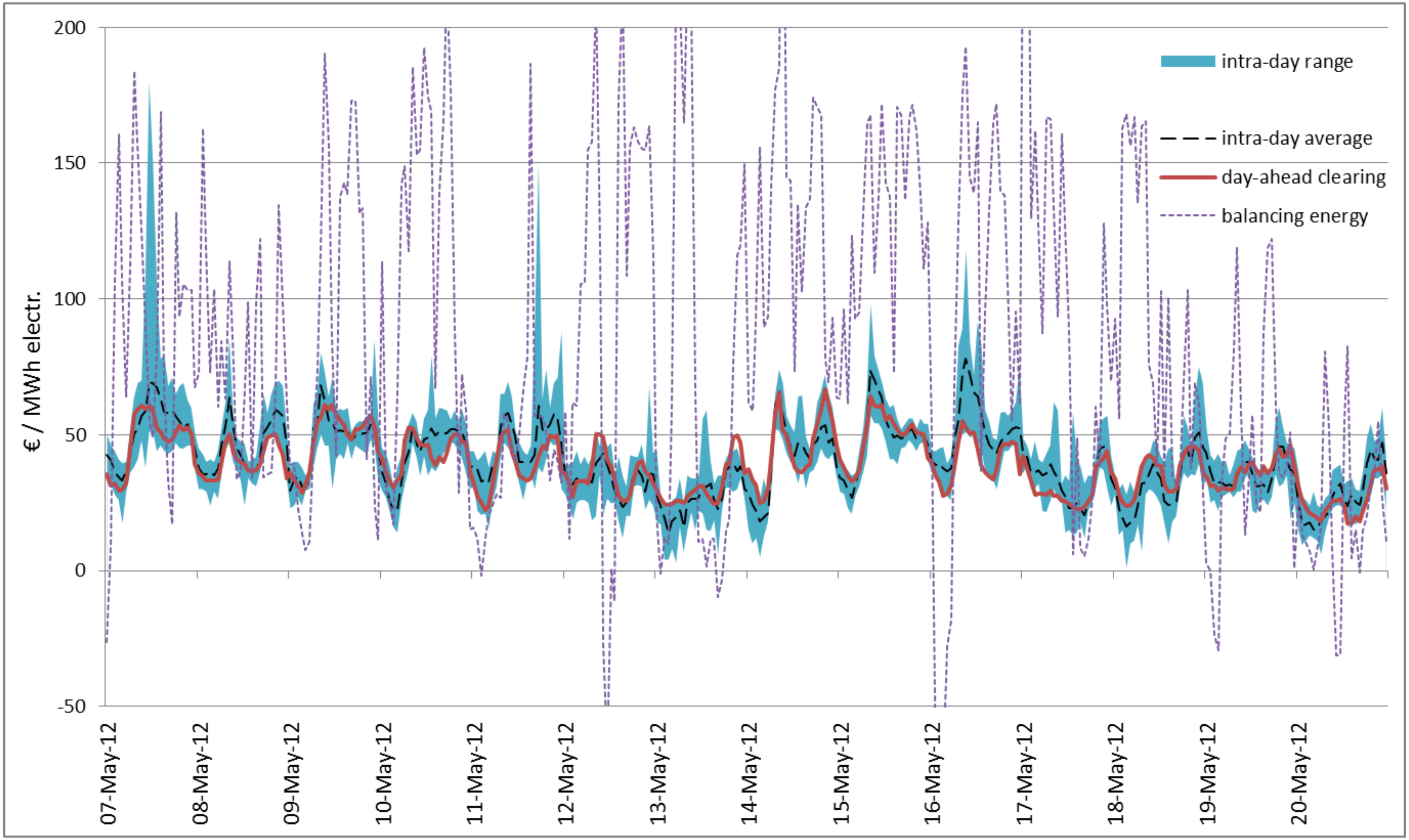
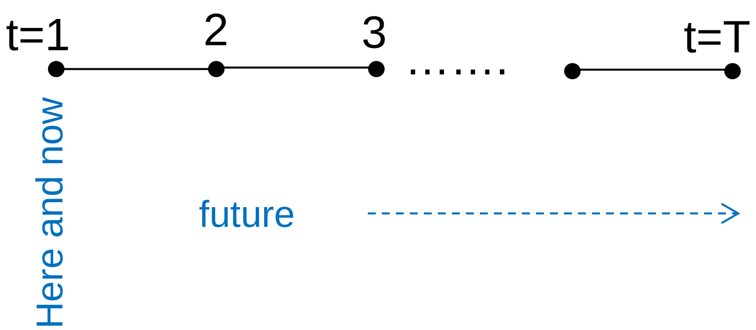
Market Characteristics in Austria & Germany



Optimization Models for Planning, Scheduleing, Dispatch

Hourly time discretization (imposed by the market):



Most commercially available optimization software tools:

- *Input*: one (deterministic) scenario (hourly power price forecast, inflows, renewable generation …)
- *Output*: one schedule for each turbine, reservoir …
- Optionally: run several deterministic decisions

- Perfect foresight, non-robust decisions
- In practice: situation and input data change very rapidly
  (renewable production, intra-day prices, ancillary services / reserve calls, …)
- Decisions to take? Auctions?

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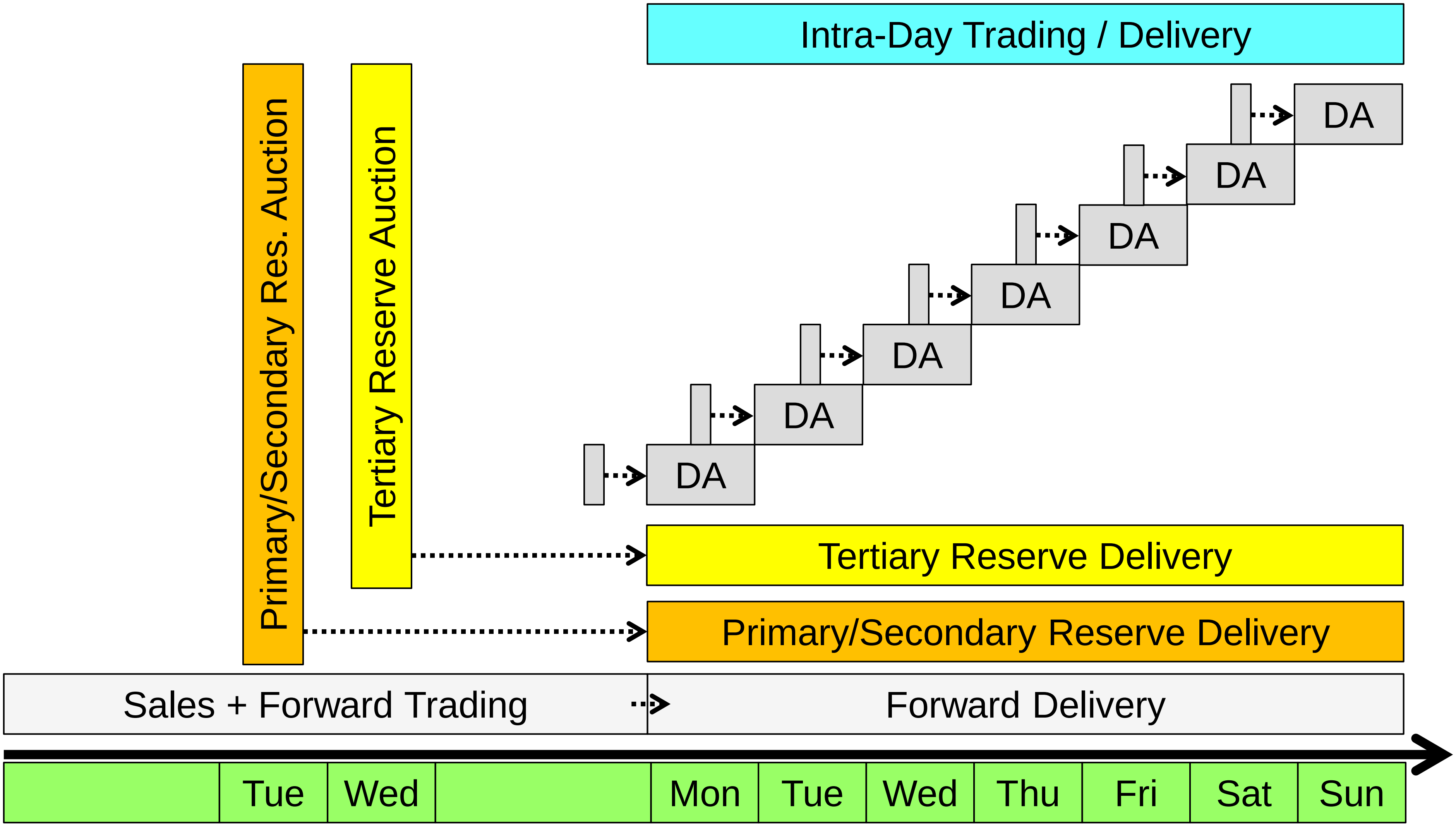
Weekly Market Decision Structure in Austria



Optimization in Practice: Short-term vs. Medium-term

Focus of this presentation

Medium-term Optimization

Planning Horizon: 1 up to 5 years

Coupling e.g. via
Water Values

Short-term Optimization

Week-ahead, Day-ahead, Intra-day

Hedging determines to a large extent the total financial result

Hedging
(Forwards, Futures, Options, …)

Control Reserve Auctions
(Ancillary Services)

Maintainance Planning

Spot Market Activities

Power Plant Commitment, Storage Charge / Discharge

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Medium-term Modelling with Stochastic Optimization / ADDP / SDDP

Major Challenges in Medium-term Optimization

in a market environment from a practical point of view: **1000s of details →**

- **Complexity of technical modeling**
  (e.g. non-convexities @hydro storage plants)

- **Long planning horizons** (required for yearly storages)
  in **hourly discretization** (required because of small storages)

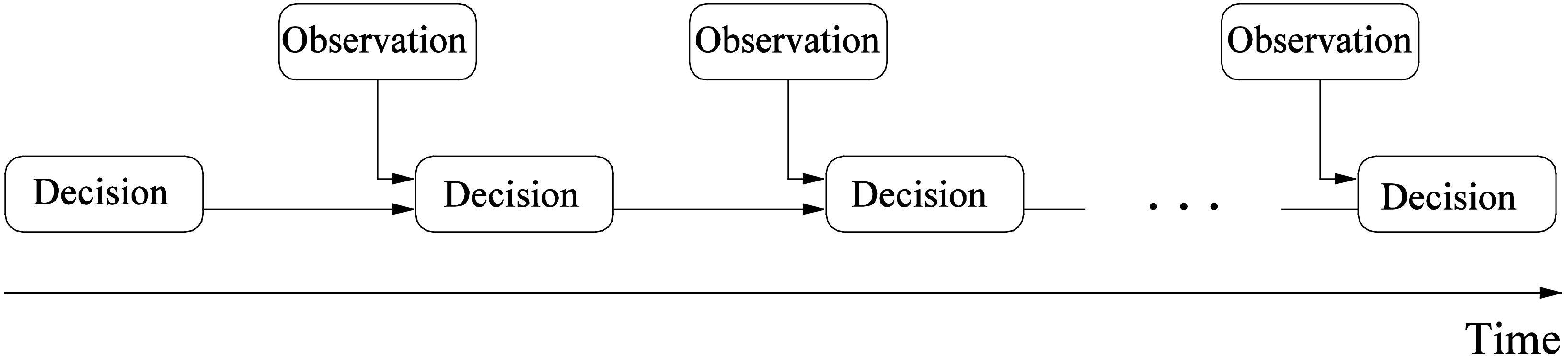
- **Linking** of storage power plants by
  - hydrological coupling
  - control reserve constraints (no separation of problem possible)

- **Uncertainty** of future input data (inflows, power prices, …)

- **Market Structures**:
  - several markets (Forwards, ancillary services / reserve, day-ahead spot, intra-day, …)
  - sequences of auctions + continuous trading
  - rapidly changing market environments → short data history for calibration of statist. models
  - game theoretic aspects …

Stochastic Optimization

Optimization textbooks → *Multistage Stochastic Programming*:



- Data that is uncertain now can be observed in the future
- Statistical information about this data is available now

→ Matches very well the market decision structures

Multi-Stage Stochastic Optimization

Abstracts standard formulation with stochastic process [$\text{data}_t := c_t, A_{t0}, A_{t1}, b_t$] (t=1,…,T):

objective with expectation

costs

decisions

stoch. data: $\texttt{data}_t := (c_t, A_{t0}, A_{t1}, b_t)$
(e.g. inflows, power prices)

$$\text{minimize} \quad \mathbf{E}\left[\sum_{t=1}^{T} c_t' x_t\right]$$

$$\text{over } x_t = x_t(\text{data}_1, \text{data}_2, \dots, \text{data}_t) \in \mathrm{R}^{n_t} \quad (\mathrm{t}=1,\dots,\mathrm{T})$$

$$\text{subject to } \; A_{t,0} x_t + A_{t,1} x_{t-1} \ge b_t \quad (\mathrm{t}=1,\dots,\mathrm{T}) \text{ for all possible } b_t, A_{t,0}, A_{t,1}$$

constraints

Theoretically:

Universal framework, copes with all kinds of stochastic processes and optionalities

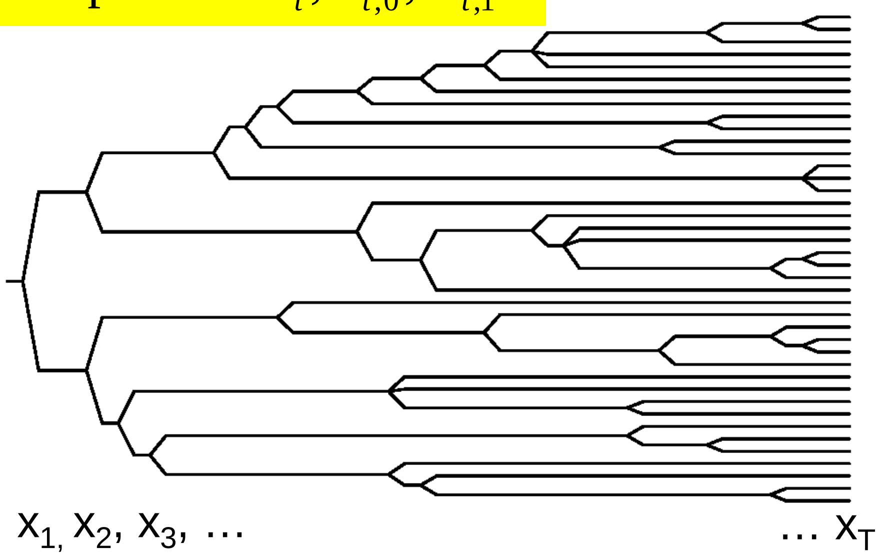
In practice:

distribution of (c_t, $A_{t,s}$, b_t) must be finite
(or be approximated by a finite one)

→ distribution of $x=(x_1,\dots,x_T)$ is also finite

→ scenario tree (gets big as T increases)

→ *curse of dimensionality*



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Multi-Stage Stochastic Optimization

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$$\text{subject to } \; A_{t,0} x_t + A_{t,1} x_{t-1} \geq b_t \quad (\mathrm{t} = 1, \ldots, \mathrm{T}) \text{ for all possible } b_t, A_{t,0}, A_{t,1}$$

constraints

Equivalent **recursive** formulation:

Future Cost Function

$$C_t(x_{t-1}, \text{data}_{1,..,t-1}) = \mathbf{E}_{\text{data}_t|\text{data}_{1,..,t-1}}\left[\min\left\{ c_t' x_t + C_{t+1}(x_t, \text{data}_{1,..,t}) \;\middle|\; \begin{array}{c} x_t \in \mathrm{R}^{n_t} \\ A_{t,0} x_t + A_{t,1} x_{t-1} \geq b_t \end{array} \right\}\right]$$

conditional expectation

immediate Cost

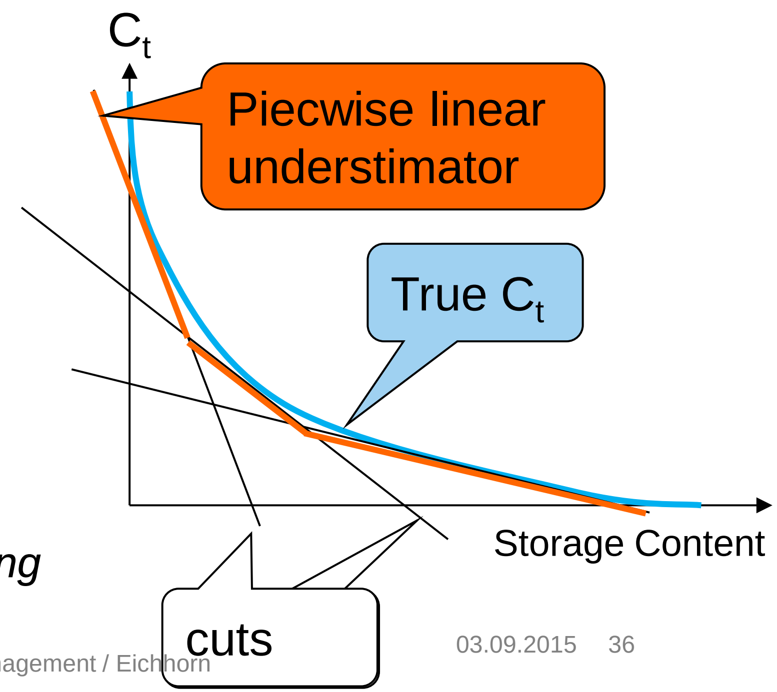
($C_{T+1} \equiv 0$)

ADDP/SDDP (Approximate / Stochastic Dual Dynamic Programming)

[Pereira & Pinto 1991], [Löhndorf, Wozabal, Minner 2013]
based on recursive formulation + *Markov property*:

$$C_t(x_{t-1}, \mathrm{data}_{1,..,t-1}) = \mathbf{E}_{\mathrm{data}_t|\mathrm{data}_{1,..,t-1}}\left[\min\left\{ c_t' x_t + C_{t+1}(x_t, \mathrm{data}_{1,..,t}) \;\middle|\; \begin{matrix} x_t \in \mathrm{R}^{n_t} \\ A_{t,0}x_t + A_{t,1}x_{t-1} \geq b_t \end{matrix} \right\} \right]$$

- The *Future Cost Functions* C_t are monotonically decreasing and **convex** w.r.t. storage contets and inflow.
- *Idea:* Iterative approximation of C_t from below by (multi-dimensional) *cutting planes* (cuts) calculated from (dual) shadow prices of balance eq.
- Cuts will be calculated only at certain presumptively relevant x positions (determined by simulation runs)
- Stochasticity of power prices not via cuts, but via ordinary (primal) *Stoch. Dynamic Programming*

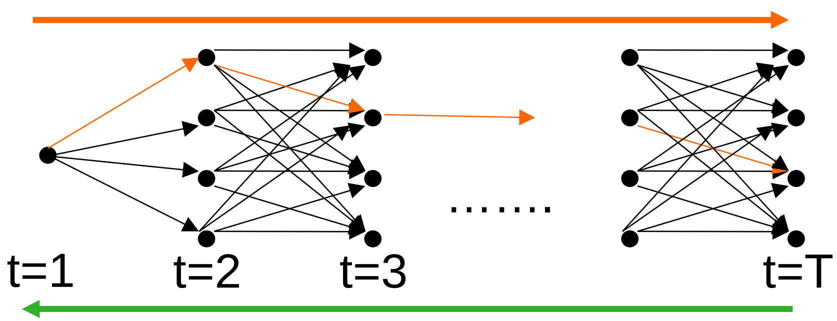


ADDP/SDDP (Approximate / Stochastic Dual Dynamic Programming)

Algorithm:

- Fix a *recombining scenario tree* / *lattice* (carrying inflows and prices) together with some sample paths

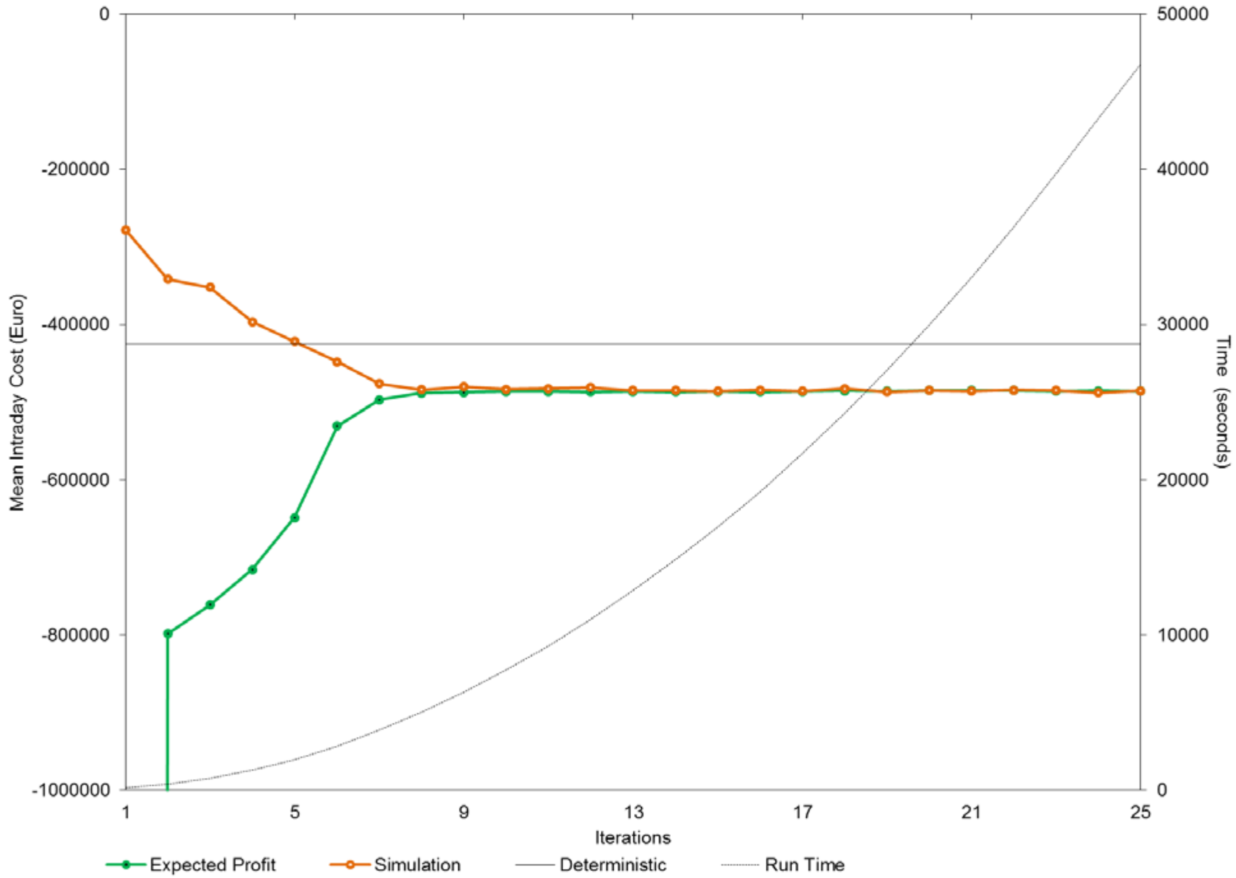
- Iterate n=1,2,3,…
  - "Forward Pass" (simulation based on existing cuts) along the sample paths, determine x-position for new cuts



  - "Backward Pass" allong all nodes:
    - determine y-position and slope (=shadow price) for new cuts
    - Add new cuts to the list
  - Eliminate superflowus cuts

ADDP/SDDP (Approximate / Stochastic Dual Dynamic Programming)

- „Forward Pass“ bzw. „Backward Pass“ yield upper and lower bounds, resp.;
- bounds converge in practice:



Medium-Term Stochastic Optimization

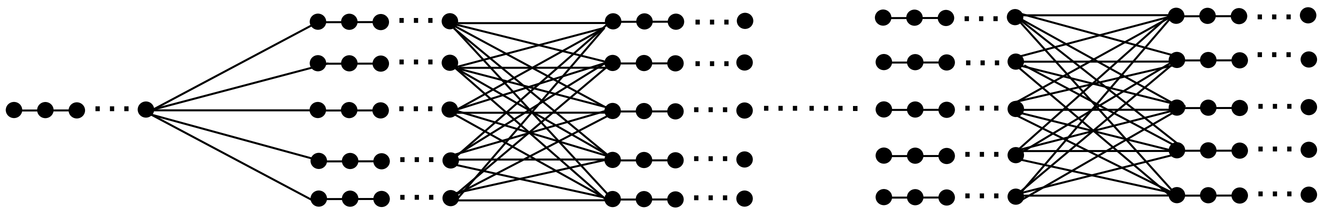
- Short-term optimization has to be anticipated (consistency!)

- Strong simplifications necessary (LP, Markov, …)

- Stochastic Programming is attractive here to anticipate
  - short-term uncertainty
  - different medium-term trends (oil price, economic trends, wet vs. dry years, …)
  - optional character of storage plants

- Stochastic Programming with non-recombinig scenario tree: Limited #branchings! (but sufficient for anticipating different medium-term trends)

- ADDP/SDDP methods with *recombinig scenario trees* / *lattices* useful in practice



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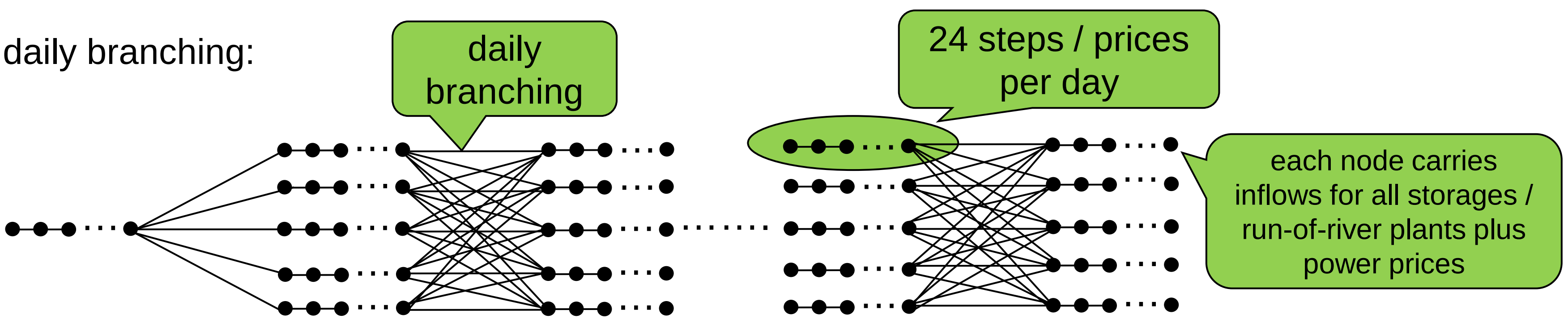
Medium-Term Stochastic Optimization @VERBUND

- ADDP model based on the QUASAR Java API by Quantego.com (Löhndorf)
- 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 (EPEX spot day-ahead)
- control reserve / ancillary services as fixed constraints
- approximate modelling of effect of storages on run-of-river plants and flow times
- daily branching:



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Stochastic Inflow Model

Cf. presentation of Nils Löhndorf / Quantego

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Stochastic Price Model

(alomost the) same model as for the inflows!

Idea:

1. Interpret hourly prices as a 24 dimensional daily time series

2. Using the same type of model as for inflows, i.e.,
   - Fourier analysis (here for yearly *and* weekly cycles)
   - PCA of the residuals
   - directly fit a Markov chain to the principle components!

3. In addition: *bootstrap* daily patterns from historical data

4. Final shift such that for each hour expectation = Price Forward Curve

Input to Stochastic Optimization: *Cartesian product* of inflow and price model

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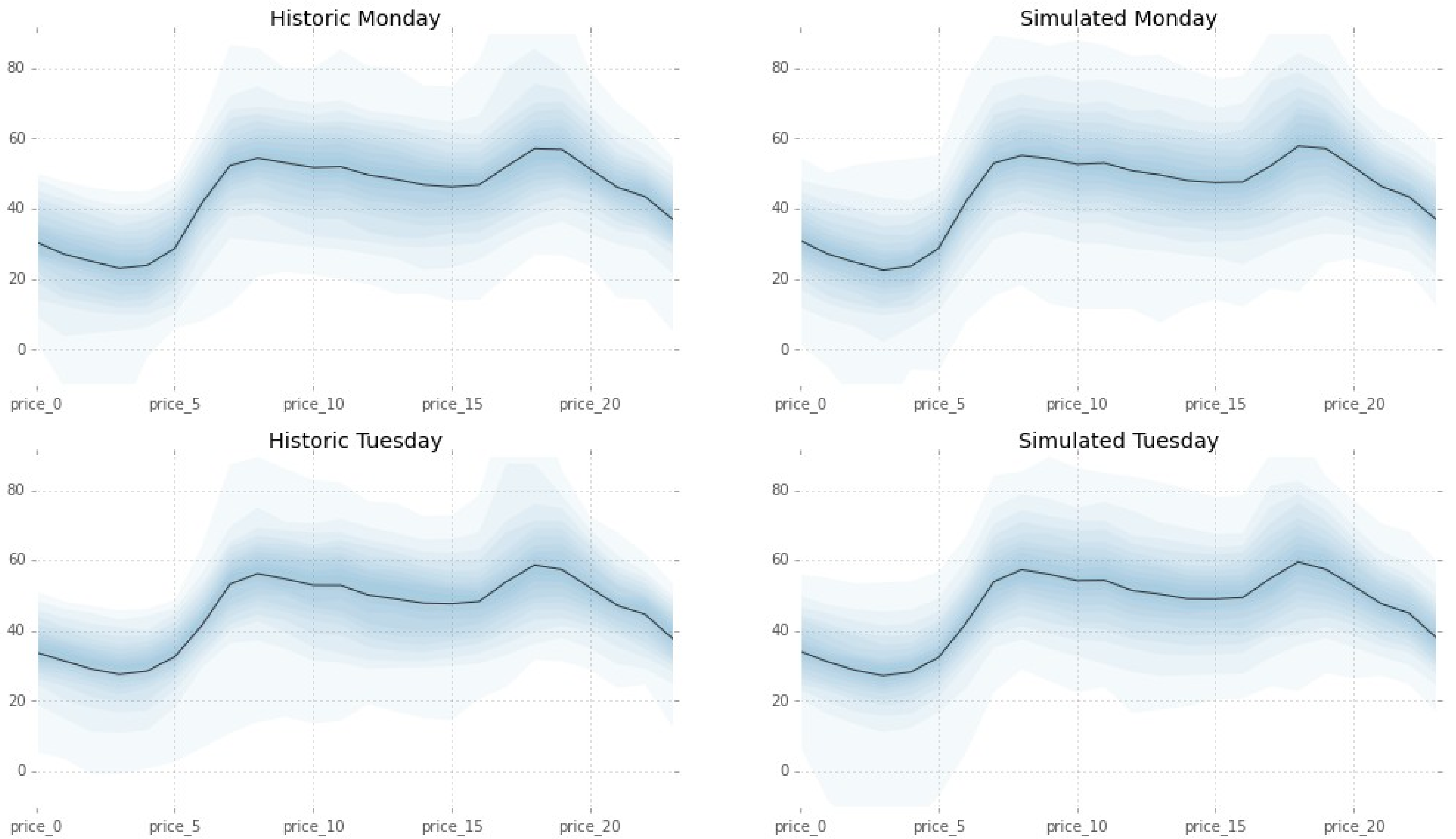
Stochastic Price Model



Optimization Results

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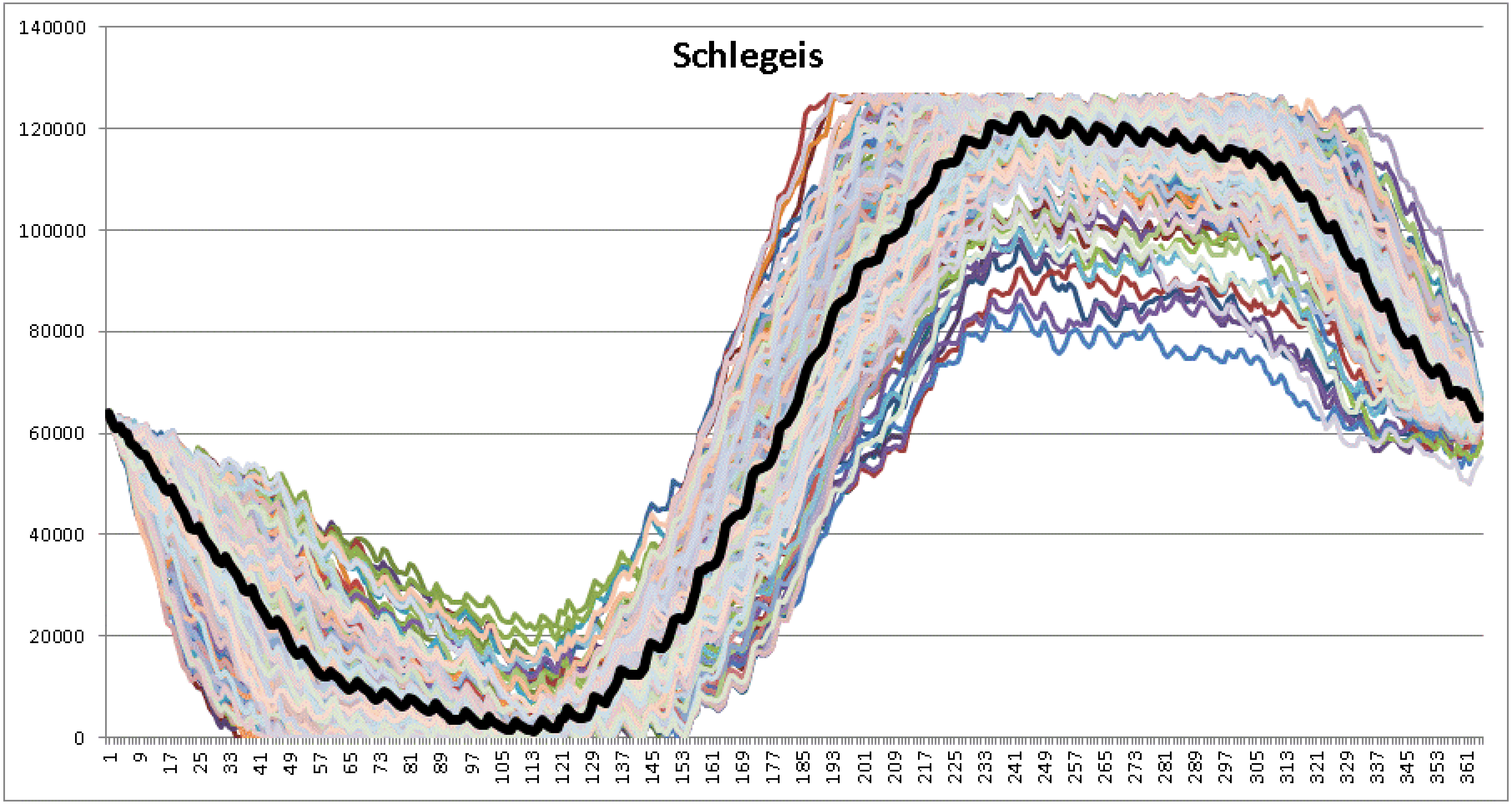
Results Stochastic Medium-term Optimization

Output: Scenarios storage content over 1 year



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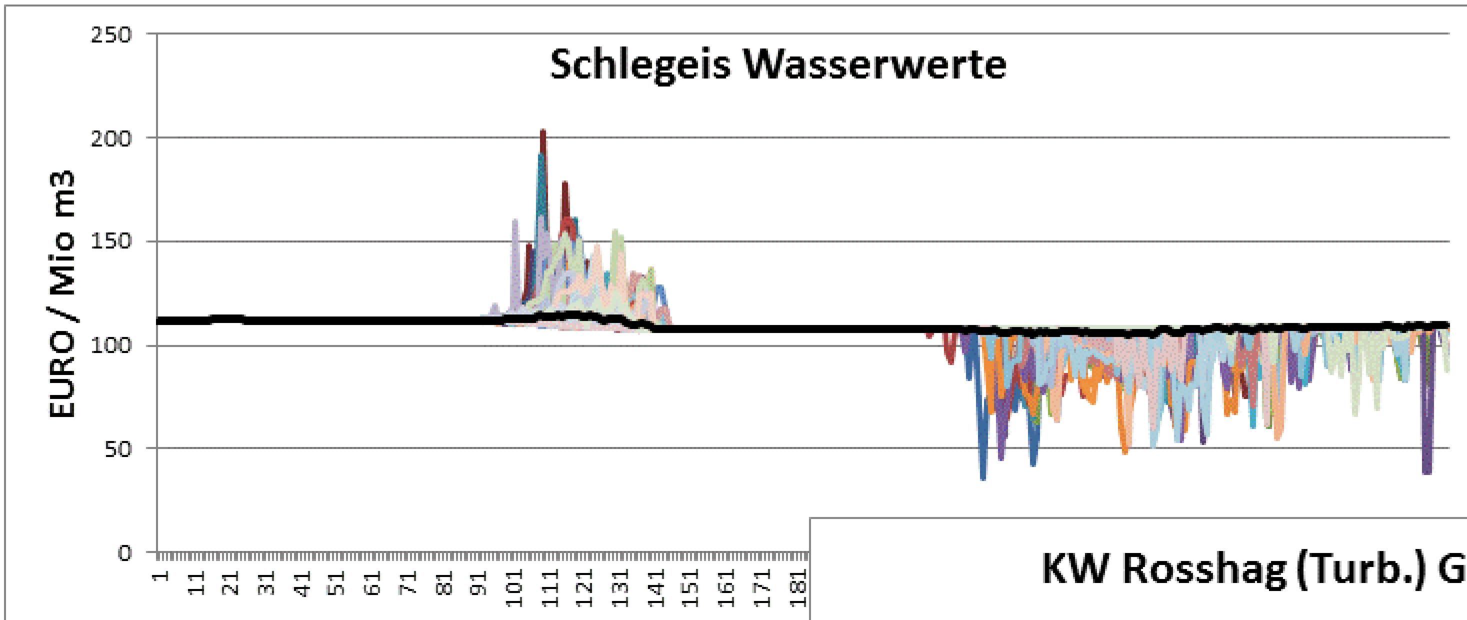
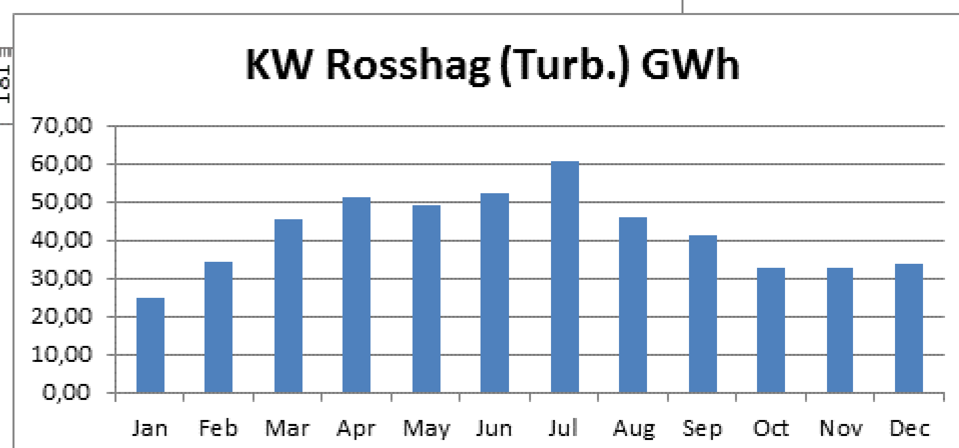
Results Stochastic Medium-term Optimization

Output: Scenarios water values over 1 Jahr





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Results Stochastic Medium-term Optimization

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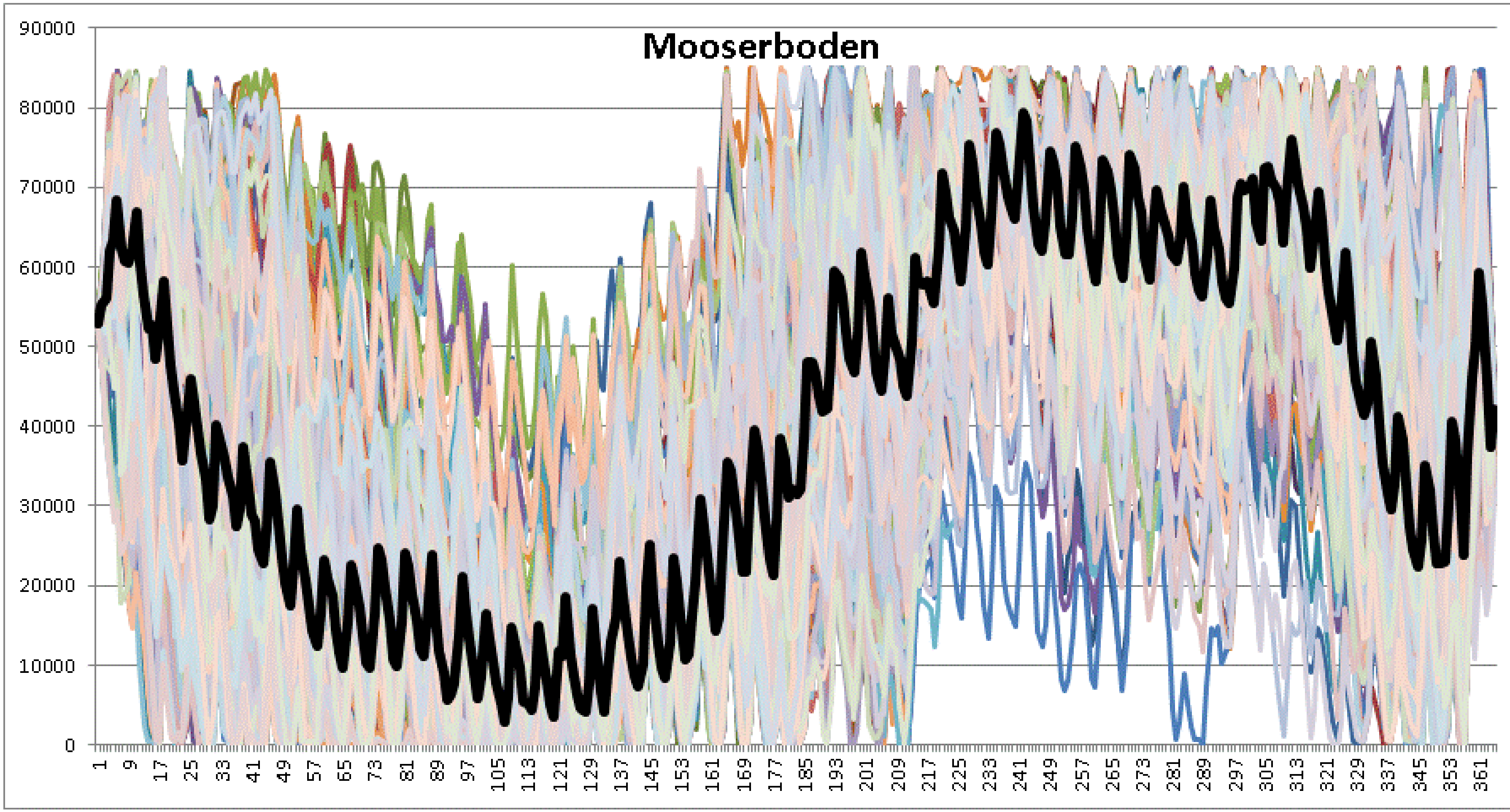

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Results Stochastic Medium-term Optimization

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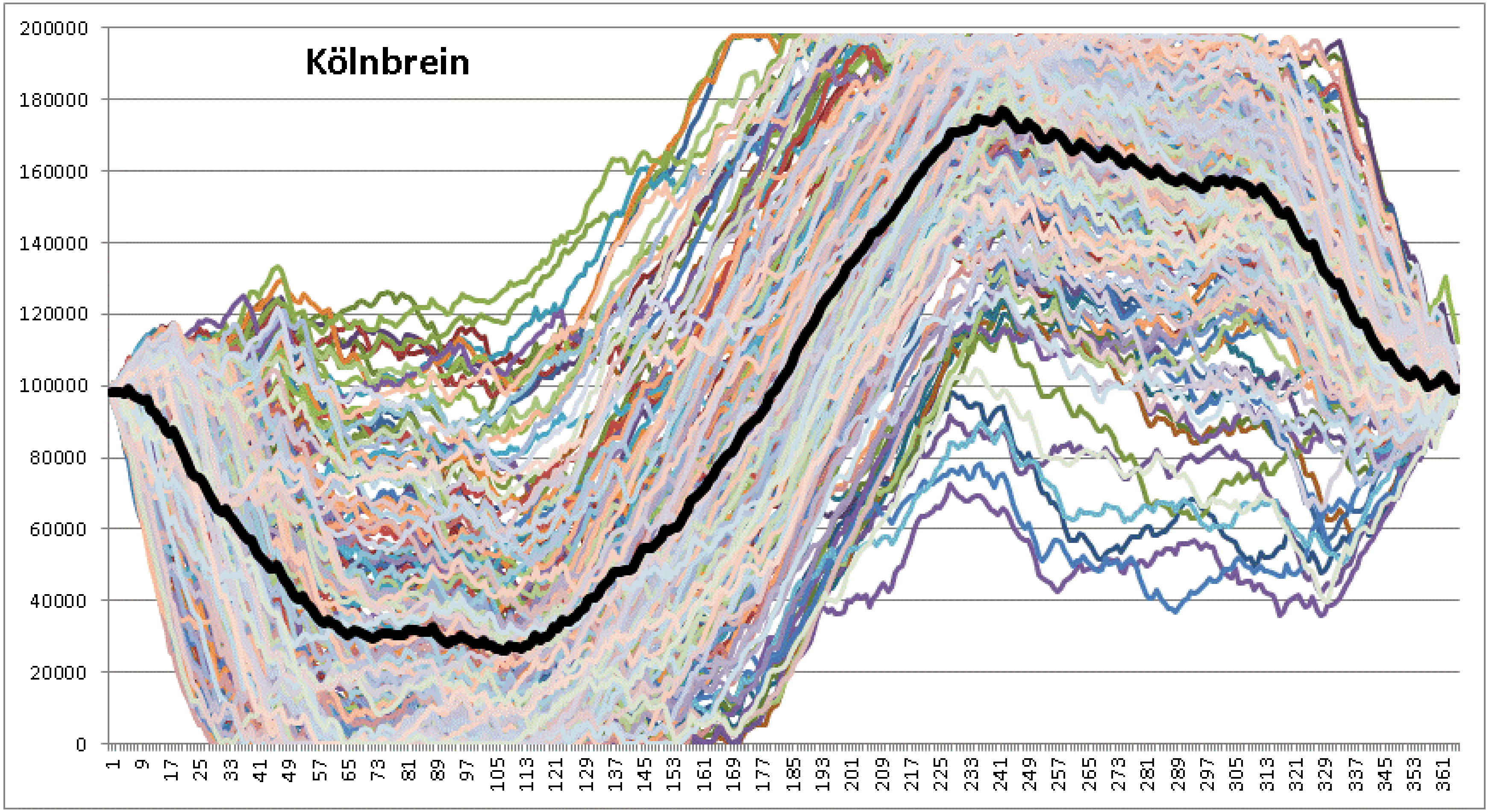
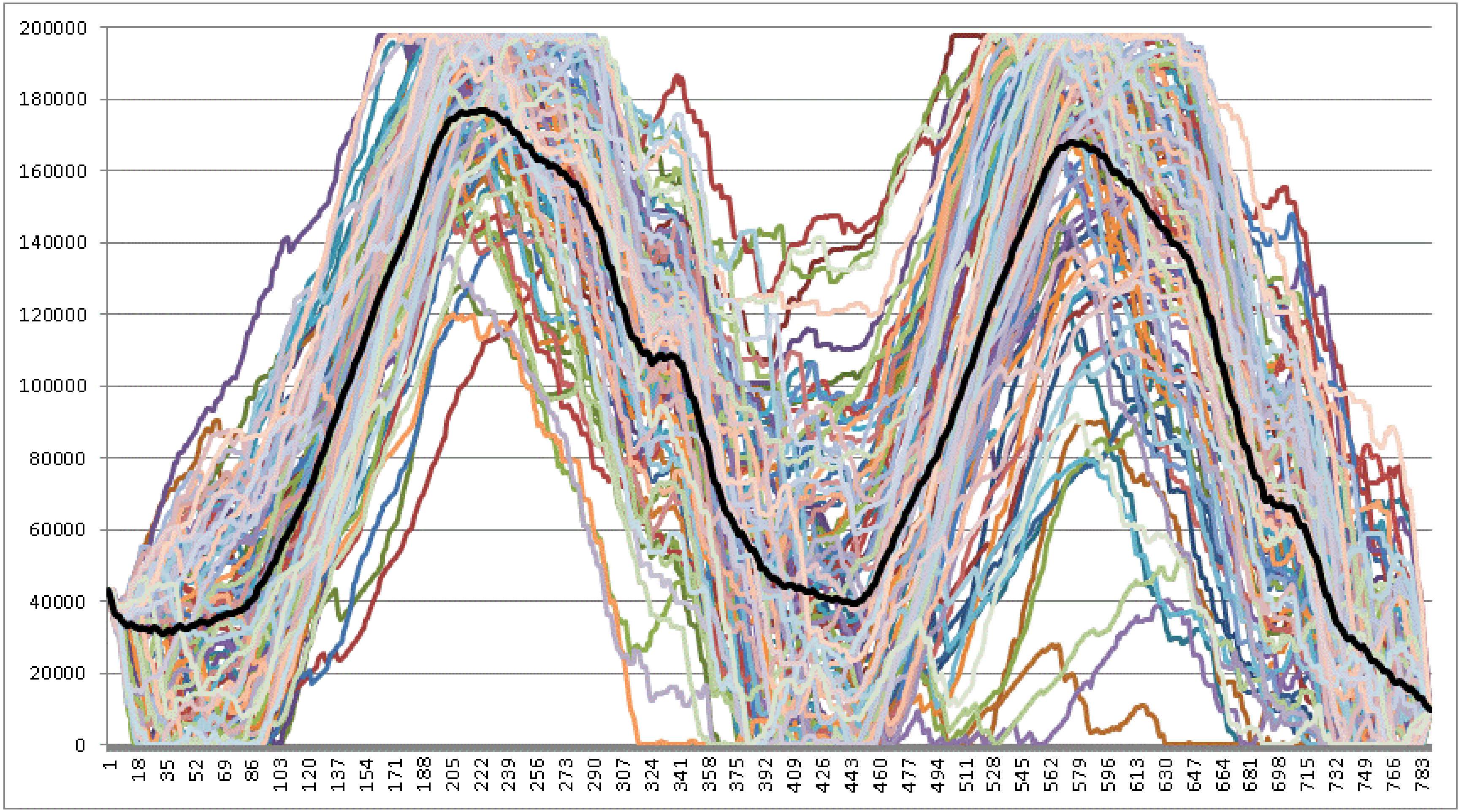


Results Stochastic Medium-term Optimization

Output: Scenarios storage content over 2 years



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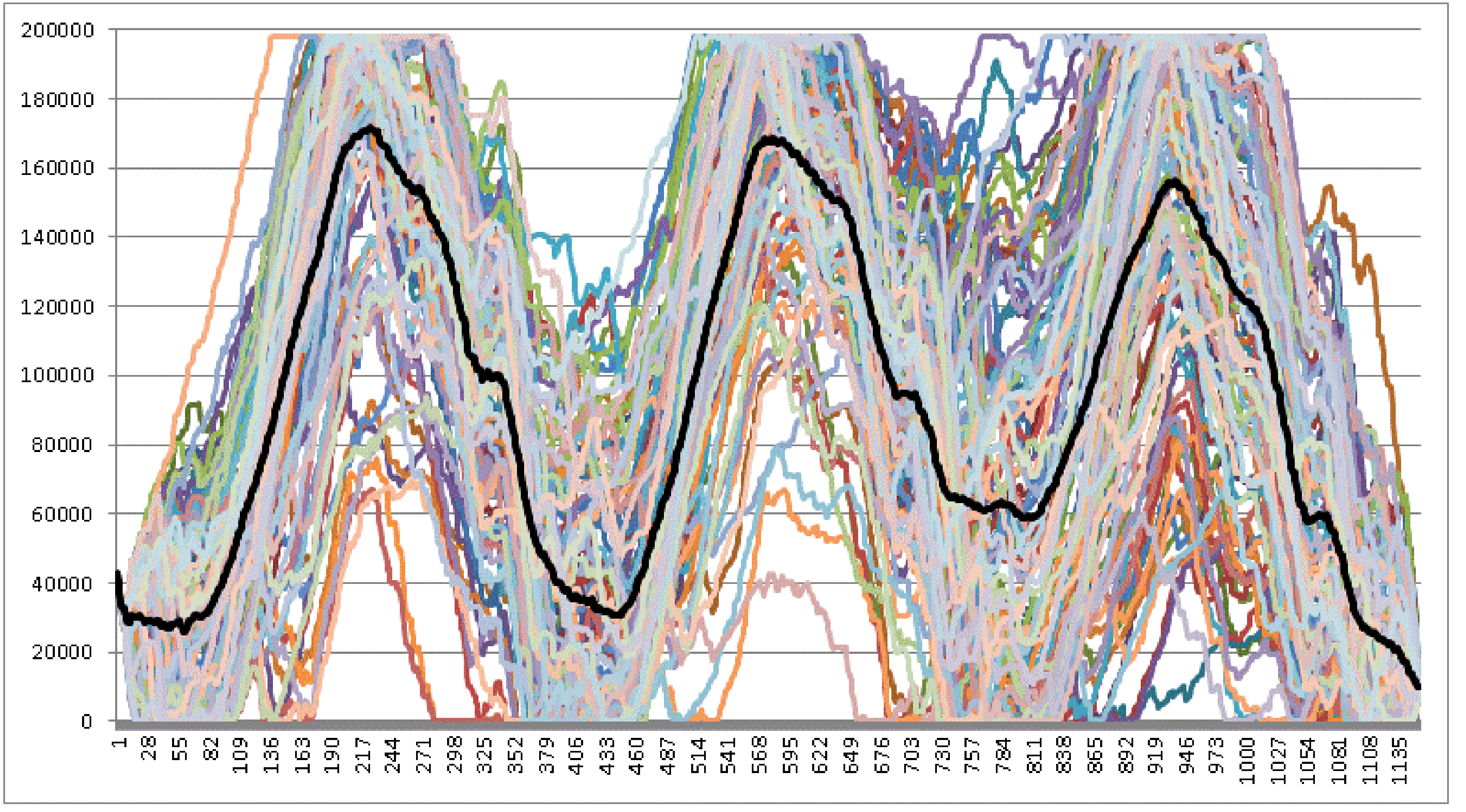
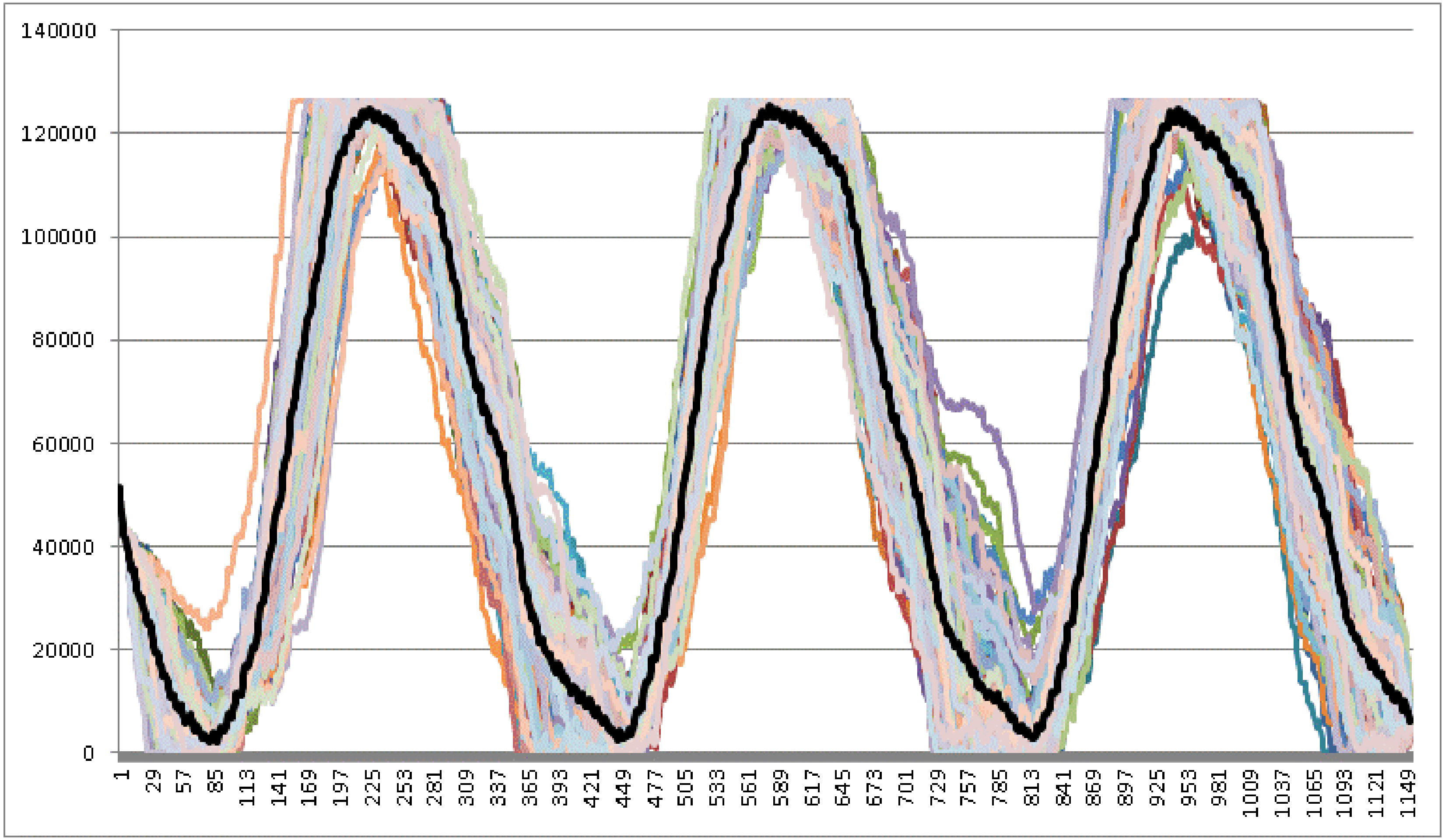
Results Stochastic Medium-term Optimization

Output: Scenarios storage content over 3 years



Results Stochastic Medium-term Optimization

Output: Scenarios storage content over 3 years

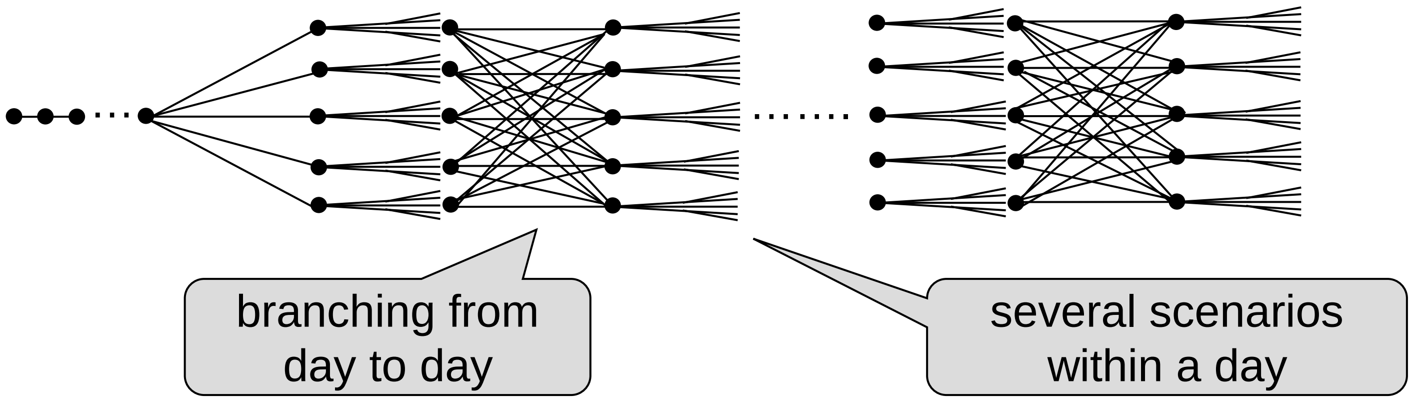


Conclusions

Medium-term stochastic optimization in hourly discretization is reasonably possible with Stochastic ADDP / QUASAR by Quantego.com, even for bigger real hydro power systems.

Outlook:

- More accurate (piecewise linear convex) approximation of nonlinearities of power plants
- More accurate (piecewise linear convex) modelling of spinning reserve
- Explicit modelling of day-ahead auction and intra-day prices:



Verbund