Scheduling when reservoirs are batteries for wind- and solar-power

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Renewable power generation in EU

- More than doubled since 2000
- Targets for further increases towards 2020 and 2030
- Reducing the cost of this policy is an important motivation for the ongoing liberalization/legislation process in the EU

Can hydropower reservoirs be batteries for wind- and solar-power?

- The battery idea
  - 86 TWh storage capacity in Norwegian reservoirs
  - Could we utilize some of it to balance renewables in Europe?
  - Then we need to increase generation capacity and build new cables!

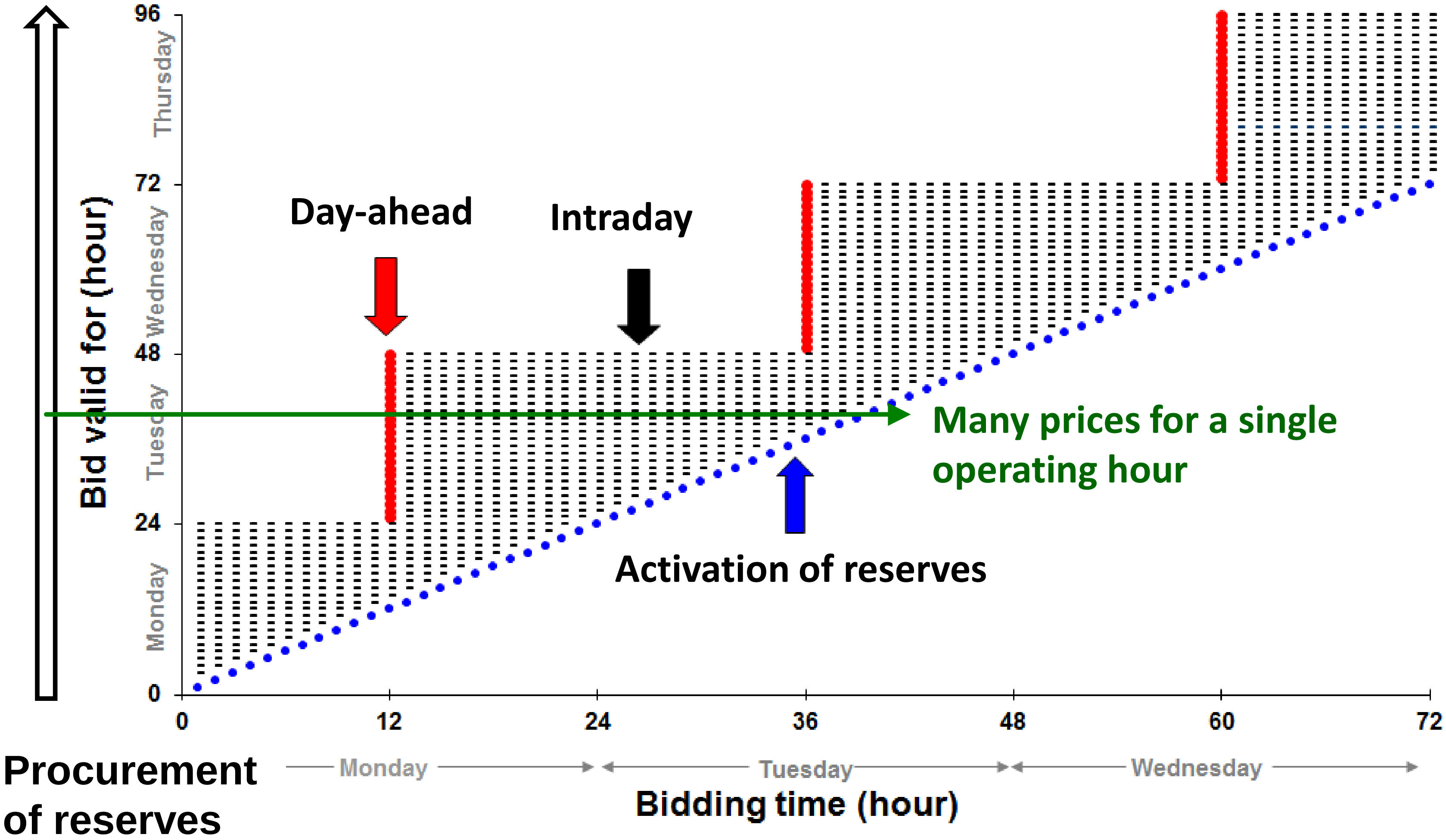
- Some existing studies
  - Solvang et al. (2012): Identified a potential 20 GW extra generation capacity, utilizing existing reservoirs in Southern Norway
  - Solvang et al. (2014) studied the impacts on the expected hydropower operation based on wind-power variability
  - Korpås et al. (2015) introduced the concept "levelized costs of peaking capacity", and compared hydropower incl. cables with gas-power

Our study

- Within CEDREN HydroBalance (KPN)
  - Feasibility check for large-scale balancing from Norway
  - http://www.cedren.no/Prosjekter/HydroBalance

- Research questions
  - How will hydropower be operated in the future?
  - What is the impact of several markets?
  - Will pumped storage investments be profitable?

Market types



General approach

Develop methodology

- Hydropower optimization
- With several markets

Forecast prices

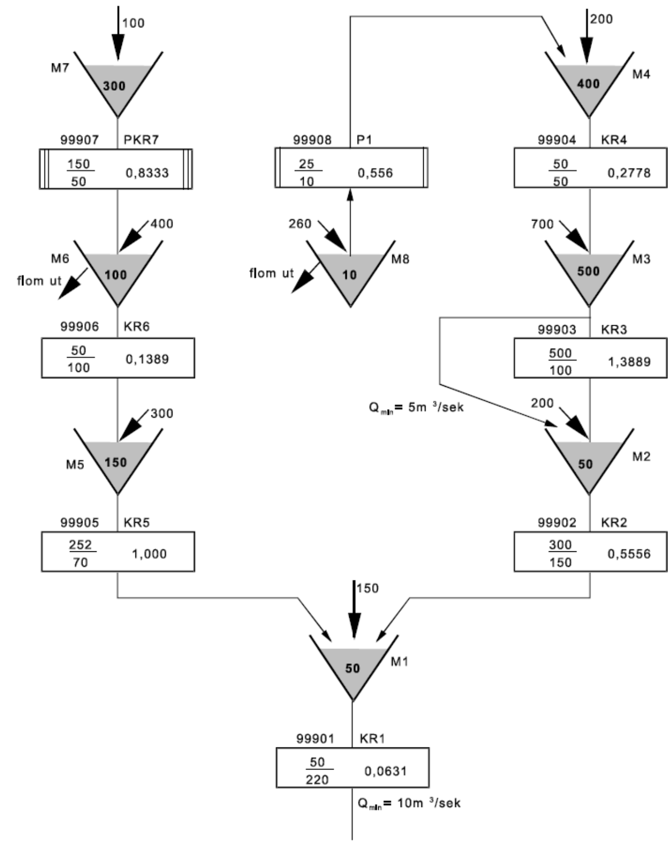
- HydroBalance scenario
- 2050
- Several markets

Case-study

- Real river system
- Relevant pumped-storage project

Applied model: ProdRisk

- One of SINTEF's optimization tools for hydropower
  - Local producer / river system
  - Objective: Maximize profits
  - Stochastic variables: inflow, prices
  - Time-resolution/horizon: e.g. hour/year
- However, model is only for one power market (day-ahead)



Accounting for several markets

Develop methodology

- ❑ Hydropower optimization
- ❑ With several markets

- A full multi-market optimization not feasible in ProdRisk
- However, the following strategy can be evaluated
  - Supply for day-ahead market as if it was the only market
  - Adjust production in subsequent market when profitable
  - Reserve capacity is a parameter (to be optimized iteratively)
- Similar approach taken by others, e.g. ECN's COMPETES model
- Klæbu and Fosso (2013): So far not many studies have indicating gains of coordinated bidding for several markets

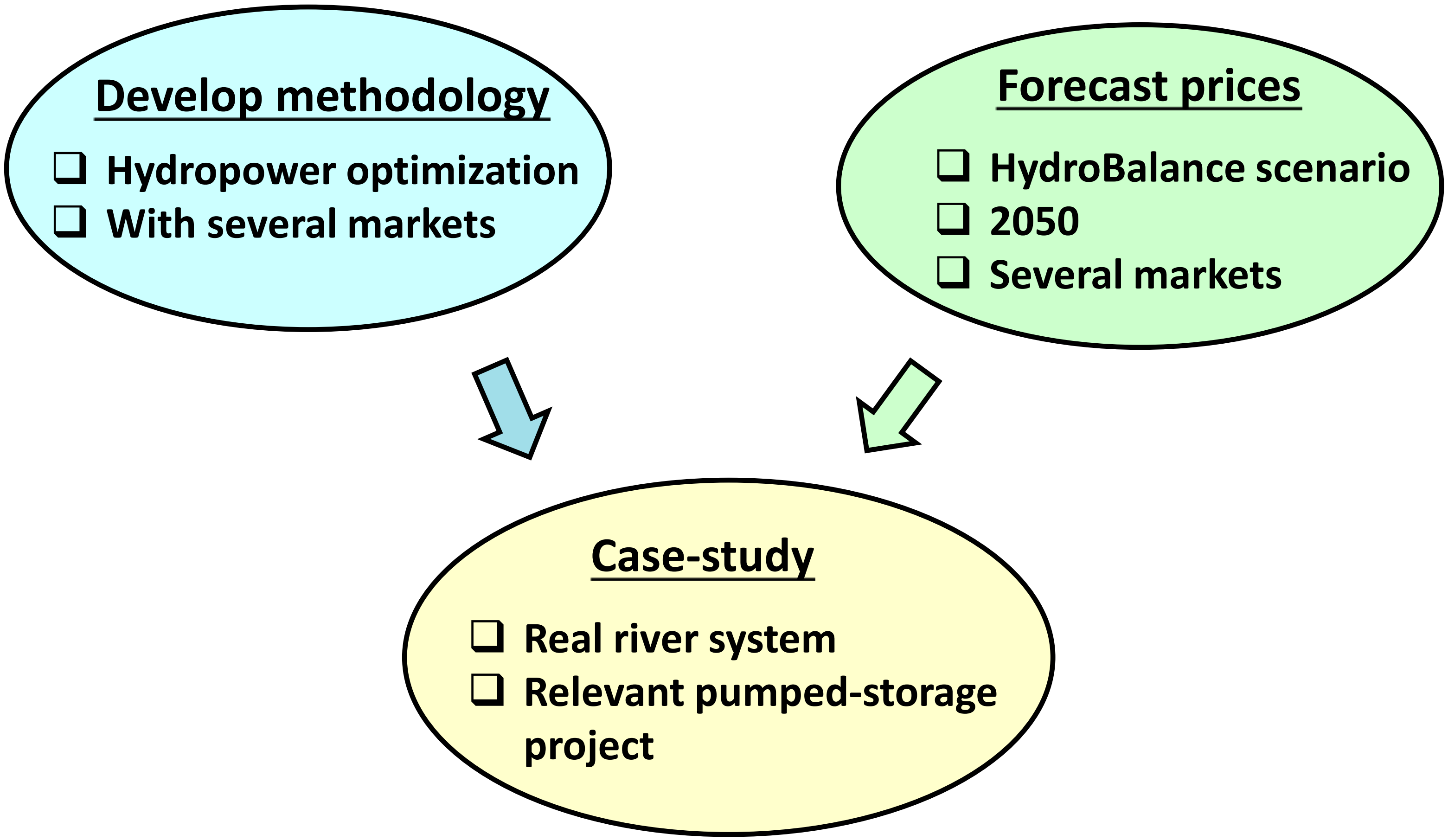
Implementation in ProdRisk

- So far we have included only two markets
  - Day-ahead
  - Activation of replacement reserves (e.g. 15 min response)

- ProdRisk production for a given hour: *f(p)*
  1. Optimize for day-ahead prices: $f(P^{\text{day-head}})$
  2. Optimize for price of reserves: $f(P^{\text{reserves}})$
  3. "upward" / "downward" regulation: $\Delta f = f(P^{\text{reserves}}) - f(P^{\text{day-ahead}})$
  4. Total income for hour: $P^{\text{day-head}} \cdot f(P^{\text{day-head}}) + P^{\text{reserves}} \cdot \Delta f$

- Water values and reservoir levels are calculated from actual operation: $f(P^{\text{day-ahead}}) + \Delta f$

General approach



IAEW study on future prices

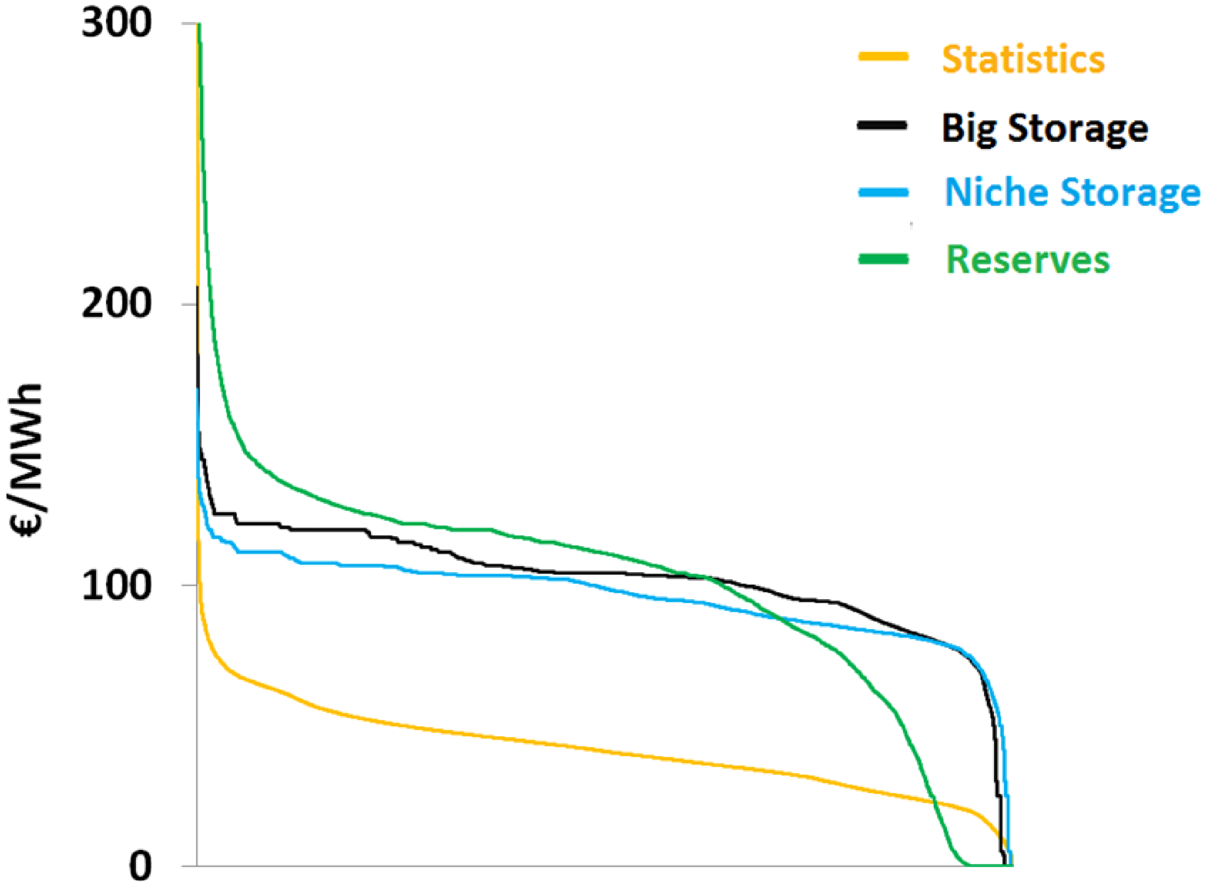
Forecast prices

- ❑ HydroBalance scenario
- ❑ 2050
- ❑ Several markets

- Quantification of HydroBalance scenario for 2050
  - Based on EU trend study, Eur. Commission (2013)
  - Adjustments include:
    - 20-30 GW new generation capacity in Norway
    - Sufficient increase in cable capacity

- Price simulation
  - Model concept: Schäfer et al. 2014
  - Day-ahead prices for European countries, weather years 2007-2011
  - Reserves (procurement and activation: FCR/FRR/RR), Germany, 2008

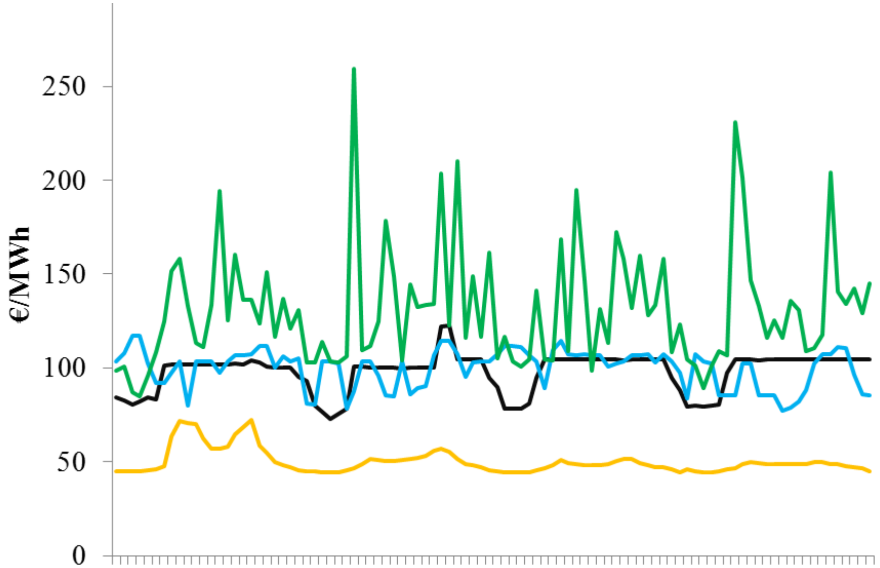
Prices: Duration curves



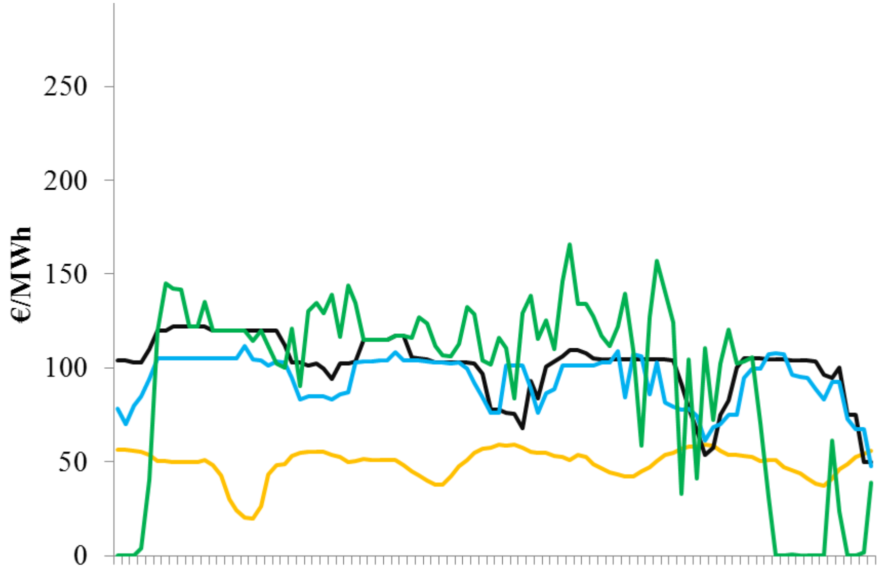
Example of within-week variability

Statistics
Big Storage
Niche Storage
Reserves

Winter



Summer



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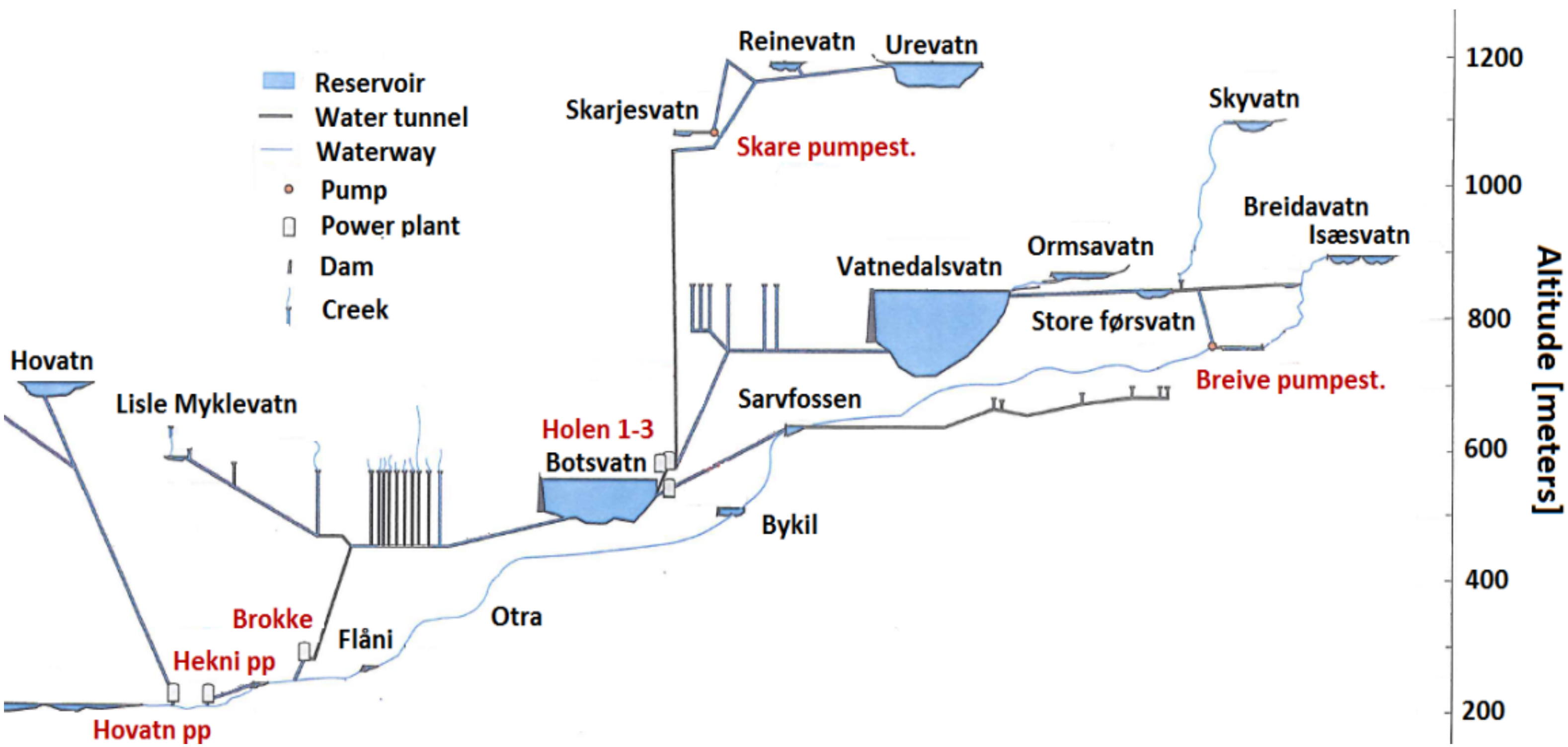
Otra river system

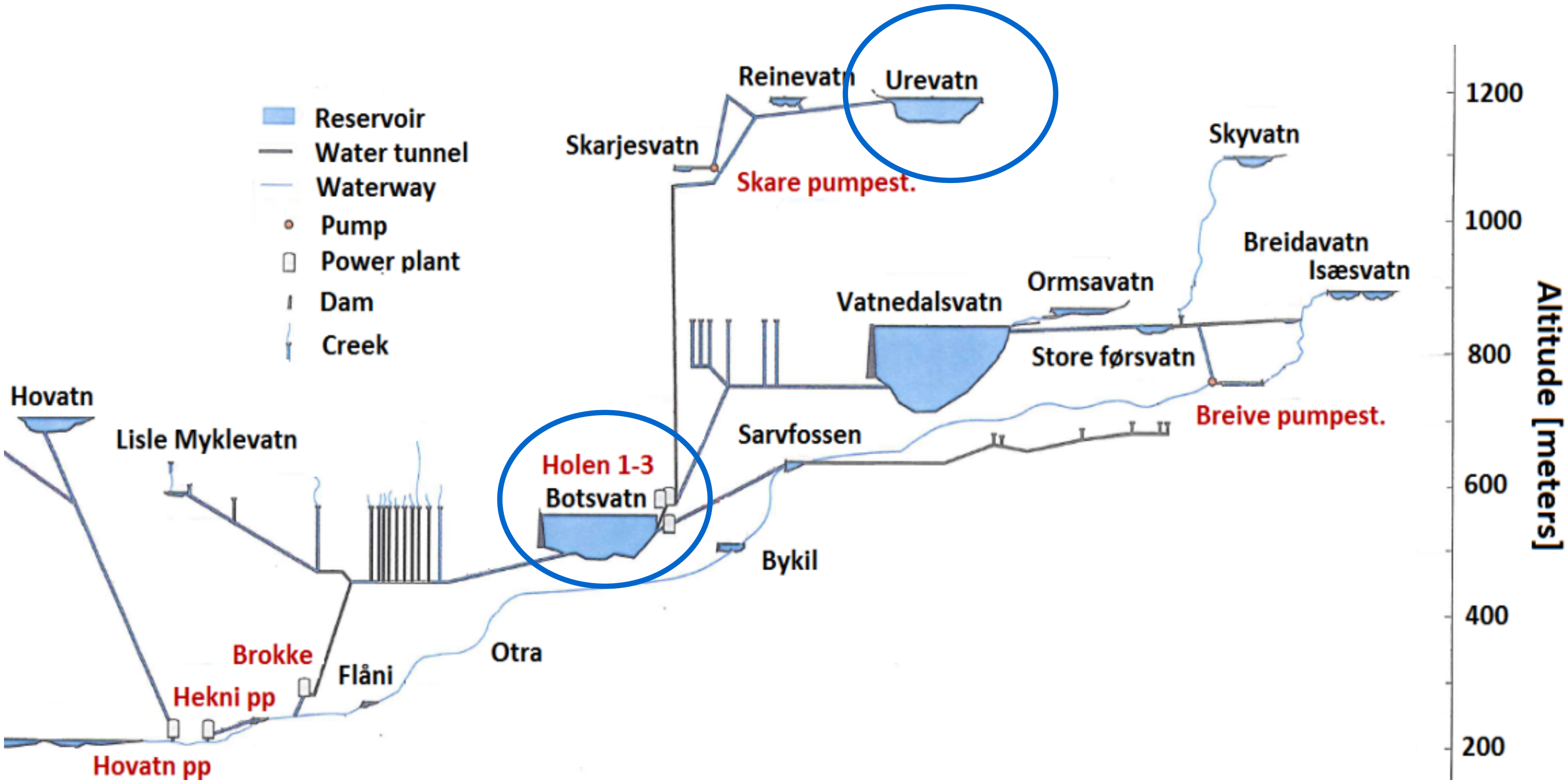
Case-study
- ❑ Real river system
- ❑ Relevant pumped-storage project

- Production capacity: 1.1 GW (14 plants)
- Storage capacity: 3.7 TWh (13 reservoirs)
- Annual production: 5 TWh
- ProdRisk input provided by Agder Energi

Otra river system - upper part



Pumped storage investment



- 1000 MW: extra generation capacity and pump
- Reservoirs: 15 days to empty/fill
- Total efficiency (pump x generation): 72.2 % (conservative, cf. Ibrahim 2007)
- Estimated total costs: 416 M € (Henden, 2014)

Scenario

- Statistics
- Big Storage
- Niche Storage
- Multi-market

Statistics, Big Storage, Niche Storage: Supply only for day-ahead market

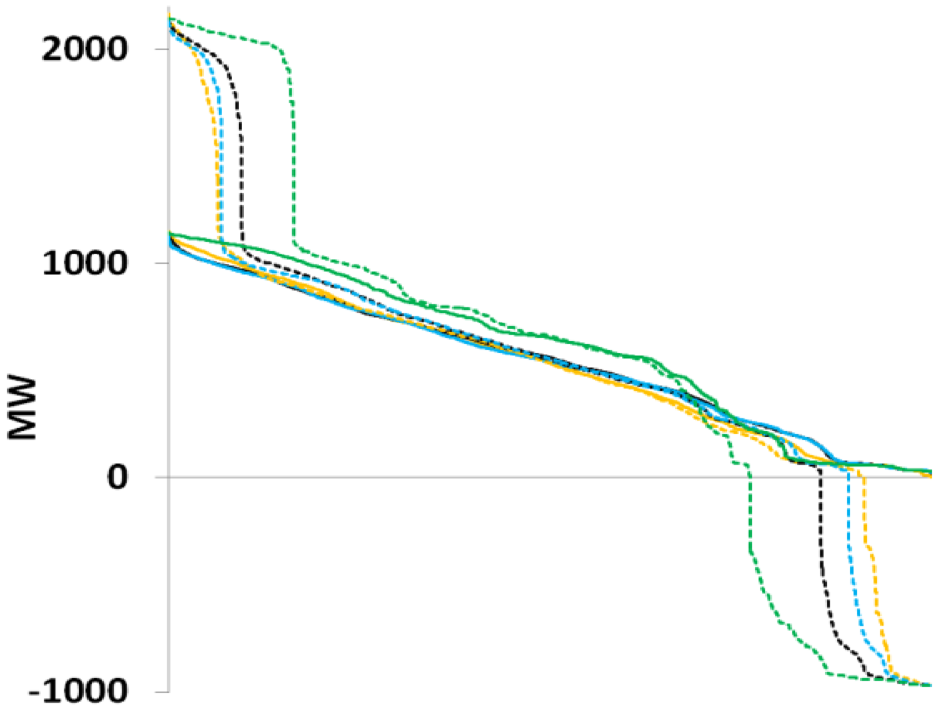
Multi-market: day-ahead + RR activation

➢ **All scenarios: With and without investment**

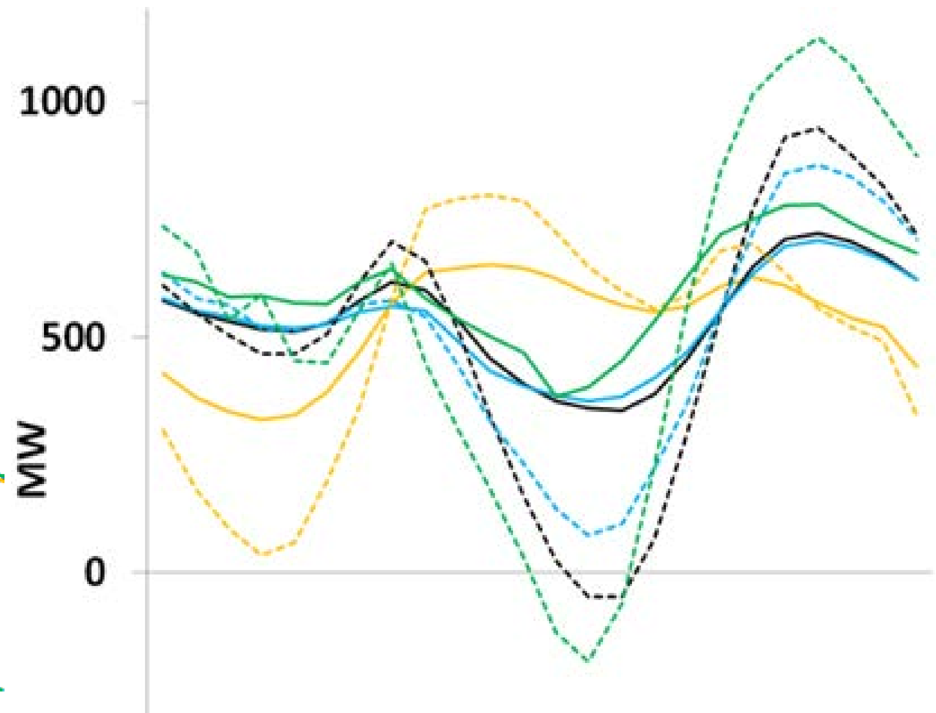
Results - Production

- Statistics
- Big Storage
- Niche Storage
- Multi-market

Duration curve

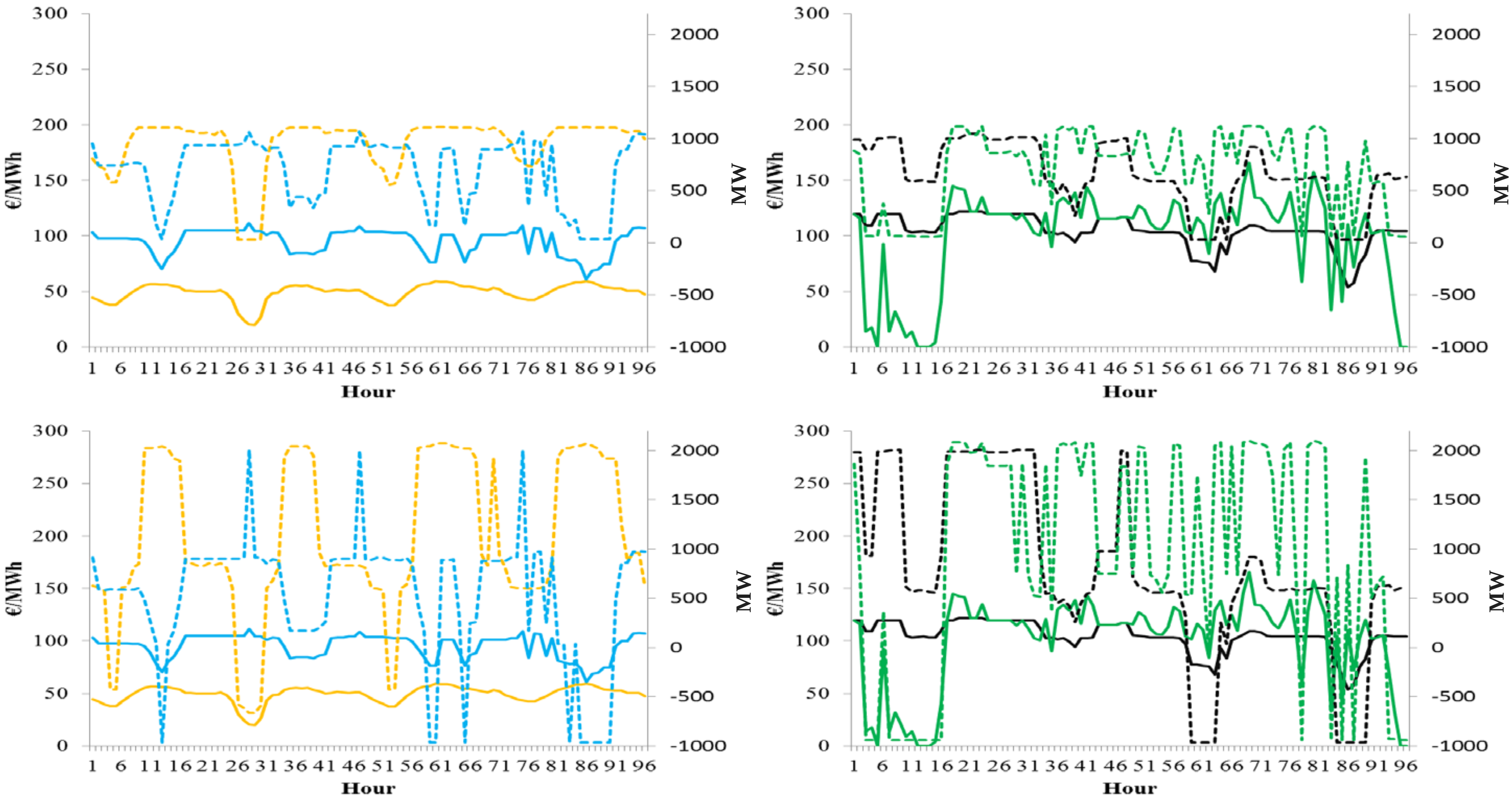


Average day



Continuous lines is existing production system
Dotted lines is with investment

Production and prices within a week

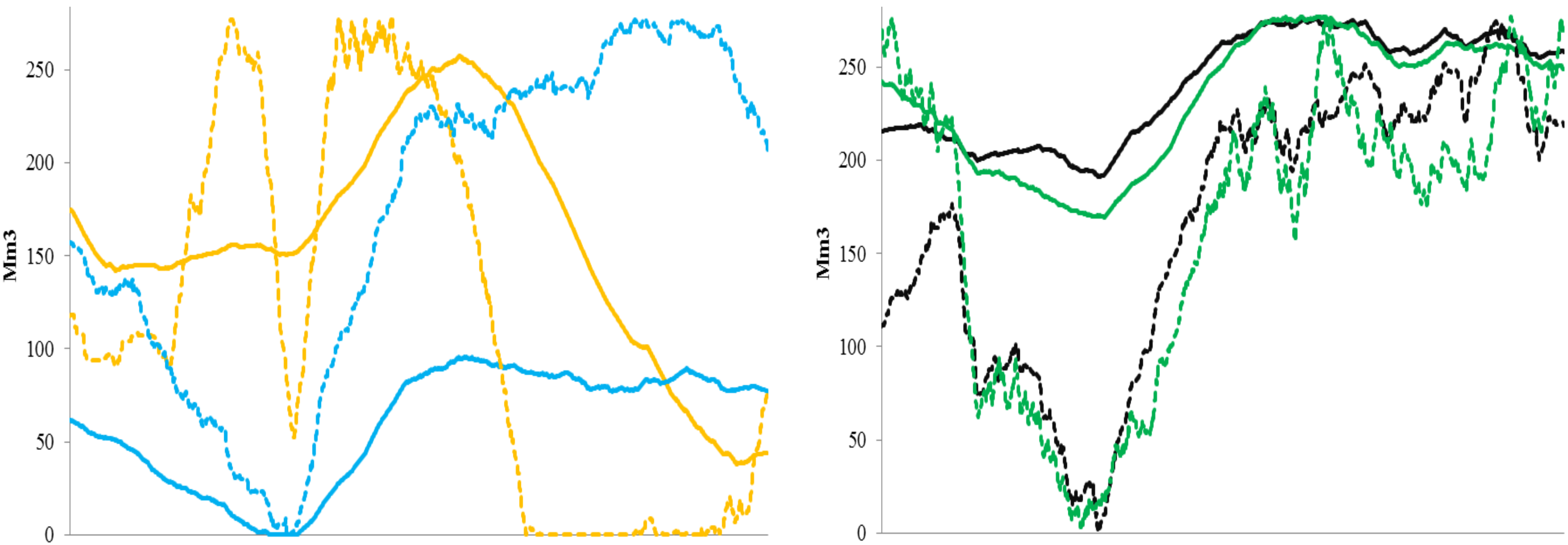


Continuous lines are prices
Dotted lines are productions

Figure at the top is existing production system
Figure at the bottom is with investment in 1000 MW PSP

Results – Reservoir level

- Upper reservoir, Reinevatn/Urevatn
- 2008



Continuous lines are existing production system
Dotted lines are with investment

Economic results (in M € per year)

	Day-ahead only (Climate years 2007-2011)			German prices (Climate year 2008)	
	Statistics	Niche Storage	Big Storage	DA only	Multi-market
Average yearly income	205	474	517	654	669
Additional operating profits	9	23	30	133	161
Investment cost *)	-24	-24	-24	-24	-24
Investment profits *)	-15	-2	5	109	137
Break even interest rate	-0,5 %	4,5 %	6,6 %	31,1 %	38,8%

*) With 5 % annual interest rate

Summery of results

- Variability in operation
  - Increased with pumped storage (short term and during a year)
  - Highest for multi-market strategy
  - Traditional day/night trend is changed because of solar radiation
- Income
  - Future scenarios gives 2-3 times higher total income
  - Multi-market strategy gives about 2% extra income
- Payback for investment in pumped storage
  - Negative profits for historical prices
  - About break-even for day-ahead strategy at future prices
  - Multi-market strategy: Income from investment increase by 21%

Conclusions

- Multi-market
  - Methodology is performing as intended
  - Evaluated strategy is not 100% optimal but reasonable / pragmatic
  - Next: Include reserve power (MW), and possibly intra-day
- Price-level is important for total income
- Price-variability (and therefore market participation) is important for profitability of pumped-storage investment
- Based on our study, environmental impacts in reservoirs will be studied further in HydroBalance

References

- Cf. full paper