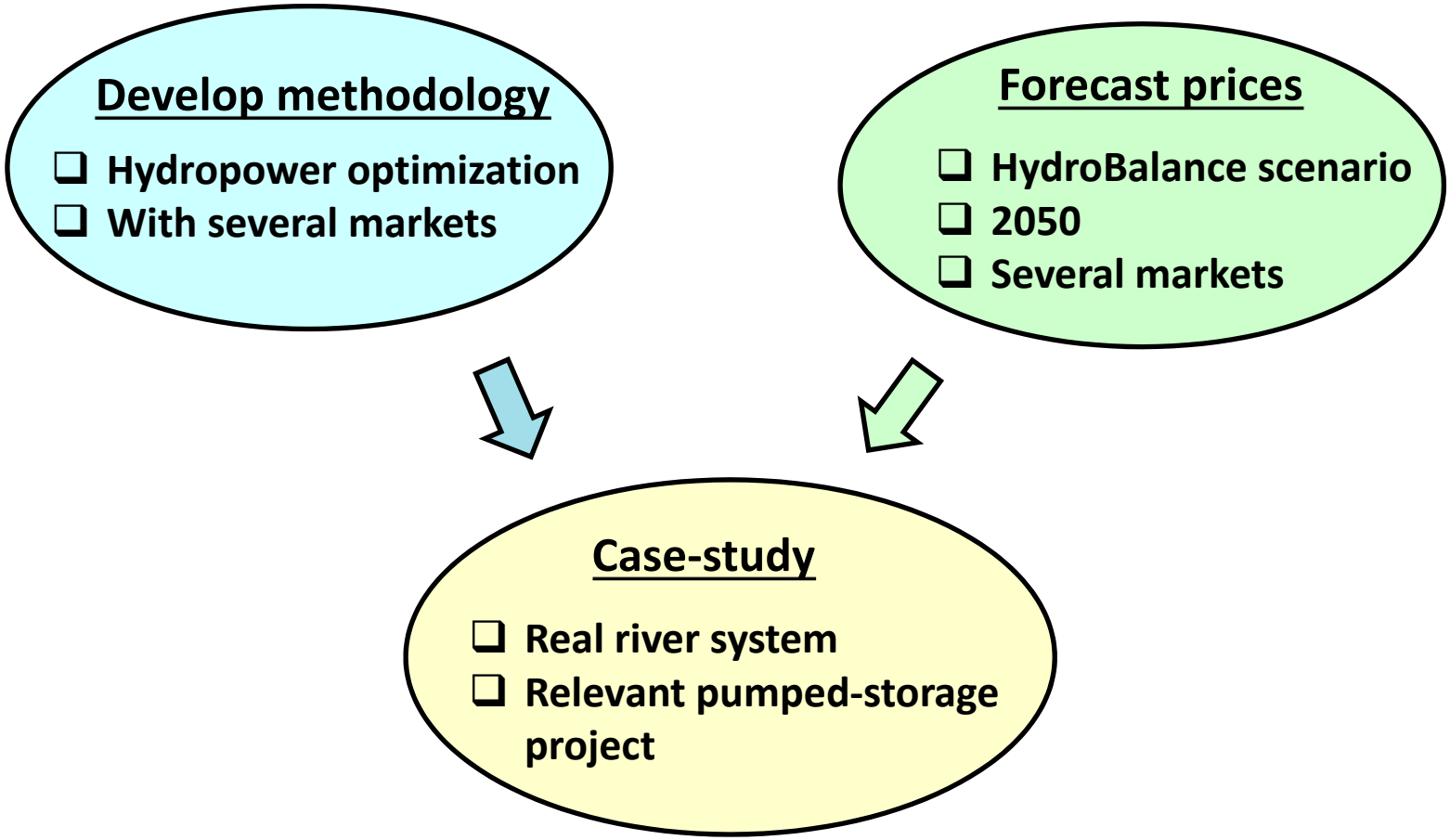
Central research questions in WP3

1. How will hydropower be operated in the future?

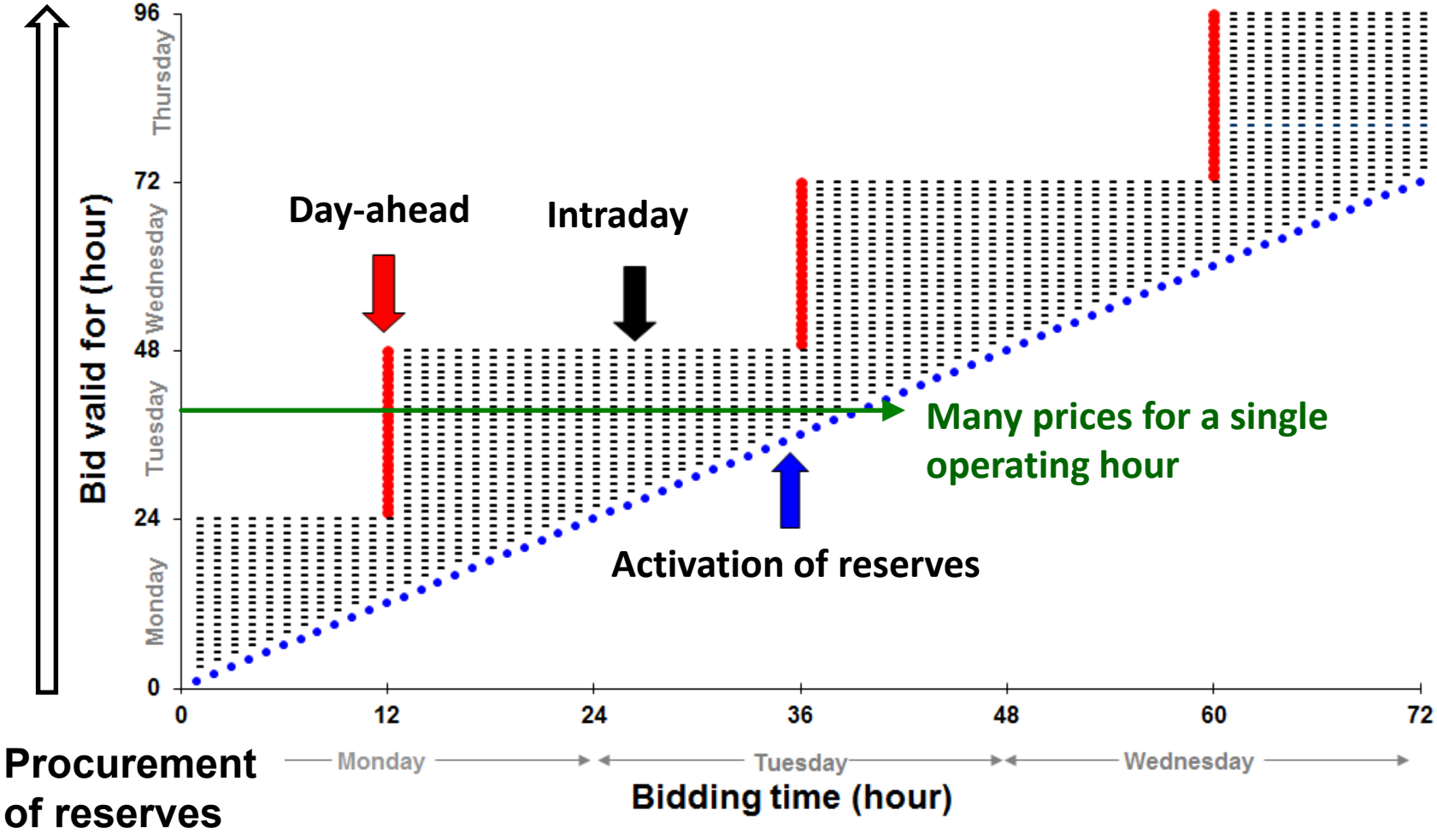
2. How large share of the income will come from different markets?

3. Will investments in new pumped storage be profitable in Norway?

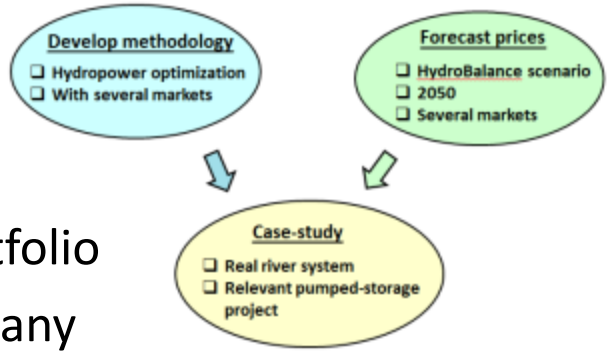
General approach



Market types



International cooperation for calculation of prices within HydroBalance



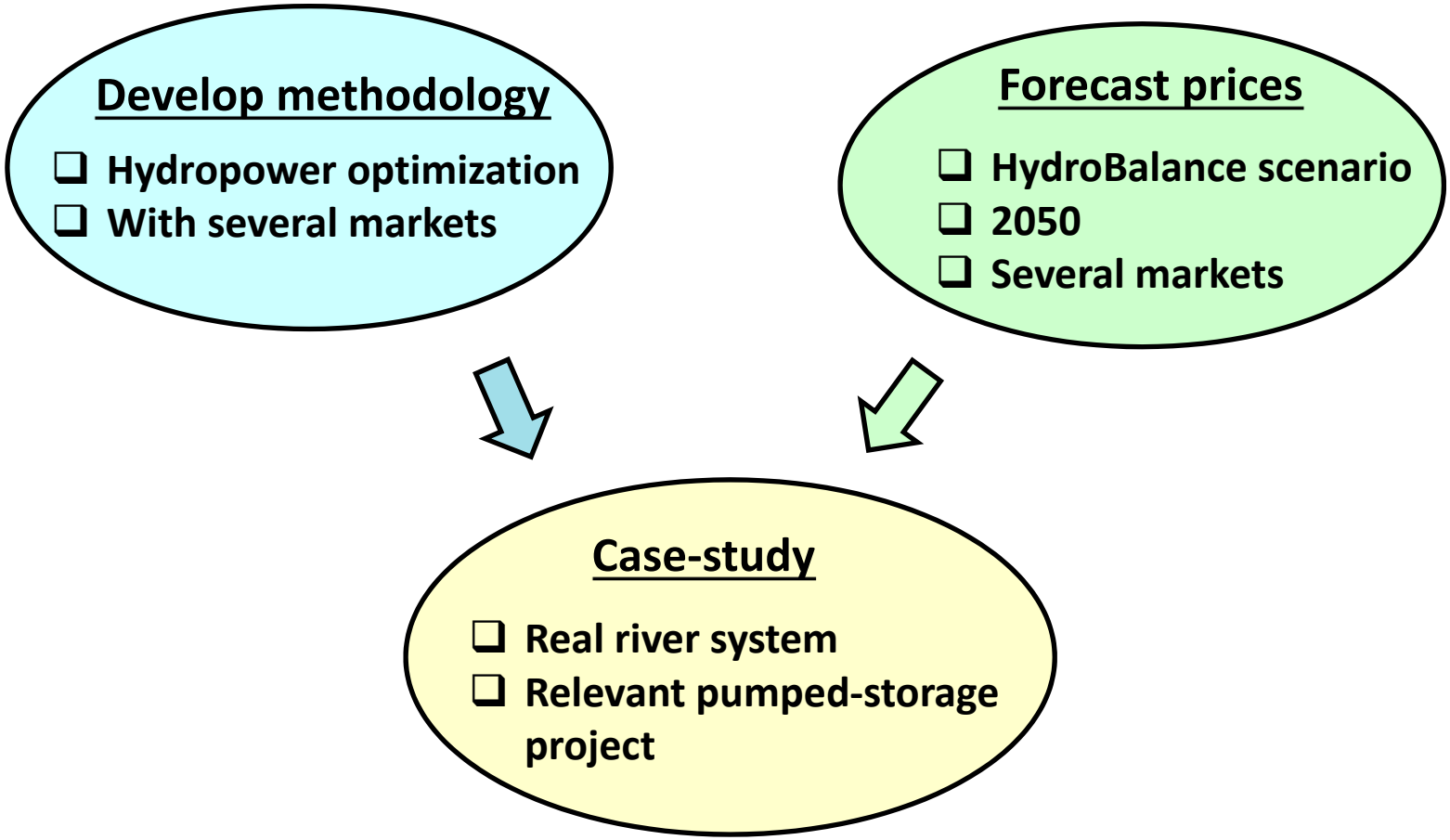
- IAEW study for E.ON. / HydroBalance
  - Value of Norwegian hydropower in a German portfolio
  - European price-simulation; more details for Germany
  - Several project-meetings and workshop
  - Forthcoming report
- ECN
  - European price-simulation, with details for Netherlands
  - Ongoing

Results from WP3

Profitability for pumped storage in Otra river system for HydroBalance scenario

Hydrobalance user meeting 2015

General approach

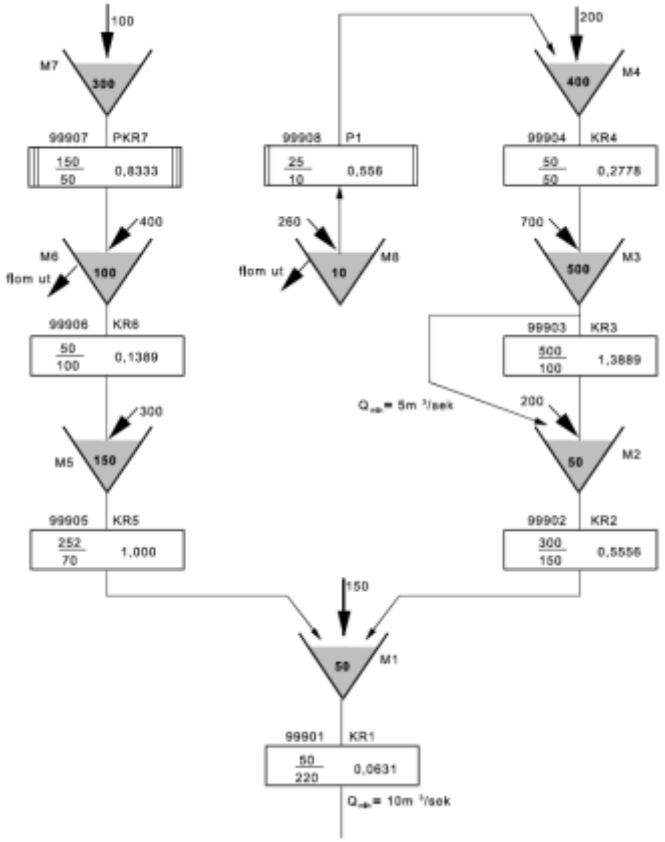


Develop methodology

- ❑ Hydropower optimization
- ❑ With several markets

Applied model: ProdRisk

- One of SINTEF's optimization tools for hydropower
  - Local producer / river system
  - 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

- 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)

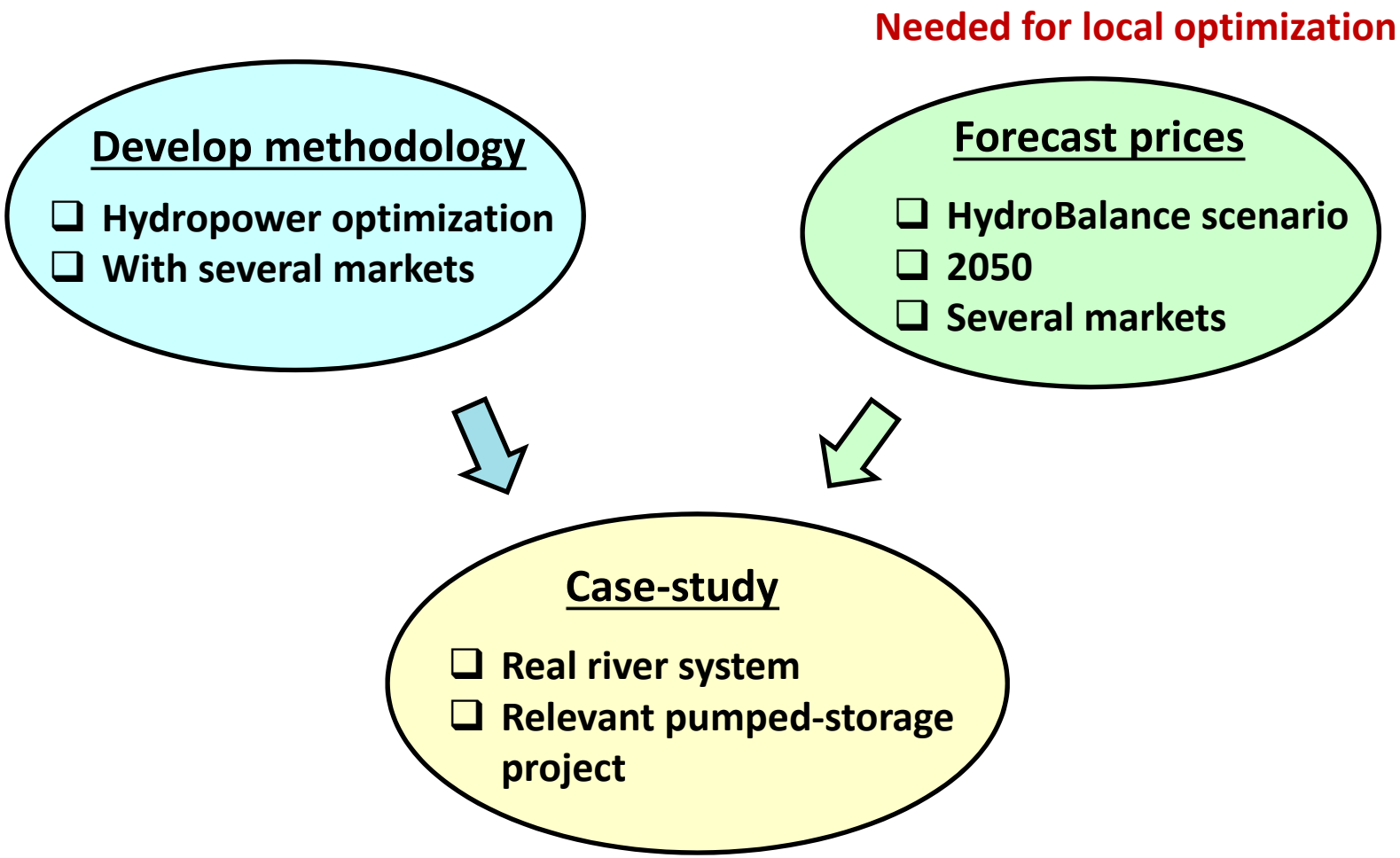
Implementation in ProdRisk

- Only two markets implemented so far
  - Day-ahead
  - Activation of replacement reserves (e.g. 15 min response)

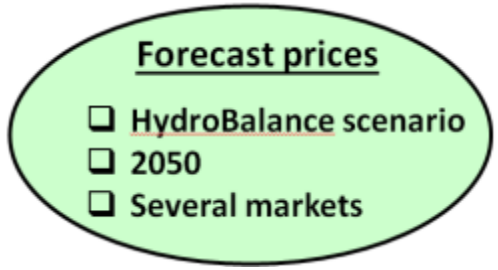
- ProdRisk production for a given hour: *f(p)*
  1. Optimize for day-ahead prices: $f(P^{\text{day-head}})$
  2. Optimize for price of reserves: $f(P^{\text{reserves}})$
  3. "upward" / "downward" regulation: $\Delta f = f(P^{\text{reserves}}) - f(P^{\text{day-ahead}})$
  4. Total income for hour: $P^{\text{day-head}}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

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

General approach



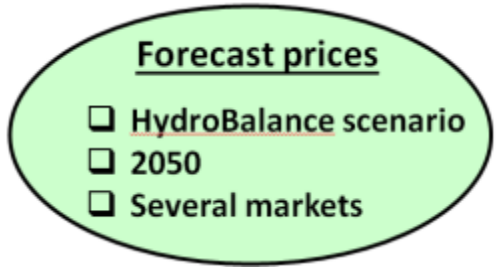
HydroBalance scenario



- Extra hydropower capacity in Norway
  - Technical potential to develop 20 GW has been identified
  - TR A7195 (Solvang et al., 2012)

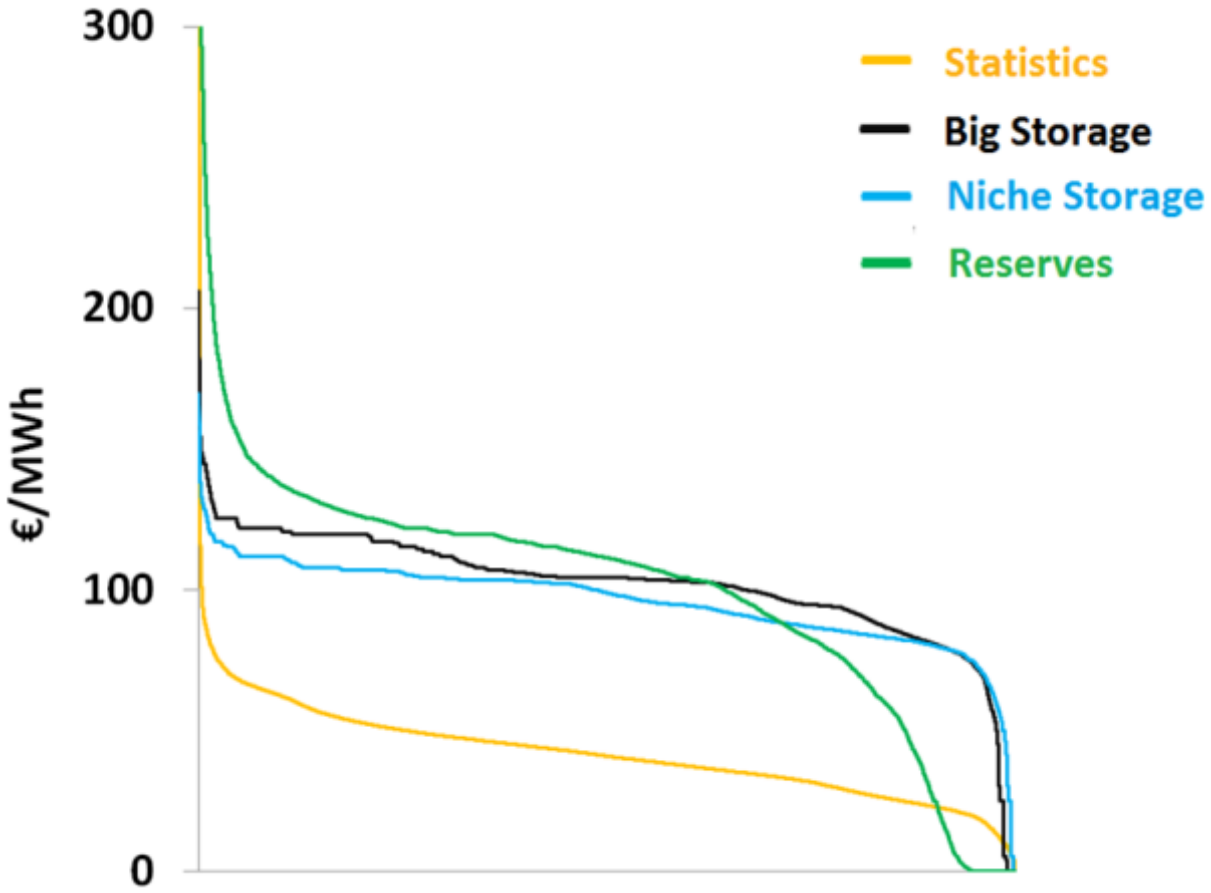
- Process with involvement of users in HydroBalance
  - {Futures, strategies}: 4 scenario
  - TR A7433 (Sauterleute et al., 2015)

Price-scenario and strategies

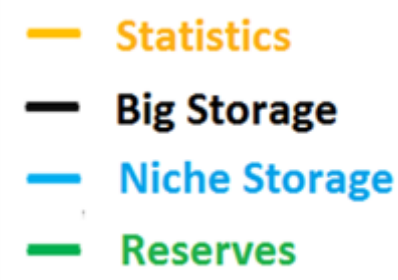


- Future prices calculated by IAEW
- Day-ahead prices for Norway (2007-2011)
  - **Big Storage** full market integration in Europe, + 30 GW, …
  - **Niche Storage** integration only for day-ahead market, +20 GW, …
  - **Statistics** Nord Pool system price
- Several markets from detailed study for Germany (2008)
  - One market (full integration in Big Storage, and cable capacity)
  - **Multi-market** Day-ahead + activation of replacement reserves (RR)

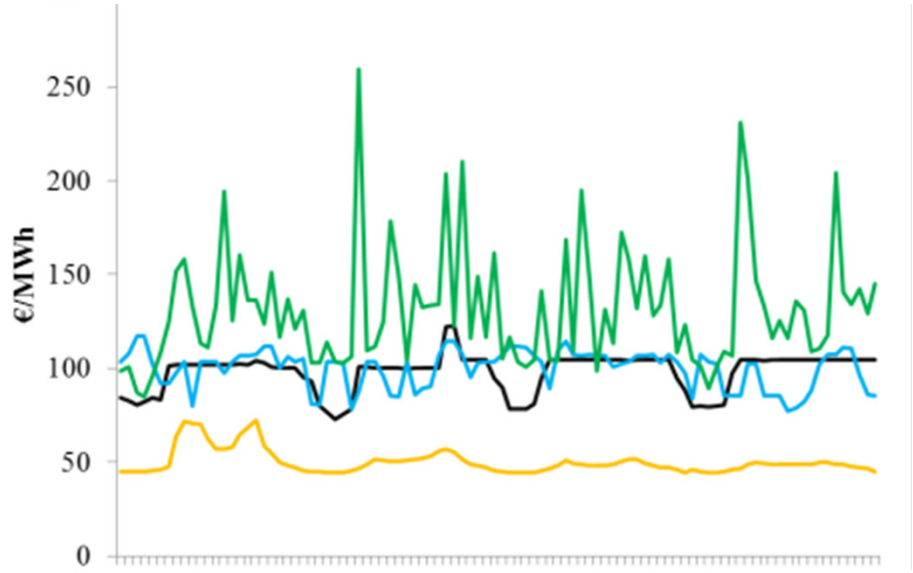
Prices: Duration curves



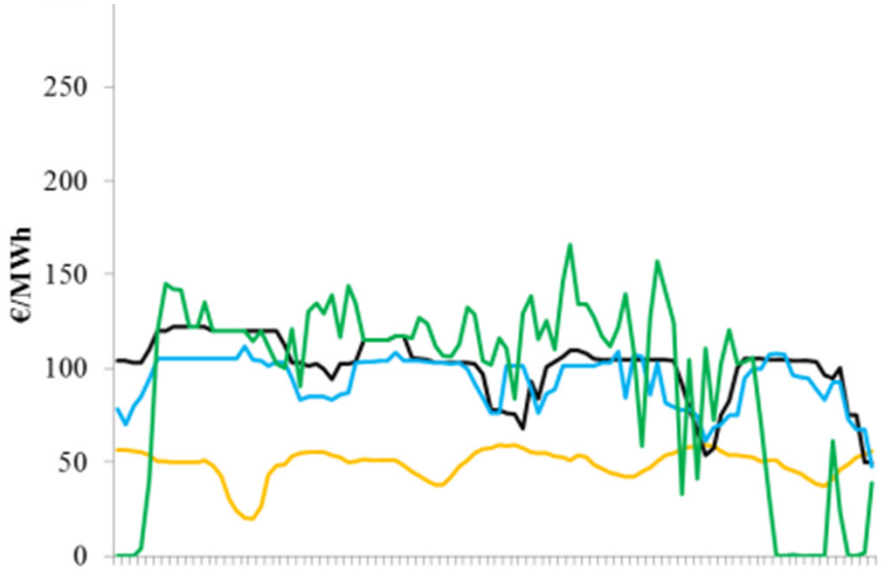
Example of within-week variability



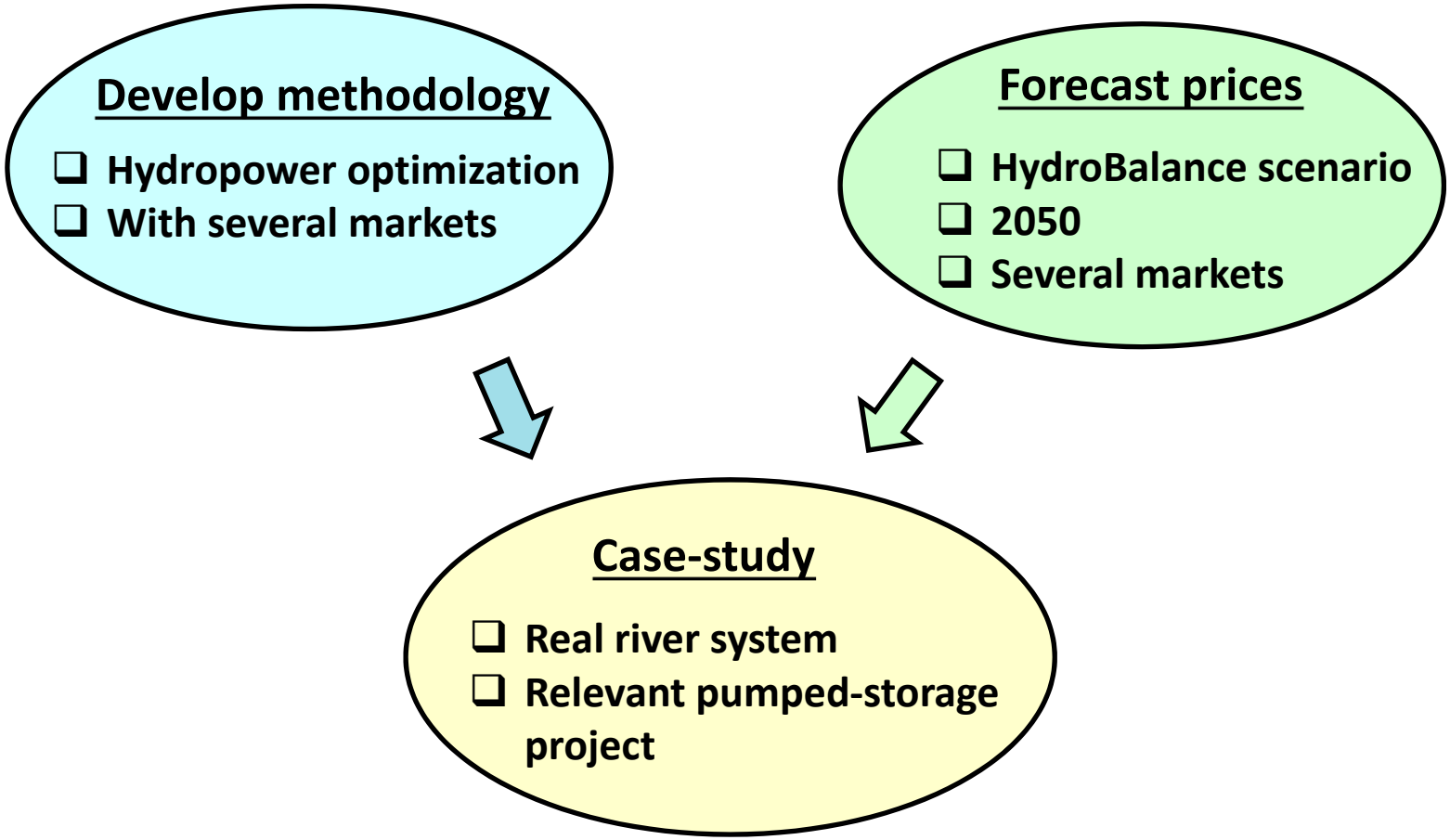
Winter



Summer



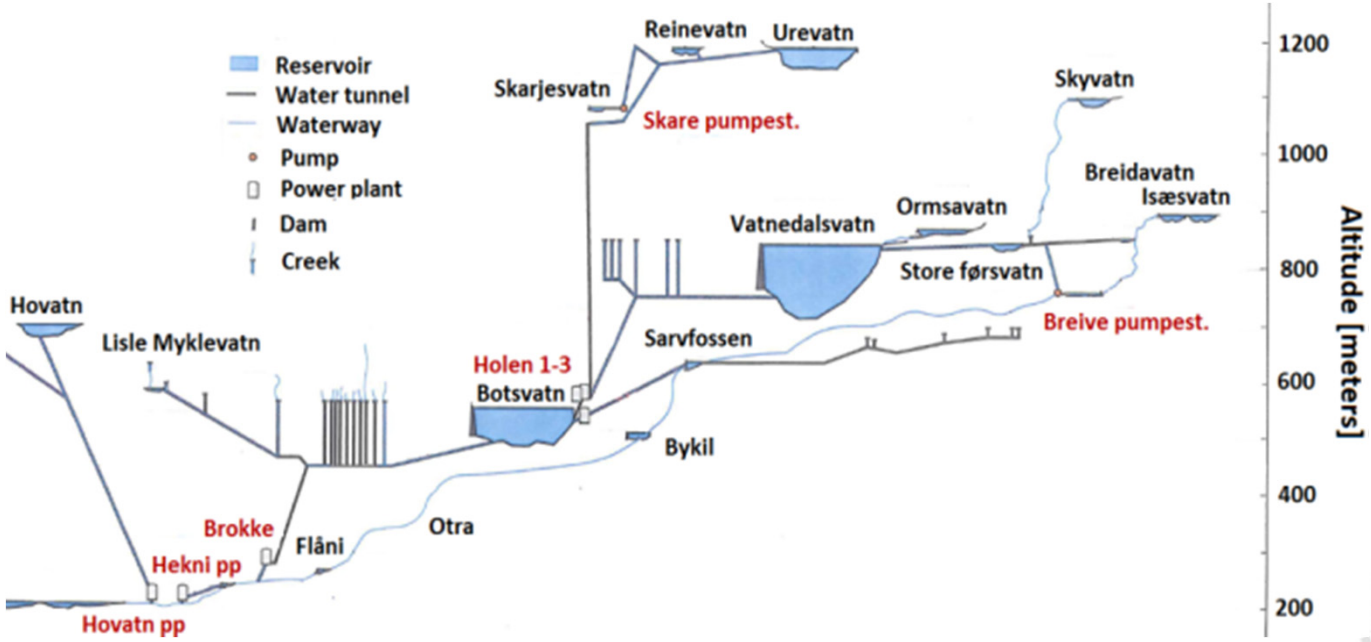
General approach



Otra river system (upper part)

Case-study

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



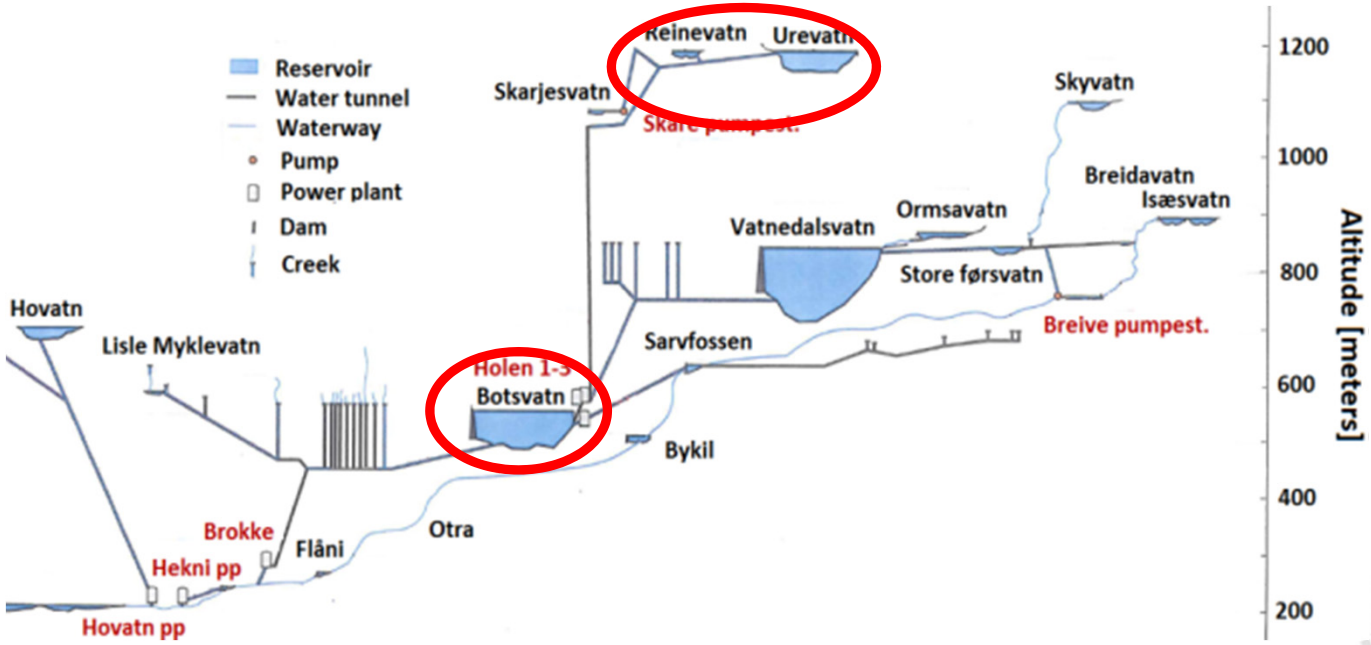
- 1 122 MW production capacity – 14 plants
- 36 MW pumped capacity – 2 pumps
- 3.75 TWh storage capacity – 13 reservoirs
- 5 TWh average annual production

- Complex river system

Otra river system - Investment

Case-study

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

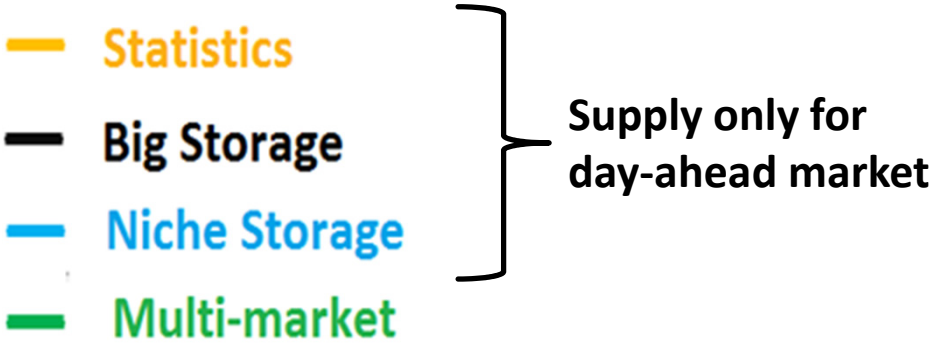


- Exist 165 MW production capacity
- 1000 MW
- 15 days to fill or empty
- 72.25 % total efficiency
- Cost 416 M€
  - 24 M€/year (lifetime 40 years, 5% discount rate)

Results

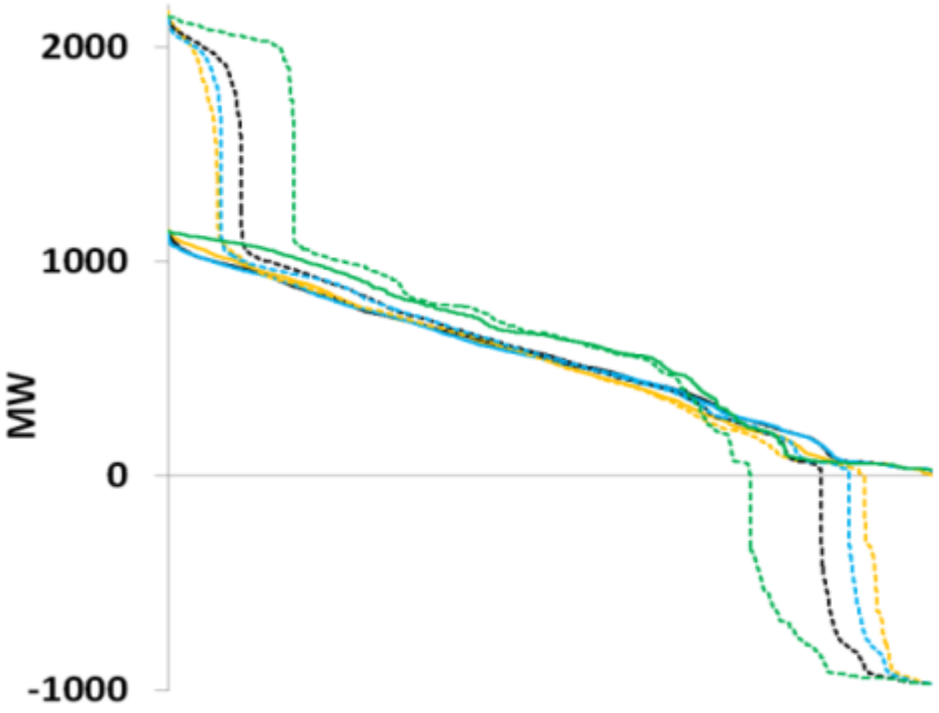
- Production
- Reservoir level
- Economic

- With and without pumped storage plant
- Results for 4 scenario:

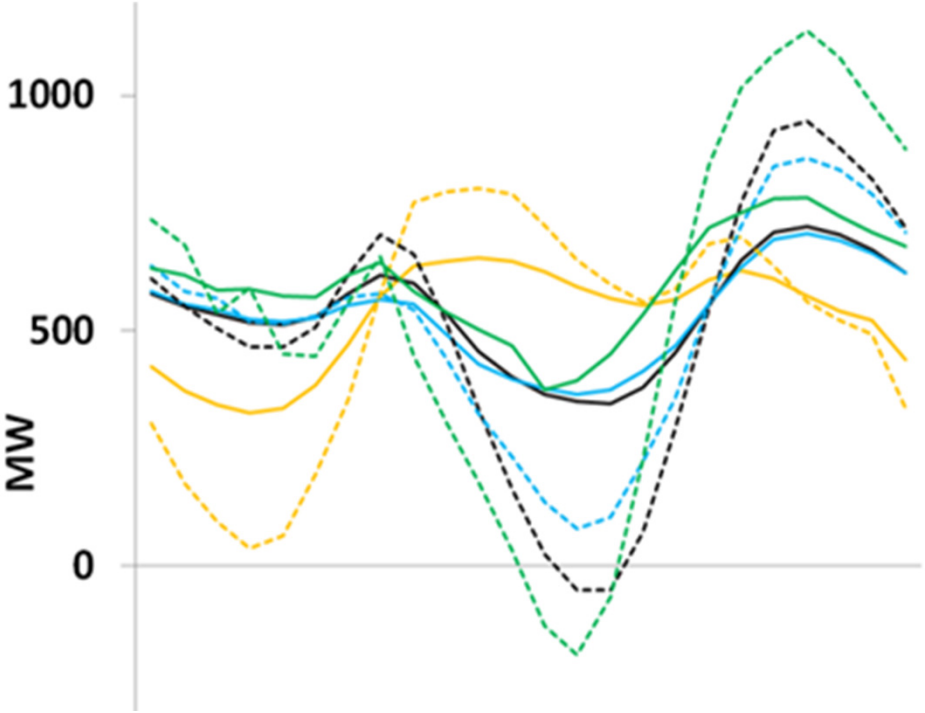


Results - Productions

Duration curve



Average day

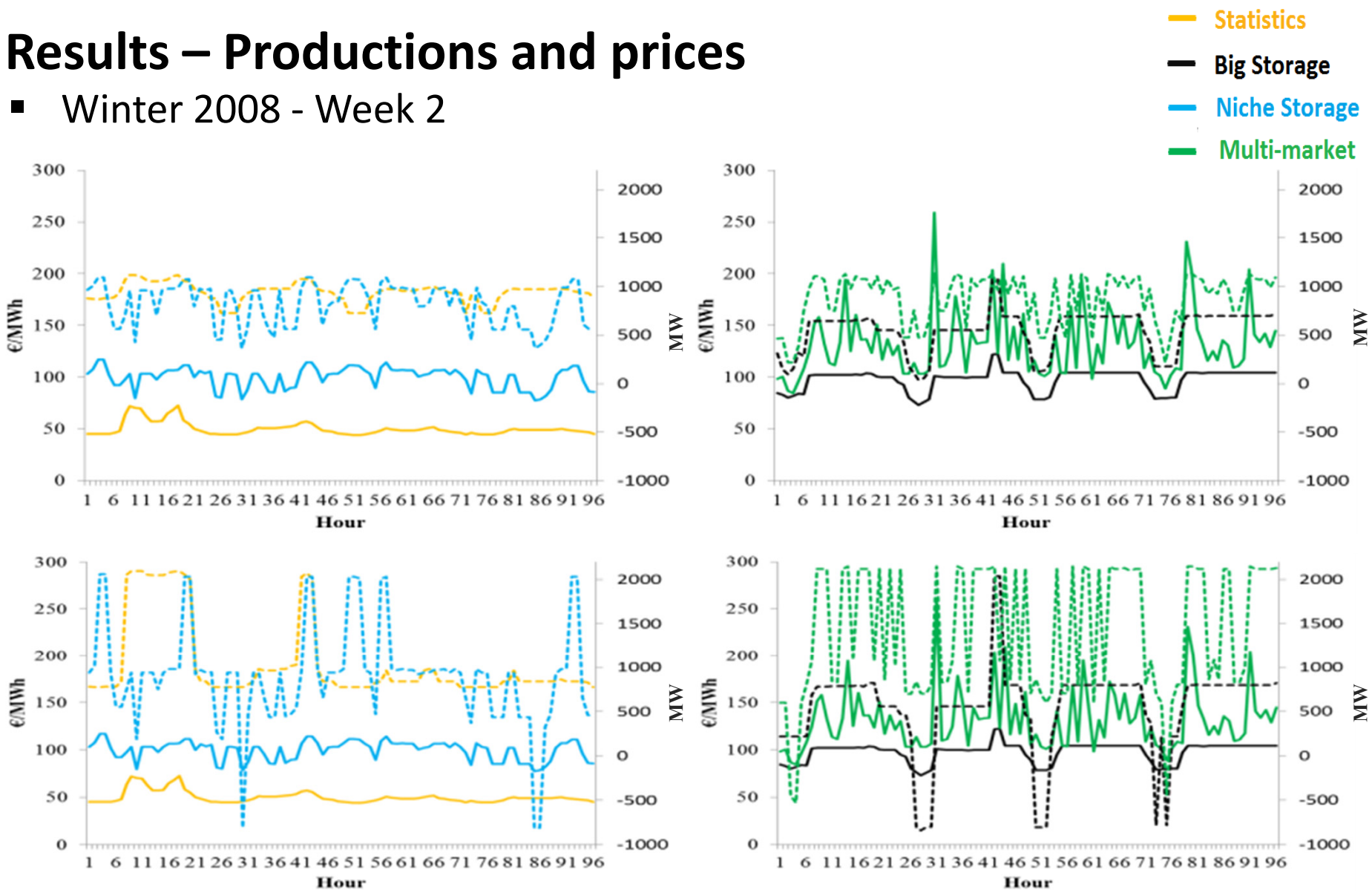


Statistics
Big Storage
Niche Storage
Multi-market

Continuous lines is existing production system
Dotted lines is with investment

Results – Productions and prices

- Winter 2008 - Week 2

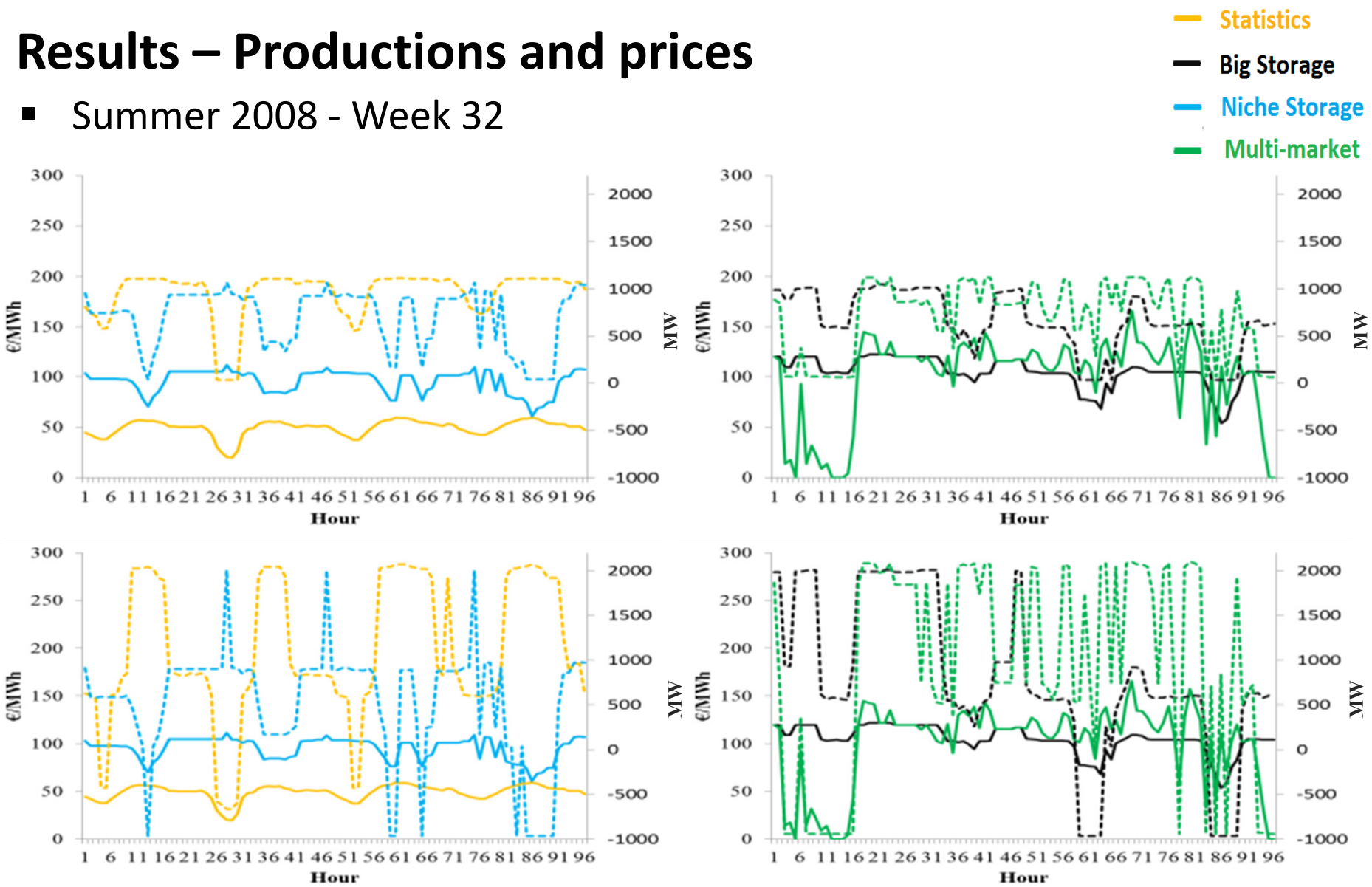


Continuous lines are prices
Dotted lines are productions

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

Results – Productions and prices

- Summer 2008 - Week 32

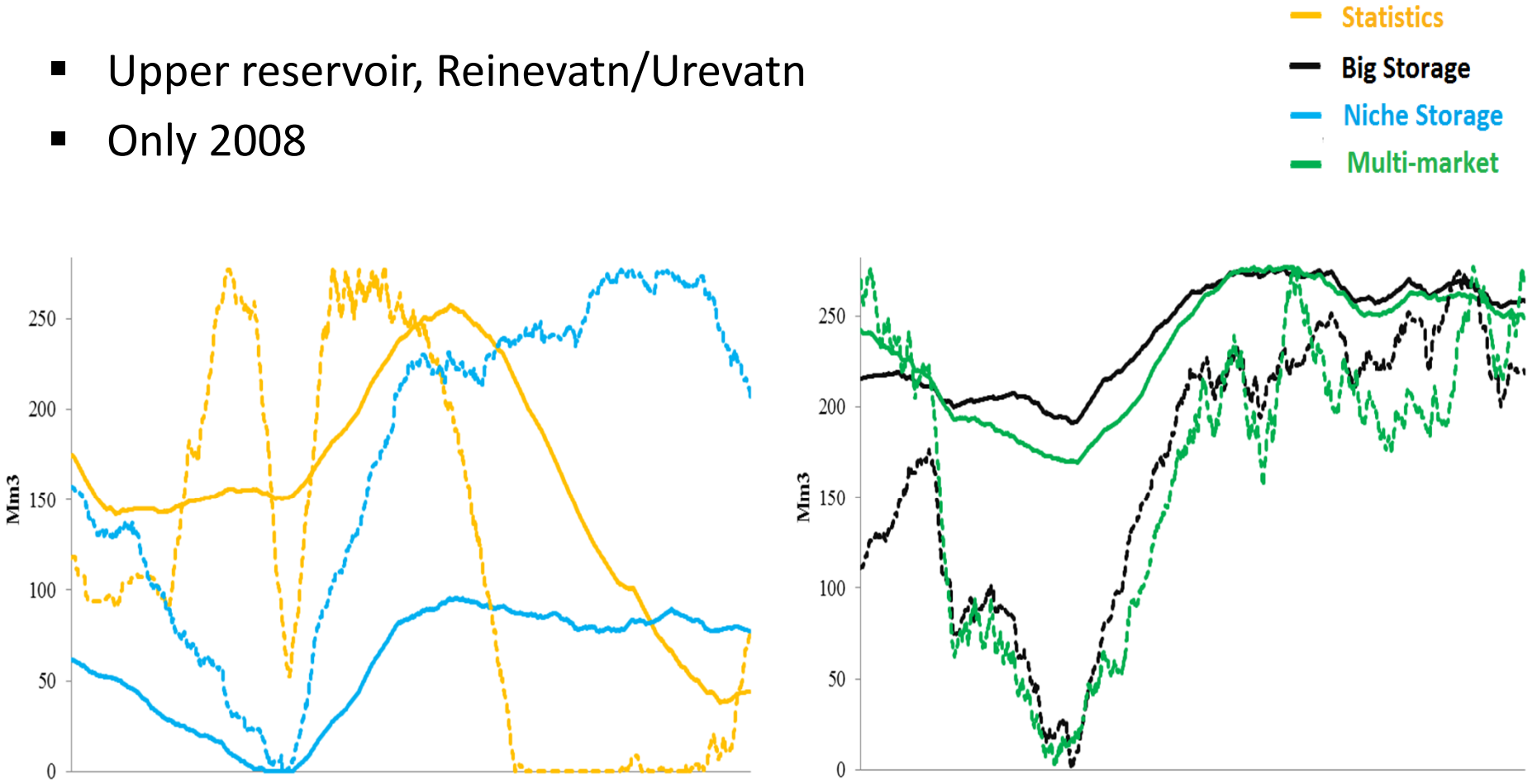


Continuous lines are prices
Dotted lines are productions

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
- Only 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
- Finalized internal deliverable: reservoirs variability

Some references

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A. Gjelsvik, B. Mo and A. Haugstad, "Long- and medium-term operations planning and stochastic modelling in hydro-dominated power systems based on stochastic dual dynamic programming," in *Handbook of Power Systems I*, Heidelberg, Springer-Verlag Berlin Heidelberg, 2010.

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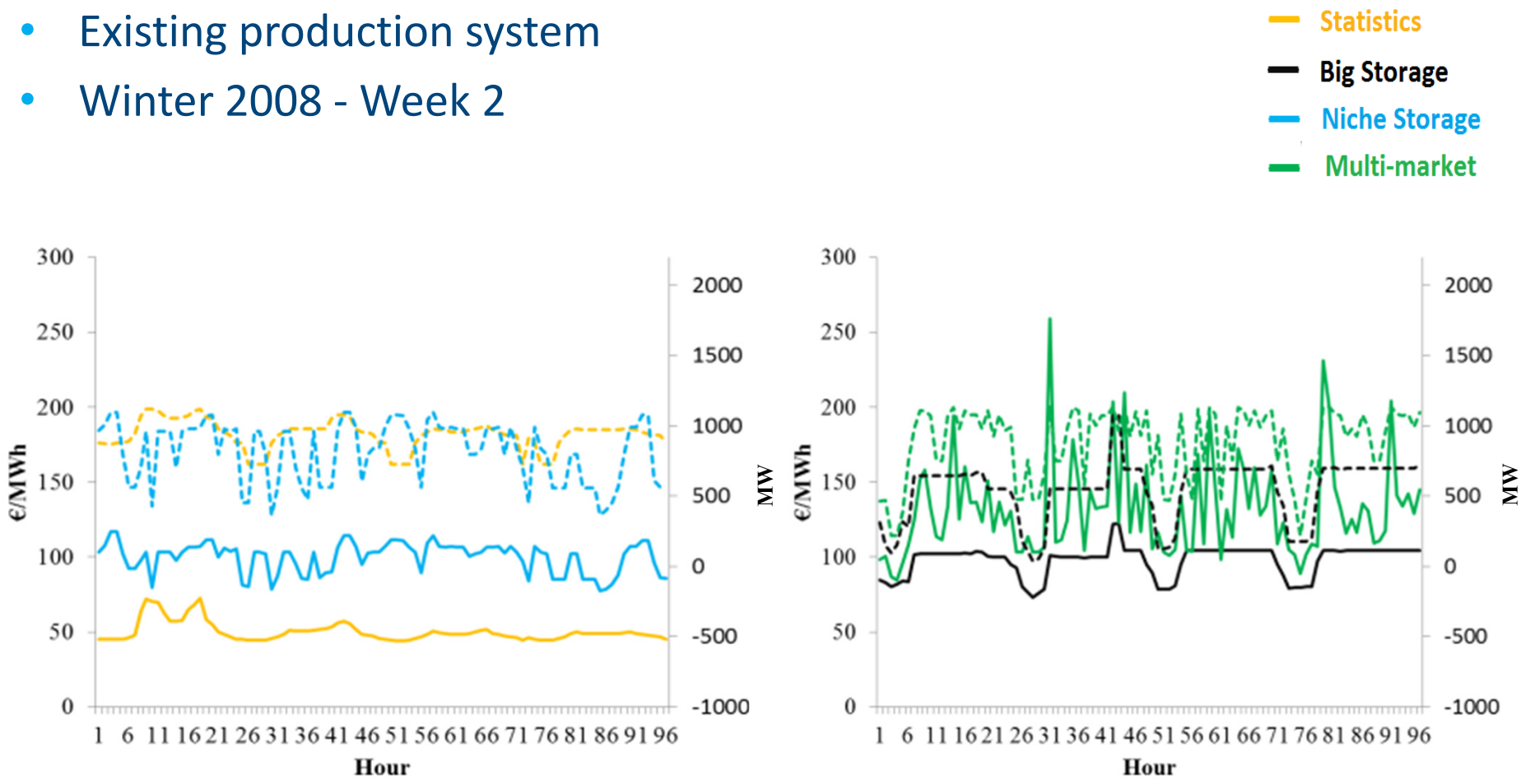
RWTH Aachen University, IAEW "Value of large-scale balancing and storing from Norwegian hydropower for the German power system and generation portfolios", forthcoming.

O. Wolfgang, A. L. Henden, M. M. Belsnes, C. Baumann, A. Maaz, A. Schäfer, A. Moser, M. Harasta and T. Døble (2015), "Scheduling when reservoirs are batteries for wind- and solar-power", will be presented at 5th Int. Workshop on Hydro Scheduling in Competitive Electricity Markets

Results – Productions and prices

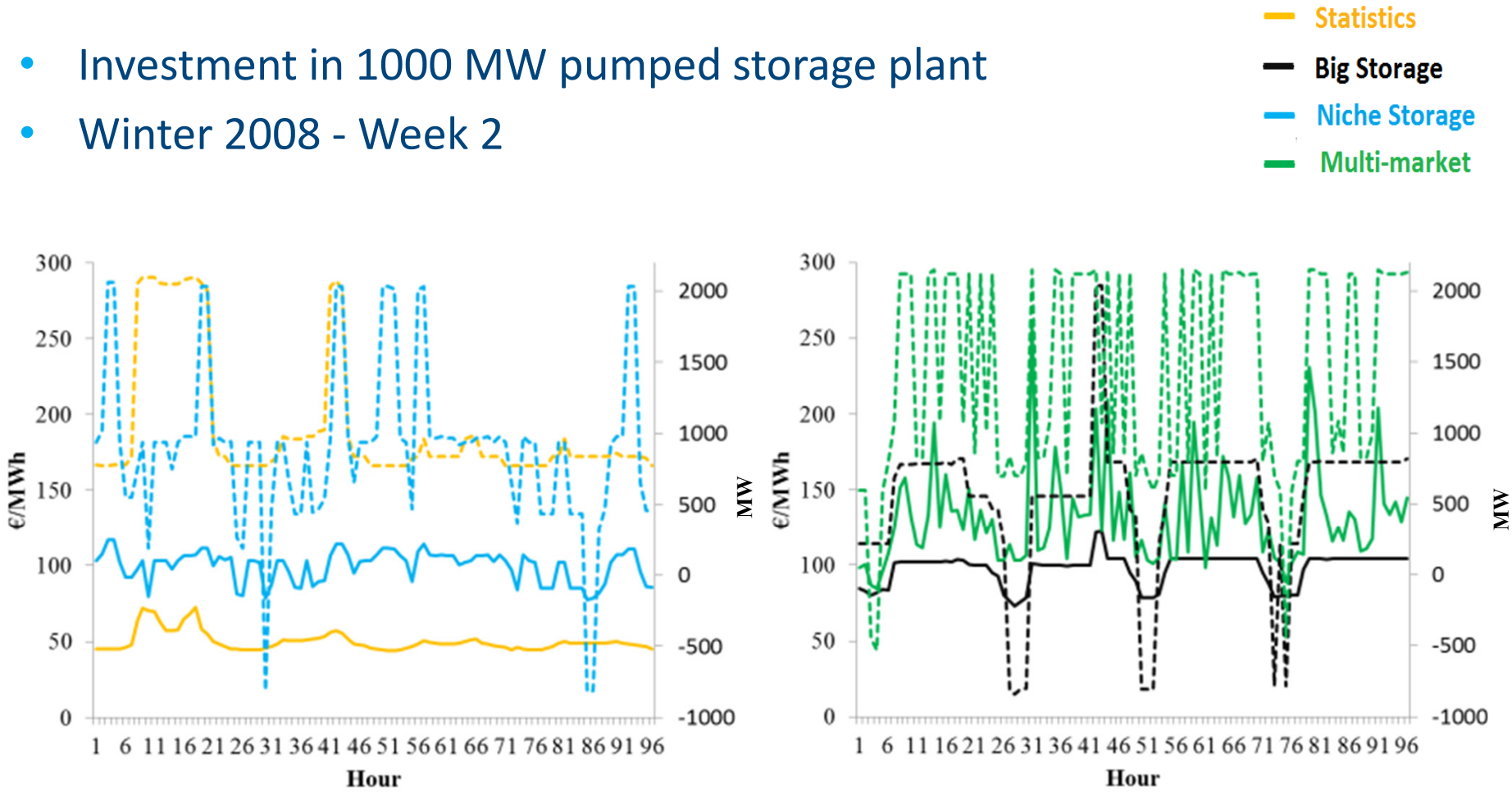
- Existing production system
- Winter 2008 - Week 2



Continuous lines are prices
Dotted lines are productions

Results – Productions and prices

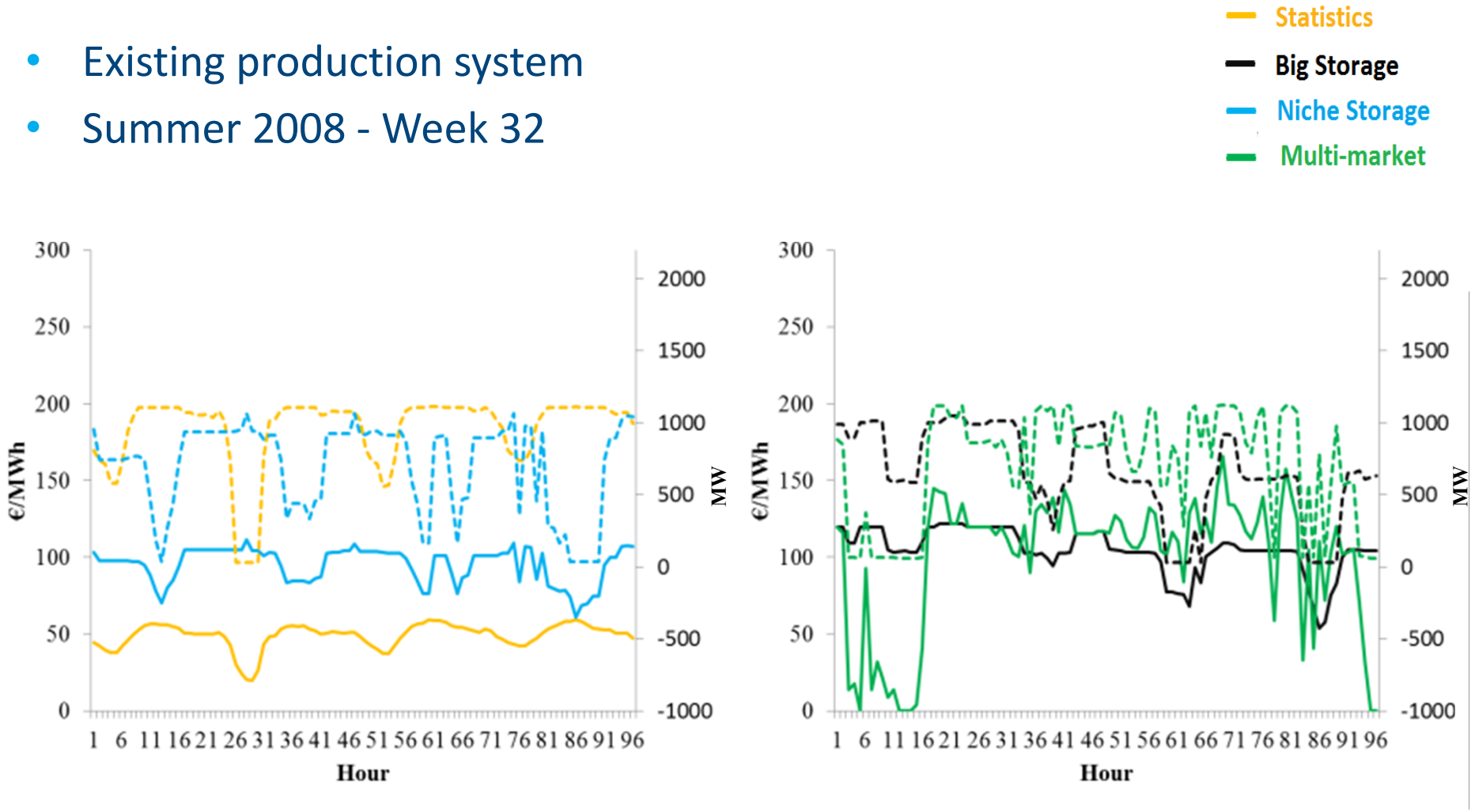
- Investment in 1000 MW pumped storage plant
- Winter 2008 - Week 2



Continuous lines are prices
Dotted lines are productions

Results – Productions and prices

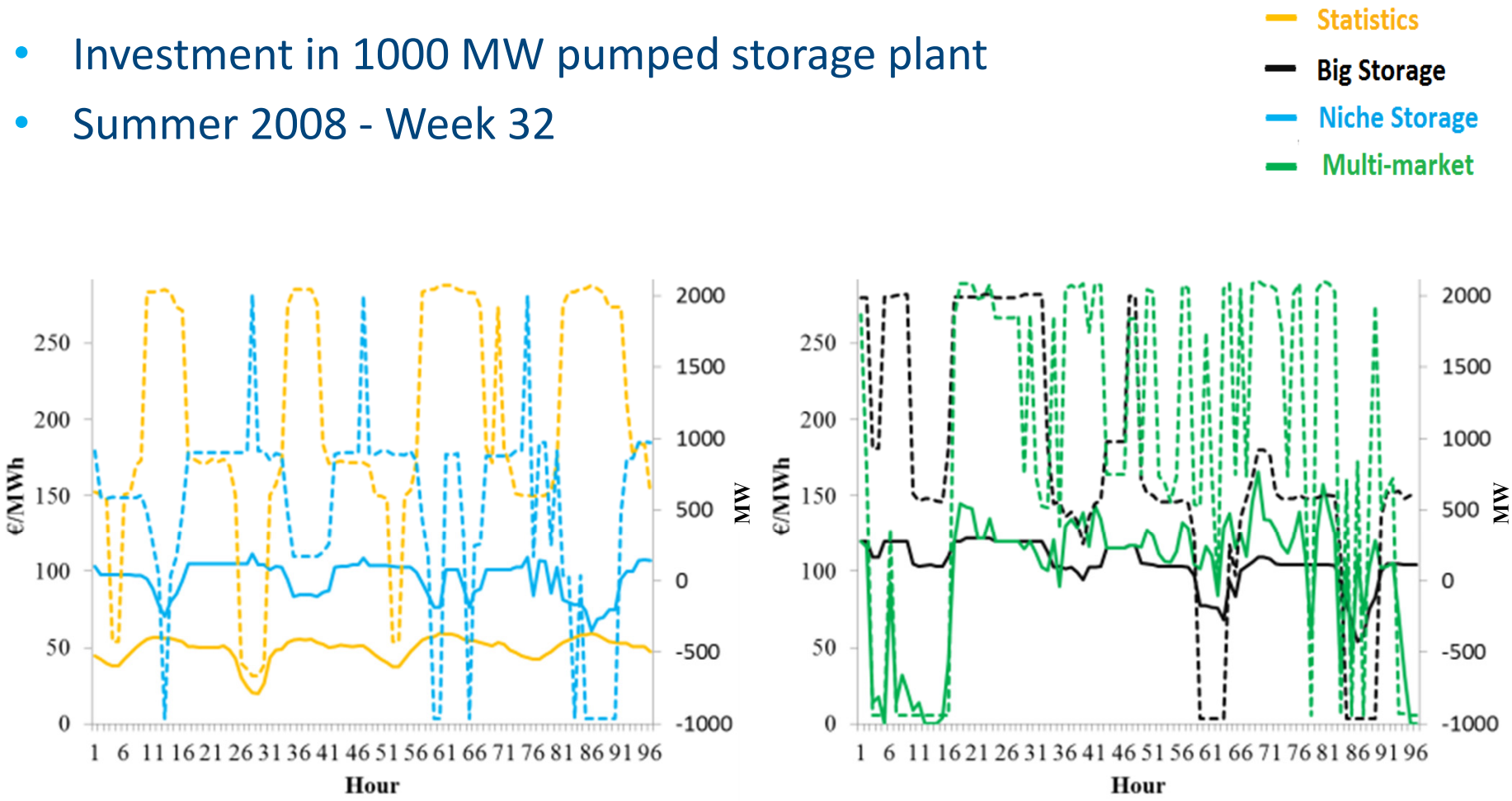
- Existing production system
- Summer 2008 - Week 32



Continuous lines are prices
Dotted lines are productions

Results – Productions and prices

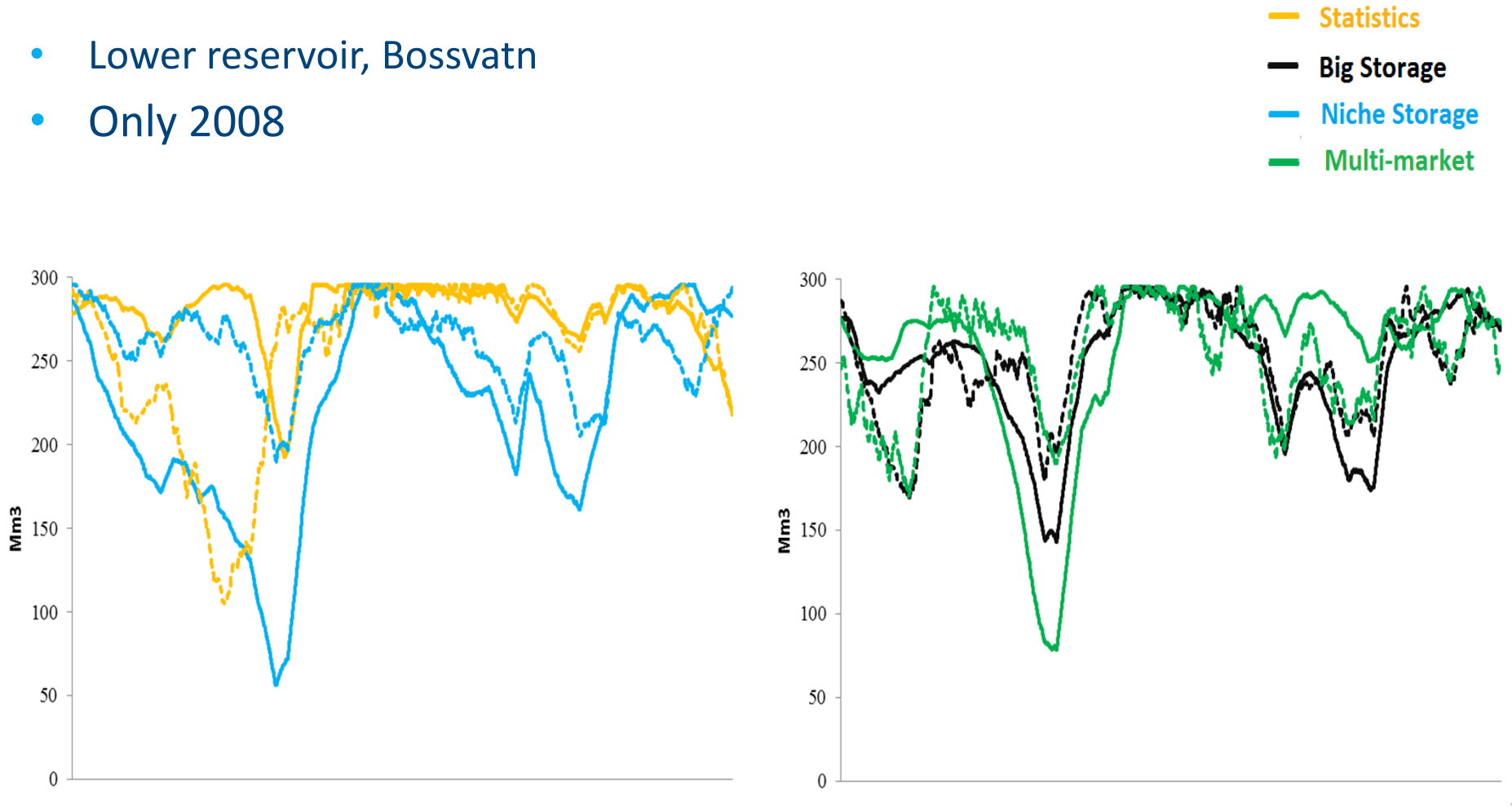
- Investment in 1000 MW pumped storage plant
- Summer 2008 - Week 32



Continuous lines are prices
Dotted lines are productions

Results – Reservoir level

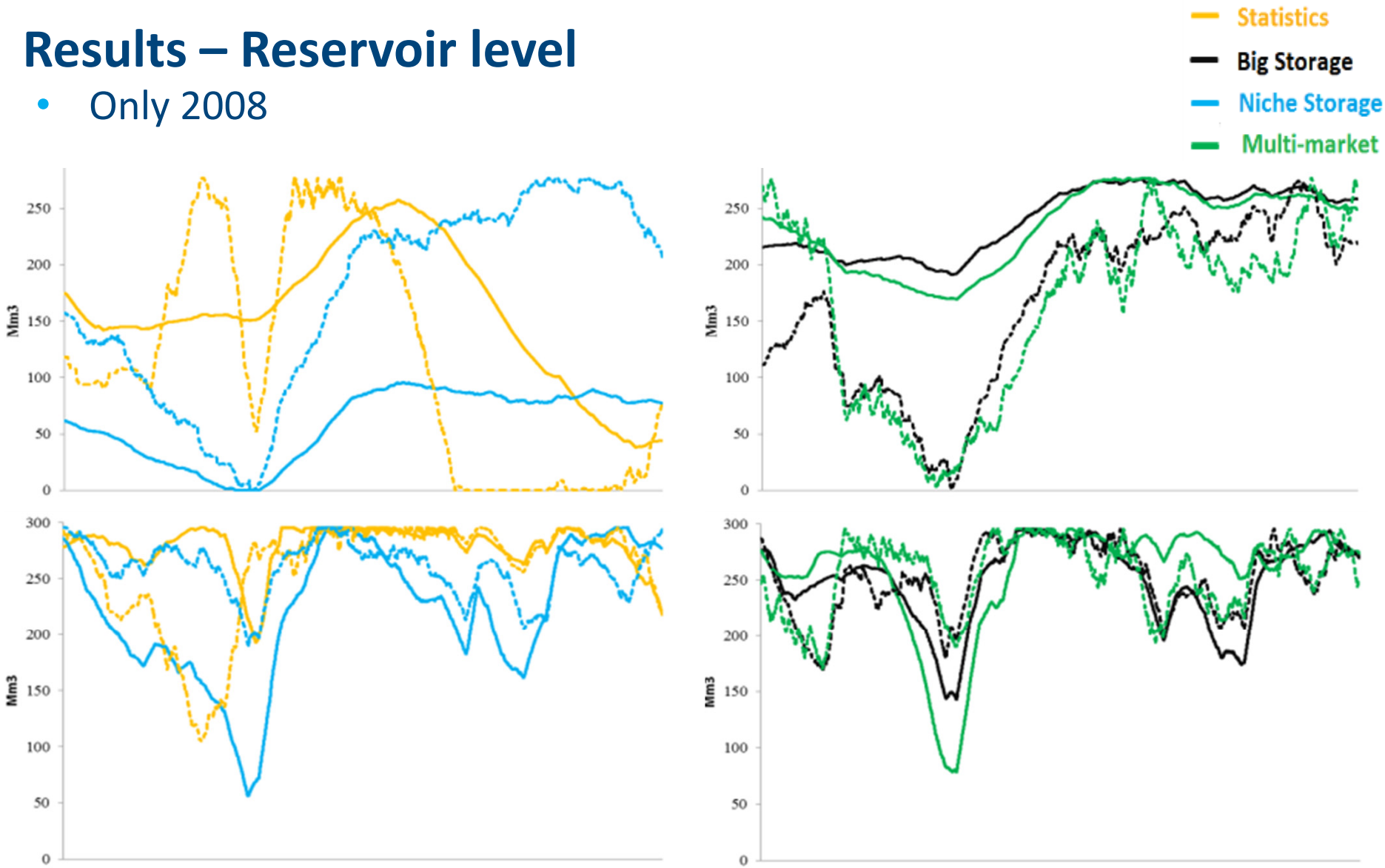
- Lower reservoir, Bossvatn
- Only 2008



Continuous lines are existing production system
Dotted lines are with investment

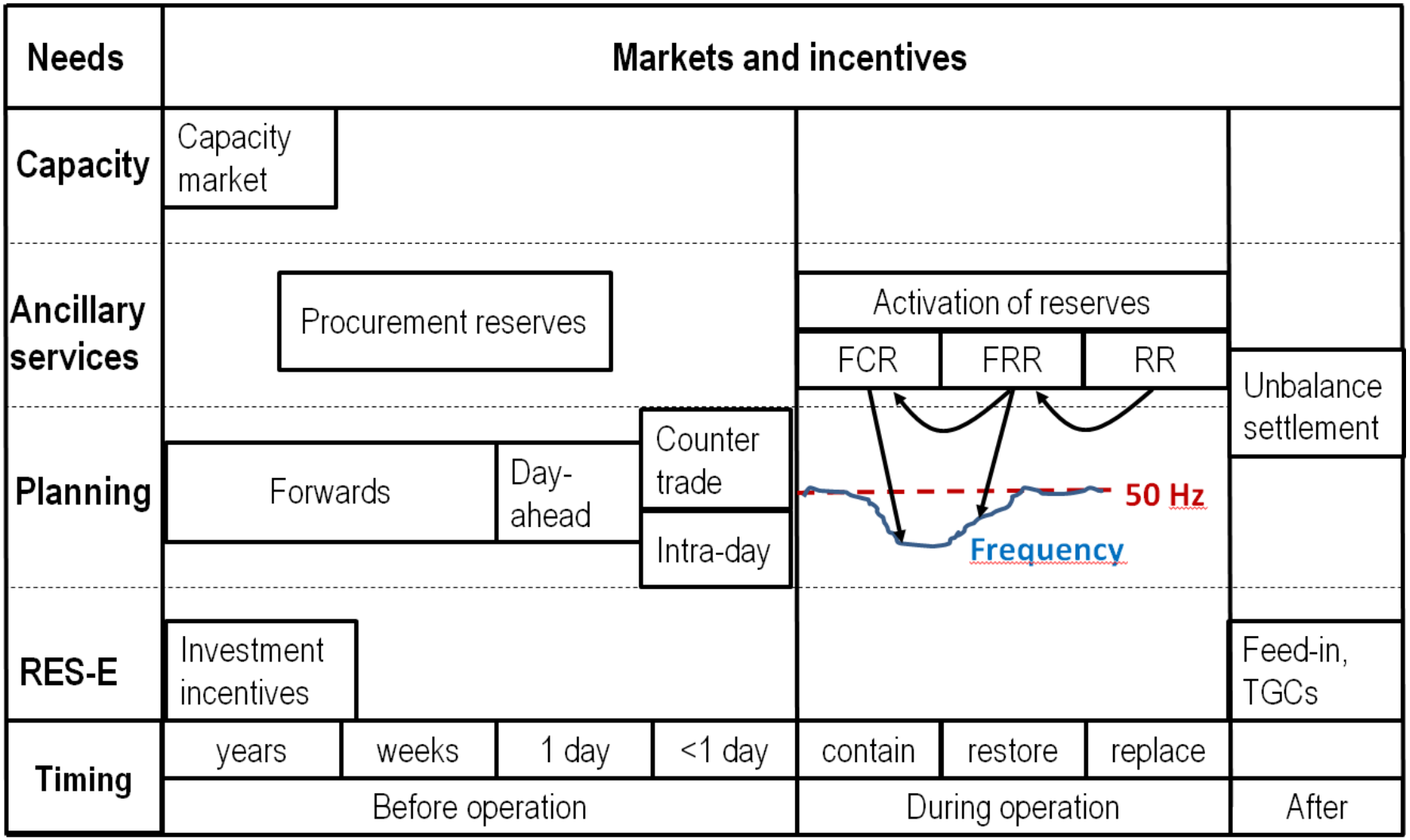
Results – Reservoir level

- Only 2008



Continuous lines are existing production system
Dotted lines are with investment

Top figures are upper reservoir, Reinevatn/Urevatn
Bottom figures are lower reservoir, Bossvatn


Needs
Markets and incentives
Capacity
Capacity market
Ancillary services
Procurement reserves
Activation of reserves
FCR
FRR
RR
Unbalance settlement
Planning
Forwards
Day-ahead
Counter trade
Intra-day
50 Hz
Frequency
RES-E
Investment incentives
Feed-in, TGCs
Timing
years
weeks
1 day
<1 day
contain
restore
replace
Before operation
During operation
After

Simulated prices for one single week