NTNU – Trondheim
Norwegian University of
Science and Technology

CEDREN Hydrobalance

WP 2: Demand for energy balancing and storage

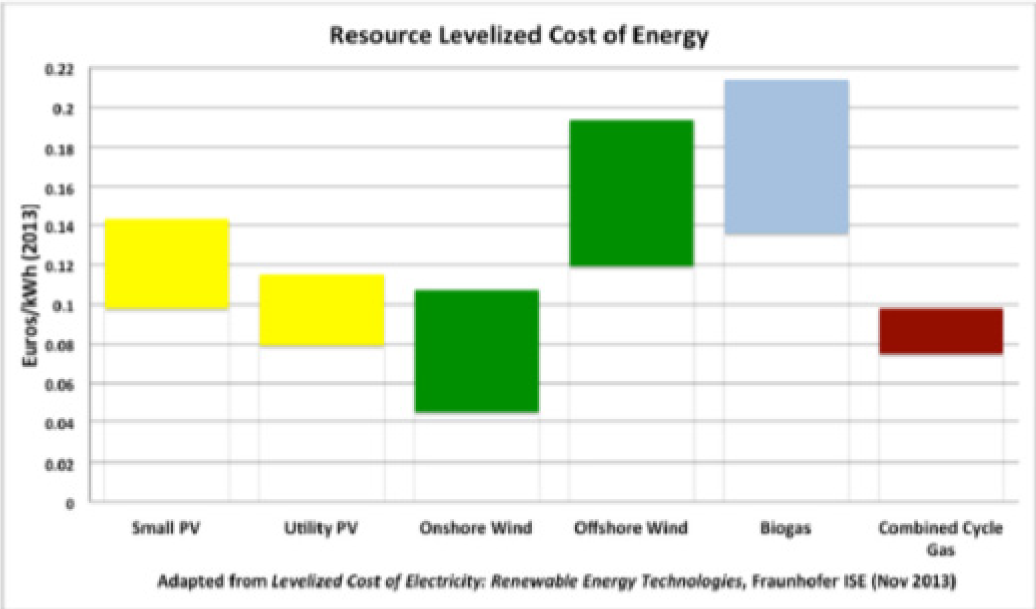
Trondheim, 15/9 - 2015

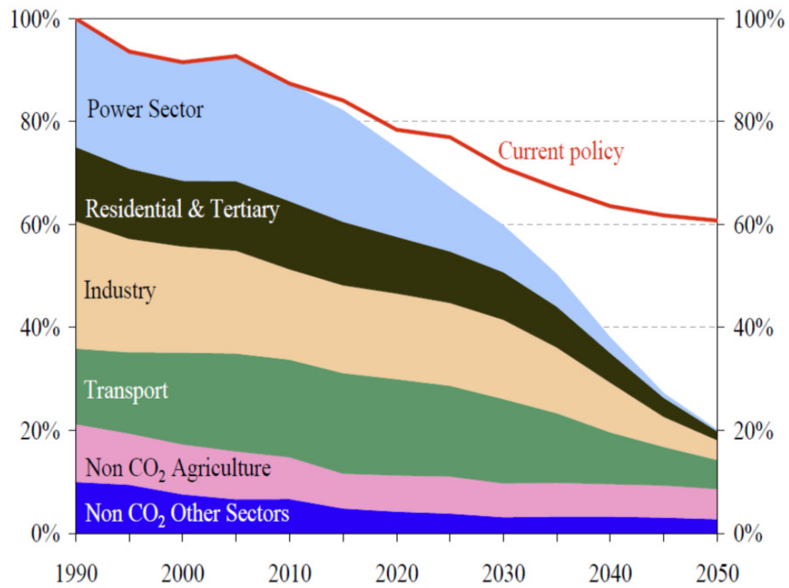
Prof. Magnus Korpås
Dept. of Electric Power Engineering
NTNU

WP 2 in brief so far

- Balancing cost comparison PHS vs Gas
  - EEM 2015 paper by Korpås, Wolfgang, Aam
  - MSc Thesis Hanne Ommedal
- Cost comparison of energy storage options in progress
  - PHS, Batteries, Power2Gas, Flywheels, Compressed Air
- PhD-candidate Ingeborg Graabak started sep 2014
  - 2 papers submitted
    - “Variability Characteristics of wind and solar power resources – a review with focus on Europe”
    - “Balancing of variable wind and solar production in Continental Europe with Nordic hydropower – A review of simulation studies”
- Simulation study of PHS wind power smoothing
  - Guest researcher Nicola Destro, Univ. of Padova
- Several media contributions and public presentations on the role of Norwegian (pumped) hydro in the future European energy system

Renewables are «on track»



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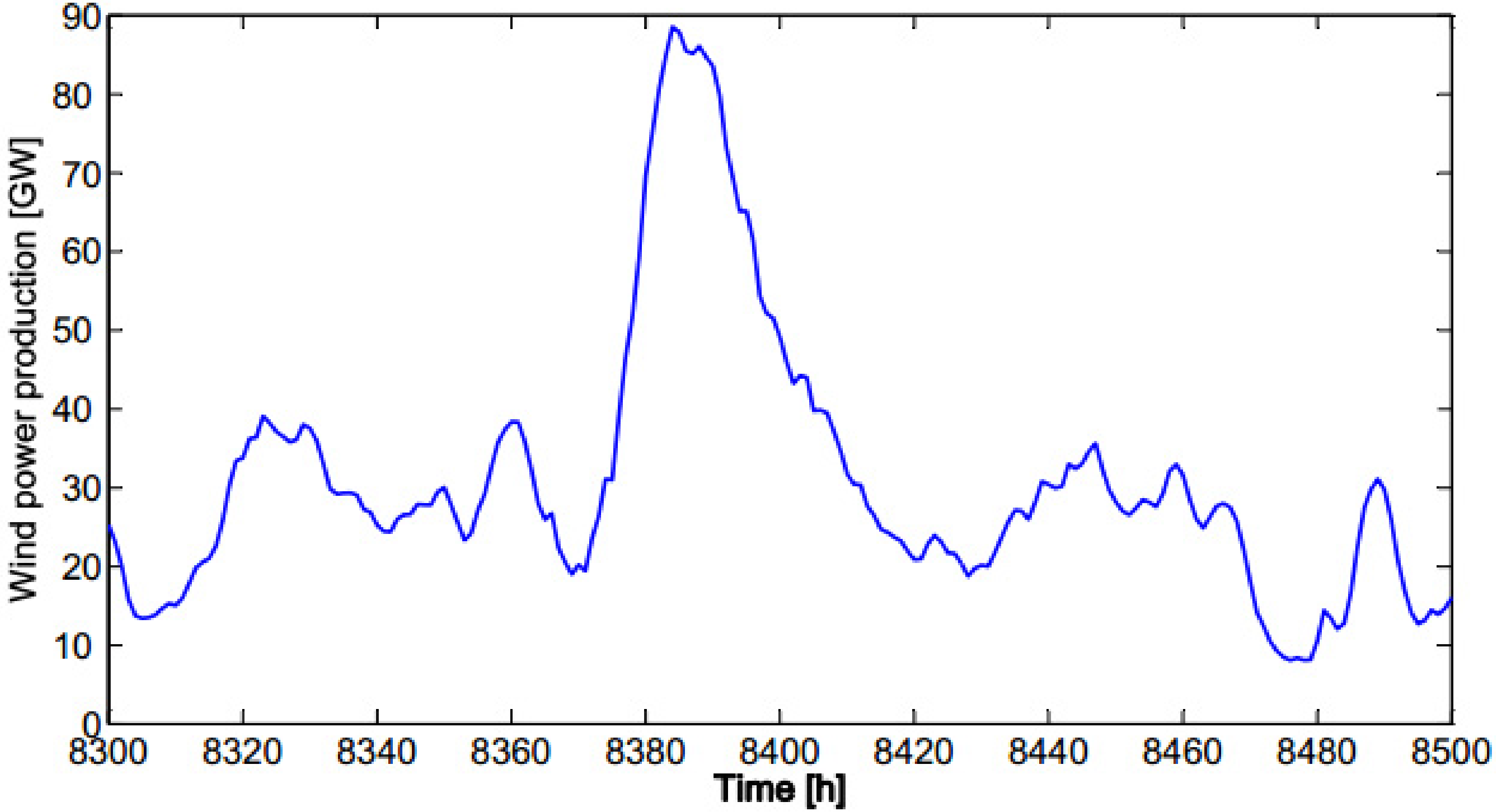
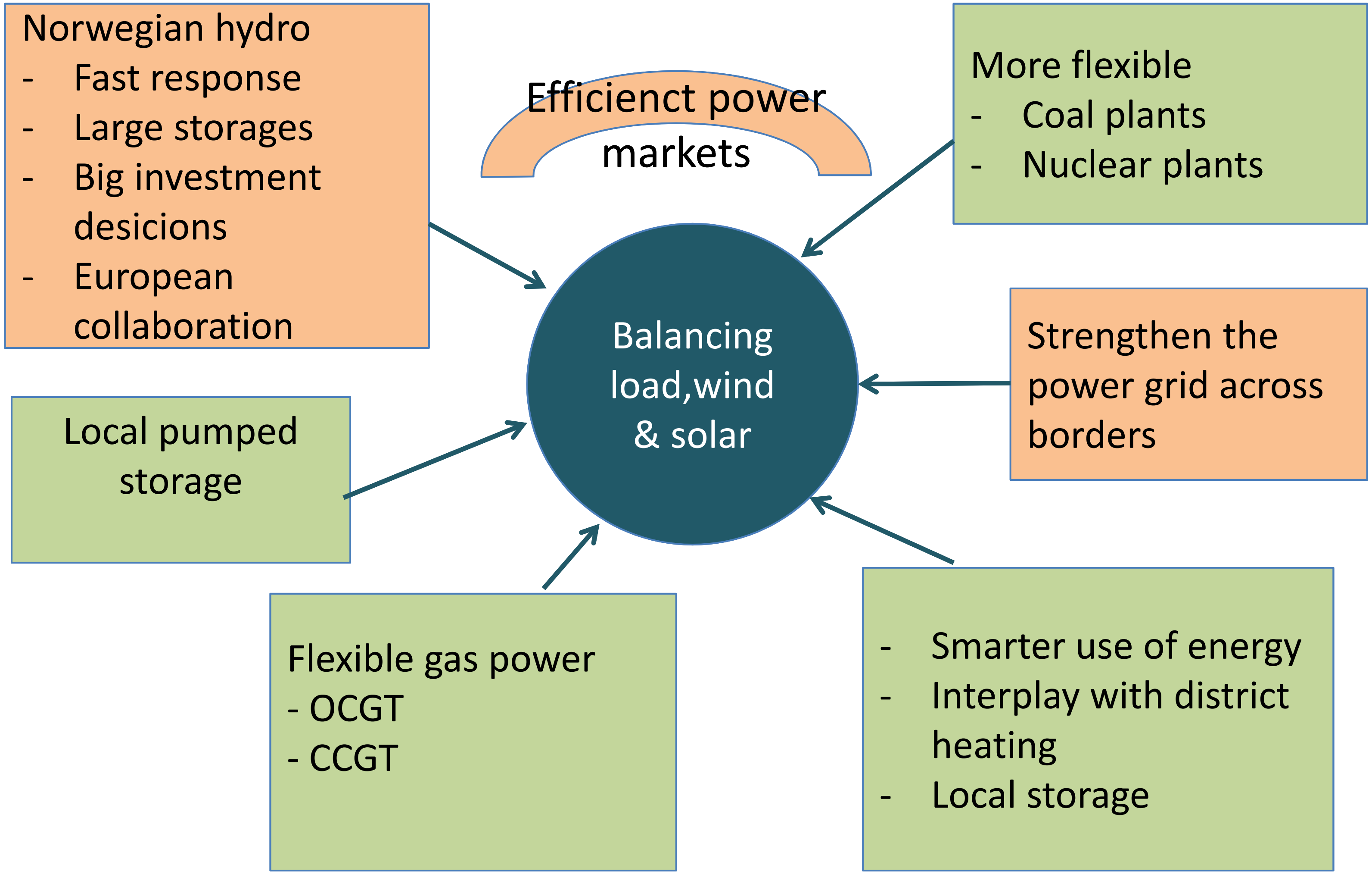
Houston, we have a ~~problem~~ ..challenge!



Source: Aigner (NTNU)

...and a whole lotta solutions!

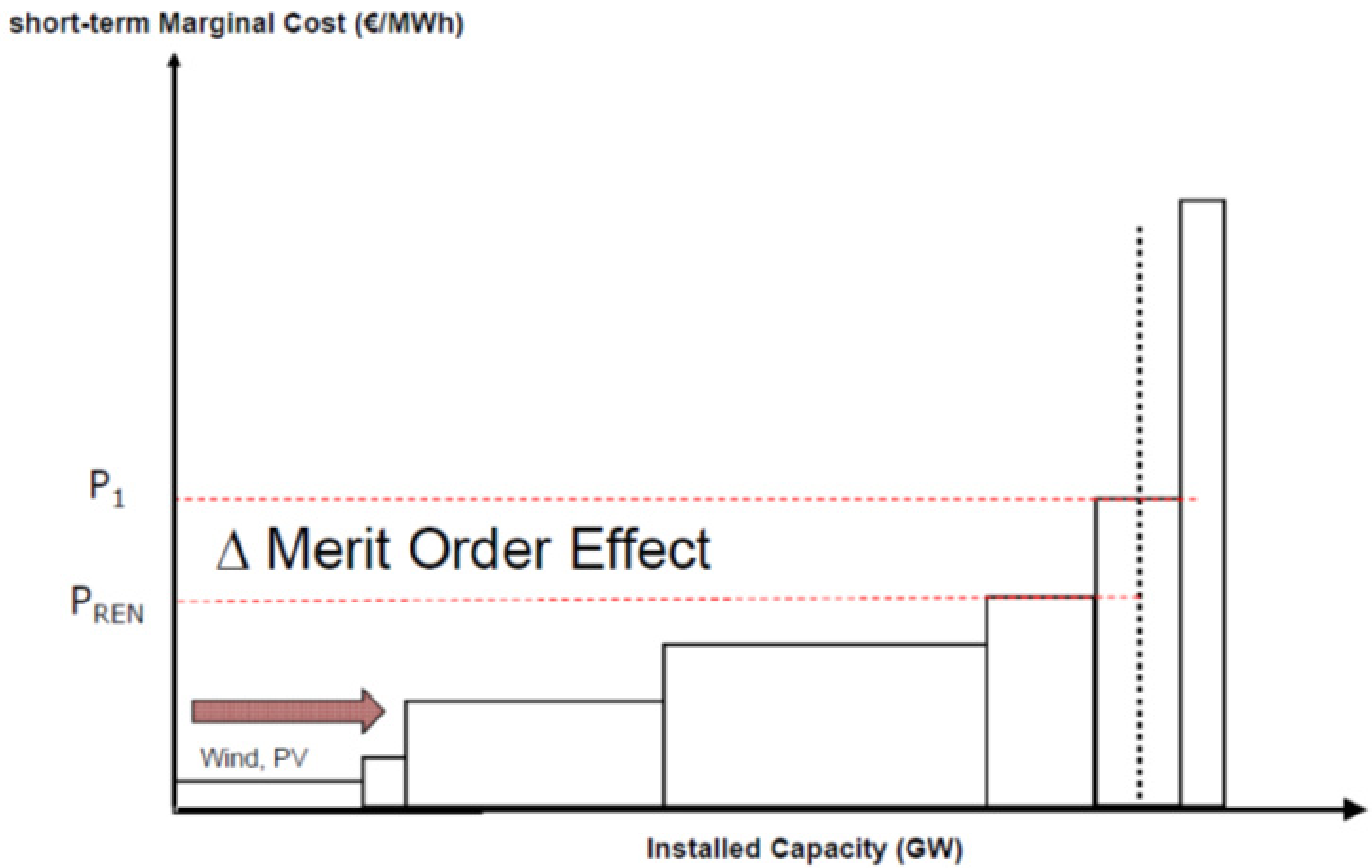


Characteristics of a RES-based power market

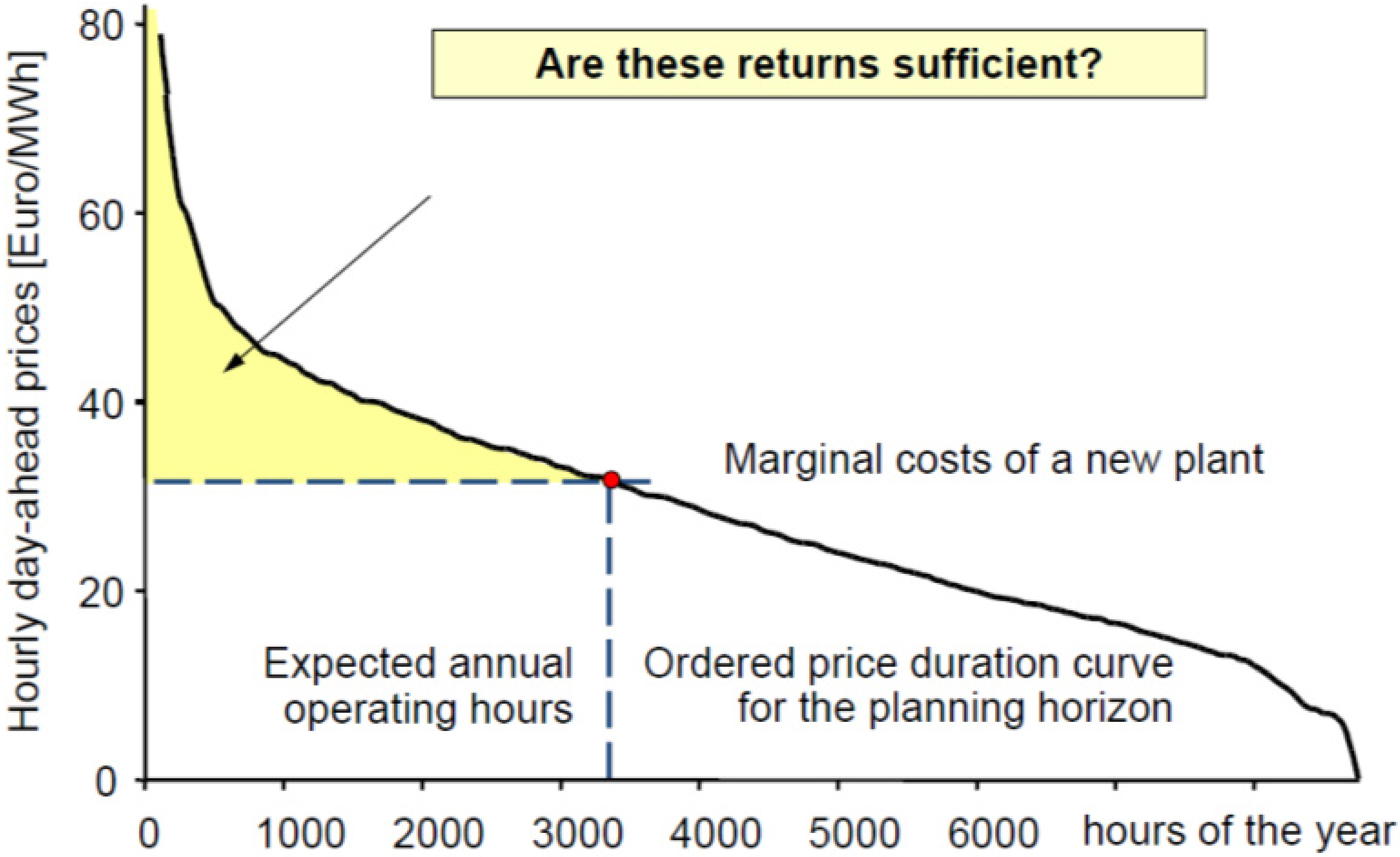
- Common markets for spot, balancing and ancilliary services across borders
- More rapid update of production plans
- Market clearing closer to operation
- Demand-side participation

- Allow extreme prices OR establish capacity markets
  – The «Merit order effect»

Variable Renewables and Implications for Market Prices: Merit Order Effect

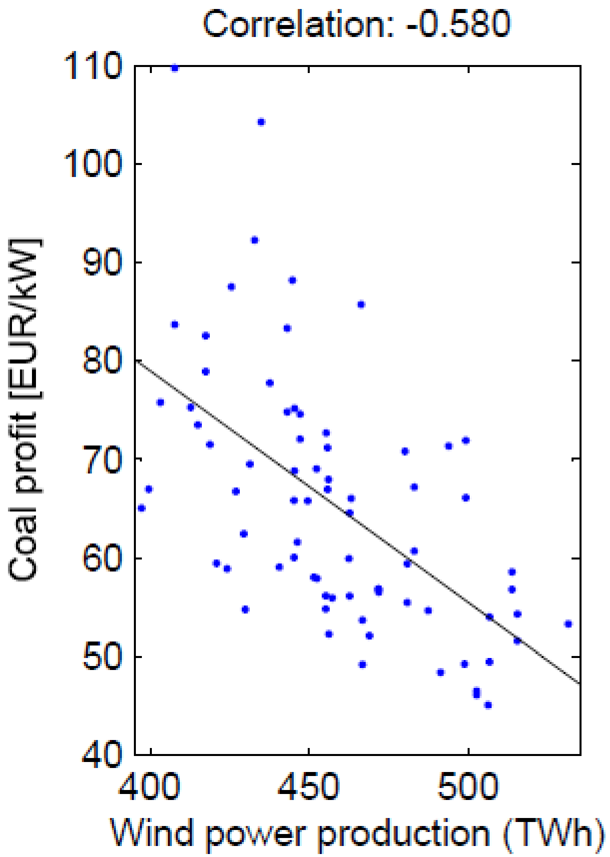


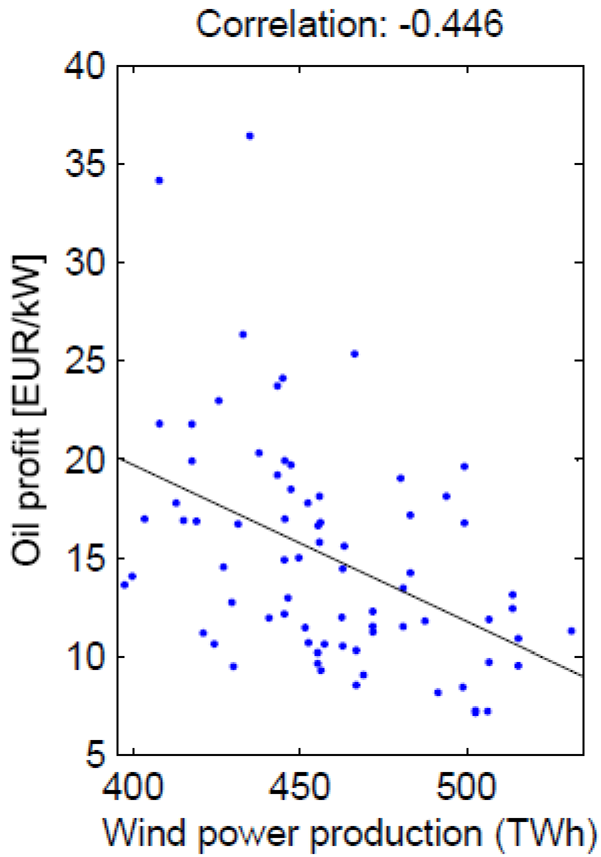
Price-Duration-Curve: Power Plant Investments on Competitive Markets



Source: Erdmann 2011

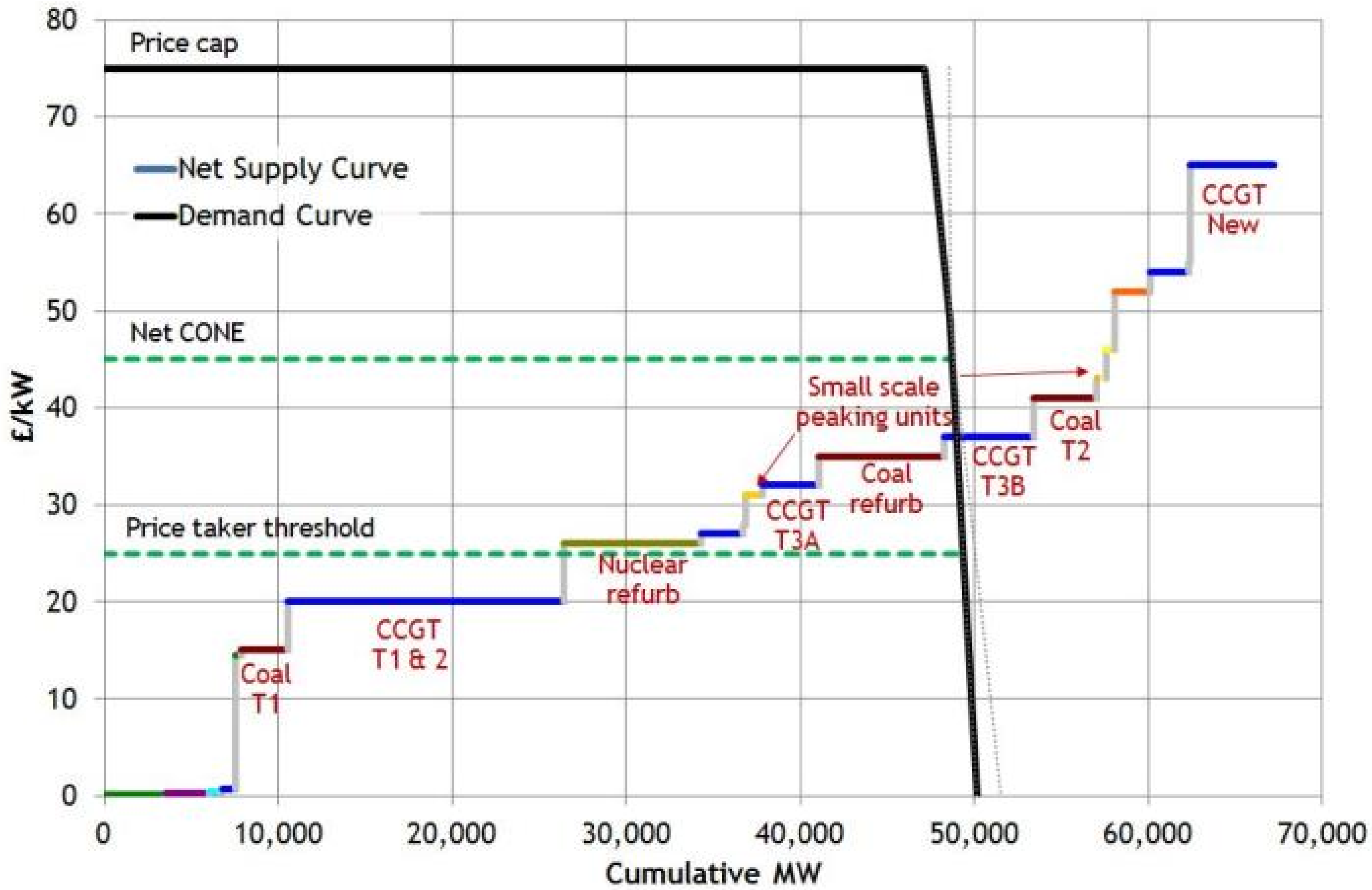
Wind and solar pushes fossils out of the spot market…





Source: Jaehnert, Korpås, Doorman (NTNU)

…and into the (emerging) capacity markets

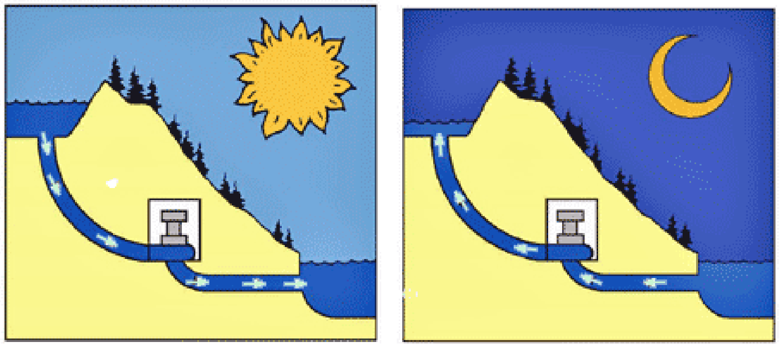


Source: Timera Energy (UK)

Norwegian hydropower for balancing

- The reservoirs are natural lakes
  - Multi-year reservoirs
  - Largest lake stores 8 TWh
  - Total 84 TWh reservior capacity

- Balancing capacity estimates 2030
  - 29 GW installed at present
  - + 10 GW with larger tunnels and generators
  - + 20 GW pumped storage
  - 30 GW total new capacity
    - Within todays environmental limits
  - Requires more transmission capacity



What is the value of the lake Blåsjø??

	BLÅSJØ	POWERWALL
Capacity (kWh)	8 000 000 000	10
Installation cost ($)	-	3,500
Lifetime (years)	∞	10

→ 8 TWh of Powerwalls cost 2800 Billion $...

Isolated wind-storage systems

Increasing the renewable fraction beyond 75-80% results in an exponential increase in the marginal cost of energy

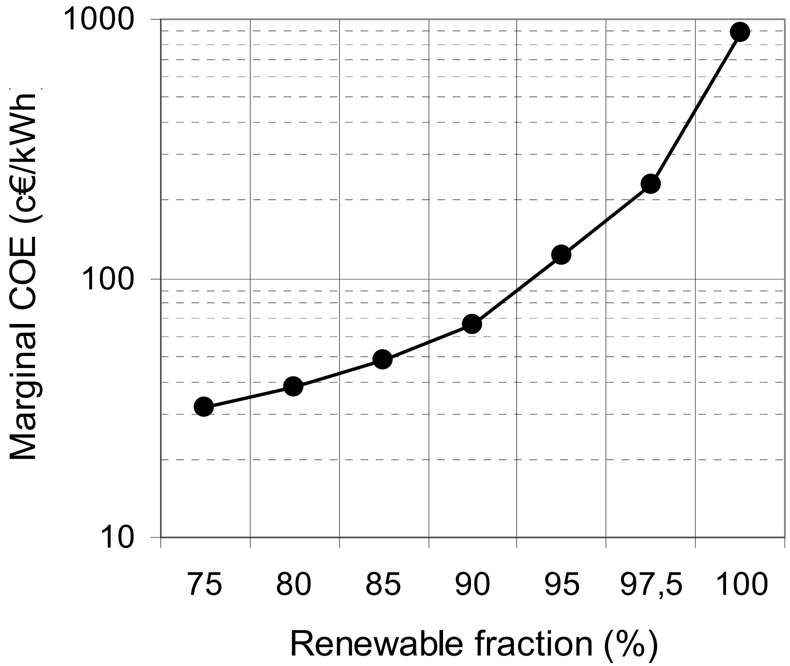


Figure 3: Marginal cost of energy of increasing renewable fraction. Wind power with 3500 full load hours.

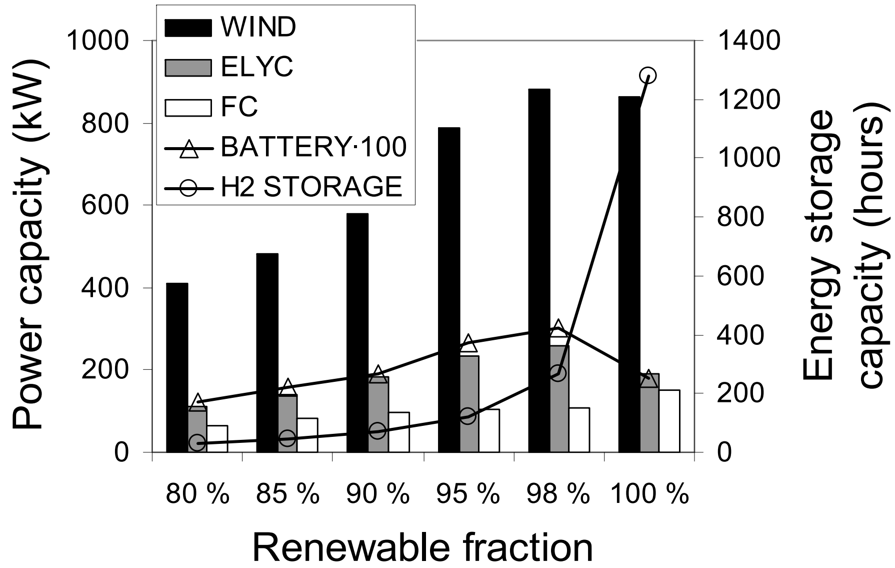
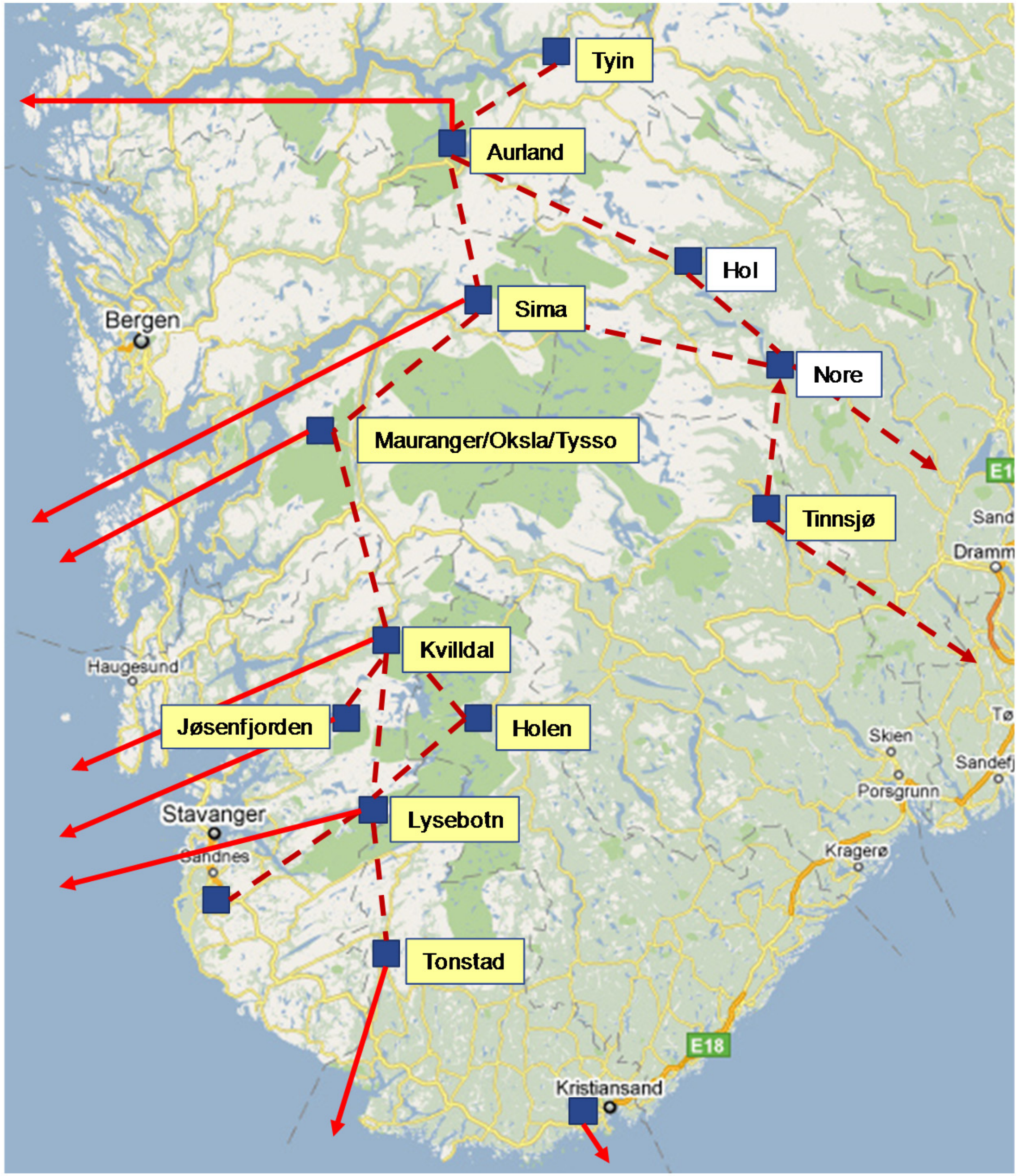


Figure 4: Optimal system configuration for various renewable fractions. Battery capacity is multiplied with a factor of 100 for graphical reasons.

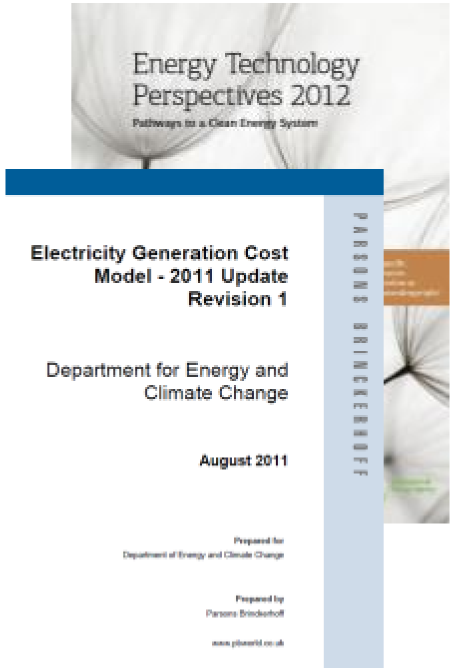


Case study 2030

10-20 GW new pumping and generation capacity using existing reservoirs

Overview of study

- Only cost is considered
  - Market operation “translated” to load factors
  - Assessment of the most cost-effective flexibility options in the near term



- Input data
  - Time period 2030-2040
  - Based on IEA WEO scenarios and figures
  - Gas plant models and costs according to report for UK Dept. of Energy and Climate Change
  - Pumped hydro storage and grid data based on Norwegian figures; Producers, Regulator, TSO, Univ.

Levelised Cost of Electricity (LCOE)

$$LCOE = \frac{\text{Discounted total investment costs and variable costs}}{\text{Discounted total generation}}$$

- Treating all years equal
- Only initial investments

$$LCOE = \frac{\text{Specific InvCost} \cdot (\text{AnnuityFactor} + \text{O\&Mpct})}{\text{Availability} \cdot \text{FullLoadHours}} + \sum \text{VariableCosts}$$

$$LCOE = \frac{i \cdot (\delta_{n,r} + OM)}{\alpha \cdot T_{fl}} + \sum_{j=1}^{J} c_{var,j}$$

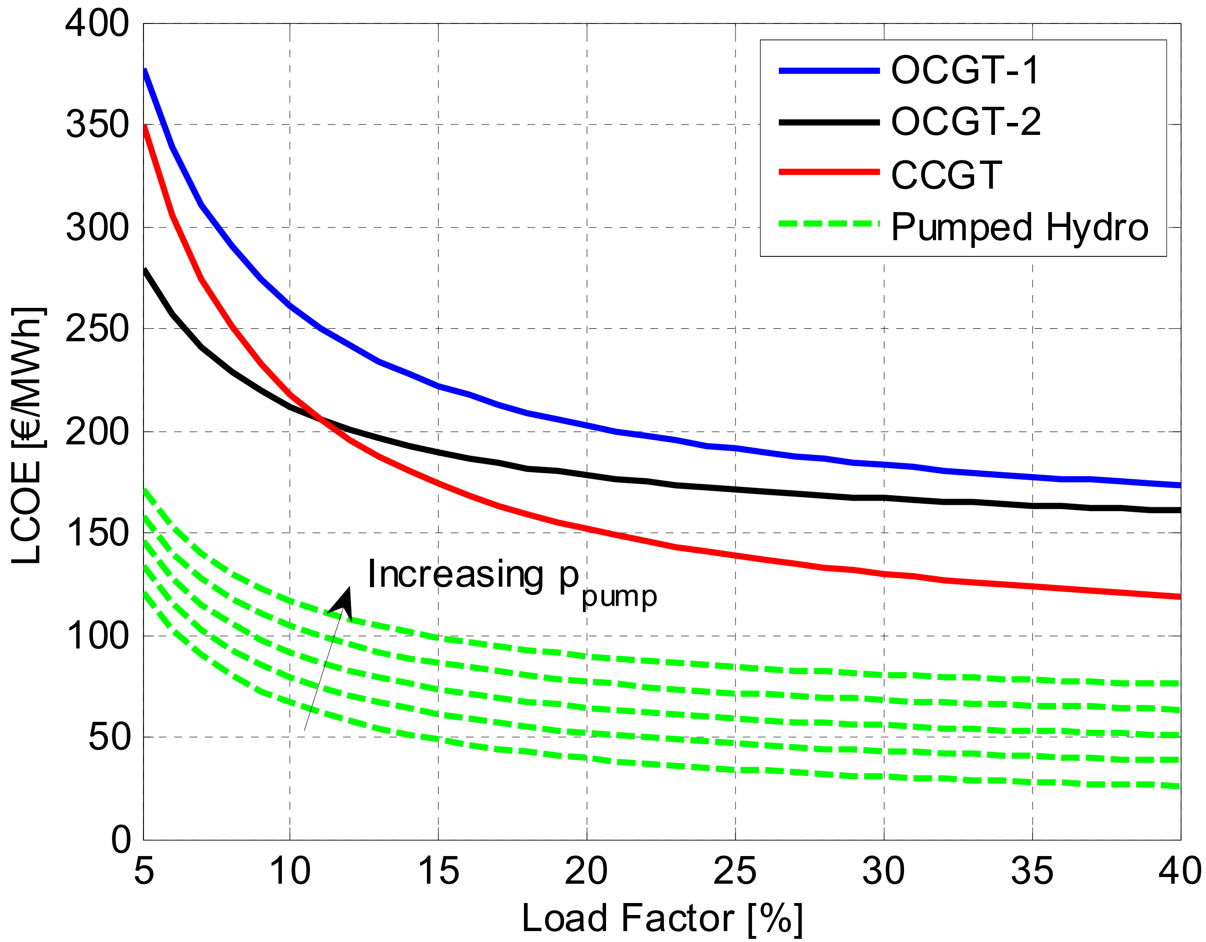
Natural gas: $(p_{ng} + p_{CO_2} \cdot e_{ng})/\eta_{ng}$

Pumped hydro: p_{pump}/η_{ph}

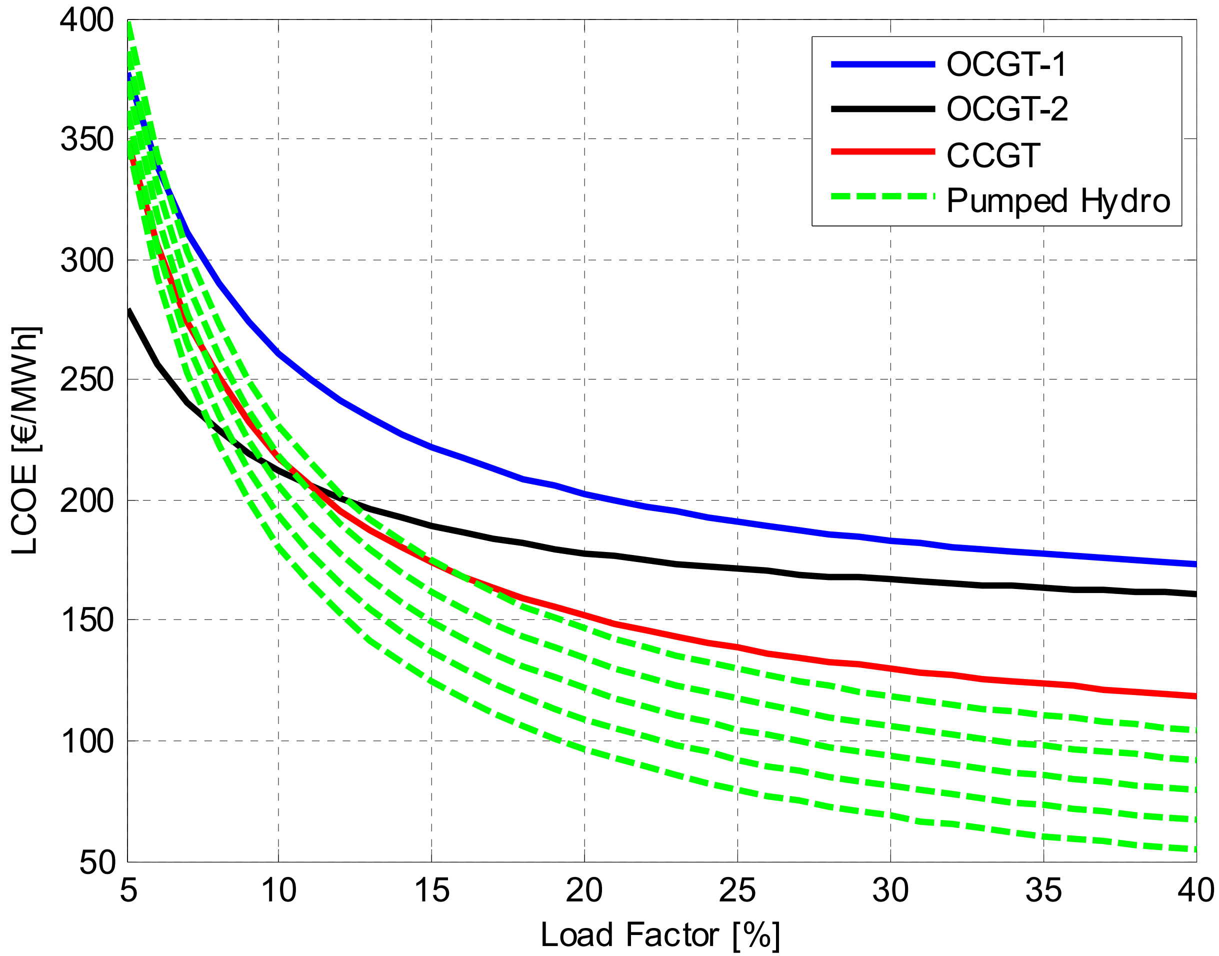
Parameter	CCGT	OCGT-1 (Aeroderivative)	OCGT-2 (F-class)
i_{ng} [€/kW]	718	705	377
n_{ng} [yr]	25	40	25
OM_{ng} [%]	3.9	3.5	3.4
η_{ng} [%]	59	35	35
α_{ng} [%]	92.8	94.7	91.9

Pumped hydro plant		Subsea cable and grid	
i_{ph} [€/kW]	400	i_{cable} [€/kW]	1153
n_{ph} [yr]	30	n_{cable} [yr]	40
OM_{ph} [%]	0.75	α_{cable} [%]	95.0
η_{ph} [%]	80	GR [%]	30
α_{ph} [%]	95.7	n_{grid} [yr]	70

Norwegian pumped hydro has a relatively low LCOE…



…even when grid and cable costs are included



Levelised Cost of Peak Generation (LCPG)

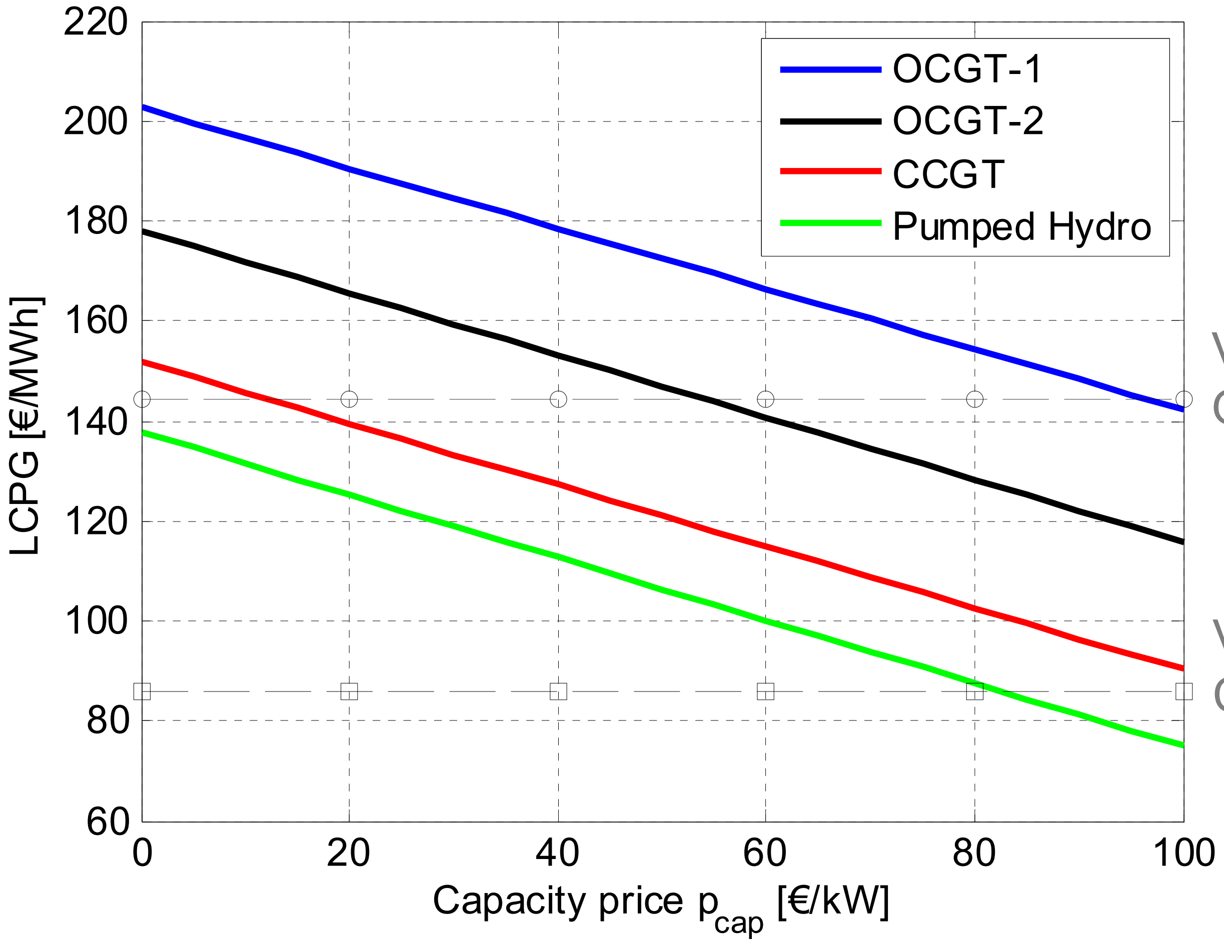
- A proposed new metric for *the cost of providing electricity when fluctuating renewables and inflexible thermal generation cannot meet the (fixed) demand*
  - Peak generation must cover the residual load
- In this paper, we use fixed scenarios for capacity prices, and calculate the needed payment for delivered energy.
  - Flexible demand not considered in the specific case study, but can be treated equally

Natural gas:

$$LCPG_{ng} = \frac{i_{ng} \cdot (\delta_{n_{ng},r} + OM_{ng}) - p_{cap}}{\alpha_{ng} \cdot T_{ng}} + \frac{\left(p_{ng} + p_{CO_2} \cdot e_{ng}\right)}{\eta_{ng}}$$

LCPG for 20 % load factor

Sensitivity on capacity price



Variable cost of OCGT

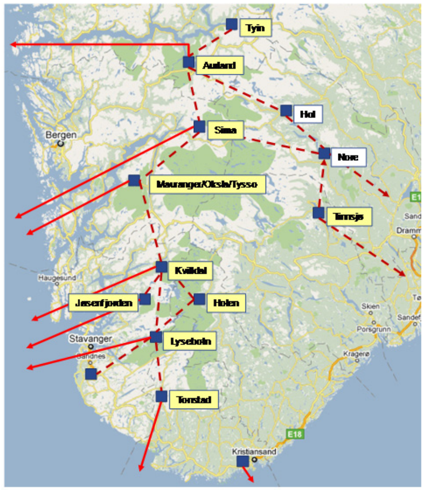
Variable cost of CCGT

Summary of study

- A method for calculation of the Levelized Cost of Peak Generation (LCPG)
  - Peak periods are defined as the time of the year when non-flexible resources cannot cover all the demand
  - The method account for possible capacity payments and additional revenue during off-peak periods
- A case study of a future European power system with high penetration of wind and solar power
  - Building new reversible pumping stations between existing reservoirs in the Norwegian hydro system can be economical advantageous over new CCGT and OCGT plants
  - Additional costs of subsea cables across the North Sea and corresponding reinforcements of the mainland grid is included

Conclusion so far..

Interconnectors must be given full access to all markets, including capacity markets, for utilization of the most economical viable sources of storage and flexible power in Europe



WP 2 MSc thesis

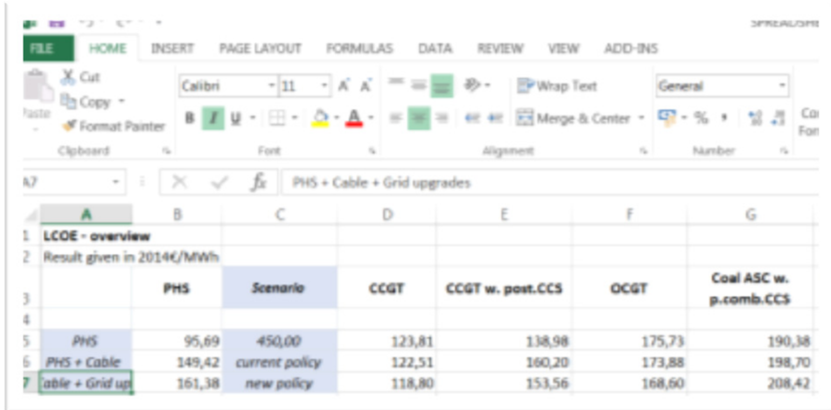
Hanne Kristin H Ommedal

Cost of flexibility in the future European power system

Trondheim, June 2015

Master's thesis

NTNU – Trondheim
Norwegian University of
Science and Technology



PHS + Cable + Grid upgrades

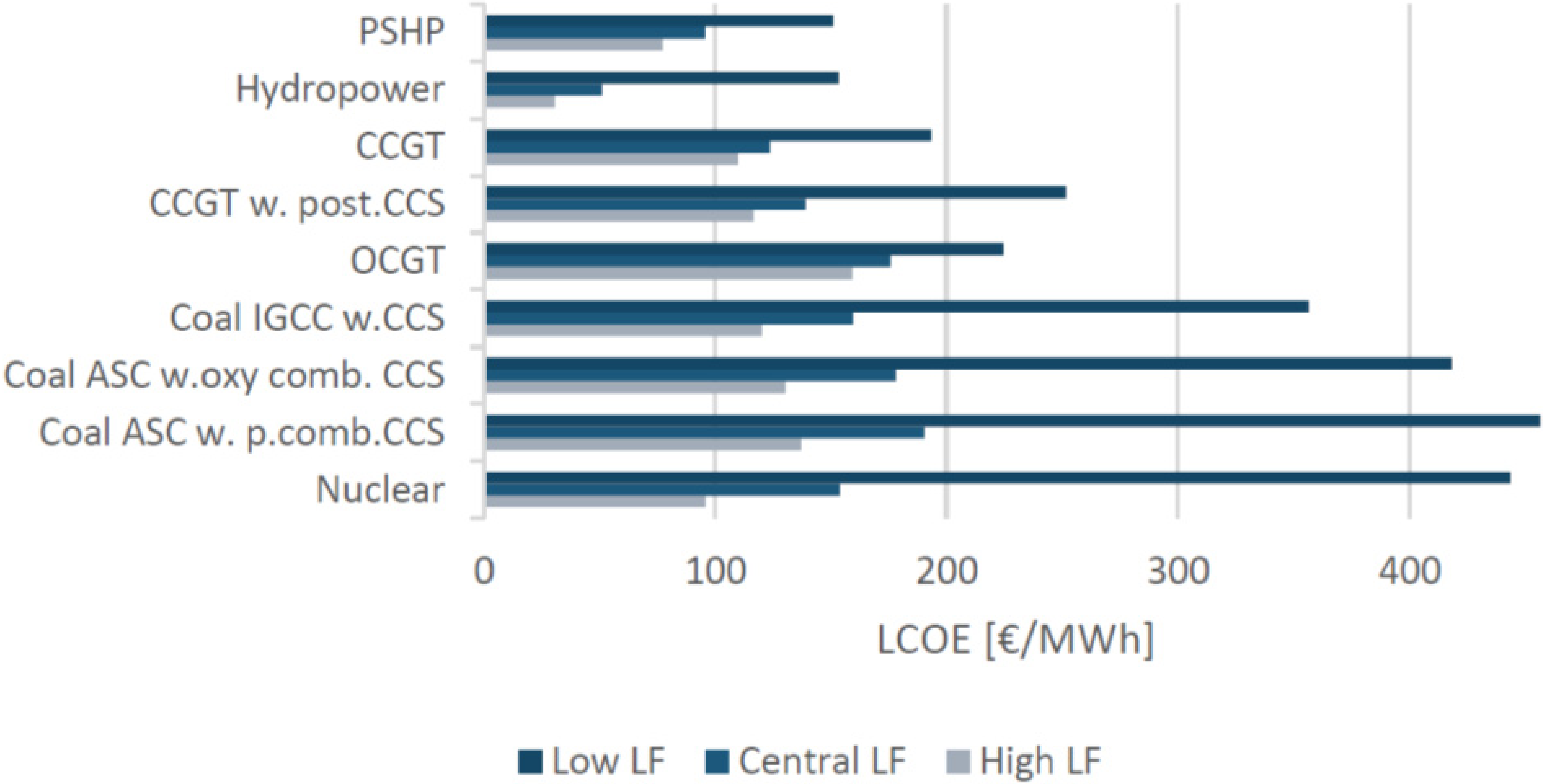
	A	B	C	D	E	F	G
1	LCOE - overview						
2	Result given in 2014€/MWh						
3		PHS	Scenario	CCGT	CCGT w. post.CCS	OCGT	Coal ASC w. p.comb.CCS
4							
5	PHS	95,69	450,00	123,81	138,98	175,73	190,38
6	PHS + Cable	149,42	current policy	122,51	160,20	173,88	198,70
7	able + Grid up	161,38	new policy	118,80	153,56	168,60	208,42

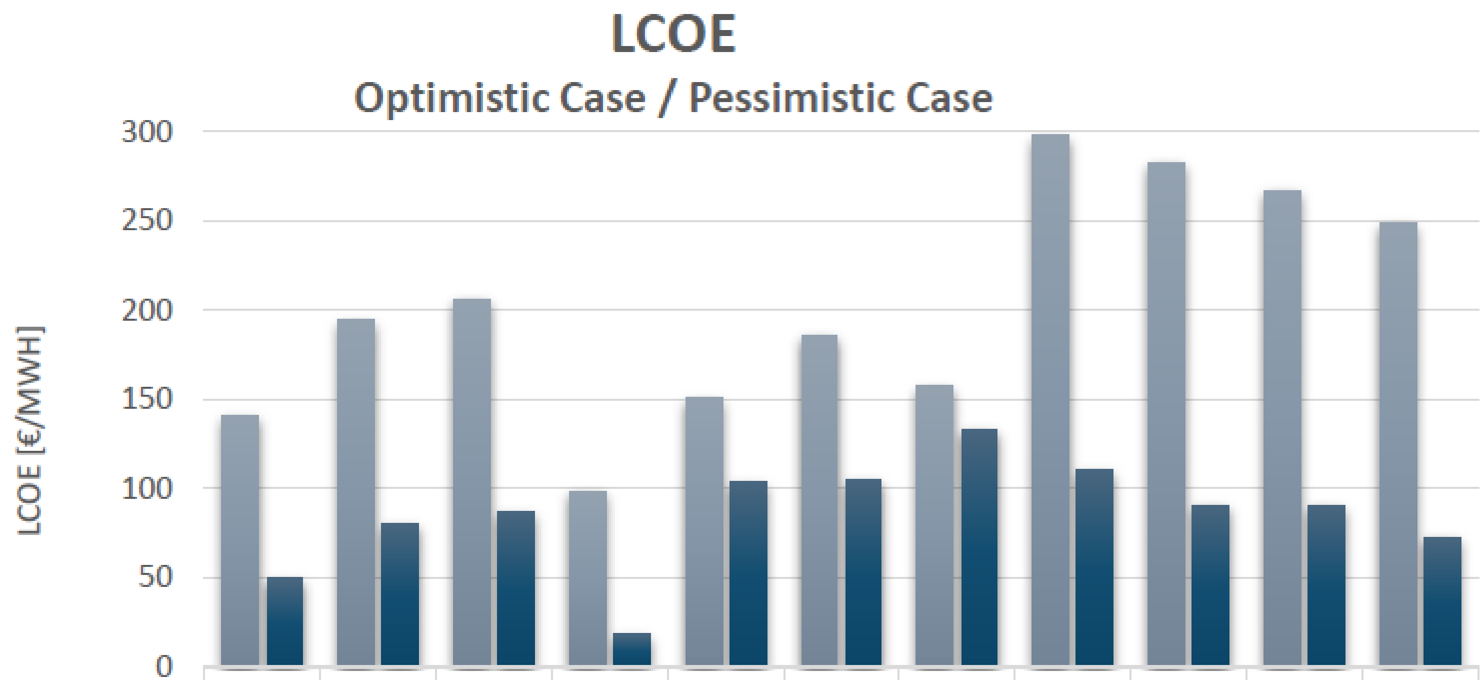
Spreadsheet cost model available for Hydrobalance partners

MSc thesis: Cost of flexibility

- Technologies: PHS, conv. hydro, several types of thermal with and without CCS
- Main sources: IEA, DECC, EIA, NVE
- Sensitivity analysis on assumptions
  - Discount rate
  - Load factor for all technologies
  - Investment cost of pumped hydro
  - Average pumping price
  - Fuel and carbon prices
  - Costs for cables and grid upgrades

Base Case Result





	PSHP	PSHP + cable	PSPH + cable + grid upgrades	Hydropower	CCGT	CCGT w.CCS	OCGT	Coal ASC p. comb. CCS	Coal ASC o. comb. CCS	Coal IGCC CCS	Nuclear
Pessimistic Case	140,7	194,4	206,4	98,6	150,4	186,1	157,3	297,5	282,8	267,2	248,7
Optimistic Case	49,5	80,2	87,0	18,3	103,7	105,1	133,4	110,4	90,9	90,7	72,9

	Investment	**Capacity**	**Load factor**	**Price for pumping**	**Fuel price**	**Carbon tax**
Optimistic	*Low values*	*Central values*	*0.6 (0.35 for PSHP)*	*Low [20 €/MWh]*	*450 Scenario*	*450 Scenario*
Pessimistic	*High values*	*Central values*	*0.2*	*High [40 €/MWh]*	*450 Scenario*	*450 Scenario*

PhD project: Demand for energy balance and storage

PhD Fellow:	Ingeborg Graabak
Nationality	Norwegian
Supervisors:	Magnus Korpås and Olav Fosso
Department:	Dept. of Electric Power Engineering,NTNU
Start:	September 2014
Finished:	September 2017
CEDREN project:	HydroBalance

Develop methodology and models for assessing the value of Norwegian hydro for balancing wind and solar variations/uncertanty

- Categorization of variability of wind and solar for different time horizons
- Develop data model with high spatial and temporal resolution for different scenarios of wind and solar production in Northern Europe
- Establish a possibility for analyses of several markets (day-ahead, intraday, balancing)
- Assess the value of applying Norwegian (pumped) hydro for balancing of large shares of wind and solar production in future Northern Europe

Balancing of variable wind and solar production in Continental Europe with Nordic hydropower – A review of simulation studies

Topics studies

1) The need for balancing and storage
2) Possible further development of the Nordic power system
3) Consequences of different market solutions
4) Changes in operation patterns of the Nordic system

Selection

Twelve scientific papers are reviewed.

Main findings

None of the studies have modelled the future variability in both wind and solar power sufficiently realistic.
Further research should start with establishing such a model.

Title / Year of publishing/ Reference	Main research question	Need for balancing and storage	Develop-ment of Nordic power system	Conse-quences of market solution	Changes in hydro operatio n pattern
Balancing of Wind Power Variations using Norwegian Hydro Power/[4]	The role of the Norwegian hydropower system to provide balancing power to a future European system, e.g. how such a role will affect the Norwegian hydropower system.	X	(X)		X
The effect of Large-Scale Wind Power on System Balancing in Northern Europe/[5]	i) Simulation of actual and forecasted WPP for 5 scenarios in 2010 and 2020. ii) Analyses of procurement of reserves capacities and their activation. iii) Analyses of the potential of integrating Northern European regulating power markets	X		X	
Nordic hydropower flexibility and transmission expansion to support integration of North European wind power/[6]	Assess the challenges related to WPP variability, especially offshore in the North and Baltic Seas and the transmission grids needed to enable the optimal use of hydropower flexibility in a long term cost-benefit analysis.	X	X		X

Title / Year of publishing/ Reference	Time perspective /Geographical resolution	Main input data	Model(s)	Main findings
Balancing of Wind Power Variations using Norwegian Hydro Power/ 2013/ [4]	2030/ NO *), DK, NL, BE, UK. In the EMPS analyses also SE, FI FR, PL and AU	EMPS analyses: "Europe": wind power generation: 323-474 TWh/y, no increase in Norwegian hydropower capacity, exchange capacity NO – "Europe": 2,3 GW and 5,8 GW, Wind speed data from the Reanalysis global weather model for the years 2000-2006	2 analyses: one with a simplified model and one with the EMPS model	The generation constraints and the exchange capacity, and not the aggregated reservoir size, are the most important physical limiting factors of the amount of balancing that can be provided.
The effect of Large-Scale Wind Power on System Balancing in Northern Europe/ 2012/[5]	5 scenarios covering 2010 and 2020, NO, SE, FI, DK, GE, NL, BE	Exchange capacity NO – other countries: 3.7 GW (2010) and 6.8 GW (2020), 6 GW increased capacity in Norwegian hydro power WPP based on a mixed input data set including measurements of wind speed and values from the COSMO EU tool, Installed WPP capacity 2010: 34 GW, 2020: 96 GW	EMPS and IRiE (Integrated Regulating power market in Europe)	Integrated market: 2020 procurement costs reduced by 30% compared to non-integrated markets, balancing costs reduced by 50%, gross reserve activation in the Nordic area nearly doubled in 2020 with integrated regulating market
Nordic hydropower flexibility and transmission expansion to support integration of North European wind power/ 2014/[6]	2030, Europe including the North-Sea	Installed wind capacity in NO, SE, DK, FI, NL, BE, GE and UK are onshore: 98 GW and offshore: 97 GW, solar production: 30 GW based on reanalysis data. Increased capacity of 18.2 GW in the NO hydropower system. The grid is an extrapolation of	EMPS and PPST (Power System Simulation Tool)	Long term strategies for the expansion of the transmission grids must be defined in a coordinated way to ensure optimal developments. The analysis shows high correlation between pumping patterns in southern part of NO and WPP in Northern GE

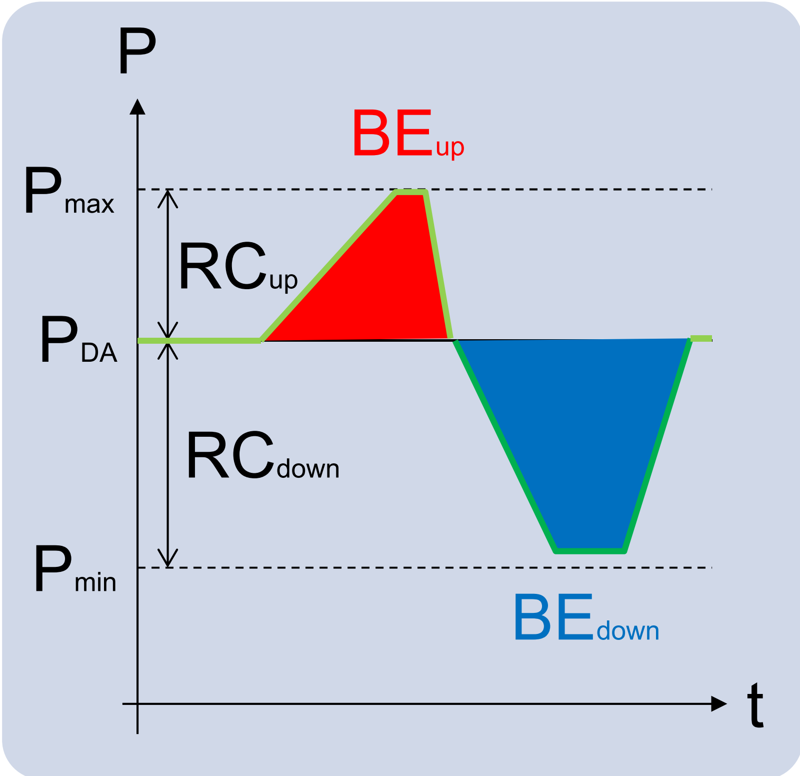
Balancing Reserve Capacity vs Energy

Reserve procurement

- Reserve capacity (RC) [EUR/MW]
- TSOs ensure sufficient reserves in the system during operation

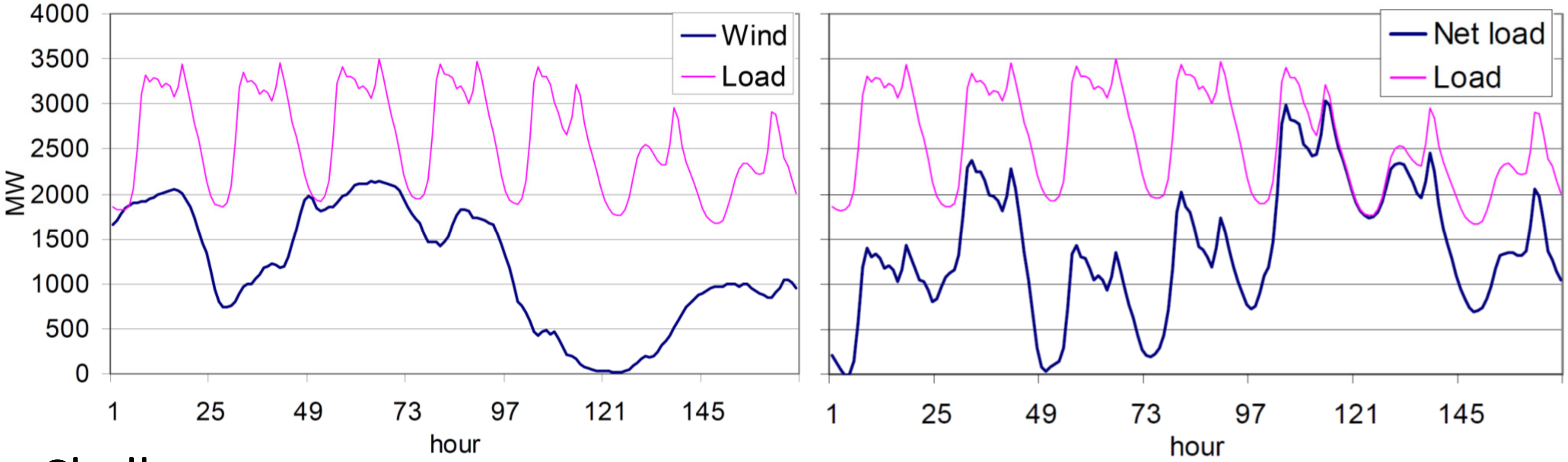
System balancing

- Balancing energy (BE) [EUR/MWh]
- TSOs activate reserves to counteract system imbalances



It is the Net Load that matters

- The system will see the aggregated net imbalance
  - Unforeseen variations in load, wind and solar
  - Net load = Load – Wind – Solar

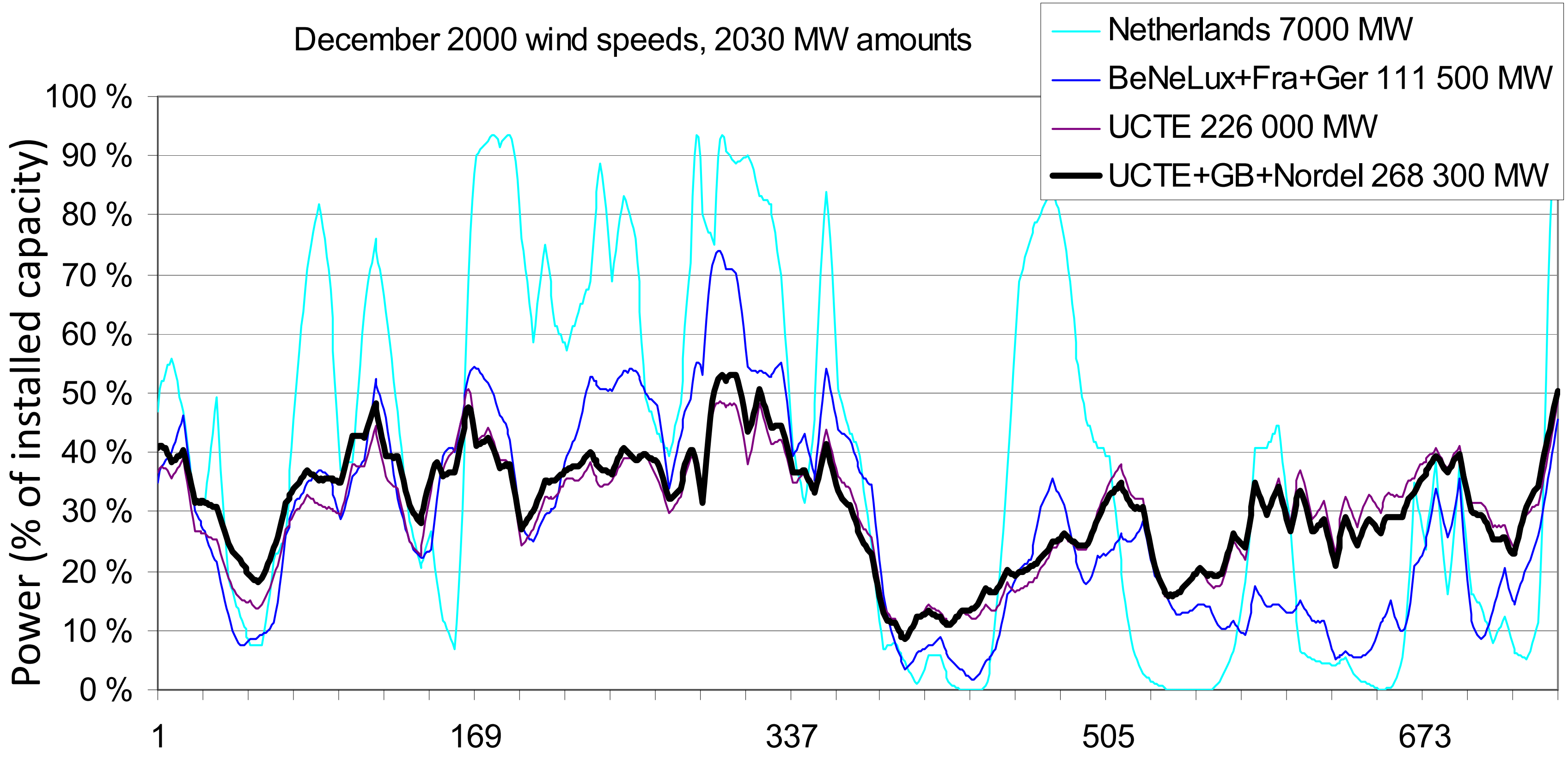


Challenges:

- Flexibility of thermal power plants (ramp rates, start/ stop operation)
- With very high RE share, thermal plants can be pushed out of the market – security of supply has to be fulfilled

Sources: NREL, Holttinen (VTT)

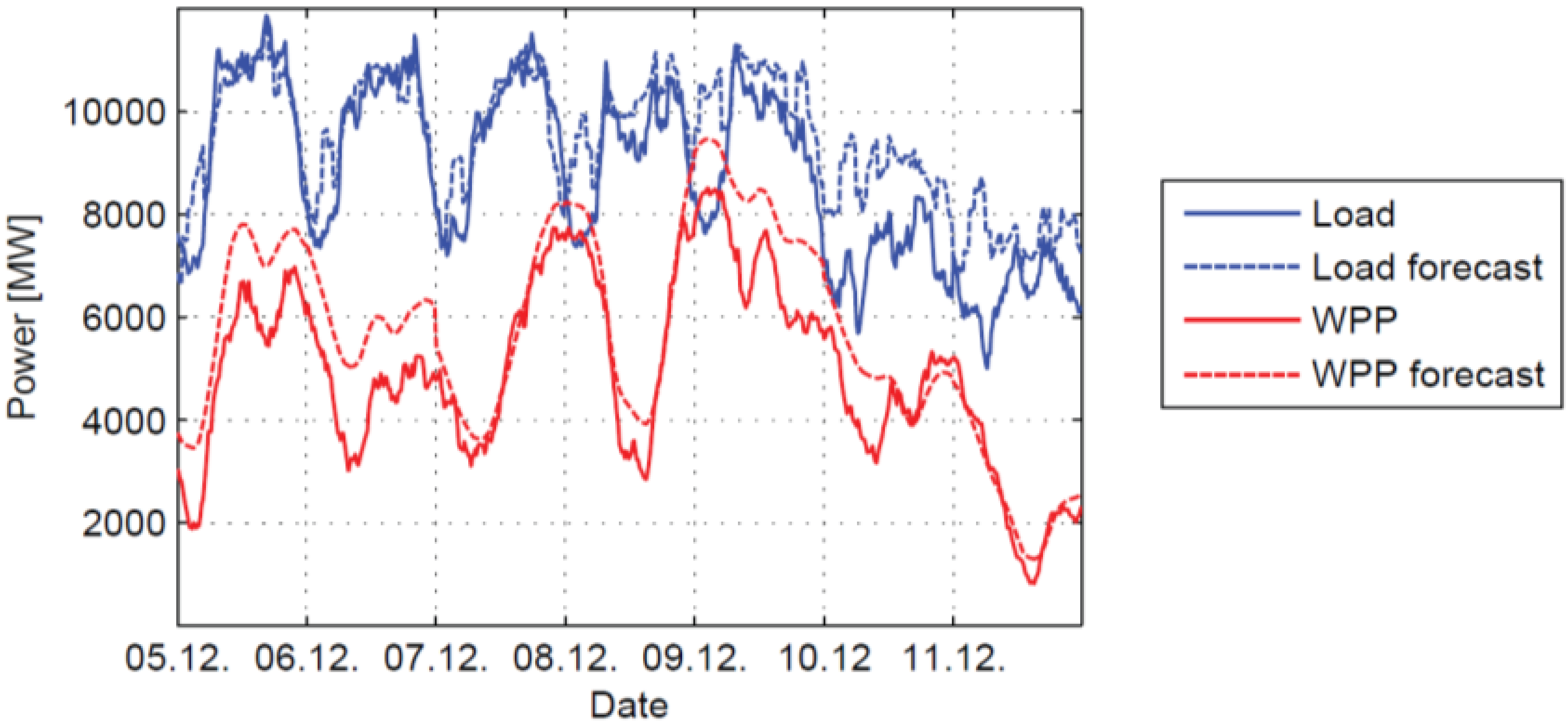
Smoothing effect of variability



Pan-European balancing can reduce storage needs of wind+PV by a factor of 11 compared with regional storage

Source: Fraunhofer IWES

Wind forecasts are not that bad…

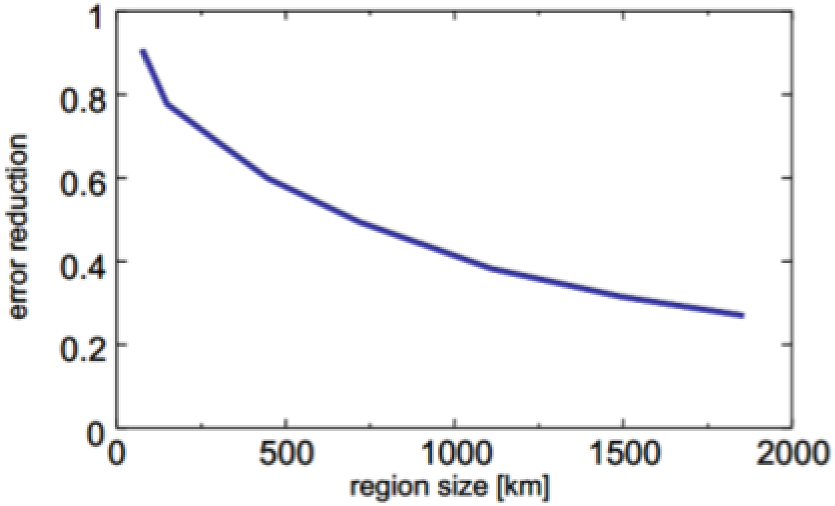


- Actual and predicted load and wind power forecasts in the 50Hertz area in Dec. 2011

 Sources: Jaehnert (NTNU), www.50hertz.com

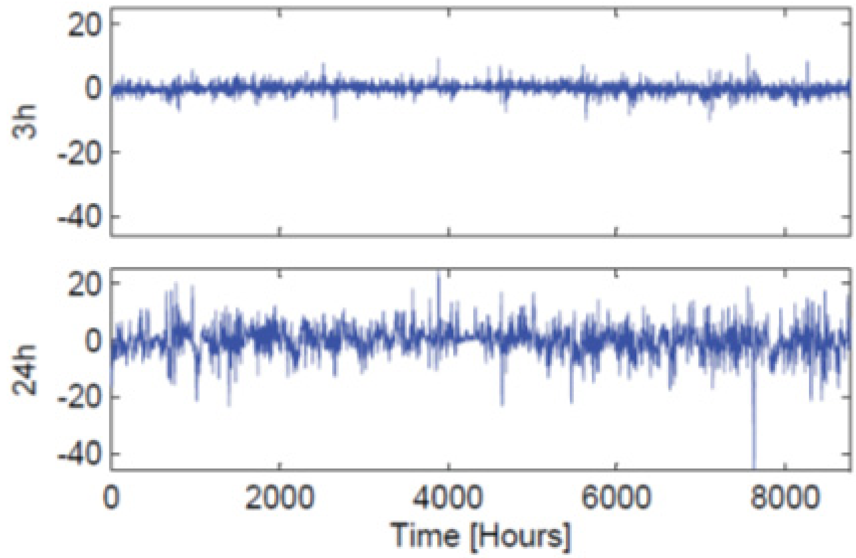
..but forecast horizon and geograpichal spread are essential

Geographical smoothing of forecast errors
based on 40 German wind farms



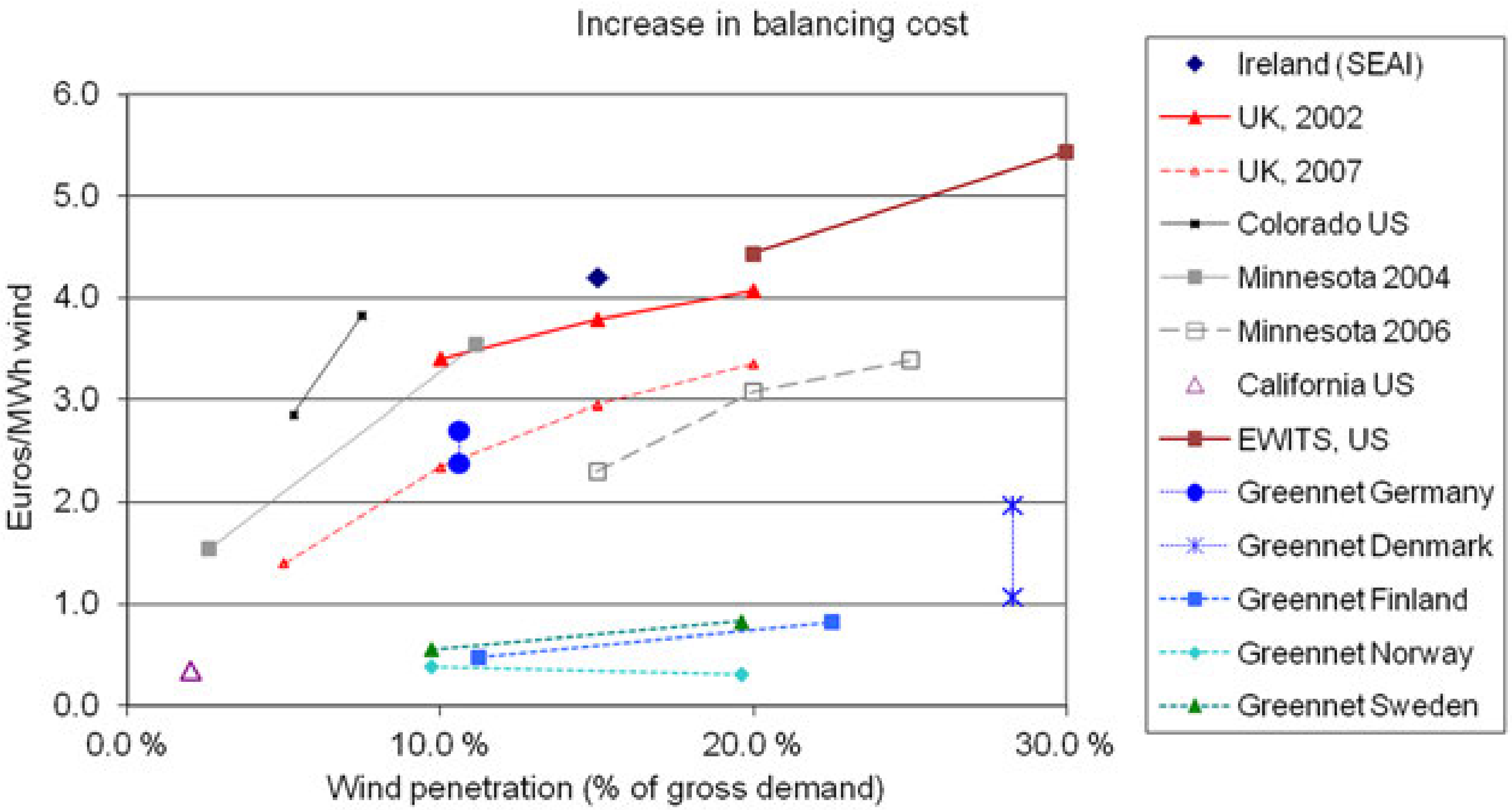
Source: energy & meteo systems, IEA Wind

Simulated forecast error [GW] in Northern Europe in 2020

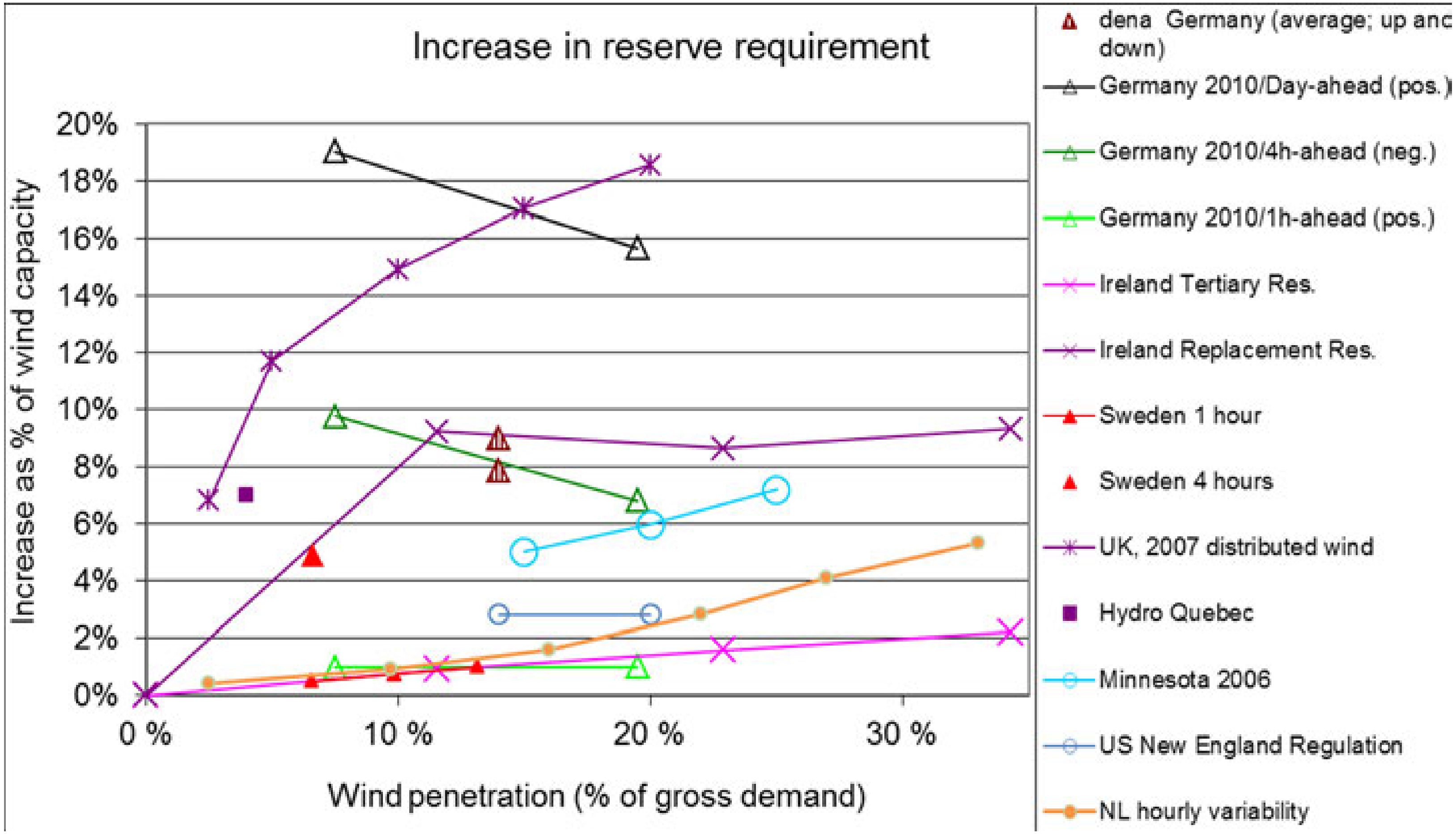


Source: Jaehnert (NTNU)

Increase in balancing costs due to wind



Increase in reserve requirement due to wind



Study model 1 – Integration of balancing markets

Fundamental model

Detailed water course description
About 300 thermal power plants
Transmission corridors (NTC)

Northern Europe

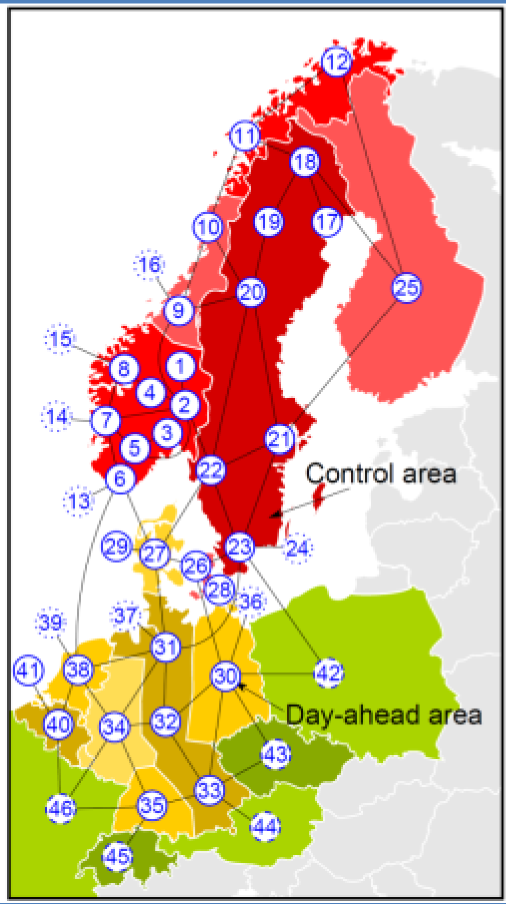
Denmark, Finland, Norway, Sweden
Germany, Netherlands, Belgium

System scenarios

2010 – current state of the system
2020 – a future state of the system

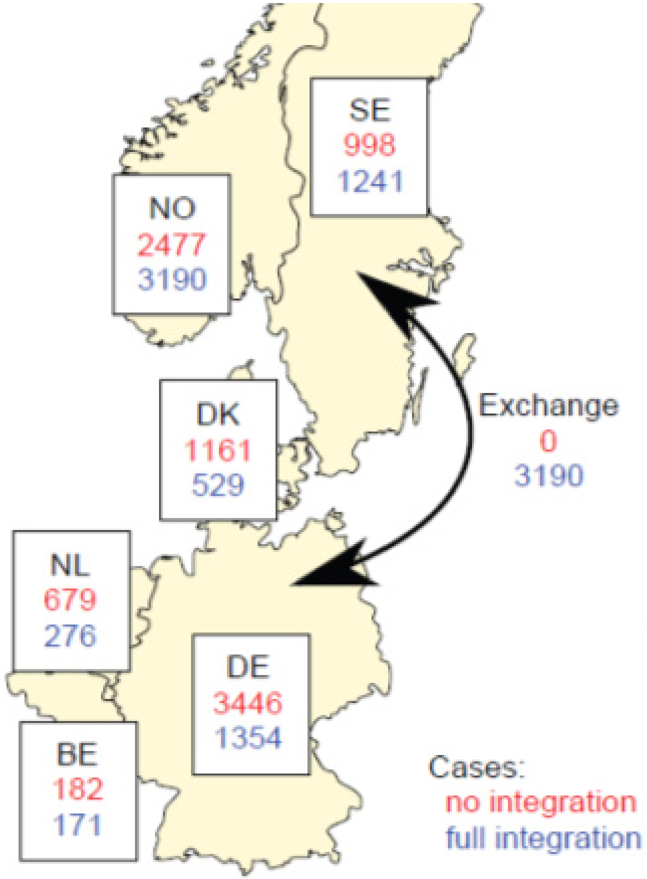
Several climatic years

Hydrology (Inflow)
Temperature
Wind speed

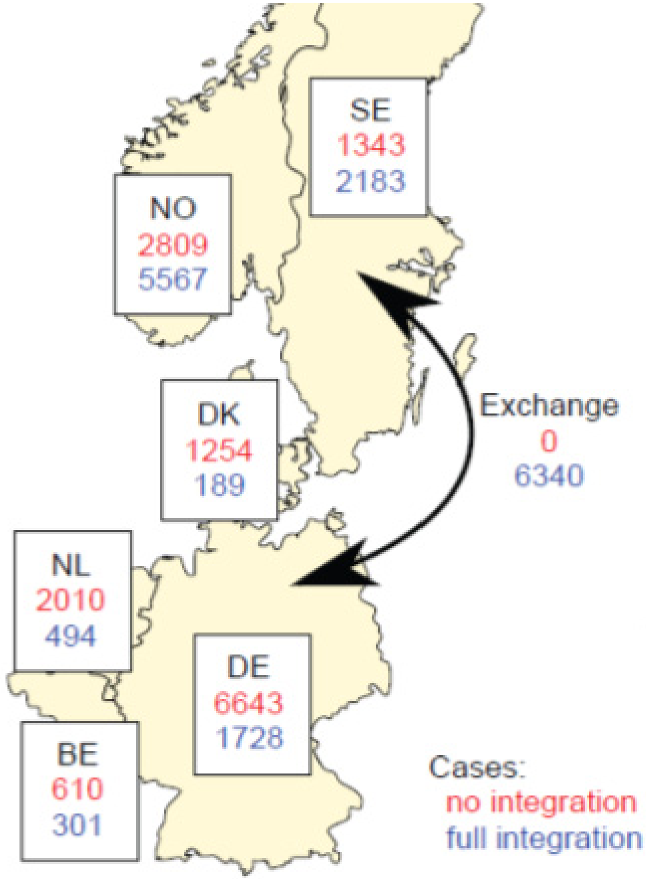


Source: Doorman (NTNU)

Country wise annual balancing reserve allocation (GWh/yr)



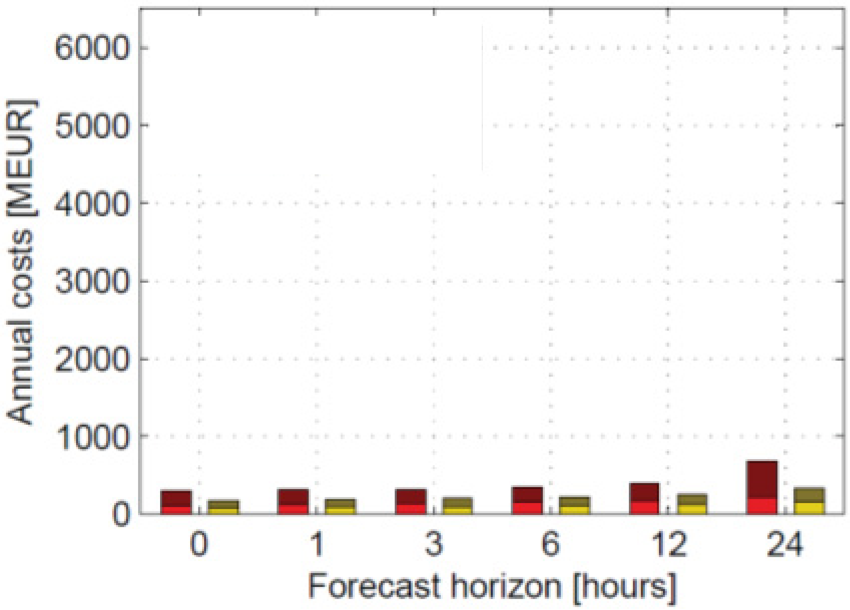
(a) 2010



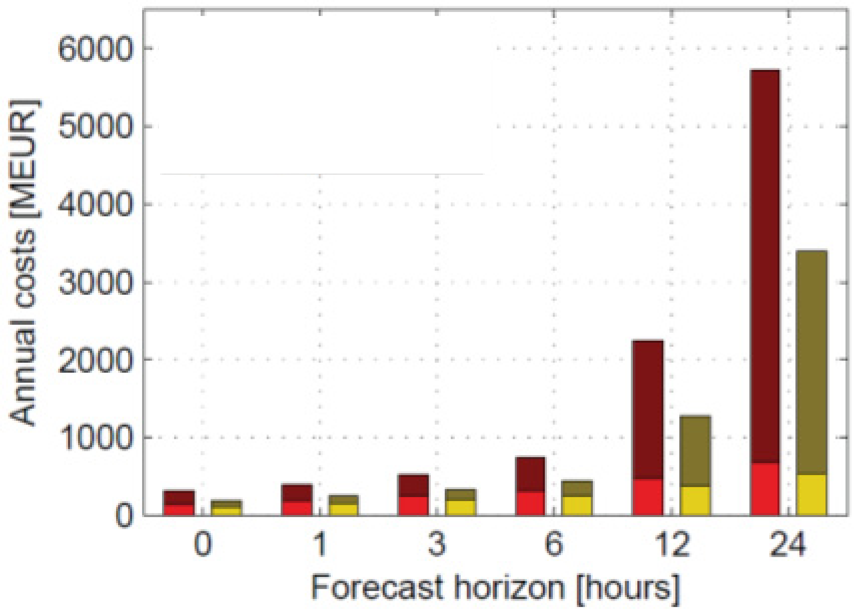
(b) 2020

Source: Jaehnert (NTNU)

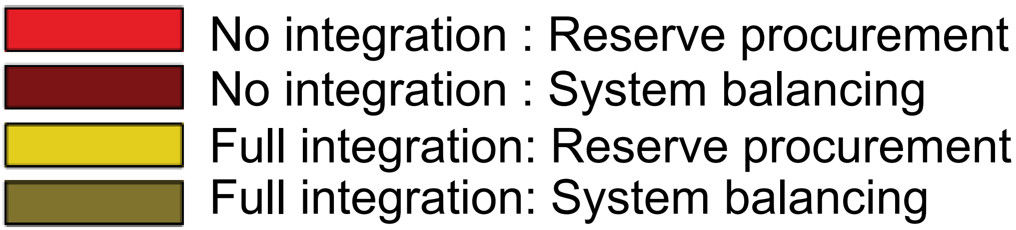
Total balancing market costs for different wind forecast horizons



(a) 2010



(b) 2020



Source: Jaehnert (NTNU)

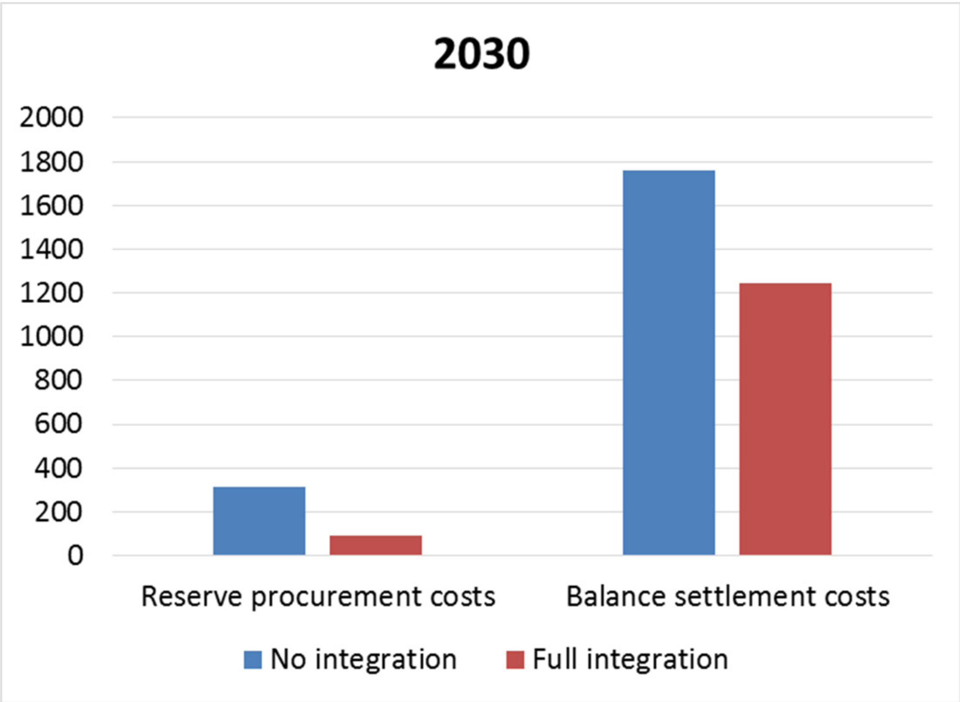
Study model 2 – Integration of balancing markets

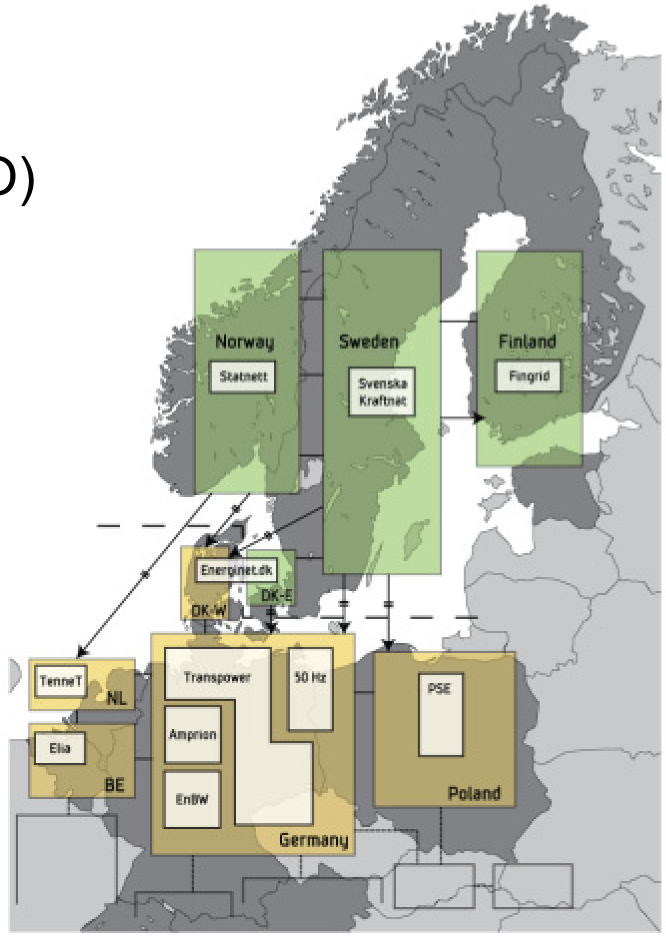
- Detailed European grid model based on DC power flow
- Representation of day-ahead, intra-day and balancing markets
- Co-optimizating day-ahead scheduels and reserve procurements based on forecasts
- Scenarios for load, generation and grid capacity year 2020 and 2030

Source: Farahmand (NTNU/SINTEF)

Large benefits of integrating the Northern and continental balancing markets

Total annual balancing cost savings (Mill.EURO)

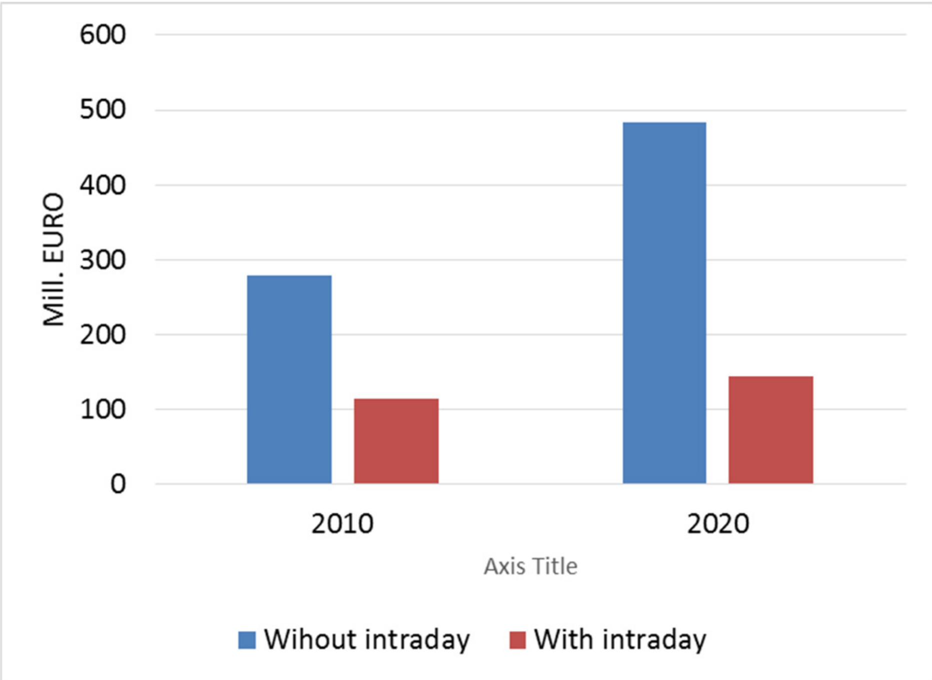




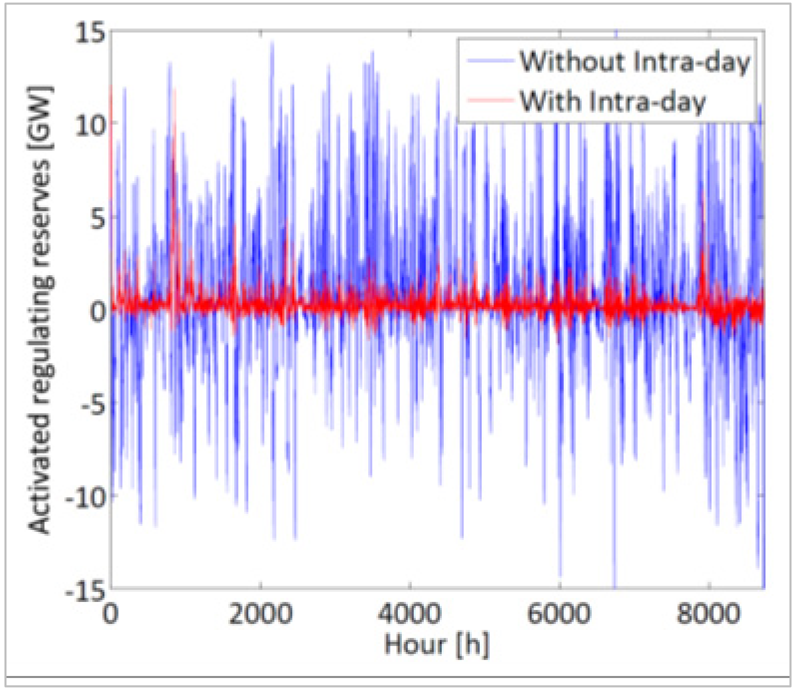
Source: Farahmand (NTNU/SINTEF)

Significant additional savings are achieved with intra-day markets

Total annual balancing cost savings

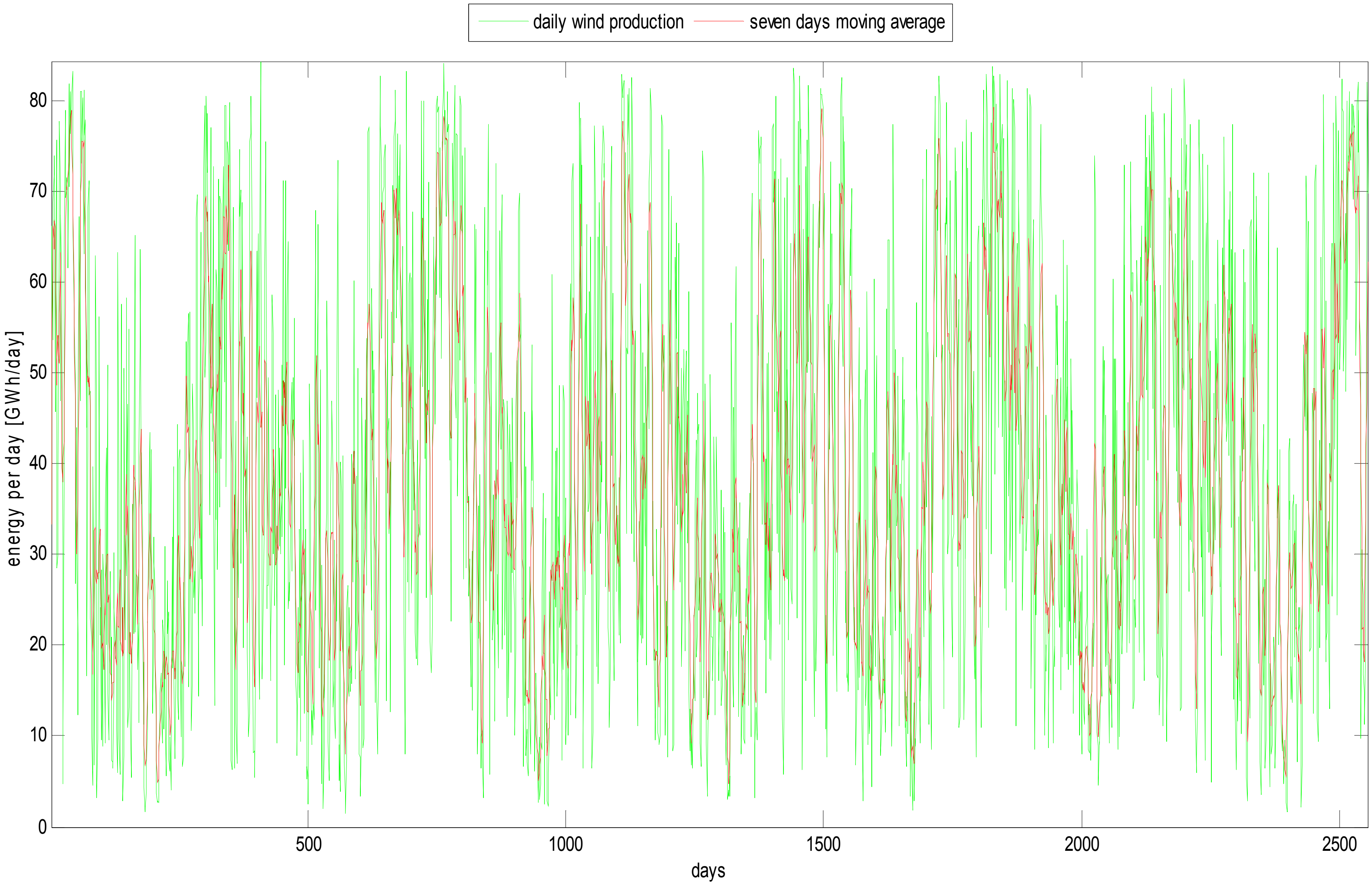


Activated reserves



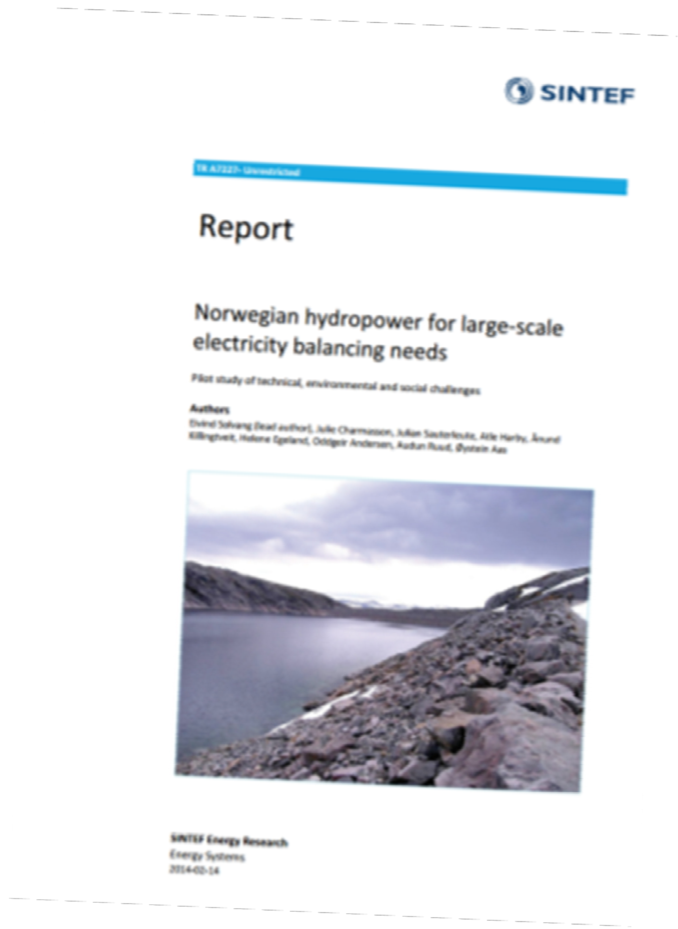
Source: Aigner (NTNU)

Smoothing of offshore wind power variations with Norwegian pumped hydro: A case study

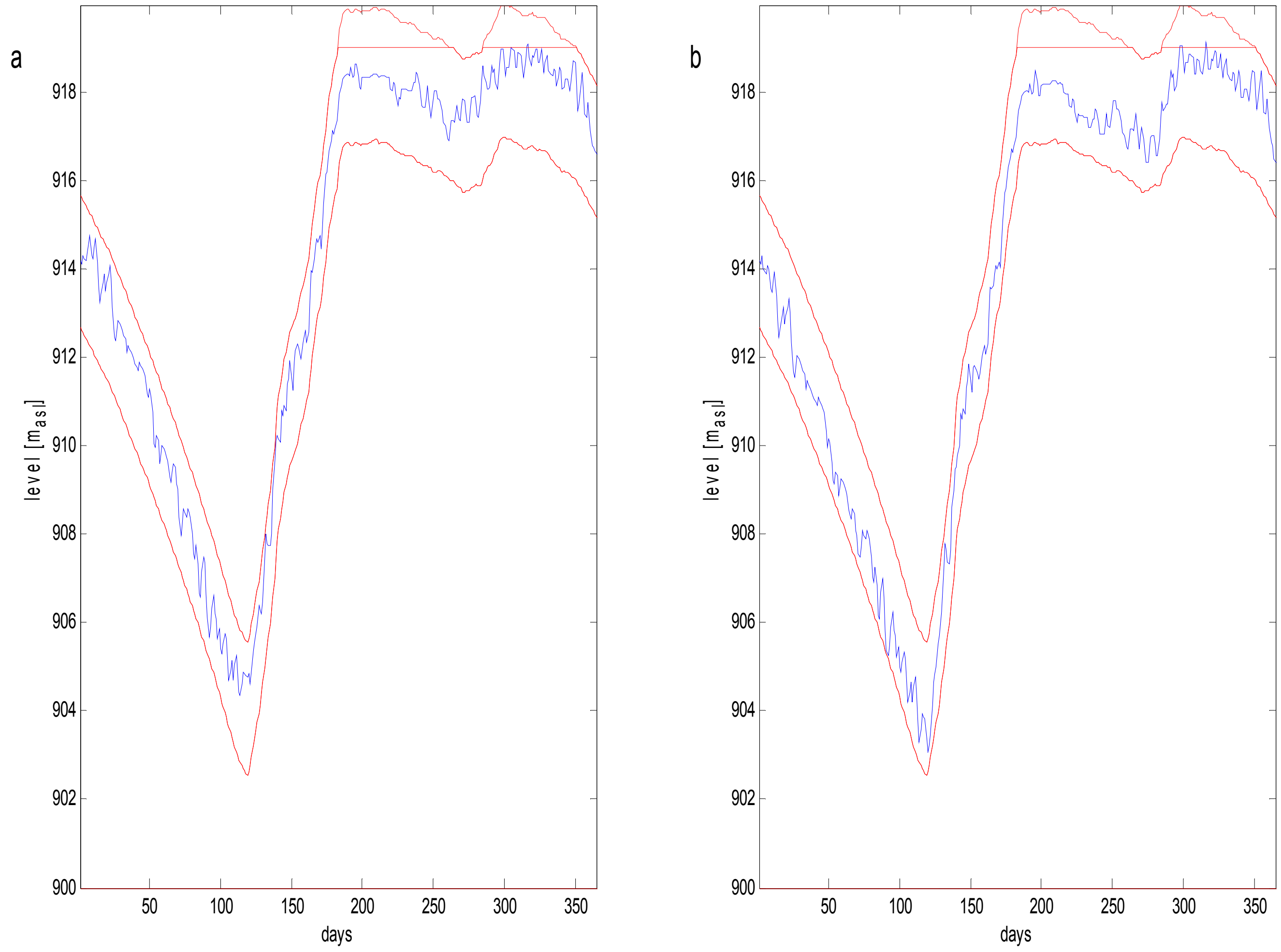


Approach

- Builds on previous work and case study at SINTEF Energi
- New optimization model is developed
- Adress the trade-off between
  - Fulfilling the balancing request
  - Not deviating from planned reservoir level target
- Different time-steps and planning horizons are investigated



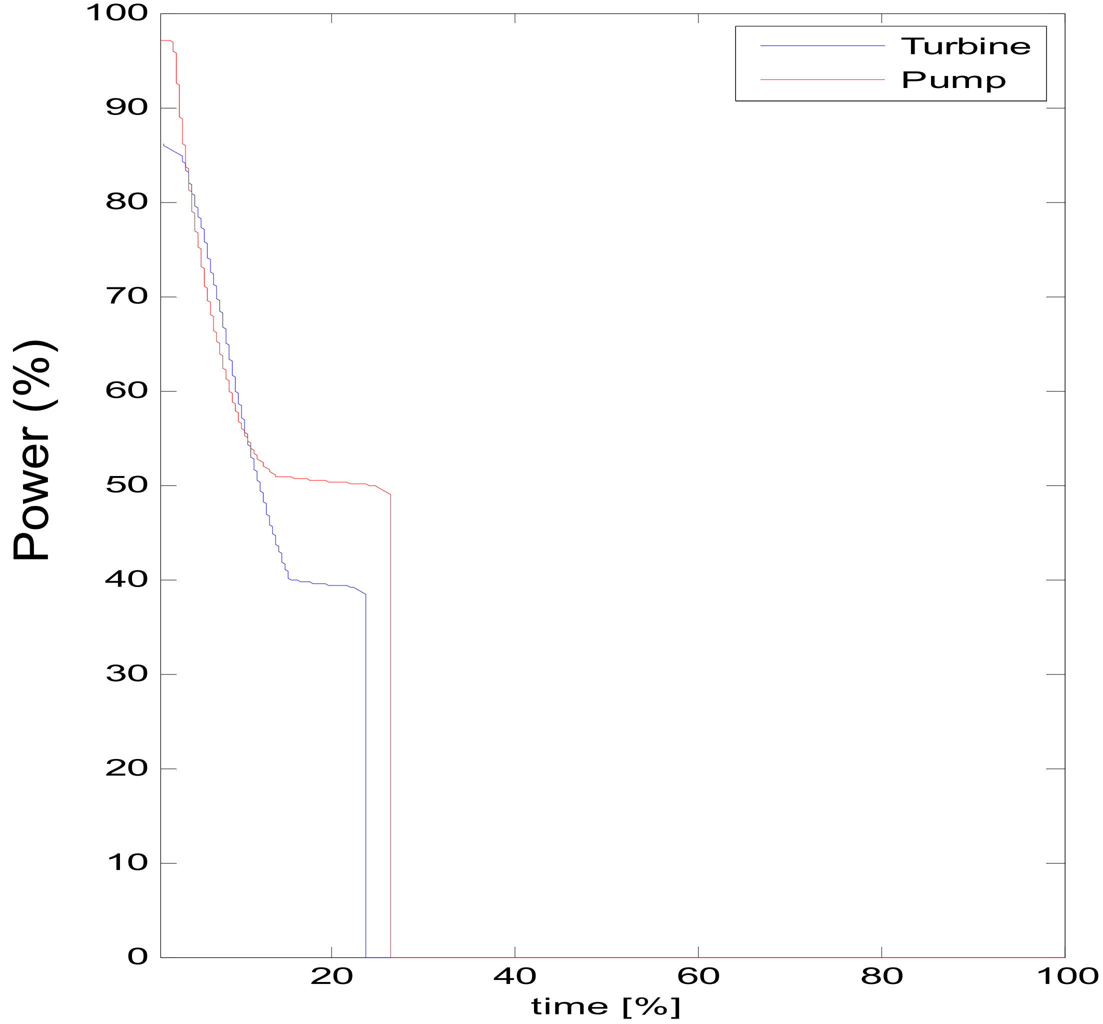
Perfect forecast vs «rolling horizon» strategy



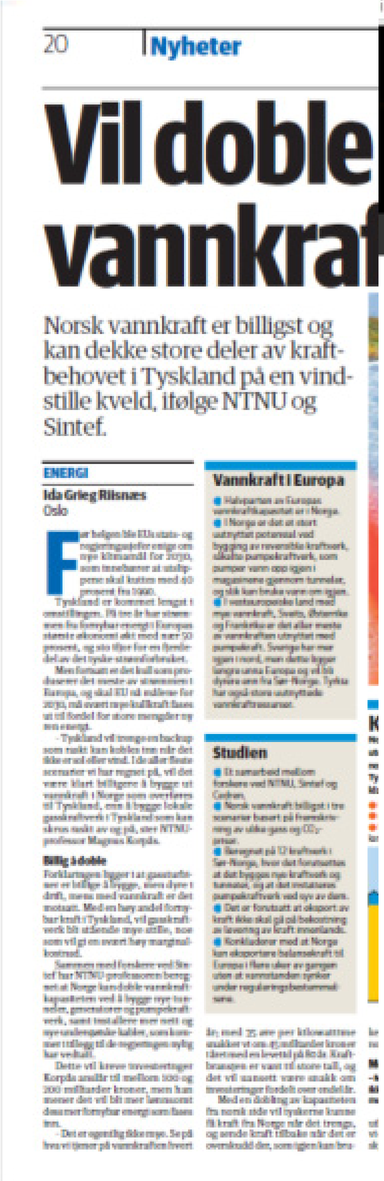
Sensitivity of operation strategy parameters

Hydropower plant	Bands on the levels	β_{usag}	Balancing request $= \lvert E_{br} \rvert$	Balanced energy $= \lvert E_{be} \rvert$		Unbalanced energy $= \lvert E_{uel} \rvert + \lvert E_{uee} \rvert$		Lack of production $= \lvert E_{uel} \rvert$		Excess of production $= \lvert E_{uee} \rvert$	
	(m)		(GWh)	(GWh)	(%)	(GWh)	(%)	(GWh)	(%)	(GWh)	(%)
Holen	± 0.5	0.98	33230	23188	70	10042	30	6687	67	3356	33
Holen	± 1.5	0.98	33230	23257	70	9973	30	6588	66	3386	34
Holen	± 3.0	0.98	33230	23271	70	9959	30	6561	66	3398	34
Rjukan	± 0.5	0.95	36717	14273	39	22444	61	16851	75	5593	25
Rjukan	± 1.5	0.95	36717	14280	39	22437	61	16724	75	5713	25
Rjukan	± 3.0	0.95	36717	14257	39	22460	61	16650	74	5811	26
Tonstad	± 0.5	0.98	32870	23112	70	9758	30	6180	63	3578	37
Tonstad	± 1.5	0.98	32870	23037	70	9833	30	6298	64	3534	36
Tonstad	± 3.0	0.98	32870	22897	70	9972	30	6279	63	3693	37

Usage of pump-generation pair



Media contributions



20 Nyheter

Vil doble vannkraf

Norsk vannkraft er billigst og kan dekke store deler av kraftbehovet i Tyskland på en vindstille kveld, ifølge NTNU og Sintef.

ENERGI

Ida Grieg Riisnæs
Oslo

Vannkraft i Europa

Studien

Billig å doble

illigste-batteri/

GEMINI.no

FORSKNINGSNYTT FRA NTNU OG SINTEF

Teknologi Energi og miljø Naturvitenskap Fisk og havb

I framtida kan norske vannkraftmagasin bli viktige når det ikke blåser ... blåser igjen, kan billig overskuddskraft brukes til å pumpe vann tilbak

Norge er Europas billigste b

Norsk vannkraft er den rimeligste energikilden Tysklan... solceller og vindkraft, viser ferske beregninger.

Av Svein Tønseth
Publisert 28.10.14

– Tyskland har fått mye sol- og vindkraft inn i energisystem... må ha tilgang til strømkilder som kan kobles raskt inn når s... Magnus Korpås. Han er vitenskapelig rådgiver ved SINTEF

Sammen med kolleger fra SINTEF har han det siste året re... koste å dekke Tysklands back-up-behov. Forskerne har be... for to konkurrerende løsninger:

Onsdag 3. juni 2015

Meninger | 33

FNs klimapanel

Kronikk

«Det overveldende flertall av det norske folk anser religion for å være et personlig anliggende uten mellomfolkelig konsekvens.»
Ordet fritt, neste side >

FNs klimapanel lanserte sin femte hovedrapport før jul. Der stadfester panelet at det er ekstremt sannsynlig at menneskeskapte klimagassutslipp har forårsaket over halvparten av den observerte temperaturøkningen de siste seksti år.

Viktig rolle i et fornybart Europa

Kronikk

MAGNUS KORPÅS

AMUND KILLINGTVEIT

WP 2 in brief so far

- Balancing cost comparison PHS vs Gas
  - EEM 2015 paper by Korpås, Wolfgang, Aam
  - MSc Thesis Hanne Ommedal
- Cost comparison of energy storage options in progress
  - PHS, Batteries, Power2Gas, Flywheels, Compressed Air
- PhD-candidate Ingeborg Graabak started sep 2014
  - 2 papers submitted
    - “Variability Characteristics of wind and solar power resources – a review with focus on Europe”
    - “Balancing of variable wind and solar production in Continental Europe with Nordic hydropower – A review of simulation studies”
- Simulation study of PHS wind power smoothing
  - Guest researcher Nicola Destro, Univ. of Padova
- Several media contributions and public presentations on the role of Norwegian (pumped) hydro in the future European energy system