NTNU – Trondheim
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Norwegian pumped hydro for providing peaking power in a low-carbon European power market

Cost comparison against OCGT and CCGT

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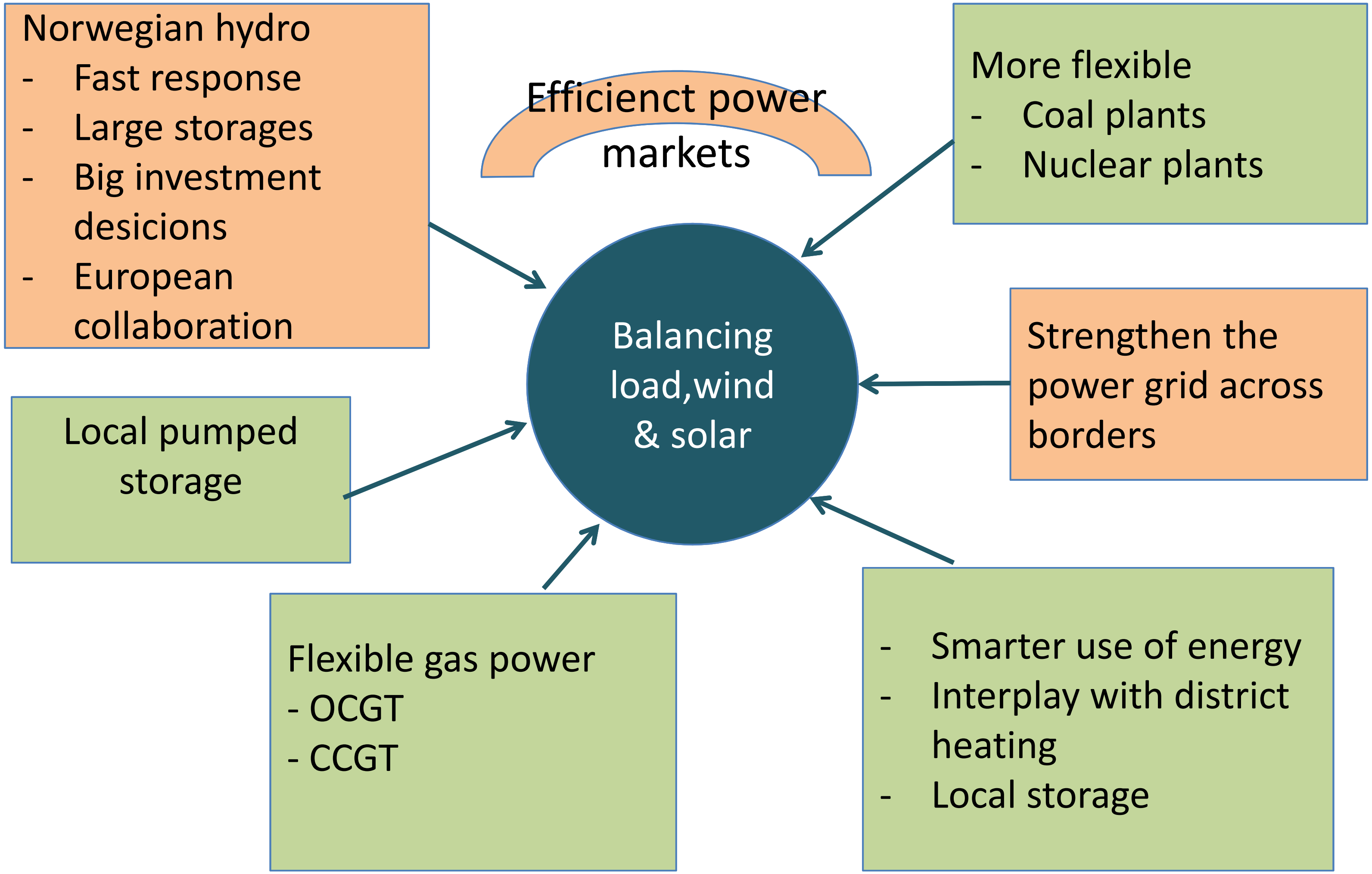
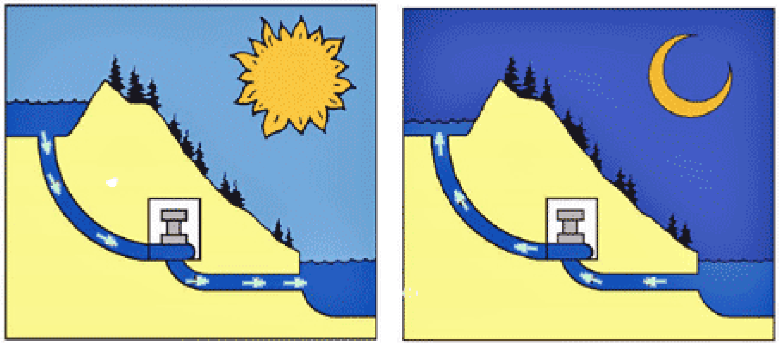
Flexibility options in Europe



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



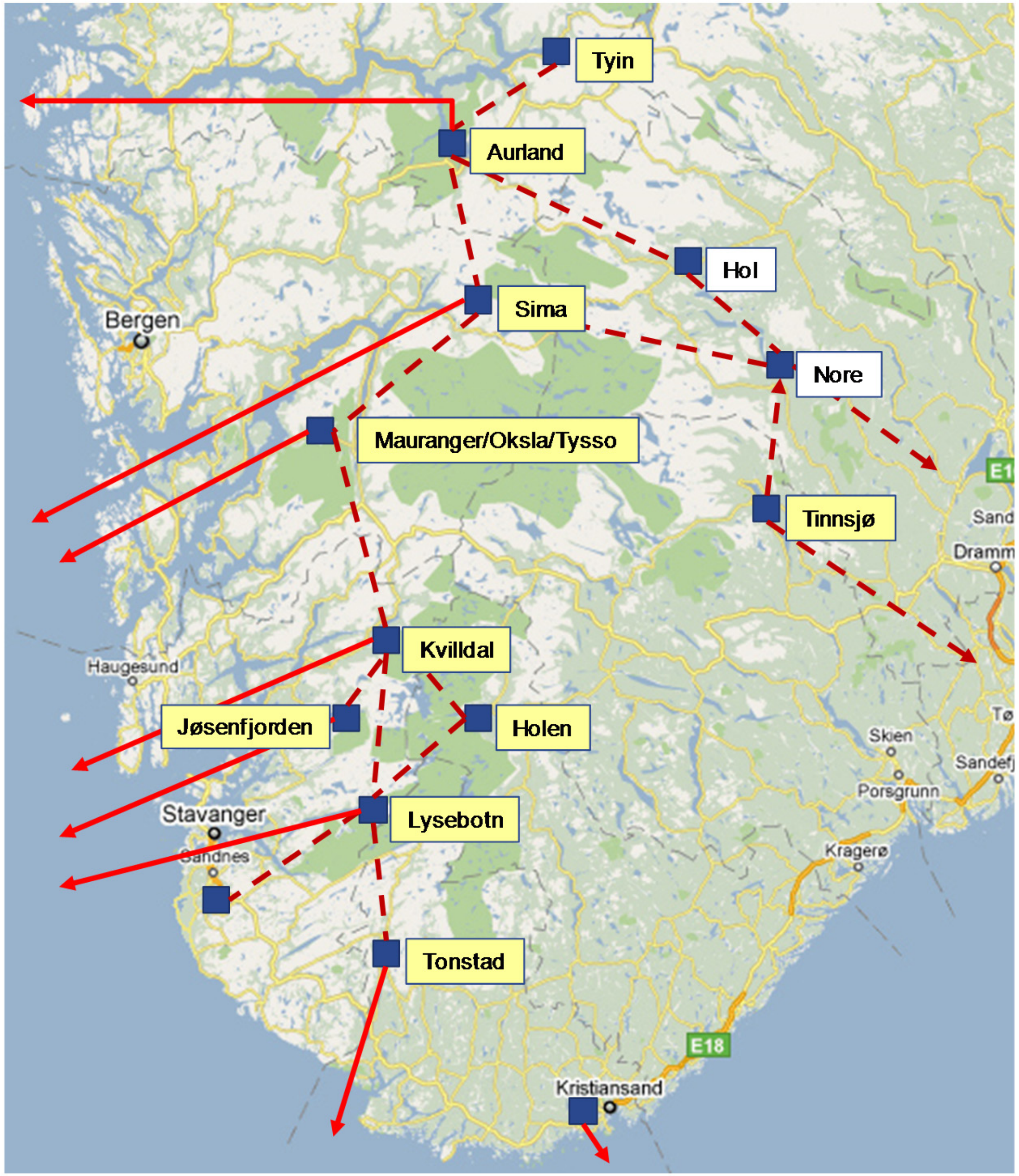
What is the value of the lake Blåsjø??

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

→ 8 TWh of home batteries cost 2800 Billion $

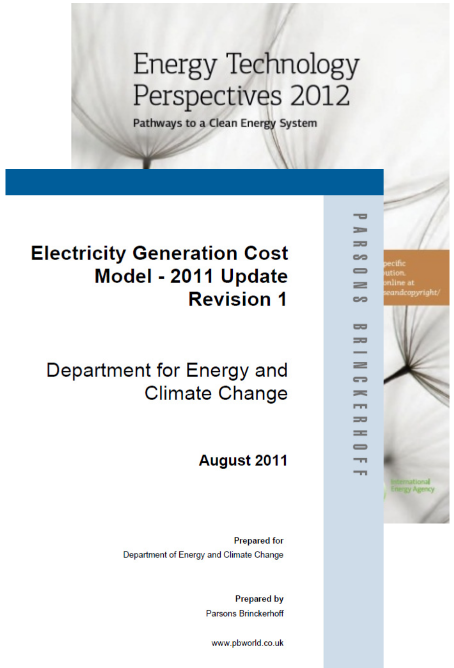
Case study 2030

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

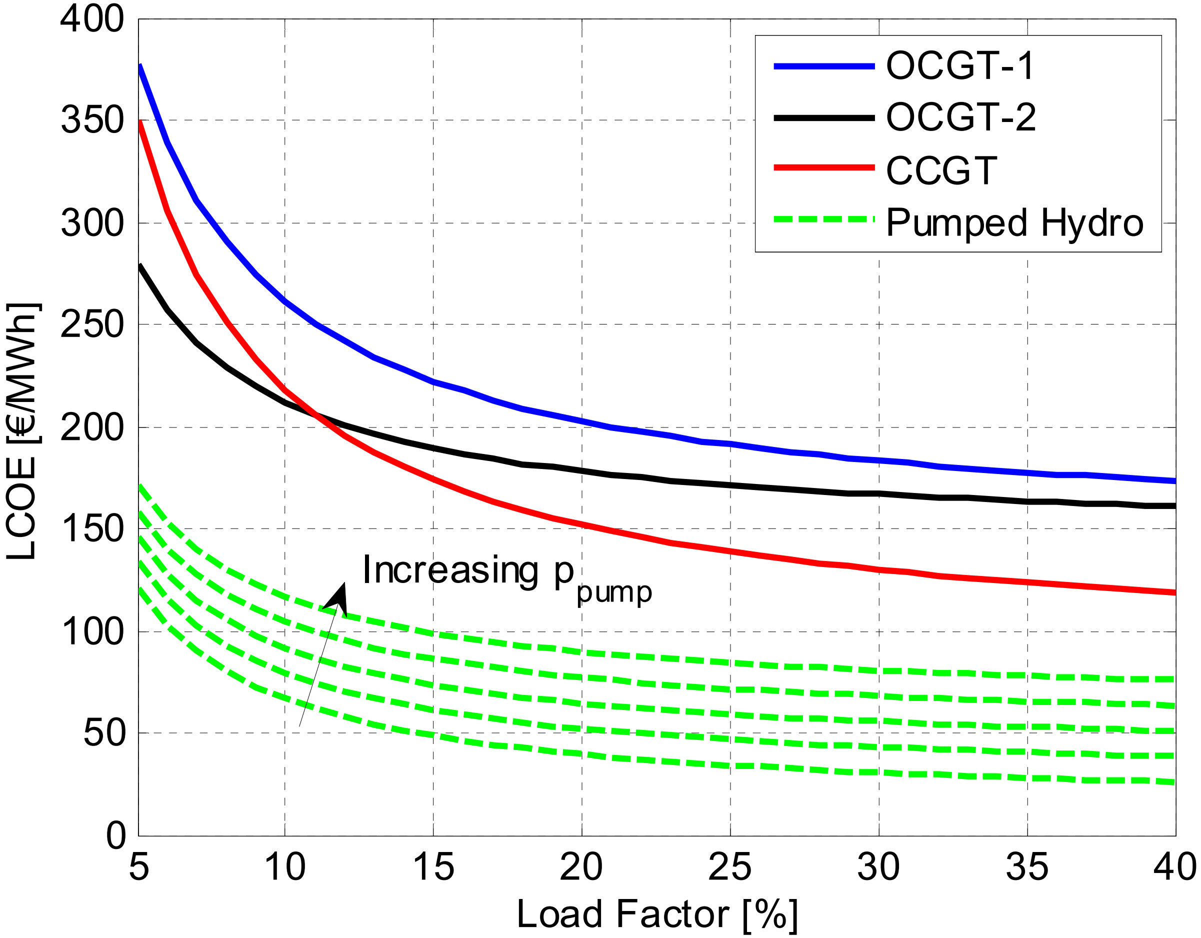
$$LCOE = \frac{\text{Specific InvCost} \cdot (\text{AnnuityFactor} + \text{O\&Mpct})}{\text{Availability} \cdot \text{FullLoadHours}} + \sum \text{VariableCosts}$$

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

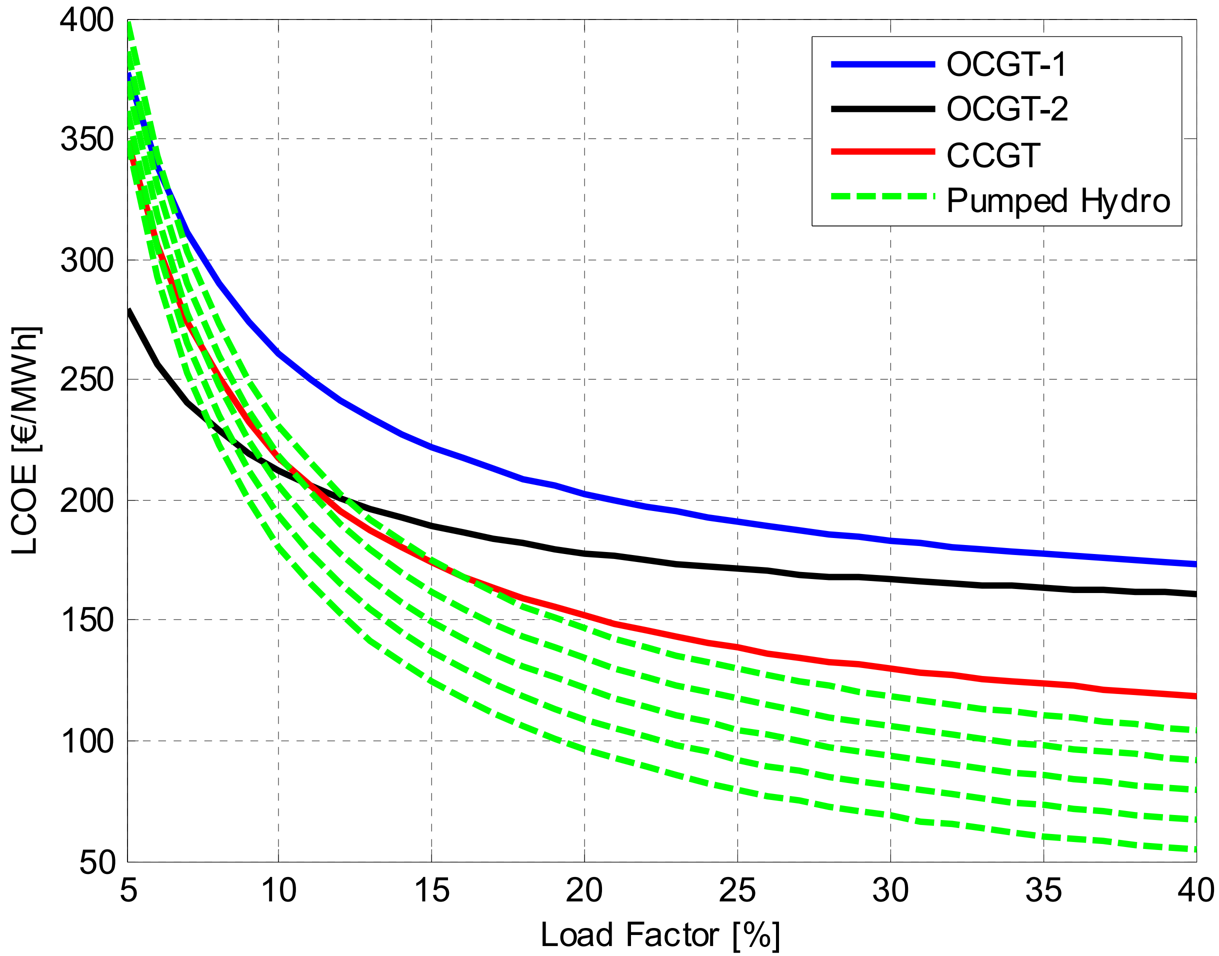
Natural gas → $(p_{ng} + p_{CO_2} \cdot e_{ng})/\eta_{ng}$

Pumped hydro → p_{pump}/η_{ph}

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 pumped hydro

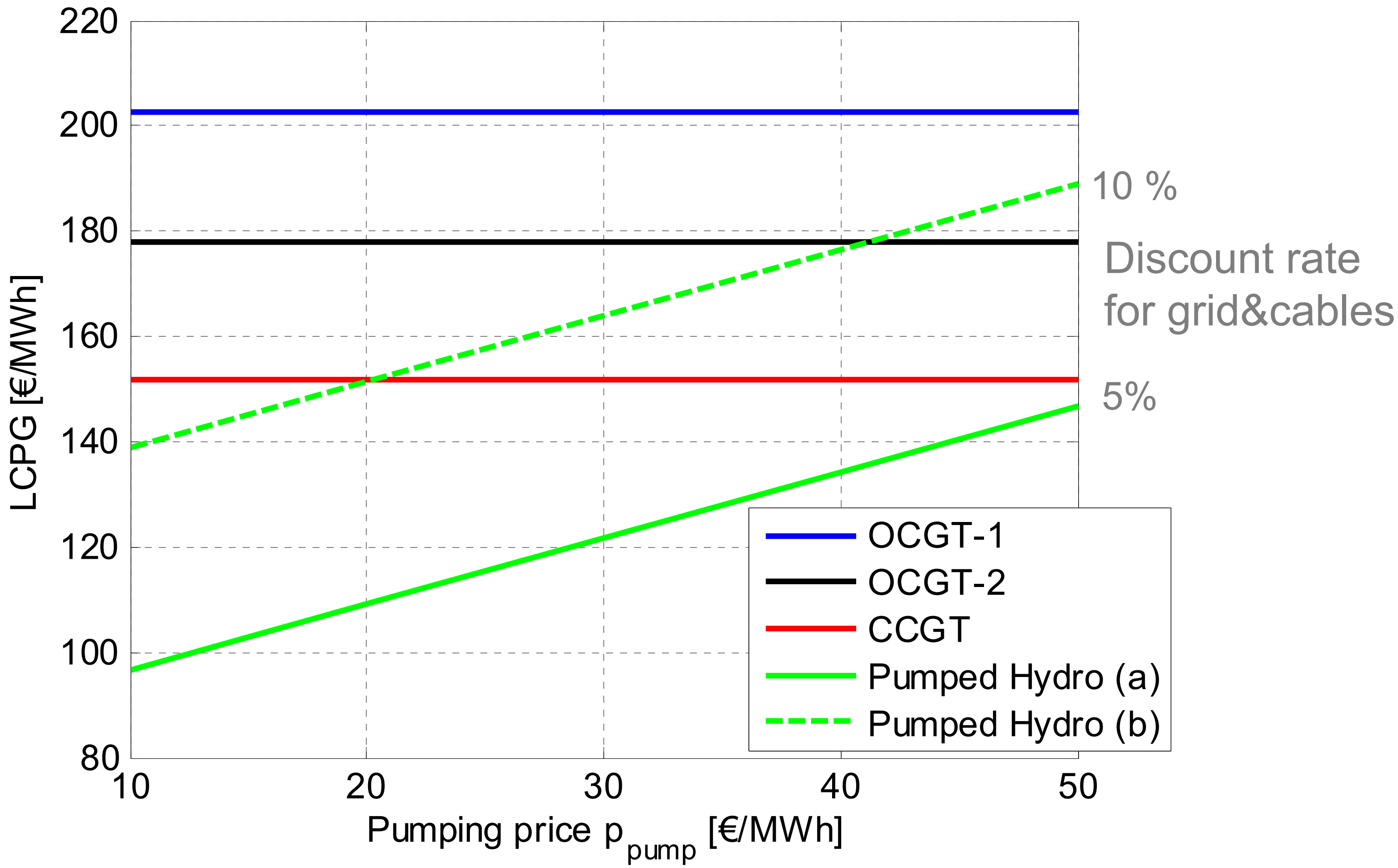
- Peak generation must cover the residual load
  - This is the basis for the cost comparison
- In addition, pumped hydro can be used for price leverage the rest of the year
  - Dependent on relative price variations vs storage efficiency
  - Dependent on plant characteristics and storage volumes
  - Dependent on production planning methods

Peaking Full Load Hours $T_{ph,peak} = T_{ng}$

Total Full Load Hours $T_{ph} \geq T_{ph,peak}$

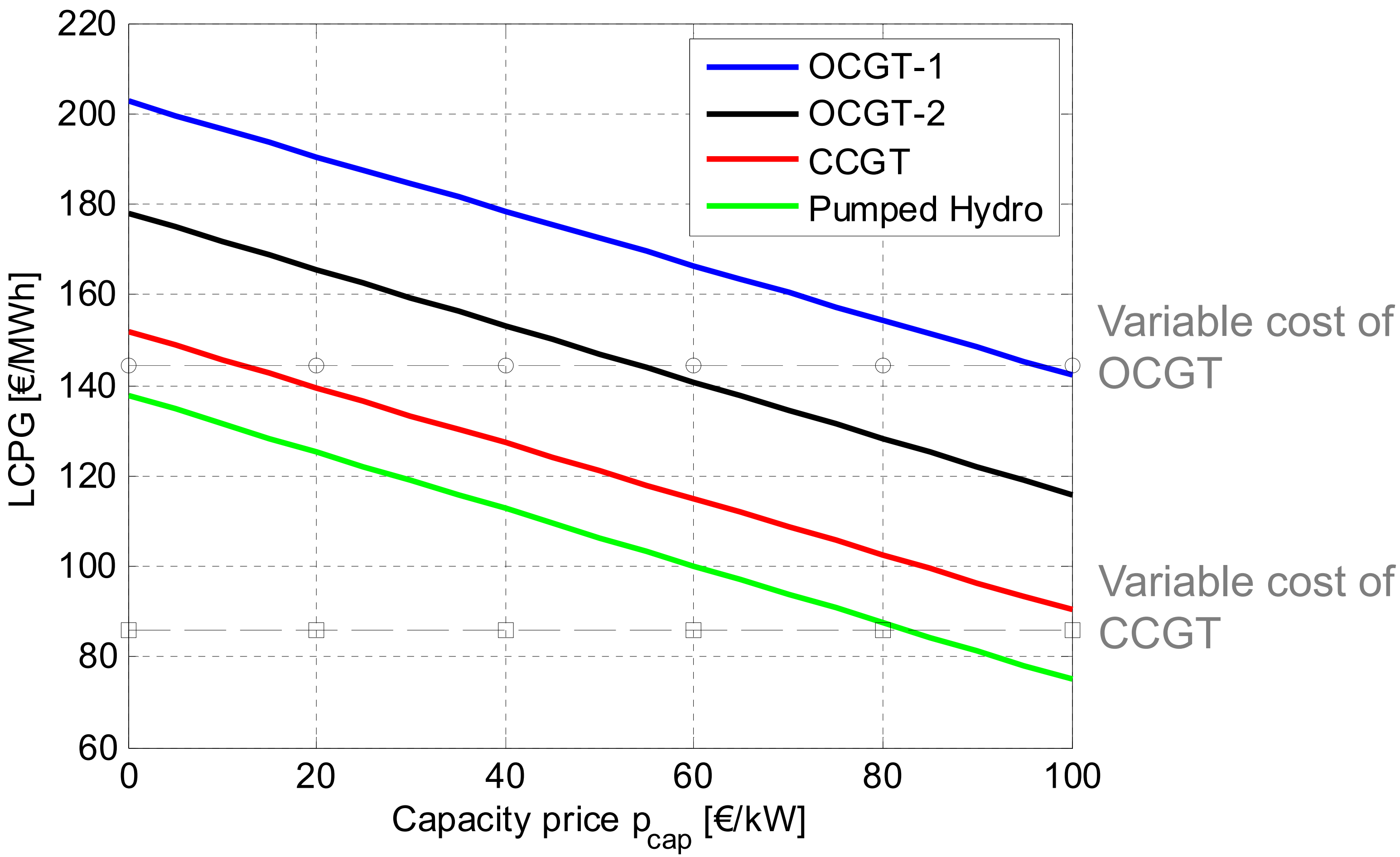
LCPG for 20 % load factor

Sensitivity on pumping price and cable discount rate



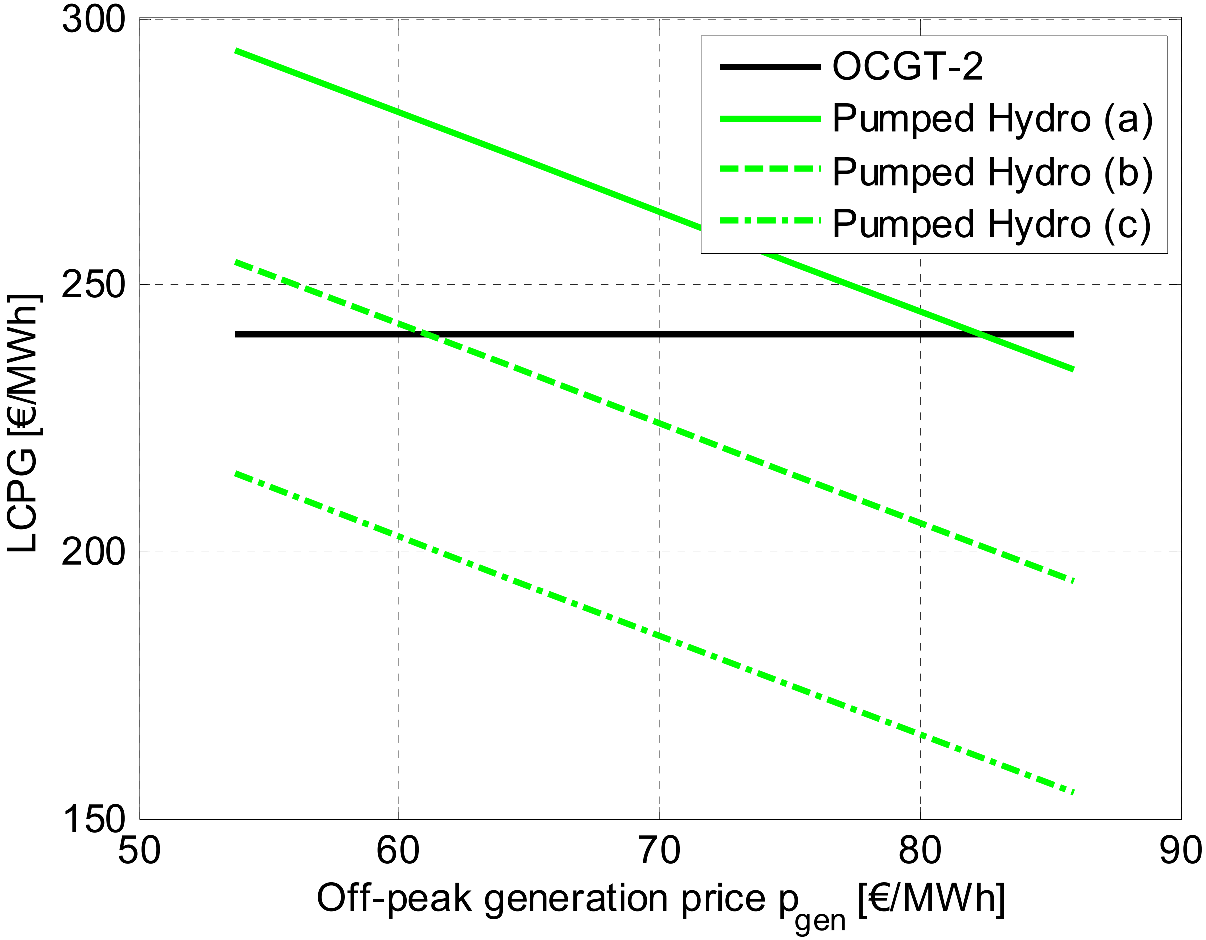
LCPG for 20 % load factor

Sensitivity on capacity price



LCPG for 7 % load factor

Sensitivity on off-peak prices and cable costs



Cable&grid costs covered by Norw. pumped hydro

100 % of total

75 % of grid costs

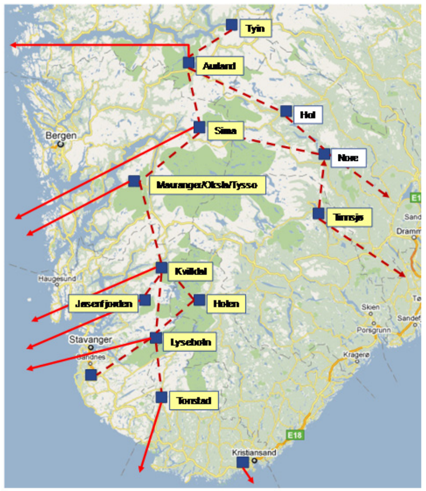
50 % of grid costs

Summary

- 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

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



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