CEDREN
Centre for Environmental Design of Renewable Energy

HydroBalance Policy Brief 2/2016

Cost of flexible generation and storage

Main findings

This work has analysed the cost of providing flexible generation from Norwegian pumped hydro plants as an alternative to thermal "backup" power plants in a European power system with high penetration of wind and solar power. The well-established method of Levelized Cost of Electricity (LCOE) have been applied, with some modifications to represent pumped hydro in a realistic way.

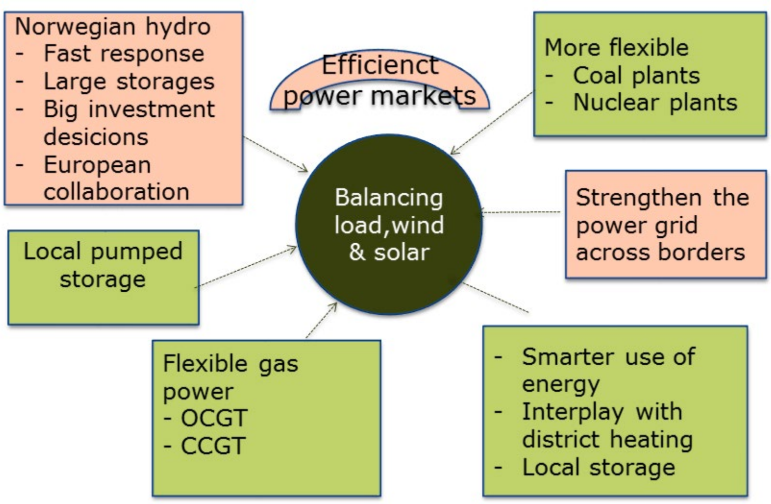
The results from the case study gives clear indications that building new reversible pumping stations between existing reservoirs in the Norwegian hydro system can be economical advantageous over new flexible thermal generation in Northern Europe, even when including additional costs of subsea cables across the North Sea and corresponding reinforcements of the mainland grid.

Key take-away from the cost analysis are:

- Conventional hydropower is cheapest flexible generation technology
- For a combination of unfavourable pumping price and load factor, pumped hydro becomes more expensive than gas power. Otherwise, pumped hydro from Norway is preferable, even when taking into account sea cables and grid upgrades for connection to the European market.
- The cost of electricity from coal power plants with carbon capture and from nuclear power has a high spread due to big uncertainties in investment and decommissioning costs.

As with all types of economic analyses and comparisons, the results are of course determined from the assumptions and data that has been used. To build confidence in the method and results, it is necessary to perform sensitivity analysis on critical parameters and let the model simplifications and presumptions be as transparent as possible. With respect to this work, the interested reader can use the developed Excel model herself, adjusting any parameter to see the effect on LCOE.

Figure 1. *Flexibility options for balancing of variable renewables in Europe.*



Introduction to the study

European climate and energy goals towards 2030 and 2050 imply massive integration of wind power and solar power, which are variable of nature and often difficult to forecast. To be able to operate the European power system in an efficient and secure manner in the future, it is necessary to exploit several means to provide sufficient flexibility in the system. An opportunity that has received increased attention the last years, is to expand the Norwegian hydropower system with new pumping facilities in order to contribute with significant balancing and peak load power in Continental Europe and UK. **Figure 1** shows the main categories of flexibility that has been identified for balancing the *residual demand*, i.e. the demand subtracted wind and solar generation. Green boxes illustrate options that can be realised within one country while red boxes refer to alternatives that requires extensive cross-border collaboration. In brief, the options in the green boxes are easier to implement, but synergy effects - and thus economic gains - between countries will remain unutilized.

The aim of this part of HydroBalance WP2 is to study the costs of expanding Norwegian hydropower system to provide balancing and peak power in a future European power market with high shares of variable renewable resources. In this context we refer to balancing of variation for residual demand due to fluctuating renewable generation, and not specifically to the balancing market and activation of reserves. The main question raised here is whether new hydro stations (with and without pumping) are attractive compared with new thermal generation technologies based on coal, gas and nuclear power. The study has been conducted partly by researchers at NTNU and SINTEF Energy [1] and partly through a master thesis at NTNU [2]. The results presented in this Policy Brief is mainly from the master thesis.

Levelized Cost of Electricity

For the comparing of different generating power plants and their costs, the method of *Levelized Cost of Electricity* (LCOE) is often used. LCOE is a convenient measure that summarize the overall competiveness of several different generating technologies. LCOE represents the per-kilowatthour cost of building and operating a power generating plant over its lifetime and duty cycle. LCOE is expressed in net present value terms, which means that all predicted future costs and generation are discounted to a specific date. It can in a more precise way be defined as (DECC, 2013) *"the ratio of the net present value of total capital and operating costs of a generic plant to the net present value of the net electricity generated by that plant over its operating life"*.

One of the major advantages of the LCOE method is the final single aggregated value that can serve as a proxy. The LCOE method can be used to compare cross technologies even though they have different cost assumptions and structures. Key parameters and assumptions can be adjusted, regarding site specifics or differences between realities in the local and regional market. However, the LCOE method does not give an introduction to the financial performances in the different stages of the projects lifetime. For this, it is necessary to obtain a comprehensive analysis of the cash flows. Here, both cost and revenues may not necessarily be fixed over time, but vary due to different conditions in market, like energy availability, demand and so on. LCOE alone is not enough to make a conclusion about the extent of profitability or how the project respond to the competition to other projects, but nevertheless it is a very useful indicator.

Levelized cost of electricity are in most cases given in this common expression (IEA):

$$LCOE = \frac{\sum_t \frac{\text{Investment}_t + \text{O\&M}_t + \text{Fuel}_t + \text{Carbon}_t + \text{Decommissioning}_t}{(1 + discount\ rate)^t}}{\sum_t \frac{\text{Electricity}_t}{(1 + discount\ rate)^t}}¶$$

Table 1. *Drivers and barriers at the national level.*

Parameter	Information
t	Year of lifetime [0,1,2,..]
Electricity	Electricity: Produced quantity of electricity in the respective year [kWh]
Investment	Investment in year t
O&M	Operational and maintenance cost in year t
Fuel	Fuel cost in year t
Carbon	Carbon cost in year t
Decommissioning	Decommissioning in year t
Discount rate	Discount rate

The spreadsheet model that are used for calculation of LCOE from different flexible generation technologies are available for all HydroBalance partners (send email to magnus.korpas@ntnu.no to receive the Excel model).

Flexible technologies and their costs

The flexible technologies that has been compared are:
- Hydropower with reservoir
- PHSP (Pumped Hydropower Storage Plant)
- Nuclear power
- Gas – CCGT (Combined Cycle Gas Turbine)
- Gas - CCGT with post combustion CCS (Carbon Capture and Storage)
- Gas – OCGT (Open Cycle Gas Turbine)
- Coal – ASC (Advanced Supercritical) with post combustion CCS
- Coal - ASC with oxy combustion CCS
- Coal – IGCC (Integrated Gasification Combined Cycle) with post combustion CCS

Cost estimates and technical parameters used as inputs was obtained from a number of sources. As data for thermal generation technologies are largely based on studies by Department of Energy and Climate Change in UK. Concerning CCS, only carbon capture and compression are included. Estimates for fuel prices and carbon taxes has been fully adapted from World Energy Outlook 2014. NVE and Statnett has been important sources for cost analysis of hydropower and PSHP systems, including costs for HVDC cables in the North Sea and associated grid upgrades at the mainland. The investment cost for PSHP is based on upgrading of existing hydropower plants.

A very important factor in LCOE calculations is the *load factor,* which is the average power output of a power plant relative to its capacity. A load factor of 1 means that the power plant produces at maximum power during the whole year. Traditionally in LCOE calculations, load factors of CCGT and coal power plants have been set very high (typically 0.7-0.9) since they have been expected to cover much of the base load in a power system. With integration of more wind and solar power (which has zero marginal costs) the thermal power generation must be reduced more frequently, leading to lower load factors, and consequently higher LCOE values.

The strategy for pumping and generation with PHSP depends on several factors such as the reservoir levels, forecasts of power prices and forecasts of hydro inflow. In cascaded hydro systems, which are common in the Nordic countries, the optimal pumping/generation strategy of one lower/upper reservoir pair also depends on the reservoir levels and generation potential in other parts of the hydrological coupled area. However, instead of performing detailed optimization and simulation studies, a simplified method has been used as a first approach to calculate the LCOE of pumped hydro, by specifying the average electricity price for pumping (to be on the conservative side, the pumping price is set to the marginal cost of coal) as well as the load factor for generation.

All data used in the analysis can be found in [2] and in the Excel Spreadsheet model that are available for HydroBalance partners by request.

Highlighted results from the cost study

Figure 2 shows the resulting cost of electricity from the various flexible generation technologies for increasing load factor. The fuel and carbon cost scenario is chosen to be the WEO "current policies" scenario with low carbon prices and moderate fuel prices. Similar calculations has been carried out for the WEO "New policies" and "450 ppm" scenarios, but the results does not change substantially due to the combinations of low fuel prices / high carbon prices and vice versa used by the IEA WEO.

Conventional hydropower is the cheapest flexible option except for very low load factors. The reason why pumped storage is cheaper than conventional hydro power for low load is because pumped hydro here refers to upgrading of existing hydropower plants with pumping facilities, while conventional hydropower refers to building a new power plant "from scratch". A third, and cheaper, alternative that has not been quantified in this study, is to upgrade existing hydropower plants with more generation capacity (no pumping).

For very low load factor (less than 0.1) gas turbines are the cheapest option. Above this, Norwegian hydropower (with or without pumping), including North Sea cable costs and grid upgrades, is the preferred choice. Combined Cycle Gas Turbines are always more expensive than hydropower for the assumption used here, but is less costly than the Open Cycle variant for higher load factors than 0.15. All the other technologies requires a relatively high load factor due to high investment costs, which might be challenging in a future European power system with very high amounts of wind and solar power as the "new" base load in the system.

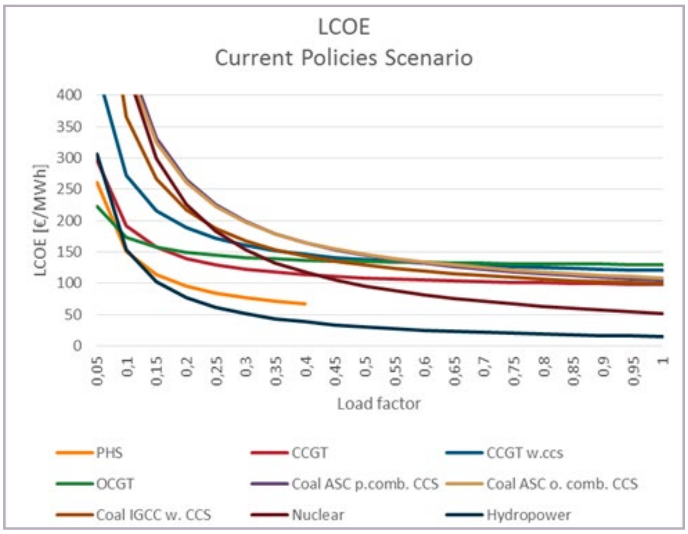


Figure 2. *Levelized Cost of Electricity of various flexible technologies.*

For sensitivity analysis, there is "optimistic" and "pessimistic" scenarios for investment cost, load factor and pumping price, as shown in **Table 1**. The resulting LCOE values are shown in **Figure 3**, and a number of interesting observations can be made:

- Conventional hydropower is cheapest flexible generation technology
- For a combination of unfavourable pumping price and load factor, PHSP becomes more expensive than gas power. Otherwise, PHSP from Norway is preferable, even when taking into account sea cables and grid upgrades for connection to the European market.
- The cost of electricity from Coal CCS and Nuclear has a high spread due to investment (and decommissioning) uncertainty.

Table 1. *Parameter settings for "optimistic" and pessimistic" cases for costs and load factor. All fuel and carbon prices are from IEA WEO 450 ppm scenario.*

	Investment	Load factor	Price for pumping
Optimistic	Low values	0.6 (0.35 for PSHP)	Low [20 €/MWh]
Pessimistic	High values	0.2	High [40 €/MWh]

Facts about the HydroBalance project

The project addresses key questions regarding the increasing need for balancing variable generation from renewable energy sources and providing flexibility by the use of Norwegian hydropower including deployment of pumped storage. These key questions are investigated in the research tasks of five work packages. The interdisciplinary project integrates perspectives on the topic according to CEDREN's vision: technology, nature and society:

WP 1 - Roadmap for energy balancing from Norwegian hydropower

WP 2 - Demand for energy balancing and storage

WP 3 - Modelling and analyses to develop business models

WP 4 - Environmental impacts of new operational regimes in reservoirs

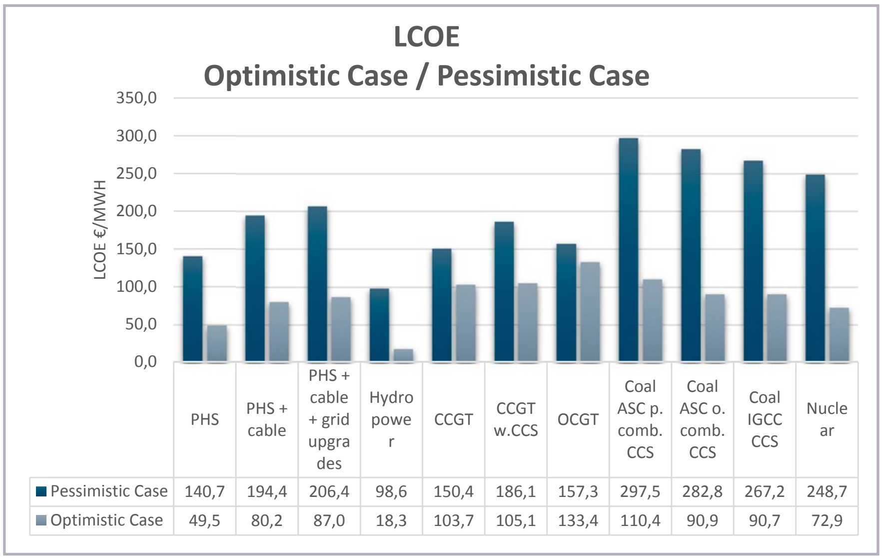
WP 5 - Social acceptance and regulatory framework

Project period: October 2013 to September 2017

Total budget: 25 million NOK

Financing: About 70 percent from the Research Council of Norway, and about 30 percent from industry and research partners from Norway and abroad.

Figure 3. *Levelized Cost of Electricity for "optimistic" and "pessimistic" case.*



References

[1] M. Korpås, O. Wolfgang, S. Aam, "Norwegian pumped hydro for providing peak power in a low-carbon European power market - Cost comparison against OCGT and CCGT", 12th International conference on the European Energy Market, EEM 2015. IEEE Press 2015 ISBN 978-1-4673-6691-5

[2] H. K. Ommedal, "Cost of flexibility in the future European power system", MSc Thesis, NTNU, 2015

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