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

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Abstract

The objective of this paper is to identify the state-of-the-art related to use of Nordic hydropower for balancing and storage of variable wind and solar based power production in the future Northern European system. The following topics are studied: 1) The need for balancing and storage; 2) Possible further development of the Nordic power system; 3) Consequences of different market solutions and 4) Changes in operation patterns of the Nordic system. Twelve scientific papers are reviewed. 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.

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Keywords: Variability; Balancing power; Storage; Hydropower.

1. Introduction

Based on EU targets and ambitions the share of power production from wind and solar resources is expected to continue to grow. In 2050 wind and solar may be as much as 65 % of gross electricity generation in EU [1] (High RES scenario). These resources are variable in its nature and may also be hard to predict. The need for balancing

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and storage is therefore expected to increase with increasing shares of production from wind and solar resources in the power system.

The future solution to the need for balancing and storage may be a combination of several technologies such as more flexible thermal production, local storage in terms of e.g. batteries or flywheels and also to some degree flexibility in demand. In Europe, hydro power can also be an important part of the solution, and the large hydro reservoirs and production facilities in the Nordic region is often mentioned as a one of the main contributions to balancing and storage of variable new renewable production in Continental Europe and UK. Norway alone has approximately half of the reservoir capacity in Europe with possibilities to store about 85 TWh. The production can be regulated up and down in very short time frames and to very low cost.

Norway is considered as a possible battery for Europe based on the idea that water could be pumped up to higher levels when there are surplus from wind and solar production and that the hydropower production could be increased in periods with low production from the wind turbines and solar cells.

Use of the flexibility of the Norwegian hydropower system may benefit several actors in the power market: power suppliers in Northern Europe may sell surplus in wind and solar production to Norway in low price periods and avoid dumping of the energy. In periods with low power production from wind and solar resources, they can buy power to fulfil delivery obligations. Norwegian power suppliers can buy cheap wind and solar power production in low price periods and store the water in the reservoirs until periods with higher prices. The impact on the power prices in other countries than Norway will be limited because the volume of the exchanged power will be small compared to the total system in Northern Europe. The impact on the power prices in Norway will depend on the prices differences between Norway/the Nordic region and Northern Europe.

There is hardly any physical pumping in the Nordic system today, but the hydropower system already works as a kind of a battery because production is increased in daytime when power prices are high in neighboring countries. Furthermore, the production is decreased below domestic load in the night when prices are lower than in the countries Norway, which the highest storage capacity and pumping potential, is presently connected by subsea HVDC cables to Denmark (1700 MW) and the Netherlands (700 MW). Connections to UK (1400 MW) and Germany (1400 MW) are under development and possibly an additional cable to the Netherlands after 2020. Today's exchange pattern is related to the production pattern of the thermal based power system in Continental Europe. The future exchange pattern will most likely be more variable and uncertain due to increase in wind and solar production.

2. The objective of this study

The objective of this paper is to identify the state-of-the-art related to the need for balancing and storage for scenarios of large shares of wind and solar production in the Northern Europe, and the possibility for using the Nordic hydropower for balancing the variability and uncertainty. Based on the state-of-the-art overview, the research gap is identified. Variability shall be understood as the expected or foreseen variation in production from wind and solar resources, i.e. it can be scheduled how to balance the variability. The uncertainty shall be understood as the unexpected variation in the production, which has to be reacted to in short times frames and typically through reserves markets.

To assess the capability of Nordic hydropower for balancing wind and solar power, increased knowledge is necessary related to several fields of research: The need for balancing and storage in the future power system; the future prices for power production flexibility; consequences of different market solution; economic impacts for different actors; risk in investments; possibilities for further development of the Nordic hydropower system; changes in operation patterns of the hydropower system; alternative storage technologies; impact on greenhouse gas emission and impacts on local environment. This review paper investigates state-of-art related to a selection of these research questions/topics.

The need for balancing and storage in the future power system

The need for balancing and storage may be different in different time perspectives, e.g intra-hourly, hourly, per day, season, etc. Another aspect is how fast the need for balancing capacities is changing from one time step to another (step changes) ref Figure 1. Last, but not least, extreme values, like maximum duration of periods with low or high production from wind and solar resources (ref Figure 2) could be useful to study.

How can the Nordic power system be further developed to cover a larger share of the need for balancing and storage?

The Nordic hydropower system can work as a "battery" in its present version as described above. It is possible to further develop the Nordic system by upgrading the capacity in existing plants to produce more in periods with low WPP (Wind Power Production) and SPP (Solar Power Production). By installing pump capacities in the hydropower system, even more excess in renewable production can be used for moving water to higher reservoir levels. Upgrade of national and cross-border transmission capacities may also increase the possibilities for exchange of balancing power.

Consequences of different market solutions

Different market solutions have different impact on the need for balancing and storage, e.g. in larger geographical markets there will be a "netting" of imbalances. On the other hand, national power markets limit the possibilities for Nordic hydropower to become a battery for variable renewable power production. Ref. [12] shows that the forecast error for WPP is reduced 3 hours before production compared to 24 hours before production. Thus, "gate closing" closer to operation time will impact the need for balancing and storage.

Changes in operation patterns of the Nordic hydropower system

The Nordic hydropower system is presently operated with a distinct seasonal pattern where the reservoirs are filled in the summer and depleted in the winter season. It should be simulated how the operational pattern can be in the future e.g. in periods with long lasting extreme low or high production from WPP and SPP in Continental Europe, how much pumping is realistic and how will it impact on the reservoir levels.

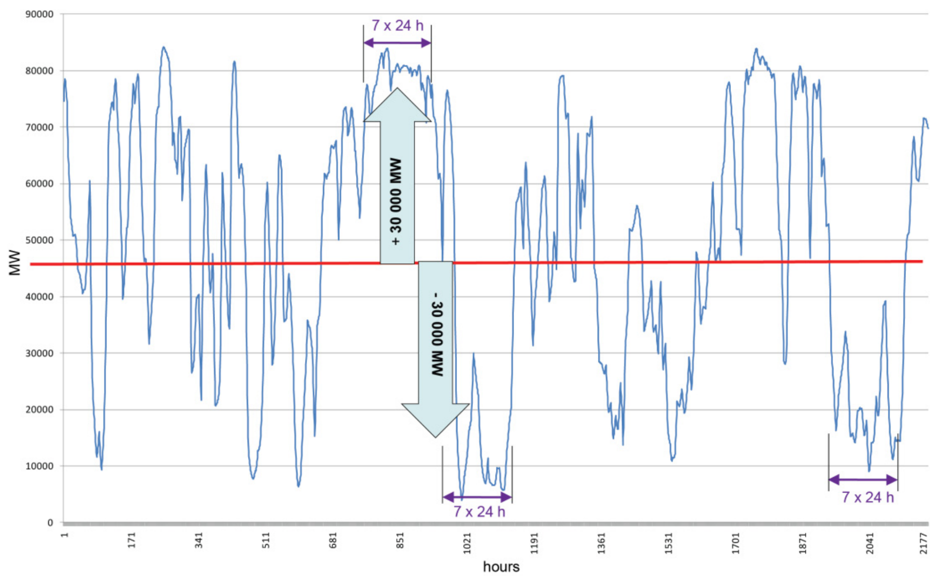

Figure 1. Wind Power North-Sea region: January – March 2001 hourly resolution. Illustration of very fast changes in production capacities [2]

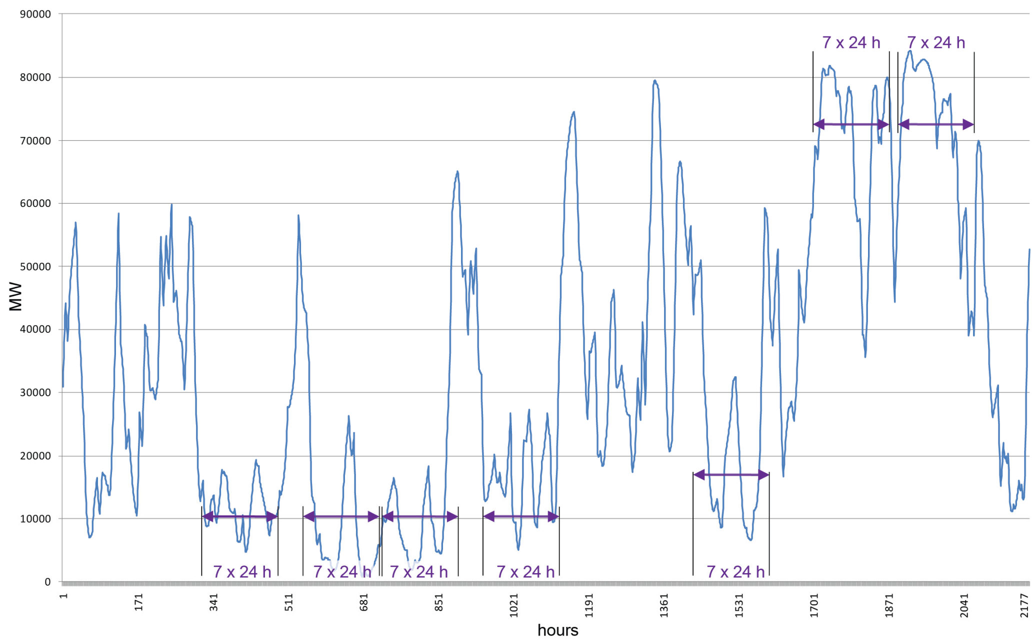

Figure 2. Wind Power North-Sea region July – September 2001. Periods with persistent low production [2].

3. Review of simulations studies

The results from reviewing the simulations studies are structured in two tables below. Table 1 gives an overview of the main relevant research result in each of the studies and an indication of which of the research questions raised in section 2 are answered. Table 2 gives more detailed information about each of the studies. In the leftmost column in Table 2 the title of the publications and the year of publications are given. The second leftmost column gives information about the geographical resolution and the time perspective of each of the studies. The main input data are available in the column in the middle, e.g. quantification of input capacities for wind and solar power and database used for simulating the wind and solar resources. The models used for the simulations can be found in the second rightmost column, and finally the main findings are described to the right.

Table 1. Overview of simulation studies about balancing variations of WPP and SPP in Northern Europe with Nordic hydropower

Title / Year of publishing/ Reference	Main research question	Need for balancing and storage	Further develop-ment of Nordic power system	Conse-quences of market solutions	Changes of operation patterns of hydro-power system
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	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	X	X		X

support integration of North European wind power/[6]	flexibility in a long term cost-benefit analysis.				
Balancing of wind power and hydro power in Northern SE/[7]	Studies the hydropower capability to balance various amount of wind power in Northern Sweden	(X)	(X)		
Impacts of wind power on energy balance of a hydro dominated system/[8]	Impacts on energy balances and power prices when integrating up to 30% WPP in the Nordic system				(X)
Imbalance costs of wind power for a hydropower producer in Finland/[9]	Example study from Finland about imbalance cost for wind power for different options of managing imbalances from a large power producer			(X)	
Pumped Storage Hydropower. Transition to Renewable Energy Systems/[10]	i)Examples of need for balancing and storage for large volumes of WPP ii)Examples of impacts on the Nordic hydropower system for integration of large volumes of WPP	X			X
Transmission expansion planning in Northern Europe/[11]	Analysis of power system in 2030: i)Profitable transmission expansions ii)Price development (level and volatility) iii)Operation of the Nordic hydropower system (production and reservoir disposal)		X		X
System Impacts from Large Scale Wind Power /[12]	Wind power variation and effect on inter-area and cross-border cost-optimal grid expansion. Effects on day-ahead prices. Cost-benefits for integration of intra-hour and regulating power markets.	X	X	X	
A Power Market Model for studying the Impact of Wind Power on Spot Prices/[13]	Quantify the impact of wind power on spot prices in Western Denmark, both today and future scenarios with higher wind penetration		(X)		
Climate-friendly, reliable, affordable: 100% renewable electricity supply by 2050/[14]	Possible German roadmap for transition to a 100% reneweable electricity supply and the policy instruments needed to implement such a grid.	(X)	(X)		
The Role of Norwegian Hydro Storage in Future Renewable Electricity Supply Systems in Germany: Analysis with a Simulation Model. /[16]	The benefits of cable capacity between Germany and Norway and new pumped storage capacity in Norway in a 100 % renewable electricity system are explored. The profitability and technical and environmental feasibility of the scheme are analysed as well	X	X		X

Table 2. Detailed information of simulation studies about balancing variations of wind and solar power production in Northern Europe with Nordic hydropower

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	2030, Europe	Installed wind capacity in NO, SE,	EMPS and	Long term strategies for the expansion

flexibility and transmission expansion to support integration of North European wind power/ 2014/[6]	including the North-Sea	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 today's system taking into account projects that are already started or feasible for implementation by 2030. Different offshore grids in the North Sea	PPST (Power System Simulation Tool)	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 of wind power and hydro power in Northern SE/2009/[7]	Northern SE (north of cut 2 in SE), no specified time perspective	154 hydro power plants in Northern Sweden representing 80 % of the installed hydro power capacity in Sweden. Simulation with 1, 4, 8 or 12 GW installed wind power.	LP model with hourly resolution.	The hydro power can balance the WPP in most cases for installed wind capacities less than 12 GW. Challenges rather to find outlet for the electricity.
Impacts of wind power on energy balance of a hydro dominated system/2006/[8]	2010. Nordic region + GE	2010 system but with 10, 20 or 30% wind power production included in the system	WILMAR model, hourly time scale	Regulation is not likely to be a problem in the simulated system, but further studies with more detailed representation of the hydropower system are needed.
Imbalance costs of wind power for a hydropower producer in Finland /2012/[9]	2004, Finland seen from a single producers perspective	200 and 400 MW wind, 400 MW hydro power	Simple model	With limited flexibility of hydropower (run-of-river with small reservoirs) a large part of forecast errors can be provided for, However, more efficient to bid all flexibility of hydropower to the balancing market to correct the systems imbalances
Pumped Storage Hydropower. Transition to Renewable Energy Systems /2013/[10]	2030/North Sea including BE, DK, GE, UK, the NLs, NO	94 GW of offshore wind production based on reanalysis data with weather data for 2001-2006		Examples of need for flexibility related to variation in the 94 GW offshore wind power production, e.g. power output down to 15-25 GW for a week, in extreme cases output down to 10 GW for a few days or even 2 GW for some hours.
Transmission expansion planning in Northern Europe/2013/[11]	2030/Nordic region + UK, NL, BE and GE	Reanalysis wind and solar data. 192 GW WPP in Northern Europe, significant SPP in NL and GE, phase out of nuclear in GE, increase of nuclear in UK	EMPS and investment algorithm	Present diurnal power price pattern substituted with more stochastic price pattern
System Impacts from Large Scale Wind Power/[2013/[12]	2010, 2020, 2030, Northern Europe	COSMO EU data for onshore and offshore wind resources, 4Coffshore for offshore wind power capacities, www.thewindpower.net for onshore wind power capacities, UCTE, ENTSO-E and NORDEL data	EMPS, PSST	Despite geographical distribution of WPP in 2030, the WPP varies between 2 and 62% of installed capacity. This is among other due to clustering of offshore wind power in the North Sea.
A power market model for studying the impact of wind power on spot prices/ [13]	Denmark West - Norway	2.3 GW WPP for West DK, 0.8 GW for East DK, 19 GW for GE	Simple and flexible model developed in study.	Expansions of transmission capacity between NO and DK reduce price fluctuations and increase income to Danish wind turbine owners.
Climate-friendly, reliable, affordable: 100% renewable electricity supply by 2050/2010/[14]	2050, focus on GE, but includes European countries and Northern Africa. GE: large shares of offshore and onshore WPP and PV. Also geothermal	GE totally supplied by RES. 2 alternatives for demand in GE: 500 or 700 TWh/y. 8 scenarios where 4 are focusing on GE-DK and DK-NO in a network structure. In 2 scenarios GE are annually self-supplied but interchange up to 15% of consumption with DK and NO. In 2 scenarios GE imports up to 15% of consumption in addition. Assumes up to 50 GW of pump storage in NO.	REMix model, hourly resolution,	Transmission capacities between GE-DK: 41.9 – 61.6 GW and between DK-No 46 – 68.8 GW dependent on scenario. The electricity costs in an inter-regional GE-DK-NO or European – North Africa network would be substantially lower than would be the case in a self-sufficient German system.

	with CHP.			
The Role of Norwegian Hydro Storage in Future Renewable Electricity Supply Systems in Germany: Analysis with a Simulation Model /2014/[16]	GE in 18 onshore and 3 offshore nodes, all countries bordering the Baltic Sea and Norway	100% RES in GE, wind from 5 and solar from 38 weather stations in GE for 1998, 2003 and 2010. Offshore wind from 3 plants and onshore measurements close to shore. Load data from 2011. Twice the existing grid capacity is assumed. The main scenarios differ in the connection capacity between GE and NO and pumped storage capacity in NO. Both parameters are varied in steps of 10 GW from zero to 50 GW (36 combinations). Sensitivity: varying the grid capacity in GE, RES capacity in GE and NO, weather data for hydro inflow, wind speed and solar radiation, storage capacity in GE and the scarcity price for electricity.	Renpass, one year simulated in hourly or 15 min time steps, Hydro storage plants and their connected reservoirs are modelled individually	The most beneficial is the installation of 10 GW cable capacity between GE and NO and 10 GW additional pumped storage capacity in NO. The results are very sensitive to assumptions for amount and distribution of renewable capacity and storage capacity. Also the value of security of supply, expressed in the scarcity price of electricity, has large influence on the benefits of additional storage capacity.

*) Follows ISO 3166-1 standard of naming, **) SPP – Solar power production

Ref. [3] is a collection of several studies and does not fit directly in the structures in Table 1 and Table 2. Two of the studies in [3] are included in the review in this paper: [7] and [8]. Other studies in [3] are based on integration of small volumes of wind power production compared to the size of the Nordic system, i.e. wind power system in the size less than 1500 MW.

4. The Research Gap

The objective of this paper is to identify the state-of-the-art related to the need for balancing and storage in scenarios with large shares of wind and solar power production in Northern/Central Europe, and the possibility for using the Nordic hydropower for balancing the variability and uncertainty in this type of production. Several questions/topics need to be investigated related to this possible solution to secure supply in a future low emission power system. This paper focuses on four questions:

- The need for balancing and storage in the future power system
- How can the Nordic power system be further developed to cover a larger share of the need for balancing and storage
- Consequences of different market solutions
- Changes in operation patterns of the Nordic hydropower system

Twelve scientific papers are reviewed related to these questions/topics and a research gap can be identified based on the review.

Simulations based on wind and solar resource data with high spatial and temporal resolution will increase our knowledge about the variability of the resources. However, to get as realistic results as possible, the simulations must include high (expected) volumes of both wind and solar resources. [15] is based on current trends and adopted policies in EU before spring 2012. More ambitious policies may result in even higher shares of RES. [15] expects 200 GW of WPP in BE, DK, GE, NL and UK in 2050. The only studies meeting these expectations for WPP are [11], [14] and [16]. [11] does not include SPP. [14] and [16] both have Germany as their main perspective and do not include results for countries like UK and the Netherland. To assess the value of use of the Nordic hydro power for balancing purposes, also other countries than Germany must to be included. Finally, a main part of the studies have a temporal resolution of several hours and simulated variations will to some degree be smoothed out within these timeframes. Except for [5], [7], [8], [12], [14] and [16] all are based on reanalysis data which has a time resolution of 6 hours. [7] and [8] have a too limited scope for the topic of this review (see Table 1). [16] is based on only five weather stations for onshore wind measurements. The spatial resolution for solar data is better based on measurements from 38 weather stations. Five stations could be too limited to get a realistic modelling of the smoothing effect of geographical distribution.

As shown above, none of the studies includes large volumes of both WPP and SPP, are modeled with a temporal and a spatial resolution which identifies the future need for balancing and storage and in addition has a geographical scope that fully identifies the variability of the future combined wind and solar power production in Continental Europe. A review of nearly 70 articles about variability characteristics of European wind and solar power resources has a similar conclusion [17]. Thus, there is a need to develop a wind and solar resources model with high enough resolution to get a realistic modelling of the variability from the combined production.

The three other research questions are dependent on the quality of the identification of "the need for balancing and storage". If the "need for balancing and storage" is not identified, it hard to discuss how can the Nordic power system be further developed to cover a larger share of the need for balancing and storage. E.g. it is difficult to quantify how much pumping capacity will be profitable in the future Nordic hydropower production. There is a lot of flexibility in the Nordic power system already related to both production and consumption, and the Nordic region can probably play a considerable role as provider of flexibility without upgrade of the pumping capacity.

When it comes to simulations of consequences of different market solutions, this is also difficult to identify without knowledge about the variability of a power production with large shares of WPP and SPP. Thus, further research should start with building a data model with high temporal and spatial resolution and to identify the need for balancing and storage in different time perspective based on simulations with this model. Based on the simulation results, it can be studied in which markets (reserve, spot, intra, regulating) Nordic hydro power will be most valuable. Furthermore, the effect of geographical integration of markets can be studied.

The last of the four research questions, changes in operation patterns of the Nordic hydropower system, is studied in several papers: [4], [6], [10], [11] and [16]. E.g. [4] shows wind power surplus as a function of installed wind power in Europe, development of reservoir level over the year and hydro power production over the year dependent of some increase in cross border capacities. However, the results may be different with more WPP and SPP in the system and with a further development of Nordic power system.

There will always be a lot of uncertainties in simulations of the future power system. But, for the question about balancing of wind and solar power production in Continental Europe with Nordic hydropower, the uncertainties can still be reduced by developing data models of the resources with higher spatial and temporal resolution and simulating the system based on these models and large shares of wind and solar power production.

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