Economic comparison of technical options to increase power system flexibility

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***Abstract*—Flexibility is required to integrate variable and partially unpredictable sources of power generation like wind and solar. The paper compares several flexibility options from the economic perspective using unit commitment and dispatch model for Nordic countries and Germany. The analyzed scenarios have 20 % electricity from wind power on annual basis. At this penetration level flexibility from different heat measures appear to economic, new transmission between the Nordic countries and Germany is also profitable while other flexibility measures are not economic. Demand response, pumped hydro power, and more flexible conventional generation show markedly low system benefits, but this may be due to the high flexibility in the existing reservoir hydro power.**

Keywords-flexibility; wind power; variable generation; balancing; transmission; pumped hydro; demand response; electric boiler; heat pump; heat storage

I. Introduction

As the share of wind and solar power generation grows, the additional variability and uncertainty will increase the need for power system flexibility. This paper makes an economic comparison of several technical options to increase the capability to economically adjust generation or demand over different time scales, i.e. flexibility. In the comparison annual operational cost savings are measured against annualized investment costs. The latter is based on literature estimates, while the former is calculated with a unit commitment and dispatch model WILMAR. All the scenarios are analyzed in relation to the base scenario, which represents a future Northern European power system (Nordic countries and Germany) where wind power is providing 20 % of electricity over the year. The hydro power in the Nordic system makes it relatively flexible while the German thermal system is not so flexible to start with. Hence, the value of flexibility can be studied in two distinct settings and the value of increased transmission between the two can also be compared.

The compared technical options include: building new more flexible thermal generation units, building more transmission lines, electric boilers in district heating systems, heat pumps in district heating systems, heat storages in district heating systems with electric boilers and combined heat and power (CHP) units, price sensitive demand response, and pumped hydro power in Norway.

The literature on the comparison of flexibility options in the face of large scale wind and solar power generation is still rather thin. Ummels *et al* [1] have made a cost-benefit comparison of CCGT, pumped hydro, underground pumped hydro, CAES and natural gas heat boilers as means to decrease operational costs of the system at different levels of wind power penetration. Purvins *et al* [2] review options to manage variability of wind power generation. The paper contains examples from literature about the spatial distribution of wind power plants, electricity storages, wind power induced reserve requirements, and the benefit of additional interconnections. Mathiesen and Lund [3] demonstrate that heat storages can have an important impact on power system flexibility. They also show that the use of electrolysers to produce hydrogen for fuel cell vehicles or combined heat and power plants does not appear to be cost competitive with the flexibility mechanisms provided by heat measures and battery electric vehicles. A report by Pöyry Energy [4] analyses different options to create a low carbon energy system for the UK. It concludes that electrification of especially space heating may provide the necessary flexibility to incorporate large amounts of variable power generation. Kiviluoma and Meibom [5] compared the flexibility from EVs, electric heat boilers, heat pumps, and heat storages with a generation planning model. This paper offers more comprehensive review of different flexibility measures using a common set of assumptions with a relatively large power system and robust modeling methodology for operational costs.

II. Method

The benefits of different flexibility measures are compared by modeling a future system. Flexibility measures are added to a base scenario one at a time and comparison is made against the base scenario. This means that no re-optimization of the generation investments is made due to the impacts of increased flexibility. This assumption gets more unrealistic as the share of variable renewables grows and therefore this analysis is limited to a 20 % annual penetration level.

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The analysis is made using unit commitment and dispatch model WILMAR [6]. One year of market operation is simulated with the model for each scenario. If available, day-ahead wind power forecasts are taken from the TSO websites. For Norway, Sweden and Finland a new forecast is used every three hours in the intra-day solves of the model. For Germany and Denmark the day-ahead forecast holds until the hour of operation. The first three hours of the model horizon contain realized wind power and electricity demand and these are the final results from the model.

The WILMAR model simulates a zonal market design with liquid spot, intra-day, and balancing markets. It minimizes the operational costs of the interconnected power system assuming transmission constraints based on net transfer capacities. The model procures reserves dynamically based on the forecast stochastics in addition to more conventional reserve requirements. It includes unit start-ups, part-load efficiencies, forecast errors for wind power and demand, CHP plants serving heat demand in district heating, as well as a separate model for calculating the water value for the reservoir hydro power. In this paper a relaxed version was used, where unit start-ups were linearized [7]. This was due to high computational burden with the relatively large number of units in the geographical area.

III. SCENARIOS

The geographic scope contains the hydro dominated Nordic power system and Germany, which is mostly thermal. A long term power system scenario has been built to facilitate a meaningful comparison between the flexibility options. To this end, wind power provides a large portion of the electricity demand (20 % on annual basis), conventional generation fleet reflects current plans including pumped hydro in Germany (based on the Platts powerplant database), and new transmission lines are based on existing plans by the transmission system operators. Conventional power plant capacity was kept near the peak loads by retiring oldest plants from the system. Largest portion of the wind power capacity is located in Germany. Time series for electricity consumption, wind generation, and heat demand are based on real data from 2010. Wind generation time series have been scaled up to reach the 20 % penetration level.

TABLE I. presents the scenarios, their differences and their estimated cost. In the transmission scenario the new capacity was built between South Sweden and Germany (1,400 MW) and South Norway and Germany (1,400 MW). The investment cost for this was about 2,000 M€. An investment of similar size was assumed for pumped hydro. Due to lower investment costs heat measures created large amounts of MWs with less costs. Therefore the investment to each heat measure was about 200 M€, expect for heat storage for which the investment was only 89 M€.

Different flexibility measures will cause different impacts in the system. Transmission increases flexibility by smoothing the output and forecast errors of variable generation as well as by sharing flexibility resources between the regions. More flexible generation may enable faster and less costly ramps and start-ups as well as lower minimum load factors. In the flexible generation scenario the minimum load factor of some thermal power plants was decreased by 10 percentage points, e.g., from 50 % to 40 %,

TABLE I. FLEXIBILITY SCENARIOS COMPARED TO THE BASE SCENARIO

	Transmission	***Estimated cost***
Trans-mission	2,800 MW additional tranmission between Nordic countries and Germany	2000 M€, published TSO plans
Flexible Gen.	14,665 MW of conventional generation with 10 percentage points lower minimum load factor	No estimate
Electric Boiler	3,079 MW of resistance heater capacity split into heat areas	216 M€, [8]
Heat Pump	308 MW_{elec} of heat pumps (COP 3.5) split into heat areas	216 M€, [8]
Heat Storage	98,536 MWh (assuming 8 hours for full charging) of heat storage split into heat areas	89 M€, [8]
Pumped Hydro	6,094 MW of pumped hydro replacing 3047 MW of reservoir hydro	~2000 M€, based on [9]
Demand Response	Four price levels of demand response split between regions Block 1: ~80 €/MWh; 900 MW Block 2: ~150 €/MWh; 1,800 MW Block 3: ~290 €/MWh; 2,700 MW Block 4: ~580 €/MWh; 3,600 MW	No estimate

which also improves their part-load operation efficiency. The power plant set consisted of combined cycle, steam turbine, gas turbine and steam condensing types of power plants that were built after 2010. No additional capacity was included in the scenario. Electric boilers are useful in situation with low load and high variable generation. In the model they are likely to provide heat for district heating networks and replace heat production from fuel boilers, CHP units or heat pumps. Heat pumps in their scenario are likely to perform a similar function, but the better efficiency in the utilization of electricity (COP of 3.5) will lead to much higher full load hours and therefore heat pumps offer less flexibility. It was assumed that the ambient heat source for heat pumps is a large body of water with reasonable winter temperatures. Heat storages improve the efficiency of CHP units by enabling their operation more often at full load efficiency. They also partially uncouple electricity generation from heat production in backpressure units where this ratio is constant. Also CHP units can be shut down if there is enough stored heat. All this increases flexibility and hence decreases operational costs. Furthermore, electric boilers and heat storages could create mutual benefits. In the pumped hydro scenario pumped hydro power is increased in South Norway by approximately 6 GW. It is built as upgrades to existing reservoir hydro plants and partially replaces reservoir hydro capacity. This scenario looks at the benefits of balancing central European variability with Nordic resources.

IV. RESULTS

A. System cost savings and investment annuity

From policy perspective the most important result concerns the system cost. Figure 1 presents the decrease in total operating costs when moving from the base scenario to different flexibility scenarios. The total annual operating costs for the base scenario were 26,101 M€. In order to get a

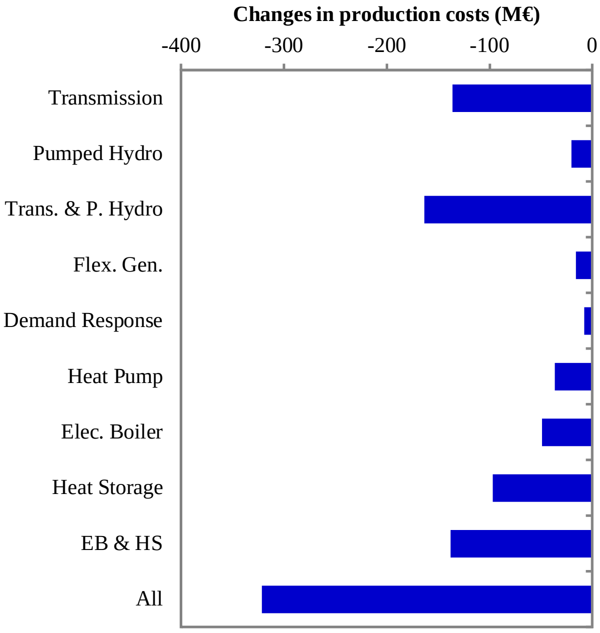

Figure 1. Change in system costs

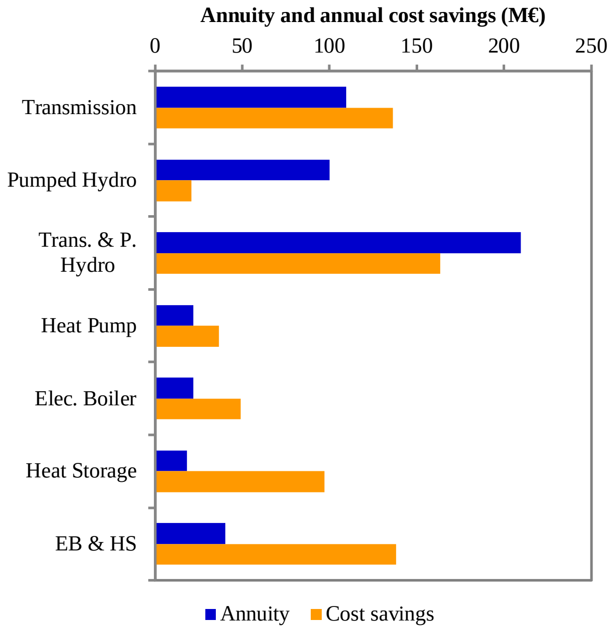

Figure 2. Cost savings compared to the investment annuity

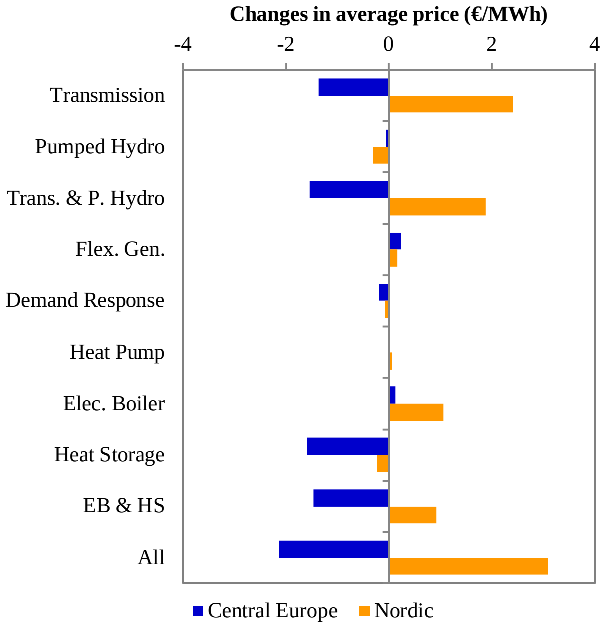

Figure 3. Change in the average intra-day market price

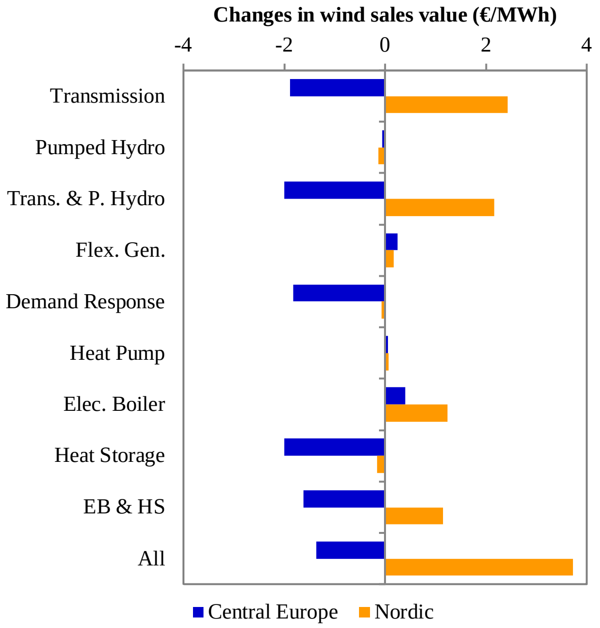

Figure 4. Change in the average income for wind power producer

measure of profitability the cost savings have to be compared against the annuity as in Figure 2.

The results in Figure 2 indicate that only heat measures and transmission are profitable in the analyzed scenarios. However, demand response and flexible generation are not included in Figure 2 because it was not possible to estimate the annuity. Among the measures for which the annuity could be estimated, heat storages and electric boilers are the most profitable.

B. *Impact on market prices*

Average prices in the intra-day market are impacted by the different flexibility measures as can be seen from 0In the base case average intra-day market price in Germany was 58.4 €/MWh and in the Nordic countries is 42.5 €/MWh.

Wind power investor is concerned about the possible market income. In the base case the income is 53.6 €/MWh in Germany and 39.0 €/MWh in the Nordic countries measured from the intra-day market prices. Figure 3 shows the change from the base scenario. The change in the possible income for the wind producer is in Figure 4. Additional transmission decreases price differences between Germany and the Nordic countries. Electric boilers, which increase electricity consumption during low price hours, naturally increase the revenue for wind power. Some of the flexibility increases decrease operational costs and make it

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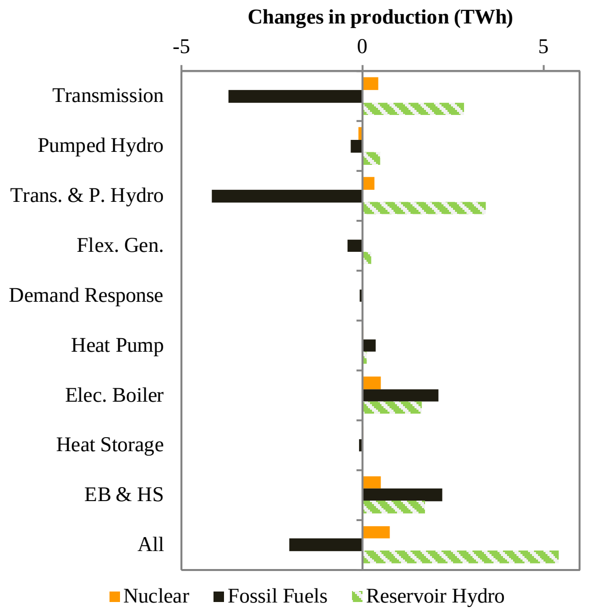

Figure 5. Changes in conventional generation

easier to integrate variable generation, but at the same time they can lower the income for variable generation. E.g. heat storages allow more optimal operation of CHP units, which leads to lower power prices, but at other times it allows shutting down CHP when there is high wind power generation.

C. Impact on conventional generation

Flexibility measures will also alter what conventional generation is used over the year. The impact should be minor for hydro power, which will try to use the available inflow in any case. However, reservoir hydro can end up at different water level at the end of the year and this causes production differences between the model runs. Conventional generation might switch from mid-merit and peaking plants to base load plants due to increased flexibility. Figure 5. shows that at least in some scenarios fossil fuel generation is replaced by base load nuclear generation.

V. DISCUSSION AND CONCLUSIONS

As variable generation increases – exemplified in this paper by wind power – the need for power system flexibility increases. At different levels of variability the value of different kinds of flexibility will increase. This paper has studied a 20 % annual wind power penetration in a joint hydro-thermal power system. The positive impact of most flexibility measures was limited in the study setting. One of the main reasons for this result is probably the high flexibility of existing reservoir hydro power in the Nordic countries. To reach more conclusive results, larger thermal system footprint from the Central Europe should be covered and more realistic restrictions on reservoir hydro power flexibility should be included in the model.

The results do not include all possible benefits from the flexibility measures. The model captures only balancing at hourly level, which means that sub-hourly benefits are missed. Reserves are only required to be procured, they are not actually utilized. Also any benefits related to long term adequacy, load flow control, reactive power control, or power quality are not quantified. Demand response was allowed to participate only in the day-ahead market, which is a severe limitation to the possible benefits it could offer. Furthermore, only price-sensitive demand response was modeled and no time-shifting demand response was included. The latter can have low variable costs and could be a valuable source of flexibility.

REFERENCES

[1] B. C. Ummels, E. Pelgrum, W. L. Kling, "Integration of large-scale wind power and use of energy storage in the Netherlands' electricity supply", IET Renewable Power Generation, 2008, Vol. 2, No. 1, pp. 34–46.

[2] A. Purvins, A. Zubaryeva, M. Llorente, E. Tzimas, A. Mercier, "Challenges and options for a large wind power uptake by the European electricity system", Applied Energy, Volume 88, Issue 5, May 2011, Pages 1461–1469, ISSN 0306–2619, DOI: 10.1016/j.apenergy.2010.12.017.

[3] B. V. Mathiesen, H. Lund, "Comparative analyses of seven technologies to facilitate the integration of fluctuating renewable energy sources", IET Renewable Power Generation, Vol. 3 (2), pp. 190–204, 2009.

[4] Pöyry Energy 2010. Options for low-carbon power flexibility 2050.

[5] J. Kiviluoma and P. Meibom, "Influence of wind power, plug-in electric vehicles, and heat storages on power system investments", Energy, Vol. 35 (3), pp. 1244–1255, 2010.

[6] P. Meibom, R. Barth, B. Hasche, H. Brand, and M. O'Malley, "Stochastic optimisation model to study the operational impacts of high wind penetrations in Ireland", IEEE Transactions of Power Systems, Vol. 26, Issue 3, pp. 1367 - 1379, 2011.

[7] R. Barth, H. Brand, P. Meibom, and C. Weber, "Stochastic Unit-commitment Model for the Evaluation of the Impacts of Integration of Large Amounts of Intermittent Wind Power," in *Proc Int. Conf. on Prob. Meth. Applied to Pow. Sys.*, 2006, 11-15 June 2006.

[8] Danish Energy Agency and Energinet.dk, Technology Data for Energy Plants, June 2010, ISBN: 978-87-7844-857-6.

[9] E. Grøv, A. Bruland, B. Nilsen, K. Panthi, and M. Lu. Developing future 20 000 MW hydro electric power in Norway - Possible concepts and need of resources, SINTEF 2011.

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