Balancing needs and measures in the future West Central European power system with large shares of wind and solar resources

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***Abstract*—The future European power system will include large shares of variable wind and solar resources. This paper analyses the variability for the eHighway2050 scenarios (from the EU 7th Framework project) by modelling wind and solar resources from the COSMO-EU model. It quantifies the variability for the countries in West Central Europe, separate for each country, and integrated assuming there is no transmission limitations. The analysis results show that integration of systems by grids will have a smoothing effect on the variability. However, main challenges with periodically very low output will remain. The paper quantifies need for balancing taking present and future load profiles into consideration. The paper shows that many aggregated small-scale batteries only will have a limited effect on the need for balancing beyond a few hours. Finally, the paper discusses how the large reservoirs in the Norwegian hydropower system may serve to the balancing needs.**

***Index Terms*—Energy storage, power system planning, solar energy, wind energy.**

BACKGROUND

The EU has stipulated a long-term goal to reduce greenhouse gas (GHG) emissions by 80%–95% compared to 1990 levels by 2050 [1]. The future power system in Europe will include large shares of wind and solar resources. Power production from wind and solar plants vary due to the variable resources. Since production has to meet demand all the time, measures are necessary in order to balance the production. In the present power system, dispatchable power plants balance the net load (the load minus the wind and solar power production). Reduction of conventional capacities based on fossil fuels is likely due to long periods with low power prices and because of the need to reduce GHG emissions. Other measures will be necessary to balance the variability in the renewable based power production. EU plans to expand interconnectors and to promote demand response for future balancing purposes [2], [3]. In Northern Europe, the flexible hydropower system in Scandinavia is an opportunity for balancing variable production [4].

METHOD

This paper analyses the balancing needs for the future production from wind and solar resources in West Central Europe (see Table 1). It quantifies the need for balancing for scenarios from the EU 7th Framework project e-Highway2050 [5]. The e-Highway scenarios are consistent with EUs targets for reduction of GHG emissions, and provide assumptions for development of wind and PV (photovoltaic) capacities for 106 clusters (regions) in Europe. E.g., there are assumptions for 7 cluster in Germany,15 in France etc. This study uses three of the eHighway scenarios: X5 (large scale Renewable Energy Sources (RES) including high amounts of offshore wind power), X7 (100% RES both large and small scale, including bio, hydro etc) and X16 (small scale RES with high amounts of PV power). In addition, we have developed a new scenario, called MaxRES. The eHighway project quantified maximum potential for wind and solar power production for the 106 clusters. The MaxRES scenario uses these maximum potentials. This paper uses wind and solar resources from the COSMO EU model. That model provides hourly wind and solar resources for the years 2011 – 2015 with a spatial resolution of 7 km x 7 km for the whole Europe [6]. Reference [7] describes the COSMO model, calculation of wind and PV power production and validation of the calculations by comparison with real production data from Transmission System Operators. Based on the same methodology as described in [7], this paper calculates wind power and PV power productions hour by hour by using COMSO weather data and capacities from the eHighway project. The hourly resulting time series with high spatial resolution are aggregated to national level. Wind and PV power production are added together to one combined hourly time series with variable RES production.

This paper uses yearly demand for 2050 from the eHighway project and the present load profile (from ENTSO-E [8]) as a starting point, but consider adjustment of the load profiles according to published scientific results. The reference [9] provides hour by hour load profiles for 2050. This study analysis the need for balancing for each of the countries separate and for all the countries integrated assuming there are no transmission limitations within or between them in order to quantify the maximum smoothing effects. Furthermore, the paper quantifies how aggregated small-scale batteries can balance part of the variability. Finally, the paper discusses how the balancing needs might interact with the Nordic hydropower.

RESULTS

Variability in wind and solar power production

Table 1 shows key figures for wind and solar power production based on weather data for 2011-2015. For each year aggregated wind and solar power production is calculated hour by hour. Minimum, maximum, 10 and 20 percentiles production values as percent of installed capacity are calculated for each year. As a next step, the yearly values are averaged over the five years in the analysis period. Simulation results are for the following countries/group of countries: United Kingdom (UK) (Great Britain + Northern Ireland), France (FR), Ireland (IE), and Benelux (BENEL) and these countries aggregated as R1. Furthermore, the countries Austria + Switzerland + Czech Republic + Slovenia (AU,SW,CZ,SI), Germany (DE), Denmark-West (DK-W) and these countries aggregated as R2. Finally, all countries are analysed together (column marked "All").

Table 1 Key figures for wind and solar power production based on weather data for 2011-2015

Scenario		AU,SW,CZ,SI	DE	DK-W	BENEL	FR	UK	IE	R1	R2	All
X5	Minimum value [%]	0,7	1,4	1,1	1,0	1,6	2,0	1,5	3,0	1,6	2,8
	Maxium value [%]	75,2	71,8	79,7	76,2	71,2	76,8	80,2	68,7	70,7	65,3
	10 percentile [%]	1,9	5,2	7,7	5,7	5,7	9,9	5,6	10,2	6,6	10,0
	20 percentile [%]	2,9	8,3	13,1	9,6	8,6	14,3	9,3	13,9	10,3	13,7
	Yearly RES prod/demand [%]	19,4	37,9	472,6	31,7	26,0	66,1	79,0	41,2	45,4	42,8
X7	Minimum value [%]	0,5	1,1	1,2	0,6	1,3	1,5	1,2	2,1	1,3	2,2
	Maxium value [%]	77,2	70,1	79,8	77,9	71,1	75,2	81,7	68,1	70,2	64,9
	10 percentile [%]	1,4	4,5	7,7	4,2	4,2	7,7	5,2	6,9	5,5	7,4
	20 percentile [%]	2,1	7,3	13,0	7,6	6,3	11,8	9,0	10,0	8,7	10,4
	Yearly RES prod/demand [%]	30,8	56,6	487,9	59,5	55,4	96,4	94,4	70,1	61,6	66,7
X16	Minimum value [%]	0,3	0,9	1,4	0,5	1,0	1,1	1,0	1,5	1,0	1,5
	Maxium value [%]	81,6	70,4	80,2	78,2	71,1	83,2	84,4	69,9	69,7	66,2
	10 percentile [%]	0,9	3,1	7,3	2,9	3,1	5,0	4,3	4,6	3,2	4,4
	20 percentile [%]	1,4	4,9	12,2	4,9	4,5	7,6	7,8	6,4	4,9	6,1
	Yearly RES prod/demand [%]	22,0	61,3	77,4	58,2	38,2	48,9	78,3	46,6	50,9	48,3
Max RES	Minimum value [%]	0,3	1,0	1,0	0,7	1,1	1,3	1,1	2,0	1,1	2,0
	Maxium value [%]	84,9	71,0	78,0	77,9	71,9	72,4	83,1	66,2	71,6	64,1
	10 percentile [%]	0,8	4,1	7,9	4,2	3,8	6,8	4,7	6,6	4,6	6,8
	20 percentile [%]	1,3	6,9	13,2	7,7	5,6	10,3	8,4	9,3	7,4	9,3
	Yearly RES prod/demand [%]	64,1	70,8	645,8	69,1	95,4	149,5	330,3	113,9	84,7	102,3

An observation from Table 1 is that there are smoothing effects by integration of the countries in West Central Europe. The minimum values, the 10 and the 20 percentiles increase when all the countries are totally integrated compared to considering each of the countries separately. Similarly, the maximum values decrease. However, the minimum values of production are very low, even in the totally integrated system, only 1.5 – 2.8 % of installed capacity. The 10 and the 20 percentiles are also very low. The 10 percentiles are in the range 4.4-10 % and the 20 percentiles in the range 6.1-13.7 % of installed capacity. The minimum values and the 10 and 20 percentiles are lowest for the scenario with the highest share of solar power production in the wind/solar mix (X16) and highest in the scenario with the highest share of wind power production in the wind/solar mix (X5). The very low minimum 10 percentile values for Austria Switzerland, the Czech Republic and Slovenia are because the eHighway scenarios assumes a very high share of PV power relative to the wind power production for those countries. On the other hand, UK has a relative high wind share in the wind/PV mix and very good wind resources which results in the highest 10 percentile of all countries in the X5 scenario.

Further studies focus on scenario X7 since it is close to the assumptions in the scenario with the highest wind/solar share in [1], and represent as such a possible development for the wind and solar power production in Europe. There are several alternatives for how to calculate the need for balancing of the variable wind and solar power production. This paper calculates the need for balancing by assuming that base-load units cover the mean net load in 12 periods per year. Positive net load means that wind and solar power production is not fully covering the load. We assume that e.g. nuclear power, bioenergy or fossil plants with CCS can be the base-load that is covering the mean net load in each of the twelve periods of the year. For negative net load, there must be an additional constant load in the period, e.g. hydrogen production running or alternatively that the excess energy is unutilized. In the next step, we study a situation where storage is covering the deviation between the mean and the real value of the net load in each hour in each of the 12 periods of the year. This can be expressed as follows:

L_i – load in hour i
$P_{pv,i}$ – pv power production in hour i
$P_{w,i}$ – Wind power production in hour i
NL_i – Net load in hour i
M_p – No. of hours in period p, $p \in (1 \dots 12)$
MNL_p – Mean net load in period p:

$$MNL_p = \frac{1}{M_p} \sum_{i=1}^{M_p} (L_i - (P_{pv,i} + P_{w,i})) \quad \text{(Eq.1)}$$

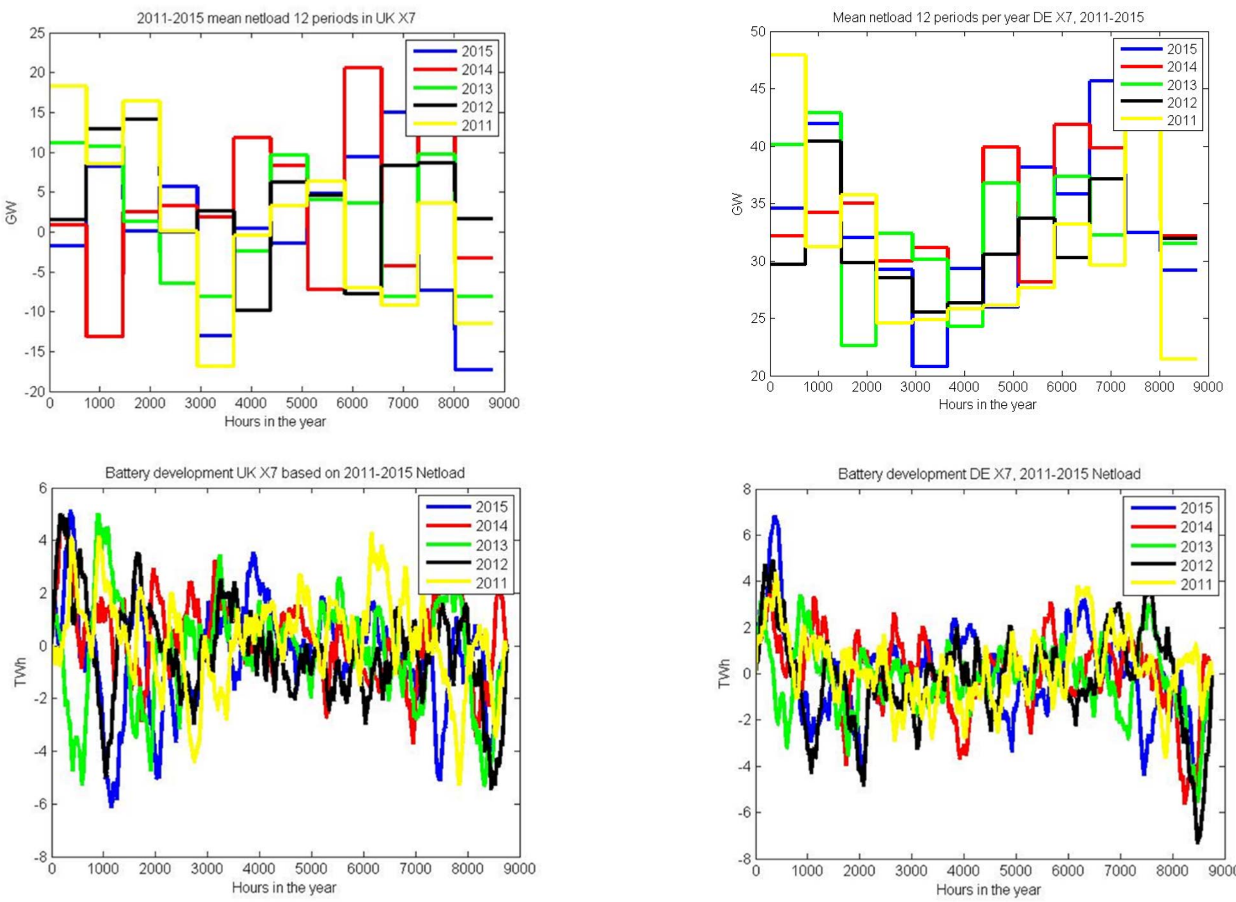
Battery charging and discharging in hour i in period p:

$$BC_{ip} = MNL_p - (L_i - (P_{pv,i} + P_{w,i})) \quad \text{(Eq.2)}$$

Battery/storage development over a year

$$\sum_{p=1}^{12} \sum_{i=1}^{Mp} BC_{i,p} \quad \text{(Eq. 3)}$$

Fig. 1 upper row shows the mean net load (Eq.1) for 12 periods for each of the years 2011-2015 for United Kingdom, and for Germany. The row in the middle shows the development of a hypothetical energy storage (Eq.3), if it is charged every hour in the period where the net load is lower than the mean net load and discharged every hour where the net load is higher than the mean net load. The lowest row in the figure shows charging and discharging of the storage hour by hour (Eq. 2). We assumed no limitations in the charging and discharging of the battery in order analyse the total storage needs of the future power system. Fig. 2 shows the corresponding results for all countries in West Central Europe aggregated. Fig. 2 down to the right shows the charging and discharging hour by hour for the hours 1500 to 2500 in 2015. The figure shows how the deviation from the mean net load changes from -173 GW to +266.5 GW in 18 hours for West Central Europe, i.e. a change of 439 GW that must be balanced in few hours.



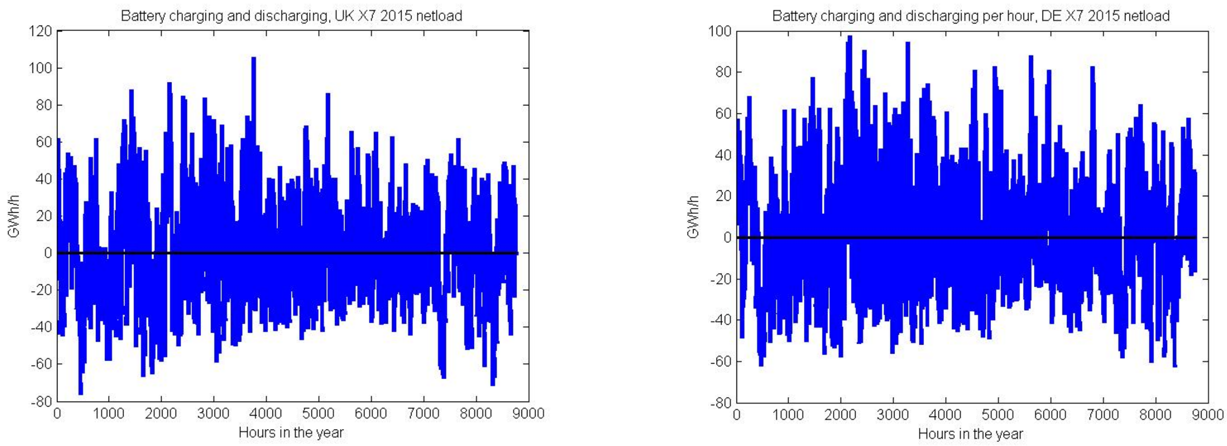


Figure 1 Mean net load in 12 periods per year for the 2011-2015 (upper row), need for storage in each of the periods (row in the middle) and deviation from the mean load hour by hour for 2015 for UK (column to the left) and Germany (column to the right), scenario X7

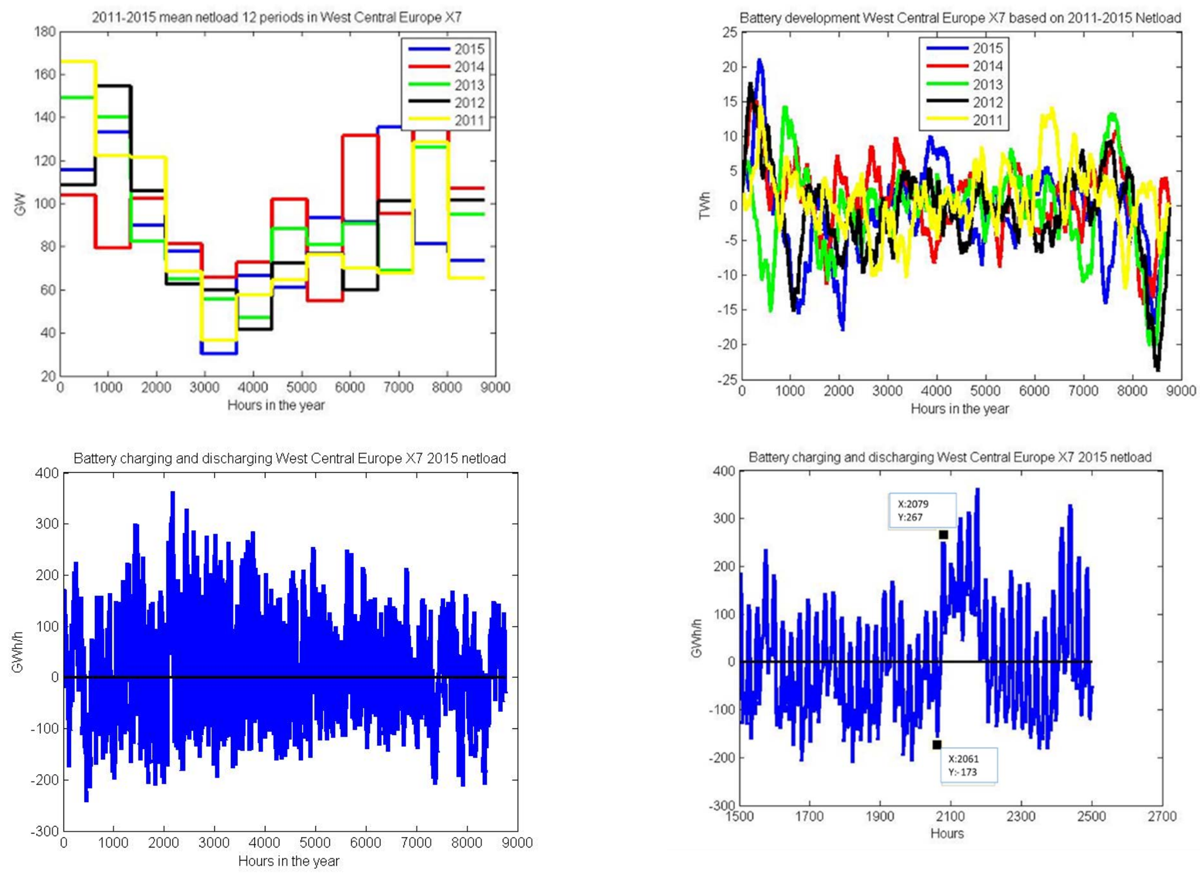


Figure 2 Mean net load in 12 periods per year for the 2011-2015 (up to the left), need for storage in each of the periods (up to the right). Deviation from the mean load hour by hour for 2015 for all countries in West Central Europe (down to the left for 2015) and enlarged for hours 1500-2500 (down to the right), scenario X7

Changes in load profile

Possible changes in the future load profiles for UK and Germany are shown in [9]. The profiles develop different for the two countries since expected population growth and deployment of heat pumps are higher in UK than in Germany. On the other hand, a higher number of electric vehicles are expected in Germany than in UK. This paper uses the hourly load profiles for 2050 from [9], but adjust them such that the total yearly consumptions are the same as for the eHighway2050 scenarios, see Fig. 3 to the left. The blue curve marked "2015" is the same load profile as for Fig. 1. The reason for the high load some hours each day in the smart charging case for Germany (green curve down to the left), is that the high share of EVs are charged in the middle of the day when production from many PV plants are high. Fig. 3 in the middle shows the impact on the need for storage in 12 periods of the year and the impact on the charging and discharging of the battery hour by hour to the left based on the load profiles from [9]. The results in the column in the middle and to the left must be considered as "outer frames" regarding need for battery, since there is no connection between the wind and solar data from the COSMO EU model and the load profiles from [9]. In a real future case, it is reasonable to expect that the load will be more adapted to the wind and solar power production every hour, and that there will be a reduction in need for storage.

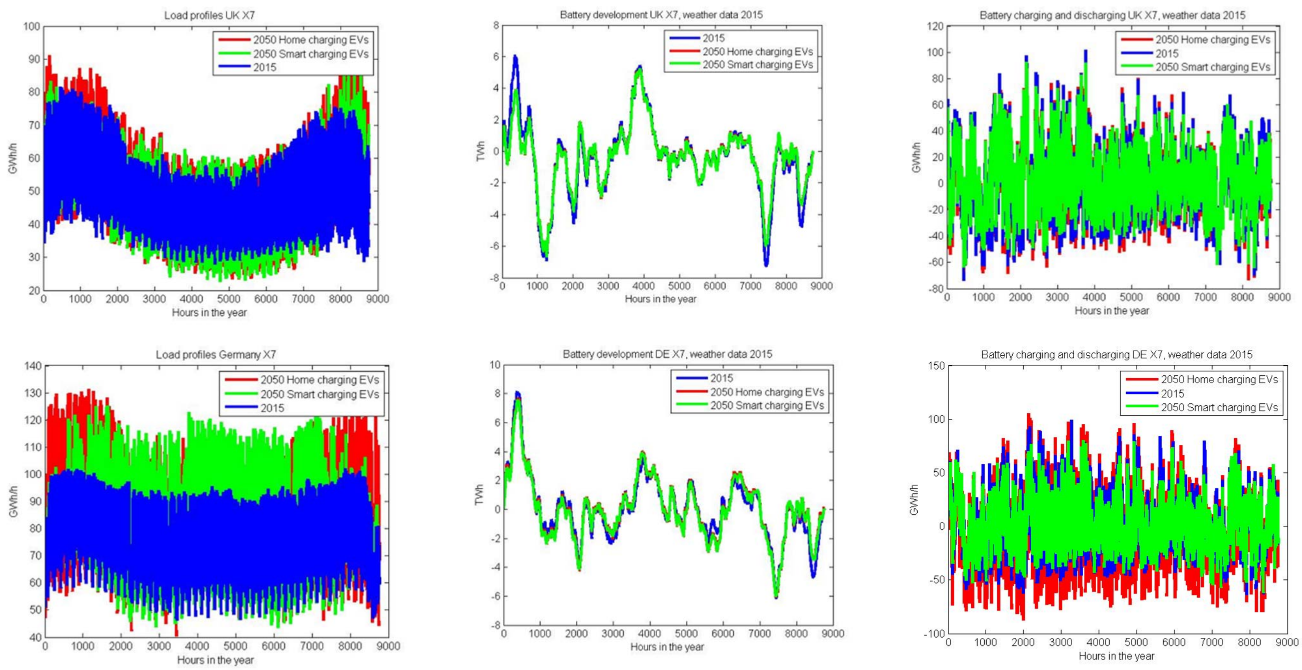


Figure 3 Load profiles (to the left), need for storage when a large battery is balancing deviation from mean net load in 12 periods of the year (in the middle), battery charging and discharging hour by hour (to the right), scenario X7, UK in the upper row, Germany in the lower row.

Many small scale batteries

In this section we discuss the effect many small batteries may have on the need for large scale storage, e.g. the effect of many residential batteries coupled with local PV production. It is difficult to estimate the amount and the capacities of such batteries in 2050. The Norwegian Transmission System Operator, Statnett, operates with a number of 5% of installed solar power production capacity as small scale battery capacity in a study of the European power market for 2030 [10]. That study assumes that batteries can discharge in 3 hours, and we have assumed the same. Fig. 4 shows the results for UK if 15% of solar power production have a battery that can discharged in 3 hours. The PV capacity in UK is 59.2 GW, the battery capacity is 8.9 GW and the battery storage capacity is 26.7 GWh. The green curve shows the development of the storage if the small scale batteries are aggregated. It is assumed that the batteries are discharged when the net load is above the mean value for the period while the batteries are charged when the net load is below the mean value. As shown in Fig. 4, the batteries have limited impact on the net load curve.

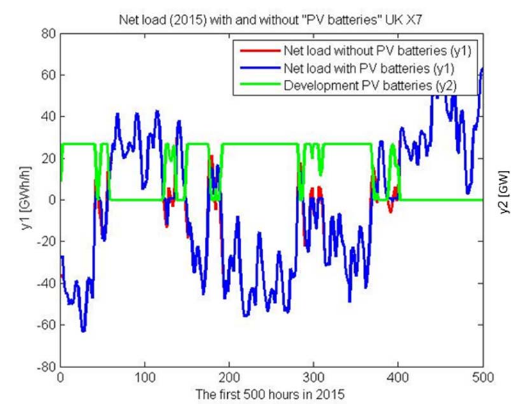


Figure 4. Impacts on net load in UK from batteries with capacity equal to 15% of installed PV capacity

Balancing variability with Norwegian Hydropower

Norway has ca 85 TWh of hydropower storage potential in present reservoirs, which is nearly half of all hydropower storage capacity in Europe [11]. As shown in Fig. 1 and Fig. 2, based on the approach we have used in this paper considering the deviation from the mean net load in 12 periods in the year, the storage need for West Central Europe may fit into the Norwegian storage capacity. The need is varying between + 21 TWh to -23 TWh at most. However, further studies are necessary before we can make conclusions. Among other, the present filling and depletion of reservoirs have a strong seasonal profile. The reservoirs fill up during the summer season and deplete in the winter period. Thus, storing another 14 TWh in the beginning of the winter period, as shown for West Central Europe in 2013 (green peak, Fig 2) may be difficult. Climate changes may change the filling and depletion pattern, so further studies should also consider this aspect.

When it comes to the needed capacity, the present capacity both in terms of interconnectors and in the hydropower production system are far below the needs. Fig. 1 shows that the need in UK is in the range 100/-80 GW, in Germany 100 GW/-60 GW and in the West Central Europe ca 300 GW / – 200 GW. The present capacity in the hydropower system is ca 30 GW. The first interconnectors between Norway and UK and Norway and Germany will probably be in operation in a few years and will have a capacity of 1.4 GW each. Two studies have indicated possibilities for increases in the hydropower production capacities. Reference [11] discusses the possibilities for increases of the power production from 48 power plants in the South Western part of Norway by reduction of time-of-use. By reduction of time-of-use from 3480-3800 hours per year in the present form to e.g. 1500 hours per year, the capacity will increase with 16.1 GW for these plants. Possibilities for installation of pump-storage comes in addition. Norway has very limited pumping capacity in the present system. The report [12] identifies possibilities for installation of pump-storage and thus, further increases of capacity in the hydropower production system.

CONCLUSIONS

This paper analyses variability of aggregated wind and solar power production in West Central Europe in 2050 based on scenarios from the EU 7th project eHighway2050 and the COSMO EU model. The paper shows results for each of the countries separately assuming that there is no transmission limitations internally in each country and for the whole region assuming there are no transmission limitations in the region. The analysis show very variable production from hour to hour for the countries with minimum production values of only 1-2% of installed capacity. Furthermore, in 10% of the hours there is production from less than 10% of the installed capacity. Even though the variability smooth out in the integrated West Central Europe, all the important problems related to energy security remain in the system. In real life, the challenges will be even greater, since there will always be bottlenecks in the transmission systems. In further analysis, the paper includes the load and assumes that base load production covers the average net load in 12 periods per year. It analyses the deviation between the mean net load and the simulated net load hour by hour. In this way, the paper quantifies the need for balancing e.g. in terms of batteries. Assuming that large batteries cover the deviations between real and mean net load hour by hour, the paper shows that the storage needs of West Central Europe are between +21 TWh to -23 TWh over the year for the X7 scenario. The need for balancing hour by hour varies between ca +300 GW and -200GW. In real life, the needs for balancing will be less, since the base load may provide some balancing capacity. The paper takes many small scale batteries into consideration, and studies the effect of storage corresponding to 15% of installed PV capacity. It is assumed that the batteries can fully charge and discharge its energy in three hours. The analysis show that present battery technology can only balance the variability of wind and solar power production in a few hours. Finally, the paper discusses the possibilities for the Norwegian hydropower system to balance the variability of the deviations from the mean net load. The hydropower system may have sufficient storage capacity to balance all the variability. However, if Norway is going to play a major role in balancing the variability in West Central Europe, large increases in the hydropower production and the interconnector capacities are necessary. Previous work has identified possibilities for increasing the capacity in the hydropower system.

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