Project Memo

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30 GW offshore wind in Norway

Time series analysis based on numerical weather model datasets

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Abstract

This memo investigates impacts of integrating 30 GW offshore wind in Norway

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Contents

1 Introduction

The Norwegian government has announced plans to develop 30 GW of wind power capacity by 2040. This amounts to an annual power production of about 140 TWh, which is larger than today's annual power consumption of about 120 TWh. How all this power can be integrated with the Norwegian power system is therefore of great importance. Clearly, much of the power production will be exported to neighbouring countries. However, the power will still need to be transported, and the question of power balancing within national limits is nevertheless highly relevant.

This memo summarises preliminary analyses based on power time series obtained from publicly available numerical weather model reanalysis data. It may be seen as an update of previous analysis [2, 10].

A recent study [6] uses a unique set of observed hourly wind speed data from five Norwegian offshore locations over a period of 16 years to quantify the potential of collective offshore wind power production. Another recent report by the Norwegian Water and Energy directorate (NVE) [1] has looked at how renewable power production is a challenge for the power systems, based on ERA5 data from 1979-2019. The study is based on existing onshore wind farm locations only

2 Wind power sites

The Norwegian Energy and Water Directorate (NVE) has identified 15 potential areas for offshore wind development in Norway. These have been chosen in the present study as locations for the future 30 GW of wind farm capacity. The distribution of the capacity amongst these wind farms have been assumed to be proportional to their surface areas. The result is a set of wind farms with capacities ranging from 0.2 GW to 9 GW, with *Sørlige Nordsjø II* being the largest. The locations of the wind farms are illustrated in Figure 1, and their assumed capacities shown in Figure 2. For part of the analysis we have included three offshore wind farms in the UK, Denmark and Germany. These are also shown in the map.

3 Wind power time series

For the creation of power time series, wind speed data from the MERRA 2 dataset [4] has been used, obtained via *Renewables ninja* [5]. Wind speeds covering the 29 year period from 1991 to 2019 has been used. Wind speeds at 100 m height have been converted to wind power using an effective wind farm power curve obtained by applying a Gaussian filter with standard deviation $\sigma = 0.2$ on a single wind turbine power curve [7, 8]. This is done directly by Renewables ninja. It should be noted that this Gaussian filtering method to obtain wind farm power curves is a crude simplification. The turbine assumed in our case is the Vestas V80 2000. Wind turbine power curves are fairly similar, so the precise choice of wind turbine power curve is not important in the present study, considering the high uncertainty in other assumptions.

The resulting wind power time series have significant uncertainty in their capacity factors. However, the variability from hour to hour, which is our main concern here, is still considered to be well represented.

Figure 3 shows the duration curve for wind power output from individual wind farms vs. the combined output, with a clearly visible smoothing effect. As expected, the combined power output is more often in the mid-range between about 30% and 80%. From the combined curve, we see that the power output is above 30% in about 85% of the cases.

Figure 4 shows correlation coefficients between the power output on hourly, daily and weekly basis for the various wind farm sites. Firstly, the figures show that there is little difference in the correlations whether considering hourly time series or daily mean values, but significantly stronger correlations for weekly mean

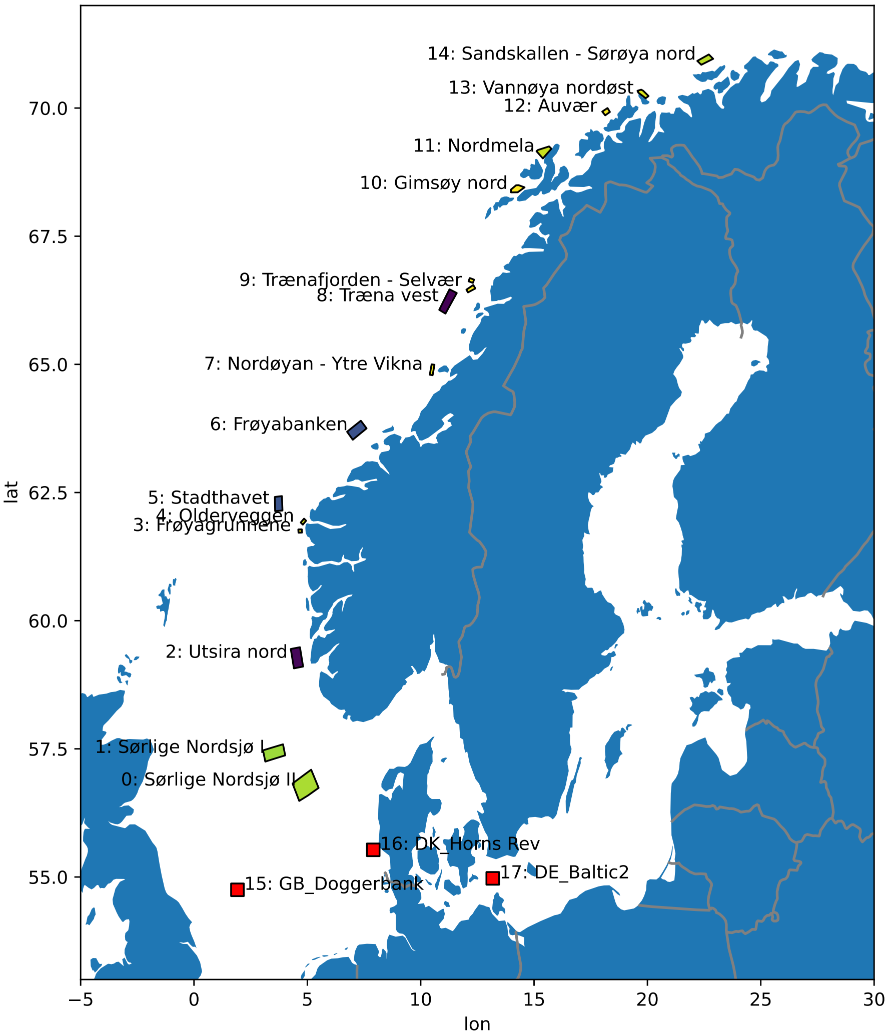


Figure 1: The 15 Norwegian offshore wind farm sites (0-14), and 3 other wind farms (15-17)

values. Secondly, we see clearly that the correlation reduces with geographical distance. For example, the power output of the Sørlige Nordsjø II area (number 0) has a correlation coefficient of less than 0.2 for all wind farms from Frøyabanken (number 6) and northwards for daily or hourly mean values. Thirdly, we see that Sørlige Nordsjø I and II are strongly correlated with the European wind farms (Doggerbank, Horns Rev and Baltic2). For wind farms further north the correlation is low.

wind farms. are more correlated with each other than the Norwegian sites typically are, and that they are strongly correlated with the Sørlige Nordsjø I and II areas.

Figure 5 illustrates this further with a 2D histogram plot of power output at Sørlige Nordjø II vs. Sørlige Nordsjø I (highly correlated), Utsira Nord (highly correlated), and Frøyabanken (less correlated). In the highly correlated cases, there is a clear relationship between power output from the wind farms: When one is low the other is low, and when one is high the other is high. In the less correlated case, there is no such pattern. For example, maximum power output from Sørlige Nordsjø II often occurs with minimum power output from Frøyabanken.

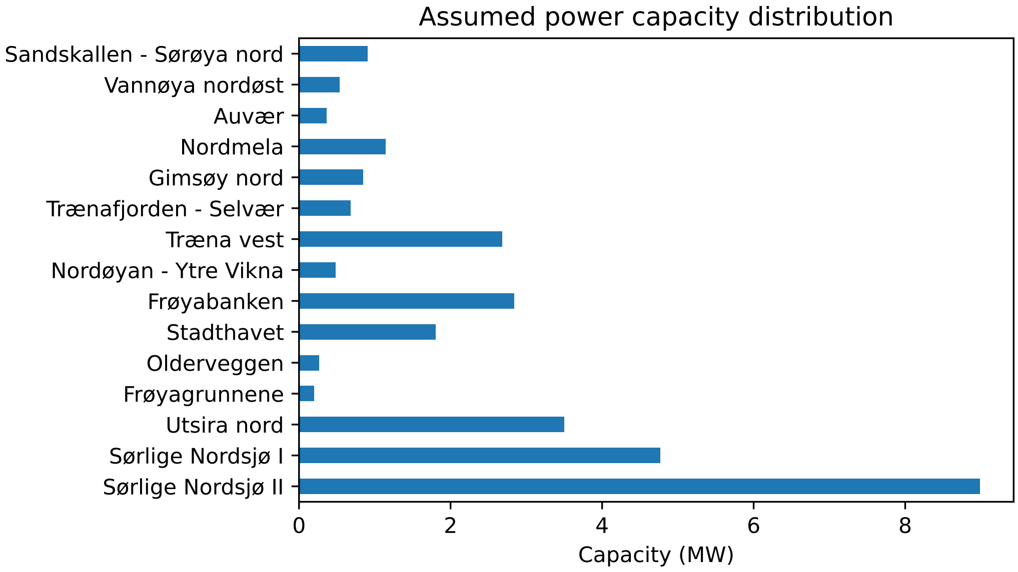


Figure 2: Wind farm capacities

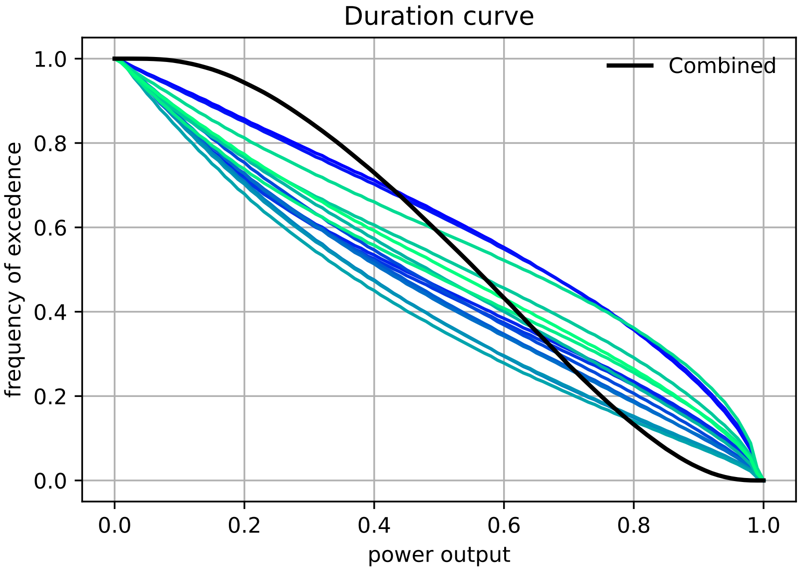
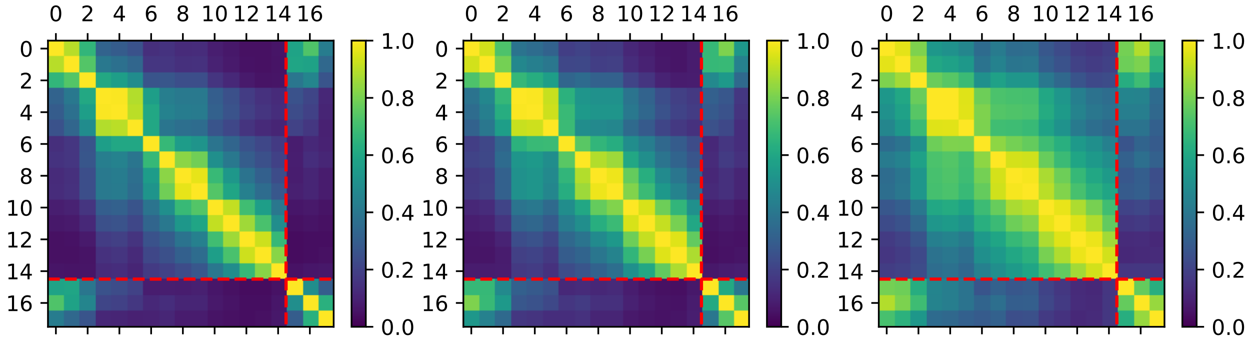


Figure 3: Duration curve of wind power output from individual wind farms and combined output

4 Wind power ramp rates

An aspect of wind power that is very important for power system balancing is the change in power output over time scales up to a few hours. A simple way to characterise this is to compute the absolute difference in power output $p(t)$ between two instances separated by a time shift s:

$$R_s(t) = |p(t_i + s) - p(t_i)|. \tag{1}$$



(a) Hourly (b) Daily (c) Weekly

Figure 4: Correlation coefficients for power time series for the various wind farm sites (ordered from south to north) and different time resolution. The dashed red line separates the Norwegian wind farms to the three other wind farms (15,16,17).

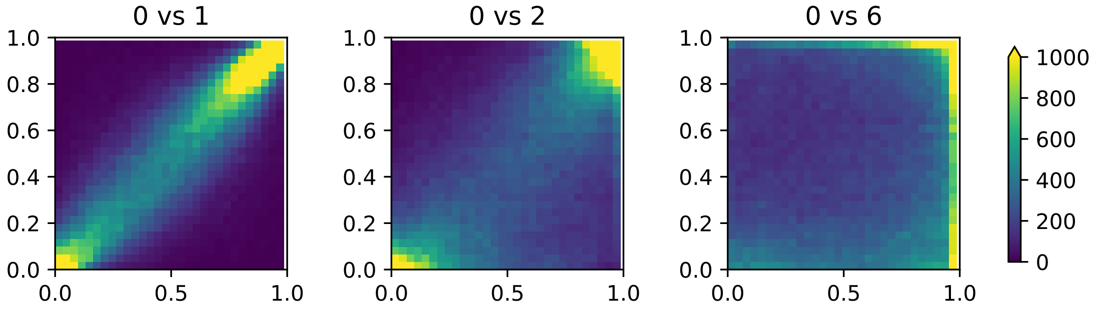


Figure 5: 2D histogram of wind power output at Sørlige Nordsjø II (0) vs. Sørlige Nordsjø I (1), Utsira Nord (2), and Frøyabanken (6). Note that the colour bar has an upper cap.

Figure 6 shows the 80% quantile for this difference as a function of the time shift s. It is plotted for the individual wind farms as well as the combined power output. The 80% quantile curve is defined such that in 80% of the cases the value is below the curve. For a time shift of 5 hours, we see that in 80% of the cases, power output from the individual wind farms changes less than 20% of the wind farm capacity, whereas the combined power output changes less than about 11%.

Figure 7 shows four different quantiles for a single individual wind farm (solid line) and the combined power output (dotted line). The 80% quantile in this plot is the same as in the previous one. From this we see for example that for the same time shift of 5 hours, the change in the combined power output is less than about 20% of the capacity in 95% of the cases (the 95% quantile).

5 Low wind periods

Another critical aspect of wind power is the duration of extended periods with low wind power output (sometimes referred to as “dunkelflaute” events). These are important for understanding the need for alternative power generation capacity, energy storage or demand-side flexibility.

This has been evaluated in the present time series by counting consecutive hours with combined (sum)

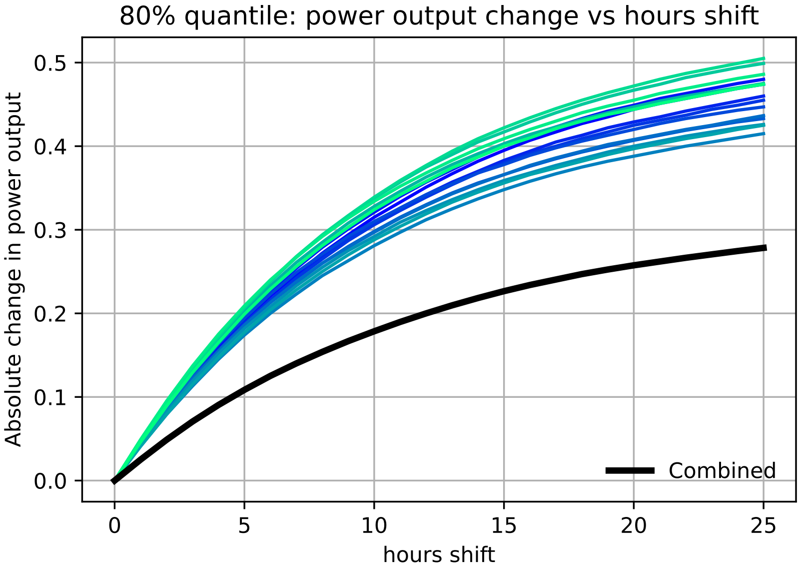


Figure 6: Change in wind power output after a time shift for individual wind farms vs. all combined (black line). The curves represent the 80% quantile, i.e. in 80% of the cases the value is below the given curve.

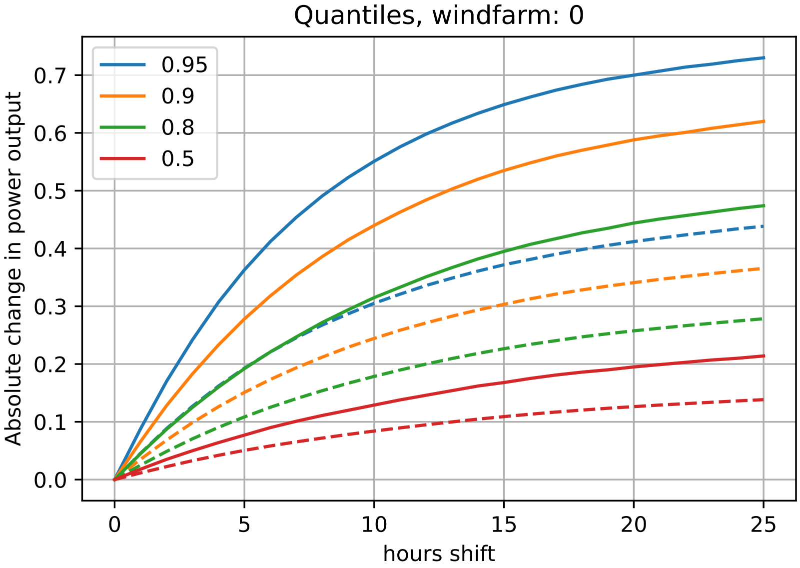


Figure 7: hange in wind power output after a time shift for a single wind farm (solid lines) and for all combined (dotted lines). The curve shows 50%, 80%, 90% and 95% quantiles.

power output below a given threshold value, and then counting the number of such events with prolonged low wind power over the entire time series. Figure 8 illustrates this as a filled contour plot with colours indicated the number of occurrences per year. For example, we see that the maximum time period of combined power output below 20% is less than about 4.5 days. The number of events with power output below 20% for more than 2 days is in the range between 1 and $10^{0.5} = 3.16$ per year (and closer to 1). An example time-series illustrating one such low wind period is given in Figure 9.

These results may be compared with similar analysis in [3].

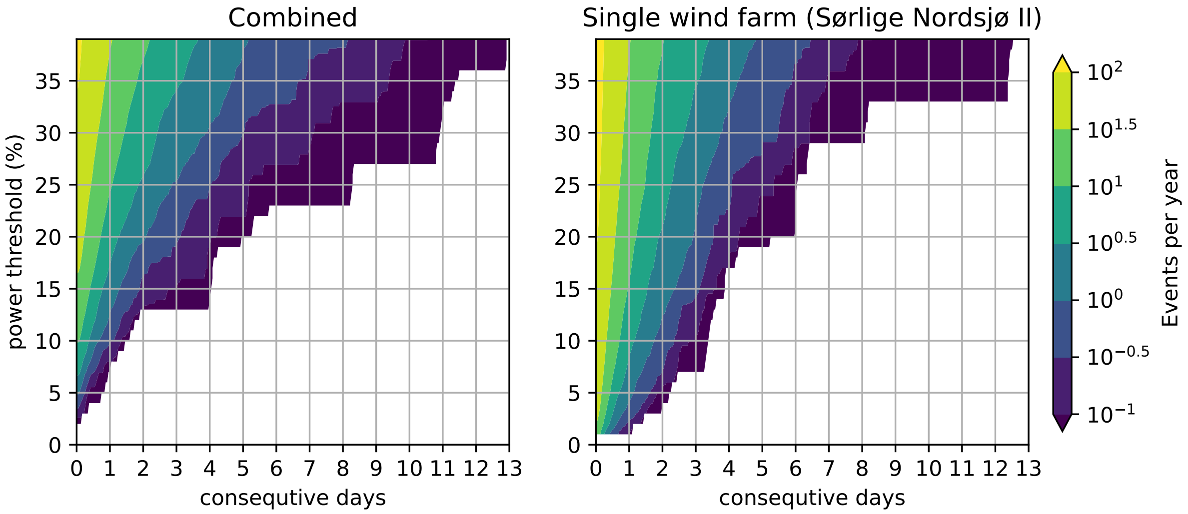


Figure 8: Number of events with consecutive hours of wind power below a given threshold

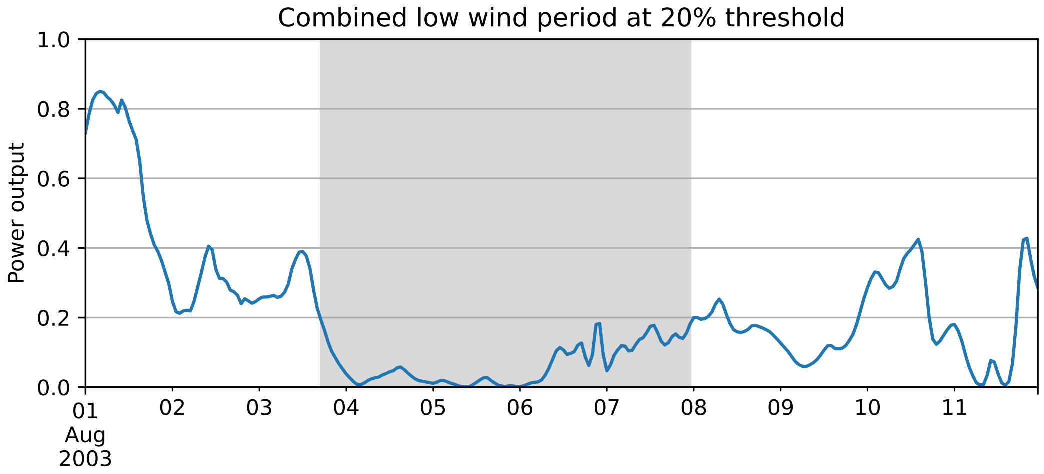


Figure 9: Example of extended period with wind below 20%

6 Seasonal variations

Winds in Norway are generally stronger in the winter and therefore wind power production is higher in the winter. This seasonal variation is beneficial since the power demand is also higher in the winter, while water inflow into hydro power reservoirs is low due to winter frost.

Figure 10 shows the seasonal variation of the combined power output. The figure shows the mean value and standard deviations within each week of the year. The mean value varies between a maximum of 68% in

January and a minimum of 37% in July.

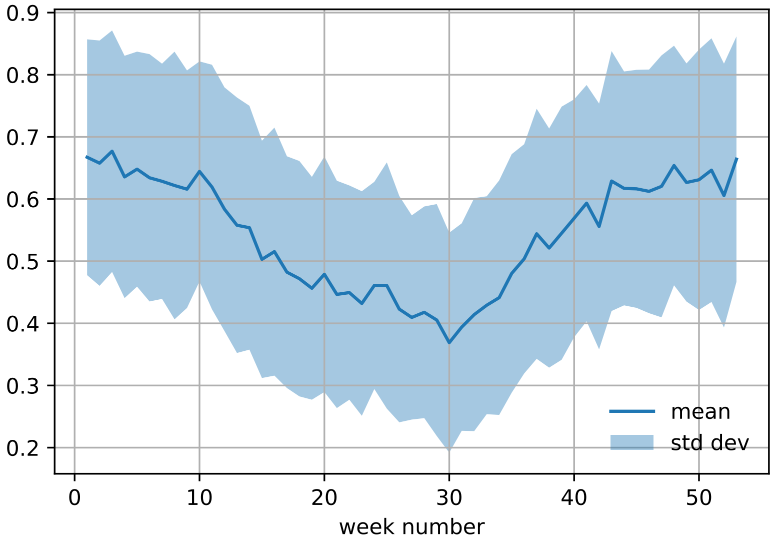


Figure 10: Seasonal variation. Solid line indicates weekly mean value, shaded area shows standard deviation within that week

7 Correlation with power consumption

Power consumption data for Norway is available from Statnett [9]. The seasonal pattern is illustrated in Figure 11 for the seven years from 2015 to 2021. The minimum power demand in the summer is about 60% of the maximum power demand in the winter, with significant variations from year to year.

It is interesting to compare this power demand profile with the power output from 30 GW offshore wind power. This is done in Figure 12. On average, the wind power profile matches very well with the power consumption.

This is important for the use of Norwegian hydro power and reservoir capacity. In fact, the inclusion of large amounts of offshore wind seems to reduce the need for seasonal balancing by the hydro power system. At the same time, however, the need for balancing on shorter time scales will increase due to wind power variability.

8 Comparison with actual wind power data

The Norwegian Water and Energy Directorate (NVE) publishes wind power production data with an hourly resolution for wind farms in Norway.

Here we compare actual wind power production in the period 2016–2021 from the 150 MW Smøla wind farm which is located at the coast south west of Trondheim, and from the Hywind demo single 2.3 MW floating offshore turbine, to wind power time series obtained as explained in Section 3.

Figure 13 shows one month comparing actual time series with modelled time series for power output from the Smøla wind farm. The overall variability appears to be well captured by the model, but with major discrepancies on a more detailed level. This is as expected with the lack of detail in the wind farm modelling.

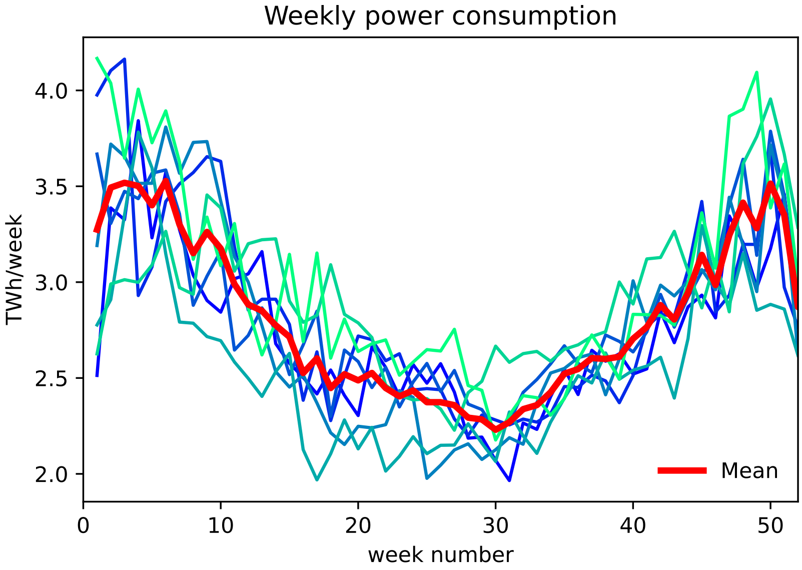


Figure 11: Seasonal power consumption in Norway, shown as weekly average for individual years 2015–2021. The red line is the mean value for all years.

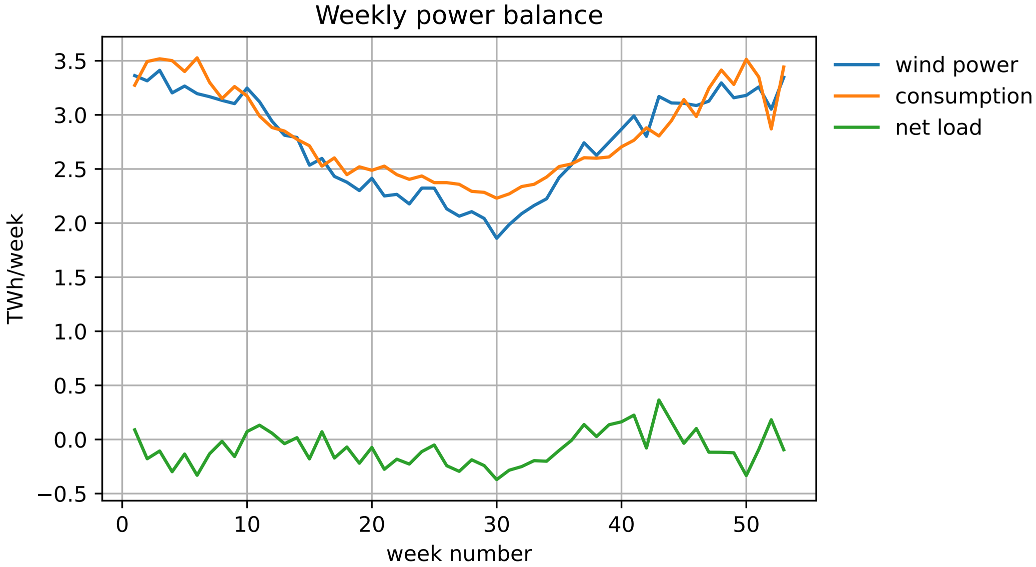


Figure 12: Comparison of seasonal wind power output (average over 29 year period), power demand and the resulting net load

Figure 14 shows duration curves for wind power output at Smøla and Hywind demo, comparing actual power output from NVE with what we obtained from the model based on weather model data. For the Hywind case, the Siemens 2.3 MW turbine power curve without any Gaussian filtering was used.

We see that in both cases, the model underestimates both low and high wind power production. For the Smøla wind farm we note especially that the model underestimates the amount of wind power output below

50%. For example, the model indicates that wind power exceeds 20% of capacity 60% of the time, whereas the actual data shows this to be below 40% of the time. For Hywind, the discrepancy is particularly noticeable at high wind power.

In terms of capacity factors (i.e. mean power output divided by capacity) we find for Smøla a value of 0.31 in the model vs. 0.25 in the actual data. For Hywind, the values are 0.40 in the model vs. 0.46 in the actual data.

We note these differences as a reminder to be cautious when interpreting the results presented in this memo, and as a motivation for further analysis with more refined approaches. In particular, the conversion from a single hourly wind speed data point provided by the Reanalysis data set, to wind power output from a geographically dispersed wind farm is a crucial step that should be improved as much as possible.

However, even if the modelled wind power deviates significantly from the actual wind profile, the variability and correlations may still be captured quite well. Figure 15 shows the relationship between actual power output at the Hywind demo wind turbine and the Smøla wind farm. As Hywind demo was located in the southern North Sea and Smøla is close to Frøyabanken, this may be compared with the third plot in Figure 5. Note that in these time series, the Hywind turbine has extended periods with zero power output due to maintenance or similar.

The correlation coefficient in hourly power output from Hywind vs Smøla is 0.013, once we have removed all data points with zero power output from Hywind (to eliminate that as a source of error). In other words, power from the two wind farm sites are completely uncorrelated. For comparison, we found the correlation coefficient between Sørlige Nordsjø II and Frøyabanken to be 0.08 – higher, but still a very low value.

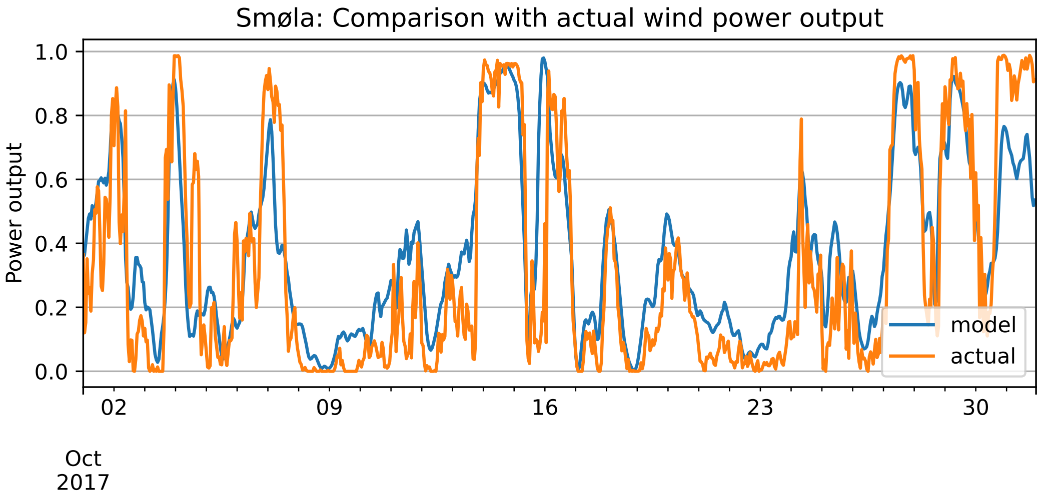


Figure 13: Wind power output at Smøla. Comparison between model and actual data

9 Conclusion

30 GW of offshore wind in Norway has been found give a combined power output that matches well with the seasonal variation in the power demand. This will have a big impact on the operation and planning of Norwegian hydro power, and power exchange with neighbouring countries.

We have estimated the power output from publicly available numerical weather model reanalysis data,

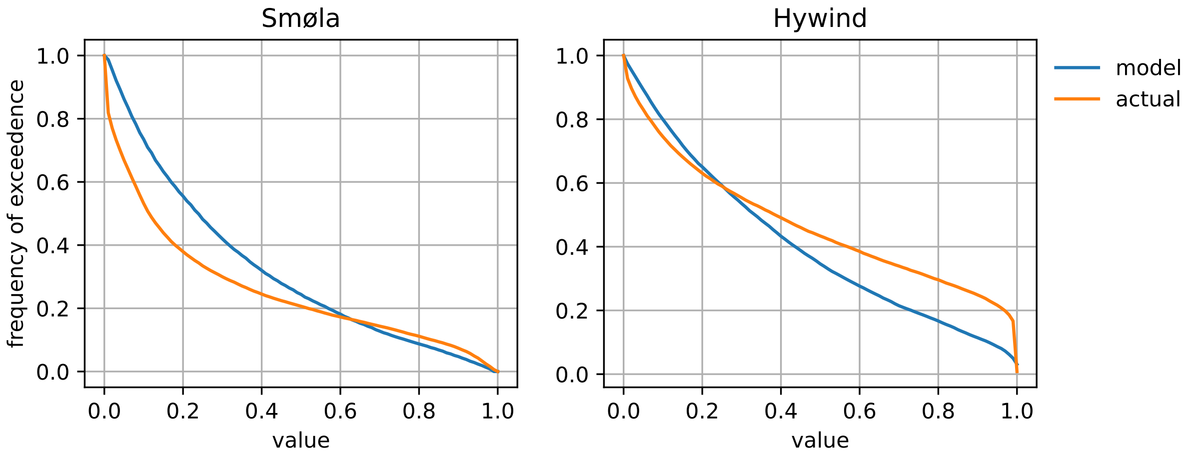


Figure 14: Comparison of duration curves for actual wind power vs modelled wind power output

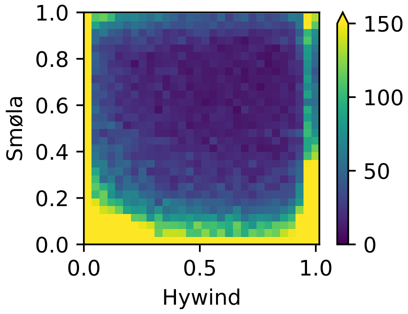


Figure 15: 2D histogram showing relationship between actual power output at Hywind (x-axis) vs Smøla (y-axis).

and have characterised various statistical properties that are relevant for investigating the impacts of olarge-scale offshore wind power integration in Norway.

The 30 GW offshore wind scenario that has been addressed here represents plans presented by the Norwegian government for 2040. Presently, this is 18 years into the future. We can remind ourselves that 2004, which may not seem so long ago, is already 18 years ago.

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