HRensembleHR - High Resolution Ensemble for HornsRev

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Final Project Report

- Executive Summary -

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Summary

The HRensembleHR project has been one out of several PSO projects targeted to offshore wind power. The project objectives comprised a quite comprehensive selection of topics related to forecasting of offshore wind power. These included:
- Ensemble forecasting
- Coupling between ocean and NWP models
- A study on ocean waves
- Wind power forecasting on multi-day horizons
- Wind power forecasting on the intra-day horizon
- A wind variability study
- A wake effect forecasting study
- A 5-month demonstration phase

At the end of the project all objectives except the wake effect has been addressed at least as detailed as planned. The wake study was replaced by a 2nd phase of the variability study, because it was found that a new approach published in 2009 would be of higher interest than the wake study.

An expert panel discussion has been carried out at the end of the project, because it was found that the topic of wind power integration is rather difficult and links to the research conducted in this project. The aim of the discussion was to provide different views on the challenges from a number of experts in the area without direct economic interest in offshore wind power.

The HRensembleHR project was originally planned to be a 3-year project. However, the project was extended by 6 months due to a delayed start, which was related to the takeover of the former owner of the Horns Rev wind farm. The new shared ownership required considerable more work on NDA's as well as on getting the technical data arrangements sorted out than expected .

The total project delay of 9 months became nevertheless a major benefit for the project, because considerable more insight was gained from the longer experience in working with the topic. Some additional synergy was also achieved, because two of the partners were getting involved in the German offshore wind power project "Research at Alpha Ventus" (RAVE), where insights and project developments from this project can now be further advanced and demonstrated.

The need of producing more CO_2 free energy has increased significantly during the project due to new political commitments. There is no doubt that offshore wind power has been intended to play a key role in the Danish policy on how to produce the required additional CO_2 free energy to meet the new targets. Offshore wind power solves two problems in that respect. One is that more energy per unit installed capacity is produced and the other is that a great part of the visual impact and noise problems will no longer be an issue for the public support of wind power. The drawback of offshore wind power has been found to relate to the price of building an offshore wind farm, which seems to have doubled since the first Horns Rev wind farm was built. There are many causes behind the price increase. One issue is reduced competition; another issue is the general price increases on wind turbines. At the time when the first Horns Rev wind farm was under planning no wind turbine vendor could make any profit on wind turbines. With increasing demand of clean energy, this has changed significantly.

The impact of the price increase is certainly setting a higher incentive to make offshore wind power more efficient in the energy system. Therefore, the main objective in this project has been to contribute with forecasting methodologies and a deeper understanding of the processes that have influence on the forecast quality to make offshore wind power more reliable and in this way achieve that offshore will no longer only be regarded as an investment in a power plant that operated non-scheduled with high generation capabilities. Instead, future offshore wind farms should become semi-scheduled and dispatchable resources that can compete with scheduled generation in a fair market structure.

The challenge in wind power integration is to produce wind power with a positive market value with continuously increasing amounts of wind power penetration. If wind power does not replace scheduled generation, but instead increases the generation above the level of the local demand with few regulation possibilities, then the market value will gradually be lost and investments in renewable energy will be withheld or directed elsewhere.

Increased reliability of offshore wind power will enable the TSO to trust in offshore wind power and use this power as base load generation for the load centres, while the dispersed wind power will cover the local feed-in.

This is a fast way forward to increased wind power penetration on market terms.

At present, it is expected that Denmark will have 3 clusters of 350-400MW offshore wind power installed in a triangle covering a large area of Denmark by 2013. At that time, Denmark West and Denmark East will also be directly interconnected. This corresponds effectively to a 1.1GW offshore wind power plant with a huge potential for improved renewable energy penetration, if the “plant” will be used for this purpose.

These 1.1GW offshore will produce as much energy as 2.5GW on land and therefore help to increase the average load factor in the Danish area. A high average load factor is important, because this reduces the number of over-production hours and increases therefore the overall efficiency of the energy system. This is required, because wind turbines produce in the range of 28-33% of their rated capacity in the developing markets, while an increasingly amount of old turbines in Denmark produce only 21% of their rated capacity. A political target of 50% wind power penetration would in that case require an installed additional capacity of 2.5 times the average demand. This would reduce to a ratio of only 1.25 times the demand, if the target would be met by offshore wind power alone. A pure offshore supply means less hours of excess production, but a lower correlation between demand and wind power generation. A mixture of new and modern wind farms on land and offshore wind farms will therefore be more beneficial, as it will reduce the generation at night and thereby increase the correlation between demand and wind power.

The scope of the work in the project has therefore been to push the evolution to a point, where offshore wind power reaches the required level of reliability and where synergy with existing wind power can be achieved. The work in the project contributes with a significant understanding of the offshore challenges and the project group is convinced that this will further enhance the planning of new and potential offshore wind power in the near future.

Understanding is of course not enough, but new forecast methodologies will be made available from the project results within less than a year that are tailored for the challenges and that will ensure that the 2013 milestone can be achieved.

Variability and Sea Surface Parameterisation

Results from the wave study, variability study, the demonstration, ocean coupling, findings in the sensitivity experiments and the iEnKF short-term forecast have given significant synergy in this project.

The most basic research result in the project were the findings from a study on variability using two Empirical Mode Decomposition (EMD) approaches, a Hilbert-Huang and an ensemble EMD. Both approaches confirm the existence of significant variability in offshore conditions. It was found that the variability of the short time-scales below 24 minutes are either not explicitly visible in the grid-scale of the NWP models or in the best case significantly smoothed out in all of the tested model configurations.

It was found that the first 20 days of the investigation period in 2004 had 50 events with variability on time scales between 24-120 minutes. This is not equivalent to 50 critical events for the power system, but evidence of the variability of offshore wind. This variability was not detected by more than 25-30% of the individual ensemble members.

This seemed to be a surprisingly low number for a 5km resolution NWP model. Therefore, it was decided to conduct an extreme test of the Ensemble Empirical Mode Decomposition to study how the approach handles the important extreme events with return periods of maybe 3 years and longer. Unfortunately, it was found that energy was showing up on nearly all time scales at this particular event, although the artificially induced extreme event was only present in the observations over a 24 minute period.

The result forced us to limit the conclusions drawn from the EEMD studies, because the test revealed that the true time scale of the variability is uncertain. Obviously, an event with a time scale of a few minutes can turn up on a multi-hour time scale in the verification. The results presented in this report and the corresponding referenced sub reports and journal publications contain events on a number of time scales that are mixed within specific time scale ranges. An example range of such time scales is the 24-120 minute scale. The extreme test suggests that considerable measured variability within a 24 minute interval turn up on scales between 24 and 120 minutes. This pattern creates a skew picture of the variability pattern of the weather and consequently also the score of the forecasts.

Before the extreme case study, it appeared as if all forecasted variability on the time scale 24-120 was suppressed. However, the extreme test showed that the Ensemble Empirical Mode Decomposition (EEMD) approach is not reliable enough to state that. There is a possibility that only 24 minute variability is consistently suppressed. It is of course always possible to find events that was not forecasted well on longer time scales, but it is unclear how often such events take place and if the models have deficiencies on this matter.

It is likely that the reliability issues of the EEMD is related to that variability events often occur as a single peak and not as a wave. Obviously EEMD is not suitable for this kind of variability. The approach seems to be constructed for long waves and not instant extremes.

It appears that the approach is best suited to compare time series containing similar time scales. The absolute performance of the individual time series against the measurement time series should therefore be ignored. As a consequence, this means the approach should be used to compare similar model configurations rather than performance compared to measurements. This is also how it has mostly been applied to in the project. Nevertheless, some comparisons with observations are also shown is this report. The results are interpreted in the light of the conclusions of the extreme event analysis given above.

We have reason to trust the result that the predictability of atmospheric "waves" increases significantly with increasing timescale. However, but the amount of measured events on the time scales of 24-120 minutes have been a surprise. The 24-minute wave alone could be dominant, but EEMD mixes the modes.
The measurements were fed into EEMD in 6-minute intervals. Thus, we can trust that there is significant variability well above this scale. This is an important finding for the wave study, because such long time scales cannot be generated by friction due to ocean waves.
The presence of significant variability on time scales above the friction process and below the synoptic scale is confirmed by the results from the wave study. There, it was demonstrated that significant variability exist that cannot be explained by the wave pattern and that this variability causes a dominant background error in the computation of wind speed. This was found by predicting wind speed in 15m height with a number of other available measurements and comparing the forecasts with measured wind speed at that height.
We can also compare this background error with the magnitude of a NWP forecast RMSE error on a point wind speed, which is equivalent to the approx. 2-2.5m/s background error of the 15m wind speed calculation.

Thus, three independent results confirm the theory that considerable offshore variability exist, which is not explained nor generated by friction or by synoptic scale meteorology and consequently not modelled by NWP models as such. The NWP simulations, the EEMD and wave study have hence led to an important finding on the predictability of offshore wind variability.
We have to conclude from these results that the generation of the offshore variability is therefore mostly non-local. This means that some external forcing somewhere else due to either inhomogeneous, sea surface temperature, a convective cell or instability mechanisms may generate a wave measured at one location.

The measured wind field at one location is therefore a superposition of many interfering waves generated at different places at different times. Their lifetime is longer than on land, because of the lower friction of the sea surface.

The frequent occurrence of variability suggests that variability is connected to waves due to by some kind of disturbances rather than meso-scale weather caused by instabilities. However, this interpretation is dependent on the correctness of EEMD's capability to count events. If the true number of events is approximately 30% of what EEMD counts, which is what the forecasts suggest, then it is possible that the cause is meso scale weather activity.

If EEMD is correct, then it is also possible to interpret 2/3 of the events are propagating waves and the remainder as present on the mean flow. If so, all results fall in place. The ensemble forecasts and EEMD are both correct. What EEMD counts as additional variability are then horizontally probagating waves with vertical amplitude in the PBL where the variability is then due to the wind shear. We do not have the proof of this theory yet from the results, but it is a possible interpretation, which brings consistency between model results and measurements.

Regardless of the nature of the variability,the effects should not be ignored in the calculation of the air/sea interaction, because the kinetic energy transfer between air and sea relates with a power of three of the wind speed. The finding from the variability study may therefore explain why theories on sea surface stress are inconsistent and very approximate equations apparently work as good as more advanced approaches.

It almost seems like the contribution of the variability is overlooked and the net result is that the wind and waves can only reach a balance very seldom. This finding is likely to have impact on all kinds of modelling, where the ocean and atmosphere interacts. Storm surge modelling is an example of a discipline, where calibration has been required to compensate for the wind variability, because such models otherwise would under-predict the surges. The results have brought an understanding that allows parameterisation the friction more intelligent and taking account of the variability in the integral of the effective sea surface stress.

Although the results indicate that there may also exist similar long time-scale variability on land. This is however not nearly as important as for the ocean. What differs is that the ocean surface changes roughness characteristics with the wind speed, while the surface roughness on land is wind speed invariant.

There is no doubt that the result will bring focus on how to predict variability of the wind, not because variability forecasting is important for wind power prediction and thereby the power system, but because this is the key to improve the friction process over the ocean.

Since 70% of the surface of the Earth is covered by water, it is obvious that a new basic understanding can add value in various forecasting disciplines.

Numerical 3D Simulations

The project used a large number of different ensemble forecasts. Some were from WEPROG's operational archive, others were generated specifically for the partners and a number of sensitivity experiments were used to study how the air/sea interaction can be improved. The conclusions that can be drawn from all these different simulations is that the forecast uncertainty offshore is high, but it is not the sea surface roughness that is the predominant uncertainty generator.
The effect of the sea surface temperature appears to be stronger and there is a positive effect on the uncertainty forecast of the intra-day forecast when coupling the weather and ocean ensemble models. This is an important finding, because the result demonstrates that the sea surface temperature generates forecast uncertainty even on the intra-day horizon. Normal satellite data does not give sufficient information about the sea surface temperature for NWP modelling purposes. Thus, even though the ocean coupling did not improve the traditional RMSE score yet, there is now evidence that the sea surface temperature is generating wind power forecast error, which is not even limited to offshore conditions.

It has been shown in this project that the achievable improvements on the day-ahead are very small compared to the improvement gained by applying an intelligent short-term forecasting models. The purpose of the 3D ensemble forecasting work therefore was to produce a comprehensive and easy to use forecast for the day-ahead operation with consideration of the variable forecast uncertainty. However, a forecast user has to expect frequent refinements of the forecast based on the available online data as discussed below.

Wind Power Prediction in Offshore Context

The higher error of point forecasting compared to area forecasting was from the outset of the project considered an obstacle for the quality of offshore wind power forecasts.
An offshore wind farm operates more frequent at full load than wind turbines on land do, because the wind speeds in the range 12-20m/s are frequent in the North Sea.
Such conditions tend to increase the forecast error, because the wind speed peaks in this range do not always last very long. The risk of a double error due to a forecast phase error is therefore highest for the short peaks.

The forecast difficulty increases with the variability and as mentioned above this variability is only partially present in the weather forecasts.
Power curve training therefore needs to consider the frequent large mismatches between forecasted wind speeds and power measurements. Different approaches have been used in this project to change the influence of outlier pairs of wind speed and power measurements. Along with this work, a combination of different variables was conducted. This work has essentially been testing, whether the weather forecast has systematic errors in certain weather conditions. If such errors are detected, then the power curve is modified to correct the forecast for the error. These corrections built on correlations between variables on certain conditions and are technically done in a general Neural Network software package.

At the end of the project it is fair to say that there has been conducted significant amount of work on the wind power forecasting approach, although it is difficult to point out achievements that will become next generation state-of-the-art.
There are still unused opportunities in this discipline for offshore conditions, because data from two masts near offshore wind farms could be defined as a requirement in the future to increase the amount of measurements available for forecasting. The combination of mast measurements, power measurements and weather forecasts would give the possibility for an efficient screening and thereby the means of eliminating effects of outliers with increased mismatches between wind and power.
The output power curve of such a training would be considerable more accurate and the forecast would be very responsive with unfortunately potentially high errors. The error of the mean of many ensemble forecasts would however not increase, because the average would not be nearly as responsive, if the weather is uncertain and hence dampen the forecast error significantly.

The conclusion from the variability study on the existence of offshore wind variability, which is not present in forecasts, raises some issues on how to interpret weather forecasts and how to use them for power curve training in offshore conditions. These issues relate to that power generation is limited between zero and the full capacity and any error near both extremes result in skewness and smoothing of the power curve. It has been shown that the resulting ensemble wind power forecast may easily be interpreted to be under-dispersive, unless the power curve training is using the ensemble weather input in a consistent way.

State Estimation and Short term Forecasting

The energy system is collecting a large number of instantaneous measurements with a frequency that is one or two orders of magnitude higher than the collection of meteorological measurements. The measurements of wind power are not always uniquely invertible to a wind speed, because of the flat ranges of a power curve. Wind power measurements do however provide significant potential for the improvement of forecasting, if they are used in connection with meteorological measurements and forecasts. This theory is based on the experience from data assimilation, which claims that all information essentially adds value.

Following this idea, a new approach was developed for the purpose of data assimilation and short-term forecasting based on ensemble forecasts and measurements. The approach has been named "inverted Ensemble Kalman Filter" (iEnKF), because of similarities with other approaches using the so-called Kalman Filter technique. However, the approach is fundamentally new, because the approach is a state estimate and a forecasting system in one. It is built upon a direct translation of measurements and the help of inversions into a non-dimensional ensemble forecast percentile space. The algorithm is unique, because it has a *must trust* constraint, which is fulfilled with out compromising dynamical balance of the model system. The iEnKF can therefore generate forecasts with the same resolution as the incoming measurements, which is highly relevant in the power system. The iEnKF is compatible with the use of localised measurements as well as area summations of raw meteorological data or non-linear functions of multiple variables. Regardless of the complexity of the data, the iEnKF can conduct a complete state estimate in a few seconds and a forecast based on all the available measurements.

The iEnKF is essentially a pure mathematical approach, because all physical considerations are inherent in the ensemble forecast data. The approach is therefore applicable in any discipline, where ensemble forecasts can be generated for each of the input variables and all output variables of interest.

The core of the iEnKF algorithm can be summarised to its ability to determine the influence of arbitrary variables on other arbitrary variables by sending influence around in a non-dimensional common model space, where all information is weighted via correlations in ensemble space.

As an example, the iEnKF has the potential of translating the raw signals of a radar to a variability forecast on wind farm level. Another application is to generate a 4D analysis in ocean model space only with the use of sea surface temperature measurements from satellite data.

So far, the iEnKF has only been demonstrated for wind power usage, although the approach is not restricted to wind power.

Future Outlook

The challenges ahead of us are also opportunities to achieve a higher reliability of offshore wind power and thereby reach a higher penetration of wind power without lowering the market value of wind power below zero. A 1.1GW offshore wind power pool in year 2013 in Denmark will produce approximately a similar amount of wind power as today's 2500MW dispersed wind power spread over the western part of Denmark. The need for an efficient integration strategy into the energy system is therefore obvious.

Offshore wind power risks lowering the market value of exiting dispersed wind power without a dedicated effort. Over time, no action will not only be to the disadvantage of owners of dispersed wind power but to the entire community, because the incentive to invest in wind power is reduced. This will indirectly reduce the competition on the energy market to the disadvantage of the community. Offshore wind power in the right environment can therefore act as a catalyst to an increased wind power penetration and effective market system. Without an increase of reliability of offshore wind power a higher penetration will become an expensive CO_2 free energy source.

A 2-3 year start-up period with an extra high bonus to offshore wind power followed by a transition to a common production incentive scheme based on market prices plus bonuses will ensure that all wind power has an incentive to work together and thereby keep wind power investments attractive. In this way, offshore wind power will fit into the market and still be a viable investment. The proposed scheme would automatically limit the fixed price supported wind power generation on the grid to the capacity of the newly built offshore wind. This amount of energy would then fit into the market along with other wind power operating on market terms and bonus schemes.

A primary goal by conducting offshore wind power research is to contribute positively to the Danish energy system and the findings in this project have this potential. However, experience has shown that it is sometimes difficult to see how research findings are disseminated into the energy system, partly because the tradition is to keep information confidential, although transparency is widely recognised to enhance competition.

It is the consortium's hope and ambition to assist that the results will find their way into operations and contribute to continued higher renewable energy penetration. The project's web page (www.hrensemble.net) with information about the project, its findings and available publications related to the project will be further maintained by WEPROG to ensure the results will be available also for the public outside of Denmark, where the potential for successful further dissemination will be highest in the densely populated central Europe, the United Kingdom, around the Great Lakes in North America and in China.

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