ENERGINET/DK

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Final report

1. Project title	Integrated Wind Power Planning Tool
2. Project identification	Energinet.dk project no. 2010-1-10464
3. Project period (date, year)	01.01.2011-31.03.2015
4. Entity responsible for the project	Technical University of Denmark, Department of Wind Energy (CVR 30060946) Frederiksborgvej 399, 4000 Roskilde
5. Reporting period	Full project

6. Signature of authorised signatory

Date: 7.7.2015

Name: Gregor Giebel

Signature: Gregor Gi...

7. Project summary

The project had a long phase between inception and eventual start, where several iterations of negotiations already before the projects kick-off changed some details in the description of work. The project also had been reduced significantly to essentially a PhD study and some senior time for supervision. The overall guiding topic of the proposal is still valid though: "*The purpose of the project is to improve and validate newly developed models for simulation and prediction of wind power fluctuations, by integrating the tools with meteorological tools for wind resource assessment and the output of mesoscale numerical weather prediction models.*" As the modelling of power fluctuations using meteorological tools had been taken care of already through other projects and would have required an additional run of WRF at great personal expense of Martin, and since the investigation of the interface between the meteorological and the statistical forecasting tools was more in focus of our industrial partner ENFOR A/S, the project concentrated on forecasting. After an initial candidate had pulled out of the employment process at a late stage, the project's timeline was delayed and already extended early in the project. Eventually, on 1 October 2011, Martin Rosgaard (née Olesen) started his employment at ENFOR and his PhD at DTU. After the extension to his PhD was granted due to difficulties finding the exact course for his PhD project, he delivered his PhD thesis called "*Limited Area Forecasting and Statistical Modelling for Wind Energy Scheduling*" on 20 April 2015 and successfully defended it on 2 July.

As one of his first assignments, he attended the WRF tutorial in Boulder (Colorado) in January 2012. Apart from a follow-up course during his stay abroad, most further ECTS points required for the PhD were done in the subsequent years in courses at DTU. This was interrupted by his paternity leave for 10 weeks in summer and autumn of 2012. Before this, Martin initiated four daily downloads of WRF input files from the global weather prediction system GFS (Global Forecasting System) from servers at NCEP in the US. In the end of 2012 and the first part of 2013, the runs of the meso-scale model WRF (Weather Research and Forecasting) on the supercomputer at Risø were prepared. This involved work on the source code level in WRF. During this time it also became clear that the initial perspective of preparing files suitable for both forecasting research and power fluctuations could not be fulfilled with the same model runs, so the power fluctuations and CorWind integration was scrapped. In the summer of 2013, he attended two courses at the European Centre for Medium Range Weather Forecasts (ECMWF), stayed for 3 weeks at the Naval Postgraduate School in Monterey (California), presented at the annual WRF Workshop, and had an extended stay at the National Center for Atmospheric Research (NCAR) in Boulder (Colorado). With the guidance from those two institutions, the parameters for the WRF runs were fixed. Also during summer, the first WRF runs were completed, but just using the automated script, the amount of valid runs was good but not good enough, so for some dates, WRF runs had to be manually initiated. Finally, in the first half of 2014, all WRF runs were finished, and the statistical analysis could commence. ENFOR during this period put in considerable effort into the statistical modelling and evaluation of WRF and GFS for the different sites, and had weekly meetings with Martin when necessary, e.g. the whole first half year of 2014.

7 project meetings were held from the kick-off meeting at DTU in Risø on 31 January 2011, on 13 October 2011, on 7 March 2012, on 27 November 2012, on 19 September 2013, on 28 November 2013, and one in February 2014 at ENFOR. In between, several meetings in the actual supervisor team (Andrea Hahmann, Poul Sørensen, Gregor Giebel and Torben Skov Nielsen) guided the PhD work further.

The budget has been kept by the partners. The largest part was the employment of Martin Olesen, which also followed a steady schedule. At DTU Wind Energy, DTU Compute and ENFOR, the budget was within usual deviations for man-power, expenses and salaries. ENFOR had a possible expense in the budget regarding external services, which was a provision for the acquisition of additional meteorological data from national or international providers. Since we decided in the project to use the freely available GFS data as the main workhorse, we did not need that, and could convert some of it to salaries.

8. Scientific summary

The main scientific report is the PhD thesis of Martin Rosgaard. The abstract and some highlight result plots (with caption numbering as in the thesis) are given here, the whole thesis is attached. The main emphasis was to get a WRF run with different horizontal resolution (down to 1 km) for the three sites we used for comparison: Horns Rev, Rejsby Hede and Stor Rotliden in Sweden, i.e. an offshore site, a coastal site in gentle terrain and a complex terrain site. From this run, and in conjunction with ENFOR's Wind Power Prediction Tool, a state-of-the-art statistical forecasting tool, the benefits of higher resolution NWP modelling was to be assessed taking into account that bias was not an issue after using the statistical forecasting tool.

This thesis concerns forecast accuracy for operational wind power scheduling. Numerical weather prediction history and scales of atmospheric motion are summarised, followed by a literature review of limited area wind speed forecasting. Hereafter, the original contribution to research on the topic is outlined. The quality control of wind farm data used as forecast reference is described in detail, and a preliminary limited area forecasting study illustrates the aggravation of issues related to numerical orography representation and accurate reference coordinates at fine weather model resolutions.

For the offshore and coastal sites studied limited area forecasting is found to deteriorate wind speed prediction accuracy, while inland results exhibit a steady forecast performance increase with weather model resolution (see Figure 2). Temporal smoothing of wind speed forecasts is shown to improve wind power forecast performance by up to almost 1 %, and the explanatory value for wind power forecasting of six different prognostic and diagnostic weather model variables modelled semi-parametrically is found to differ depending on the local terrain. In terms of wind speed ramp predictability, the study finds consistent improvement for better resolved forecasts, and indications of wind speed fluctuation phase-drift with weather model integration time are countenanced, which in part explains the faster decline in limited area forecast performance with leadtime, relative to global model forecasts.
The limited area forecasting study is rounded off with a demonstration of the feasibility of forecasted wind speed variability for predicting wind power uncertainty. Finally, a statistical postprocessing framework for numerical wind speed forecasts is developed and evaluated, and the proposed methodology made possible the discovery of the lifted index weather model diagnostic as containing systematic corrective potential for wind speed forecasts generated by the weather model studied.

Some highlight results are given below:

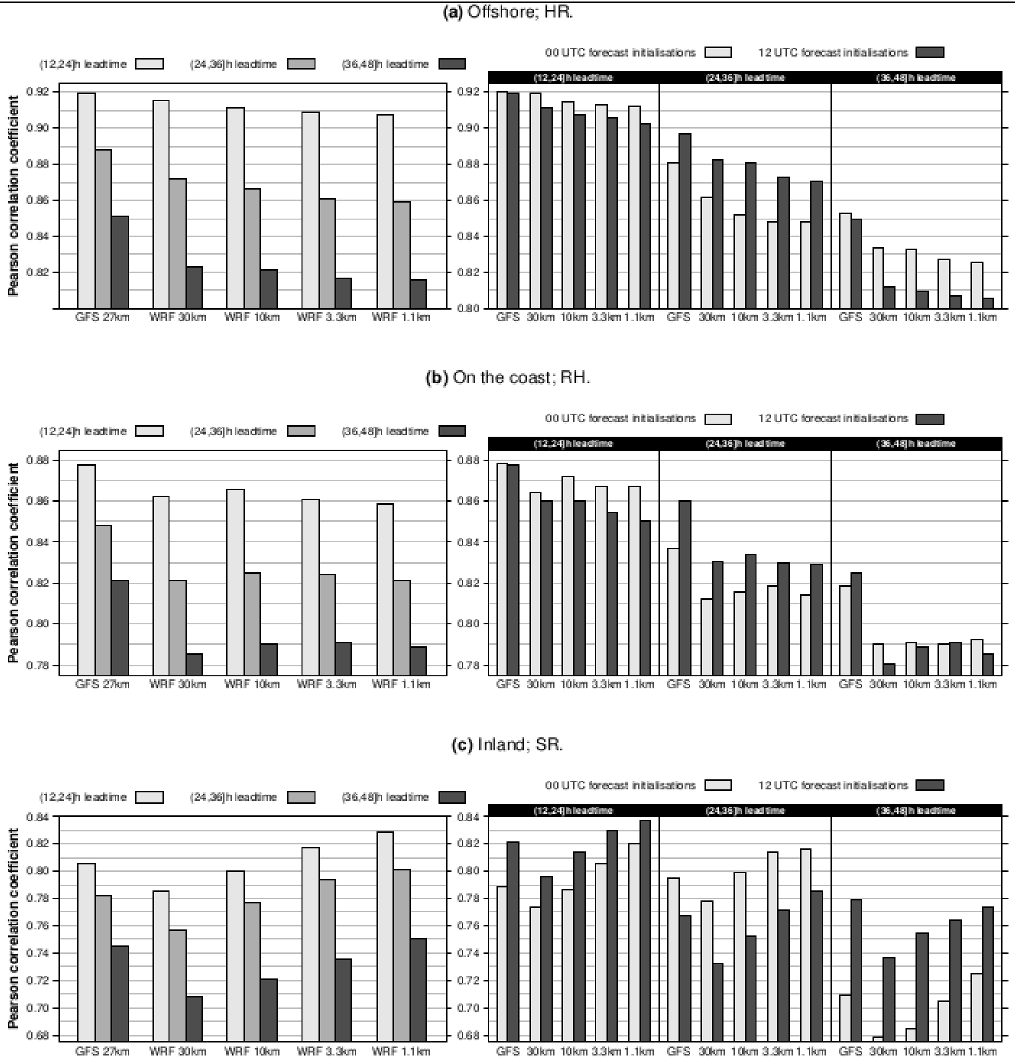

Figure 2. Wind speed forecast performance. **Left**: Assessment according to the three forecast leadtime groups, cf. Section 2.1. **Right**: Separate assessment for 00 and 12 UTC forecast initialisations, cf. Section 3.1.

The Pearson Correlation Coefficient was chosen as a main verification error score for the meteorological models as it is independent of bias and scaling errors, which are caught by the subsequently used statistical tool anyway. In Figure 2 (thesis p. 71), we see that the forecast performance decreases from GFS with increasing WRF resolution for the offshore and coastal case, while the increased resolution seems to contribute with valuable information in the complex terrain inland site.

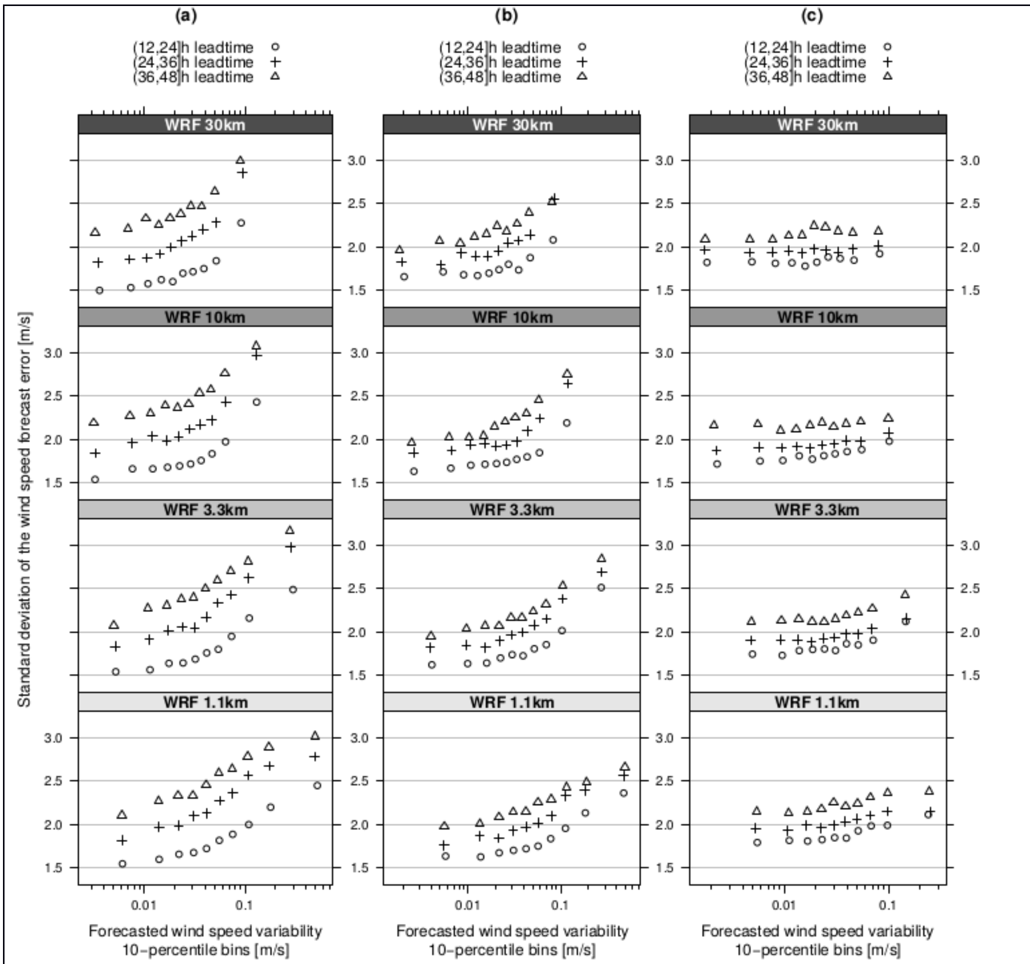

Figure 6. Wind speed uncertainty in terms of Eq. (7) vs. WRF modelled wind speed variability based on the raw 10 minute datasets for **(a)** HR, **(b)** RH, **(c)** SR.

Figure 6 (thesis p. 96) shows that access to the source code of WRF enabling to write out additional components can add knowledge to improve the forecasts. Here, the variability of the wind speed is assessed within every 10-min time step, and plotted against the eventual forecast uncertainty. In most cases, a clear signal emerges, making the intra-10-minute variations from WRF a good predictor for the forecast uncertainty.

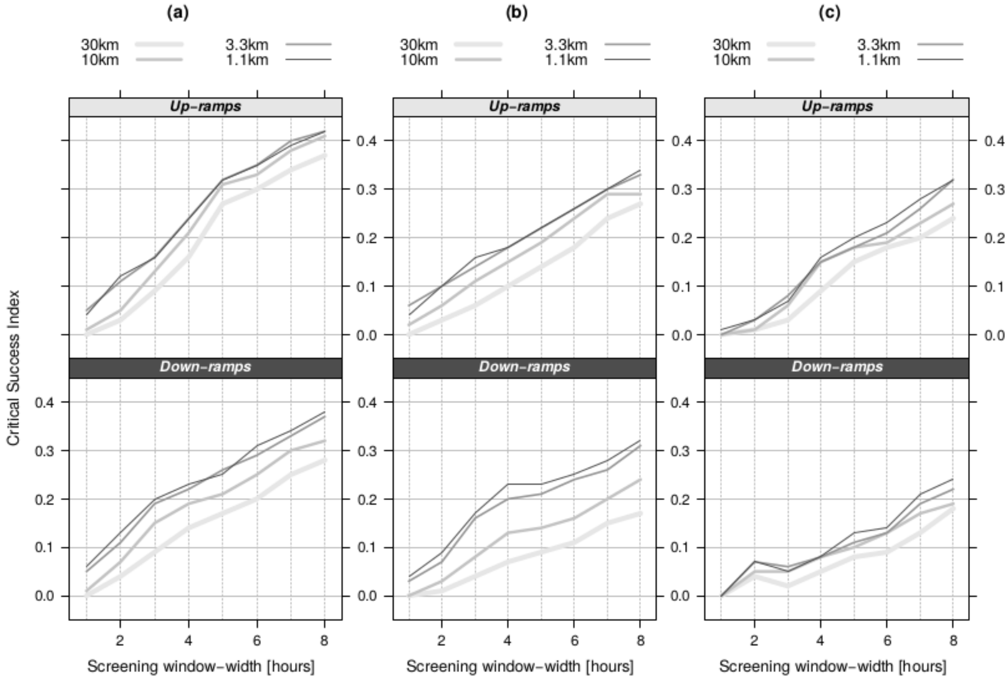

Figure 5. The Critical Success Index, Eq. (6), for wind speed ramps at **(a)** HR, **(b)** RH, **(c)** SR.

Figure 5 shows two results: First of all, the more intuitive result that ramps can be detected better if we allow for some variation in their timing (the x-axis). The Critical Success Index is a measure of how many ramps were detected correctly. More importantly, it also can be seen that higher resolution of the WRF modelling in all cases improves the ramp detection capability of the forecasts. In other words, the value of the additional effort of running a meteorological model in very high resolution depends on the use case.

Table II. Overview of models evaluated. Wind direction, Eq. (3), includes up to four Fourier expansion terms. Wind speed, wind direction, and temperature are at wind turbine nacelle hub-height, specific humidity is at 2 m AGL. † superscript denotes Eq. (2) modelling, while ‡ marks an Eq. (1) type model.

Model #	Constituent GFS-derived quantities included in predictor terms
Model 1†	Raw wind speed
Model 2‡	LLS wind speed, wind direction, temperature, lifted index, 4-layer lifted index, specific humidity, friction velocity, planetary boundary layer height
Model 3‡	LLS wind speed, wind direction
Model 4‡	LLS wind speed, wind direction, temperature, lifted index
Model 5‡	LLS wind speed, temperature, lifted index
Model 6‡	LLS wind speed, wind direction, temperature
Model 7‡	LLS wind speed, wind direction, lifted index

Table II and Figure 6 (thesis p. 108) show the previously unknown influence of the lifted index on the forecast performance. Models 4 and 7 work better (inland site) or equally well (coastal and offshore sites) than a model just based on wind speed and direction (as the current implementation of the Wind Power Prediction Tool employed by ENFOR does). The lifted index is a predictor of latent instability, i.e. severe weather.

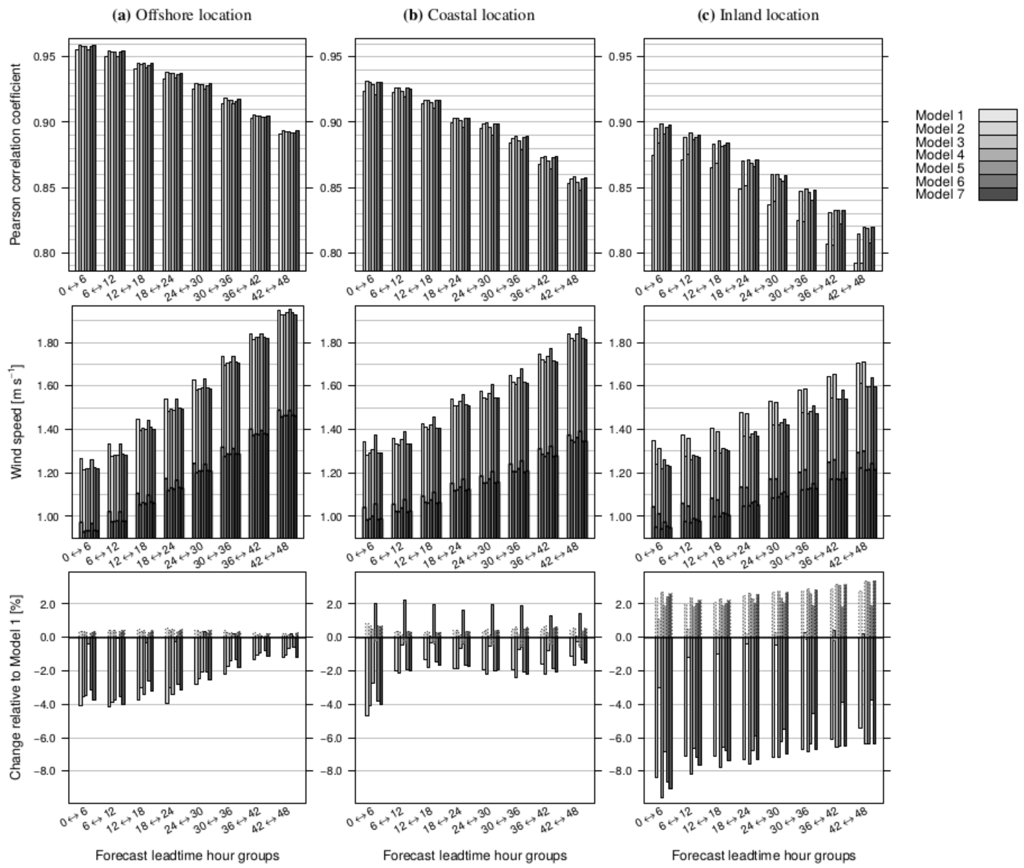

Figure 6. Top row: Forecast performance in terms of PCC. **Middle row:** Forecast performance in terms of RMSE superposed by forecast performance in terms of MAE (bold type). **Bottom row:** Forecast performance relative to Model 1 performance in terms of RMSE superposed by PCC (dotted). **(a)** Horns Rev, **(b)** Rejsby Hede, **(c)** Stor-Rotliden.

9. Publication and dissemination

Already early in the project, an external webpage with minimal information about the project was put up (now moved to the Terminated Projects section): http://www.vindenergi.dtu.dk/english/Research/Projects/Terminated-projects/Integrated-Wind-Power-Planning-Tool

As Gregor Giebel, the project head, was Convenor of the Energy Meteorology Session at the European Geosciences Union (EGU) General Assembly every spring in Vienna, the project always had a poster presentation there (see the detailed list below).

Martin H. Rosgaard, Andrea N. Hahmann, Torben S. Nielsen, Henrik Madsen, Gregor Giebel, Poul E. Sørensen: *Integrated Wind Power Planning Tool*. Poster 163 on the EWEA Annual Event 2012, Copenhagen (DK), 16-19 April 2012

Martin H. Rosgaard, Andrea N. Hahmann, Torben S. Nielsen, Henrik Madsen, Gregor Giebel, Poul E. Sørensen: *Integrated Wind Power Planning Tool*. Poster on the European Geophysics Union General Assembly 2012, Vienna (AT), 22-27 April 2012

Martin Rosgaard, Gregor Giebel, Torben Skov Nielsen, Andrea Hahmann, Poul Sørensen, and Henrik Madsen: *Integrated Wind Power Planning Tool*. Poster on the European Geophysics Union General Assembly 2012, Vienna (AT), 8 April 2013

Martin Rosgaard et al.: poster presentation on the DTU Cleantech Bazar, 29 May 2013

Martin Rosgaard, Andrea Noemi Hahmann, Poul Ejnar Sorenson, Gregor Giebel, Henrik Madsen, Torben Skov Nielsen: *Integrated wind power planning tool*. Poster on the 14th Annual WRF Users Workshop, 24-28 June 2013, Boulder (Colorado)

Martin H. Rosgaard, Andrea N. Hahmann, Torben S. Nielsen, Poul E. Sørensen, Henrik Madsen and Gregor Giebel: *Integrated Wind Power Planning Tool*. Poster on the DTU International Energy Conference 2013 "SUSTAINABLE ENERGY FOR GREEN ECONOMIC GROWTH", 10-12 September 2013

Martin H. Rosgaard, Andrea N. Hahmann, Gregor Giebel, Torben S. Nielsen, Henrik Madsen and Poul E. Sørensen: *Evaluation of NWP Resolution Effect on Wind Speed Forecast Quality for a Wind Farm in Central Sweden*. Poster on the EWEA Technology Workshop: Wind Power Forecasting in Rotterdam, 3-4 December 2013

Martin Rosgaard, Andrea Hahmann, Torben Skov Nielsen, Gregor Giebel, Poul Ejnar Sørensen, and Henrik Madsen: *Evaluation of Dynamical Downscaling Resolution Effect on Wind Energy Forecast Value for a Wind Farm in Central Sweden*. European Geosciences Union General Assembly, Vienna (AT), 27 April – 02 May 2014

Martin Rosgaard et al: poster presentation on the CITIES (Centre for IT-Intelligent Energy Systems in Cities) Annual Meeting, Lyngby, 26 May 2014.

Poster presentation given and conference proceedings paper accepted at the conference on 21st Century Challenges in Climate Modeling, Lund, Sweden (Spatial smoothing)

Martin Haubjerg Rosgaard: *Limited Area Forecasting and Statistical Modelling for Wind Energy Scheduling*. PhD Thesis, PhD-0046(EN), Department of Wind Energy, DTU, Risø 2015.