

# Short-Term Forecasting Fact Sheet for Prediktor

## ***Institute***

Risø National Laboratory

## ***Operational status***

The first version of the model was developed during an EU project by Lars Landberg and, published 1994 as his PhD thesis [1]. It was implemented using the European grid of DMI-HIRLAM (57km resolution at that time, going up to 36 hours forecast, and coming twice a day). The WAsP analyses were the ones used for the European Wind Atlas [2]. It ran for close to 60 stations in a number of European sites, from Greece to Portugal, Ireland and Denmark (to name just the corner points).

Since then, the model has been run in Spain and Ireland (with ESB), and is currently running tests in Texas and California (both with EPRI). In the US, it uses the ETA model with a 48 hour horizon.

Prediktor is also used as the forecasting tool in CleverFarm [3], running in two wind farms in Denmark and Germany.

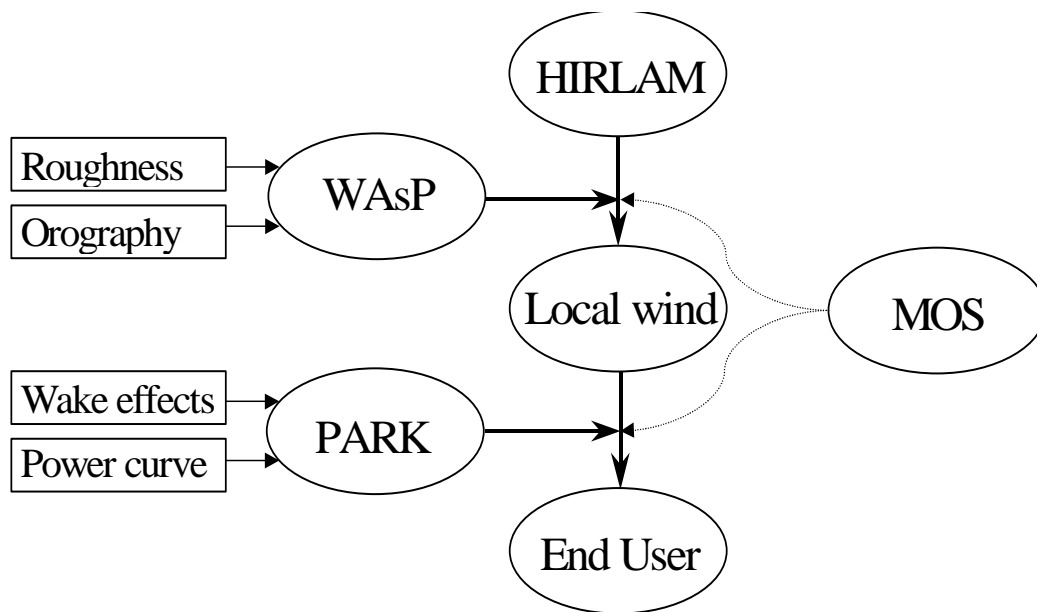
The performance is highly depending on the input data. While in Europe typically Mean Absolute Errors (MAE) down to 10% of the installed capacity appear for the 24 hour forecast, the errors in the US are rather 15-20% at 48 hours lead time in the best cases. Typically, the cross-over point to be better than persistence is at about 4 hours.

## ***Short description***

*From my thesis [5]:*

Landberg [1] developed a short-term prediction model based on physical reasoning similar to the methodology developed for the European Wind Atlas [2]. The idea is to use the wind speed and direction from a NWP, then transform this wind to the local site, then to use the power curve and finally to modify this with the park efficiency. This general idea is shown in Figure 1. Note that the statistical improvement module MOS can either set in before the transformation to the local wind, or before the transformation to power, or at the end of the model chain trying to change the power. A combination of all these is also possible. Landberg used the Danish or Risø version for all the parts in the model: the HIRLAM model of the DMI as NWP input, the WAsP model from Risø to convert the wind to the local conditions and the Risø PARK model (now integrated into WAsP) to account for the lower output in a wind park due to wake effects. Two general possibilities for the transformation of the HIRLAM wind to the local conditions exist: the wind could be from one of the higher levels in the atmosphere, and hence be treated as a geostrophic wind, or the wind could be the NWP's offering for the wind in 10m a.g.l. Usually this wind will not be very accurately tailored to the local conditions, but will be a rather general wind over an average roughness representative for the area modelled at the grid point. In the NWP, even orography on a scale smaller than the spatial resolution of the model is frequently parameterised as roughness. If the wind from the upper level is used, the procedure is as follows: from the geostrophic wind and the local roughness, the friction velocity  $u_*$  is calculated using the geostrophic drag law. This is then used in the logarithmic height profile, again together with the local roughness. If the wind is already the 10m-wind, then the logarithmic profile can be used directly.

The site assessment regarding roughness is done as input for WAsP. There, either a roughness rose or a roughness map is needed. From this, WAsP determines an average roughness at hub height. This is the roughness used in the geostrophic drag law or the logarithmic profile. In his original work, Landberg [1] determined the ideal HIRLAM level to be modelling level 27, since this gave the best results. However, the DMI changed the operational HIRLAM model in June 1998, and Joensen *et al* [4] found that after the change the 10m-wind was much better than the winds from the higher levels. So in the last iterations of the Risø model, the 10m-wind is used. Of course, this analysis has to be done for each new weather model.



**Figure 1: The set-up of the Risø model.**

The model ran operatively in the dispatch centre of SEAS and Elkraft, the utilities for Sjælland (Eastern Denmark). However, it lacks an upscaling model to relate the wind farm predictions to the output of the whole region.

### ***On-line Data Input***

None.

### ***Numerical Weather Prediction Model***

In Denmark, we used to use (and use for CleverFarm) the DMI HIRLAM (see dmi.dk). It is a grid being run on a  $0.05^\circ$  resolution (ca 5 km), with 31 vertical levels. The area covered is a grid just around Denmark, using a 30s time step internally. The model is run every 6 hours, and takes about 2 hours to compute. This is fed by another model running on a 15km grid (also 31 vertical levels) encompassing the area between the central Atlantic Ocean, the Mediterranean, Greece in the East and the North Cape in the North. This model uses a 90 s time step. This model in turn is fed by a model running nearly all the northern hemisphere (45km horizontal, 31 levels vertical, 240 s time step). The boundary conditions for this come from ECMWF.

In Ireland, we used the Irish HIRLAM system. In the US, we use AVN.

We currently use just the four points around the wind farm and do a bilinear interpolation. Input data is wind speed and direction in 10m above ground.

### ***Downscaling***

*From my thesis [5]:*

The Wind Atlas Application and Analysis Program WASP [i] has been developed at Risø National Laboratory for the European Wind Atlas [ii]. Usually it is used for resource assessment in flat to medium complex terrain, to translate meteorological measurements from one site to another one in the vicinity, taking the local terrain, the local roughness and obstacles around the meteorological site into account. The idea of WASP is to clean the measurements of local effects, to obtain a wind climate that is representative for the region around the met station, and reintroduce the local effects of the site in question. This is done with three submodels: One describing the effects of hills and other orography features, one describing the effects of different roughnesses on the wind, and a third one describing shelter effects behind obstacles. The resulting wind atlas is described as a set of Weibull  $A_W$  and  $k_W$  parameters for each sector (see the Appendix

for an explanation of the Weibull distribution). Hence, wind speed distributions not fitting Weibull statistics are not well suited for a WAsP analysis. Typically, these occur when a large fraction of the wind comes from driving forces other than the pressure gradient field of the atmosphere, such as thermally induced winds. In addition, the stability treatment of the atmospheric flow is rather generic.

The model for the orography goes back to Jackson and Hunt [iii], but has since been updated by several others [iv,v,vi,vii]. Troen and Petersen [viii] then moulded it into its current form within their work on the European Wind Atlas. The main feature modelled is the speed-up on top of a hill and the corresponding deceleration in the valley. This special model is based on potential flow, which means that the equations depend on a potential only. This also means that the model does not consider flow separation. Although theoretically well understood [ix], the flow separation described in the K- $\epsilon$  theory is numerically more expensive. Therefore, it was chosen to use the simple model. With gentle terrain, flow separation does not occur. The definition of gentle terrain used to describe the operational envelope of WAsP is embodied in the Ruggedness Index RIX [x,xi]. According to Wood [xii], the onset of flow separation is at a slope of 0.3. Hence, the fraction of the surrounding terrain with a slope higher than this critical slope is defined as the RIX. Pairs of stations in areas with similar RIX usually give good resource estimates, since the errors introduced by the orography model are cancelling each other to a certain extent. For stations in areas with different RIX, the error scales linearly with the difference in RIX value.

The roughness model of WAsP is used to generate one effective roughness per sector at a given height, typically the hub height of the turbine. The concept of roughness is linked to the surface stress of the wind, where the wind over a smooth surface is decelerated differently than over a rough surface. At a roughness change, the surface stress changes abruptly, and this change propagates upwardly as the wind moves past the change line. An internal boundary layer develops, where the wind above has not yet seen the effect of the change, while the wind below is already completely in equilibrium. Within the internal boundary layer, a superposition of both effects is taking place. After about 10km, the wind has reached a new equilibrium with the surrounding roughness. For distances from the turbine shorter than this, WAsP takes all roughness changes subsequently into account, according to the theories of Rao *et al* [xiii] and the measurements of Sempreviva *et al* [xiv]. The resulting average roughness is strictly valid for the hub height only, but since the roughness in most landscapes typical for a wind farm does not vary much, the roughness is representative also for other heights. This is not true for sites close to seashore. There, the roughness change is rather pronounced.

The obstacle model of WAsP was not used here, since for any reasonable wind farm there should be no obstacles nearby.

WAsP compares favourably to similar models, even in difficult terrain [xv]. Two recent studies ascertained the accuracy of WAsP in real world situations: Krieg [xvi] showed that for most wind farms in Sweden the calculated and measured yearly production differed by not more than  $\pm 15\%$ . However, it was deemed important to normalise the calculated yearly production to a standard year, since the deviations from the long-term mean wind power output even for 5-yearly means reached over 20%. Mortensen [xvii] used a derivative of the WAsP methodology for all of Denmark and compared the results to measured production data. More than 80% of all turbines were within 10% of the calculated production.

The PARK program [xviii] (now a part of WAsP itself) takes the reduction in wind speed behind the turbines due to wake effects into account. It is therefore used to establish a mean efficiency for any of the turbines in the wind farm. The underlying theory was developed by Jensen [xix] and states that the wake spreads linearly behind the turbine. The only parameters going into the model are the initial velocity deficit at the start, and the wake decay constant describing the expansion of the wake. The necessary input for the program is therefore the coordinates of the turbines, the power and thrust curves, the hub height and rotor diameter and meteorological data for the site. The output is one number per sector, giving the efficiency of the wind farm.

For Prediktor we use WAsP in a once-and-for-all fashion, yielding a look-up table of correction factors for different sectors. The running time of WAsP is rather short (in the order of seconds). The resolution is in the order of meters, with higher resolution in the centre. The orography model needs an orography map, with an

extent of about 10 km around the wind farm. The roughness model needs a map, also about 10 km around the farm, or a roughness rose (less advisable). Additionally, if there is a coastline further out, it is reasonable to take that into account, too. We also need the turbine positions and power curves (incl ct-curve), to be able to calculate the wake effects.

## **Model Output Statistics**

Prediktor has two linear terms in the MOS system, one for the local wind speed and one to adjust the power afterwards. Both can be optimised offline, which means that it is good enough to have some retrospective farm performance data available. Local wind speeds are an additional tool for verification, but are not required. The power curve is usually the one delivered by the manufacturer, but can be estimated offline as an additional MOS step.

## **Upscaling**

No real upscaling algorithm exists for Prediktor.

## **Output**

The primary output is a text file with time series of the expected production. A very simple uncertainty (one size fits all) is included, based on the average historical prediction uncertainty. From this, graphics for web use can be derived. Alternatively, the CleverFarm system can be used, putting the data in a database and plotting it interactively from there with a web interface (jsp).

## **System**

Since the original version was written in C-code and a few shell scripts by Landberg, a few Java versions have been added to the family. We ran the system successful on Windows, but prefer to have a Unix/Linux system to run on. The Java version written in the CleverFarm project obviously runs on nearly every system. Again, while the standard set-up of Prediktor just uses plain text files, the CleverFarm version uses MySQL as the underlying database (but could be relatively easy ported to another DB, and has been ported to MS SQL Server). The forecasts are made in well below one minute after the NWP file arrives.

## **Literature**

- [1] Lars Landberg: [Short-term Prediction of Local Wind Conditions](#). PhD-Thesis, Risø-R-702(EN), Risø National Laboratory, Roskilde, Denmark 1994, ISBN 87-550-1916-1
- [2] see [windatlas.dk](#)
- [3] see [CleverFarm.com](#)
- [4] Joensen, A., G. Giebel, L. Landberg, H. Madsen, and H. Aa. Nielsen: *Model Output Statistics Applied to Wind Power Prediction*. Proceedings of the European Wind Energy Conference, Nice, France, 1-5 March 1999, pp. 1177-1180, ISBN 1 902916 00 X

Landberg actually showed later that the mathematics of the wind power prediction are close to linear, except for the wind direction (when derived from the geostrophic wind) and of course, the power curve.

Landberg, L: [A Mathematical Look at a Physical Power Prediction Model](#). Wind Energy **1**, pp. 23-28 (1998). DOI: 10.1002/(SICI)1099-1824(199809)1:1<23::AID-WE9>3.0.CO;2-9

The benefits of a Kalman filter as MOS for Prediktor has been researched by Giebel. Since generally the error in the NWP varies randomly and not so much in a correlated fashion, the use for an adaptive system

such as the Kalman filter is limited. While it is possible to tune the filter to yield better results than a static MOS system, the improvements are pronounced in only few cases. Part of this is the need for the filter to be relatively “stiff” (non-varying between two data points) to discourage runaway behaviour.

[5] Giebel, G.: *On the Benefits of Distributed Generation of Wind Energy in Europe*. PhD thesis from the Carl von Ossietzky Universität Oldenburg. [VDI-Verlag, Schriftenreihe Energietechnik](#), 2001. ISBN 3-18-344406-2

Nielsen, T.S., A. Joensen, H. Madsen, L. Landberg and G. Giebel: [A New Reference for Predicting Wind Power](#). *Wind Energy* **1**, pp. 29-34 (1998). DOI 10.1002/(SICI)1099-1824(199809)1:1<29::AID-WE10>3.0.CO;2-B

Giebel, G., G. Kariniotakis, R. Brownsword: *The State-Of-The-Art in Short-Term Prediction – A Literature Overview*. Position paper for the ANEMOS project, to be downloaded from [anemos.cma.fr](#). 38 pp., 2003

## **Previous and Current Projects**

### **EU JOULE:**

JOUR-00091 “Short term prediction of local wind conditions” (see [1])

JOR3-CT95-0008 “Implementing Short-Term Prediction at Utilities”

JOR3-CT97-5004 “European Wind Energy Capacity Effects” (see [5])

JOR3-CT98-0272 “Short-term prediction of regional wind power production”

JOR3-CT98-0286 “Predicting offshore wind energy resources”

ERK6-CT1999-00001 ENDOW “Efficient Development of Offshore Wind Farms” (ongoing)

ERK6-CT-1999-00006 CLEVERFARM “Advanced management and surveillance of wind farms”

ENK5-CT-2002-00665 ANEMOS “Development of a Next-Generation Wind Power Forecasting System for the Large-Scale Integration of Onshore and Offshore Wind Farms”

### **Energiforskningsprogram (EFP, national Danish funding):**

EFP99 - Jnr 1363/99-0017 “Vindmøllepark Produktionsprediktor” (a.k.a. Zephyr-project - ongoing)

### **PSO (Public Service Obligation – Danish grants):**

Ordre 101295, FU nr. 2101 “Ensemblevindkraftforudsigelse” (Short-term forecasting with Ensembles – ongoing)

## **More Literature**

i Mortensen, N.G., L. Landberg, I. Troen, and E.L. Petersen: *Wind Atlas Analysis and Application Program (WASP) - User's Guide*. Risø-I-666(EN)(v.2), Risø National Laboratory, Roskilde, Denmark, 133 pp.

ii Troen, I., and E.L. Petersen: *European Wind Atlas*. Published for the EU Commission DGXII by Risø National Laboratory, Denmark (1998), ISBN 87-550-1482-8

iii Jackson, P.S. and J.C.R. Hunt: *Turbulent flow over a low hill*. Q. J. R. Meteorol. Soc. **101**, pp. 929-955 (1975)

iv Mason, P.J. and R.I. Sykes: *Flow over an isolated hill of moderate slope*. Q.J.R. Meteorol. Soc. **105**, pp. 383-395 (1979)

v Taylor, P.A., J.L. Walmsley and J.R. Salmon: *A Simple Model of Neutrally Stratified Boundary-Layer Flow Over Real Terrain Incorporating Wavenumber-Dependent Scaling*. *Boundary-Layer Meteorol.* **26**, pp. 169-189 (1983)

- vi Mason, P.J. and J.C. King: *Measurements and Predictions of Flow and Turbulence over an Isolated Hill of Moderate Slope*. Q.J.R. Meteorol. Soc. **111**, pp. 617-640 (1985)
- vii Walmsley, J.L., P.A. Taylor, and T. Keith: *A Simple Model of Neutrally Stratified Boundary-Layer Flow Over Complex Terrain with Surface Roughness Modulations (MS3DJH/3R)*. Boundary-Layer Meteorol. **36**, pp. 157-186 (1986)
- viii Troen, I.: *On Diagnostic Wind Field Models*. From College on Atmospheric Boundary Layer Physics, Trieste, Italy, 1990.
- ix E.g. de Baas, A.: *The K-ε model in separating flows*. In: Proceedings of the Ninth Symposium on Turbulence and Diffusion, Roskilde. American Meteorological Society, pp. 359-362
- x Bowen, A.J., and N.G. Mortensen: *Exploring the Limits of WasP, the Wind Atlas Analysis and Application Program*. Proceedings of the European Union Wind Energy Conference held at Göteborg, Sweden, 20-24 May 1996, pp. 584-587, ISBN 0-9521452-9-4
- xi Mortensen, N.G., and E.L. Petersen: *Influence of Topographical Input Data on the Accuracy of Wind Flow Modelling in Complex Terrain*. Proceedings of the European Wind Energy Conference held at Dublin, Ireland, October 1997, pp. 317-320, ISBN 0 9533922 0 1
- xii Wood, N.: *The onset of separation in neutral, turbulent flow over hills*. Boundary-Layer Meteorology **76**, pp. 137-164 (1995)
- xiii Rao, K.S., J.C. Wyngard, and D.R. Coté: *The Structure of the Two-Dimensional Internal Boundary Layer over a Sudden Change of Surface Roughness*. J. Atmos. Sci. **26**, pp. 432-440 (1974)
- xiv Sempreviva, A.M., S.E. Larsen, N.G. Mortensen, and I. Troen: *Response of Neutral Boundary Layers to Changes of Roughness*. Boundary-Layer Meteorol. **50**, pp. 205-225
- xv Sempreviva A.M. and A. Lavagnini: *Approccio modellistico alla climatologia del vento*. Convegno Societa' Italiana di Fisica, Sif, Padova 2-7 Ottobre 1986. IFA-C.N.R. Internal Report 86/39. (in Italian)
- xvi Krieg, R.: *Verifiering av beräknad vindenergiproduktion*. SMHI Rapport 1999 No. 28 (in Swedish)
- xvii Mortensen, N.G., P. Nielsen, L. Landberg, O. Rathmann and M.N. Nielsen: *A Detailed and Verified Wind Resource Atlas for Denmark*. Proceedings of the European Wind Energy Conference, Nice, France, 1-5 March 1999, p. 1161-1164, ISBN 1 902916 00 X
- xviii Sanderhoff, P.: *PARK - User's Guide, A PC-program for calculation of wind turbine park performance*. Risø-I-668(EN), 1993, Risø National Laboratory, Roskilde, Denmark, 8pp.
- xix Jensen, N.O.: *A Note on Wind Generator Interaction*. Risø-M-2411, 1984, Risø National Laboratory, Roskilde, Denmark, 16pp.