Implementing Short-term Prediction at Utilities

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Contents

Executive summary

Outcome

The project has

Developed techniques and on-line tools for forecasting wind farm production

These techniques and tools

- *are being used by utilities in day-to-day dispatch*
- *have been evaluated to quantify the financial benefits of wind power forecasting*
- *have been applied internationally*

In the following a brief overview of the project will be given and at the end a number of other achievements are listed.

The Project Partners

The project partners were the following:

- Risø National Laboratory, Denmark: model development, model implementation, model verification, co-ordination.
- Elsam/Eltra, Denmark: model usage, wind farm data
- Elkraft, Denmark: model usage, wind farm data
- SEAS/NESA, Denmark: model usage
- Rutherford Appleton Laboratory, UK: model verification
- National Observatory of Athens, Greece: model development, model verification
- Danish Meteorological Institute, Denmark: operate HIRLAM model and deliver on-line predictions to partners
- Institute of Mathematical Modeling, Denmark: model development, model implementation, model verification (sub-contractor to Elsam/Eltra)
- Electrical Power Research Institute, USA: model verification (sub-contracted to WECTEC, USA)

Brief Technical Description

The project consisted of the following parts all of which will be described in the following:

- Model development
- Model implementation
- Model evaluation

Model development

Two models were developed:

1. The Risø model

2. The IMM model

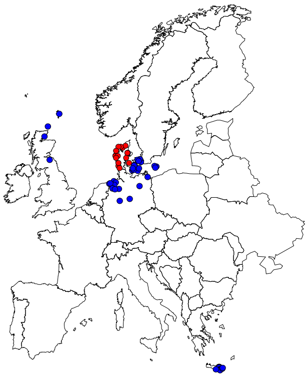
The two models both use weather predictions from Numerical Weather Prediction (NWP) (here the Danish Meteorological Institute HIRLAM model) models as input. The way this input is used is different for the two models:

Risø model

The Risø model uses mainly physical relations to transform the predicted wind into predicted power: the geostrophic drag law, the logarithmic wind profile, WA^{S}P corrections for local influences, PARK calculations for actual wind farm output. The results are corrected using a mathematical filter (a MOS filter). The model predicts for individual wind farms or groups of wind farms representing an area.

In *the IMM model* statistical methods are applied for predicting the expected wind power production in a larger area using on-line data covering only a subset of the total population of wind turbines in the area. The approach is to divide the area of interest into sub-areas each covered by a wind farm. Predictions of wind power with a horizon from half an hour up to 39 hours are then formed for the individual wind farms using local measurements of climatic variables as well as meteorological forecasts of wind speed and direction. The wind farm power predictions for each sub-area are subsequently up-scaled to cover all wind turbines in the sub-area before the predictions for sub-areas are summarized to form a prediction for the entire area.

Model implementation



The two models were implemented in two ways: The Risø model was implemented in an on-line version where predictions were automatically fed to the Internet, via a WWW server. The Danish Elkraft and NESA utilities used these predictions. Predictions were made for Denmark, UK, Greece and Germany (at a later stage). The IMM model was implemented on-site at the Elsam utility, where the predictions were used in the daily dispatch.

The wind farms for which predictions were made are shown in the margin.

The Risø model was also used in a off-line version to make predictions for several wind farms in the US.

Model evaluation

The models were evaluated in three ways:

1. utilities using the models in the daily dispatch.
2. using the predicitons in the RAL National Grid Model, to give economic values to the savings resulting from using the model in a dispatch setting.
3. by directly comparing the predictions to observations for a great number of wind farms.

In the following each of these will be explained in some detail.

Results

The results of the abovementioned three evaluations are:

1. The models were used by the two major Danish utilities in their daily dispatch with good results, the predictions were used for trading and planning.
2. Using the National Grid Model it was shown that the forecasts gave improved fossil fuel savings over persistence for the England & Wales grid - at least 13% better at 40% penetration.
3. Comparing the predictions to actual observations revealed that the predictions were very accurate. Severe storms were also predicted well.

The Project

The project ran over 36 months and was finished on time with all tasks fulfilled. The total project costs were kEUR 1 333 of which the Commission of the European Communities covered kEUR 694 (52%).

Total cost: MEUR 1.3

The project was a continuation of two JOULE projects: 'Short-term prediction of local wind conditions' (JOUR–0091-MB(C)) and 'Wind Power Prediction Tool in Central Dispatch Centres' and furthermore, a continuation of the Danish Ministry of Energy EFP project 'Implementing Wind Forecasting at a Utility' (ENS–1363/94–0005).

Further Information

The full technical contents of the project are described in the report:

L Landberg, et al, 1999: *Implementing short-term prediction at utilities*. Final report to the European Commission.

and the following papers:

• L Landberg, A Joensen, G Giebel, SJ Watson, H Madsen, TS Nielsen, L Laursen, JU Jørgensen, DP Lalas, J Tøfting, H Ravn, E McCarthy, E Davis, J Chapman, 1999: *Implementing short-term prediction at utilities*. Proceedings from EWEC99, Nice(FR).
• Landberg, L, 1999: *Short-term prediction of the power production from wind farms*. J. Wind Eng. Ind. Aerodyn., **80**, 207–220.
• L Landberg, 1999: *Operational Results form a Physical Power Prediction Model*. Proceedings from EWEC99, Nice(FR).
• TS Nielsen, H Madsen, 197: *Statistical methods for predicting wind power.* Proceedings from EWEC97, 755–758.
• TS Nielsen, H Madsen, and J Tøfting, 1999: *Experiences with statistical methods for predicting wind power*. Proceedings form EWEC99, Nice(FR)
• TS Nielsen et al., 1999: *Statistical Methods for Wind Power Prediction*. Elsam 1999 (To be published)
• SJ Watson, M Tombrou, S Pesmajoglou, D P Lalas and N Sakellariou, 1997: *Investigation of the economic benefits to utilities from wind speed forecasting at wind parks in Crete*. Proc EWEC, Dublin, October 1997, 86–89
• SJ Watson, G Giebel and A Joensen, 1999: *The Economic Value of Wind Power Forecasting to Utilities*. Proc EWEC, Nice, March 1999

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Abstract

Project objectives

To predict the power produced from grid-connected wind farms by using meteorological forecasting and to implement this prediction at electrical utilities. The time-frame is from 0 to 48 hours ahead. This is done by extending and applying the results of the JOULE project: “Short-term prediction of local wind conditions” and of the JOULE2 project: “Wind Power Prediction Tool in Central Dispatch Centres”, and EFP (Energy Research Program) project: “Using Meteorological Predictions”.

The main goal is to develop the models to such an extent that it can be demonstrated that any utility with a certain amount of installed wind energy capacity can use the models with economic benefits.

A further goal is to show that these methods and techniques developed in Europe can be used world-wide and thereby create further opportunities for the EU wind power industry.

In the project four areas have been chosen: Denmark; England, Scotland and Wales; Greece (Crete); and Iowa in the USA.

Technical approach

By using prediction models based on the forecasts from Numerical Weather Prediction (NWP) models. In the present project the HIRLAM model of the Danish Meteorological Institute will be used. This model is an operational model generating forecasts 48 hours ahead, four times a day. The output of this model is then made valid locally by one of two methods:

- a physical model where the local effects are corrected for by the WA^{S}P program and the production of the wind farm is calculated taking the shadowing of wind turbines into account by using the PARK program.
- a statistical model, where the statistical relationships between the historical observations and the output from the NWP model are being established and used in the forecasting.

Expected achievements and exploitation

A user-friendly model that utilities (in cooperation with meteorological institutes) can use to predict the energy produced by wind farms with a range of up to 48 hours ahead. The model will have been implemented and evaluated at a number of European utilities with a high penetration of Wind Energy from the generally high wind areas of Northern Europe to the low wind areas of the Mediterranean.

1 The Partnership

The project consisted of the following partners:

- Risø National Laboratory (Risø, coordinator) (DK)
- ELSAM (Danish utility) (DK)
- ELKRAFT (Danish utility) (DK)
- Danish Meteorological Institute (DMI) (DK)
- National Observatory of Athens (NOA) (GR)
- Rutherford Appleton Laboratory (RAL) (UK)

IMM (DK) acted as a sub-contractor to ELSAM developing and implementing a prediction model and Renewable Energy Systems (RES) (UK) acted as a sub-contractor to RAL providing wind farm data. NESA (and later SEAS) (DK) acted as a minor sub-contractor to Risø.

The US part of the project involved 3 contractors: Risø (co-ordinator), NOA and RAL. Finally, the Electric Power Research Institute (EPRI) (US) supplied the data and contributed significantly to the research.

2 Objectives

The project will be extending and applying the results of the JOULE project ("Short-term prediction of local wind conditions") and of two projects (JOULE 2: "Wind Power Prediction Tool in Central Dispatch Centres" and EFP (Energy Research Program): "Using Meteorological Predictions"). The main goal is to develop the models to such an extent that it can be demonstrated that any utility with a certain amount of installed wind energy capacity can use the models with economic benefits. A further goal is to show that these methods and techniques developed in Europe can be used world-wide and thereby create opportunities for the EU wind power industry. In the project four areas have been chosen:

1. Denmark
2. England, Scotland and Wales
3. Greece (Crete)
4. USA (Iowa)

3 Technical Description

Two prediction models were developed: the Risø and the IMM models. These models were implemented and evaluated in a number of ways described in the following. The two models both use weather predictions from Numerical Weather Prediction (NWP) (here the Danish Meteorological Institute HIRLAM model, cf [5]) models as input. The way this input is used is different for the two models and the differences and the implementation will be described in the following.

The main difference between the two models is that the Risø model was developed with a utility in mind with no on-line access to wind farm productions, whereas the IMM model was developed with a utility with on-line wind farm productions available. Predictions were made for a number of locations shown in Figure 1. Furthermore, the Risø model was run in an off-line mode for three sites in the US.

The total sum of findings and results form the project can be found in the final report written to the European Commission [11].

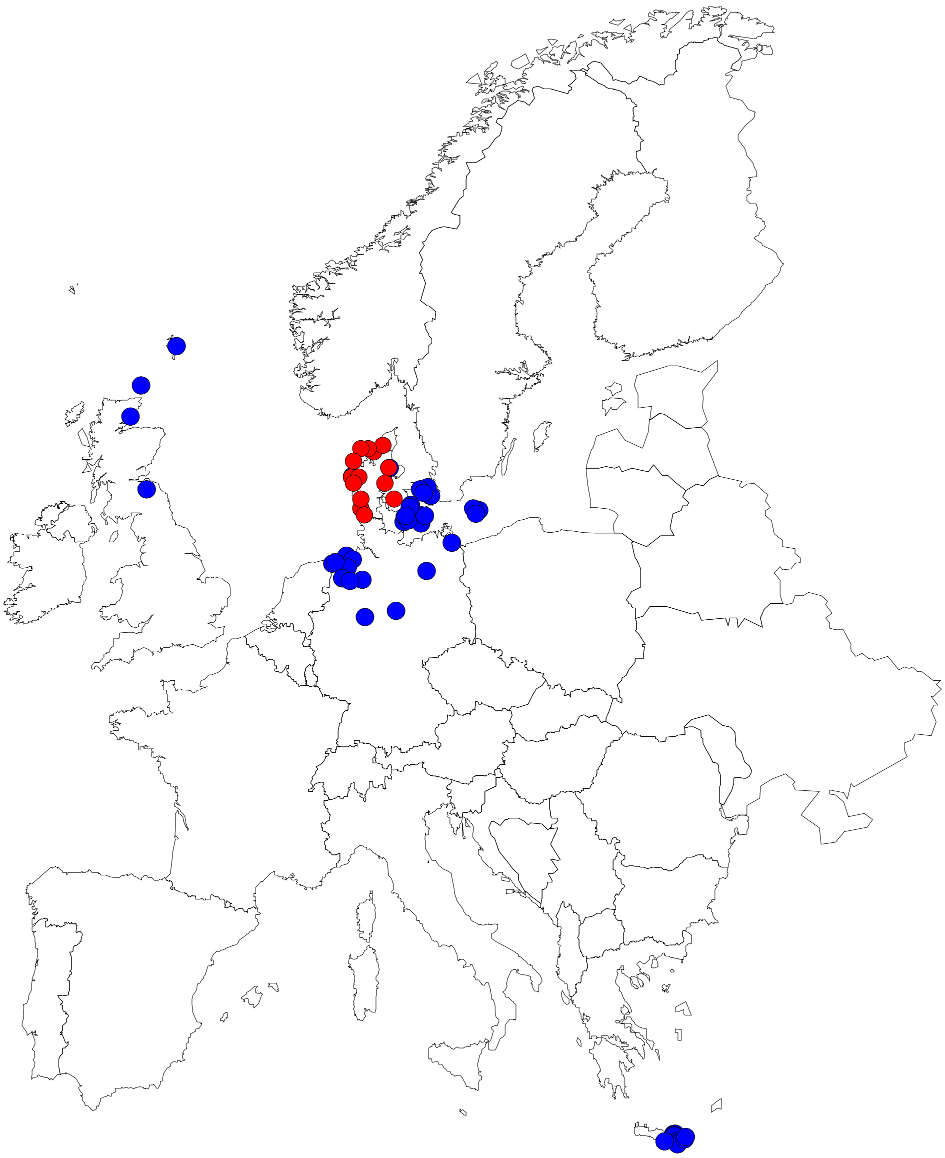


Figure 1. The location of the wind farms. Black dots are the wind farms for which Risø predicts, and gray are the ones IMM predicts for. The wind farms in Germany are not included in the present project, but in a sister project.

3.1 Risø model

The Risø model uses mainly physical relations to transform the predicted wind into predicted power: the overall HIRLAM-predicted wind is transformed to the surface using the geostrophic drag law and the logarithmic wind profile, the surface wind is corrected for local influences using the WA^S^P model [6, 8], and the PARK program [7] is used for calculations of actual wind farm output. The results are corrected using a mathematical filter (a MOS filter). For detailed description and analysis of the model see [2, 3, 4, 1].

The on-line implementation of the Risø model is shown in Figure 2. An example of the predictions as seen on the World Wide Web (WWW) is shown in Figure 3. The Risø model has been on-line serving predictions to the WWW since January 1997.

To give an example of the Risø model's ability to predict storms Figure 4 shows the development of a storm and how well the predictions agreed with the observations.

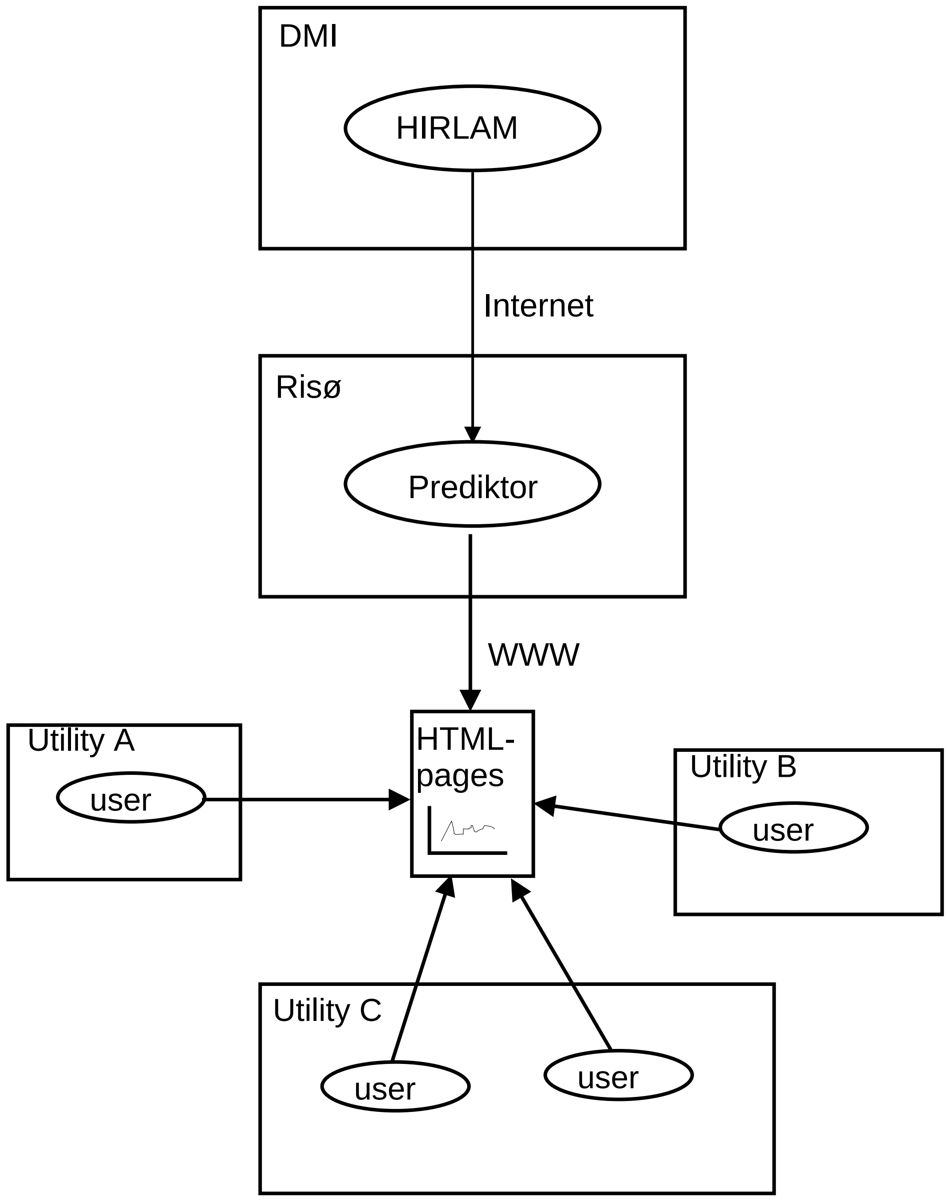
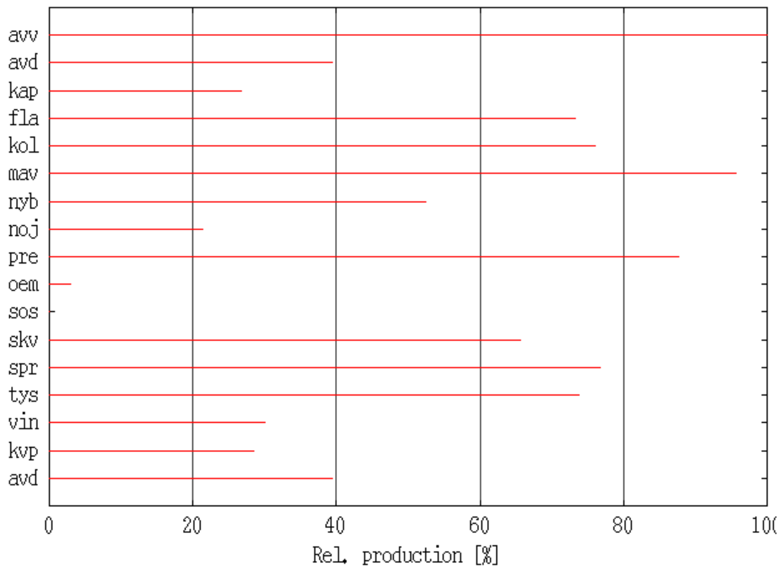


Figure 2. The idea behind the on-line implementation of the Risø model.

Predictions Page 1 of 1

Predictions +12 hours ahead

0 3 6 9 12 15 18 21 24 27 30 33 36



Absolute numbers [kW]

Click on wind farm for full predictions

Click on prediction length to get that prediction

12hrel.htm

Figure 3. The page viewable on the WWW showing the Risø predictions.

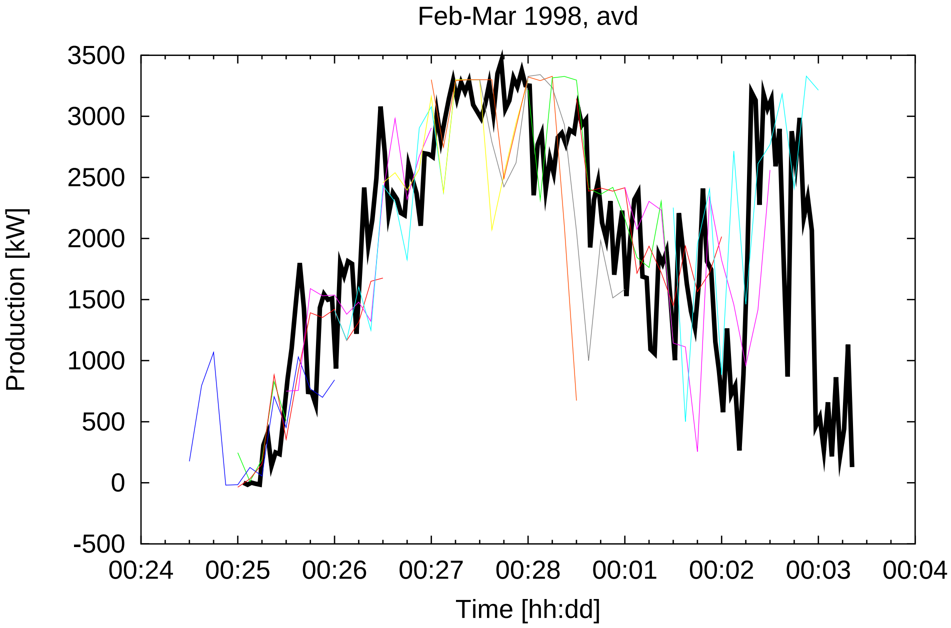


Figure 4. The storm on the 27th February as seen from the Avedøre Wind Farm. Solid line is the observed production and dashed lines are the predictions using the Risø model.

3.2 IMM model

In the IMM model statistical methods are applied for predicting the expected wind power production in a larger area, using on-line data covering only a subset of the total population of wind turbines in the area. The approach is to divide the area of interest into sub-areas each covered by a wind farm. Predictions of wind power with a horizon from half an hour up to 39 hours are then formed for the individual wind farms using local measurements of climatic variables as well as meteorological forecasts of wind speed and direction. The wind farm power predictions for each sub-area are subsequently upscaled to cover all wind turbines in the sub-area before the predictions for sub-areas are summarized to form a prediction for the entire area. The model is described in great detail in [9].

The idea behind the implementation is shown in Figure 5. The overview screen of the prediction system at Elsam is shown in Figure 6.

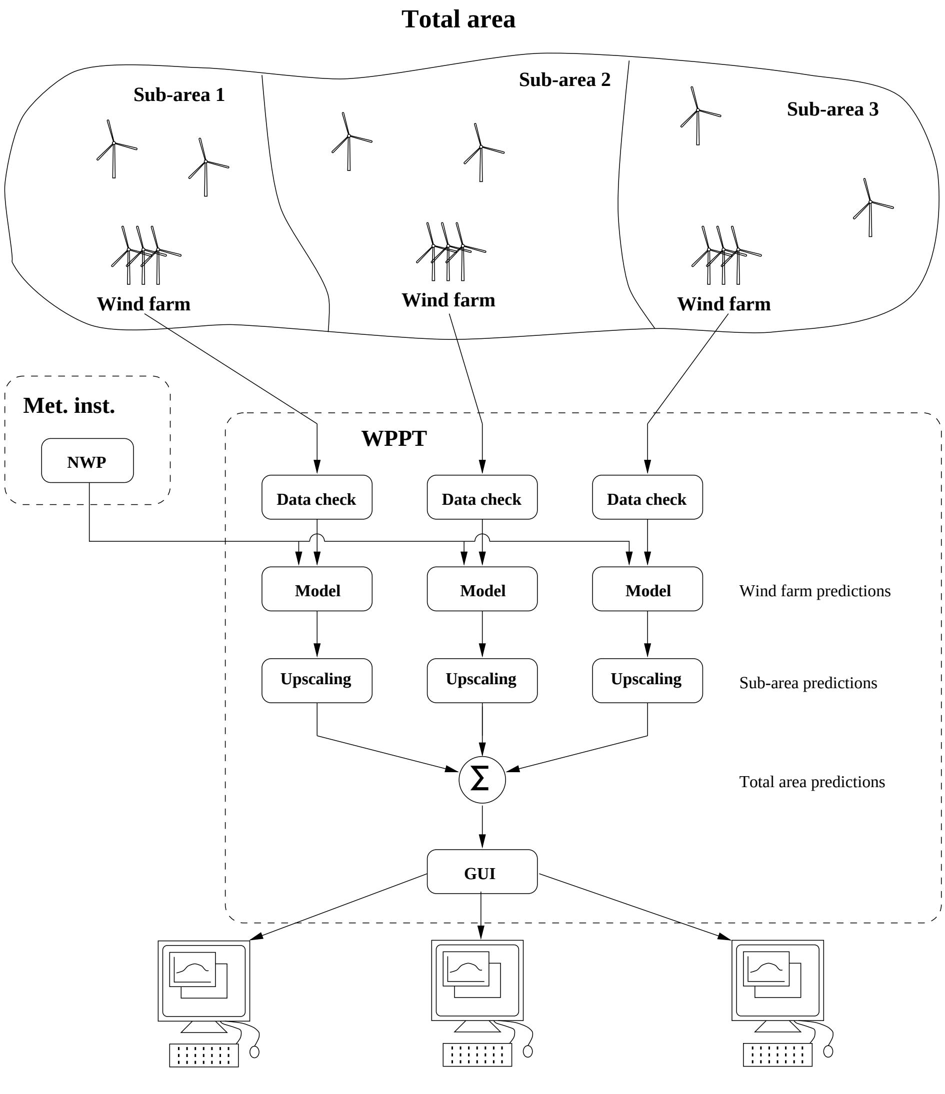


Figure 5. The idea behind the on-line implementation of the IMM model.

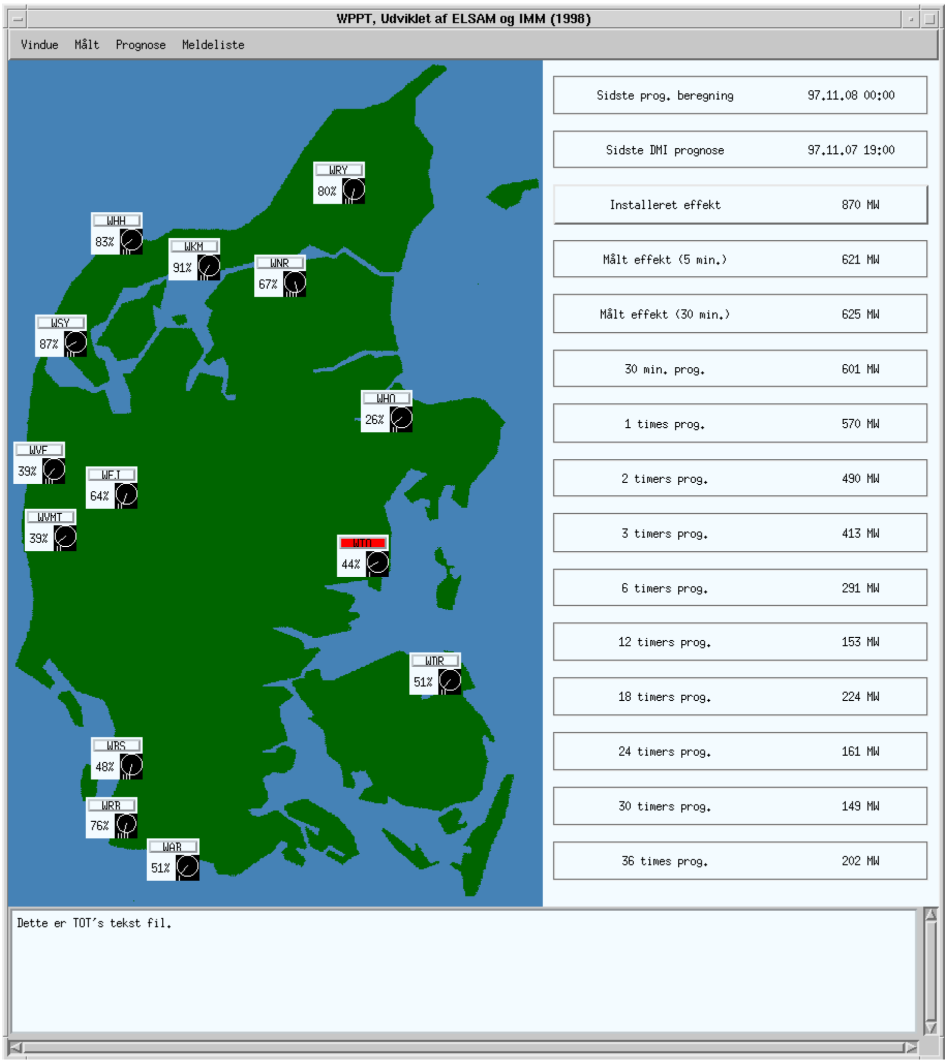


Figure 6. The overview screen of the IMM model as seen at the Elsam utility.

4 Results and Conclusions

The results can be categorised in three categories:

1. The models were used by the two major Danish utilities in their daily dispatch with good results, the predictions were used for trading and planning.

2. Using the National Grid Model it was shown that the forecasts gave improved fossil fuel savings over persistence for the England & Wales grid – at least 13% better at 40% penetration.

3. Comparing the predictions to actual observations revealed that the predictions were very accurate. Severe storms were also predicted well.

Each of these will be explained in the following.

4.1 Elkraft implementation

Elkraft Power Company coordinates energy cooperation in the eastern part of Denmark.

In the Zealand area there are now installed wind turbines with a total capacity of around 300 MW. This figure will double or triple within the next decade. The influence of the fluctuations of the wind power is already being felt in the daily control and operation of the system. Therefore efforts are being undertaken to predict the wind power production.

In the present version of the wind power prediction system the data flows may be sketched as follows. The Danish Meteorological Institute produces predictions of wind speeds for a number of specified locations, 15 in total, where major wind farms are located. The prognoses are represented as values for every third hour, with a time horizon of 36 hours.

The prognoses are transmitted to Risø National Laboratory, where the predictions of wind speed are automatically transformed to predictions of power production, based on WAsP analyses of the specific wind farms. These predictions may be seen at the homepage at Risø National Laboratory.

Elkraft Power Company takes the predictions from Risø National Laboratory via the Internet. The predictions are then combined with the available knowledge to produce a prognosis for the whole area of interest. In particular, the wind turbines, for which individual prognoses are not made, are included by using an up-scaling factor. Further, tuning of the prognoses is made, for instance to account for major wind farms under construction or revision. Longer time biases in the prognoses are detected by comparison with the available measurements, given as hourly or monthly production values.

The prognoses and online measurements are distributed via the local area network to the relevant persons, in particular to those in the control room and to those that trade power on short-term basis.

The system was introduced mid-1998, and has been functional during the last quarter of 1998. An example of the user interface at Elkraft is shown in Figure 7.

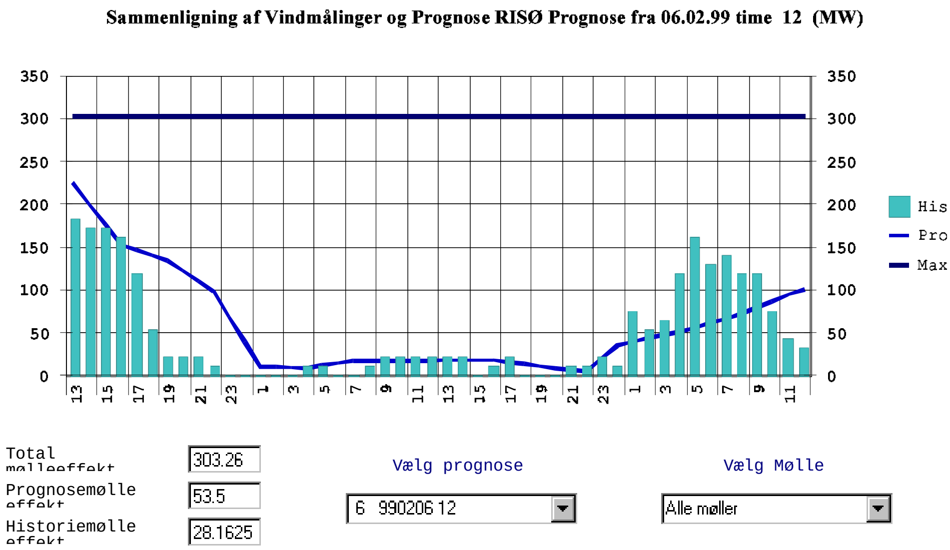


Figure 7. The predictions as displayed in the Elkraft dispatch and control centre. The columns are hourly measured wind power production, the straight horizontal line corresponds to maximum production (i.e installed capacity) and the curved line is the prediction. It is possible for the dispatcher to choose between current and previous predictions and productions, and which turbines to have displayed.

4.2 Elsam/Eltra implementation

In the western part of Denmark Elsam is responsible for the economical load dispatch of the production from the primary power stations, whereas Eltra controls the transmission grid and has the system responsibility. The power production set-up consists of 6 primary power stations equipped with 4250 MW of CHP (Combined Heat and Power) units, a large number of local CHP units with a total installed power of 1400 MW and finally wind turbines with a total rated power of approximately 1000 MW. The production from the local CHP units and the wind turbines is treated as priority production, which implies, that the available power from these sources has to be accepted by the system responsible operator. On a yearly basis the load in the Elsam/Eltra area ranges between 1200 MW and 3700 MW. It is obvious, that the management of 1000 MW of wind power in such a setup will have to rely on the availability of dependable wind power predictions.

The IMM model is implemented in a software package called WPPT (Wind Power Prediction Tool). WPPT was installed in the control centres of Elsam and Eltra in October 1997 and has been used operationally since January 1998. The assessment by the operators is that WPPT generally produces reliable predictions, which are used directly in the economic load dispatch and the day-to-day electricity trade. In periods with unstable weather the operators may choose to modify the predictions (typically smooth the pattern of the prediction) before further usage though. The economical value of the wind power predictions is difficult to evaluate directly, mainly due to the problem of assessing the course of action had the predictions not been available. Instead two cases have been analysed in order to illustrate how the predictions are used and with which consequences:

- *Case 1.* On 17 October 1998 the wind power production was characterized by large fluctuations (see Figure 8). The deviation between the actual production and the prediction given at 10.30 am the day before was too large to be covered by the running reserve in the period from 5 pm to 7:30 pm and the missing power would have had to be purchased from NordPool at a total price of approximately DKK 16,000. The prediction given at 4.30 pm the day before was so much better, that the deviation could be countered by the normal means of regulation without any additional costs compared to a perfect forecast.

- *Case 2.* On November 9th the wind power production varied from 350 MW at midnight on the 8th increasing up to 800 MW at noon before decreasing down to 100 MW at midnight on the 9th. This course of the wind power production was accurately predicted the day before and consequently did not imply any costs for the operation, see Figure 9.

As indicated by the examples above the operators rely on the wind power production from WPPT in the daily planning since the predictions are markedly better than what can be derived from other sources. This is not to say, that there is no room for improvement, and thus WPPT is subject to continuous improvement based on the experiences of the operators.

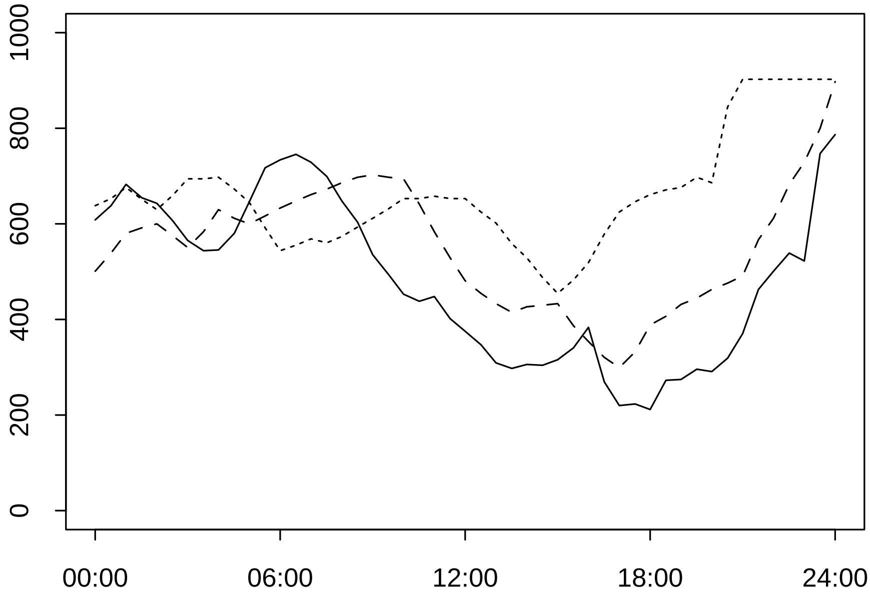


Figure 8. Case 1 (October 17th 1998) predicted by the IMM model. Solid line is the observed production, dashed lines are the predictions.

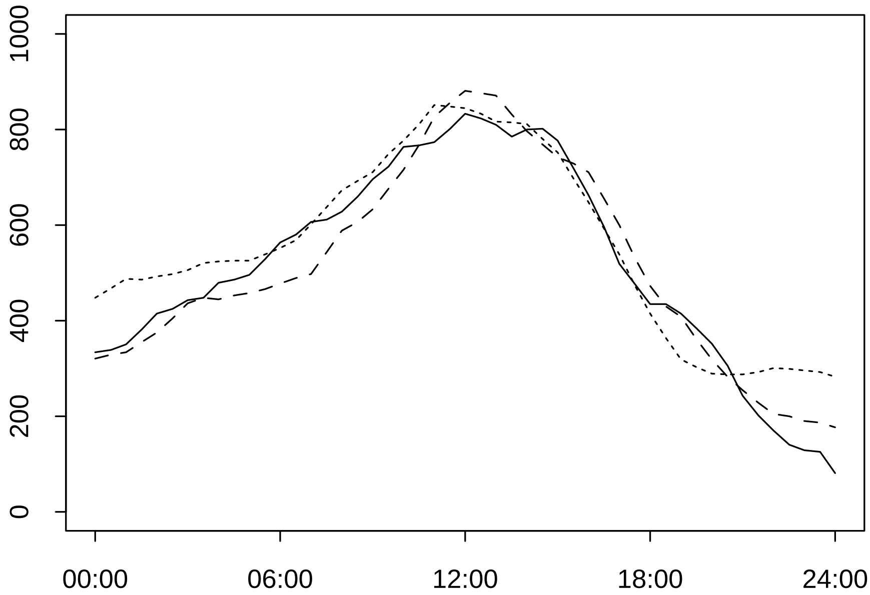


Figure 9. Case 2 (November 9th 1998) predicted by the IMM model. Solid line is the observed production, dashed lines are the predictions.

4.3 RAL calculations

The National Grid Model was run for the England & Wales, Crete and Iowa grids and the results were:

- The forecasts give improved fossil fuel savings over persistence for the England & Wales grid - at least 13% better at 40% penetration (cf Figure 10).
- The results for Crete are poor because the site forecasts are poor.
- Crete has a lot of fast response plant and so forecasting is not so beneficial anyway unless models can significantly improve upon persistence at up to 4 hours ahead. Also a study of Crete would benefit from a hybrid of the RAL NGM and the RAL islands model (which can simulate diesel start-ups on a minute by minute basis).
- The Iowa results are disappointing, this is probably because of the crude temporal resolution of the forecasts (six-hours).

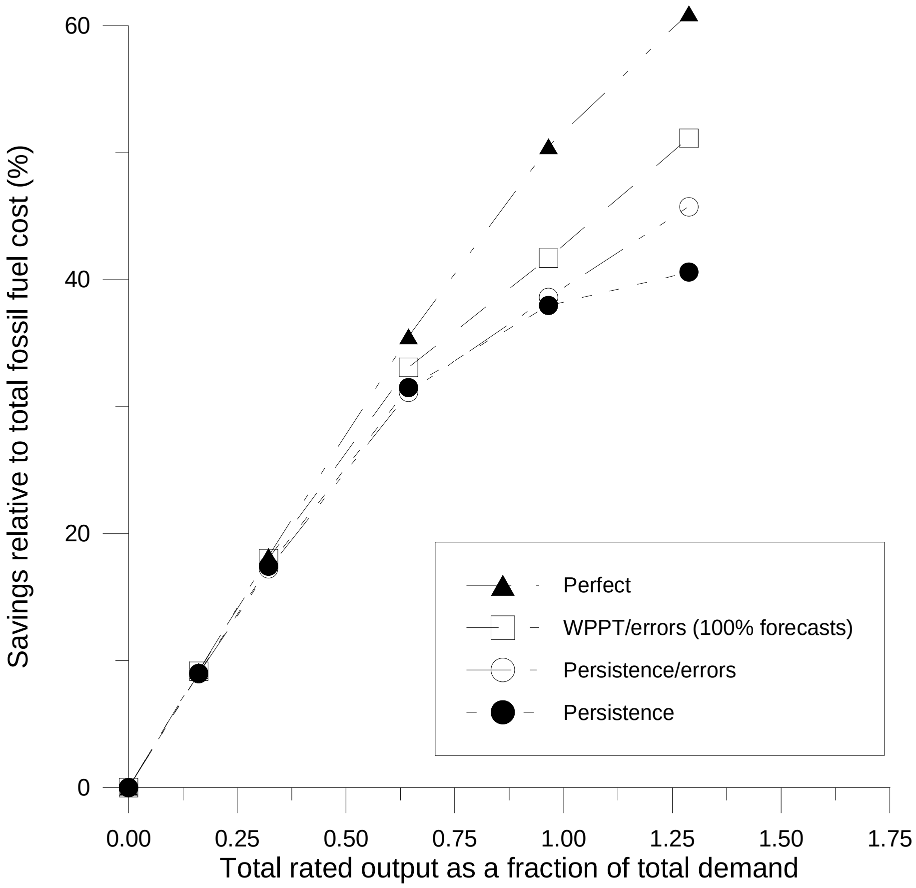


Figure 10. Fossil fuel savings during the calendar year 1994 for different installed wind power capacities into the England and Wales grid using different forecasting methods.

4.4 US results

The Risø forecasting model was applied to selected sites in the US. The general goal of this application was to understand whether the approach used successfully in Europe could be transferred to facilities in the US. When the EPRI programme was begun in 1996, it was thought that data either from the EPRI managed eight station North Dakota Wind Resource Assessment Program or the first large EPRI/DOE TVP (Turbine Verification Programme) project at Ft. Davis, Texas would be used. The availability of data from these two projects was limited, forcing EPRI to look elsewhere.

Datasets from regions where wind energy projects were either operational or being considered was a significant consideration in the choice of sites. In addition, areas where the terrain was not too complex, that is, hilly or mountainous, and areas where numerical weather prediction models might have sufficient valid data to perform successfully. The Great Plains was the prime area as the terrain is principally flat or rolling farm- and grasslands. In addition, there is a sufficient observational data base upwind of the Great Plains which should allow for good performance of numerical weather prediction models. The projected development of large wind electric generating facilities in the upper Great Plains of Minnesota and Iowa also focused EPRI on this region.

EPRI obtained data from the first operational wind plant on the Buffalo Ridge in Southwestern Minnesota for use in the forecasting application. This 25MW wind plant came on-line in mid-1994 and power data was made available by the wind plant owner for slightly over a 2-year period. Wind speed and wind direction data were also available for wind resource assessment programs conducted in Iowa during the same time period. These meteorological data were also obtained.

Application of the Risø model requires the use of numerical weather prediction data. The availability of historical data for the concurrent time period, mid 1994 to mid 1996, was researched. The National Center for Atmospheric Research (NCAR) was contacted and their archives were reviewed. The only complete prediction data set available for the US at that time was for the Nested Grid Model, the operational weather prediction model used by the National Center for Environmental Prediction (NCEP). These data sets were assembled and provided to Risø National Laboratory for testing their modeling approach on US sites.

The Risø model was applied to the Buffalo Ridge Wind Plant, the meteorological site at Alta, and the meteorological site at Sibley. For the wind plant, preparation for application of the model included:

- Creation of a digitized terrain file. This file included all terrain contours within a 10 km radius of the wind plant.
- Creation of a roughness data file. This file included an estimate of the terrain roughness for each of twelve 30 degree sectors.
- Creation of the PARK data files. These files include the power curve for the KVS33, a thrust curve for the KVS33, a meteorological data file consisting of shape, scale and frequency of occurrence of the wind speed in twelve 30 degree sectors, and the location of each (73) KVS33 turbine.

For the two meteorological tower sites, a roughness file is the only required input since these are single sites, wind speed is the predictand, and the files for WAsP and PARK are not required.

From the numerical weather prediction data file, the 10 meter, 950 hPa, 850 hPa and 700 hPa wind speed were extracted. The data for a matrix of four sites, coordinate point 42, 43, 51, and 52 are extrapolated separately to the Buffalo Ridge, Alta, and Sibley sites. This forms the basis for the predicted wind speed. For example, the predictions from the model run of 12159412 (December 15, 1994 at 1200GMT) would consist of wind speed and wind direction values for 8 time periods at six hour intervals, out to 12179412 (December 17, 1994 at 1200GMT).

The model was first applied to the meteorological data at the Alta site. Predictions of average wind speed at eight different time periods in the future twice each day are made using the model. These predictions are based on the numerical weather prediction model. These predictions are then compared to the observed values from the Alta tower. A matrix is then created comparing the predicted and observed values. This matrix is plotted in Figure 11. The poor correlation and pronounced lack of linearity between the predicted and actual values are disappointing.

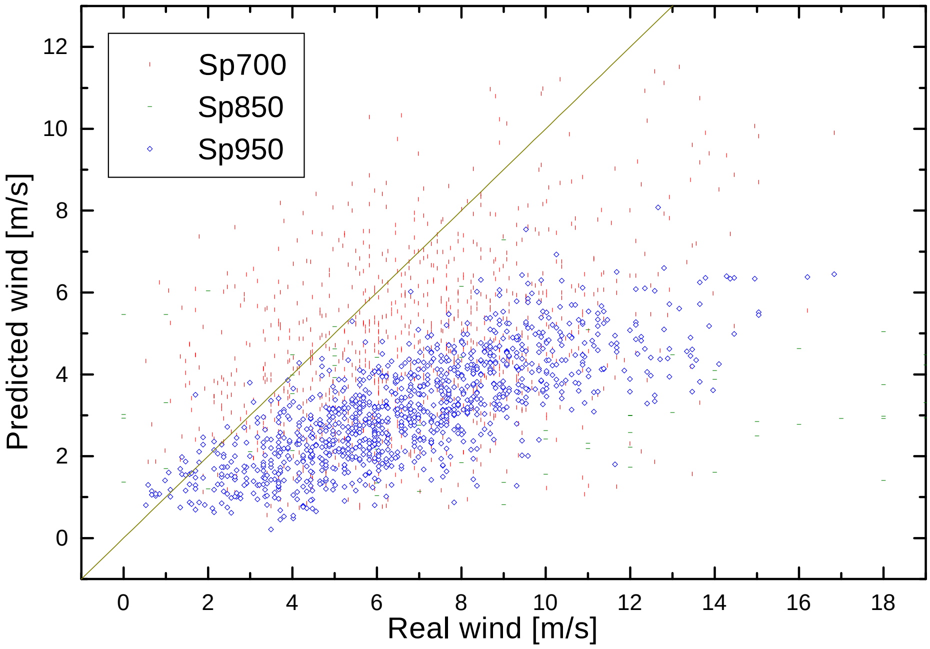


Figure 11. Scatter Plot of the Forecast Wind Speed Versus Actual Wind Speed at the Alta Site.

The reason for this is not yet clear. The data set, consisting of predicted values and actual values, either wind speed (Alta and Sibley) or wind power (Buffalo Ridge) is still being analyzed by staff at Risø. It is possible that the large grid spacing in the NGM model, compared to the smaller grid spacing in the HIRLAM model, could be one of the causative factors.

5 Exploitation Plans

This section will describe the different ways the results of this project are planned to be used in future projects and commercial applications.

In Denmark the Energy Agency via the EFP99 research programme has funded a project where the Danish utilities will be provided with a prediction system which is a combination of the Risø and the IMM prediction systems described in this report. It is planned that at the end of the project all Danish utilities with a high penetration of wind energy will have this prediction system integrated in the daily dispatch and scheduling.

In the US it is hoped that a EPRI/DOE-funded project will start in 1999. The main goal is to implement the Risø prediction system in the US, predicting for a number of wind farms in the US.

There are also numerous possible commercial applications; both for companies interested in selling power to a energy marked and utilities with balance obligations.

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