WPPT, A TOOL FOR ON-LINE WIND POWER PREDICTION

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Abstract

This paper describes WPPT (Wind Power Prediction Tool), an application for assessing the future available wind power up to 36 hours ahead in time. WPPT has been installed in the Eltra/Elsam[1] central dispatch center since October 1997. The paper describes the prediction model used, the actual implementation of WPPT as well as the experience gained by the operators in the dispatch center.

1 INTRODUCTION

During these years the world experiences an increased interest in power production from renewable sources, and it must be expected, that power production from wind turbines will be of still increasing importance in the future. In the western part of Denmark the installed wind power capacity corresponds to 13% of the total installed capacity and it is foreseen that the amount of wind power will double within the next 10 years. Such a high level of wind energy penetration clearly calls for reliable methods for predicting the future wind power production not only for planning purposes (minimization of spinning reserves, maintenance schedules for fossil fuel power units etc.), but also the marked value of wind energy on Europe's future free energy markets will depend on the availability of such methods.

In WPPT 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. Our approach is to divide the area of interest into sub-areas each covered by a wind farm (a reference wind farm). Predictions of wind power with a horizon from $\frac{1}{2}$ up to 36 hours are then formed 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.

The WPPT application has been developed as a co-work between Elsam and the Department of Mathematical Modeling (IMM) at the Technical University of Denmark (DTU). The work was initiated in 1992 as a part of a project, *Wind Power Prediction Tool in Control Dispatch Centers*, sponsored by the European Commission. During this project a statistical model utilizing only measurements of wind power and wind speed was developed and together with a graphical user interface implemented at Elsam's control dispatch center at Skærbæk. WPPT version 1 went into operation in October 1994 and was subject to a three months trial period. The experience gained as well as further details regarding the models and user interface developed can be found in [1] and [2]. In short it became apparent that WPPT 1.0 was capable of providing the operators with useful

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[1]Eltra/Elsam is the power distribution/production utility responsible for the power supply in the Western part of Denmark.

predictions up to 8 to 12 hours ahead, but for larger prediction horizons further model development was needed.

In ([3], [4]) physical models describing the wind farm layout and the influence of the surroundings are used in combination with meteorological forecasts of wind speed and direction to make predictions of power production with a horizon of up to 36 hours but their approach had less performance on shorter horizons. In our project it was therefore a natural idea to improve the previous developed models in WPPT by using meteorological forecasts from the national weather service as input to the models.

The paper is organized as follows. Section 2 gives an introduction to the Eltra/Elsam power utility. Section 3 describes the data used in WPPT as well as the data collection system. The methods applied by Elsam when planning with the wind power are presented in Section 4. The estimation methods as well as the developed prediction models for the reference wind farms are described in Section 5 and Section 6, respectively. Section 7 discusses the implementation of WPPT and describes briefly some parts of the user interface. In Section 8 the experience gained by the operators in Elsam's control dispatch center are outlined.

2 FACTS REGARDING ELSAM

From January 1998 Elsam has been divided into two companies. The transmission network is now operated by a separate company, Eltra, which also is the system responsible for the area. Thus, the new Elsam can concentrate on trade, export, production of electricity, and the purchase of fuel. Eltra/Elsam operates in the western part of Denmark (the peninsula Jutland and the island Funen).

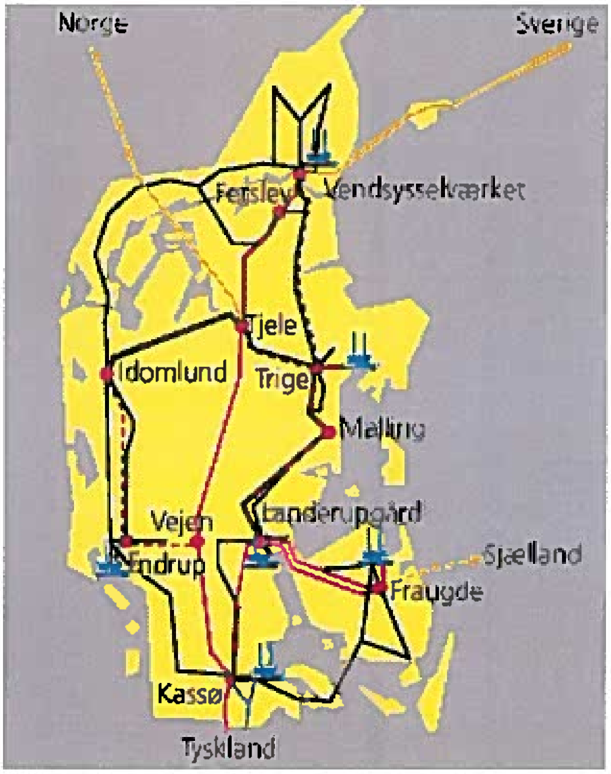

Figure 1: *Transmission network and power stations in the Eltra/Elsam supply area.*

Elsam produces electricity at six Jutland-Funen power stations. Elsam is organized in six divisions:

- *Operation Division:* Plans and operates the production at the six Jutland-Funen power stations which allocates the production capacity at the disposal of Elsam. Together with Eltra production from the local CHP-plants and wind power is handled.
- *Market Division:* Is active in the Northern European energy market. Purchases and sells electricity on long-term contracts and on the spot market.
- *R&D Division:* Is responsible for the technological development in the field of power production.
- *Finance Division:* Co-ordinates the practical financial activities between the individual power stations and responsible for financing investments in plant expansions and the construction of new plants.
- *Fuel Division:* Is responsible for the purchase, transport, handling and storage of fuels (primarily coal, natural gas, and biomass) and the utilization/depositing of the residual products from electricity production.
- *Administration Division.*

A quick overview of the size of the Eltra/Elsam activities as well as the relative importance of the wind power production can be summarized by the following key figures:
Key figures for 1997 (incl. Eltra):

- Electricity consumption: 20.5 TWh.
- Production: 24.8 TWh (primary power stations: 17.6 TWh, local CHP-units: 5.7 TWh, wind: 1.5 TWh).
- Export, net: 4.3 TWh.

Expected key figures for 1998 - Elsam only (approx.):

- Turnover (incl. district heating): 3.6 billion DKK (0.5 billion $).
- Sale of electricity in Denmark: 12,5 TWh.
- Sale of district heating: 35000 TJ.
- Export of electricity: 4 TWh.

Installed power in the Elsam/Eltra area (January 1, 1998):

- Primary power stations: 4625 MW.
- Wind power: 870 MW (incl. utility owned: 125 MW).
- Local CHP units (more than 250): 1300 MW.

The maximum load in 1997 was about 3700 MW.

2.1 Elsam and Wind Power

The era of wind power in Denmark started in 1975 when a carpenter connected his homemade windmill in the backyard to the public network without permission.

In the first years the development was driven by enthusiasm from a growing number of "grass-roots". In the 1980'ties the first industrial manufacturing of windmills started and it is now the fastest growing industry in Denmark.

In 1988 about 100 MW wind power was installed in the Elsam/Eltra-area growing to 870 MW now. This will grow to about 1500 MW in the year of 2005. Today we have only one off-shore park (5 MW) - in the future most of the new parks will be off-shore.

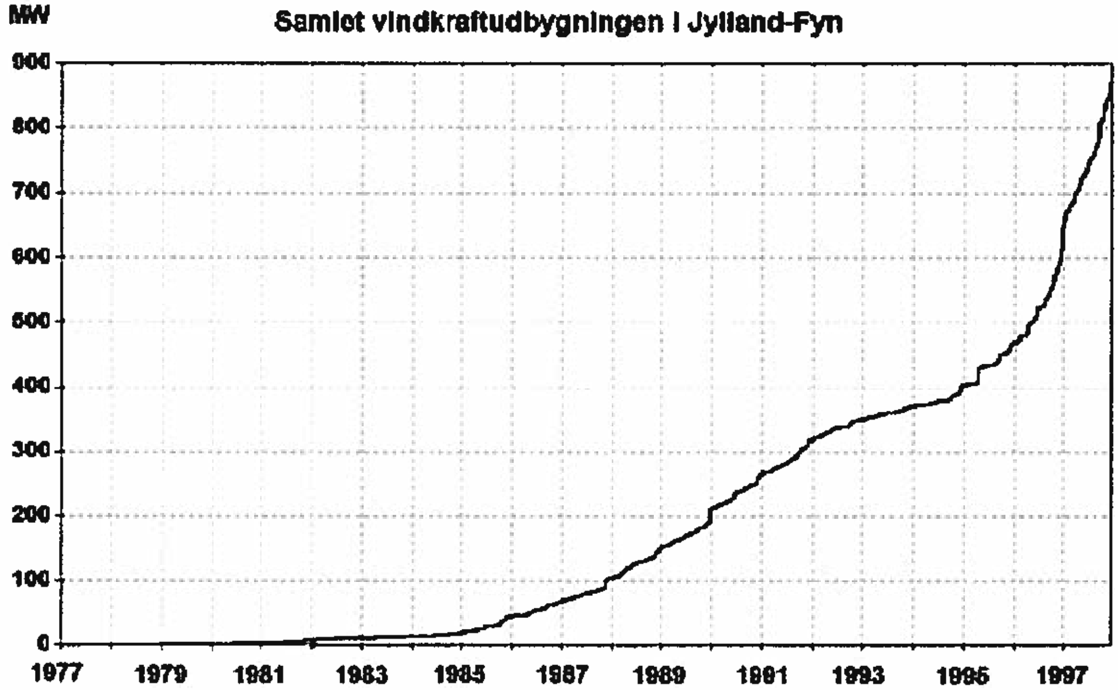

Figure 2: *Development in installed wind power capacity from 1977 to 1997.*

3 DATA AND DATA COLLECTION

For this project 14 wind parks was selected to represent all the wind power in the Eltra/Elsam supply area. The criteria for the selections were geographic distribution and the possibilities to get reasonable data.

From the parks we collect the following measurements:

- wind speed 1.
- wind speed 2 (reserve).
- wind direction.
- air temperature.
- production.

All values are sampled as 5 minute mean values.

The measurements mean values are calculated locally and transmitted to Elsam on the public X-25-network every 5 minutes. This is controlled by a SCADA system from ABB-Denmark at Eltra. This SCADA system is also handling other data as a front-end-system for the EMS/SCADA-system in the Elsam and Eltra Dispatch Centers. The data is converted to ASCII-files and transmitted to the VAX computer running the WPPT software.

Almost all measurements are obtained using new equipment for this project, and is not based on existing equipment in the parks. Our experience is, that such equipment is not stable enough for this purpose.

In any case measurement systems will always be equipment with errors, so WPPT is designed to be robust against errors in data and most important: it produces an error report, when bad measurements are detected. It is also important to have an organization that can handle errors on equipment fast and correctly.

The meteorological forecasts used as input to the models in WPPT are provided by the Danish Meteorological Institute (DMI) using their HIgh Resolution Limited Area Models (HIRLAM) system. The forecasts are updated every 6 hour and cover a horizon of 48 hours ahead with a 1 hour resolution (See [5] for details).

The observations and meteorological forecasts are subsampled, respectively interpolated, to form the 30 minute values used as input to the statistical model for forecasting.

4 Planning with Wind Power

For several years now, Elsam has planned with the power from windmills as production rather than a disturbance/uncertainty on the load. This implies that we, as for the power stations, have to make a "plan" for the wind power production.

In the long term planning (week/months) the production from wind is calculated simply by using the annual mean value of the production. This can in some cases be corrected with the statistical determined diurnal variation.

WPPT (Wind Power Prediction Tool) is used in the daily planning at Elsam and Eltra. Every day the production plan for tomorrow is prepared before noon. One of the inputs for the Economic Load Dispatch calculation is the 36 hours prediction of wind power production from WPPT. The operator in charge of the load dispatch compares the WPPT prediction with the weather forecasts on TV or other sources. The operator decides then the "plan" for wind power production (half-hourly). In general the WPPT system provides very reliable forecasts but reasons for overruling the WPPT-forecasts can be:

- Instability of the weather (high or low pressure domination).
- Consequences of bad predictions (risk of lack of productions capacity or the opposite).
- Obviously bad input data to WPPT (measurements, forecasts from the Danish Meteorological Institute).
- malfunction of WPPT.

When the predictions are bad, the operator on duty has to take care of the difference. He has different choices:

- small differences ($<$ 100 MW) are managed by sending the power stations short
- order message to regulate (Elsam has no AGC (automatic generator control))

- large differences (> 100 MW) are managed by a recalculation of load dispatch and maybe selling/buying with foreign companies (today in Norway, Sweden and Germany)

A special problem in the Elsam-system is a very large amount of combined production of electricity and district heating. This means, that in periods with large heat production, there will be a certain amount of electricity production. In periods with low electricity load (nights and weekends) there is very little "space" for the wind power production. We have several hours during a year, where we have to sell electricity too cheap. We say, that we have an "overrun" of electricity. Being able to predict this situation is very valuable, because it means that a better price can be obtained for the surplus electricity.

To handle the overrun-situation, the operator has some possibilities:

- Sell to foreign companies.
- Change of district heating production to lower the electricity production.
- Use of heat storage.
- Reduce efficiency at power plants (e.g. disconnect high pressure units).
- stop of local CHP units.

The operator has a priority list with the possible operations on each plant to lower the electricity production.

5 Model Estimation

The approach taken in WPPT is to use statistical methods to determine the optimal weight between the on-line measurements and the meteorological forecasted variables in ARX (Auto-Regressive with eXogenous input) type models. Using this approach the power production from a wind farm is described by a stochastic process, which by nature is non-linear as well as time varying (and consequently non-stationary). Models describing this kind of stochastic processes can not be handled successfully using ordinary least squares estimation techniques. When modeling systems containing non-stationary or non-linear dynamics two extremes in the modeling approach can be outlined as follows: A model containing all the physical relations governing the system is drawn up. Such a model will be capable of describing the complex dynamics and should ideally have constant (and known) parameters. Alternatively a model approximating the complex dynamics by linearization around the current working point is applied. Such a model will only give a reasonable description of the system dynamics in a region around the current working point and the model parameters will be time varying as the working point changes over time. This paper describes how the latter approach can be applied using a recursive least squares method to estimate the model parameters instead of direct linearization of a physical model.

5.1 Recursive Least Square Estimation

The estimation method used is often referred to as recursive least squares estimation with exponential forgetting ([6]). This method requires, that the model is linear in the parameters, i.e. it can be formulated as

$$y_t = \phi_t^T \theta + e_t \tag{1}$$

where θ is the parameter vector, ϕ_t is a vector of regressors and e_t is a independent identically distributed (*i.i.d.*) noise sequence.

The least squares method is based on minimizing a criterion of the form

$$\begin{aligned} V(\theta) &= \frac{1}{N}\sum_{t=1}^{N}(y_t - \hat{y}_{t|t-1}(\theta))^2 \\ &= \frac{1}{N}\sum_{t=1}^{N}(\tilde{y}_{t|t-1}(\theta))^2 \end{aligned} \tag{2}$$

where N is the number of observations, y_t is the observation at time t and $\hat{y}_{t|t-1}(\theta)$ is the prediction of the observation at time t given observations up to time $t-1$.

For the recursive least squares method with exponential forgetting the criterion (2) is changed to a criterion of the form

$$\begin{aligned} V(\theta_t) &= \frac{1}{N}\sum_{s=1}^{t}\lambda^{t-s}(y_s - \hat{y}_s(\theta_t))^2 \\ &= \frac{1}{N}\sum_{s=1}^{t}\lambda^{t-s}(\tilde{y}_s(\theta_t))^2 \end{aligned} \tag{3}$$

where λ is a forgetting factor ($0 < \lambda \leq 1$). It is seen that the adaptivity is obtained by multiplying the older observations with an exponentially decreasing weight function.

The choice of the forgetting factor λ is determined by a trade-off between the needed ability to track time-varying parameters and the noise sensitivity of the estimate. A low value of λ results in a system with a good ability to track time-varying parameters but a higher sensitivity against noise in the data. A typical choice of λ is in the range $0.95 \leq \lambda \leq 0.999$. The number of effective observations is given as

$$N_{eff} = \frac{1}{1-\lambda} \tag{4}$$

For $\lambda = 1$ and $t = N$ it is noticed that the least squares estimate in (2) is obtained.

5.2 1-Step Predictions

Conventionally the 1-step prediction errors are used in the recursive least squares method, see e.g. [6]. Later on in this section it is shown how the method can be extended to provide k-step predictions.

The adaptive recursive least squares algorithm is given by the following steps at time t

1. Calculation of 1-step prediction error using the estimate of θ at time $t-1$:

$$\tilde{y}_{t|t-1} = y_t - \varphi_{1,t}^T\hat{\theta}_{t-1} \tag{5}$$

2. An update of the covariance matrix for the parameter estimates is obtained using:

$$P_t = \frac{1}{\lambda}\left(P_{t-1} - \frac{P_{t-1}\varphi_{1,t}\varphi_{1,t}^T P_{t-1}}{\lambda + \varphi_{1,t}^T P_{t-1}\varphi_{1,t}}\right) \tag{6}$$

The matrix $P(t)$ constitutes, except from a factor σ_e^2, an estimate of the covariance matrix for the parameter estimates at time t.

3. Update of the parameter estimates:

$$\hat{\theta}_t = \hat{\theta}_{t-1} + P_t\varphi_{1,t}\tilde{y}_{t|t-1} \tag{7}$$

The initial estimates of the parameters may be chosen quite arbitrarily – often zero is used. The initial covariance matrix has to be chosen such that the variance of the initial estimates is large – often selected as a diagonal matrix with all elements on the diagonal set to 100 or 1000.

The 1-step prediction of y_{t+1} at time t is calculated as

$$\hat{y}_{t+1|t} = \varphi_{1,t+1}^T \hat{\theta}_t. \tag{8}$$

5.3 k-Step Predictions

If a prediction horizon larger than one is needed a choice between two alternative ways of updating the estimates must be made.

- The estimates $\hat{\theta}_{t-k}$ and the regressors $\varphi_{k,t}$ are used instead of $\hat{\theta}_{t-1}$ and $\varphi_{1,t}$ in the algorithm described above, or
- pseudo prediction errors are used in the update of estimates. The pseudo prediction error at time t is calculated as

  $$\tilde{y}_{t|t-k}^{pseudo} = y_t - \varphi_{k,t}^T \hat{\theta}_{t-1}, \tag{9}$$

  from this equation it is seen that the pseudo prediction error corresponds to variables known at time $t-k$ (i.e. $\varphi_{k,t}^T$) and the most recent estimates (i.e. $\hat{\theta}_{t-1}$).

In both cases the true k-step prediction is calculated as

$$\hat{y}_{t+k|t} = \varphi_{k,t+k}^T \hat{\theta}_t. \tag{10}$$

Using the true k-step prediction error in the update of the most recent estimates will result in highly inappropriate estimates. This is due to the fact that the prediction error will give a feed-back not corresponding to the estimates that are to be updated.

6 MODELS FOR FORECASTING WIND POWER

Previously it has been shown ([1],[2]) that a reasonable ARX model based solely on measured data for predicting the power production from a wind farm is given by

$$\begin{aligned} \sqrt{p_{t+k}} &= a_1\sqrt{p_t} + b_1\sqrt{w_t} + b_2 w_t + m_{t+k} + e_{t+k} \\ m_t &= m + c_1 \sin[\frac{2\pi t}{48}] + c_2 \cos[\frac{2\pi t}{48}] \end{aligned} \tag{11}$$

where p_t denotes the measured power production at time t, w_t is the measured wind speed at time t, e_{t+k} is an *i.i.d.* noise sequence and m_t is a function describing both a level and the diurnal variation in the power production. Model (11) will also be referred to as the *WPPT version 1 model.*

The square root transformation of power and wind speed is motivated by the skew density of power and wind speed. In [1] it is shown that the square root transformation leads to distributions of the prediction errors, which can be approximated by the Gaussian distribution. Note that the transfer function from $\sqrt{w_t}$ to $\sqrt{p_{t+k}}$ is formulated using a second order polynomial expression.

The model given by (11) has a good performance for a prediction horizon up to 12 hours ($k = 24$), but in [7] it is made clear that for longer prediction horizons meteorological forecasts of wind speed and direction must be taken into account. Section 6.1 and 6.2 describes two different approaches for including meteorological forecasts into model (11).

The results obtained is assessed by comparison to the well known persistence predictor

$$\hat{p}_{t+k|t} = p_t \tag{12}$$

which simply states, that what you see now is what you will get in the future.

Furthermore the results are compared with a new statistical reference proposed in ([7],[8]). The reference proposed in ([7],[8]) addresses the fact that the persistence predictor performs very badly compared to a predictor given as the simple mean value for prediction horizons larger than 12 to 18 hours.

The statistical reference is simply calculated as the optimal weight between the persistence and the mean value predictor. In both cases the estimated standard deviation for the prediction error (denoted S.E. from here on) is used as the measure of performance.

6.1 Polynomial Extension to WPPT Model

As a first approach the meteorological forecasts have been included in model (11) using the same polynomial expression as used for the observed wind speeds. This leads to a model of the form

$$\begin{aligned} \sqrt{p_{t+k}} &= a_1\sqrt{p_t} + b_1\sqrt{w_t} + b_2 w_t + \\ &\quad b_3\sqrt{w^{HIR}_{t+k|t}} + b_4 w^{HIR}_{t+k|t} + \\ &\quad m_{t+k} + e_{t+k} \\ m_t &= m + c_1 \sin[\frac{2\pi t}{48}] + c_2 \cos[\frac{2\pi t}{48}] \end{aligned} \tag{13}$$

where $w^{HIR}_{t+k|t}$ is the forecasted wind speed at time $t+k$ given at time t.

This approach results in a simple extension, but it is a bit problematic if any dependency of wind direction exists, as both b_3 and b_4 must depend on the wind direction.

Some of the parameter estimates in the full model are not significant and especially b_1 and b_2 are found to be of little significance for most values of k. To assess the potential improvements by tailoring the models to the different prediction horizons, a model without the $b_1\sqrt{w(t)}$ term was estimated. A small reduction in S.E. is found for all values of k indicating that it is advantageous to tailor the prediction models to the individual prediction horizons. The reason is probably that the reduction in the parameter set makes the adaptive model less sensitive to noise thereby improving the prediction performance. The observed prediction performance is illustrated in Figure 3 as "P_{pol}".

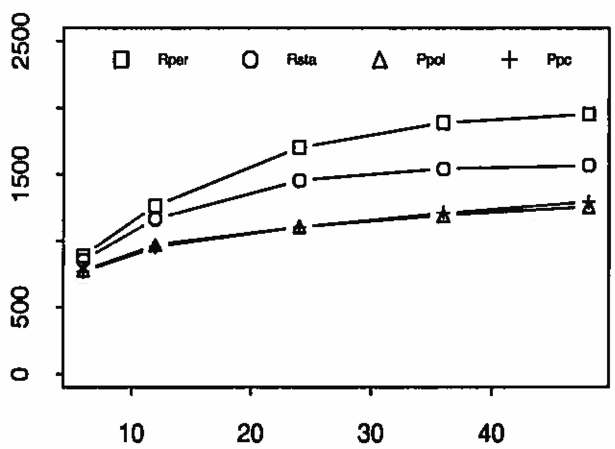

Figure 3: *S.E. [kW] versus prediction horizon [$\frac{1}{2}$hour] for the persistence reference (R_{per}), the statistical reference (R_{sta}), the WPPT version 1 model with polynomial extension (P_{pol}) as well as with power curve extension (P_{pc}).*

6.2 Power Curve Extension to WPPT Model

The model suggested in the previous section relied on a simple polynomial relationship between forecasted wind speed and power production. An alternative approach is to include the meteorological forecasts in model (11) through a power curve model.

$$\begin{aligned} G(w_t, \phi_t) &= \exp\left[-b \exp\left[-k(\phi_t)\, w_t\right]\right] \\ k(\phi_t) &= k_0 + \sum_{i=1}^{N_{tric}} \left[k_{i1} \sin\left[i\phi_t\right] + k_{i2} \cos\left[i\phi_t\right]\right] \end{aligned} \tag{14}$$

where ϕ_t is the wind direction at time t, and a Gompertz parameterization with a wind direction dependent power curve model is used.

Replacing the observed wind speed and direction in (14) by the forecasted wind speed and direction leads to the following power prediction model

$$\begin{aligned} \sqrt{p_{t+k}} &= a_1\sqrt{p_t} + b_1\sqrt{w_t} + b_2 w_t + \\ & \quad b_3\sqrt{G(w^{HIR}_{t+k|t}, \phi^{HIR}_{t+k|t})} + \\ & \quad m_{t+k} + e_{t+k} \\ m_t &= m + c_1 \sin\left[\frac{2\pi t}{48}\right] + c_2 \cos\left[\frac{2\pi t}{48}\right] \end{aligned} \tag{15}$$

where $\phi^{HIR}_{t+k|t}$ is the forecasted wind direction at time $t+k$ given at time t.

Contrary to model (13) such a model is already prepared for wind direction dependencies; but, as the power curve model has to be estimated separately, at the cost of a higher model complexity.

The observed performance for model (15) can be found in Figure 3 as "P_{pc}".

6.3 Summary

Comparing "P_{pol}" to "P_{pc}" in Figure 3 it is seen that for $k \leq 24$ model "P_{pc}" is slightly superior to model "P_{pol}" whereas the opposite is the case for $k > 24$. As the longer prediction horizons are of most importance and considering the added complexity in the "P_{pc}" model we have chosen to implement the "P_{pol}" model in WPPT version 2. This model is also referred to as the *WPPT version 2 model.* The reductions achieved in S.E. by introducing meteorological forecasts into model (11) are ranging from 13.7% for $k = 6$ to 35.6% for $k = 48$ when using the persistence predictor as a reference. When comparing with the statistical reference the similar reductions in S.E. range from 10.3% for $k = 6$ to 19.8% for $k = 48$.

An analysis of the weighting of the various input variables to the model shows, that for short prediction horizons (less than 4 hours) meteorological forecasts are of little value compared to on-line measurements of power production and local climate variables. For prediction horizons larger than 4 hours the meteorological forecasts become of increasing value as the prediction horizon increases.

7 IMPLEMENTATION

WPPT is implemented as two fairly independent parts, a numerical part and a presentation part, in the following denoted WPPT-N and WPPT-P respectively. Data exchange between the two subsystems is implemented via a set of files. A file based interface between WPPT-N and WPPT-P has been chosen for portability reasons as it is foreseen that WPPT will have to run on wide range of platforms. Currently WPPT have been successfully tested on HP Unix systems, VMS systems as well as a PC systems running Linux.

WPPT-N is meant to be running continuously whereas any number of WPPT-P processes can be running at a given time, i.e. WPPT is not restricted to be used by only one user at a time. In the following two sections WPPT-N and WPPT-P is presented in more detail.

7.1 The Numerical Part of WPPT (WPPT-N)

WPPT-N has been implemented in ANSI C and is designed to be straight forward to port to a new platform for which an ANSI C compiler is available.

WPPT-N can roughly be considered to consist of five major modules: data input (measurements and meteorological forecasts), data validation, model estimation and prediction, up-scaling module and finally performance logging and data output for WPPT-P. The measurements are given as 5 minute average values and the data validation is carried out on the 5 minute values before these are subsampled to the 30 minute values used by the models. The meteorological forecasts are given as hourly values which are interpolated to form 30 minute values before being used in the models. A brief description of the functionality within each module is given in the following.

- *Data input.* The data interface for exchanging measurements and meteorological forecasts between the local SCADA system and WPPT-N is established via a set of plain ASCII files. An ASCII file interface has been selected for two reasons:

  1. The interface is simple to establish on a wide range of systems.
  2. The input files provide a history for the measurements to the system. This is very helpful for fine tuning of the models as well as further model development.

  The input files are checked for consistency both with respect to timing as well as the number of values.

- *Data validation.* Experience have shown that despite large efforts on-line measurements are prone to failures (errors). It is therefore essential to have some sort automatic error classification of the measurements not only for protecting the models against the influence of erroneous measurements but also to ease the surveillance tasks for the operators (see Section 7.2).

  - Range check. The measurements are checked versus predetermined minimum and maximum values.
  - Stationarity check. The measurements are checked for stationarity, i.e. it is hung on a constant value. Measurements of wind speed and power are allowed to become stationary around 0 for longer periods of time but otherwise stationary measurements are discarded as erroneous.
  - Confidence check. Here the output models describing the relationship between related measurements, e.g. wind speed and power production, are compared with the actual measurements. If a measurement falls outside the confidence bands of a model it is classified as erroneous. This test is not implemented in the current version of WPPT but will become available in the next release.

  Only the measurements are subject to the data validation methods described above. It has been decided to leave the validation of the meteorological forecasts to the quality control of the national weather service. Hereafter the 5 minutes observation are averaged to form 30 minutes value.

- *Model estimation and prediction.* Each wind farm have a set of models covering the prediction horizon (30 minutes up to 36 hours) in steps of 30 minutes. Each model is a k-step prediction model for which estimation of model parameters and prediction of wind power is implemented as described in Section 5. The model implemented is the WPPT version 2 model – see Section 6. Every 30 minutes a new 36 hour forecast is calculated for the power production for each wind farm. During periods where model input is marked as erroneous the model estimation is inhibited in order to protect the model from the influence of bad data and the predictions for the actual park are marked as being unavailable.

- *Up-scaling.* Both power production measurements and forecasts for the selected wind farms are up-scaled and summarized so as to calculate an estimate for the power production in the entire Elsam supply area. For each wind farm a number of substitute wind farms have been defined and in case the values for a wind farm becomes marked as unavailable the wind farm in question is replaced by one of its predefined substitutes in the up-scaling.

- *Performance logging.* Every 30 minute the updated 36 hour forecasts for the reference wind farms as well as the total forecast for the entire Elsam supply area are logged and saved in individual files.

- *Data output for WPPT-P.* Finally the interface files between WPPT-N and WPPT-P are updated (5 minute values as well as 30 minute values).

It should be stressed that the models applied in WPPT-N are self calibrating, they so to speak learn from the observed data as time goes by, thereby rendering re-calibration superfluous. On the other hand this means that they have to run for some time, typically 7 - 14 days, before the forecasts can be considered to be reliable. To overcome this drawback in applying self calibrating models some additional features have been incorporated into WPPT-N:

- Accelerated learning enables WPPT-N to be started back in time and then use historical input files to calibrate the models before moving into real time operation.

- Saving of current model state ensures that the system will be able to restart quickly in case of power interrupts, system reboot or similar.

7.2 The Presentation Part of WPPT(WPPT-P)

WPPT-P is implemented in ANSI C++ and is based on the X11 and Motif graphical libraries. It has been tested under VMS, HP Unix and Linux and is expected to run on any platform for which X11, Motif and an ANSI C++ compliant compiler is available.

In the configuration used by Elsam WPPT-N is a rather large system taking 70 measurements and 14 meteorological forecasts as input. WPPT-P thus have to serve several purposes:

1. Display the 36 hour forecast of the total wind production in the Elsam supply area.

2. Provide an overview over the climatical conditions and the power production throughout the Eltra/Elsam supply area.

3. Provide an overview of the current status for the measurement equipment installed in the wind farms.

4. Display detailed information for each wind farm for diagnostic purposes, e.g. if an forecast seems to be unrealistic the detailed plot for the wind farms can be used to determine the reason for the bad forecast.

The need for providing both an overview as well as detailed information is reflected in the design of WPPT-P. The main window together with a number of plots directly accessible from the menu bar on the main window provides the operators with an overview of the system state whereas the system engineer have access to more detailed information through a set of sub-windows dedicated to the individual wind farms.

The following sections provides an overview of the functionality build into WPPT-P.

7.2.1 The Main Window

The main window consists of four elements - menu bar (top), map area (left), value field (right) and information field (bottom).

- *The menu bar* provides access to some system functionality as well as some overview plots (See Section 7.2.2).
- *The map area* contains a map of the Jutland/Funen area where the location of each reference wind farm is marked by a wind farm symbol. The symbol consists of a reference code for the wind farm (W*) (top), a number giving the farms current production as a percentage of the installed capacity (left) and a wind rose giving the current wind direction and wind speed (right). In case a measurement error have been detected in the wind farm the symbol turns red to alert the operator to the error. Furthermore clicking on a symbol with the mouse opens the wind farm window.
- *The value field* provides some key figures regarding the current system state. Field 1 and 2 from the top shows the calculation time for the current forecast respectively the reception time for the last meteorological forecast. Field 3 shows the total installed capacity in the Jutland/Funen area as registered by WPPT-N. Field 4 and 5 gives the current estimate of the total power production as a 5 minute and 30 minute average respectively and finally fields 6 to 15 presents the current power forecast for selected forecast horizons.
- *The information field* provides the system engineer with a bulletin board to give relevant information to the users of WPPT.

7.2.2 Plots available from the Main Window

A number of plots regarding the observations and the forecasts for the total power production are available from the menu bar in the main window.

In order to provide a mean for comparing the measurements from the 14 wind farms relative power production, wind speed, wind direction and air temperature for the 7 Northern most and 7 Southern most can be plotted together (See Figure 5 for an example).

The forecasted power production in the Eltra/Elsam supply area for the next 36 hours is presented together with the observed power production for the last 6 hours in a plot (See Figure 6). In order to provide an overview of the prediction performance for the total power production the observed power production is plotted together with historical predictions for selected prediction horizons (See Figure 7).

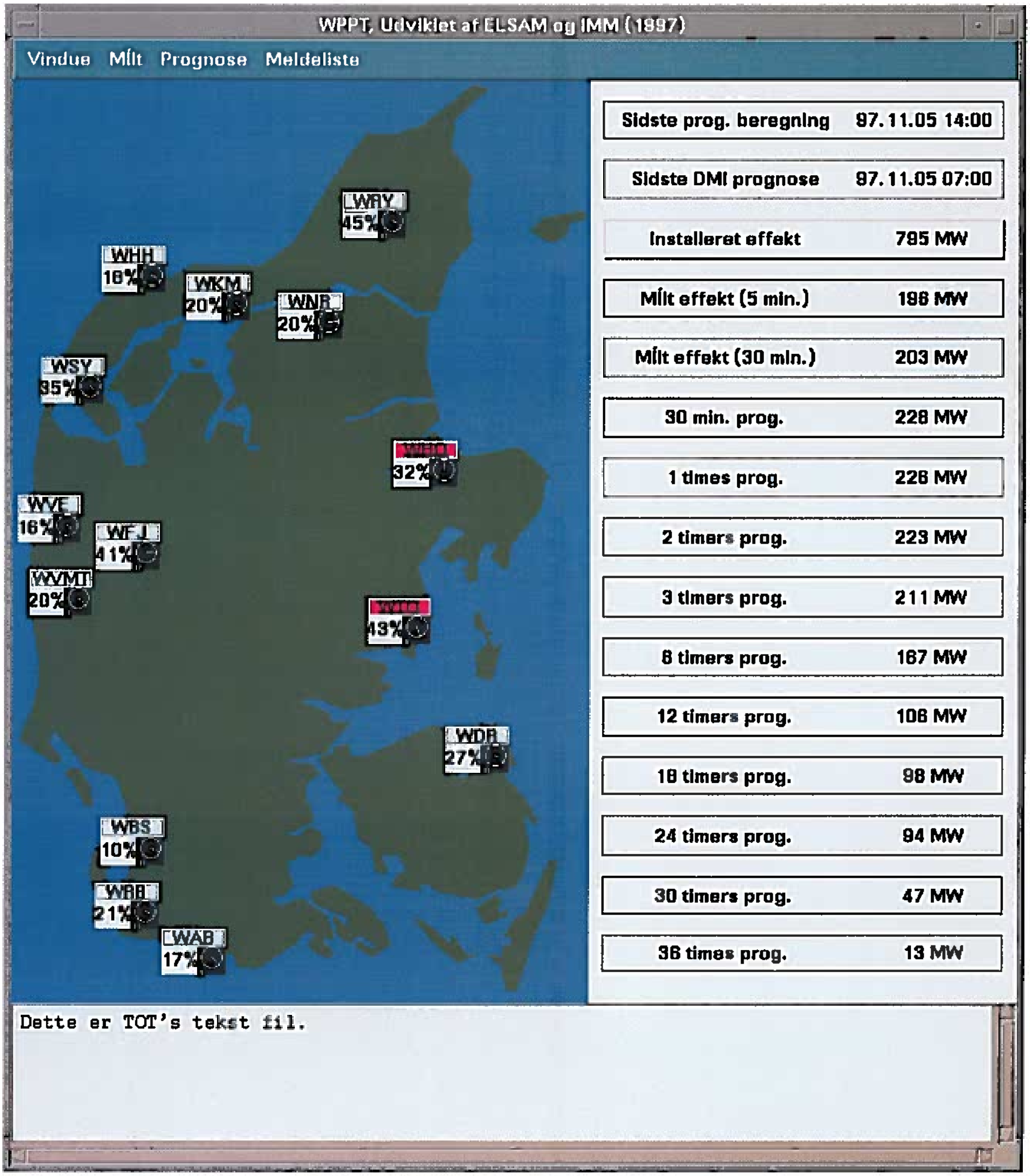

Figure 4: *Main window in WPPT-P.*

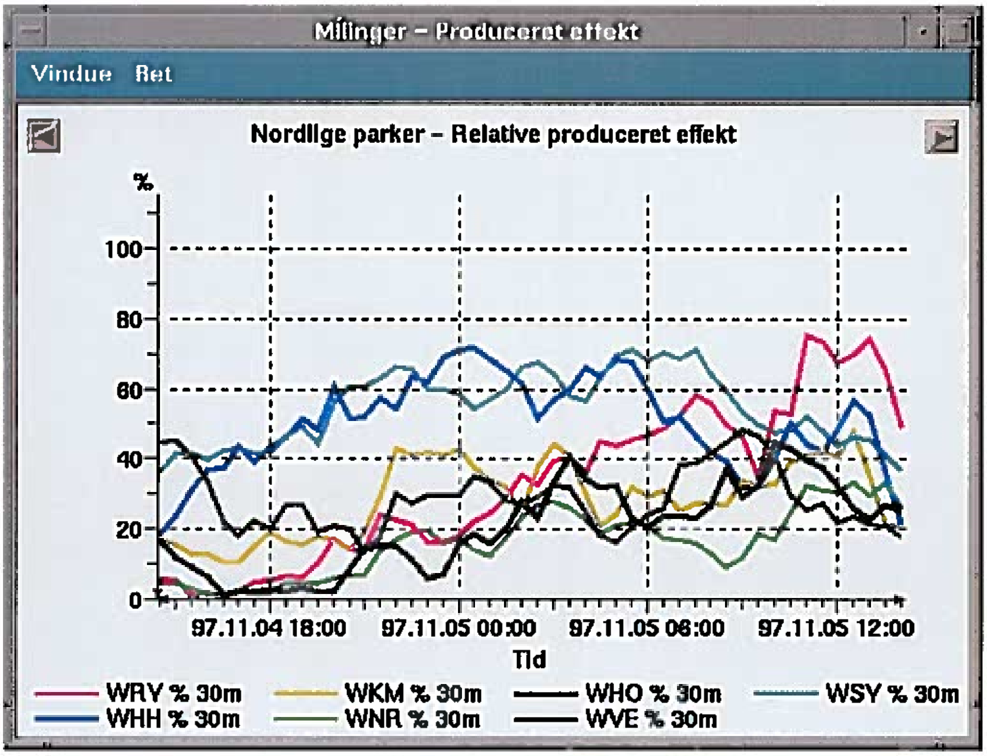

Figure 5: *The relative power production for the Northern wind farms. The plot covers the last 7 days.*

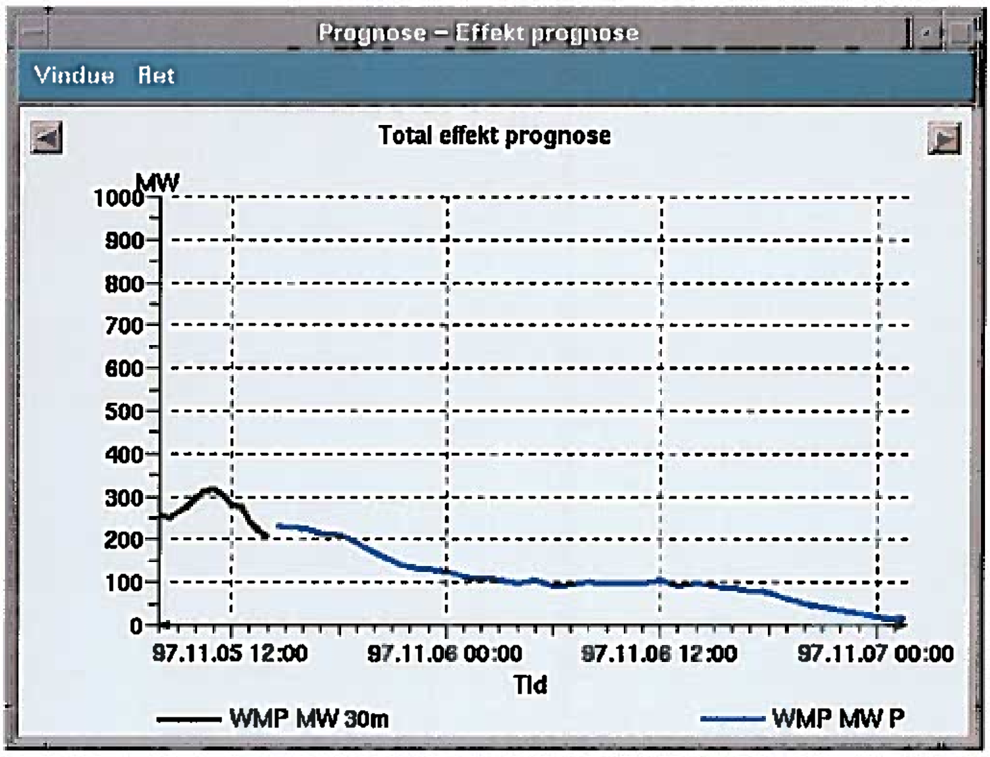

Figure 6: *Plot of the forecasted total power production for the next 36 hours together with the most recent observed values.*

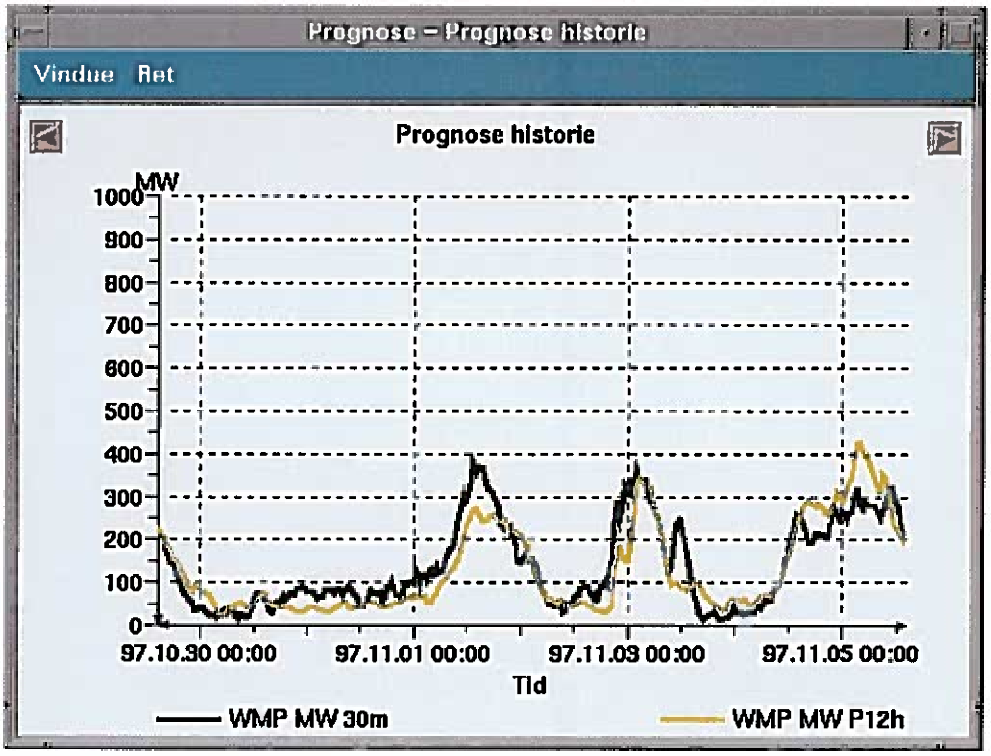

Figure 7: *Plot of the observed power production together with the historical 12 hour predictions. Also the 6 hour, 18 hour, 24 hour and 36 hour predictions can be selected for comparison.*

7.2.3 The Wind Farm Window

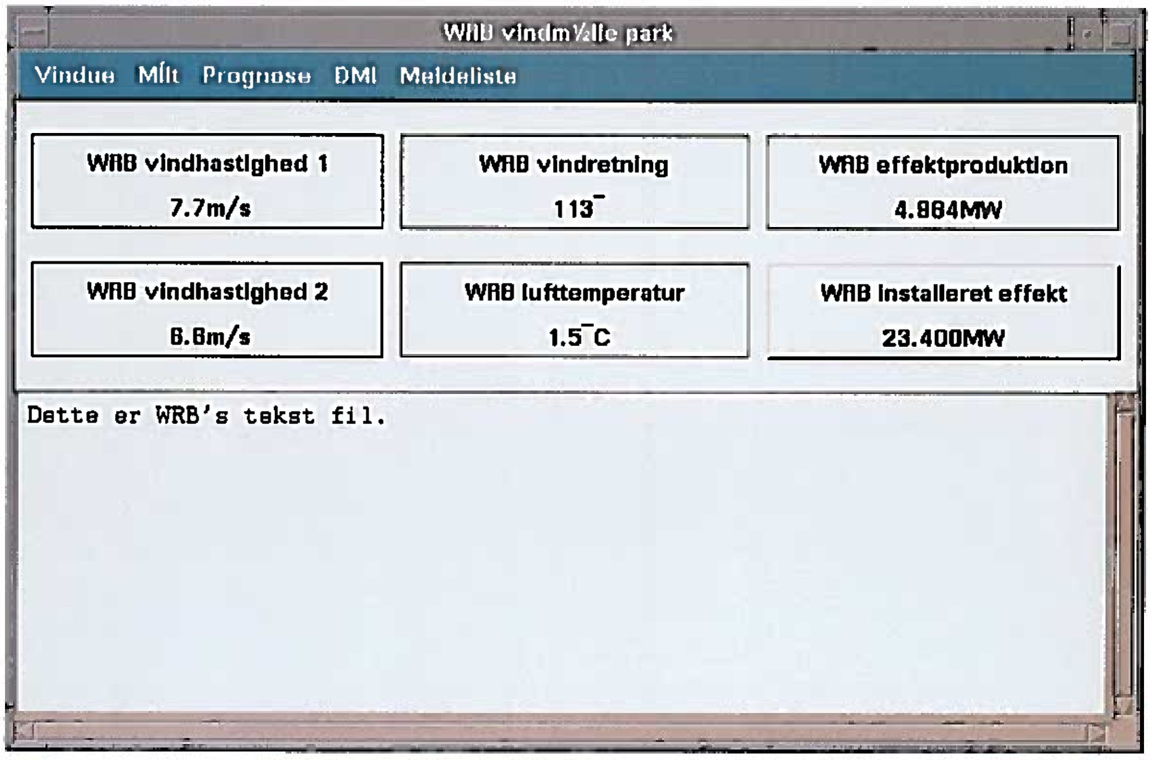

Figure 8: *The wind farm window in WPPT-P.*

The wind farm windows consists of three parts: a menu bar (top), a measurement value field (middle) and an information field (bottom).

- *The menu bar* gives access to some system functionality as well as a large number of plots for the wind farms (See Section 7.2.4).
- *The measurement value field* displays the most resent 5 minute values for the wind farm measurements (two wind speeds, one wind direction, one air temperature and one power production). In the case that a measurement has been classified as faulty the measurement in question is marked by a red background colour. The last field shows the installed capacity for the wind farm as registered by WPPT-N.
- *The information field* provides the system engineer with a bulletin board where information concerning the wind farm can be given to the operators.

7.2.4 Plots Available from the Wind Farm Window

The wind farm window gives the user access to a number of plots which falls into 3 separate categories:

- *Plots of observations.* Plots of the 30 minute average values versus time are accessible directly via the menu bar for all of the five measurements (See Figure 9) but WPPT-P also enables the user to compose new plots where the various measurements can be plotted against each other.

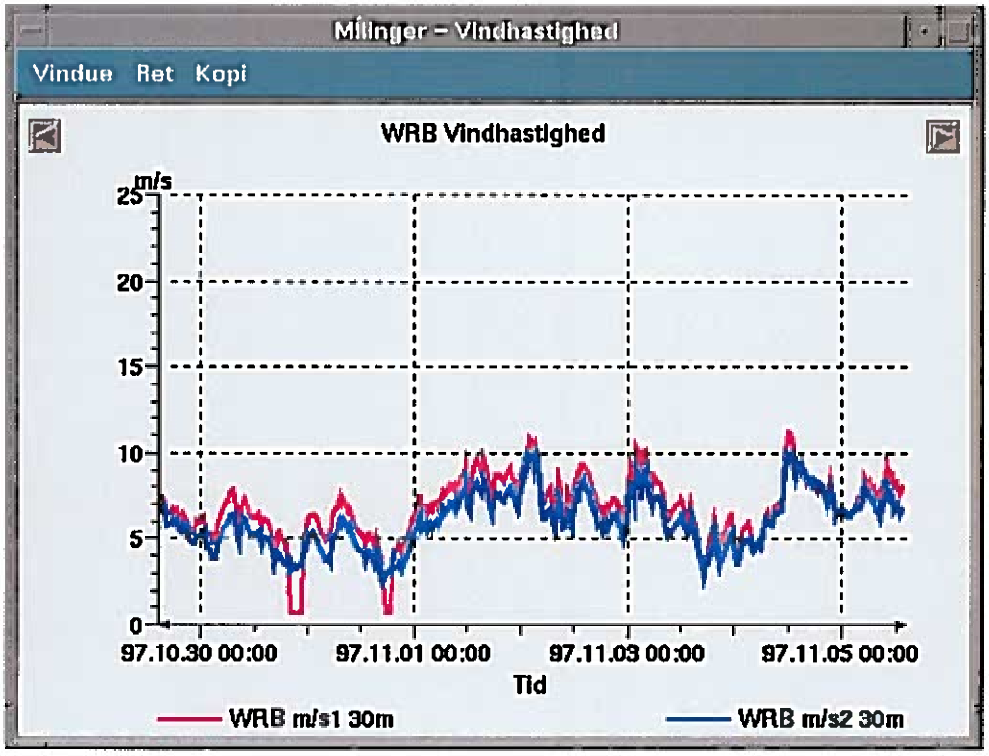

Figure 9: *Plot of the two wind speed measurements. Per default the plot covers the most recent 7 days.*

- *Plots derived from the power production forecasts.* Here the user has the possibility of plotting the forecasted power production for the wind farm (Figure 10), the historical forecasts for the wind farm as well as the uncertainty quantiles for the current forecast.
- *Plots derived from the meteorological forecasts.* Gives access to a plot of the most recent meteorological forecast of wind speed (Figure 11) as well as a plot of the historical performance for the meteorological forecasts.

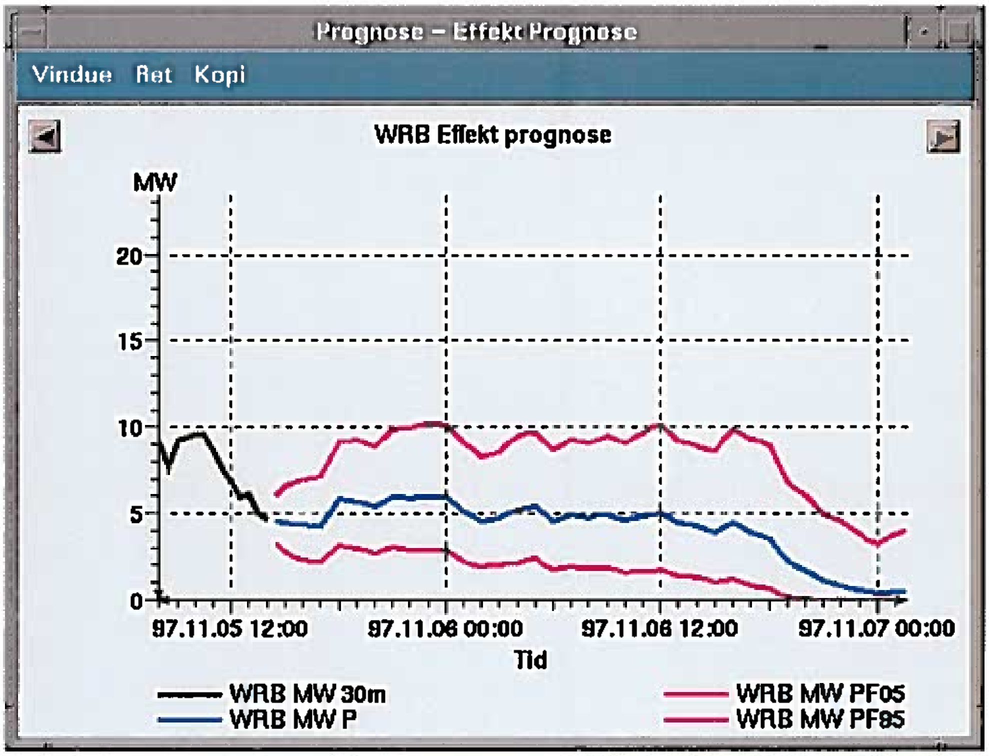

Figure 10: *Plot of the forecasted power production for the next 36 hours including the estimated uncertainty bands for the forecast together with the most recent observed values.*

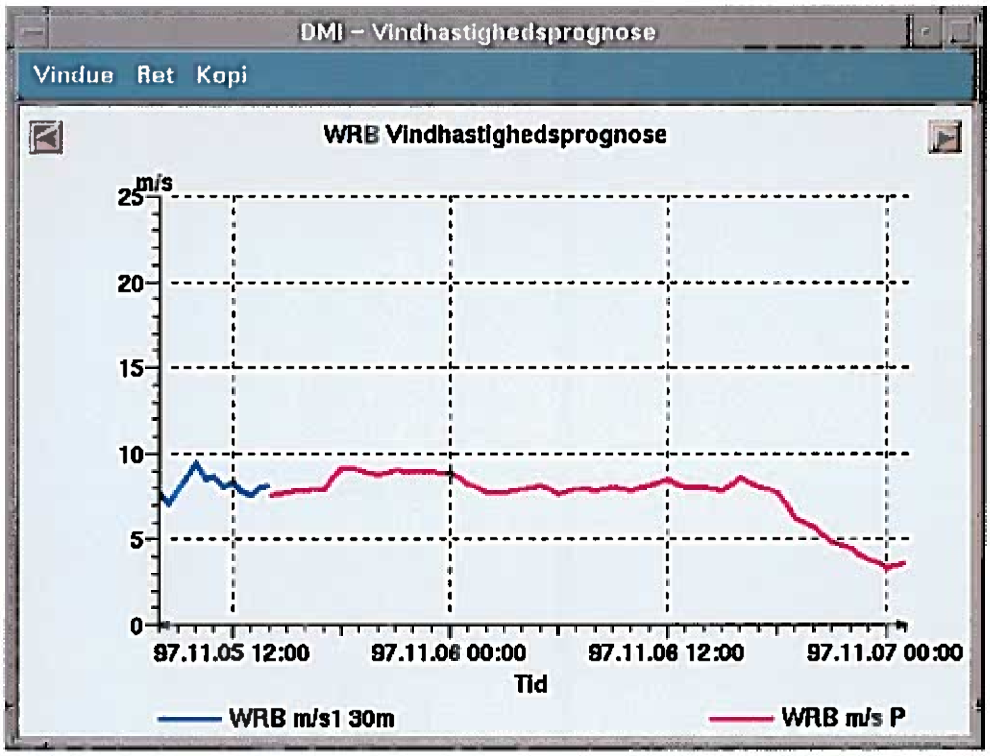

Figure 11: *Plot of the meteorological forecasted wind speed for the next 36 hours together with the most recent observed values.*

7.2.5 Options Available from a Plot Window

All plots can be printed if a postscript printer is available at the site. Furthermore each plot can be tailored by the user through a dialogue box. The dialogue box allows the user to change the time period considered, the scaling of the axis and the plot variables.

The following contains a brief description of the various options:

- *Time period.* Allows the user to select start and end date for the data plotted. Option modes:
  - **Fast.** The start/end date of the plot is fixed to a given date set via the scrollbar or the entry fields.
  - **Rel.** The start/end of the plot is set as an offset relative to the current time.
- *Axis scaling.* Allows the user to select the scaling of the x- and y-axis. Option modes:
  - **Fast.** The axis scaling is a fixed value set through the min/max entry fields.
  - **Rel.** The scaling is automatically selected according to the extreme values in the data set.
- *Plot variables.* Allows the user to select the variables to plot and the plot type (x-y plot or time series plot). Option modes:
  - **Ændre.** Change the plot variable.
  - **Tilføj.** Add a plot variable to the plot.
  - **Slet.** Remove a plot variable from the plot.

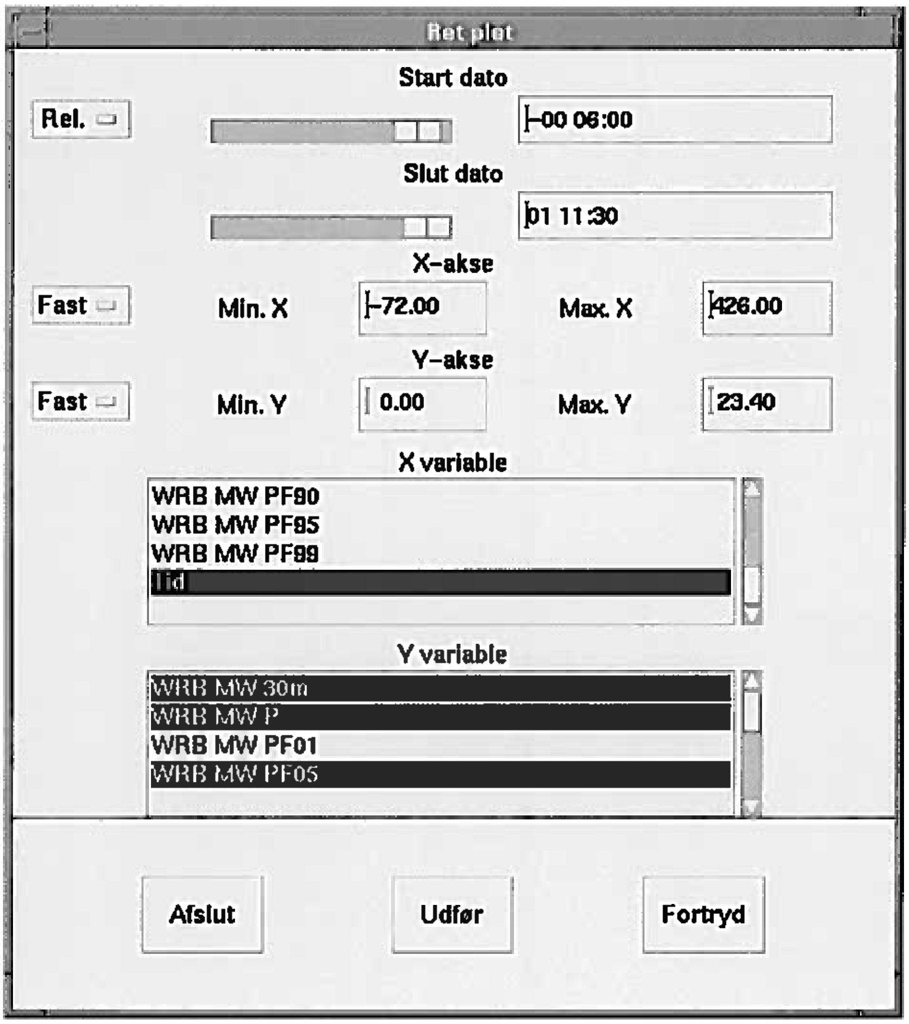

Figure 12: *The plot window dialogue box.*

8 EXPERIENCES AT ELSAM WITH WPPT

The need for good predictions of wind power production in the Eltra/Elsam area is evident.

In 1992-95 the first version of WPPT was developed. The predictions was based on statistical analysis on measurements from only 7 wind parks. The version was in operation in the Elsam Dispatch Center for some months, and the final conclusion was, that the predictions was inadequate for prediction horizons larger than 8 to 12 hours. The main reasons was:

- Bad reliability of measurement equipment.
- Too few wind parks included.
- Lack of meteorological forecasts.

A new project was started in 1996 with the aim to get better predictions by including more wind parks, better reliability of equipment and getting good meteorological forecasts.

A preliminary version of WPPT version 2 has been in operation at the Dispatch Centers of Eltra and Elsam since October 1997, and we now have a good tool for the operators for the planning of the production.

The goal is to predict the production within 50 MW up to 36 hours ahead. This seems to be possible most of the time, at least up to the 12-hour horizon, but it depends much on the type of weather at the time (stable or turbulent). The wind power production can in special cases change with up to 250 MW pr. hour. This can be predicted, but we have seen that prediction of the time point is difficult, so the difference can be large for some hours.

Anyway, the predictions are much better than an experienced operator can provide on basis of weather forecasts from any other known source (TV, Internet ...). The operators rely on the WPPT predictions and use them as basis for planning the production on the primary power stations and selling and buying electricity from day to day and from hour to hour. In periods with stable wind, the running reserve capacity on primary power stations are not changed due to the wind production. In an unstable wind situation it will be considered to raise it. Planned stop of primary power stations on the basis of the wind predictions is not used, because the prediction horizon is not long enough.

Bad predictions have been seen in some situations:

- Very fast developing depressions running fast over the area.
- Very high wind situations (storm) when windmills are stopped.
- Very local weather changes (thunderstorms) give problems to the up-scaling.
- Bad measurements that are not automatically detected.
- Delayed or missing forecasts from DMI (due to computer problems at DMI or Elsam or problems on the Internet).
- Bad forecast data from DMI (DMI has now increased their quality control).

These weather situations have been rare and are therefore not a big problem. The technical problems with the measurement equipment have already been reduced to a minimum.

The final version of WPPT is planned to go into operation in August 1998. Due to more measurements and hence a better modeling, we expect to get even better predictions by then. Because of the new free market for electricity in Northern Europe in the future, it is becoming more and more important to have good predictions of the wind power production.

ACKNOWLEDGEMENTS

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