Next Generation Short-Term Forecasting of Wind Power – Overview of the ANEMOS Project.

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Abstract:

The aim of the European Project ANEMOS is to develop accurate and robust models that substantially outperform current state-of-the-art methods, for onshore and offshore wind power forecasting. Advanced statistical, physical and combined modelling approaches were developed for this purpose. Priority was given to methods for on-line uncertainty and prediction risk assessment. An integrated software platform, 'ANEMOS', was developed to host the various models. This system is installed by several end-users for on-line operation and evaluation at a local, regional and national scale. Finally, the project demonstrates the value of wind forecasts for the power system management and market integration of wind power.

Keywords: Wind power, short-term forecasting, numerical weather predictions, on-line software, tools for wind integration.

1. Introduction

In 1997 the European Commission adopted the White Paper on renewable energies. It sets out a Community Strategy and an Action Plan to double the share of Renewable Energies Sources (RES) in gross domestic energy consumption in the European Union from the present 6% to 12% by 2010. Under this target, the problem of integration of RES and namely of wind energy in the actual energy framework is of tremendous importance.

Wind energy is one of the RES with the lowest cost of electricity production and with the largest resource available. Wind power technologies are presently mature enough to represent a major contribution. The projection of the European Wind Energy Association EWEA, for installed wind capacity by EU 15 at horizon 2010 is 75 GW, while this target was recently updated upwards.

The large-scale integration of wind power in any type of power system, interconnected or autonomous (i.e. islands), imposes a number of difficulties to the power system operation. This is due to the fluctuating nature of wind generation that operators need to balance, for example, by allocation of spinning reserve. The requirement for a secure and reliable operation of the power system acts as a limiting factor for wind penetration.

Experience from countries that witness today considerable wind integration shows that advanced tools are necessary to assist end-users such as utilities, independent power producers, or transmission system operators to the management of wind generation. Accurate and reliable forecasting systems of the wind production are widely recognized as a major contribution for increasing wind penetration.

Moreover, European utilities experience today restructuring in the landscape of electricity generation, transmission and distribution. The evolution towards deregulation is supported by appropriate legislative and financial frameworks that permit new actors to enter the electricity market. However, for the case of wind energy, the variability of the resource limits the competitive advantage of wind production compared to dispatchable conventional electricity. The availability of accurate predictions of wind production for the next hours permits to reduce penalties in a spot market coming from over- or underestimations of the production. As a consequence, the economic attractiveness and acceptability of wind power is increased. Higher financial and operational benefits enable further investments on wind power installations.

Under this general context, the 4-years project ANEMOS was launched in October 2002 by pioneer research institutes in the area and end-users, in order to develop wide research and advanced solutions for onshore and offshore short-term wind power forecasting. The consortium contains 23 partners from 7 countries.

The prediction tools developed within ANEMOS are expected to contribute to an optimal, from the technical and economic point of view, integration of wind power in European interconnected and islands systems. The assessment of wind predictability and uncertainty in this project permits to further define appropriate storage systems or reserve requirements to operate in parallel to wind farms, or appropriate management strategies, to balance the intermittence of wind resource.

Nowadays, several tools [1] have been developed for wind power forecasting (i.e. Predictor, Previento, WPPT, More-Care, Sipreolico, AWPPS, Zephyr and others), some of which by the partners of this project. They focus on onshore applications and are based either on physical (detailed terrain representation, roughness etc) or statistical modelling (i.e. black-box models based only on data). Physical modelling benefits from advances in the area of wind resource assessment. The project gives the possibility to advance towards both statistic and physical modelling, but also to examine in detail combination of the two approaches, which is expected to outperform each single one in several cases.

A wind power forecasting tool is composed by an ensemble of modules (downscaling, power curve modeling, model output statistics, etc), each one expected to have a good performance, in order to achieve an acceptable global accuracy. The software requirements become more complex when the aim is to predict wind power at a regional or even a national level. The project develops research over a wide spectrum of functions, which are implemented in the form of modules and integrated in a software platform, called ANEMOS, able to operate on-line.

In order to be applicable in a wide range of applications, the ANEMOS platform was developed following a thorough specification and pre-standardisation procedure by industrial partners. The architecture of the forecasting system is modular in order to permit combination of different models for an optimal global accuracy. It give the possibility to run in parallel alternative models in order to increase the reliability of wind prediction. This can be a major requirement in cases of large geographical concentration of wind power like is often the case of offshore wind parks.

The paper presents the structure of the project, the main axes of research and the complementarities in the consortium set up to carry out the technical objectives.

2. The ANEMOS approach

The project is structured into nine work-packages, which address the following technical objectives:

- Data collection & evaluation of needs.
- Off-line evaluation of prediction techniques.
- Development of statistical models
- Development of physical models.
- Offshore prediction.
- ANEMOS prediction platform development.
- Installation of the platform for on-line operation.
- Evaluation of on-line operation.
- Overall assessment and dissemination .

The following Paragraphs present an overview of the various developments.

2.1 Detailed evaluation of needs of end-users and state-of-the art review.

At a first stage of the project several audits with various actors like utilities, transmission or distribution system operators, independent power producers, regulatory authorities, etc., took place, with the aid of appropriate questionnaires, in order to evaluate requirements related to wind power prediction. Emphasis was given on the experience (confidence, level of use, etc) end-users have with existing forecasting tools. The results were synthesized to an “end-users requirements” report that consists a basic guideline for the developments in the project.

Moreover a detailed mapping of the literature on wind power forecasting was performed with the review of more than 120 references. A detailed report [2] is available on-line at [3] and a summary at [1].

2.2 Benchmarking of wind power forecasting models.

During the first phase of the project a detailed evaluation of a number of base-line forecasting systems (and some versions of them) was performed including:

- AWPPS (Ecole des Mines/Armines).
- LocalPred (CENER, CIEMAT)
- Prediktor (RISOE)
- Previento (U. Oldenburg, EMSYS)
- Sipreolico (UC3M/REE)
- WPPT (DTU/IMM)
- Prediction model of NTUA
- Prediction system of RAL
- Prediction model of ARIA.

These models were tuned on real data from a number of case studies in Spain, Germany, Denmark (including an offshore one), Ireland, Greece and France. The case studies are selected to correspond to different terrain types and climatic conditions. The

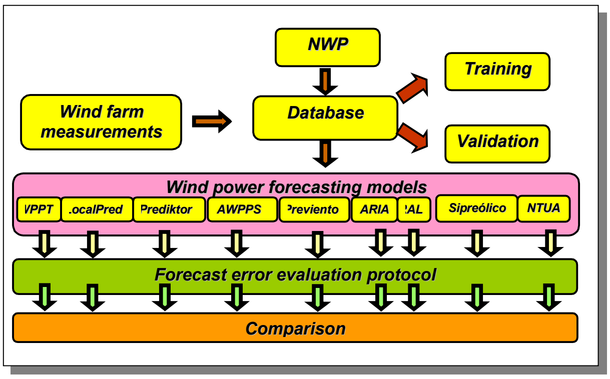

Fig. 1: *Design of the virtual laboratory set-up for the models benchmarking.*

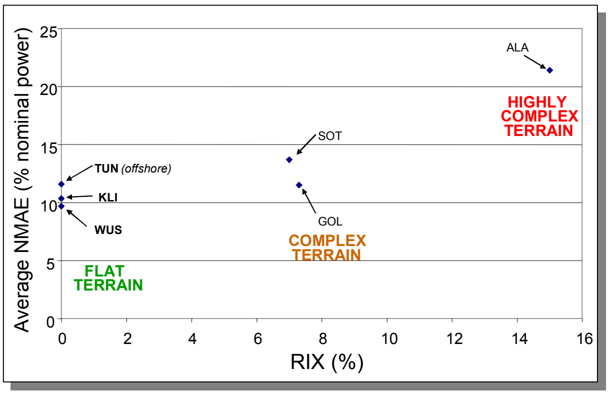

Fig. 2: *Average NMAE for 12 hours forecast horizon vs RIX at each test case. Qualitative comparison. TUN is an offshore wind farm in Denmark, KLI is also located in Denmark, WUS in Germany, GOL in Ireland and ALA and SOT in Spain.*

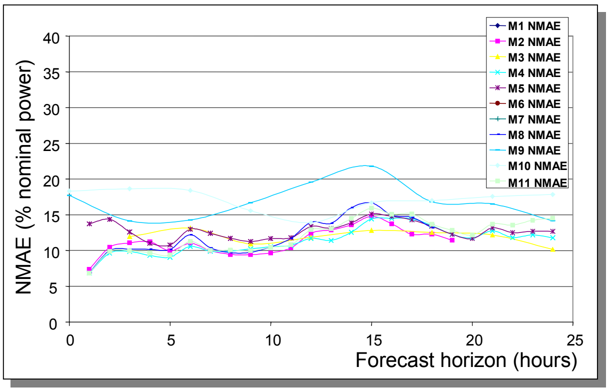

Fig. 3: *Comparison of the performance of 11 prediction models on the Alaiz wind farm in Spain (very complex terrain). The NMAE is given as a function of the prediction horizon which here is 24 hours ahead.*

consideration of the above base-line models permitted to identify the advantages and the limits of each approach, and the areas of improvement. At a later stage of the project, the evaluation process was extended to the new models developed within the project and to new test-cases including upscaling ones.

A well-defined benchmarking framework was developed for this evaluation focusing on different

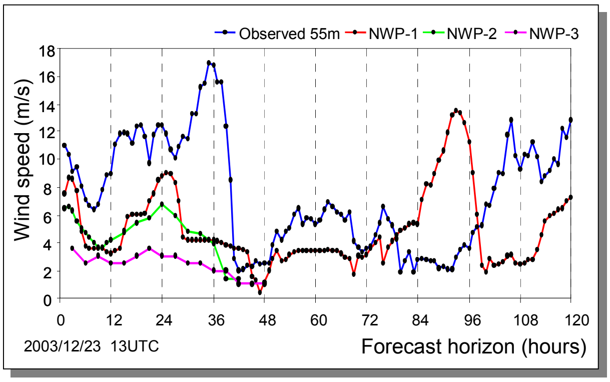

Fig. 4: *Comparison wind speed measurements (at 55m – bleu line) to NWPs (at 10m) provided by 3 different meteorological models for a complex terrain wind farm site.*

time scales (e.g. short-term up to 6 hours or longer term, up to 48 hours), on different criteria etc [42]. File exchanges were performed through a secured web site. Appropriate error measures were selected for the evaluation of the methods with emphasis to their performance in extreme weather conditions as well as their robustness in on-line environment. Experience shows that common measures, such as Root Mean Square Error, are not sensitive enough to properly indicate the prediction quality. The ensemble, shown in Fig. 1, consisted a *virtual laboratory* for evaluating the different modelling approaches in the project.

Fig. 2 shows a representative result of this comparison. The normalized mean square error (NMAE – normalization with wind farms nominal capacity) is depicted for 6 wind farms as a function of the terrain complexity. This latter is expressed by the RIX index which reflects the slope of the terrain around the wind farm.

Each value in Fig. 2 is the average of the NMAE performance obtained by the 11 models. The figure depicts well how the performance is a function of the terrain. It gives also the level of predictability for single wind farm prediction. It is noted that predictability is better when regional wind production is predicted due to the spatial smoothing effect from the geographical distribution of the wind farms [25].

Fig. 3 shows a comparison of the performance of the various physical and statistical models on a test case in Spain (ALA) as a function of the prediction horizon.

Part of the uncertainty in the wind power predictions comes from the error in Numerical Weather Predictions (NWP). In parallel to the evaluation of the prediction models, forecasts generated by different meteorological systems (Hirlam, Skiron, Aladin, etc) were compared for the case of two wind farms corresponding to different climatic conditions – example in Fig. 4. This is an original part of the work that provides much insight on the role of NWPs in wind power forecasting [40].

2.3 Short-term forecasting using advanced physical modeling

In this project focus was given to challenging situations like prediction of wind farms output at complex terrain sites. A possible solution to that problem comes in the form of high-resolution, advanced numerical flow models trying to improve on the NWP models shortcomings.

These models can be linear flow models like Risø's WAsP, or AriaWind, meso-scale models like the well-known MM5 community model, MeteoFrance's MesoNH or IASA's RAMS model, or full-blown CFD models (Computational Fluid Dynamics) like Fluent or Mercure.

The idea of all models is the same: use higher resolution calculation and input data bases plus a more complete physics descriptions than the NWP model to try to capture the local air flows, be it in the mountains or at a land-sea border – see Fig. 6, Fig. 7. While NWP models typically have a horizontal resolution of 5-10km, the meso-scale models employed here can go down to 500m.

The new approaches were tested at three sites: Alaiz, a complex terrain site in northern Spain, Ersa-Rogliano, a two-cluster wind farm on the narrow tip of Corsica, and four wind farms in the eastern end of Crete.

For MM5, several Planetary Boundary Layer parameterisations were tried out, and it was found that the Blackadar scheme performed not as good as the MRF or ETA PBL schemes. The last bit in horizontal resolution might not be necessary, the same accuracy can be gained with a larger finest nested area. A higher number of vertical levels in the lowest 100m above the surface helps. MM5 could improve on the simple HIRLAM forecasts in Alaiz. The accuracy of the MM5 forecasts seems to depend a lot on the accuracy of the driving model (NCEP 6-hourly or GFS hourly).

KAMM could explain the turning effects of the wind for the Spanish test case. A domain size of 400x400 km2 was needed -see Fig. 5. However, a MOS system (where data is available) might do as good.

For RAMS in Corsica and Crete, the second model level (46m a.g.l.) performed usually better than the 10 m wind. Using 500 m horizontal resolution helped here (probably due to the much better orography description used in comparison to MM5).

In general, the models revealed the problem of representativity of a single measurement for a whole region. We are comparing model output valid for an area with a measurement in one particular point. Another issue which has to be solved from case to case is whether it is worth to use the calculation power needed.

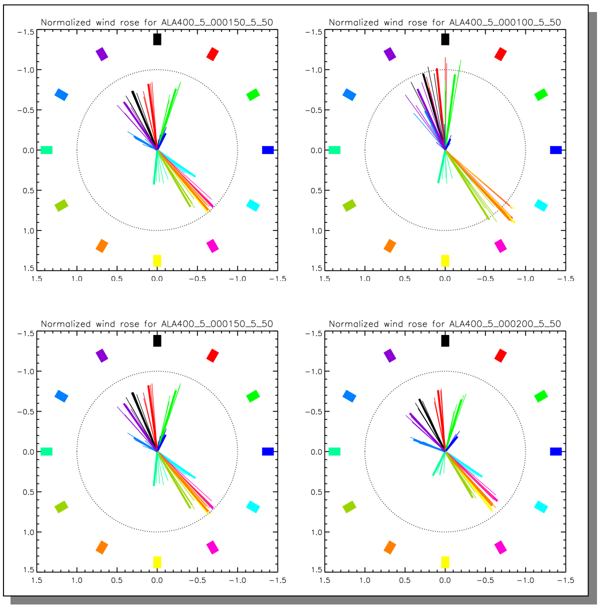

Fig. 5: *The wind speed enhancement and turning effect of the topography are dependent on the wind speed, profile and stability configurations. These effects are displayed in the above diagrams showing the mesoscale effect on the geostrophic wind forcings. Details are reported in [39].*

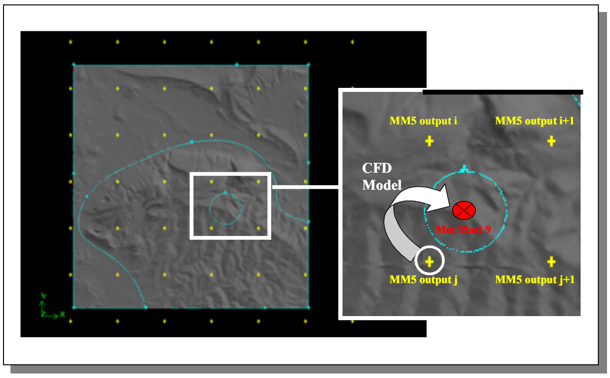

Fig. 6: *CFD downscaling of MM5 NWP. 3D view of the area at Alaiz wind farm in Spain and MM5 grid.*

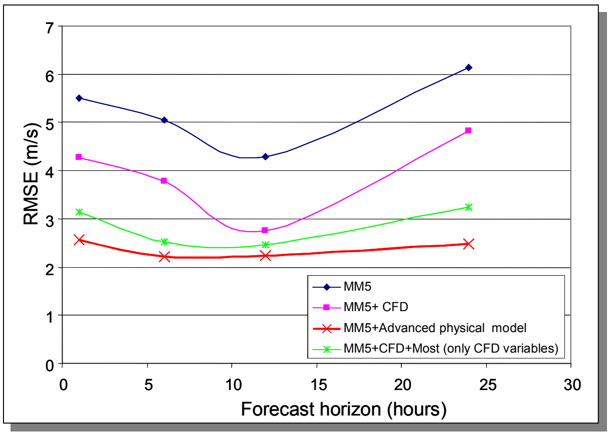

Fig. 7: *Comparison of Root Mean Square Error (RMSE) of wind speed forecasts for Alaiz wind farm using MM5, MM5+CFD, MM5+an advanced physical model, MM5+CFD+MOS (only CFD variables).*

2.4 Advanced statistical modelling and uncertainty assessment.

A first topic of interest in statistical modelling was to develop approaches for post-processing NWPs in order to reduce systematic errors. For example, a new way of encapsulating non-linear dynamics in the Kalman filter was developed and applied to improve NWPs data and in particular wind speed – see [30] for further details. This permitted to reduce up to 20% the error of power predictions as shown in Fig. 8.

A large number of methods have been investigated for the prediction of power production or local meteorological variables including neural networks, fuzzy logic, Kalman filtering, support vector machines, radial basis functions, combined forecasting, a.o. These techniques permit to combine various types of explanatory input like wind direction, wind speed from neighbour sites, numerical weather predictions etc.

A topic of interest was power curve modelling where approaches based on neural networks, fuzzy logic and local regression were evaluated. Such models aim to describe the relationship between local power production and local meteorological measurements or forecasts - Fig. 9. Experience so far shows that one of the main error sources in wind power prediction lies in insufficient power curves. The use of certified power curves does not guarantee that the relation between wind speed and power output is accurately described.

Work on statistical downscaling aimed at developing models describing the dependency between meteorological forecasts from nodes surrounding a location (the global wind field) and local observations. Statistical downscaling can here be seen as an alternative technique to explicit terrain and roughness modeling.

Emphasis was given on developing upscaling approaches for predicting regional/national wind power production from a sample of wind farms for which power predictions are available. Also the statistical smoothing effects arising when considering the production for a number of wind farms in a larger region was investigated. The developed approaches were evaluated on the test cases of Jutland/Funen in Denmark and EWE in northern Germany, each in the order of 2200 MW and in Ireland [40].

A priority axis of the project concerned uncertainty. Methods for assessing the situation-specific uncertainty in the power predictions have been developed able to provide prediction intervals for pre-selected confidence levels – see Fig. 10. Furthermore, prediction risk methods were developed able to exploit information in ensemble meteorological forecasts for assessing the expected level of uncertainty in wind power predictions. This information can be particularly useful for the decision making processes

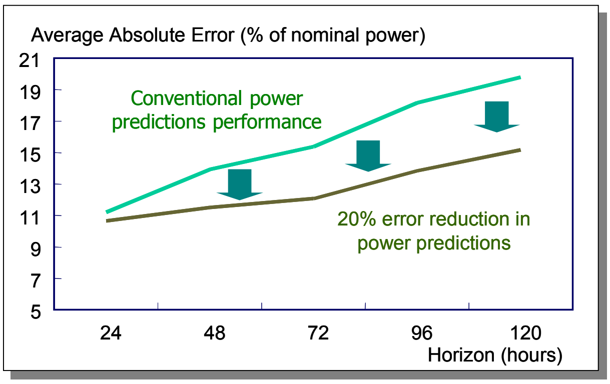

Fig. 8: *Improvement on the performance of power predictions by using the Kalman approach to filter NWPs.*

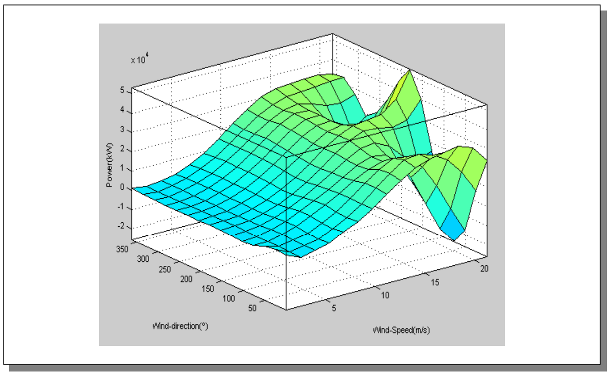

Fig. 9: *A two dimensional power curve model based on fuzzy-logic approach for the Alaiz wind farm in Spain (very complex terrain).*

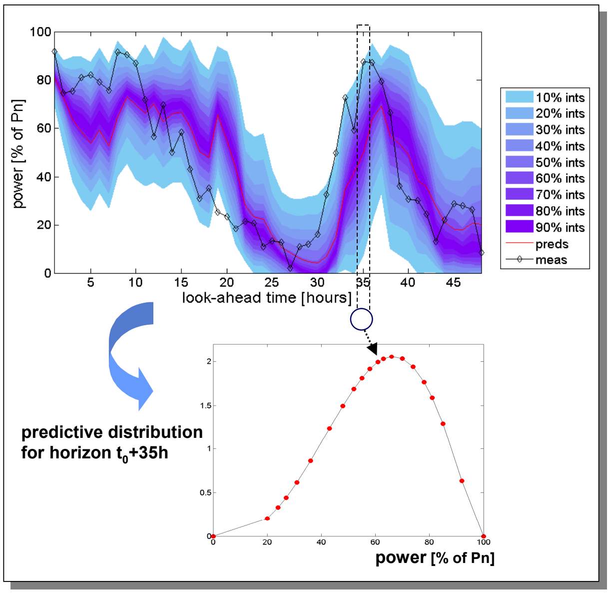

Fig. 10: *Example of forecasts for the next 48 hours compared to measured values. Prediction intervals for various levels of confidence are displayed. Intervals are estimated with the adapted resampling approach.*

related to wind power management or trading. The risk indices consist a complementary tool to prediction intervals. It is a mean to "forecast" the level of uncertainty – see Fig. 11. I.e. when a high value of the

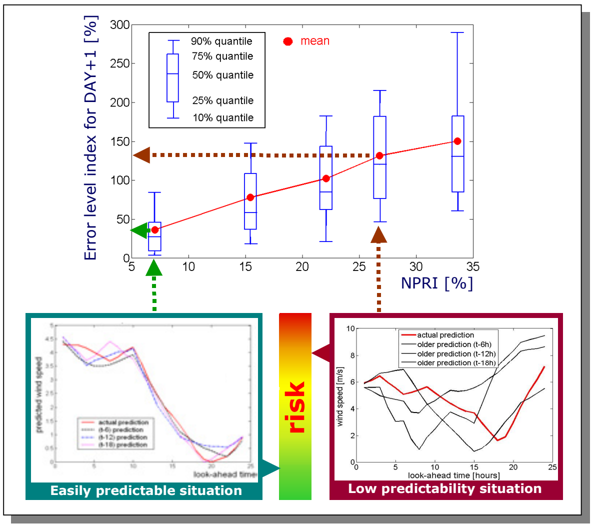

Fig. 11: *Translation of weather predictability to power predictability for next day using the Normalised Prediction Risk index (NPRI). Bottom-left: the alternative predictions for the next day are very similar resulting to confidence on what will happen. Bottom-right: the alternative predictions significantly differ – this lower the confidence on the future weather predictability. Each situation is represented by a value of the risk index. Though the upper diagram this can be translated to an error level of the power predictions (100% corresponds to the average error level of the model).*

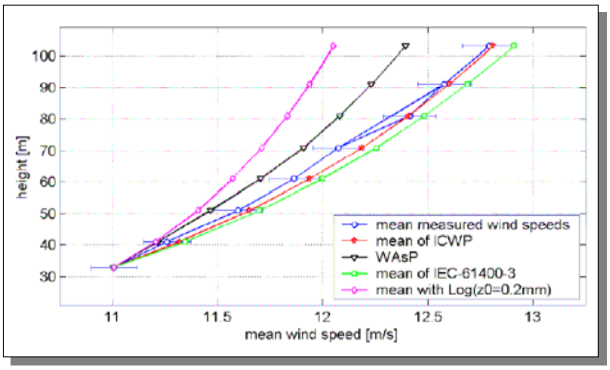

Fig. 12: *Mean measured "open sea" sector (135°-360°) wind profile at Horns Rev compared to mean of ICWPs and average offshore WAsP profile. Period 10/2001-04/2002.*

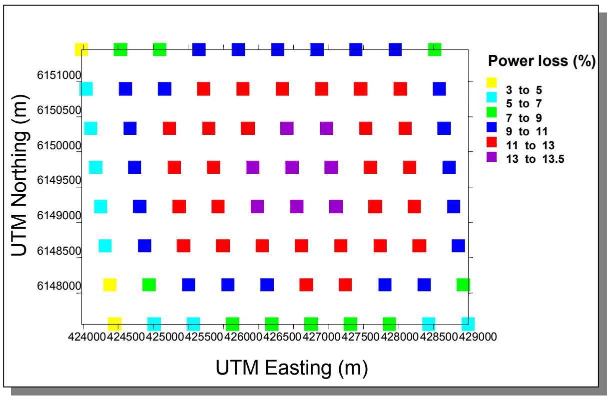

Fig. 13: *Evaluation of wake effect in a large offshore wind farm. Total wakes power loss is ~10% but individual wake losses are much larger.*

risk index is provided for the next day, the operators may adapt their strategies by taking preventive actions like higher spinning reserves.

The various statistical methods have been implemented in modules and integrated within the ANEMOS prediction platform and are operational in the various installations of the project.

2.5 Short-term forecasting of offshore wind farms production

A priority of this research work has been related to high-resolution marine meteorological forecasts and the analysis of different meteorological conditions offshore. The sea surface roughness is very low, and the thermal stratification of the atmosphere, i.e. the thermal stability of the wind flow, is for long periods very different from the near neutral case observed onshore. Additionally, the low roughness increases the influence of stability on the wind speed profile. The project investigated the most important parameters which influence the wind speed profile offshore. Pure numerical meteorological forecasts were compared with measured time series from several sites.

A new air-sea-interaction model for calculating marine wind speed profiles was developed, i.e. the theory of inertially coupled wind profiles (ICWP). The model is based on inertial coupling of the wave-field to a wave boundary layer with constant shear stress which is matched to the Ekman layer of the atmosphere. Evaluation with Horns Rev (Fig. 12) and FINO1 data [41] showed good agreement, especially regarding wind shears.

Next, emphasis was given on modelling spatio-temporal characteristics in large offshore farms. New approaches were developed to model wakes behind such farms. Wake losses are anticipated to be at least 5-10% of power output. Wind speed recovery can be predicted to occur between 2 and 15 km downwind of such farms according to the model type chosen.

A new whole wind farm model was developed (Storpark) based on conserving momentum deficits. Also, comparison of mesoscale model results with WAsP predictions was performed to quantify gradients of wind speed over large wind farms. These gradient corrections were compared with corrections needed for vertical wind speed profiles and for wake losses in order to identify which have the largest impact on power output on a case by case basis.

A new module for FLaP, which is the wake-model from Oldenburg University, was developed. The underlying Ainslie-model is based on eddy viscosity closure of the Reynolds equations with a boundary layer approximation and leads to a modified Gaussian distribution of speed losses. The turbulence intensity profile in the wake is now modelled with the Magnusson-formula, which improves the calculation of added turbulence.

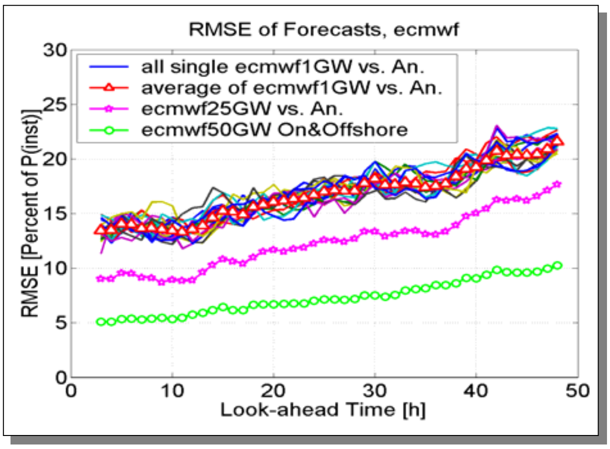

Fig. 14: *RMSE of ECMWF wind power forecasts. Thin lines: all single 22 sites. Red triangles: Average of single sites. Pink stars: Aggregated 25GW offshore forecast. Green circles: Aggregated 50GW on-&offshore forecast.*

A study was performed on the regional forecast for a total capacity of 25GW in the German Bight which showed an RMSE of 9-17%, credited to spatial smoothing effects that reduce the error by a factor of 0.73 compared to a single site. Hence, a combined regional forecast for all offshore sites would show an RMSE of 12% at 36h forecast time, i.e. an absolute RMSE of 3GW. It was then of interest to estimate the respective spatial error smoothing for the sum of onshore and offshore wind farms in Germany. An aggregated forecast for a situation with 25GW installed offshore capacity and 25GW onshore for the year 2004 was calculated. As a reference, it was used the sum of the offshore wind power time series calculated from the weather analysis and the real German onshore wind power production time series from 2004 that was scaled from 17GW to 25GW. The resulting RMSE ranges from 5% to 10% (Fig. 14), i.e. the area size of 800km leads to an error reduction

In a dedicated task, the contribution of satellite data in offshore prediction was studied.

Finally, various physical (i.e. MM5) and statistical (i.e. neural networks) models were calibrated on power data from two offshore wind farms: Tunoe and Middelgrunden in Denmark [41].

2.6 The ANEMOS forecasting platform.

Today wind power prediction is an operational, commercial task which must fit into the requirements of ambitious customers like utilities, TSOs and operators of large wind farms. Although being operational, many approaches for power forecasting are originated in a research environment.

In the framework of the ANEMOS project, a professional, flexible platform was developed for operating wind power prediction models, laying the main focus on state-of-the-art IT techniques, inter-platform operability, availability and safety of operation. Currently, several plug-in prediction models from all over Europe are able to work on this platform.

They cover a wide range of end-user requirements such as short-term prediction (0-6 hours) by statistical approaches, medium term prediction (0-48/72 hours) by statistical and physical approaches, combined approaches, regional/national forecasting through upscaling techniques, on-line uncertainty estimation, probabilistic forecasts, risk assessment, multiple numerical weather predictions as input and others. The flexibility of the platform permits simple settings for single wind farm prediction up to more complex ones corresponding to large wind power capacities. It can run at a remote mode by the ANEMOS Consortium as a prediction service or installed to run as a stand alone application.

All interfaces, data formats and data base structures are well-defined and well-documented. For the actual prediction models, different ways of data retrieval and sending are available, starting with simple but standardized file exchange up to web service interfaces. Following this approach, the integration of different models was made easy and effective for the modellers.

Also, for safe operation, an option for operation on multiple servers was implemented. By this way, it is possible to operate two ore more servers at different physical locations for the same prediction tasks, independent concerning power supply and network infrastructure. These servers will automatically mutually overtake the tasks of data retrieval, production and delivery if any problem occurs at one place. With this approach, we could reach an 100 % availability of our services in the last 18 months.

The advantages of this platform approach for wind power prediction customers are quite obvious: safe operation, high availability, easy integration in own IT structures and access to a variety of forecasting models with only one starting infrastructure investment and a single user interface. More information is given in [43].

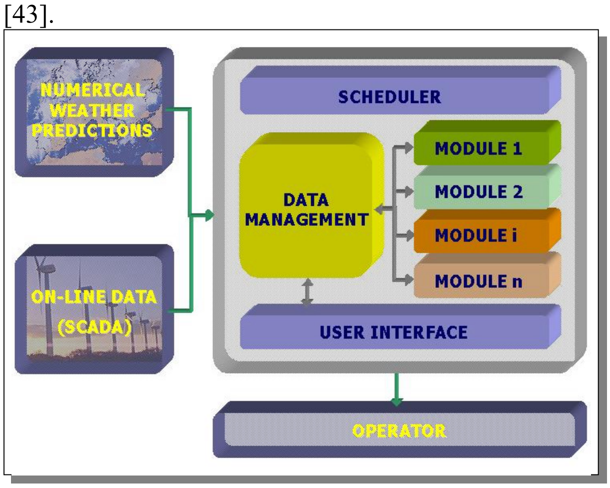

Fig. 15: *General architecture of the ANEMOS prediction platform.*

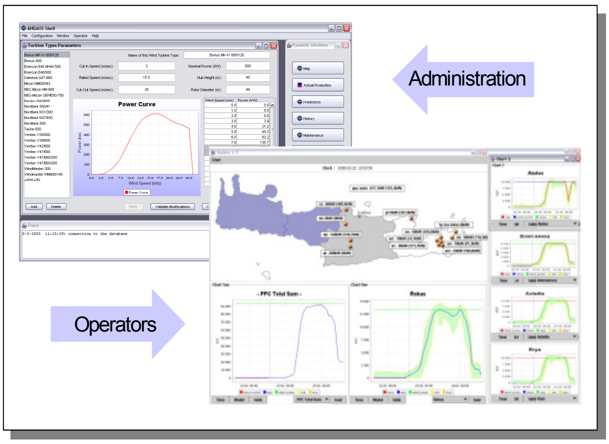

Fig. 16: *Ergonomic, graphical users interfaces were developed to visualise predictions and administrate the system.*

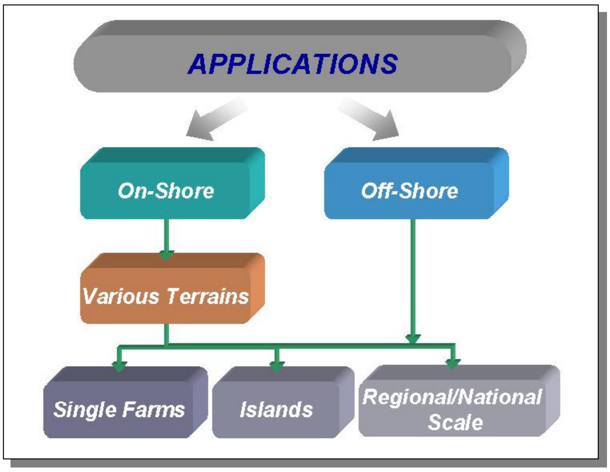

Fig. 17: *A wide range of on-line applications is planned for detailed evaluation and optimal exploitation of the results.*

The platform is installed in 7 countries for online operation by 8 end-users including TSOs, utilities and windfarm developers. The installations cover applications like onshore and offshore parks, island power systems and regional/national forecasting.

2.7 Evaluation of benefits from wind prediction

The above range of applications permits to evaluate in detail the performance of the models developed within the project under various operating conditions.

The benefits by the use of a forecasting model are estimated in two levels: by the use of specific models that simulate the operation of a power system in detail. By this way the monetary value of the forecasts can be estimated (i.e. due to fuel savings) but also their influence to the security of the system.

Benefits will also be evaluated from the end users (utilities, wind farm owners etc.) point of view. Interfaces with energy management systems are established (e.g. More-Care) in order to quantify the value of wind prediction for the power system management functions (i.e. economic dispatch, unit commitment).

The influence of forecasts on aspects like system stability, definition of penetration limits, pollution prevention will be addressed during the evaluation phase in the last year of the project. Finally, emphasis is given on analyzing the correlation between prediction uncertainty and electricity prices and how to develop optimal strategies for wind power participation in electricity market. An example is shown in Fig. 18, which depicts the revenues of a wind farm from its participation in an electricity market. Revenue 100% corresponds to perfect forecasting where no penalties apply for imbalances. The simple method of persistence gives the lower bound. Bidding strategies based on the uncertainty information permit to increase benefits compared to the case where only spot predictions are used.

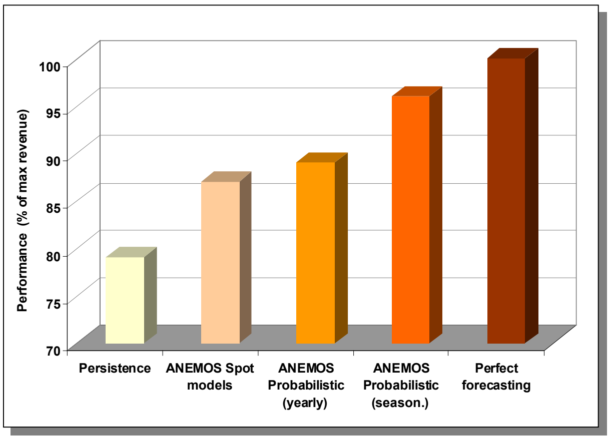

Fig. 18: *Evaluation of the revenues obtained from the participation of a wind farm in an electricity market.*

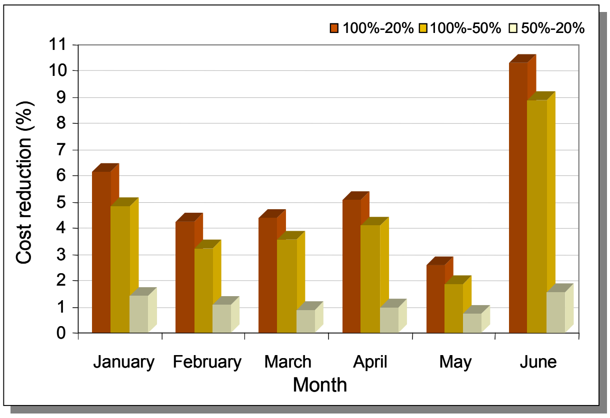

Fig. 19: *Study on the power system of Crete. Estimation of monthly cost reduction due to improvement in the wind forecasts accuracy. A 6-10% reduction is achieved also in GHG emissions (SO_2, NO_X, CO_2) by the use of an advanced forecasting tool that permits to avoid excessive reserves allocation.*

3. Conclusions

The ANEMOS project provides an advanced technology for wind power forecasting applicable on a large scale: at a single wind farm, regional or national level and for both interconnected and island systems. For detailed information on the results of the project, a list of References is given below.

A next generation forecasting software, ANEMOS, has been developed to integrate a variety of modules covering a wide range of requirements for wind prediction and uncertainty estimation. The platform is enhanced by advanced Information & Communication Technology functionality and is able to operate both in stand alone or remote mode, or be interfaced with standard Energy Management Systems. The software was installed for on-line operation at a number of onshore and offshore wind farms. The benefits are under evaluation during on-line operation, while guidelines will be produced for the optimal use of wind prediction systems.

After running 3 and a half years of the project, it is worth mentioning that the large size of the consortium has been extremely beneficial. It permitted to establish a high synergy from experts from various fields. It led to achievements that would have been very difficult for single partners or smaller groupings to realise. It permitted an accurate 'mapping' of the wind forecasting technology useful for developing grid and market regulations. Moreover, having together end-users with different perspectives regarding wind prediction, permitted to have a clear view regarding requirements and priorities. Last but not least, it permitted to create a data base of valuable information (i.e. measurements) for extensive validations of the modelling work. The project has globally contributed to extend the wind power forecasting technology as shown below:

Prior to the project		Project contributions
Deterministic forecasting	→	Towards probabilistic forecasting
The classic model chain	→	Extension by inclusion of new solutions (combined models, multiple NWPs, ensemble predictions)
Accuracy oriented models	→	Accuracy + robustness + value oriented models
Research prediction tools	→	Standardized, pre-industrial tools.

As wind penetration increases, end-user requirements diversify and become more and more complex. Even throughout the current project new priorities emerged (i.e. uncertainty estimation, upscaling) revealing the necessity of research to meet requirements. In the future it will be necessary to continue research in the field; go back to the basics, develop further synergy with meteorology, work on the "value" of wind forecasting. In particular, the "value" relates to the integration of predictions and their uncertainty in management functions and decision making processes related to wind power.

The output of this research is expected to facilitate wind power integration at two levels. Firstly, at an operational level, since it will allow better management of wind farms and more efficient participation of wind production in the electricity markets. Secondly, it is expected to contribute in promoting an increase in the installed capacity of wind farms; an accurate power prediction capability reduces the risk to wind farm developers, who are then more willing to undertake new wind farm installations, especially in a liberalized electricity market environment.

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