Towards smart integration of wind generation

Gregor Giebel, Peter Meibom, Pierre Pinson, Georges Kariniotakis

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G. Giebel[a], P. Meibom[a], P. Pinson[b], and G. Kariniotakis[c] for the ANEMOS.plus Team.

a - Risø National Laboratory, The Technical University of Denmark, Denmark, Gregor.Giebel@risoe.dk
b – Informatics and Mathematical Modelling, The Technical University of Denmark
c – ARMINES, Ecole des Mines de Paris, France

Summary

This paper presents current and future challenges for the integration of wind power into the grid using short-term predictions. This includes the currently running virtual laboratories of the EU project POW'WOW as well as the research methodology of the soon-to-start EU projects ANEMOS.PLUS and SafeWind, which aim to develop advanced tools for the management of electricity grids with large-scale wind generation and to get a better handle on extreme events. Focus in ANEMOS.PLUS is given to functions such as optimal scheduling, reserves estimation, bottleneck management, storage management and also optimal trading in electricity markets. For all of them, short-term forecasting as well as uncertainty estimation plays a major role. However, this information is not yet fully integrated in daily practices. The aim is thus to propose advanced tools for the above functions that integrate the full information on the expected wind generation. In order to demonstrate the value of these tools for end-users, demonstration projects in eight European countries including Denmark are defined. SafeWind on the other hand is a project more focussed on research, especially research in extreme events. Those can be extreme winds, but also extreme forecast errors, requiring an extraordinary amount of reserve capacity. In order to help forecasters to estimate their models against the state-of-the-art models, a Virtual Laboratory for short-term prediction has been instantiated under the POW'WOW project.

Introduction

Wind energy high penetration grids

Nowadays, wind power has an increasing share in the electricity generation mix in several European countries with Germany, Denmark and Spain witnessing already a high wind-energy penetration. Due to the fluctuating nature of the wind resource, the large-scale integration of wind power causes several difficulties in the operation and management of a power system. This paper focuses on larger time scales ranging from few minutes to hours or days. When it comes to large-scale wind integration one has to consider as given the different wind turbine technologies already connected to the grid. Wind integration can then be enhanced by bringing Information and Communication Technologies and Intelligence in the decision processes related to the power system management.

Often, a high level of reserves is allocated to account for the variability in wind production, thus reducing the benefits from the use of wind energy. Today it is widely recognized by end-users such as Transmission System Operators (TSOs), independent power producers, utilities a.o. that forecasts of the power output of wind farms a few hours up to few days ahead contribute to a secure and economic power system operation. Increasing the value of wind generation through the improvement of prediction systems' performance is one of the priorities in wind energy research needs in the last years and is expected also to be one in the future[1,2,3]. This is especially true for the reduction of extreme errors, which can bring down the entire system. In March 2005, the UTCE[1] published recommendations for "Seven Actions for a Successful Integration of Wind Power into European Electricity Systems". Among them, the necessity is stressed for further research in the area of improved forecasting tools for wind generation.

From weather prediction to end-use at client

Producing and using wind power forecasts operationally is a complex issue. The whole chain contains

- the data acquisition and transmission process,
- the production of numerical weather predictions by meteorological models,
- the production of forecasts and uncertainty estimates for the power output of wind farms,
- the use of these forecasts in the decision making process of the operators,
- the application of these decisions in practice and the evaluation of their impact on the power system economics and security.

The ANEMOS.plus Project Team contains members

- from research institutes: ARMINES/Ecole des Mines de Paris, Danish Technical University, CENER, ICCS/NTUA, INESC Porto, RISOE, University Carlos III of Madrid, University College of Dublin, University of Antilles,
- and industrial partners: Overspeed, Energy & Meteo Systems, Enfor, ACCIONA, EDF, EIRGRID, DONG EWE, PPC, REE, REN, SONI, Vattenfall.

[1] *The "Union for the Co-ordination of Transmission of Electricity" (UCTE) is the association of transmission system operators in continental Europe, providing a reliable market base by efficient and secure electric "power highways".*

It is not obvious how to apply and integrate the forecasting information into the day-to-day operation of power systems. The integration of wind generation itself in a power system is highly dependent on how system operators will be able to adapt their management practices to account for the intermittent nature of wind. Traditionally, system operators manage the power system based on forecasts of the electricity demand. Demand is highly predictable due to periodicities related to the human activity and to high smoothing effects from individual consumptions (typical errors in predicting demand in interconnected systems are less than 5%). For this reason, power system management tools (i.e. unit commitment, economic dispatch etc) are in general based on deterministic approaches and thus not appropriate when high amount of intermittent resources are considered in the process. Applying wind power prediction results in the daily work of TSOs, energy suppliers and traders is far from straightforward. It requires the development of a stochastic optimization paradigm, which is technically challenging and will require a change of operators' attitudes and practices.

By integrating advanced wind power forecasts and information on their uncertainty in the power system key management functions, the ANEMOS.PLUS project aims to provide new intelligent management tools for addressing the variability of wind power. The objective is to demonstrate the applicability of such management tools at an operational level for managing wind generation in power systems and for participating in the electricity markets.

State of the Art

The "Anemos" Wind Power Prediction System

A number of leading institutes in the area of wind power forecasting have launched in 2002 the 4-year EU Research and Development (R &D) project ANEMOS, which aimed at improving the available technology. Forecasting solutions were developed to meet a variety of end-user requirements (i.e. different time and geographical scales, reliability and robustness of operational tools, uncertainty estimation etc) and types of applications (management of the power system, bidding in an electricity market).

The project has produced an advanced pilot wind power forecasting system, called ANEMOS, able to run operationally for predicting wind power at single wind farm scale as well as on a regional/national scale. A major contribution of the ANEMOS project in the area of wind forecasting was the development of the first operational approaches for on-line uncertainty estimation of wind predictions and also the so-called risk indices explained below. The prediction models together with the uncertainty tools provide the necessary information (but not yet the tools) needed for advanced decision making procedures for the optimal integration of wind power.

The ANEMOS wind forecasting technology makes extensive use of Information and Communication Technology since the various wind power prediction models, the meteorological forecasting models, the data acquisition systems data bases, the user interfaces can be distributed. Communication capabilities are enabled through internet.

Wind Power Forecasting and Uncertainty

The state of the art in wind power forecasting has been pushed forward during the EU funded ANEMOS project (see *www.anemos-project.eu*). Usually, the forecast starts with Numerical Weather Prediction (NWP) from a meteorological institute and online data from the targeted wind farm. Then, either using physical considerations or statistical adaptive tools, a horizon-dependent connection is made between the NWP wind speed and direction input on the one hand, and the measured power output on the other hand. The estimated power curve is used to forecast up to the horizon of the NWP model output. ANEMOS contributed to the state of the art with improved statistical estimation methods, improved physical parameterisations and downscaling, dedicated models for offshore use, and better upscaling algorithms for regional forecasts.

The ANEMOS project has also provided appropriate approaches to estimate on-line the uncertainty of wind forecasts. The adapted resampling approach based on statistics and fuzzy logic provides an estimation of the whole distribution of wind generation in the next hours as shown in Figure 1. Moreover, the project proposed new tools, such as risk indices based on ensemble weather predictions, able to predict the level of error for the next hours. The wind power uncertainty is also assessed using an optimal combination of various short-term prediction models or models fed by different NWP models. Direct quantile forecasts were developed[4] that directly (based on either a simple NWP input or an ensemble of NWP inputs) estimate the quantiles of the likely wind power distribution. The use of ensemble predictions has also been used to yield direct estimation of the quantiles of the predicted wind power[5]. Although the probabilistic approaches open up for an alternative to wind power forecasts, they have not been fully utilised by end-users yet.

ANEMOS has also developed an industrial strength plug-in architecture and platform allowing the integration with existing Energy Management Systems installed at utilities.

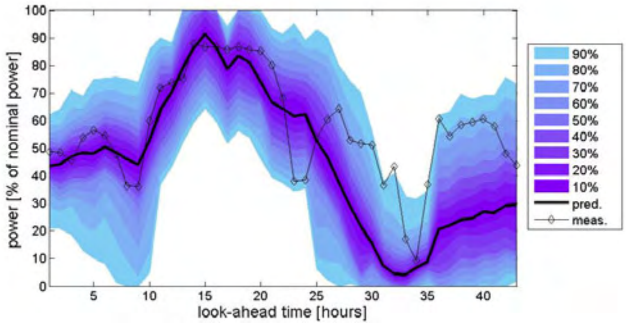

Figure 1: Example of forecasts for the next 48 hours compared to measured values. Prediction intervals for various levels of confidence are displayed. Intervals are estimated with the adapted resampling approach.

Management of Power Systems

Power systems are traditionally operated on a deterministic way. For instance, Economic Dispatch and Unit Commitment are based on accurate load forecasts considered to be perfect. Reserves are carried in case of a loss of generation. In spite of great advances in wind forecasting there are relatively large forecast errors that need to be managed. As wind penetration levels rise, these errors would dominate other error sources (i.e. load forecasting errors). Therefore it will be necessary to account for them inside the unit commitment and economic dispatch algorithms. Wind penetration levels at this time are only starting to have a major impact and the state of the art is to simply carry additional reserves. Quantifying these additional reserves is not trivial and considerable research work has been recently done in this field[6]. The challenge now is to integrate wind farm output forecasts and information on their uncertainty into the unit commitment and economic dispatch algorithms.

The use of storage capabilities provides an interesting approach to increase the profits of wind generation plants in electricity markets. The definition of the combined wind-hydro-pumping strategy leading to the maximization of trading profits needs wind power forecasts and market prices for the next hours as well as grid restriction information. Research work has already been developed in this field by using optimised approaches and techniques able to identify the operational pumping, wind-hydro generation strategy for each hour in a daily time horizon[9, 7]. This approach has been initially designed for a single cluster of wind parks together with a hydro pumping station and has latter been extended to several clusters of wind parks and several hydro pumping power stations in a network area.

The combined wind energy storage techniques can also be used to solve operational restriction related with congestion management in some network areas or to allow the integration of large amounts of wind generation in isolated grids, by storing wind energy during the valley hours and delivering it back to the grid during peak hours. Such a management always requires a wind forecast to deal properly with the available storage limits.

The assessment of the uncertainty in these forecasts plays here also an important role. Research works have also been developed to identify robust operational strategies regarding this issue. Namely Monte Carlo techniques have been used so far to deal with this problem. Results from the ANEMOS project have shown that uncertainties in wind predictions depend on several factors such as the terrain complexity, the meteorological conditions, the time of the year, the spatial and temporal resolution of the NWP system considered, the level of predicted power, the spatial smoothing effect of wind farms etc. By developing a synergy with the area of wind power forecasting in the frame of the ANEMOS.PLUS and SafeWind projects it will be possible to consider realistic information in these functions. This is a necessary condition to evolve towards operational tools.

A Virtual Laboratory to establish the state of the art

As development and operational use of forecasting solutions take more and more importance in the wind energy sector, the consortium of the European Coordination Action 'Prediction of Wakes, Waves and Offshore Wind' (POW'WOW) has taken the initiative of setting up a Virtual Laboratory (ViLab)[8]. The related objectives are to stimulate research efforts in this field, to tighten the collaboration between forecasters and forecast users, as well as to follow and communicate the state of the art in short term prediction of wind generation.

More and more research organizations and companies invest efforts in the development of operational tools for the short-term prediction of wind power production. The relevant and common forecast length of these tools is up to 48- or 72-hour ahead, corresponding to the needs of forecast users for management or trading purposes. A state of the art on wind power forecasting has been published by Giebel et al[9]. Such forecasting systems are fully recognized as a cost effective solution for an optimal integration of wind generation into power systems. TSOs, wind farm operators, and traders among others, usually rely on a unique or on several forecasting systems for making optimal decisions.

In the frame of the European Coordination Action 'Prediction of Waves, Wakes and Offshore Wind' (POW'WOW, see *powwow.risoe.dk*) an initiative is undertaken consisting of setting up a Virtual Laboratory (ViLab) for the evaluation of state-of-the-art prediction methods and systems, in addition to stimulating collaborative research in the field of wind power forecasting. It can be seen as a follow-up of the benchmarking exercise carried out in the frame of the European project ANEMOS, in which more than 10 prediction systems have been evaluated on a variety of test cases with different terrain characteristics and wind climatologies, see eg. [10].

By setting up the ViLab, the main scientific and technological objective is to promote the evaluation of operational methods and systems for the short-term prediction of wind generation in order to follow and stimulate the advances in this area. Since wind predictions provided by meteorological offices are the principal input used by the various prediction methods, it is also crucial to evaluate the quality of the wind forecasts used as input. A second objective is to disseminate results that can help the wind energy sector to have a better appraisal of the state of the art in short term forecasting. Through the ViLab, forecasters will have the opportunity to test their models on wind farms representing a set of representative environments and forecasting conditions, for which a large quantity of high quality data would be made available. They can also compare the performance of their prediction models against other participants. This will permit to identify advantages and drawbacks of rival methodologies and to point towards the necessary scientific and technological developments in the field. Another advantage for these participants is to be included in the dissemination actions of the POW'WOW project eg. web page, presentations, workshops, etc.

The essential dates for the ViLab benchmarking exercise are the 1st June 2007 for its starting data, and the 30th April 2008 as the deadline for the forecasters participating in the ViLab to provide their final results. A commitment of the POW'WOW consortium will finally be to compile, analyse and communicate these results, in parallel to defining directions for further research in wind power forecasting.

Scientific and technical objectives of ANEMOS.PLUS

The ANEMOS.PLUS project aims to bring to the day-to-day practice of key end-users (such as TSOs, Utilities, Independent Power Producers, Energy traders) advanced tools in order to help them managing wind power in an optimal way. Demonstration cases with already high wind penetration are selected in order to have a realistic environment to prove the viability of the proposed new technology. The scientific and technical objectives of the project are described hereafter:

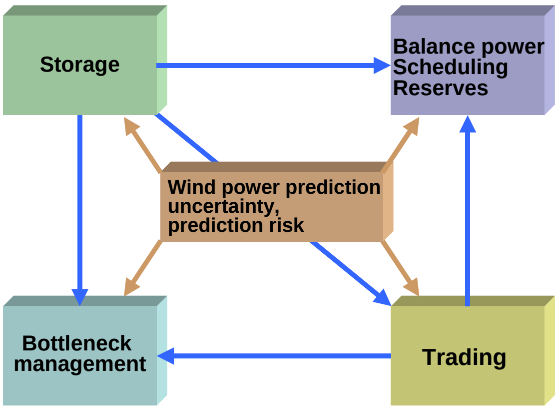

Figure 2: *The ANEMOS.PLUS project aims to enhance the synergy between wind power forecasting and power system management functions.*

1. **Reliability, Ergonomy and Monitoring in Wind Power Forecasting. Embedding into the energy data management and the planning procedures used by grid operators, power plant operators and energy traders.**

Experience with the operation of hybrid wind power prediction systems shows that end-users require:

- Highly accurate forecasts
- 100% reliable delivery of forecasts
- full compatibility with energy management systems
- smooth embedding into decision procedures

The first item has been thoroughly addressed by the FP5 ANEMOS project where a considerable research effort has been put into the improvement of wind power predictions. The remaining items are of equal importance to meet the high standards of operational availability commonly used in the energy industry. Especially reliability is compromised by various factors such as the availability of communication with SCADA systems providing input measurements, the availability of NWP provided by weather services, the reliability of the computing infrastructure etc. The ANEMOS.PLUS project will focus on the development of techniques permitting to detect such situations and restore missing information using rule-based intelligent approaches. The ergonomy and the transferability of the prediction systems in general, and of the ANEMOS pilot system in particular, will be studied in collaboration with end-users and the graphical user interfaces will be adapted accordingly.

2. **Operational probabilistic wind power forecasts and prediction risk for use in decisional processes.**

In the frame of the FP5 ANEMOS project various wind power prediction models were developed covering a wide range of end-user requirements. In the ANEMOS.PLUS project, the Anemos platform will be extended to integrate probabilistic models like models based on Numerical Weather Predictions ensembles. A priority is to extend uncertainty estimation tools for the case of regional forecasting for which no models exist today (uncertainty estimation focus on single wind farm predictions). This is a major requirement by end-users such as TSOs that manage regional/national grids.

The ANEMOS.PLUS project aims to provide operational modules for the "prediction risk indices" developed and evaluated in the frame of Anemos. These indices permit, together with power predictions and their intervals, to develop decision support tools to manage or trade wind power.

3. **Demonstration of new operational tools for intelligent power system management**

As mentioned above, the available deterministic software tools for the optimal scheduling of conventional power plants are not appropriate when considering an energy mix with high share of intermittent sources. Current Unit Commitment or Economic Dispatch algorithms consider wind as a "negative load" and foresee usually a fixed margin to account for wind variability. In cases of high penetration, operators often consider high reserve margins leading to a less economic operation of the power system. This reduces the benefits from wind energy.

The ANEMOS.PLUS project aims to develop and demonstrate new operational tools appropriate for the case of large-scale wind penetration for key power system management functions like unit commitment and economic dispatch. As mentioned above, the challenge now is to integrate wind forecasts and their uncertainty into these functions; to switch from wind "variability" towards wind "predictability". This will require a reframing of the objective. The state of the art is to maximise social welfare subject to the constraints, where a deterministic approach is taken. With large levels of wind power a more pertinent question will be to maximise the expected social welfare subject to the constraints both deterministic and stochastic. It is this last question that will require careful consideration in ANEMOS.PLUS.

In the demonstration case studies considered in the project, the developed tools will run operationally at the control centres and in parallel to the existing Energy Management Systems (EMS). The management tools of ANEMOS.PLUS will provide their output in a "consultative" way to the operators. It would be unrealistic to propose to replace the existing management functions in the existing EMSs. This can be potentially an objective after the demonstration phase of the ANEMOS.PLUS project. The monitoring of the ANEMOS.PLUS tools during the demonstration phase will permit to quantify the advantages of the new methods compared to the existing ones on a set of predefined criteria (robustness, cost of system operation, CO2 savings etc). The aim of the project is to improve the operational costs, fuel savings and CO2 savings by at least 10% compared to the actual EMS technology.

In this project emphasis is given in autonomous systems or systems with weak interconnection. In the first case belong the systems of islands where wind generation contributes to fuel displacement. In several European islands like in Greek ones (Crete, Cyclades etc), French (Guadeloupe, Corsica etc), Portuguese (e.g. Azores) and others, wind energy appears to be an attractive alternative to conventional generation. However, when it comes to large shares of wind penetration, which can be quickly attained in a small grid, it is necessary to assist operators in their management task through advanced prediction and scheduling tools. The case of the grids of Republic of Ireland and Northern Ireland-UK is also examined here. Both systems face increasing wind integration and the need for operational solutions to manage the combined system.

4. Advanced tools for managing secondary and tertiary reserves

In large interconnected grids with high wind penetration it is of primary importance to use wind power forecasts to estimate the necessary reserves required to operate safely the system and to meet demand. In practice operators apply the UCTE criteria for defining reserves. However, these are deterministic ones and do not take necessarily into account situations with large penetration from intermittent sources.

The work on the estimation of reserves and on wind predictability in the frame of this project is expected to provide useful input in the development of efficient balancing mechanisms by TSOs. The integration of large shares of wind generation requires an increase in the amount of reserves that are needed to balance generation and consumption according to the different time frames defined by the UCTE criteria.

Developing new techniques for the on-line definition of the reserve needs within each control area, taking into account the risk indices of the forecasts for each time horizon of interest, will be one the tasks of the project. A minimization of the reserve amounts needs to be developed taking into account the mentioned forecast risk indices. This will allow a decrease in the balancing costs that result from the integration of wind generation. Fuzzy techniques can be applied to deal with this problem.

A decision making tool able to deal with different risk strategies and risk aversion levels that the system operators may adopt, will be developed for the management of secondary and tertiary reserves. Hydro storage capabilities will be exploited for this purpose. It will be tested and demonstrated during the project in control areas characterized by large amounts of wind energy penetration (cases of Portugal / Spain).

5. Congestion management in large power systems as well as local grids

Areas with high wind potential are often areas with very low energy consumption. The medium voltage grids are not built for the transport of these enormous wind capacities. In high wind situations the limit of the grid capacity can be reached so that at certain grid points congestions can occur. Today wind power predictions are not used in load flow calculations or daily congestion forecasts. The standard practice is to enforce the grid by building new power lines and connectors based on the worst-case scenarios of maximum wind power production combined with low power consumption.

Often the erection of new grid lines is not realized due to high costs and, primarily, time-consuming building permits with planning periods of up to 10 years. This leads to curtailment of wind power production by shutting down wind farms on demand to ensure grid stability restricted connection of new wind farms to the grid in areas with frequent congestions

Connecting the wind power forecast to the load flow calculations will be the major task for an improved integration of wind power at this grid level. This will allow more realistic load flow predictions and increase the capacity of the grid.

The grid can be used more efficiently with a higher penetration of wind energy while at the same time the high security standard of the grid is kept. Consequently, grid enforcements and extensions can be minimised or even avoided. In addition, the assumption of a maximum wind power production together with a minimum load is unrealistic, e.g. storms occur mainly in winter where the load is typically higher than average.

Hence, the integration of intermittent wind power into grid management leads to:

- reduced curtailments of wind power
- allows for new wind farm installations (or repowering) in areas with high penetration

6. **Decision making tools for optimal trading of wind power in electricity markets with advanced strategies based on forecasts and prediction risk.**

A major application of wind power forecasts concerns the electricity trading by wind power producers participating in a liberalised market. Together with information on the uncertainty of the forecasts, strategies can be developed to reduce financial risks from imbalances induced by forecast errors. Imbalance costs reduce the revenues of wind farm owners, having a direct impact on the economic efficiency of their investment. Understanding the behaviour of wind energy actors in liberalised markets is also a key point important for TSOs. In fact, TSOs may conceive wind farms bids as forecasts for the next hours. However, such forecasts might be biased whether motivated by economic criteria and do not necessarily represent the best objective guess such as provided by weather forecasts.

The use of storage capability provides an interesting tool for trading wind energy in electricity markets, allowing the displacement of wind energy from low-load hours to peak hours where energy is more expensive. The definition of the optimum combined wind-hydro-pumping strategy needs forecasts about wind power generation and market prices for the next hours.

This project proposes to use an operational tool input by wind power forecasts and the electricity costs. It will provide to the power producers trading scenarios for the energy market (daily and intra-daily markets) based on alternative bidding strategies. These strategies will account for the uncertainty, prediction risk and storage options. The efficiency of each alternative strategy will be monitored as a function of the effective wind production, prediction errors, electricity prices and imbalance penalties.

7. **Implement tools for optimal management coordination of storage and wind power forecasting technology in managing wind intermittency.**

In grids with storage potential, wind power forecasts could be used for optimizing the assignment of different storage devices like hydro dams or pump-storages. In conventional systems, utilities perform storage coordination and planning (e.g. for dams) taking into account forecasts of the demand and of water inflows. Nowadays it is necessary to demonstrate how wind energy can be integrated in the process.

8. **An efficient methodology and advanced monitoring tools to quantify the benefits from large-scale wind integration.**

Wind energy is criticised at various levels. As an example it is mentioned that additional reserves, required to compensate intermittency, may result to higher CO_2 emissions. When it comes to large-scale wind integration and one has to modify well-established operation practices, there are impacts at different levels that are difficult to evaluate. The project aims to develop a detailed evaluation methodology to quantify the impact of wind integration in the various demonstration cases, i.e. in terms of CO_2 emissions, power system security, monetary benefits from fuel saving etc.

9. **Standardization of wind power output forecasting technology.**

Further standardization of the emerging wind power forecasting technology has to be carried out. Benefits for TSOs from using a standardized forecasting system output in view of exchanging information about wind production at a European level have to be evaluated (for example in the frame of UCTE).

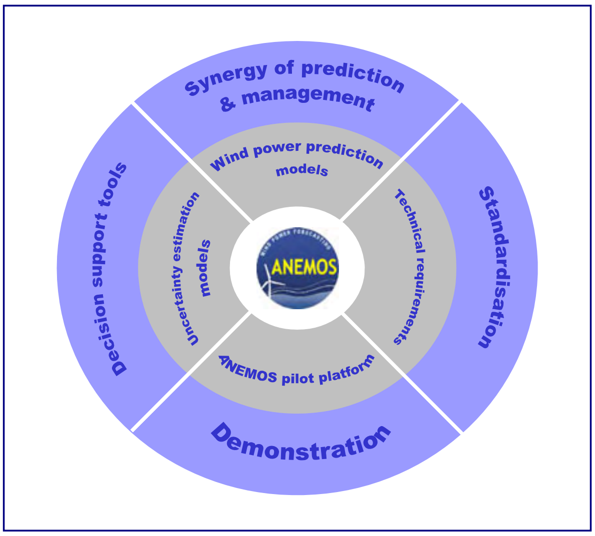

Figure 3: Added value of the ANEMOS.PLUS project.

The added value of the project compared to the current state of the art is shown pictorially in Figure 3. The project will contribute in maximizing the benefits of modern power systems from the use of wind power forecasts and appropriate management tools accounting for the wind intermittency. An advanced forecasting system will be fully integrated into the energy data management process of different utilities and optimized for practical use under the specific requirements of grid operation, power plant scheduling, and energy trading.

Two types of tools are designed: the wind power forecasting system and the management tools on a highly integrated approach welding together the worlds of fluctuating wind power and traditional energy systems. For reaching this goal, technical demonstrations are not sufficient. The use and integration of the needs and knowledge of daily users like operators and traders are key parts of this project.

SafeWind

While ANEMOS.PLUS is a project with a large demonstration and development part, SafeWind will go further into new fields of research. As already mentioned above, the integration of wind generation into power systems is affected by uncertainties in the forecasting of expected power output. Misestimating of meteorological conditions or large forecasting errors (phase errors, near

cut-off speeds etc), is very costly for infrastructures (both the turbines themselves and the electricity grid as a whole) and reduce the value of wind energy for end-users. The state of the art in wind power forecasting focused so far on the "usual" operating conditions rather than on extreme events. Thus, the current wind forecasting technology presents several strong bottlenecks. End-users urge for dedicated approaches to reduce large prediction errors or predict extremes at local scale (gusts, shears) up to a European scale as extremes and forecast errors may propagate in space and time. Similar concerns arise from the areas of external conditions and resource assessment where the aim is to minimize project failure. The aim of SafeWind project is to substantially improve wind power predictability in challenging or extreme situations and at different temporal and spatial scales.
The project concentrates on: using new measuring devices for a more detailed knowledge of the wind speed and energy available at local level; develop strong synergy with research in meteorology; develop new operational methods for warning/alerting that use coherently collected meteorological and wind power data distributed over Europe to early detect and forecast extreme events; develop models to improve medium term wind predictability; develop a European vision of wind forecasting taking advantage of existing operational forecasting installations at various European end-users. Finally, the new models will be implemented into pilot operational tools for evaluation by the end-users in the project.

Conclusions

Wind energy industry is a success story in Europe. This is to a large extent thanks to ambitious research programs undertaken in the last decades aiming to provide a reliable wind turbines technology and solutions for optimising wind integration in power systems. As wind penetration increases, new problems arise and require new solutions. This is highly recognised by the European Commission that supports actively projects such as ANEMOS, POW'WOW, ANEMOS.plus and SafeWind mentioned here. These projects deal with integration of wind energy in power systems and focus on improving wind predictability and increasing the value of wind energy. They try to put together researchers from various disciplines and countries in order to exploit synergies and move ahead the state of the art. Tightly integrated with the research is the exchange of knowledge with the industry through demonstration projects that aim to quantify the benefits of the innovations proposed.

Acknowledgements

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