ANEMOS Advanced Wind Power Forecasting. Operational Challenges and On-line Performance

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Abstract

A new integrated wind power forecasting system has been developed in the frame of the EU project ANEMOS. The system manages Numerical Weather Predictions (NWP) from different sources and alternative state-of-the-art Wind Power Prediction (WPP) models, producing an optimised forecast for each individual wind farm or clusters of wind farms. Forecast horizons can range from a few hours to a few days ahead. The forecasting system has been tested on-line in wind farms covering different environments in several countries in Europe. In this work the results of the first year of operational experience are presented. The paper focuses on the operational challenges and on benefits of the integrated multi-model approach versus forecasting by a single prediction model.

1. Introduction

The European project ANEMOS [1] has developed wide research on several topics related to wind power forecasting such as physical and statistical modelling, uncertainty estimation, upscaling and others. At a very first stage of the project it was recognized by both end-users and modellers the necessity for an exhaustive survey of the existing wind power forecasting technology both in terms of modelling approaches and also in terms of performances. The resulting state of the art on short-term wind power forecasting was described in [5].

In the course of the same project, a comparison of several state-of-the-art prediction models, described in [3] has been carried out in an off-line prediction exercise [5]. This exercise has been designed to cover different wind farms and also different modelling approaches (physical, statistical, combined). The test cases defined included complex terrain and relatively flat areas to take into account the effects of the topography; distance to the shore, different altitudes and climatic conditions. This was the first comparison of wind power prediction models that has been made at European level. The results were valuable information for the potential users of the prediction models about the typical ranges of error level, and the relation of the accuracy with the wind farm characteristics. It was shown that the accuracy of the wind speed and wind power forecasts highly depends on the features of the targeted wind farm as well as on the prediction model.

A major deliverable of the project has been the ANEMOS Wind Power Forecasting System, which aims to cover a wide range of end-user requirements. The System is modular and integrates several state-of-the-art models appropriate for single wind power forecasting or for regional forecasting, for uncertainty estimation as well as for a number of additional functionalities. Currently, the ANEMOS System is installed for on-line operation in several European countries (Greece, Spain, France, Germany, Eire, Denmark and United Kingdom), as well as outside Europe.

Despite the extensive literature in wind power forecasting, no detailed results are found for the performance of prediction models at operational conditions. Usually results are produced using historical data in an off-line ("laboratory") mode. In such exercises, the available data are usually filtered for erroneous values and separated into learning and testing sets for an objective evaluation. The installation of the ANEMOS System at different end-users in Europe has provided a wealth of data for evaluation. A first conclusion of this experience is that the evaluation under operational conditions becomes more complex than the case of off-line conditions. In this latest the conditions for obtaining the prediction results are ideal.

However, operationally, challenges concern the robustness of the prediction software and the models and especially as a function of the quality of data, which is very often an issue. I.e. data feed to the forecasting system may be interrupted due to a data acquisition (SCADA) or data transmission problems. The same can be for NWPs. In some situations, SCADA may be received with a delay. This is rather the rule with NWPs, which have a delivery delay that can be of several hours. In practice, operationally, the NWPs for the first 4-6 hours are never used. In fact the time of arrival of the NWPs is a random variable. In off-line evaluations in the literature such delivery delays have been never considered.

This paper presents a subset of the results obtained operationally in ANEMOS project including the earliest operationally integrated models within the System. For the sake of conciseness and confidentiality, only results from a few wind farms in Spain and France are presented here.

The on-line performances of the wind power models presented in this paper can be used as reference for evaluating other models. It is of interest the comparison between the off-line results presented in [5] and those in this paper.
The paper is organised as follows. Section 2 describes the selected wind farms. The ANEMOS System is described in Section 3. Section 4 gives the methodology that the authors followed for evaluating the model performance. The results of the wind power prediction models on the test cases are presented and analysed in Section 5. Concluding remarks are given in Section 6.

2. Selected wind farms

This Section describes the wind farms selected for this paper. As the objective of this on-line evaluation is to give the performance of the prediction models under typical wind farm locations, five test cases have been selected representing a wide range of terrain profiles and climatic conditions as well as wind farm configurations:

- Alaiz (very complex terrain, northern Spain)
- Sotavento (complex terrain, north-western Spain)
- Oupia (complex terrain, southern France)
- Saint Simon (flat terrain, northern France)
- Guerledan (flat terrain, western France)

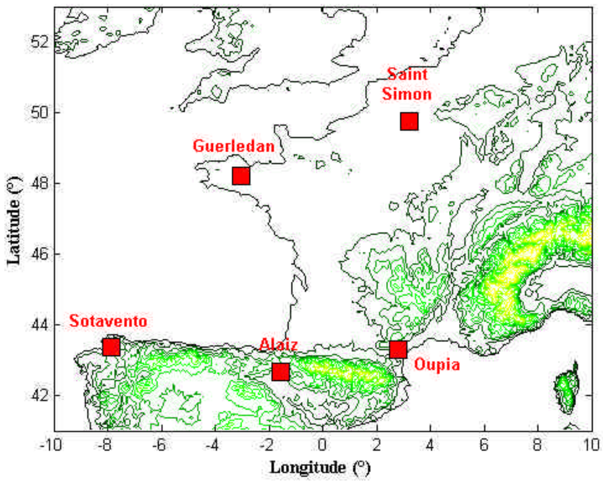


Figure 1: *Wind farm locations for the Spanish, and French test cases*

For each wind farm the roughness index RIX is estimated to denote the terrain complexity. This index is the ratio of the slopes greater than 30 % in a radius of 10 km surrounding the targeted wind farm. The terrain elevation data are extracted from interferometric Synthetic Aperture Radar measurements at 30 m resolution and are available on-line at [2]. The greater the RIX is, the more complex the targeted site is.

- **ALAIZ wind farm** (Spain) is located 15km South of Pamplona in the Navarra region in a very complex terrain 910 m – 1120 m Above Sea Level (ASL). Alaiz is a large wind farm with a rated capacity of 33.09 MW and composed by 49 GAMESA G47/660 wind turbines and one NEG-MICON LW50/750 turbine.

- **SOTAVENTO wind farm** (Spain) is located in the Galicia region in north-western Spain at 592 m AGL at approximately 40 km from the Atlantic Ocean in a semi-complex terrain. Sotavento is an experimental wind farm consisting of 24 wind turbines provided by heterogeneous manufacturers: NEG-MICON NM48/750, NEG-MICON NM52/900, ECOTECNIA 44/640, BONUS 1300, GAMESA G47/66, BONUS MK-IV 600, MADE AE46/660, MADE AE61/1320. The rated capacity of Sotavento wind farm is 17.56 MW.

- **OUPIA wind farm** (France) is located in the Languedoc-Roussillon region bordering the Mediterranean in Southern France. Whereas the wind farm is located at the top of a gentle hill at 273m ASL, the site can be considered as quite complex since the wind farm experiences strong orographic winds (called the Tramontane and Autan) that take a complex structure in a marine environment. The wind farm consists of 9 NEG-MICON 52/900 wind turbines. The rated capacity of the Oupia wind farm is 8.1 MW. *

- **GUERLEDAN wind farm** (France) is a small wind farm located in the Brittany region in Western France in a low complex area at 290 m ASL. The wind farm consists of 5 VESTAS 52/850 wind turbines. The rated capacity of the Guerledan wind farm is 4.25 MW.

- **SAINT SIMON wind farm** (France) is located at the region of Nord-Pas de Calais in a flat terrain at 89 m ASL. The wind farm consists of 4 NEG-MICON 92/2750 wind turbines. The rated capacity of the Saint Simon wind farm is 11 MW.

Test case	Classification	RIX (%)
Alaiz	Highly complex	36.0
Sotavento	Medium complex	23.5
Oupia	Medium complex	20.9
Guerledan	Low complex	3.8
Saint Simon	Low complex	1.7

Table I: *Geographical characteristics of the wind farms selected as test cases.*

3. Description of the ANEMOS Forecasting System

In the frame 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.

The following wind power prediction and uncertainty models have been integrated and run today operationally in the platform (parenthesis indicate the developer) [1], [3]:

1. AWPPS (ARMINES/Ecole des Mines)
2. Combination Module (Univ. Carlos III of Mardid)
3. LocalPred (CENER)
4. NTUA model (NTUA/ICCS)
5. PC model (baseline)(ARMINES/Ecole des Mines)
6. Prediktor (RISOE)
7. Previento (energy & Meteo Systems)
8. RAL model (CCRLC/RAL)
9. Sipreolico (University Carlos III of Mardid/REE)
10. Uncertainy module (ARMINES/Ecole des Mines)
11. WPPT (ENFOR, IMM-DTU)

The above models 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, model combination, regional/national forecasting through upscaling techniques, on-line uncertainty estimation, probabilistic forecasts, risk assessment, multiple numerical weather predictions as input and others.

This paper considers only preliminary results from a subset of 4 models for medium-term wind power prediction. A complete analysis will be presented in future publications.

A number of added value models are also included in the platform. I.e., the ANEMOS-Analysis module that permits to assess the models performances in term of various statistical criteria (described in Section 5).

Static as well as dynamic information is managed by the use of appropriate databases. The platform is validated with different types of databases (i.e. mySQL or Oracle) and also different operating systems (i.e. Linux or Windows). Static information includes among others :

- the geographical information of the specific wind farm (wind turbine locations, topographic and roughness data);
- the characteristics of the wind turbines;
- description of the prediction models etc.

The dynamic or timeseries information consists of the on-line recording of :

- the wind turbine availabilities;
- the *in-situ* meteorological measurements;
- the numerical weather predictions;
- the predictions and their historical values, etc.

Both static and dynamic information can be accessed and visualised using advanced Graphical User Interfaces. 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 in a remote mode as a prediction service or be installed to run as a stand-alone application.

All interfaces, data formats and database structures are well defined and well documented. For the 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 or more servers at different physical locations for the same prediction tasks, with independent power suppliers and network infrastructures. These servers will automatically take over the tasks of data retrieval, production and delivery from one another if any problem occurs at one place. With this approach, we achieved a close to 100% availability of the prediction service.

The advantages of this platform for end-users include among others 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. A simple overview of the ANEMOS Forecasting System is depicted in Figure 2.

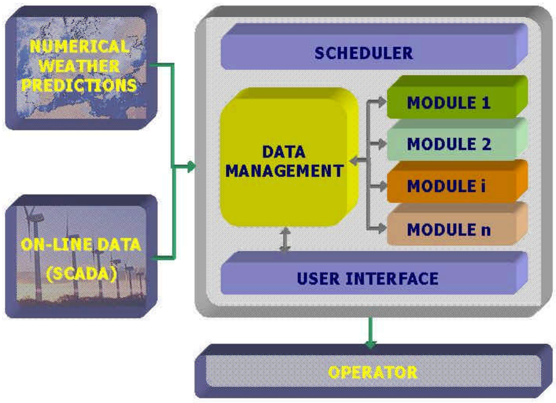


Figure 2: *Generic configuration of the ANEMOS Software.*

4. Evaluated model configurations

The ANEMOS Forecasting System can support various NWP and WPP models. In this paper, we present the results for 3 NWP models combined with 4 WPP models described below.

For the considered wind farms, the following NWP forecasts were used as input for the power prediction models:

- ALADIN (Météo-France, France):

0.1º grid resolution over France. The forecasts are updated at 00, 06, 12 and 18 UTC with a maximal horizon ranging from 36 to 48 hours.

- SKIRON/ETA model (IASA, Greece):

0.1º grid resolution over Southern Europe, domain centred in Greece. The forecasts are updated every day at 12 UTC with a maximal horizon of 120 hours.

- SKIRON/ETA model (CENER, Spain):

0.1º grid resolution over western Europe, domain centred in Spain. The forecasts are updated every day at 12 UTC with a maximal horizon of 72 hours.

The Wind Power Prediction (WPP) models considered here are:

- The **PC** model is a simple model based on the conversion of NWP wind speed forecasts to power using the theoretical power curve of the wind turbines. The PC model serves here as a reference or base-line model

- The **M1 model** is an advanced statistical model that performs a MOS correction in a dynamic and iterative way, being able to detect and remove systematic errors. It is specifically designed for complex terrain and is able to use the complete grid of NWP I addition to the closest grid point.

- The **M2 model** is based on a neural network approach.

- The **M3 model** is a statistical one based on auto-regressive techniques.

In addition, a combination module (named **COMBI**) is considered. This model is able to make a weighted on-line combination of the model forecasts minimizing the forecast error [6].

Finally, the **Persistence** model is considered as reference together with the PC model. Persistence considers the more recent wind power measurement as prediction for every horizon.

WPP models	Type	Driver for execution	Driver for maximal horizon	Time resolutior (hour)
PC	Phys.	NWP	NWP	1
M1	Stat.	NWP	NWP	1
M2	Stat.	SCADA	NWP	1
M3	Stat.	SCADA	NWP	1
COMBI	Stat.	WPP	NWP	1

Table I: *Features of the Wind Power Prediction (WPP) models considered here.*

Although in some test cases, the measurements are recorded every 10 minutes, the NWP and WPP models give the forecasts with an hourly resolution. In these cases appropriate averaging of the SCADA data is used. The execution frequency of the models is model-dependent: some models (PC, M1) are executed when the NWP forecasts are updated. The other models (M2, M3, COMBI) are executed when the *in-situ* measurements are updated (i.e. on an hourly basis). The maximal horizon of the models is also model-dependent. All these features are summarised in Table I.

It is worth to mention that models may run locally where the ANEMOS platform is installed or remotely, through Internet connection.

Test case	NWP	WPP (type of execution)
Alaiz	Skiron_ Cener, Skiron_IASA	PC (local) M1 (local) M2 (local) M3 (remote) COMBI (local)
Sotavento	Skiron_ Cener, Skiron_IASA	
Oupia	Aladin, Skiron_ Cener, Skiron_IASA	
Saint Simon	Aladin, Skiron Cener, Skiron_IASA	
Guerledan	Aladin, Skiron_ Cener, Skiron_IASA	

Table II: *NWP and WPP model configurations under evaluation.*

5. Evaluation methodology

In the ANEMOS project, an evaluation protocol was proposed [4] for standardising the wind power prediction models evaluation procedure. This protocol proposes guidelines and defines several statistical criteria for evaluating WPP models. In this paper, we have chosen three typical criteria to measure the performance of deterministic forecasts. They are:

- the normalised bias (NBIAS)
- the normalised mean absolute error (NMAE)
- the normalised root mean square error (NRMSE)

The normalising factor is the nominal capacity of the targeted wind farm.

In order to automatise the evaluation process, a dedicated module called ANEMOS-Analysis was developed. This module implements the various criteria proposed in the above-mentioned evaluation protocol. All the results given in this paper come from this module.

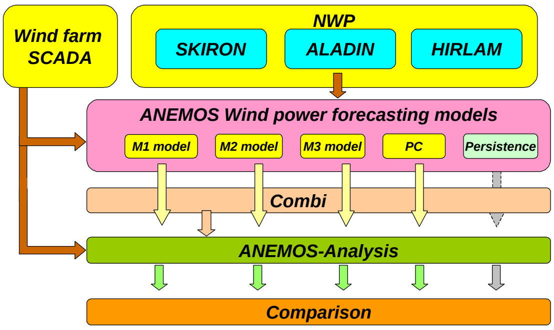


Figure 3: *Schematic representation of the data flow considered in this paper which starts with the delivery of the NWP forecasts and SCADA recorded on-site, the production of the WPPs, their combination and finally the visualization and evaluation of the forecasts.*

6. The on-line performances

This Section presents representative results of the evaluation of the operational models for the five targeted wind farms: Alaiz, Sotavento, Oupia, Saint Simon and Guerledan from September 2006 to May 2007. Although this period is inferior to one year, it includes the months with lower predictability.

In general in European climates wind predictability is higher in summer months. In this sense, the presented results are more pessimistic than if a whole year was considered. However, the relatively limited length of the evaluated sample of data explains part of the variable performance per horizon.

6.1 ALAIZ wind farm (Spain)

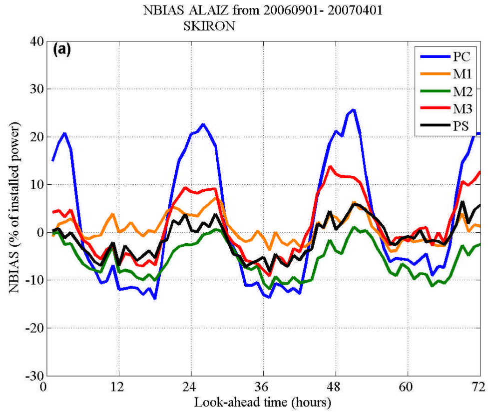
For the Alaiz test case, we present results from the prediction models using SKIRON NWPs as input. The evaluated models are the two reference models PowerCurve (PC) and Persistence (PS) and the three advanced models indicated here as M1, M2 and M3. The computed statistical criteria are the NBIAS, NMAE and NRMSE.

Figure 4-a shows the NBIAS per forecast horizon. It can be seen that while the simple PC model shows strong diurnal fluctuations coming from SKIRON forecasts, the other models reduce that fluctuation, especially M1. This reduction of NWP error is one of the main contributions of the statistical models.

Figure 4-b and -c show the NMAE and NRMSE criteria. Models M1, M2 and M3 outperform the simple PC model for horizons longer than 6 hours ahead, being M1 and M2 the most competitive models for those horizons. M2 outperforms Persistence for the first forecasts horizons.

In this very complex site M1, M2 and M3 reduce significantly the error of the simple PC model around to 10%, making evident the improvement of advanced prediction models vs a simple one. On the other hand, in this case, M1 and M2 give the best performance; however, the models are competing closely and depending on the horizon either of them may appear as best.

Finally, the same test case was considered in the off-line evaluation of 11 models presented in [5]. It is noted that the actual on-line results are better than the off-line ones partially also due to the improvement of the spatial resolution in the NWPs.



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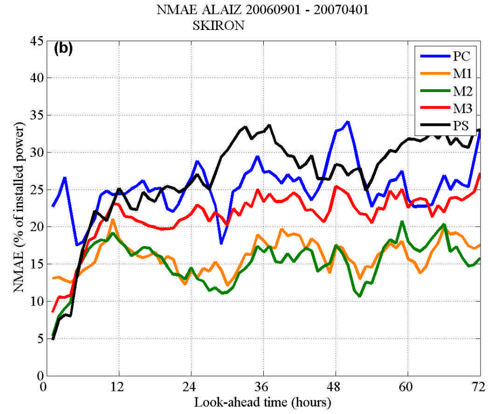

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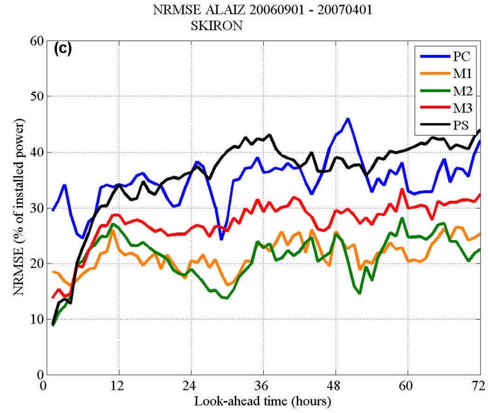


(c)

Figure 4: *(a) NBIAS (b) NMAE (c) NRMSE at ALAIZ from September 2006 to March 2007. The models are initialised using SKIRON NWPs as input.*

6.2 SOTAVENTO wind farm (Spain)

For Sotavento test case, we present results for two models initialised by SKIRON from November 2006 to May 2007 (Figure 5). The computed statistical criterion is NMAE shown in Figure 5. It can be seen that the level of errors is lower than that in Alaiz case. Models M1, M2 and M3 give a similar level of error for horizons between 6 hours and 24 hours, while for longer horizons M1, M2 and PC are more competitive. M1 gives similar performance than Persistence for the first 3 hours, while M2 is clearly better for horizons between 3 and 6 hours.

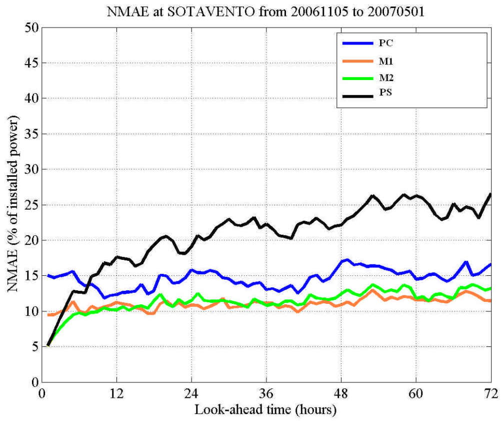


Figure 5: *NMAE at SOTAVENTO for WPP models initialised by SKIRON from November to December 2006.*

6.3 OUPIA wind farm (France)

For Oupia test case, we present results for four models initialised by SKIRON from October 2006 to January 2007 (Figure 6). The computed statistical criterion is NMAE.

The results show that the model M1 gives the best performance for horizons longer than 6 hours, while for the shortest horizons Persistence and model M3 produce the lower errors.

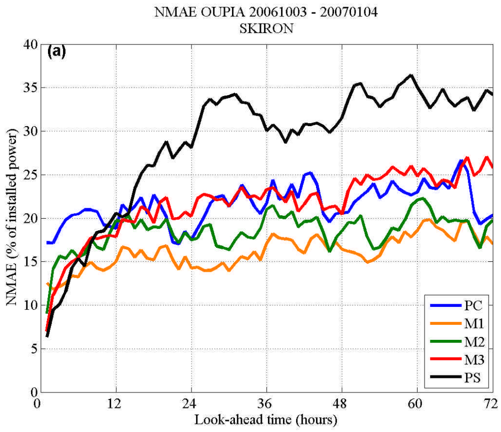
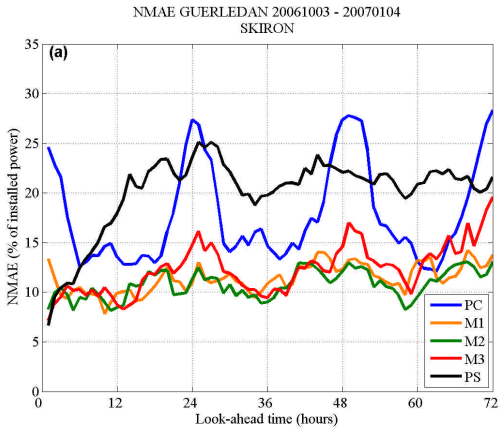


Figure 6: *NMAE at OUPIA for WPP models initialised by) SKIRON from October 2006 to March 2007.*

6.4 GUERLEDAN wind farm (France)

For Guerledan test case, we present results for four models initialised by SKIRON from October 2006 to March 2007 (Figure 7-a) and two models initialised with ALADIN from June 2006 to March 2007 (Figure 7-b) The computed statistical criterion is NMAE.

Figure 7 shows that for Guerledan wind farm the level of errors is significantly lower than in the previous cases, being the lower complexity of the terrain a determining factor. Figure 7-a shows a marked daily fluctuation of PC errors that is less significant in M1, M2 and M3 due to the contribution of the advanced models. For very short term horizons M2 and M3 give the best performance. Figure 7-b shows that M1 outperforms Persistence and PC model for all forecasts horizons.



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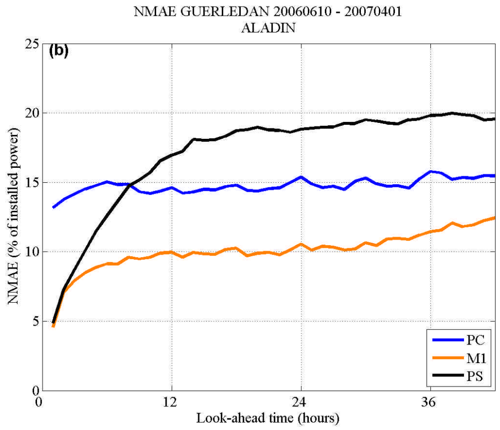


(b)

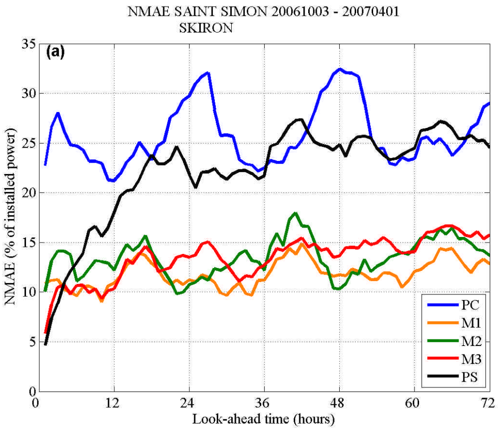
Figure 7: *NMAE at GUERLEDAN for WPP models initialised by (a) SKIRON from October 2006 to March 2007 (b) ALADIN from June 2006 to March 2007.*

6.5 SAINT SIMON wind farm (France)

For Saint Simon test case, we present the results for four models initialised by SKIRON from October 2006 to March 2007 (Figure 8-a) and two models initialised with ALADIN from July 2006 to March 2007 (Figure 8b). The computed statistical criterion is NMAE.

Figure 8-a,b show a significant reduction in the error level when comparing models M1, M2 and M3 vs PC model and Persistence for both SKIRON and Aladin NWPs. Figure 8-a shows that M1, M2 and M3 filter part of the diurnal component of the error and that the performance of the advanced models is similar without one appearing to outperform. For some forecast horizons M1 gives better results (between 50 hours and 72 hours ahead), while M2 and M3 produce the best predictions for other intermediate horizons.

Figure 8-b shows the performance of the PC model, Persistence, M1 and the ANEMOS-Combi model, using ALADIN NWPs as input. It can be seen that M1 outperforms PC model and Persistence for all forecast horizons, and that ANEMOS-Combi improves the performance of M1 for horizons longer than 3 hours ahead. The ANEMOS-Combi through the combination of the existing forecasts provides a new forecast that proves to be better than any of the three models except for the first three hours ahead horizons.



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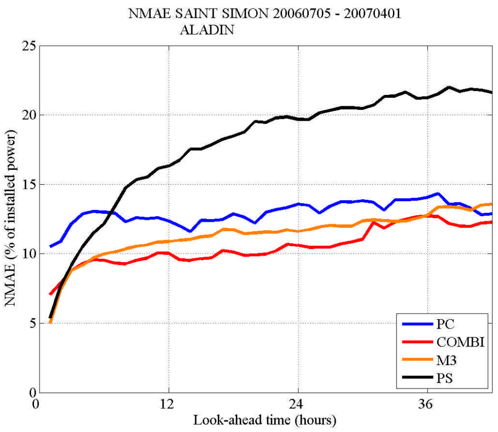


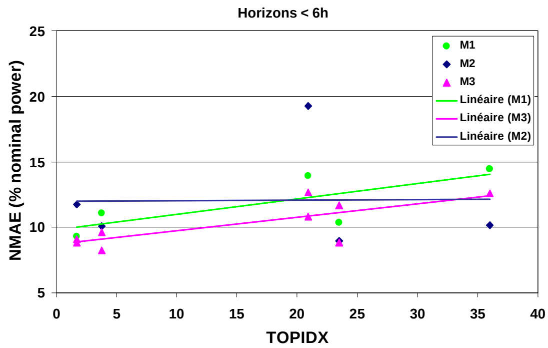
(b)

Figure 8: *NMAE at SAINT SIMON for WPP models initialised by (a) SKIRON from October 2006 to March 2007 (b) ALADIN from July 2006 to March 2007.*

7. Performance vs terrain complexity

Once the performance of the individual prediction models has been analysed, it is of interest to analyse the relation between prediction model performance and terrain complexity.

Figure 9-a shows that for very short term horizons, the model M2 has no tendency to increase the prediction errors when increasing the terrain complexity, while models M1 and M3 have a small tendency.



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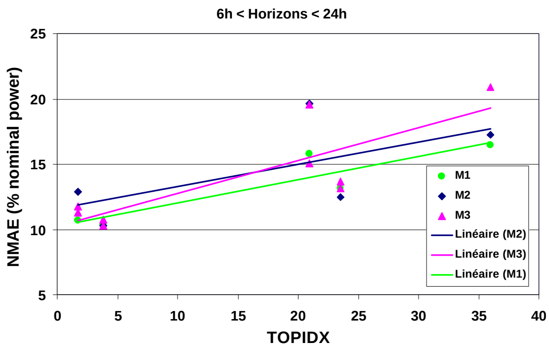

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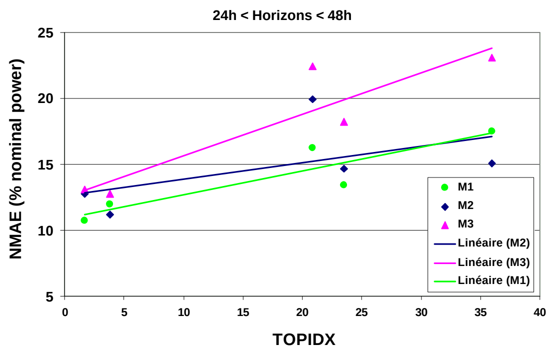

(c)

Figure 9: *NMAE vs TOPIDX index for (a) horizons < 6 hours, (b) horizons between 6 and 24 hours, and (c) horizons between 24 and 48 hours. For all the graphs dots represent NMAE for each studied wind farm, while "Linear" the linear trend for each model.*

Figure 9-b refers to horizons between 6 and 24 hours, while Figure 9-c to horizons between 24 and 48 hours ahead. They both show that prediction models M1, M2 and M3 increase the error level when the terrain complexity increases. However, M2 is less sensitive to the increase of the terrain complexity.

In general, the relation between prediction error and terrain complexity is less pronounced for horizons < 6 hours than for larger horizons. This result can be explained because the predictions for the very short-term horizons are mainly depending on the SCADA data.

For longest horizons, NWPs take a more relevant role and since NWP errors are related to terrain complexity (local features not solved) this dependence can be seen in the wind power forecasts as well.

The different design of the prediction models (M1, M2 and M3) implied a different response of each model to the terrain complexity. This feature shows that the studied prediction models can be considered complementary.

8. Conclusions

This paper presents results from three advanced models running operationally through the ANEMOS wind power forecasting system. Results from a selection of five wind farms in Spain and in France were presented.

The models are compared to simple models such as the PC model and also to Persistence. The main conclusions are the following:

- The ANEMOS Forecasting System has proven to be a reliable and powerful prediction system, being able to run operationally several prediction models including their combination. A multitude of configurations (NWP+WPP model) are set operational. In this paper a subset of the available results is presented, while a more complete analysis with the ensemble of models implemented will be published in the near future.

- The three examined models here are complementary from the point of view of performance.

- The advanced models are found to outperform significantly the simple PC model as well as Persistence, which are used as references. They can also generate forecasts with less diurnal variation in performance, minimising thus the errors coming from the NWPs.

- The combination model is able to provide improved performance compared to the individual models by combining their output forecasts.

- The complexity of the terrain affects the level of errors, increasing the prediction error with the complexity. This relation is more evident for prediction horizons longer than 6 hours ahead.

- The advanced models have different response to the terrain complexity, being this finding another proof of their complementary role inside of the forecasting system.

- The operational performances presented here are better or at least equal to the off-line results obtained at the ANEMOS Competition presented in [5]. This is the result of the methodology followed in the ANEMOS project to make the models operational and also to the characteristics of the prediction platform. In some cases like in the Alaiz one, the resolution of the NWPs increased since the time the off-line study in [5] was performed. This should be considered as another factor of improvement.

The evaluation presented in this paper constitutes part of the results obtained through the demonstration phase of the ANEMOS project. A number of additional models, NWPs and test cases have been also set-up operationally and are under evaluation.

Acknowledgements

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