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Abstract: Forecasters and forecast users have different views of what an extreme event is and how preventive information on these events should be communicated. The aim of this Task is to stimulate an exchange between meteorologists, wind power forecasters, and users of wind power forecasts, in order to define the extreme events of interest and to reach a common understanding of these events.

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Contents

List of Figures

1. Introduction

The scope of the SafeWind project mainly relates to the development, application and demonstration of new methods for extreme events for the wind power resource. Such extreme events may be defined at different spatial and temporal scales, and seen as issues for the questions of resource assessment, condition monitoring and structural design, or for the forecasting and management of wind power generation. In a first stage of the project, a crucial objective is to perform a survey among the various actors in the wind energy field in order to identify their perception of extreme events. This perception can be defined in terms of the way they identify extreme events, but also in terms of the potential consequences (and related costs) that can be associated to different types of extreme events. A result of this survey consists of the presentation of a catalogue of extreme events, which the present report attempts at giving an overview.

The methodology employed for the preparation of the catalogue of extreme events will be described in a first part. Briefly, it has been based on the distribution of a questionnaire (prepared by few project partners) to all partners involved in the project, and this regardless of their main background and activities. It is indeed important to see if meteorologists, forecasters, power system engineers, etc. have the same view of extreme events, or if actually the extremeness of an event is somehow defined by the background and field of activity of the various actors.

An overview of the answers received is given in a second stage, along with general comments on the views of the various actors on extreme events. This is followed in a third part by our proposal of a catalogue of extreme events. It first attempts at giving a unified definition of extreme events in view of the sensibilities of the various project partners who answered the questionnaire. It then proposes a classification of extreme events given their potential origins, their scale, and potential consequences. Their perceived importance with respect to their impact, consequences and costs is discussed. An extensive description of the various types of extreme events, their spatial and temporal scales, frequencies, as well as the foreseen format of solutions is finally given, based on a set of real-world examples.

2. A questionnaire for the definition and identification of extreme events

In this Section the methodology employed for the definition of the catalogue of extreme events is described. We go through the questionnaire used as a basis, question by question, and precise our expectations from each of these questions. A list of participants in various categories is also given.

2.1 Objectives of the Questionnaire

This questionnaire is to serve as a basis for the definition and identification of extreme events for all actors dealing with wind power management. This will then combine different time-scales (from few seconds to few days, to maybe years), and different angles. Indeed meteorologists, engineers, power system actors and economists have different views of what an extreme event may be. For instance, when meteorologists consider extreme events as events significantly deviating from climatology, a transmission system operator may give

more weight to the issue of system safety and security of supply, while finally traders may view an extreme as a dramatic loss due to a large forecasting error combined with high regulation unit costs.

2.2 Methodology

The questionnaire gathered a series of questions sorted so that they correspond to various views of what an extreme event can be. Broadly speaking, these views relate to meteorological, power system, economical and structural aspects. Each of the forecast users (wind farm and power system operators), and of the forecasters, should answer questions that are relevant for them. In parallel, it will be asked to give examples (if possible) of such extreme events as observed in practice. Given the responses and examples given by the various participants, generic definitions of extreme events will be proposed, along with a catalogue of situations corresponding to extremes in practice.

If going into more details about the questionnaire:

- The *first question* aims at defining *what an extreme event is*, for the various wind energy actors represented in the project, being forecasters or forecast users, meteorologists or involved with power system aspects.

The text for the first question has been formulated as:

“There may be different views of what an extreme event may be. A meteorological definition can be formulated as “an event that significantly deviates from climatology” (1). In contrast, a definition more focused on risk analysis would be “an event that potentially has dramatic consequences” (2).

Question 1: From your experience and your activity, which of definitions (1) or (2) fit best to your view of extreme events? If possible, please explain why…”

- The *second question* focuses on the idea of *categorizing extreme events*, ie. on defining broad categories of events which are seen as different extremes, either due to their origin, or to their potential consequences.

The text for the second question has been formulated as:

“During the SafeWind kick-off meeting, a first sorting of extreme events has been proposed, with the aim of reaching a first proposal definition. The 3 categories have been identified as:

- *Extreme (large-scale) meteorological events, including eg.*
    - *High wind speeds*
    - *Thunderstorms, tornadoes*
    - *Severe variability*
    - *Ramps*

- *Extreme (local) meteorological events, including eg.*
    - *Gusts*
    - *Wind shear*
    - *Turbulence*

- *Extreme power system events, including eg.*
    - *Phase errors (error in the timing of a ramp up or down)*
    - *Amplitude Errors (error in the magnitude of power production)*
    - *forecasting errors with extremely high costs*

Question 2: Do you agree with these categories, or would you consider some other categories of extreme events?"

- The *third question* concentrates on the *potential consequences of extreme events*. This is due to the fact that extremes should be associated to their 'cost' in order to define their importance in a risk-aversion point of view.

The text for the third question has been formulated as following. A Table was also provided for the various partners to perform the classification of the various extreme events in terms of their potential consequences

"Question 3: Please try to rank these 3 categories (and possibly newly proposed categories of extreme events) in terms of their potential impact on your activity, as well as the events included in each category. Ranking is from 1 to 5, with

- *1: 'Highly significant impact',*
- *2: 'Significant impact'*
- *3: 'Average impact',*
- *4: 'Low impact'*
- *5: 'Very low impact'"*

- The f*ourth question* aims at *listing all extreme events* that may be encountered (or feared to happen) by the various wind energy actors. The events collected from this question will permit to thoroughly describe and illustrate the various extreme events in the catalogue to be produced.

The text for the third question has been formulated as following. An example with related explanations was also provided

"Question 4: Please fill in the table below with a descriptive list of the type of events that are considered as extremes in your group/institute/company. The event listed may cover different time scales, and may be related to a meteorological event, or alternatively to power system or economical issues. This question obviously concerns more forecast users that forecasters. However, forecasters may fill this table from their operational experience with various forecast users.

An example is given in the Table below:

- *The column 'Type of event' gives a short description of the extreme event considered*
- *The column 'Time/spatial scale' tells on the time and spatial scale of the event considered. While gusts or extreme shear events relate more to a very-short time and local scale, forecast errors may have an importance in a time scale between few minutes to few days ahead and for entire region owing to their spatio-temporal propagation*
- *The column 'Frequency' informs on the known (or felt) frequency of such events. As an example, extreme wind speeds may be a rare extreme event in central Germany,*

while extreme wind shears may be frequent extreme events in complex terrain with windy climates

- *The column 'Consequences' tells on the potential consequences of the extreme event considered, which can be structural, related to wind farm or power system management, or finally economical*
- *The column 'Format of expected solution' gathers views on how future tools should evolve for better handling these extremes, and how those solutions should be presented. For some extremes, it may be felt that warnings are the best option, while for some others, it is new types of forecasts that should be provided*
- *The column 'Reasonable warning horizon/potential action' tells about how much in advance forecast users would like to be warned of potential extremes events, and the kind of action that would taken if those warnings were to be issued. "*

Example Table:

Type of event	Time/spatial scale	Frequency	Consequences	Format of expected solution	Reasonable warning horizon/potential action
Error in the timing of a front in the forecasts provided	few minutes to few days/ large scale (region)	frequent	Large imbalance to be compensated	More accurate timing of fronts in forecasts OR warning that such situations is likely OR uncertainty information in the timing of the fronts	30mins-3h ahead/ increase of standby backup capacity (reserves)

- The *fifth question* relates to the *possibility of studying (or not) those extreme events* from the data owned by the various project participants. Obviously, if no data is available for a given type of extreme event, it will be particularly difficult to define some test case in the future for dealing with this particular type of events.

The text for the fifth question has been formulated as:

"Question 5: For each of the extreme events listed above, please inform about the possibility of identifying them in some of your available datasets. Such datasets could then be used as a basis for the developments to be performed in the project. If possible, please insert plots that would permit to illustrate such events."

- The sixth *question* relates to the *possibility of identifying (or not) the costs of these extreme events* from the data owned by the various project participants. Identifying the cost function of the various forecast users will permit to study how the developments carried out within the project will lead reduction of the costs of extreme events for forecast users.

The text for the sixth question has been formulated as:

"Question 6: For each of the extreme events listed above, please inform about the possibility of identifying their costs or not. If not, please about which type of information would be necessary to define such costs in the future."

2.3 Participants

The questionnaire has been sent to all project partners. Response to this questionnaire was expected from:

- *End-users:* Acciona, Eirgrid, Energinet.dk, EDF, PPC, SONI, RTE (+ possibly TERI and CSIRO)
- *Meteorologists/Climatologists:* ECMWF, Météo-France, UCM
- *Wind power forecasters and consultants:* ARMINES, CENER, DTU.IMM, DTU.Risø, UC3M, University of Oldenburg, University of Oxford, OVERSPEED, NTUA, Energy & Meteo Systems

Note that TERI and CSIRO are partners which have been identified as having specific needs (eg. due to different climatic conditions). Their specific case is dealt with in a separate deliverable project report.

3. Analysis of the answers received from the SafeWind project partners

By categories, answers have been received for:

- *End-users:* 6 out of 7 (86%)
- *Meteorologists/Climatologists:* 2 out of 3 (66%)
- *Wind power forecasters and consultants:* 4 out of 10 (40%)

A reason for fewer answers from the wind power forecasters and consultants is that most of them had the idea they should not be the ones to define what extreme events are for the end-users. Indeed, their point is that what make an extreme should be defined by those in charge of the operation/management of wind power systems. It would have been beneficial however to receive more answers from these forecasters and consultants, as their experience may span more forecast users than those involved in the SafeWind project, who may have a variety of ways to use forecasts, work in different climatic conditions and within different regulation frameworks. Overall, the number of answers is satisfactory (12 out of 20 partners expected to answer, thus corresponding to 60%) and will permit us deriving the catalogue of extreme events described below.

4. A catalogue of extreme events

This Section is an attempt at introducing a comprehensive catalogue of extreme events. Focus is given to what define an extreme event, to categories of extreme events, their impact and potential consequences, etc. A detailed list of extreme events is given, with examples, while the possibility to study such extreme events is finally discussed.

4.1 Definition of an extreme event

One retrieve in the questionnaire answers the different focus of the various partners. On the one hand, meteorologists/climatologists tend to think that extremes are significant deviations from climatology (on wind speed for instance). In parallel, wind power forecasters have the feeling that extremes should be defined more in the sense of large prediction errors (due or not to meteorological forecast errors). Finally forecast users concentrate on their (potentially unknown) cost function, and see extremes as events with significant consequences (monetary or not).

In a general manner, it appears that the various actors concentrate on their own variable of interest, which can be the wind speed itself, local shear and turbulence, a forecast error, or a cost variable. Then, for such variable of interest, they define an extreme as a significant deviation from climatology. If taking the example of wind speed, extreme wind speeds may be defined as a wind speed superior to the 99.5% quantile of the available distribution of wind speed values. Similarly for forecast errors, extremes may be defined as errors in the very tails of the forecast error distributions. Finally for the cost variable, power system operators or traders for example may define some acceptable range of economic losses induced by wind power, and extremes as situations for which the perceived costs of wind power is significantly out of this range. Note that such definition of extreme events for the wind power application can then permit to accommodate the various sensibilities of the actors involved.

4.2 Categories of extreme events

Based on the answers from the various project participants, it has been agreed that extreme events for the wind power application could sorted in three categories. The different categories reflect the large-scale meteorological aspects, having a more global impact, the local meteorological aspects, mainly relating to structural aspects of (or accessibility to) wind turbines and wind farms, and finally the power-system view mainly focused on the consequences of certain events. Formally, these categories are defined as:

- *Extreme (large-scale) meteorological events*, including eg.
  - High wind speeds
  - Thunderstorms, tornadoes

- *Extreme (local) meteorological events*, including eg.
  - Gusts
  - Wind shear
  - Turbulence

- Local thunderstorms
- Local high temperatures, hail, large waves

- *Extreme power system events*, including eg.
    - Large forecasting error in numerical weather prediction (not an extreme meteorological event by itself), eg. error in track and/or intensity of pressure system
    - Phase errors (error in the timing fronts and of a ramp up or down)
    - Forecasting errors of reasonable magnitude with extremely high costs (not obviously due to the errors themselves)
    - Coincident events (drop in production + increase in demand)
    - Massive cut-offs over a geographically spread portfolio of wind parks, high wind speeds near cut-off translating increased risk of wind turbine high speed shutdown
    - Overestimation of production in winter at peak hours (expensive)
    - Severe variability of the wind power production, significant ramp rates

Note that even though events have been sorted in various categories, events listed in the first and second categories have a meteorological origin. In contrast, the events gathered under the category named ‘extreme power system events’ may have various origins (the meteorological conditions themselves, forecast errors, large potential costs or increased perceived risk). For that last category, it is mainly the consequences in terms of power system operation and management that define them as extreme.

4.3 Consequences of extreme events

Table 1 below gathers the three categories of extreme events listed above, as well as the list of extreme events listed under these categories. For each of these entries, it gives the average impact level of categories and events, the standard deviation of the answers (reflecting agreement), as well as the number of answers given (to give an idea of the support for calculation of these statistics). Remember the scale defined for the impact of extreme events, going from 1 for ‘highly significant impact’ to 5 for ‘very low impact’.

Table 1: *List and categories of extreme events, as well as their perceived impact level.*

Events	Average impact level	Standard deviation	Number of answers
Extreme meteorological events	**2.2**	**1.1**	**11**
High wind speeds	1.9	1.3	10
Thunderstorms	2.4	1.2	9
Extreme small/local scale events	**3.2**	**1.3**	**11**
Gusts (threatening turbine structure)	3.1	1.2	10
Wind shear	3.0	1.3	10
Turbulence	2.9	1.5	10
Thunderstorms/lightning strikes (directly on a wind farm)	2.5	2.1	2
Extreme temperature, hail, waves	2.3	1.2	3
Extreme power system events	**1.9**	**0.8**	**10**
Large forecast error in meteorological predictions (not necessarily a dramatic meteorological event),	1.3	0.5	8

eg. error in track and/or intensity of pressure system			
Phase error in wind power forecasts	1.6	1	8
Forecast errors of reasonable magnitude, but leading to high costs	2.1	1.5	7
Coincident events (drop in production + increase in demand)	2.1	1.5	7
Massive cut-offs over a geographically spread portfolio of wind parks - High wind speed near cut-off wind speed, translating to high risk of turbines shutdowns	1.8	0.7	8
Overestimation of production in winter at peak hours (expensive)	2.3	1.3	8
Severely variable wind power production, large wind power production ramp rates	2.9	1.5	8

One sees from Table 1 that the category of extreme events that is globally perceived as having the most significant impact is the ‘extreme power system events’ category. This certainly reflects the fact that most of the end-users in the panel are mainly interested in power system operation and management, thus ranking higher events that directly concern them. The other 2 categories, mainly focusing on purely meteorological aspects, are still seen as generally having an average to significant impact, even though increased variability in the answers indicate a higher level of disagreement among the panel of answers.

If going into details with the list of events in the ‘extreme power system events’ categories, there seem to be a large consensus on the fact that events with the most significant impacts are large forecast errors in meteorological predictions, thus directly translating to large forecast errors for wind power generation. In particular, phase errors (ie. Errors in the timing of events) are known to be a particular concern, since usually relating to large imbalances. Other extreme events in a power system point of view relate to the risk of cut-off events and to the actual occurrence of massive cut-off events: most of the answers agree on the importance of these types of events. In parallel, for the events ‘errors leading to high costs’, ‘overestimation at peak hours’ and ‘coincident events’, even though seen as generally having an impact, there is a certain disagreement among the panel, which is certainly due to the fact that in different systems with different generation mix, regulations, etc. such events may have different consequences, and may be more or less easily dealt with. Finally for the question of ‘severely variable production and significant ramp rates’, their potential characteristics may be influenced by the local wind climate and the spatial resolution at which the system is managed. In general, it seems that such events are of highly significant impact if not well predicted, but of average to low impact only if well-predicted. If having a broader view of the answers for the ‘extreme power system events’ category, they motivate developments towards better forecasting of cut-off events (in a probabilistic paradigm since risk assessment is crucial), as well as of events with severe variability or with significant ramp rates. The answers also indicate that forecasters should have a value-oriented approach to forecast improvement, since forecast users concentrate on the potential consequences and costs of extreme events.

4.4 A detailed comprehensive list of extreme events

The tables below give a list of example extreme events, for each of the categories considered, ie. extreme meteorological events, extreme small scale events, and extreme power system events. These example extreme events are characterized by their temporal

and spatial scales, their frequency, related feared consequences, and finally by the format of expected solution, reasonable warning horizon and potential action. In the following Section, illustrative examples are given for a few of these events, based on the actual experience of the forecast users.

Table 2: *A comprehensive list of extreme meteorological events.*

Type of event	Time/spatial scale	Frequency	Feared consequences	Format of expected solution	Reasonable warning horizon and potential action
Extreme events with large deviations from climate	Hours to days – Large scale	Less frequent	Impact on wind power production	Use of ensemble forecasts to specify the likelihood of the event	Very short range (1-6h) - Issue updated ensemble forecasts (or probabilistic forecasts), if new observations become available
Thunder-storms	Regional	2-3 / year	Short term supply-demand imbalance	Warning that such situations is likely	

Table 3: *A comprehensive list of extreme small/local scale events.*

Type of event	Time/spatial scale	Frequency	Feared consequences	Format of expected solution	Reasonable warning horizon and potential action
Extreme Turbulence	Minutes - Local	Low on an annual basis	Accumulates damage on wind Turbine generators. Increase costs of maintenance	Resolution solving of such small scale structures and signal warning when, clearly, such pattern behaviour is about to start. Establish a relation between a large scale situation and the occurrence of	A few hours in a first stage. Tending to increase the skill to D+1 (ie. next day).

				the small scale phenomena.	
Extreme Wind Shear	Minutes - Local	High on an annual basis	Idem	Idem	Idem
Lightning Strikes	Up to one second of total duration - Local	Medium on an annual basis	Direct strike on wind turbine generators or on other facilities within the wind park	Alert warning of thunder-storms.	A few hours
Lightening causing disconnections	Minutes (it only need to happen a few seconds in order to cause a fault) – Local	15-20 times a year. Some lead to disconnections and others not (ca. 5 severe events a year in Denmark). General information on Fault Statistics can be found on www.nordel.org and Energinet has information on specific events.	The connection will be disconnected. Action will depend on severity. The system may prepare for a disconnection and make sure that there are no additional faults.	Warning that this can happen and uncertainty information on the event	Warning can be from 30 minutes to as long as the forecast provides
Locally high temperatures causing a disconnection	1 to 12 hours - Local		Reduced capacity of the line	Warning that this can happen and uncertainty information on the event	Warning can be from 30 minutes to as long as the forecast provides
Wind causing galloping lines	Minutes (it only need to happen a few seconds in order to cause a fault / local	A couple of times a year	The connection will be disconnected. Action will depend on timescale. 3 days ahead there might be a warning of increased attention, maybe an extra workforce will be notified. A few hours before one might observe the lines on sight. Also the system may prepare for a disconnection and make sure	Warning that this can happen and uncertainty information on the event	Warning can be from 30 minutes to as long as the forecast provides

			that there are no additional faults.		
High speed shut down of wind turbines	From few minutes to few hours - Local	Depends on wind climate (from frequent in Ireland to fairly rare in Denmark)	Local area system instability, system stability, increased operational risk	Improved forecasting leading to – pre-emptive shut down and network reconfiguration - warning that such situations is likely	2-3 hours
Very low tempe-rature (<-30 deg C) yielding shut down of wind turbines (example of HydroQuebec)	From few minutes to few hours - Local	Depends on climate (certainly more frequent in Sweden and Canada than in South of Spain!)	Local area system instability, system stability, increased operational risk	Improved forecasting leading to – pre-emptive shut down and network reconfiguration - warning that such situations is likely	2-3 hours

Table 4: *A comprehensive list of extreme power system events.*

Type of event	Time/spatial scale	Frequency	Feared consequences	Format of expected solution	Reasonable warning horizon and potential action
Forecast errors of any meteorological event with the potential of generating a significant amount of wind power	hours to days, large scale	frequent	impact on wind power production	use of ensemble forecasts and/or improve forecast systems (medium-term)	Very short range (1-6h); issue updated ensemble forecasts, if new observations become available
Hourly forecast error higher than twice the average error at many wind farms, low mitigation of the error at the scale of the portfolio “France”	Current day and day ahead forecast Large areas in France	Around 10 % of the time	Potential large economic losses depending on the situation of the electrical system	Improved forecasts	-
Large	0 to 4 hours	Fairly rare	Increased	Improved	6 hours

increase in net demand (Decrease in variable generation + increase in demand)			operational risk – insufficient reserve margins	forecasting and decision making	warning
Amplitude error, either under- or overestimation	Few minutes to 2-day ahead - Local but more important on regional scale	Frequent	Large imbalances to be compensated, and insufficient reserve margins (if overestimation), or system instability and curtailment of wind power (if under estimation)	More accurate forecasts and uncertainty information (eg. probabilistic forecasts)	30-minute to 2-day ahead depending on the time-scale of interest. Potential action will partly be to reconsider reserves and for the longer time span to consider trading possibilities (if relevant).
Phase error	From few minutes to 2-day ahead - Both local and regional scales	Moderately frequent to frequent	Large imbalances to be compensated - Increased operational risk – Insufficient reserve margins	More accurate forecasts and uncertainty information in the timing of the fronts. Potentially warnings that such situations is likely	30-minute to 2-day ahead depending on the time-scale of interest. Potential action will partly be to reconsider reserves and for the longer time span to consider trading possibilities.
Large changes in aggregated wind power due to simultaneous wind variability at several wind farms	Several hours to one day, large scale	Fairly rare	Large imbalances to be compensated - Increased operational risk - Insufficient reserve margins	Identification of weather patterns which increase the risk of this event	12-24 hours
Unexpected large drop or rise in wind power (due to different meteorological reasons) – Ramp)	Few hours	Frequent	Large imbalance to be compensated	Forecast update, estimated duration of event	At least 1 hour prior to event
Significant deviation of predicted track of low	Few hours - Large scale (region)	Frequent	Large imbalance	Forecast update	At least 1 hour prior to event

Unexpected behaviour of low pressure system coming from Easterly directions	Few hours - Large scale (region)	Rare	Large imbalance	Forecast update	At least 1 hour prior to event
Incorrect prediction of fast decay/increase in intensity of low pressure system	Few hours - Large scale (region)	Frequent	Large imbalance	Forecast update	At least 1 hour prior to event
Incorrect prediction of drop in wind energy due to gap between low pressure systems	Few hours - Large scale (region)	Rare	Shortage of power/energy	Indication of level and timing	At least 1 hour prior to event
Incorrect prediction of large Ramp up/down around noon or near sunrise/sunset due to thermal stratification	Few hours - Large scale (region)	Frequent	Large imbalance	Forecast update with better timing and amplitude	At least 0.5 hour prior to event
Forecast dropped	1 – several days	Few times a year	No fresh (in few instances, none at all) forecast	More resilience	Automatic alerting by watchdog needed.

5. Illustrative examples for the catalogue of extreme events

5.1 RTE: high wind speeds and thunderstorms

The first set of examples relates to the experience of RTE (Gestionnaire du Réseau de Transport d'Electricité). Figure 1 illustrates a situation with high wind speed and high wind power generation, close or equal to the rated capacity. While one might think that such situation does not constitute an extreme, a wind farm or transmission system operator may not agree with that. Indeed, it can easily be that wind speed gets very close to the cut-off wind speed, or even fluctuate around this speed value, leading to regular cut-offs for few turbines, for a whole wind farm, or for a geographically spread portfolio. This can be clearly seen from Figure 1, where it seems that predicted wind speed is high enough so that wind power generation is at its nominal level, but not too high so that it would yield shut downs. However when looking at the measured power generation, one notices 2two very large drops in the wind power production (in the evening of the 10^{th} of March, and from the 11^{th} in the afternoon until the 12^{th} mid-afternoon). A warning on the possibility of such type of events

occurring, along with appropriate probabilistic forecasts, would clearly help both wind farm and transmission system operator.

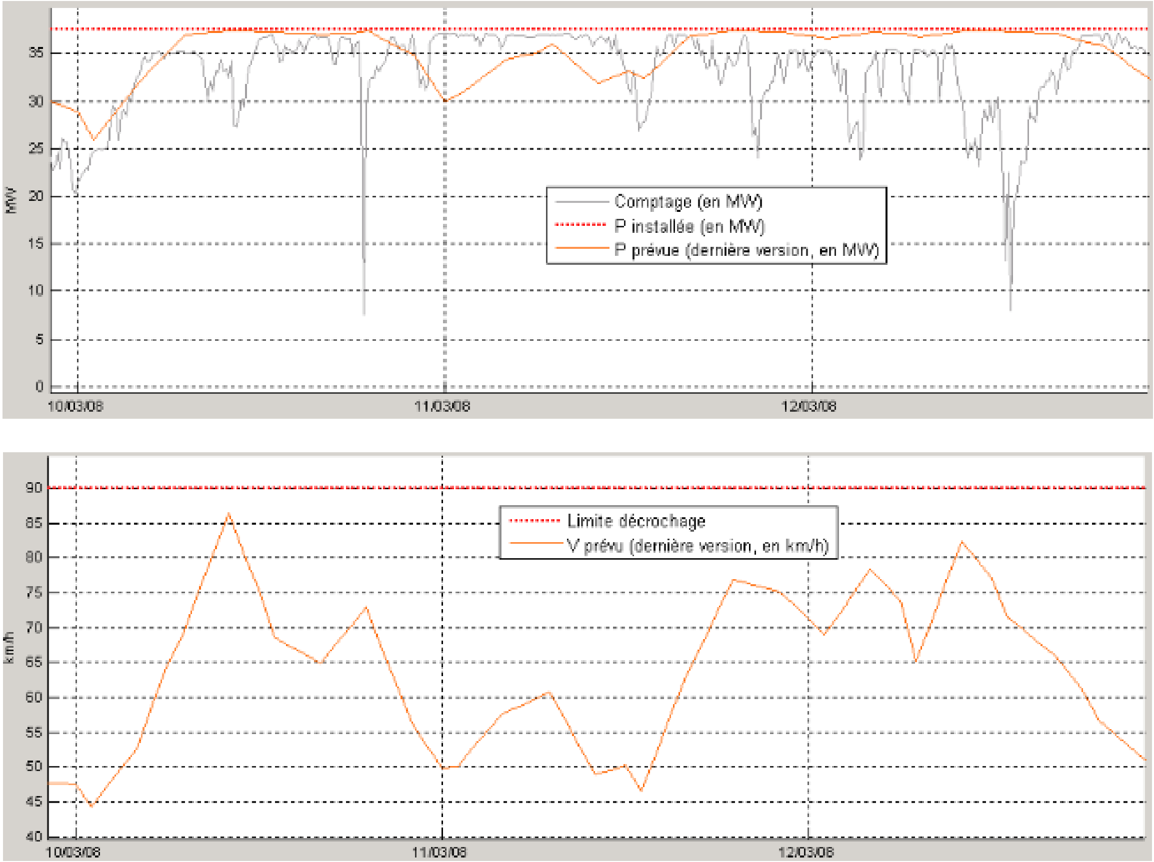

Figure 1: *Example of high wind speed situation for RTE, the Transmission System Operator in France (top: wind power generation; bottom: wind speed forecast)*

A second example for RTE concerns de case of thunderstorms (or very strong fronts) coming from the Atlantic Ocean, which leads to significant ramps in the wind power generation, that can be more or less well predicted. In the example of Figure 2, a strong front is hitting first the Brittany region, then covers the area going from Vendée to Normandie. A significant share of the wind power capacities installed in France are in these regions, and as a consequence this front yields a steady increase of wind power generation over the area, the ramp having a time-scale of almost one day. In this example, the ramp is quite well predicted, even though the final amplitude in power generation is underestimated. It may actually be for some forecast users rapid and/or significant ramps are a problem by themselves, while for some other ramps may not be that problematic, as long as they are well-predicted.

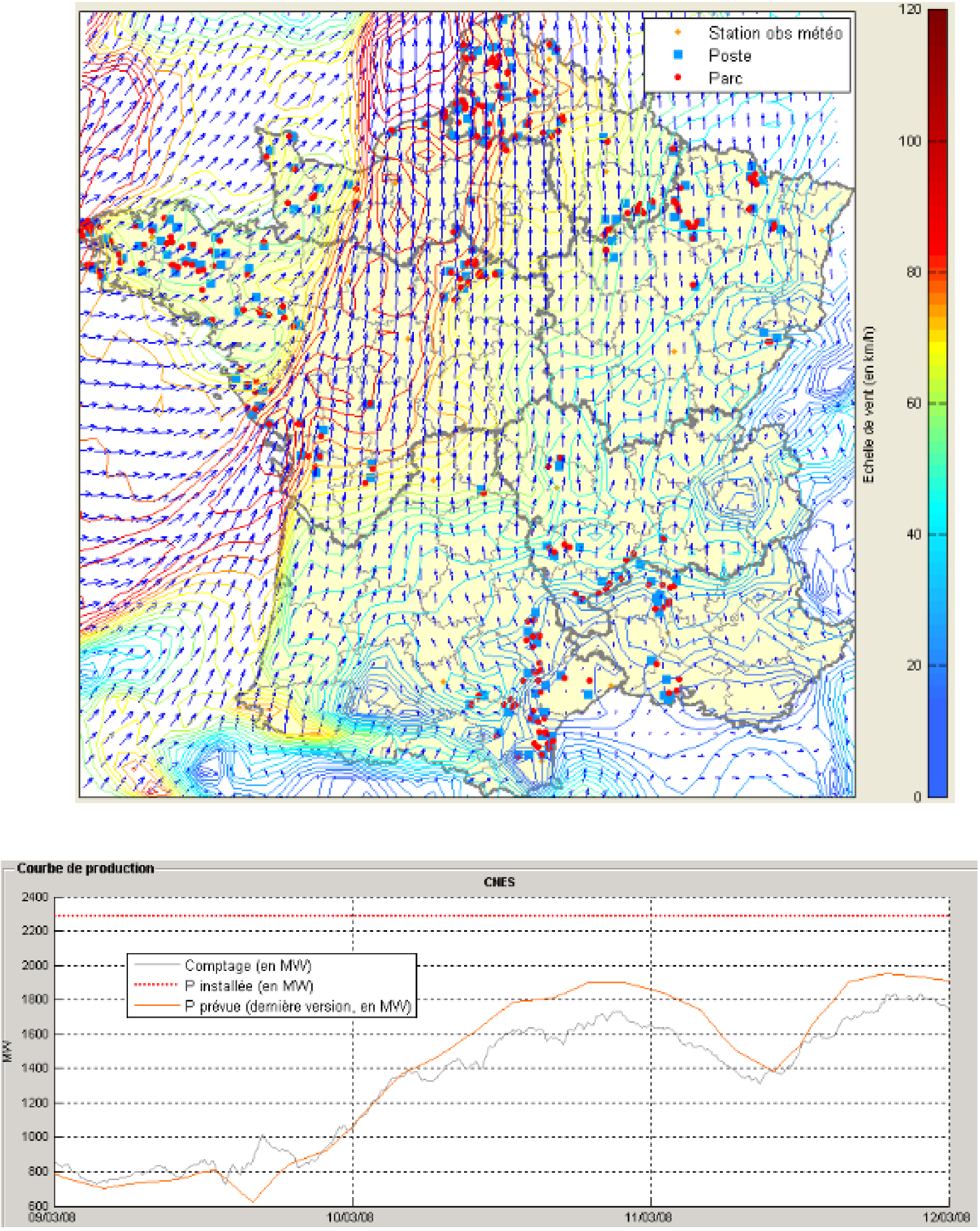

Figure 2: *Example of a large-scale front coming from the Atlantic Ocean and crossing France. This yields a significant increase in the wind power generation. (top: snapshot of the front over an axis between Vendée and Normandie – bottom: related increase in wind power generation)*

5.2 EirGrid: Amplitude and phase errors, coincident events, and turbine shutdown

Another set of example is for the case of EirGrid in Ireland. This country being located at the North-Western corner of Europe, it is in the most case the first one to be hit by strong

meteorological systems, with more risk of forecast errors both in terms of timing and amplitude of fronts, owing to fewer measurements available upwind. EirGrid therefore experiences a large number of events that can be seen as extreme both in the meteorological sense, or if focusing on their potential consequences for the power system.

A first type of extreme event that is regularly experienced by EirGrid is illustrated in Figure 3. While the forecast provided tells that a high power production close to nominal capacity is to be expected, the actual wind power generation observed is much lower due to massive cut-offs of wind parks over the country. This type of event somehow relates to that described in Figure 1 for the case of RTE, except that in Figure 1 a single wind park is involved, while in the present case this concerns the overall wind power generation for the whole country.

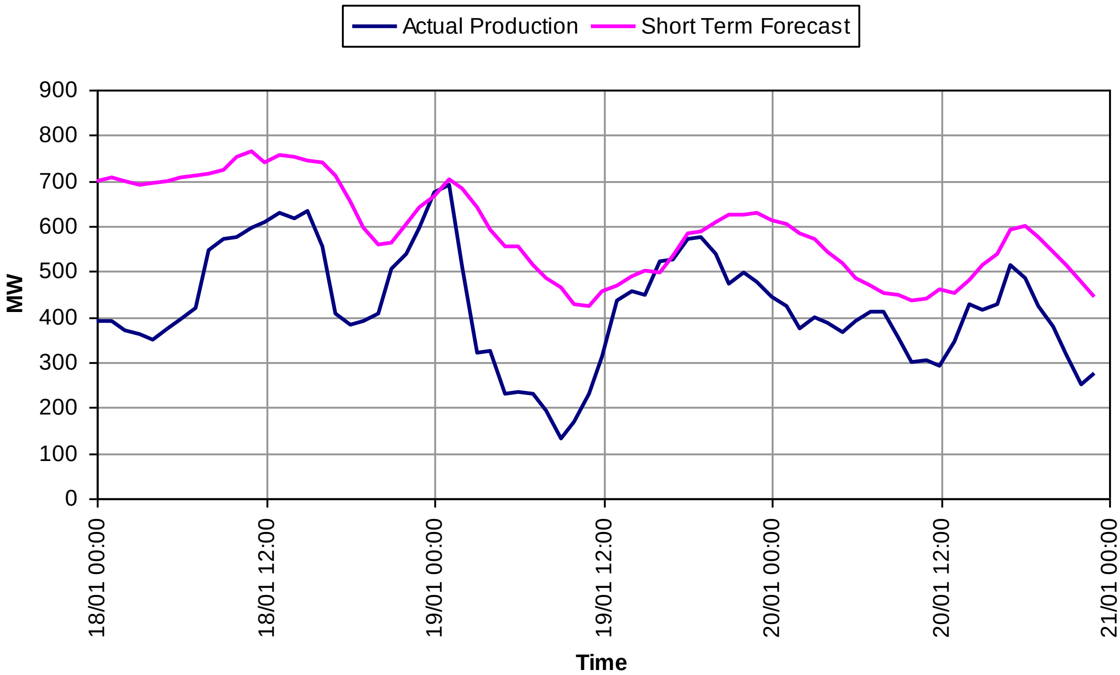

Figure 3: *Example of large forecast error (over estimate) due to high speed shut down of wind turbines on 18th January 2009*

In parallel, Figure 4 depicts a situation quite similar to Figure 2, i.e. a large-scale ramping event, here for the case of the whole EirGrid system. Similarly, the final level of wind power generation is clearly underestimated, but in addition here the timing of the front is also wrong. The sudden increase of wind power generation occurs 3-4 hours before what the forecasts stated.

A type of extreme event that seems to be quite specific to the case of Eirgrid is that for which a net increase in demand (typically in the morning) coincides with a significant (and more or less well-predicted) drop of wind power generation. An example situation is depicted in Figure 5, in which one sees that between 8:00 and 12:00, the system load increases from 2200MW to 3200MW, while the wind power generation drops from approximately 80% to 30% (of installed capacity). Such situations clearly increase operational risk and the need for additional reserve margins.

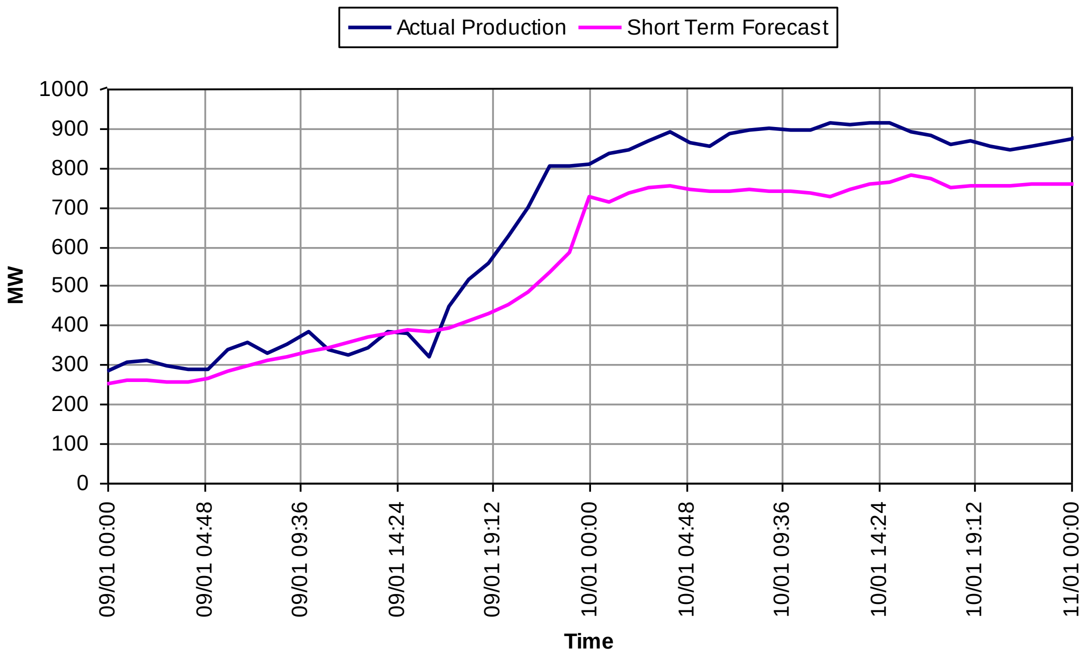

Figure 4: *Example of large forecast error on 10th January 2009. Both the amplitude and the timing of the front appear to be wrong.*

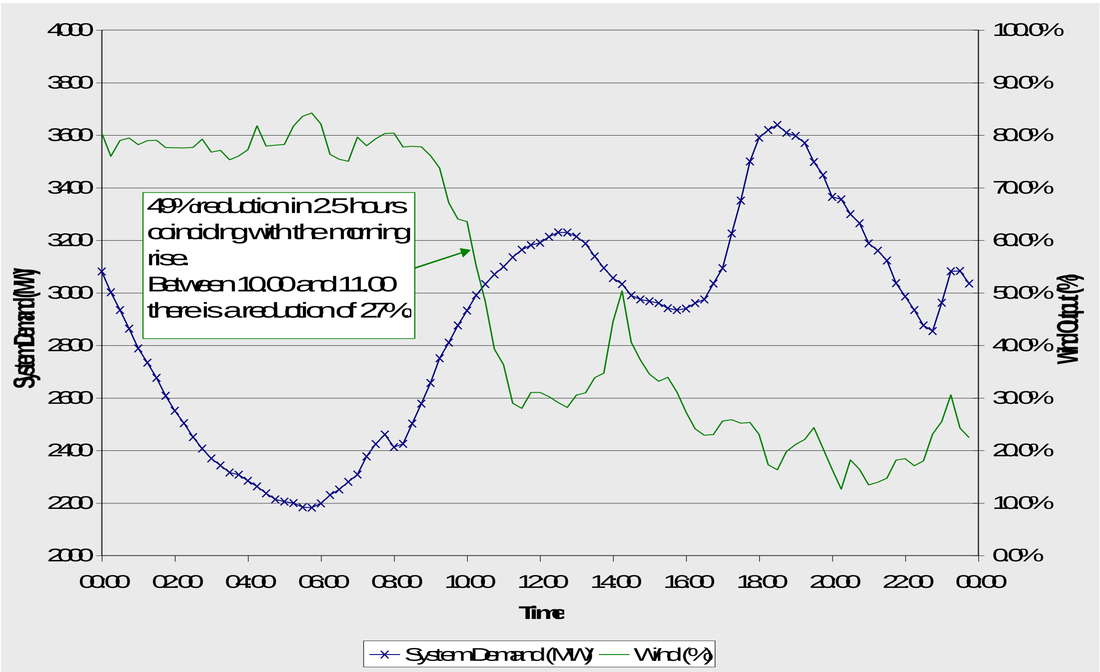

Figure 5: *Example of large net increase in demand caused by rise in demand coincident with decrease in wind production.*

A final example from EirGrid is a case of high wind speed shutdown for a given wind farm, which occurred on the evening of the 8th of April 2009. Figure 6 depicts the wind power

generation measured at a 15 minutes temporal resolution, in percentage of the wind farm nominal capacity, over a period of two days starting from the 8th April 2009 at 00:00. Figure 6 also shows the wind speeds recorded at the same time instants at four meteorological masts located at this wind farm. Over this 2 day-period, none of the meteorological masts showed wind speeds in excess of 25 m/s for the averaging period (15 minutes). The find farm reported 40% shutdown due to high wind in the evening of the first day. This means that only a portion of the farm was shutdown, also indicating localized high wind speeds.

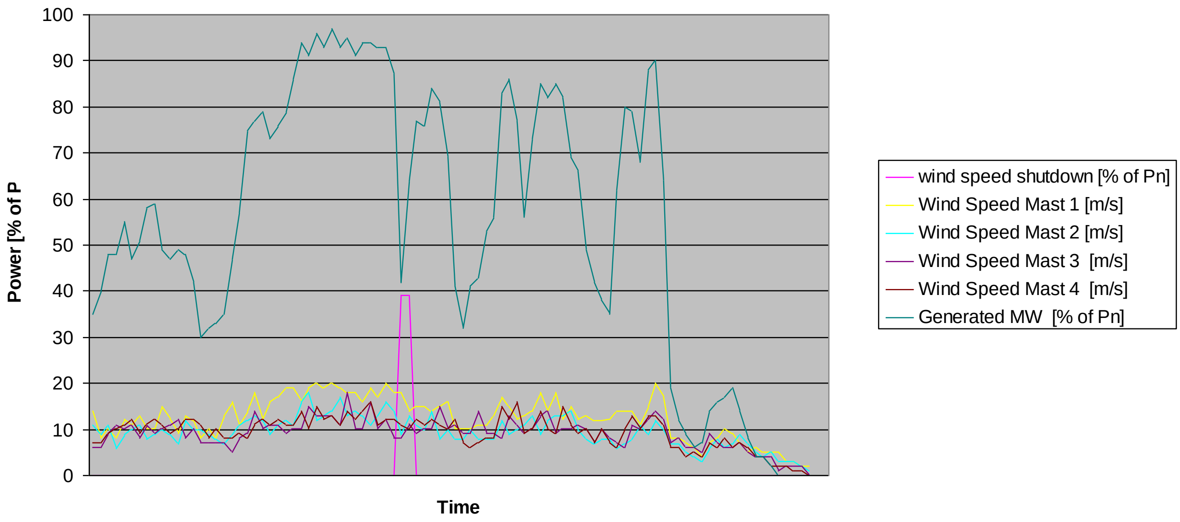

Figure 6: *Example of a high wind speed shut down on the 8th April 2009, for an Irish wind farm.*

5.3 Emsys: Incorrect prediction of low pressure systems, and effect of thermal stratification

Incorrect prediction of low pressure systems

Many forecast errors occur due to the wrong prediction of low pressure areas in the NWP data. It is possible to identify critical weather situations and certain types of forecasting errors in the NWPs that have a high impact on wind power forecasting:

a) significant deviation of predicted and observed track of a low pressure system
b) deviation between the predicted and the real intensity of a low pressure area
c) unexpected behaviour of low pressure systems coming from easterly directions
d) incorrect prediction of the drop in wind due to the gap between two following low pressure systems

(1a)+(1b) Wrong Track and Intensity

Very often forecasting errors result from the wrong prediction of the track or the intensity of a low pressure area. An example is the 22-23 January 2009 where a low pressure system developed South of Ireland and went over southern England to the North of Germany.

Figure 1 shows the pressure field of the 23/01/2009 12UTC ECMWF-Analysis and the tracks of the regarded low pressure system in the 6-hourly analysis field and the ECMWF-Forecast from 22/01/2009 00UTC. It is obvious that the track of the low is predicted further to the

South. What can't be seen in the figure is that the low developed faster than predicted and the low became much more intense than expected.

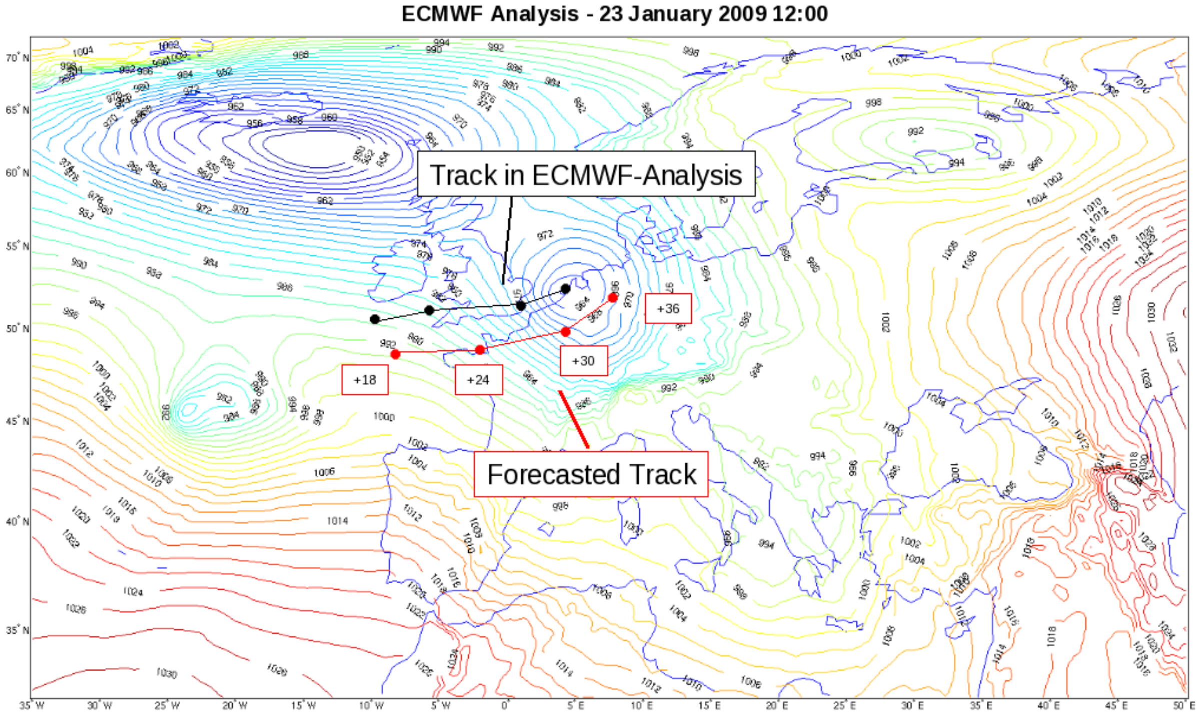

Figure 7: *ECMWF analysis at 23/01/2009 12:00UTC with tracks of the regarded low in the ECMWF analysis and the ECMWF forecast (base time: 22/01/2009 00UTC)*

Figure 8 illustrates the according wind power prediction of the ECMWF forecast and the measured power output of the German portfolio. It can be seen that the error in the NWP data leads to a forecasting error of 4GW in the 30-36 hour ahead wind power forecast.

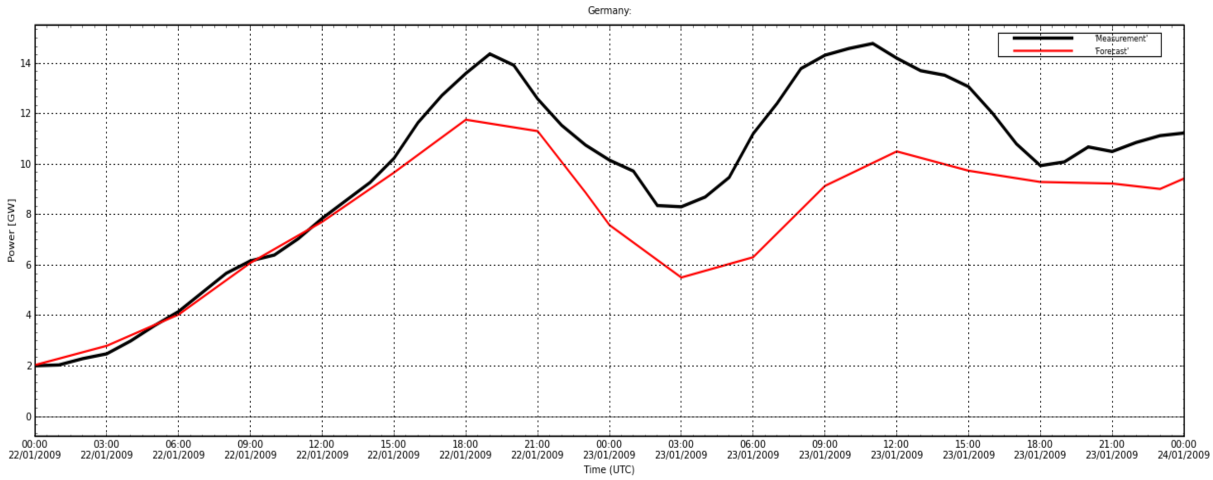

Figure 8: *According to Figure 7 the ECMWF-forecast (base time 22/01/2009 00UTC, red) and the measured wind power production (black) in Germany*

(1c) Unexpected Behavior of Low Pressure Systems Coming from Easterly Directions

Low pressure systems coming from easterly directions are not very common and mostly not well predicted by the NWPs. In such weather situations a forecast error of several GW can be detected very often in the German wind power portfolio.

In the example from the 13th of September 2009 a low pressure system over the Baltic Sea turns southwest to Germany and influences the wind power production in the northern and eastern part of Germany where most of the installed wind power capacity is located. Figure 3 shows weather situation at 06UTC (DWD Analysis 13.9.2009 06UTC) with the low over the Baltic Sea.

Below a combined forecast of several NWPs and the measured wind power production for the German portfolio is illustrated (Figure 4). Deviations of 1-1.5 GW can be seen especially between 8 and 16 UTC when the low pressure system from the Baltic Sea influences the power production in Germany.

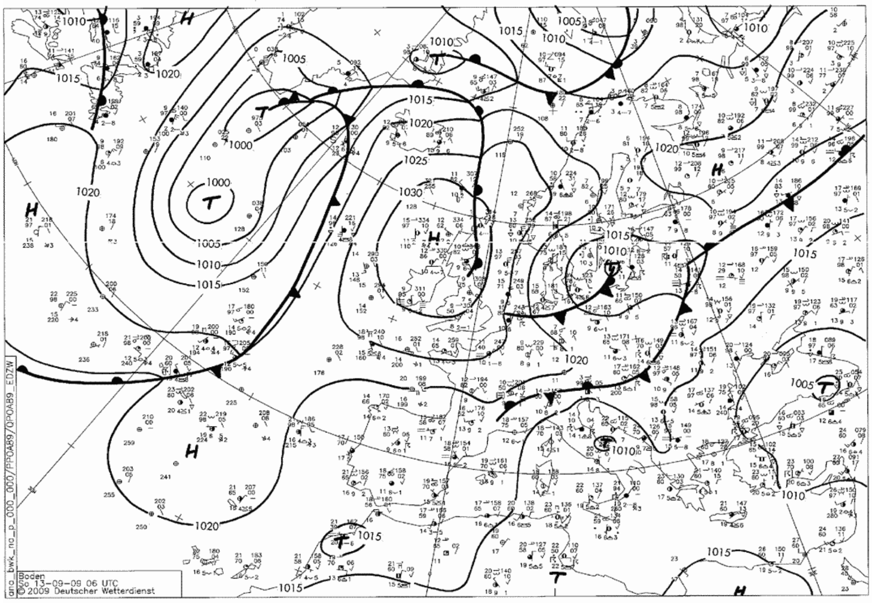

Figure 9: *DWD Analysis 13-09-2009 06 UTC*

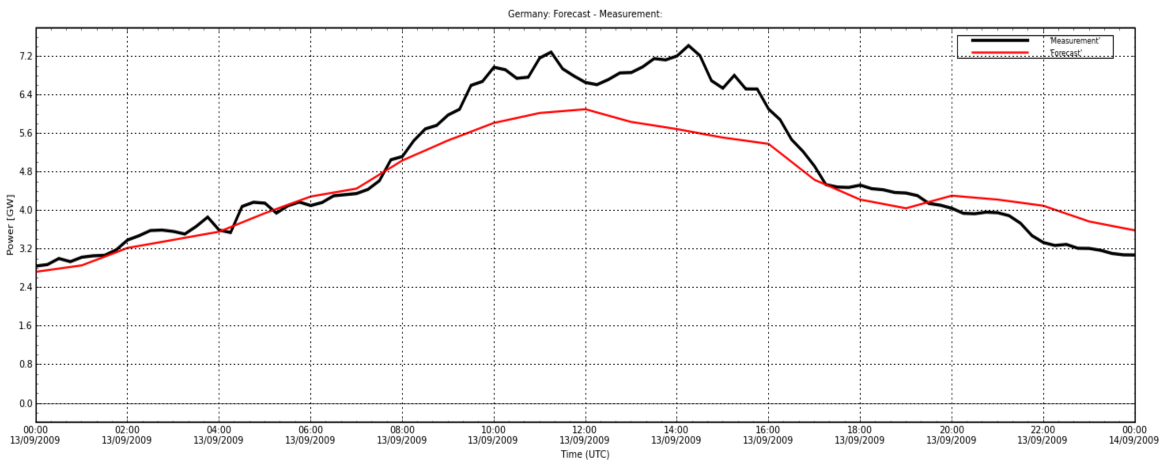

Figure 10: *According to the weather situation in Figure 9 the 24-hour forecast (base time 13/09/2009 00UTC, red) and measured wind power production (black) in Germany*

Thermal Stratification

The thermal Stratification of the atmosphere in high pressure areas leads to a strong daily pattern in wind power production. The timing of the ramps is connected to the time of sunrise/sunset and normally well predicted. But although the power output is limited to a very low level an amplitude error of 500MW is frequent.

Figure **11** shows the intra-day forecast for every day and the measured power output of the German wind power production from 29/6/2009 – 4/7/2009. Although the daily pattern is captured well by the forecast especially amplitude errors occur quite often.

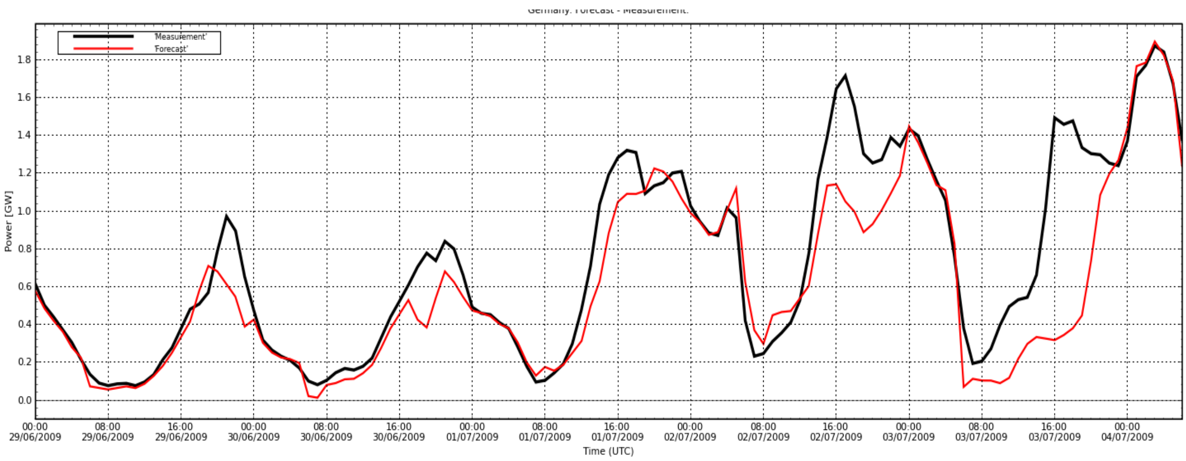

Figure 11: *Intra-day wind power forecasts from 29/06/2009 00UTC to 04/07/2009 00UTC (red) and the measured power output in Germany (black)*

5.4 Energinet: Phase errors

Energinet has concentrated on 2 types of extreme events related to the weather, and actually possesses a database containing all incidents related to the grid. That is a list of all disconnections, their reason and other circumstances. An annex report has been prepared by Energinet, which details and analyses a number of extreme events, including galloping lines, as well as a number of phase and amplitude errors. Energinet performs monthly evaluation of their forecasts. For the example of December 2008, there were a couple of amplitude errors but no severe phase errors. Note also that earlier examples of bad forecasting errors had been reported in eg. the state-of-the-art report written for the EU project Anemos.plus[3], in set of examples nicknamed “The good, the bad and the ugly”

If we shall find the phase errors we need to specify criteria, it could for example be 26th November 2008, as shown in Figure 12. The forecast for day ahead is the brown one and the online measurement is the red one. The forecast is responsible for large imbalance around 6:00-9:00. Another example is that of the 5th October 2008 (in Figure 13), for which the forecast produced on 4th October 2008 is shown. It does not look too bad although the phase in the morning is about 1½ hour too early, which here causes imbalances of about 300 MW.

[3] G. Giebel, et al. The state of the art in short-term wind power forecasting –A literature overview, 2nd Edition. Deliverable Report for the EU project Anemos.plus (D1.1), 2009

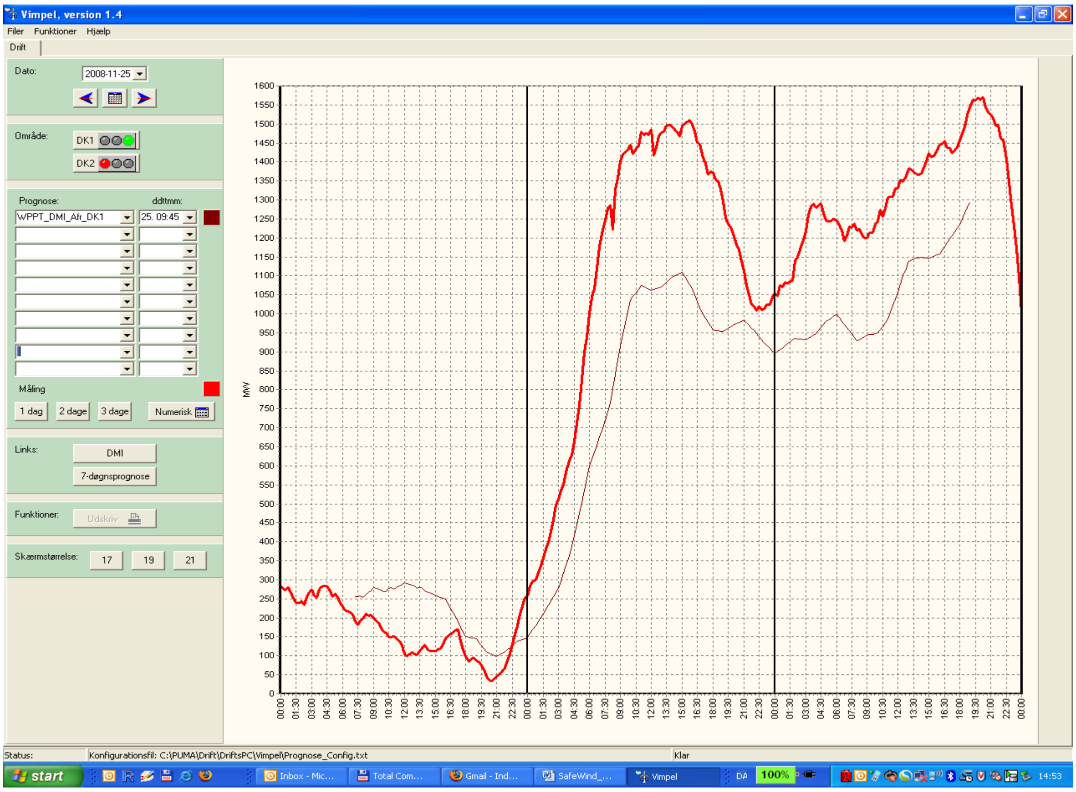

Figure 12: *Example of a phase error for the DK1 area on the 26th November 2008*

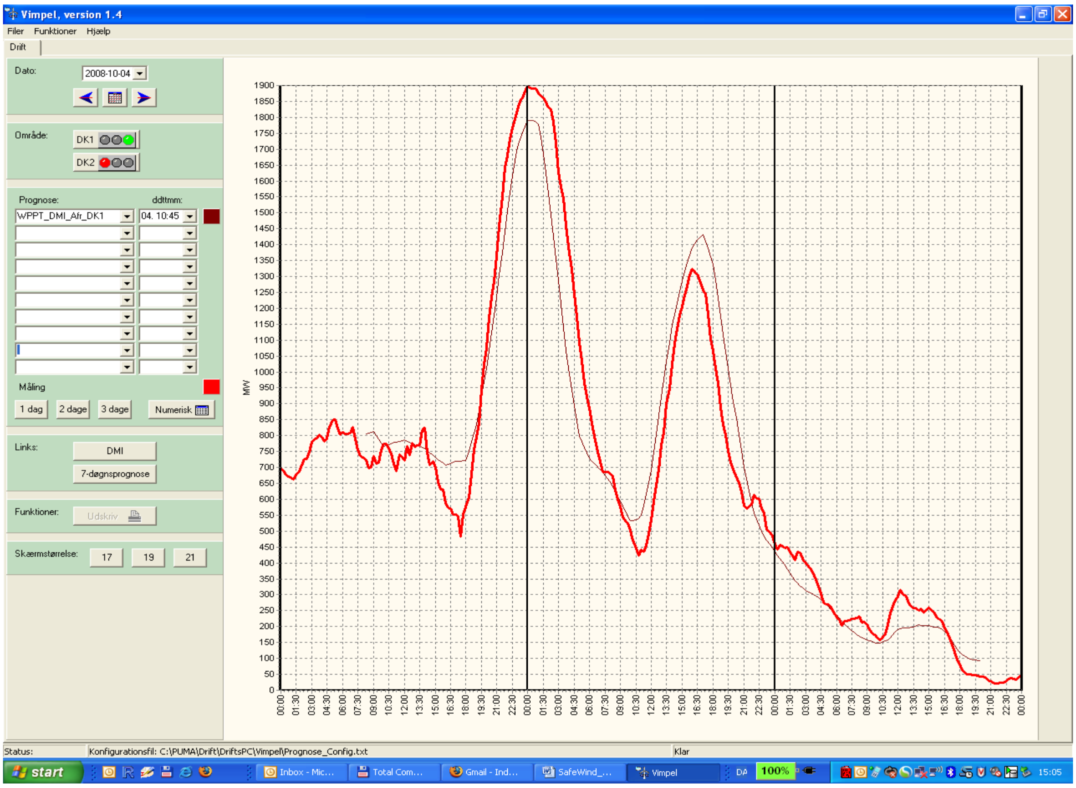

Figure 13: *Another example of a phase error for the DK1 area, here on 5th October 2008. It does not seem to be a significant one, while it actually leads to an imbalance of 300MW*

5.5 CSIRO: Severely variable wind power production for the aggregated output of a number of wind farms

A specific problem that is of interest in (South) Australia is the case of intense variability of wind power generation, even if considering the aggregated output of a number of geographically dispersed wind farms. It is generally and intuitively accepted that a smoothing effect is present if spatially distributing wind farms. In the case of spatially highly correlated meteorological events however, the variability in wind speed observed at various sites sums up, and is then magnified by the steep slope part of the wind farm power curves. This may potentially result in high frequency fluctuations (say, with a period of 5-10 minutes) of very high magnitude. As an example, Figure 14 represents a scenario of 1250MW installed capacity in South Australia. Note that it has not reached that point yet, though the combined wind power for South Australia and Victoria (neighbouring state) is currently just over 1GW according to wikipedia.

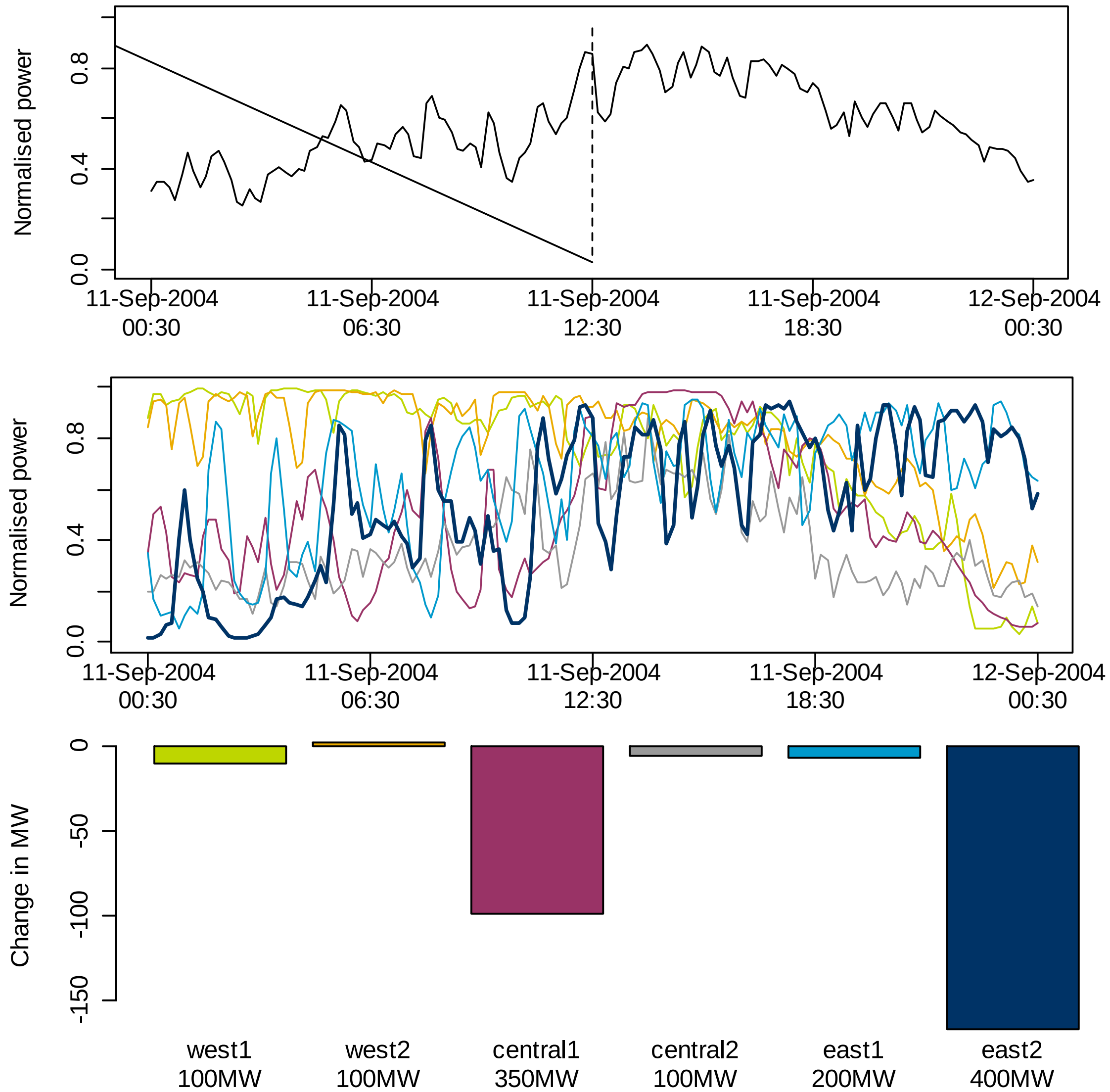

Figure 14: *Episode with 2 days of wind power production measurements for 6 locations in South Australia. This episode corresponds to some scenario for 1250MW installed capacity in South Australia, ie. based on actual measurements scaled to the scenario capacity. Top: aggregated output; Middle: individual outputs at 6 locations; Bottom: Change in 10-minute output at 12:30 for the 6 locations*

The top panel is the aggregate power, the middle panel is the power at the six locations, both having a 10-minute temporal resolution. In parallel, the lower panel shows the 10 minute changes observed on the 11th September 2004 at 12:30. This output change reaches approximately 20% of the installed capacity at that specific time (ie. app. 250MW), which would then have to be balanced by using some other types of generation. If looking at the individual locations output, one notices that the variability at these locations is even more dramatic than that of the aggregated output, indicating that some smoothing effect is present.

5.6 SONI: Series of wind speed shutdowns

Let us have a look then at the case of SONI, which is the Transmission System Operator for Northern Ireland. Figure 15 gathers an example with 3-day ahead point forecasts, prediction intervals, and (a posteriori) measured wind power generation for the whole installed capacity of Northern Ireland. One may think there is here a big amplitude error, though it is instead due to missing SCADA from a large wind farm in the system. The extreme in this situation is that neither the point forecasts, nor the prediction intervals, did provide any hint that there could be series of massive shutdowns over the whole area and over this period of time.

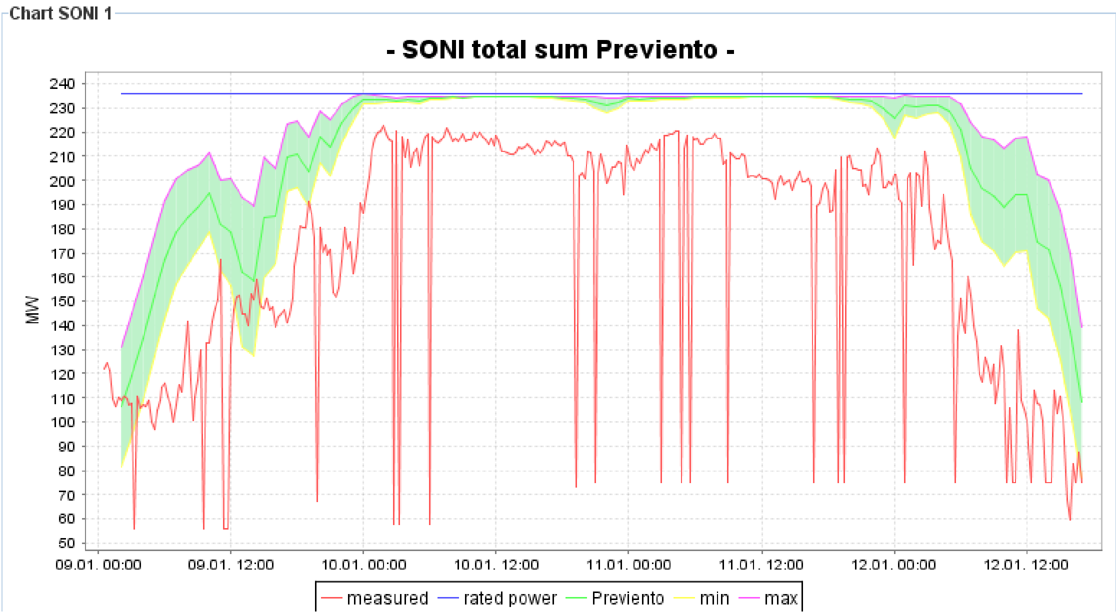

Figure 15: *Example of series of turbines shutdowns (for the case of SONI). Note that there seems to be an amplitude error, though it is instead due to missing SCADA data for a wind farm.*

5.7 HydroQuebec: low-temperature shutdowns

A final example is for HydroQuebec in Canada, and is for the case of wind farm shutdown due to very low temperature (lower than -30 degrees Celsius). This can be seen from Figure 16. Between the times labelled as 80 and 240 (being steps of 10 minutes), even though the wind is blowing and varying within an acceptable range, the output of the wind farm is greatly reduced, owing to this phenomenon of 'low-temperature' cut-off. Such phenomena might not be rare in Northern regions, therefore calling for the development of appropriate forecasting methodologies that account for such effects.

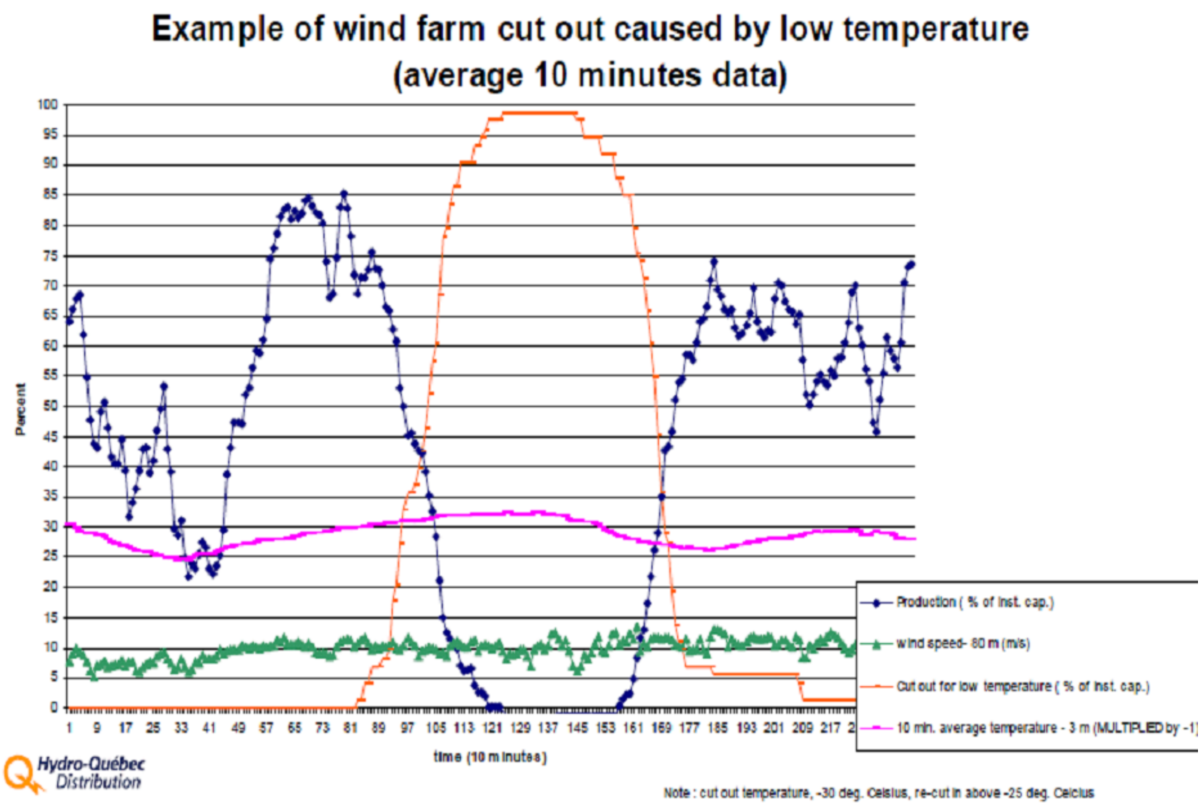

Figure 16: *Example of a wind farm massive cut-off due to extremely low temperatures (less than -30 degrees Celsius) for the case of HydroQuebec in Canada.*

6. On the possibility to study extreme events

In a general manner, there are possibilities to study extreme events, as a large quantity of data may be made available by the various participants in the SafeWind project. A concern though relates to the number of events that would be present in the provided datasets. Indeed, if events are so rare that they can only be identified very few times in the dataset, it will be difficult to thoroughly evaluate the developments performed in the frame of the project, and their potential reproducibility and resulting benefits. An obvious example relates to the case of cut-off events. One may try to develop methods allowing for the modeling and (optimally probabilistic) forecasting of potential cut-off events, but if there is no or very few events of this type in the datasets considered, it will not be possible to apply and evaluate the methodologies developed.

In parallel, the various end-users have clearly explained that in most cases, it is difficult or impossible to identify costs of the extreme events to be studied. Therefore, it will be very complicated to actually calculate or even estimate the benefits for the end-users from the developments performed.

7. Conclusions

This report goes towards the definition of a catalogue of extreme events for the wind power application. One has to realize to extreme events may have a various number of origins and potential consequences, as wind power generation is tightly connected to weather and

climate, to power systems allowing for physical integration of the power generation, and finally to market and regulation aspects ruling the economical integration of this renewable energy. This is the reason why it has been argued that extremes for the case of wind power generation should first be defined by the variable of interest, possibly being the wind itself (either averages at a certain temporal resolution or gusts), the errors in forecasts, or the costs induced by the market or related to maintenance issues. When this variable of interest is defined, one can then apply the common definition of extreme, consisting of a significant deviation from 'climatological' values, climatological values being values we are used to observe and corresponding to situations we are used to deal with.

These potential extreme events have been sorted into categories, which reflect different extreme events with different origins, different temporal and spatial scales, and a number of different potential consequences. These categories have been titled 'Extreme (large scale) meteorological events', 'Extreme (local scale) meteorological events', and 'Extreme power system events'. The first concerns more events that may have an impact on the power system as a whole, while the second corresponds to events that may damage wind turbines and wind farms. The third category includes all types of events that may have disastrous and/or costly consequences for the various actors of an electricity system and market. In view of the number of answers coming from such actors, the latter categories have been rated has potentially having the most significant impact on their activity. In a general manner, if one should designate 2 events with the most significant impact, they would be: *(i)* large forecasting error in the forecasts, especially phase errors, *(ii)* high wind speed increasing the risk of cut-off events, or leading to massive cut-offs over a wind portfolio or a control zone. Mentioning these two types of events does not mean the others are less important, just that their perceived potential impact is more significant.

An example list of extreme events has been given with illustration coming from real data and actual situations. This example list allows better describing the origin and potential impact for the various types of events considered. In parallel, the temporal and spatial scales for the various events have been specified, with focus also given to the feared consequences, their frequency of occurrence, the format of expected solution for the various energy actors, and a reasonable time for warning/alert if relevant. Such a catalogue should be used as a basis for the developments to be performed in the frame of the SafeWind project, and potential updated as more interaction takes place between researchers/developers and the other actors of the project. It would be ideal to have an easy way to identify and calculate costs of extreme events in order to evaluate the benefits from the works performed and new methods proposed. It appears that calculating such costs and evaluating benefits may be a challenge for most of the actors of the project. It may therefore be necessary to set-up a number of decision-making case-studies for which realistic cost/loss structure may be proposed, in order to have a generic way of evaluating the benefits from the research/developments works performed.