

Energy production forecasting Experiences from Lillgrund

Lillgrund Pilot Project

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Author Lasse Johansson Peter Schelander Måns Håkansson Johan Hansson		Project name Energy production forecasting Experiences from Lillgrund		
Customer Vattenfall AB Vindkraft		Reviewed by Lasse Johansson		
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PREFACE

Vattenfall's Lillgrund project has been granted financial support from the Swedish Energy Agency and Vattenfall will therefore report and publish experiences and lessons learned from the project. This report is compiled in a series of open reports describing the experiences gained from the different aspects of the Lillgrund Wind Farm project, for example construction, installation, operation as well as environmental, public acceptance and legal issues.

The majority of the report authors have been directly involved in the Lillgrund project implementation. The reports have been reviewed and commented by a reference group consisting of the Vattenfall representatives Sven-Erik Thor (chairman), Ingegerd Bills, Jan Norling, Göran Loman, Jimmy Hansson and Thomas Davy.

The experiences from the Lillgrund project have been presented at two seminars held in Malmö (4th of June 2008 and 3rd of June 2009). In addition to those, Vattenfall has presented various topics from the Lillgrund project at different wind energy conferences in Sweden and throughout Europe.

All reports are available on www.vattenfall.se/lillgrund. In addition to these background reports, a summary book has been published in Swedish in June 2009. The Lillgrund book can be obtained by contacting Sven-Erik Thor at sven-erik.thor@vattenfall.com.

Although the Lillgrund reports may tend to focus on problems and challenges, one should bear in mind that, as a whole, the planning and execution of the Lillgrund project has been a great success. The project was delivered on time and within budget and has, since December 2007, been providing 60 000 households with their yearly electricity demand.

Sven-Erik Thor,
Project Sponsor, Vattenfall Vindkraft AB
September 2009

DISCLAIMER

Information in this report may be used under the conditions that the following reference is used: "This information was obtained from the Lillgrund Wind Farm, owned and operated by Vattenfall." The views and judgment expressed in this report are those of the author(s) and do not necessarily reflect those of the Swedish Energy Agency or of Vattenfall.

Energy production forecasting

Experiences from Lillgrund

SUMMARY

Forecasts for wind energy has been used since the early 1990s, i.e. since the modern wind power entered the energy industry. Weather forecasts, also with regard to power production, in a broad sense have been applied for much longer. In Sweden, hydropower production forecasts have been made half-yearly from hydrological observations and forecasts of precipitation, snow and ground water. Forecasts of electricity demand have also been made for many years. Since most electricity demand depends on the temperature, such predictions can be made about a week ahead.

Before the start of electricity trade in the Nordic countries through the Nord Pool, the purpose of forecasting the electricity supply primarily was to regulate production. Power producers were able to use some production capacity, keep another set for increased consumption and let the others rest. Producers then, and today, had to have a preparedness to increase production. A certain production capacity must be available within seconds, another to be connected in a number of minutes and so on.

Today electricity is traded in the electricity market Nord Pool. The one who knows more about the electricity price tomorrow, the day after tomorrow and next month can make the best deals. But it's not just electricity that is traded at Europe's electricity markets today; you can also trade spare capacity that can be "powered-up" with various long notices. It could be a good business to sell spare capacity and, conversely, it may be a bad deal to buy spare capacity unnecessarily.

Wind energy is a new, and still insignificant, feature on the Swedish electricity market. But elsewhere in Europe, wind energy is at times responsible for more than 100 percent of the electrical energy production in a region. That is for example the case in Navarra and Schleswig-Holstein. The need for accurate forecasts of a highly variable power source such as the wind is evident.

Today the wind energy forecasts in the short range are produced by analysing the current production minute by minute and then predicted. Weather forecasts are thus not involved. But on longer time scales, up to a couple of days, it's inevitable to use some kind of weather forecasts. The available forecasting tools doesn't differ much in construction but quite a lot in performance. This is probably due to the fact that they are developed in countries big in wind energy, such as Spain, Germany and Denmark, and optimized to give good results in their region.

The last few years the use of probability forecasts, so-called ensemble forecasts, has increased in products aimed for us as weather consumers. For example we might read in the newspaper that there is a 70% probability for 8 mm of rain to fall tomorrow instead of

the plain and simple statement that there will come 8 mm of rain tomorrow. Even though probability forecasts like these have been around since the early 1990s they have not been used to any great extent in any forecast segment in Sweden. This way of thinking is now being implemented in the wind energy business in Sweden. This is done by weighing together several forecasts. From the result you can get an estimation of the uncertainty in the coming weather development.

Forecasting production at Lillgrund

Forecasts of energy production at Lillgrund are being made with the prediction tool WPPT. The forecasts are updated every hour with observed wind- and production data. WPPT combines statistical and physical methods and the nature of the model changes with time. In the very short range, the observed data is the dominant factor predicting energy production while the physical methods, e.g. the weather forecasts, gradually are given more weight as we go further away from the production hour.

Until recently Vattenfall has relied solely on weather forecasts from one institute, namely DMI (The Danish Meteorological Institute), in predicting the energy produced at Lillgrund. The uncertainty in the forecast has been given some attention but since only one source of information has been available the possibilities of a comprehensive uncertainty analysis has been limited.

To meet the growing demand for quality and delivery reliability, Vattenfall has begun to purchase additional weather data from the Swedish supplier WeatherTech Scandinavia. These data will be used together with data from DMI. You get a kind of ensemble forecast approach. The difference in structure, configuration and physical approaches of the models presumably makes the model related forecast errors uncorrelated. This lays the path for quality improvements when the different forecasts are combined optimally. This will make Vattenfall better prepared to face future challenges!

How accurate are we today?

WPPT has been used in forecasting the energy production at Lillgrund since production began in 2007. The average absolute error in the production forecast / turbine is 0.17 MW. If WPPT only relied on a persistence forecast for the next 24 hours the error will become almost three times as high. So far WPPT has a skill score of 86% in the 24-hour forecasts compared to an assumption of persistence. There is a clearly visible pattern that WPPT underestimates production in situations with strong winds and conversely overestimate production when winds are weak. This is also typical for pure persistence assumptions.

How does planned an unplanned maintenance stops affect the production?

Production forecasts are not used as a tool in the planning of the operation and maintenance within the wind farm. Maintenance planning is done with a much longer time horizon than the current production forecasts offer. For example, Vattenfall has to inform and coordinate with the owner of the local power network typically three weeks in advance before any maintenance that can cause significant loss of production. It's an inevitable fact that wind turbines must be stopped for maintenance with regular intervals in order to maintain secure and stable operations. However, it is in the power producers' interest to minimize these stops for maintenance work. And of even higher importance, minimize the loss of production by making sure the stops coincide with periods of expected low

production. At the end it's always the current weather that determines if the maintenance can be carried out as planned. Maintenance involving boats is dependent on calm weather and thus is correlated with periods of low wind speed and low energy production.

Due to the seasonal variations in the wind climate, the summer season offers the best opportunities for planned maintenance work in the wind park. A production stop of larger dignity where sometimes the complete park is set out of operations is always done during the summer season. An analysis of production data from the first year of operation shows that the loss of production due to scheduled stops was almost negligible. However, a six week, unplanned stop of a few turbines caused a loss in production of almost 1.5 GWh.

SAMMANFATTNING

Prognoser för vindenergiproduktion har använts sedan början av 1990-talet, det vill säga sedan den moderna vindkraften gjorde entré i energibranschen. Väderprognoser i vid mening, även för elproduktion, har tillämpats under mycket längre tid. I Sverige har vattenkraftproduktionen prognostiseras halvårsvis ifrån hydrologiska observationer och beräkningar av nederbörd, snömängd och markvatten. Prognoser av efterfrågan på elkraft har också gjorts under många år. Eftersom elbehovet mest beror på temperaturen kan sådana prognoser göras någon vecka framåt i tiden.

Före elhandelns intåg i Norden genom Nord Pool var syftet med prognoser av eltillgång och elutbud framför allt att reglera produktionen. Kraftproducenterna kunde utnyttja en viss produktionskapacitet, hålla en annan redo för ökad konsumtion och låta resten vila. Producenterna måste då, och även idag, ha en beredskap att öka produktionen. En viss produktionskapacitet måste finnas tillgänglig inom sekunder, en annan skall kunna kopplas in på ett antal minuter och så vidare.

Idag köps och säljs el på elmarknaden Nord Pool. Den som vet mest om elpriset imorgon och i övermorgon och nästa månad kan göra bäst affärer. Men på Europas elmarknader handlar man idag inte bara med el utan även med reservkapacitet som kan startas med olika långt varsel. Att sälja reservkapacitet kan bli en god affär och omvänt kan det vara en dålig affär att köpa reservkapacitet i onödan.

Vindenergi är ett nytt inslag på den Svenska elmarknaden och ännu en obetydlig del. Men på andra håll produceras tidvis mer än 100 procent av elenergin i en region av vindkraftverk. Så är fallet exempelvis i Navarra eller i Schleswig-Holstein. Behovet av bra prognoser av en så snabbt varierande kraftkälla som vinden är uppenbart.

Idag framställs vindenergi prognoser på kort sikt, upp till några timmar, genom att produktionen analyseras minut för minut och därifrån förutsägs. Man tar alltså inte in väderprognoser för detta. På längre tidsskalor upp till ett par dygn används väderprognoser. De prognosverktyg som finns skiljer sig knappast i uppbyggnad på denna punkt. De skiljer sig däremot i prestanda, vilket troligen beror på att de utvecklats i världens stora vindkraftregioner, Spanien, Tyskland och Danmark, och anpassats för att ge bra prognoser där.

Som väderprognoskonsumenter har vi vant oss alltmer vid sannolikhetsprognoser. Vi kanske läser i tidningen att risken för 8 millimeter regn imorgon är 70% istället för att det kommer att regna 8 millimeter rätt och slätt. Trots att sådana sannolikhetsprognoser, ensemblprognoser, funnits sedan början av 1990-talet har de inte använts i någon större utsträckning inom något prognossegment i Sverige. Men tankesättet börjar nu så smått att leta sig in i vindenergi branschen. Det man rent praktiskt gör är att man viktat samman flera olika prognoser och på så sätt får ett mått på osäkerheten i väderutvecklingen.

Prognostisering vid Lillgrund

Intill alldeles nyligen har Vattenfall helt förlitat sig på prognoser från ett institut, nämligen DMI (Danmarks Meteorologiske Institut) för prognostiseringen av vindkraft från Lillgrund. Prognososäkerheten har ägnats viss uppmärksamhet, men då endast en väderprognosleverantör använts har möjligheterna till omfattande osäkerhetsanalyser varit begränsade. Prognoserna uppdateras varje timme, med uppmätta vind- och produktionsdata. WPPT

kombinerar statistiska och fysikaliska metoder och karaktären på modellen ändras därmed med tiden. Ju närmare produktionstimmen man är, desto mer betydelsefull roll får utfallsdata. På längre sikt vägs väderprognoserna, den mer fysikaliska delen av modellen, in allt mer.

... och ribban höjs...

För att möta de ökade kraven på kvalitet och leveranstrygghet har Vattenfall börjat köpa kompletterande väderdata från den svenska leverantören WeatherTech Scandinavia. Dessa data skall användas tillsammans med data från DMI. Man får nu in ett slags ensemble-prognostänk i verksamheten. Skillnaderna i uppbyggnad, konfiguration och modelleringsstrategier mellan modellsystemen gör att deras modellrelaterade prognosfel kan väntas vara huvudsakligen okorrelerade. Detta möjliggör en förbättring av prognoskvaliteten då dessa kombineras på ett optimalt sätt. Vattenfall kommer därmed att kunna utöka analysen av prognosfel och osäkerhet med att även kunna beakta konsekvenser av de olika modellsystemens egenskaper. Detta kommer att göra Vattenfall mer redo att möta framtida utmaningar!

Hur pricksäkra är vi?

Sedan vindkraftsparken på Lillgrund driftsattes har WPPT använts för att prognostisera produktionen. Det genomsnittliga absoluta felet i produktionsprognosen per verk är 0,17 MW. Om WPPT enbart förlitat sig på persistens i prognosen för nästa dygn blir felet nästan det tredubbla. Hittills har WPPT en träffsäkerhet på 86% i sina 24-timmarsprognoser jämfört med ett antagande om persistens. WPPT har ett tydligt mönster att underskatta produktionen vid högvindstillfällena och på motsvarande sätt överskatta produktionen då det blåser lite. Detta är också typiskt för rena persistensantaganden.

Hur påverkas produktionen av planerade respektive oplanerade underhållsstopp?

Produktionsprognoserna används inte som ett direkt verktyg i planeringen av drift och underhåll inom anläggningen. Underhållsplanering sker med ett betydligt längre tidsperspektiv än vad nuvarande produktionsprognoser kan erbjuda. Exempelvis måste besked till nätägare lämnas flera veckor innan planerade driftförändringar, vilka innebär produktionsbortfall genom tillfälligt stoppade verk. Att verk emellanåt måste stoppas är ett oundvikligt faktum för att kunna vidhålla en hög driftsäkerhet. Däremot är det som kraftproducent önskvärt att minimera underhållstider samt kanske i ännu högre grad se till att de planerade driftsstoppa sammanfaller med perioder av förväntad låg produktion. I slutändan är det ändå rådande vädersituation som avgör i detalj när underhållsarbeten kan genomföras. Fartygsbaserat underhållsarbete kräver lugna förhållanden, och har därmed en god korrelation med tider med lägre vindhastigheter och låg kraftproduktion.

Säsongsvariationerna i vindklimatet gör att sommarsäsongen generellt sett erbjuder bättre möjligheter för inplanering av underhållsstopp, och stopp av större dignitet där bl.a. hela parken sätts ur drift sker alltid sommartid. En utvärdering av driftdata från första året visar att produktionsförlusten som skedde till följd av planerade sammanhängande stopp över ett dygn eller mer, var nästintill försumbar. Däremot fanns ett längre oplanerat frånfall i produktionen från ett fåtal verk under ca sex veckor som orsakade ett bortfall på närmare 1,5 GWh.

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1 ENERGY PRODUCTION FORECASTING

In Navarra 76% of the electricity was produced by wind power in 2006 – sometimes in the wind energy business, the term (wind power) penetration is used for this. At times, the penetration in Navarra is above 100% meaning that all electricity used there is generated by wind power and that at the same times Navarra exports electricity.

Schleswig-Holstein got over 40% of its electricity from wind power plants in 2007. In Jylland the wind power penetration is over 20%. Of course, also in these regions the penetration is sometimes much higher than these average values.

With such large portions of the energy coming from wind, an energy source that is highly and quickly variable, the need for a planning tool is readily recognised.

1.1 Objectives in wind energy forecasting

Reasons for wanting to forecast production differ between users. We identify traders, managers and service providers as main users.

Traders

For energy trading on spot markets the bidding limit typically is at least six hours. Naturally, a predictable product has a higher value than an unpredictable one. This is true even if all actors on the market have the same information and quality on their forecast. It is probable that the information will be more or less the same since if a significantly better forecast product appears, everybody will demand it.

As we shall see later, quality on these time scales come through large internationally consorted efforts financed by tax payers and therefore no energy market actor is likely to be able to own more quality than another in this respect.

For trading purposes, the mean forecast error is more important than occurrence of extreme errors. The time scale is 6-48 hours.

Product portfolio managers

A transmission system owner (TSO) has to buy or own production capacity on different time scales; spinning reserves on second to minute scales, boiling reserves on minute to hour scales, standby generators and so on. Production forecasts on the corresponding time scales will economize operation and add stability.

A low probability of extreme forecasting errors might be as important or more important than the mean errors for this application. The time scale is 0-12 hours.

Service, safety

Long-range forecasts are important for service of remote plants or off shore plants where maintenance is governing among the different costs. The time scale is 24 hours to ten days.

1.2 Potential benefits of forecasting

The energy business is not open about the gains and benefits of using forecasting. It is obvious however that much energy has been put into developing forecasting tools. A large portion of the funds come from public funding sources such as research grants and EU-projects but to some extent energy companies have financed development which indicates that they can see the advantages in using them.

Most published investigations of benefits from forecasting are scenario studies, meaning that a real or realistic scenario with respect to wind farm, weather, electricity pricing etc is identified and the hypothetical outcomes without and with energy forecasting are then compared.

For example, Hutting and Cleijne (1999) studied a Dutch scenario for offshore production. They concluded that 1500 MW wind power would sell at 35 €/MWh if 75% of the production could be properly forecasted. If 100% of the production could be forecasted the price would be 40 €/MWh. The main reason was that no backup capacity would need to be purchased.

If 6000 MW was installed instead the price would sink to 29 €/MWh because more variation is introduced into the grid through the wind variability.

If instead the park size would be increased, thereby reducing the variability – the wind variation would be partially averaged out – the price would increase by 1.5 €/MWh extra installed power.

Another study by Nielsen et al. (1999) assessed the value of Danish wind power on Nord Pool which is hydropower dominated. They concluded that the price would be 24 €/MWh (during a normal precipitation year) that would be reduced by 1.3-2.7 €/MWh (5-10%) due to forecast errors.

Mylne estimated value of forecasting for one 1.65 MW turbine on the UK NETA trading system. Assuming a capacity factor 30% the value of forecasting, i.e. the added profitability would be 0.3-3 €/MWh.

1.3 Defining forecasting

There are two sides of energy forecasting: supply and demand. We will only touch on effects due to the weather, as opposed for instance to the price of electricity or of fuel.

Supply

Hydropower forecasting is well-established since the beginning of the electrical era around 1900. The time scale here is 100 hours to 10 000 hours: the time scale of precipitation, run-off, dam filling and emptying and melting/freezing of snow.

Forecasting of wind for energy purposes is relatively new and much more difficult because of the time scales involved; less than one hour up to 50-100 hours. The wind depends on the pressure field, which changes quickly.

Demand

Demand is a standard issue in energy forecasting. A distinct portion of the demand is governed by the weather. Each region has its own characteristics but temperature is often the most important element. In Scandinavia, falling winter temperatures increase electricity demand whereas in Spain rising summer temperatures strongly increase the demand.

The demand also possesses strong variations – regular and irregular – due to non-meteorological causes; industry hours, household need, national or EU-wide TV-events and more.

1.4 History

The development of dedicated wind power prediction tools started about 20 years ago. The development appears to have been mainly institute and university driven. It has been sponsored by national research establishments such as Risø in Denmark and on a larger European scale through the big Anemos project. The electricity industry has also been involved, for example Red Eléctrica de España.

It is notable that the prediction tools are somewhat tied to specific regions (in Spain, Germany, Denmark and so on) and then exported. This is reflected in the tool performance. Further, the development has been more driven by wind power researchers and industry than the meteorological forecasting scene, which has affected the research focus and tool performance.

Today, several commercial products exist, see the compilation in Figure 1. The performance or quality of the different tools is hard to compare because

- the quality is often kept a secret by the energy companies operating it
- streamlining (at unknown cost) means that no two systems are really the same
- the input data quality is decisive for the end performance: a bad meteorological input to the tool will yield a bad output irrespective of model.

Surprisingly, the last fact is sometimes overlooked in performance studies, which is probably due to the forecasting scene having a weak foundation in operational forecasting.

Time line short term wind power prediction systems

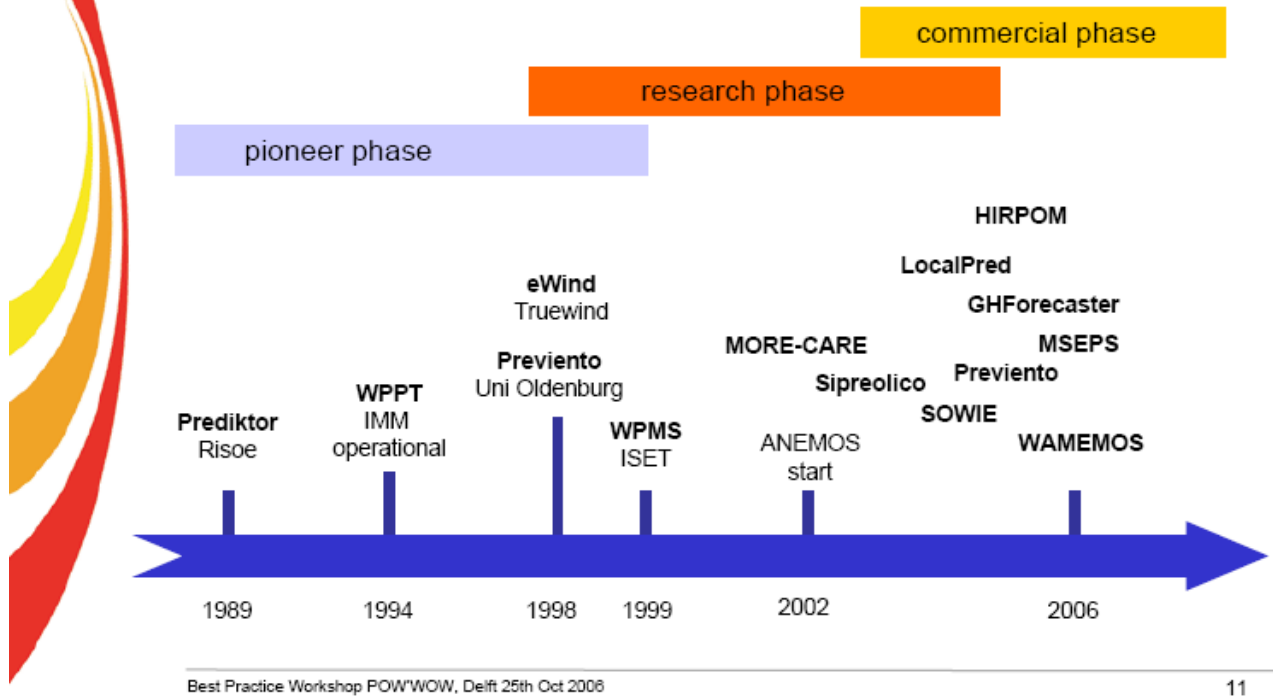


Figure 1. Prediction systems history overview from a presentation of Mathias Lange at energymeteo.com.

1.5 Forecasting principles

To keep concepts clean, we may differ between two extreme principles of wind energy forecasting: statistical and physical. In reality almost all systems nowadays are mixed.

There is a wealth of references on the details of forecasting on the homepage of the Anemos project <http://anemos.cma.fr>

Only statistics – no physics

A black box model is fed with historical production data to learn the connection between the production in the last couple of hours and the production in the coming couple of hours, see Figure 2. This approach is similar to learning to dance or to ride a bicycle: you don't think or plan what you are doing but rather try, fail, try again and so on until you know it. Also you can't describe exactly how to do it. You only do it.

The black box can contain a linear regression, an ARMA process or a neural network (ANN). More variants exist.

The common characteristic is that the black box doesn't contain any specific meteorological knowledge, power curve or other 'factual' information on the production system. Therefore,

one doesn't need to gather and process this information, which is a time and resource demanding process. Especially if the production system or the meteorological observational network or forecasting model is changed. This versatility is a big advantage with the black box approach.

A big drawback is that the black box can't utilize information about the weather. Obvious changes, such as the approach of a storm, will not influence the production forecast. This is a big drawback and effectively limits the time horizon to 3 or at most 6 hours.

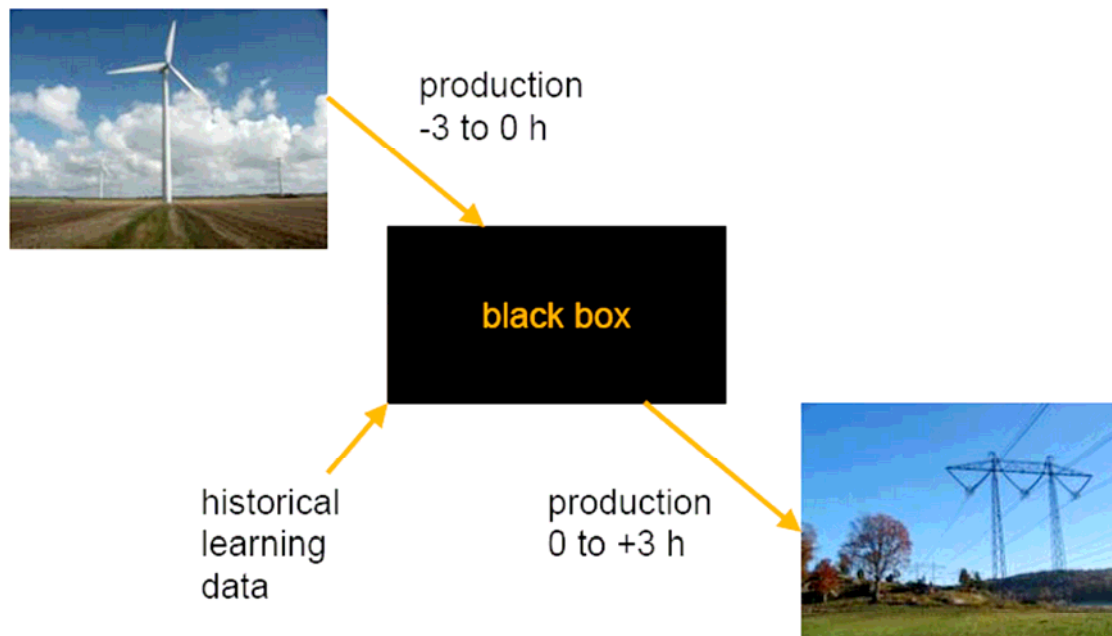


Figure 2. The black box learns how the later production usually depends on the earlier. After education it uses this 'statistical knowledge' to forecast.

Only physics – no statistics

This extreme example of the physical approach consists of a chain of calculations through which data is refined to the final form: production. Each link consists of a physical model.

The first link is one or several meteorological models. The first one is a global meteorological model which weather observations regularly are fed into. The result is then processed through a meso¹ scale model, covering for example Europe. Possibly, a micro scale or local model is then used for the final refinement and adaptation to the local conditions. The micro scale model could for example cover the wind farm area.

The result from the model or model suite is a wind time series at the turbine locations. This data is then fed into turbine models converting wind speed to electricity production.

The advantage with this approach over the statistical black box is that all available information about the (future) weather is utilized. It is taken advantage of the enormous and

¹ From mesos (μεσος), 'in the middle', referring to the forecasting spatial scale which is neither global, 1000-10000 km, nor μικρος, micros, 'small', 0-10 km but somewhere in between. Also called a local model. These limits are not strictly defined.

internationally concerted effort to gather weather observations and to run and develop models. It is also possible to consult meteorological expertise on the performance of the model and to get daily advice or advice concerning special events (storms, cold periods etc). In the black box approach there is no mechanistic explanation of the result.

The main drawback is the slowness. It takes time to compile the meteorological observations, to calculate the forecast, to disseminate results and to do the final production calculations. See Figure 3. Because of this there is a closest time horizon of 3-6 hours before which no results are available. During this starting period the last hours of the old forecast must be used. They can – on average – be poorer in quality than the black box. Another drawback of the 'physical' approach is due to the fact that a chain is not stronger than its weakest link. If, for example, the transformation from wind speed to production is poor, due to an optimistic power curve from the manufacturer, the overall result will correspondingly deteriorate.

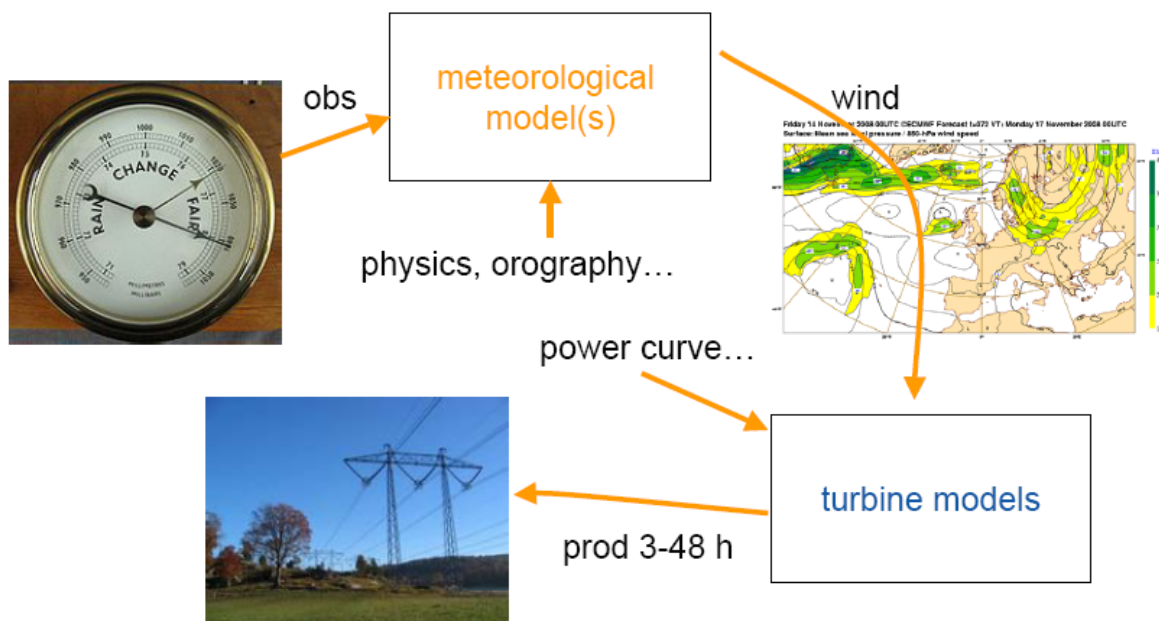


Figure 3. The physical approach is to couple a set of meteorological models to form a suite from global to local resolution. In the end each individual turbine is modelled and a production forecast results. There is thus a line from the weather observations done globally every 3 hours to production at a single turbine in a farm.

Combined physical and statistical models

It is not a very far-fetched idea to try and combine the advantages of statistical and physical models to give better results than using one or the other.

Statistical models perform better on shorter time scales whereas physical models – weather forecasts – are a must on longer timescales.

The state of the art today is to utilize a so-called model output statistics (MOS). The output from the model, statistical, physical or a combination is fed into a final stage, MOS. MOS then acts as an improver and reduce error further. See Figure 4.

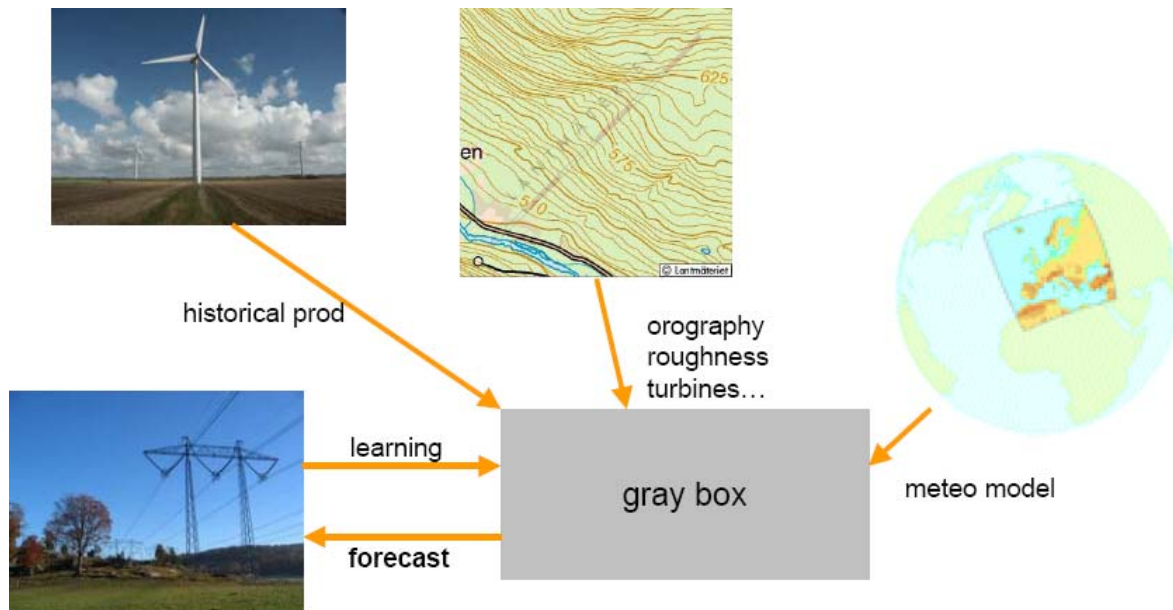


Figure 4. The gray indicates that the content partly relies on an understanding of the processes and partly on functions that mimic earlier outcome irrespective of reason.

1.6 Evaluating forecasts

We need to define two concepts as they often appear as references when discussing forecasts.

The climatic forecast

A climatic forecast assigns the future value to the average historical value. For example, the annual mean temperature in Göteborg is about 7°C. The climatic temperature forecast for Göteborg thus is 7°C. This forecast is almost always wrong but still better than nothing.

Note that the annual energy production value (AEP or P50) for a wind farm is a climatic forecast for production.

Strictly speaking, the power is not a climatic value but the name comes from use of this approach to temperature, wind speed etc.

The climatic forecast can be somewhat developed by considering for example seasonal or monthly and daily variations, but the principle is the same; the past is the future.

The persistent (or naïve forecast)

It means assuming that the value later will be the same as the value now. For example the temperature in Göteborg now is 5°C. The forecast for the coming X hours is 5°C. Considering its simplicity, it is a surprisingly effective forecast. But, effective or not, with this approach you are of course 100 percent certain to miss any changes in conditions.

1.7 Forecast quality

When comparing forecasts from different sources, the usual method is to compare how the error develops in time. The model that has the smallest absolute error over the time period in question is the one best suited for the purpose. As we have already seen, different needs must define error in different ways for this method of comparison to make sense. We saw in section 1.1 that traders are interested in keeping the mean error low while TSO:s might be interested in small errors during unusual or extreme weather events.

Figure 5 is an example of the development of the forecast error with time for different methods. The forecasted parameter is power. The diagram shows the mean forecasting error over many forecasts in percent of the production capacity of the wind power plant. The error measure is the (normalised) root-mean-square (RMS). The error measure is sometimes called the cost function, a term which stems from optimisation algorithms that work to minimize the “cost” of the error. Several other error measures are in use such as the mean of the absolute error (MAE) or skill-scores (SS).

First, lets look at the climatic forecast. It is simply the mean production of the plant². On average, the actual production differs by 30% from the mean production in an RMS sense in this example. The climate value in this case is actually the standard deviation of the production. A forecast that has got a larger error than the climate forecast is really bad, which is the case for the persistence forecast at horizons beyond about 10 hours.

Next, the persistence forecast has of course zero error at now, time = 0. Due to the physical laws of the atmosphere, one might expect that it is not good to disregard physics on larger timescales than about 3 hours. In Figure 5, we can see that the persistence forecast performs the same or better as a physical, Numerical Weather Prediction (NWP) model on very short timescales. Sometimes, such as when the production is 0, the persistence forecast is essentially nonsensical. The limiting value is 50%.

The physical method (NWP) performs worse than persistence for short time horizons and then gradually betters.

The NWP method combined with post-processing or Model Output Statistics (MOS) performs better than the raw NWP. MOS is a way to observe and analyze the NPW error and then correct for it. The correction on average improves the result, as we can see here.

The obvious thing to do to improve the NWP is to replace it with persistence for the first couple of hours. This is done in a somewhat more sophisticated way in the “stat+NWP” method. The result is the best among the methods shown here and it is somewhat more modern than state-of-the art today. I.e. it will probably soon become state-of-the art.

1. Note that it is NOT recommended to compare results expressed in different ways; e.g. RMS cannot be compared with MAE.
2. Note that results are specific to a certain region. So for example, Spanish or Danish performance results do not apply to Croatia or Austria.

² The Annual Energy Production or P50 value usually calculated during the planning phase for the financial evaluation of the project. Technically it is P50/8760 hours per year.

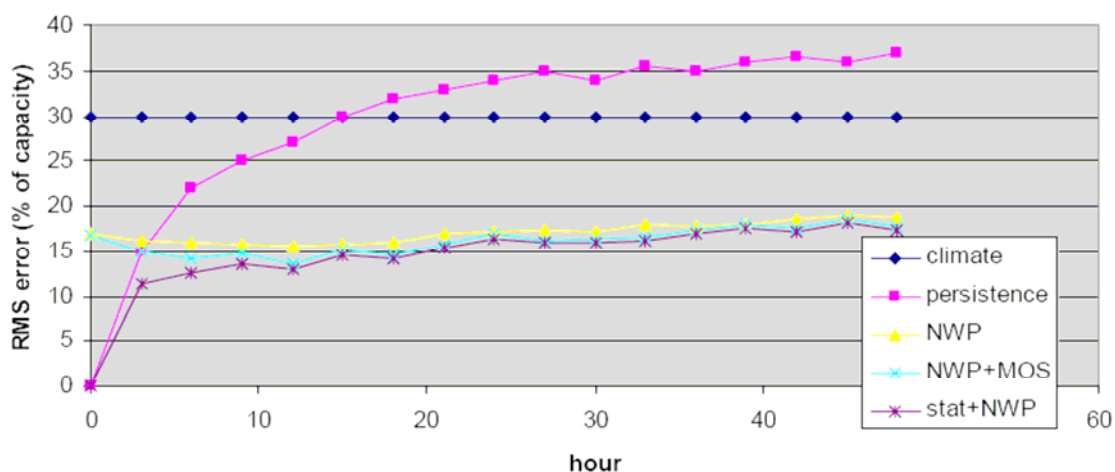


Figure 5. This is a typical picture in forecast evaluation. It shows how the forecast error develops with time for different forecasts. It is a mean of many forecasts. The climatic forecast is almost always wrong, and it has the same performance irrespective of forecast length. The mean error in this case is 30%. The persistence forecast is by definition exact at T=0. The error development is then rapid. The 'physical' or numerical weather prediction (NWP) based models have a poor starting performance. Combined approaches stat+NWP perform best. Note that the quantity evaluated can vary and one must not compare apples and bananas! In this case it is the root mean square error.

1.8 Forecast products

There is an increasing number of companies providing applications with the aim to predict wind-power production from given weather forecasts. Out of these, the product WPPT (Wind Power Prediction Tool) provided by the Danish enterprise ENFOR has been elected for the production of wind-power predictions for the wind farm at Lillgrund. ENFOR has a long experience in the field and has come up with some truly sophisticated modelling strategies.

The WPPT should be seen as a combined physical and statistical model. It accepts weather forecasts as input data and based on the properties of that data makes estimations of time-dependent power curves for a single windmill, a wind farm, a set of wind farms or any combination thereof. The power curves are then used, given the variability of the characteristics of the wind field, in the derivation of the wind power forecast. The time dependency of the effective power curves is a consequence of the variability of uncertainty over time for the forecasts (there is a strong correlation between longer forecasts – higher uncertainties). The relation between power curve and wind speed is typically weakening with forecast uncertainty resulting in less steep curves and hence less sensitivity to the precise magnitude of the wind velocity.

An example of the time-dependent performance of WPPT compared to the persistence forecast is shown in Figure 6. As expected and well in line with what has been stated above, the true benefit of utilising a system such as the WPPT lies beyond forecast

horizons of approximately 2-4 hours. So, depending on what time frame is under consideration, different strategies should be adopted.

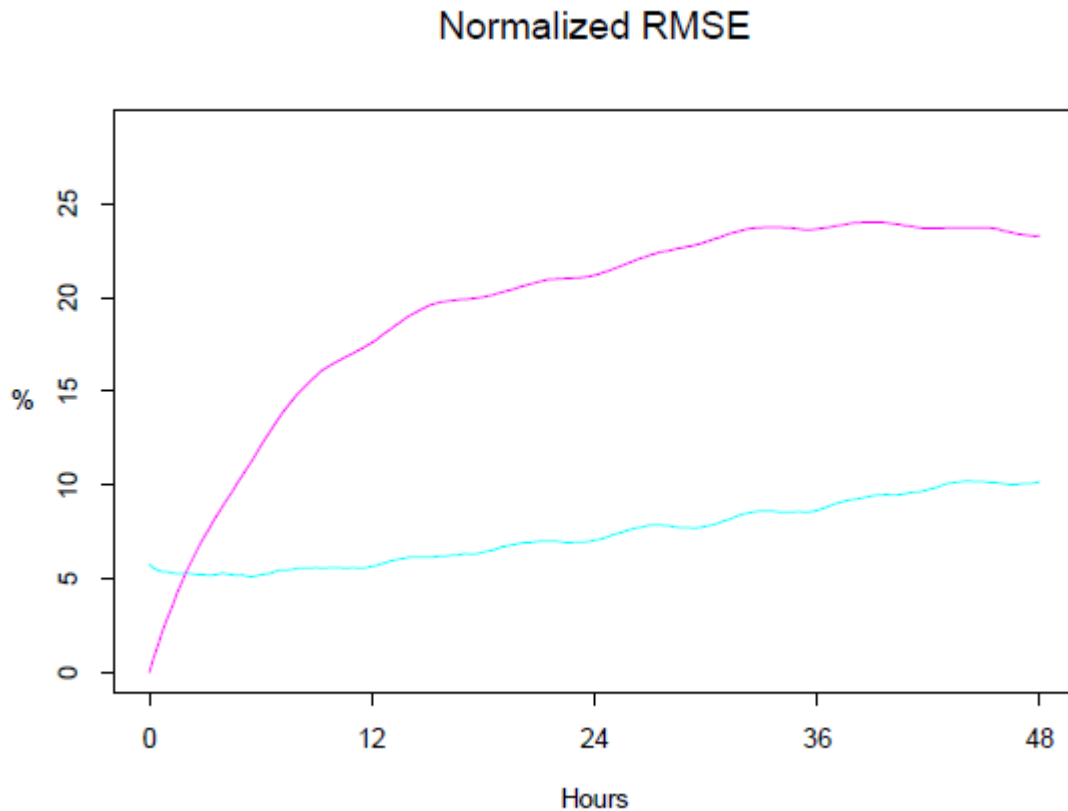


Figure 6. Time depend of forecast error in terms of Root Mean Square Error (RMSE) for the persistence (magenta) and WPPT forecasts. Adopted from [7].

The importance of forecast quality and security of delivery will be of higher importance as the amount of installed wind power capacity increases. The quality of the wind power predictions can be improved by combining multiple weather data from multiple independent models. For instance, by including a second source of weather forecasts the average increase in prediction skill would be somewhere in the range 5-10%. As an added benefit, the risk of total lack of input data is significantly reduced.

1.9 The future

We will never be able to make perfect forecasts no matter how much observations or computer power we have at our disposal. This is because of the chaotic nature of the atmosphere and uncertainties in weather observations. The theoretical limit for useful forecasts is thought to be about 14 days.

But NWP-models will continue to "get better" in the sense that the spatial resolution will continue to increase as the computers get more and more powerful (this doesn't always make the forecast better for the end-user though). The physics in the model will then be

able to resolve processes at a smaller scale (e.g. single thunderstorm cells, local sea breeze etc).

In order for the NWP-model to make a good job, it needs something to start from, an initial condition. This initial condition is derived from combining the latest forecast with weather observations. The number of observations has increased dramatically the last couple of years due to the fact that observations made by numerous weather-satellites successfully has been incorporated in the NWP-system. As more research is done in the field of remote sensing-observations they will probably be even more important in the future when it comes to improving the forecast accuracy in both the short and medium range timescales.

But just looking at only one forecast doesn't tell you anything about that particular forecasts uncertainty. For this you can, as mentioned above, combine statistics and NWP and also combine different NWP-models. But why set the limit at two models? If several models are coming to the same conclusion about the future weather development, that scenario is more likely to happen than a scenario predicted by only one out of X models. But due to the chaotic nature of the atmosphere the scenario predicted by the single model shouldn't be totally disregarded, just considered less likely to occur. This technique combining several NWP-models is called ensemble-forecasting.

Normally you don't combine different NWP-models but instead run the same model with different initial conditions. The result of all the modelruns is combined into different products giving the probability that a certain weather-event will occur. Although ensemble-forecasting has been around since the early 1990s it's use in everyday forecasting has been limited in Sweden. This is quite surprising considering that you immediately get an indication about the uncertainty in the forecast and from that can make the decision that is best suited for the particular situation.

1.10 Conclusions

There are profits to be made if you can predict the future weather with reasonable accuracy. The forecasts will never be perfect but improvements can and will be made in the different parts of the chain leading to better tools for making decisions. NWP-models will gradually become better; the software-tools used by energy-forecasters will also become more sophisticated. Ensemble-forecasting can also be used to get a probabilistic view on the coming weather situation and act as a complement to other forecast products.

2 FORECASTING AT LILLGRUND

As a power producer within the Swedish price area Vattenfall makes daily bids for its total volume of produced power from the various energy sources in Sweden for the following day. To the largest extent these bids are price-dependent, implying possibilities for profit-optimising strategies. Wind power is a small price-independent contributor to the total volume, but it could have a significant impact on the chosen strategy because of its inherent variability and uncertainty. Each producer is required to provide the power he has promised to deliver, regardless of what happens to his power producing units. Due to difficulties in achieving this, the system operator, Svenska Kraftnät, has the responsibility for maintaining

the balance in the electrical system as a whole. For this task some reserves for both generating and soaking energy are available.

Up until recently Vattenfall has relied solely on weather data from the Danish Meteorological Institute (DMI) for producing production forecasts for Lillgrund. The forecast uncertainties have obtained some attention, but since there has been only one provider of weather forecasts, the possibilities for analysis of the uncertainties have been limited. The uncertainty range is assessed through 5 and 95 percentiles given by the WPPT and primarily based on the variability of successive forecasts. As a consequence this analysis will relate to the uncertainty due to initial conditions of the forecast.

The power forecasts are updated every hour with wind and production outcome data. Since WPPT combines statistical and physical methods, the characteristics of the output changes over time. As a specific production hour approaches, the outcome data plays a gradually more significant part, to become the persistence forecast at the production hour.

If the amount of power being bid into the market differs from the amount being delivered, there are two ways in which the producer can maintain balance in the electrical system. He could either adjust the available power by utilising rapidly variable hydropower, or act on the intra-day balancing market, by either buying or selling power corresponding to the residual. These are costly processes and tried to be kept at a minimum. Depending on the hydro situation and on the conditions on the balancing market, the given uncertainty in the forecast may be considered strategically. Vattenfall tries to minimise costs due to imbalances and in doing so utilises a strategic system where the incentive to minimise costs coincides with a balanced state.

In order to meet the increasing requirements for quality and reliability of the power predictions, Vattenfall has been for some time now purchasing additional data from another provider, namely WeatherTech Scandinavia (WTS). These data are used as complement to those from the DMI. But unfortunately so far no analysis has been made to investigate if the forecast-quality has improved.

The forecasts from WTS are based on the COAMPS (Coupled Ocean/Atmosphere Mesoscale Prediction System) and are run at a 0.1-degree resolution, with boundary values from the global model GFS (Global Forecasting System) of NCEP (National Centers for Environmental Prediction). The DMI data on the other hand are derived from their version of HIRLAM (High Resolution Limited Area Model) run with a similar resolution as that of WTS's COAMPS. On its boundaries however, this model is driven by the global model of the ECMWF (European Centre for Medium-Range Weather Forecasting).

The differences in modelling strategies and configuration between the two model systems make their forecasts errors to be uncorrelated. This is in turn a prerequisite for an improved forecast when combined. We will thereby not only have a way of assessing forecast errors and uncertainty due to initial conditions, but also the possibility to analyse those corresponding quantities caused by model approximations and differences in the modelling strategies.

3 EVALUATION OF FORECAST PERFORMANCE

Since the wind farm at Lillgrund began its production in 2007, the prediction tool WPPT has been used in forecasting the production. There are a number of ways of quantifying the usefulness of prediction methods, to determine its quality. Verifying a forecast of a continuous variable, such as the energy production at Lillgrund, measures how the values of the forecasts differ from the values of the observations.

The easiest way of verifying this kind of forecast may be to visualize the outcome as a scatter plot against the forecasted values. This is shown in Figure 7 below.

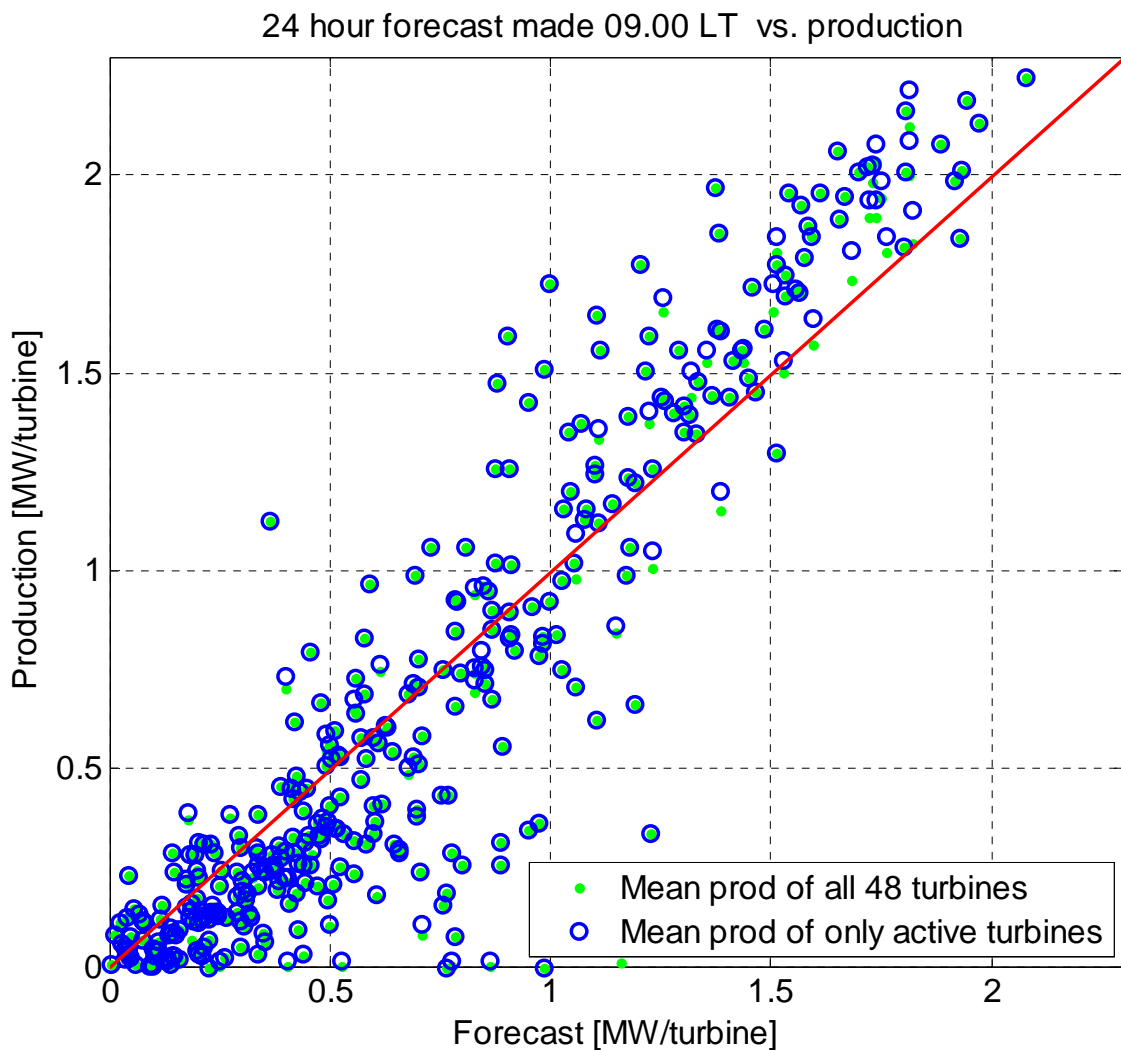


Figure 7. The produced power against forecasted. The green dots are average production for all 48 turbines of the wind park. Blue rings are average for only the active turbines at the time for the forecast.

To quantify how accurate the forecast (F) is in predicting the observed power production (O) one easy measure is the *mean absolute error* (MAE). As the measure is absolute it will only tell us how skilful the forecast method is, not if there is a systematic error.

$$\text{MAE} = \frac{1}{N} \sum_{i=1}^N |F_i - O_i|$$

Available for this evaluation are the forecasts up to 24 hours from the period February 28, 2008 to February 28, 2009. In the future use of WPPT forecasts up to 7 days will be archived [2]. The 24-hour forecast of the WPPT manages to predict the production relatively well according to the mean average error, given that the wind climate at Lillgrund is characterized by relatively large changes on a day-to-day basis. The mean error in the 24-hour forecast is 0.17 MW/turbine. If WPPT instead would use the assumption of persistency also for the 24-hour forecasting range, the mean error would be almost three times higher. Already at this stage we then realize it is of a great advantage to use a forecasting tool such as WPPT.

Another way to measure and quantify how trustworthy a prediction tool may be is a so-called *skill score*. A skill score is usually constructed in such way it will indicate how well the prediction method is working compared to a reference method.

$$\text{Skill score} = \frac{\text{score}_{\text{forecast}} - \text{score}_{\text{reference}}}{\text{score}_{\text{perfect forecast}} - \text{score}_{\text{reference}}}$$

If one wouldn't have a forecasting tool such as WPPT, the simplest way to forecast tomorrow's energy production would be to assume it is the same as the production of today. This is the so-called *assumption of persistency*. In other words, the assumption that the production at a certain time, t , is the same as the production at the time $t-1$. This is also the forecasting principal of WPPT in shorter time perspectives.

For the time that WPPT has been in use to forecast the production at Lillgrund the skill score is 0.86 for the 24-hour forecasts, given the assumption of persistency as reference forecast method. From the definition above we can see that a skill score of 1 would indicate a perfect forecast, and correspondingly 0 would indicate no improvement compared to the reference forecast.

As can be seen in Figure 8 below, there is a clear pattern of over estimation of the production at low winds, and correspondingly an under estimation at high winds. This is also a typical pattern expected from pure persistency assumptions. The figure shows the difference between the forecast and the production as a function of the mean turbine production of the wind farm.

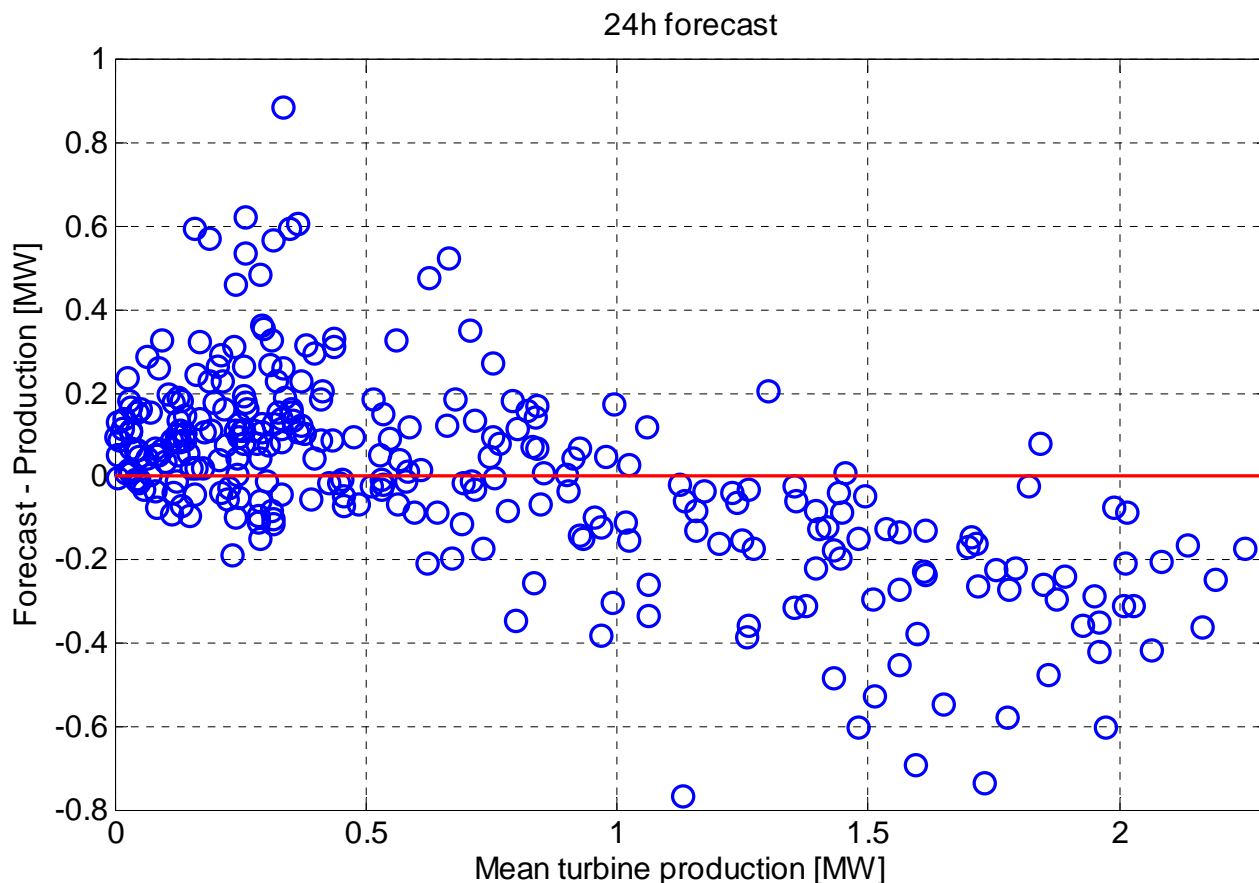


Figure 8. Difference between the forecast and the production (per turbine) as a function of the mean turbine production of the wind farm.

3.1 Could WPPT forecasting also be beneficial for maintenance planning?

Production loss will at times be the result of scheduled maintenance work. From the perspective of an optimized production, there is an obvious advantage if such work could be coordinated with production forecasts. This is not the case in present routines for scheduling maintenance work at Lillgrund, as the time horizon required is much longer than what present production forecasts can supply. One example from the planning process is that the coordination with the owner of the local power network typically begin three weeks in advance of a major scheduled maintenance stop. In addition, as Lillgrund has an installed capacity larger than 100 MW an Urgent Market Message (UMM) must be sent out well in advance to inform about the planned production loss [6]. To investigate if a forecasting tool like WPPT would be beneficial in planning production stops, data from the wind farm operation has in the following been compared to the estimated power production.

In order to maintain secure and stable operations wind turbines must sometimes be stopped, that is an inevitable fact. At the same time, it is in the interest of the power producer to minimize these stops for maintenance work. Of even higher importance to minimize the loss of production, the stops should preferably coincide with periods of expected low production. All things considered, the weather is a key factor controlling when maintenance work can be done in the wind park. All transports and work within the wind park is done by boat, and to maintain a safe working environment and minimized time loss

this type of work is, if possible, avoided during times with strong winds. Thereby, such turbine stops tend to not coincide with times of higher production.

Due to the seasonal variations in the wind climate, the summer season offers the best opportunities for planned maintenance work in the wind park. Production stop of larger dignity where sometimes the complete park is set out of operation is always done during the summer season. Let's take a look at how this affects production in reality. How large will the loss of production be as a consequence of a single turbine or a larger number of turbines standing still?

To filter out typical situations when maintenance work has been performed in the wind park, all occasions when single turbines has been stopped for at least 24 hours has been selected. Figure 9 shows the occurrence of these occasions, printed in red, when at least one turbine has been stopped for at least 24 hours. Also in this figure, printed in blue, is the estimated production loss due to turbines standing still. In the cases where more than half the wind park still is in operation, this estimation is done from production data. In the cases where less than half the park is in operation, the production predicted by WPPT is used to estimate the loss. Except the few occasions where up to five turbines has been standing still, there are three major occasions during this period where a large number of turbines are out of production. The first two periods of stand still are planned stops in operation, and as can be seen from the figure is that the first of these stops caused an almost non-existing loss of produced power. Calm conditions for a few days around the planned stop gave an optimal opportunity for stand still without loss of production. In the second case, the complete park was at stand still and yet the loss of production is estimated to be less than 50 MWh by WPPT.

The third case of a significant number of turbines at stand still occurred late in the year. The occasion itself occurred only during one day and did not imply a major production loss. More notably are the six weeks surrounding that day where only a few (averaging approximately two) turbines were standing still. Despite the small number of turbines out of production, the windy season for the time caused an estimated production loss of nearly 1.5 GWh.

Given the example from this first period of operation at Lillgrund, it seems planned stops during summer season lasting longer than one day cause a negligible loss of production compared to unplanned shutdown of turbines in more windy times of the year. Assuming the first year of operation is representative, one can conclude that the information given by a prediction tool such as WPPT, would be of minor practical importance to the operational planning at Lillgrund.

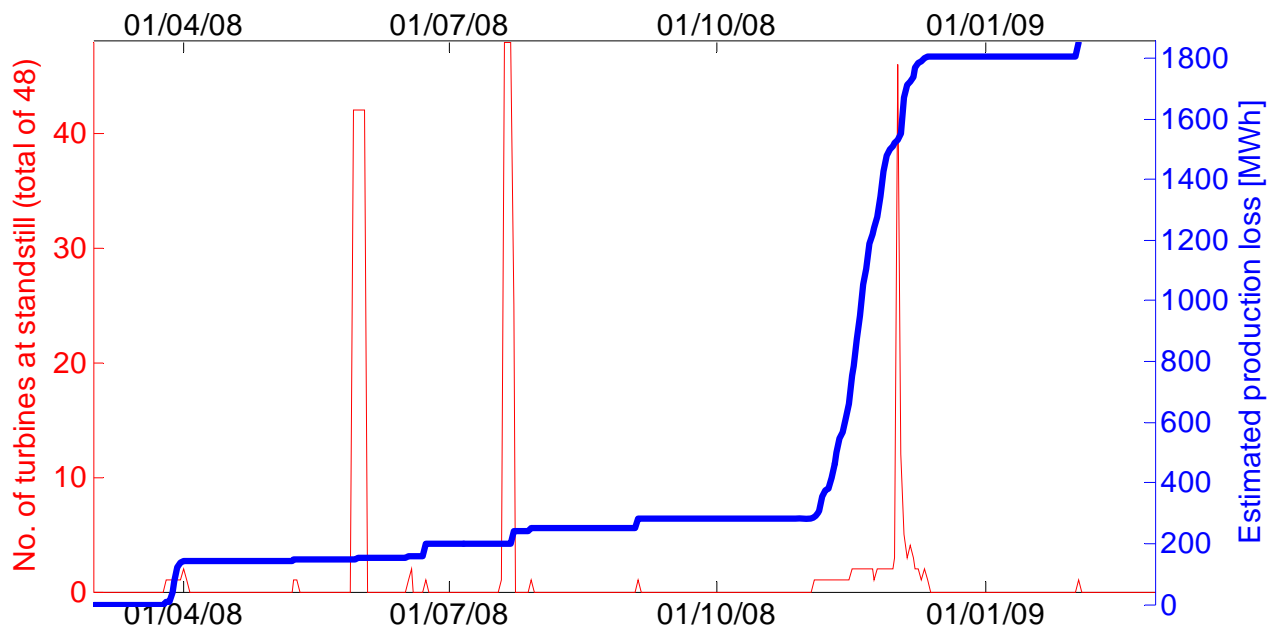


Figure 9. Number of turbines at stand still during more than 24 consecutive hours, in red. The corresponding estimated cumulative production loss due to these turbines at stand still is given in blue.

4 COMMENTS AND CONCLUSIONS

Weather forecasts will become important when it comes to predicting energy production from wind farms such as Lillgrund, but due to the low penetration of wind power in the Swedish grid today, about 1%, forecasting does not receive much attention. Vattenfall has implemented one of several available forecasting tools, WPPT. Originally, the weather forecasts used as input to WPPT came from only one distributor. But since the use of forecasts from several different NWP-models can help estimating the uncertainty, Vattenfall has recently started purchasing data from a second distributor. At the time of this report, no deeper analysis has been made to find out if this has improved the forecasts or not.

WPPT cannot be used when it comes to planning maintenance of the park. The time horizon in maintenance planning is much longer than that provided by WPPT forecasts; the local power network owner must be noticed several weeks in advance. This also means that there never will be a weather forecast to rely on when it comes to scheduling maintenance work; even if we in the future will be able to make “perfect” forecasts, uncertainties in initial conditions and the chaotic nature of the atmosphere will make the forecast useless beyond approximately 14 days. More importantly, the maintenance ship operators have their own contracts with marine forecasters independently of the production forecast supplier. This is perfectly logical considering the different demands on the meteorological and oceanographic information of a ship's captain compared to that of a production planner or trader.

To minimize the production loss due to planned maintenance, the stops should be scheduled in the summer season when the wind is normally weaker. Unplanned stops of only a few turbines can result in major losses in energy production if it occurs during a windy period. It's obvious that all available precautions should be taken to avoid unnecessary unscheduled stops.

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