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Title	Impact of wind power on the unit commitment, operating reserves, and market design
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Publication date	2011-07-24
Publication information	Kiviluoma, Juha, Mark O'Malley, Aidan Tuohy, Peter Meibom, Michael R. Milligan, Bernard Lange, Hannele Holttinen, and Madeleine Gibescu. "Impact of Wind Power on the Unit Commitment, Operating Reserves, and Market Design." IEEE, July 24, 2011. https://doi.org/10.1109/PES.2011.6039621 .
Conference details	Paper presented at the 2011 IEEE Power and Energy Society General Meeting, San Diego, CA, 24-29 July 2011
Publisher	IEEE
Item record/more information	http://hdl.handle.net/10197/3583
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Publisher's version (DOI)	10.1109/PES.2011.6039621

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Impact of Wind Power on the Unit Commitment, Operating Reserves, and Market Design

Juha Kiviluoma, Mark O'Malley, Aidan Tuohy, Peter Meibom, Michael Milligan, Bernhard Lange, Hannele Holttinen, Madeleine Gibescu

Abstract— This article highlights and demonstrates the new requirements variable and partly unpredictable wind power will bring to unit commitment and power system operations. Current practice is described and contrasted against the new requirements. Literature specifically addressing questions about wind power and unit commitment related power system operations is surveyed. The scope includes forecast errors, operating reserves, intra-day markets, and sharing reserves across interconnections. The discussion covers the critical issues arising from the research.

Index Terms—Unit commitment, power system operations, reserve allocation, economic dispatch, operating reserves, ancillary services, wind power, market design

I. INTRODUCTION

WIND power is becoming an important part of power system operations in many regions of the world. This presents a challenge, since wind power production has a large variability and is associated with a considerable forecast error [1]. The article attempts to present the challenges, how they are analyzed in the literature, and what requirements emerge for power system operations due to large scale wind power. Actual system operations and market design should be informed by current research reviewed in the article. The article focuses on unit commitment (UC), ancillary services, and market design issues directly related to the UC.

UC through a market mechanism or by a system operator creates schedules for power plant operation. The convention has been to commit generation units once per day well ahead of the hours of actual operation (day-ahead markets described in e.g. [2][3]). More wind power increases uncertainty especially in the day-ahead time scale. Larger uncertainty in the residual/net load (wind power production

subtracted from electricity demand) means that committed units will be run below rated output level more often. At the same time variability in the net load increases and this will require more start-ups, part-load operation and steeper ramps from the conventional generation units.

Together these two factors, increased uncertainty and variability, call for more flexibility in the power system. Increased demand for flexible resources could be reduced with some changes to the current practices in the system operation. These possibilities are explored in the article.

The problem is becoming current. When wind power production increases, the forecast error of wind power starts to dominate that of demand in the day-ahead UC time scale during more and more hours. As an example, around 20% penetration led to wind power causing largest part of imbalances in the Danish system [4]. Wind power production is already quite high in Portugal, Spain, Denmark, parts of Germany and Ireland while many more countries have official targets surpassing the 20% mark [5].

The article summarizes how UC and power system operations are currently performed (Section II). Section III describes how large scale wind power creates new requirements for power system operations and how that has been analysed in the literature. Section IV highlights the critical issues arising from the research. Examples are used to quantify the possible impacts, although it is clear that the level of impacts will vary between power systems. Section V finishes the article with conclusions.

II. UNIT COMMITMENT

The primary objective of the UC process is to minimize costs while ensuring that sufficient generation is online to meet the demand for electricity and for different types of reserve power over the commitment time period. Part of the UC problem is to also take into account the supply of additional reserves in the form of off-line units that can be brought online and synchronized when needed, and to also account for potential imports and exports. Key inputs to the UC process include the status and characteristics of the generation fleet, along with demand and wind forecasts.

Historically, day-ahead UC was performed by the vertically integrated utilities. As power systems have come increasingly unbundled throughout the world, UC has become a tool for the market players generating power to maximize their profits from the power markets. It is also a planning tool for TSO/ISO/RTOs who need to safeguard the

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reliable operation of the system and facilitate the market by timely reinforcement and expansion of the transmission network. UC is an essential tool for predicting the likely generation injections at various nodes in the network depending on the demand situation. The combination of generation and demand will determine the power flows that need to be monitored for system reliability.

Traditionally, UC has been carried out for units on a day-ahead basis [6]. The commitment of slower units and cross border (or system) power exchanges is done usually 12-18 hours in advance of the start of the day. Base load units with longer startup times are sometimes allowed to be recommitted intraday in this type of operation. This is the current approach used by industry, and is well covered in the literature; see for example [7]. The approach to UC has been predominantly deterministic – uncertainty in demand and power plant outages has not been considered to affect UC.

The rationale for the day-ahead UC is due to the temporal nature of the constraints on some of these units. Factors such as startup time, minimum up and down time and ramp rates need to be taken into account over a long time horizon. For example older coal units may take up to one day or more to start up, therefore necessitating the need for long time horizons in UC, see for example [8].

Fig. 1 shows a simplified UC process for a system. The day-ahead demand forecast, plus reserves¹ and losses (and perhaps other considerations such as exports and imports) is the commitment target. The commitment stack must be able to manage primary frequency control² and secondary frequency control³, tertiary frequency control⁴, and meet the ramp requirements over all time frames.

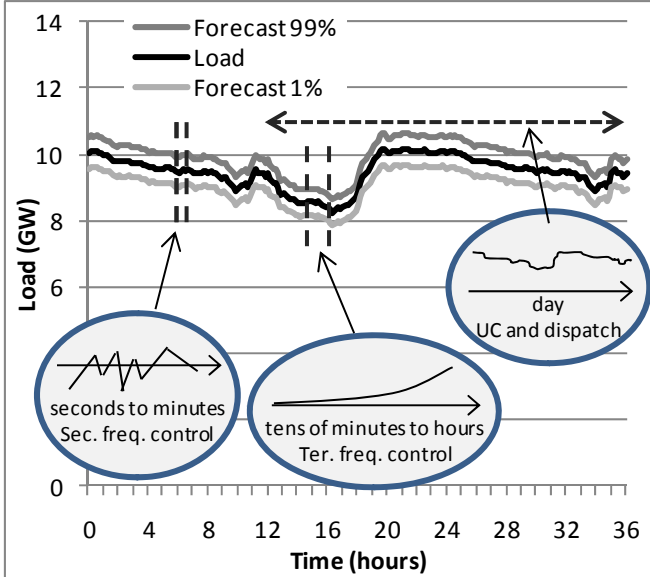


Fig. 1. Time frames of unit commitment and reserves

¹ The article uses the general terms for different frequency related ancillary services as defined by Rebours *et al* [9].

² “to restore quickly the balance between load and generation and counteract frequency variations. In particular, it is designed to stabilize the frequency following large generation or load outages.” [9]

³ “restores the frequency and the interchanges with other systems to their target values after an imbalance” [9]

⁴ “to restore the primary and secondary frequency control reserves, to manage congestions in the transmission network, and to bring the frequency and the interchanges back to their target value when the secondary control is unable to perform this last task” [9]

Primary reserves are usually dimensioned based on a n-1 criteria i.e. being able to cover the outage of the largest single source of electricity. Secondary reserve requirement is mainly driven by the n-1 criteria and the short-term variation in electricity demand. Demand forecast is relatively accurate in the 36 hour time range, as shown by the 99% and 1% bands in Fig. 1, and therefore a limited amount of tertiary reserves can ensure a reliable system operation.

III. IMPACT OF WIND ON UNIT COMMITMENT

Unit commitment and system operations are more challenging with a large amount of wind power in the system. The net load (load less wind) that must be served by the non-wind generation fleet will be more variable and more uncertain than demand alone. Fig. 2 shows an example, using the same day as Fig. 1. There are different ways to manage the changed situation. The most obvious is to increase the amount of reserves, but there are others as will be discussed later in this article.

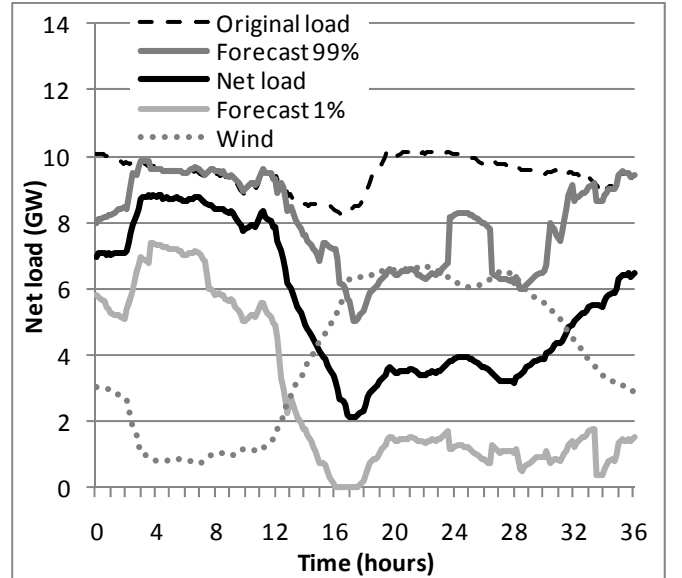


Fig. 2. Uncertainty in the net load with a large amount of wind power in the system (approx. 20% of annual consumption).

Comparing the demand with the net load, one can see that there is a need for the committed generation to achieve lower operational points and faster ramps than if there were no wind on the system. In the first figure demand had a relatively small uncertainty, which does not much change from one hour ahead to 36 hours ahead. In contrast, the uncertainty in Fig. 2 is much larger and increases in time. Variation in the faster time scales (seconds to minutes) is also increased, although not shown in the figure.

This section will first describe wind power forecast uncertainty to give some background. After that different aspects of UC and power system operations are described from the perspective of large scale wind power: scheduling the dispatch, reserves including ways to limit its increase, UC strategies, and shortly power flow and solving method issues. The article uses current literature to highlight the challenging aspects.

A. Description of Wind Power Forecast Uncertainty

In power systems with a sizable amount of wind power, UC without wind power forecasts would be inefficient and therefore cause avoidable costs. This section describes characteristics of wind power forecasts and how forecasts can be taken into account in the power system operations.

Numerical weather prediction (NWP) models create weather predictions that are used by wind power forecast tools. Forecast tools provide predictions of wind speed, wind direction and other meteorological parameters, usually in hourly resolution for forecast horizons of several days. The accuracy of the input data to the NWP models also determines the accuracy of the wind power forecast to a great extent. (See Fig. 3)

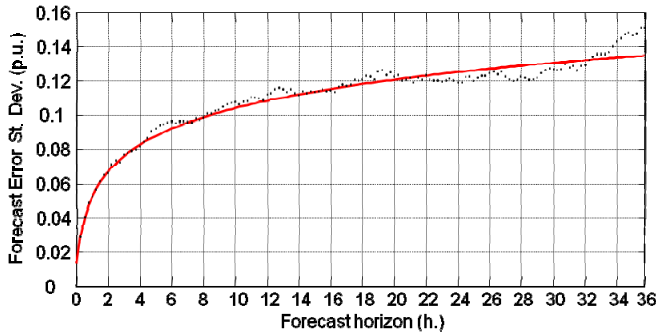


Fig. 3. Normalized standard deviation of wind power forecast error for 12 GW installed capacity versus forecast horizon [10].

So called ‘day-ahead’ forecasts use only NWP data as input. They typically have forecast horizons of 6 hours to some days. For shorter forecast horizons (up to about 8 hours), so called ‘shortest-term’ forecasts are used, which use online measurement data in addition to NWP data [11]. In most cases the online data is from wind farms, but sometimes also from wind speed measurements. Current data correlates with the near term production and significantly improves the accuracy of shortest term forecast. Shortest term forecasts can be used by mechanisms that have shorter time span than the day-ahead unit commitment. These include intra-day and balancing markets in the market environment as well as re-dispatch by the system operator in the regulated environment.

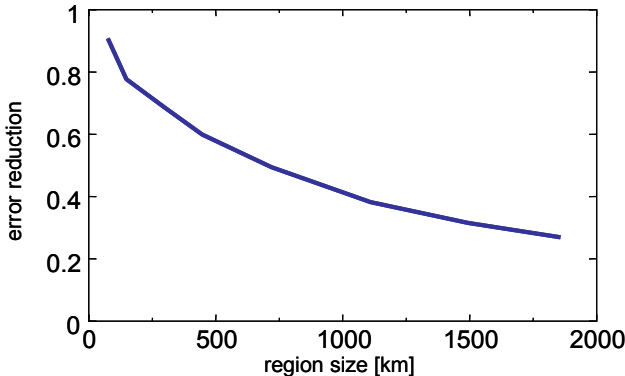


Fig. 4. Decrease of forecast error of prediction for aggregated wind power production due to spatial smoothing effects. Error reduction = ratio between rmse (root-mean-square-error) of regional prediction and rmse of single site, based on results of measured power production of 40 wind farms in Germany. Source: energy & meteo systems GmbH (www.energymeteo.com).

The accuracy of wind power forecasts depends also greatly on the spatial distribution of wind power. The larger the number of wind farms and the larger the area, the smoother is the power output and the more accurate the wind power forecast (Fig. 4). Thus, for UC and system operations, a large balancing area⁵ with more wind farms is preferable.

Another important factor for the forecast accuracy is the update frequency of the NWP input data, since older data will also increase the wind power production forecast horizon and the forecast error accordingly. The possible update frequency of wind power forecasts for the day-ahead UC depends solely on the available NWP input data updates, which usually take place between 1 and 4 times per day. Some weather services run specific shortest-term weather models, which are updated much more frequently and calculated faster, e.g. the LMK model of the German Weather Service DWD which runs every 3 hours (see [12]).

For the ‘shortest-term’ forecast, there are two update cycles: One for the online measurement data and one for the NWP data. Online measurement data can be updated constantly. The shorter the forecast horizon, the more weight have the online data and the less dependent the forecast is on the update frequency of the NWP model. Wind power generation depends on the weather systems, which are mathematically described as chaotic rather than stochastic. This means that the probability distribution of wind power forecasts cannot be approximated with normal distribution. The distributions for forecast errors and wind power ramps have ‘thick’ tails (Fig. 5). While demand forecast error distribution is not likely to be normal either, the variance and the tails are much smaller. This is important from the power system operation perspective – the UC process has to take these rare but significant events into account. This could mean larger reserves or changes in market design as discussed later.

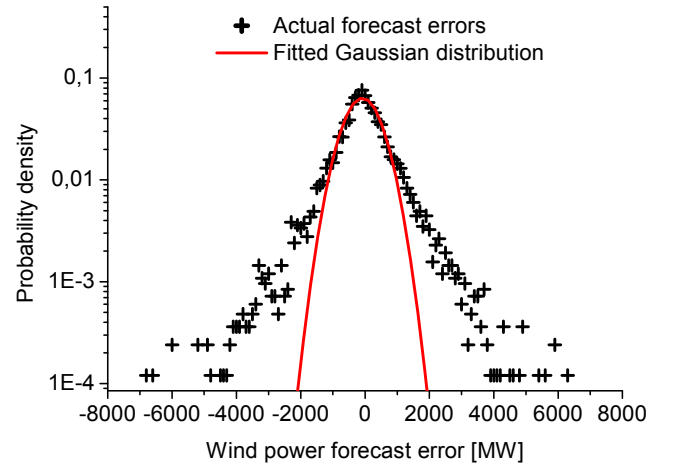


Fig. 5. Probability distribution of wind power forecast errors (from [10]).

B. Reserves

When wind power is added to the system, the uncertainty associated with wind forecasts could be met with an increase

⁵ Area where the system operator is responsible to maintain frequency and a physical balance in relation to adjacent areas. A tight co-operation between balancing areas could achieve similar results.

in reserve levels [13][14], although other approaches are also possible as discussed later. There is a considerable range of methods that are used to calculate the impact of wind energy on the required operating reserves. Although there are important differences in the methods, the goal of all methods is to capture the range of variability and uncertainty that would be seen in practice by system operators with large amounts of wind power.

Fresh wind power forecasts are not available in the sub-hourly time scale where the secondary frequency control reserves operate. At the same time, the ramps in the net load will increase with higher wind penetrations. Since the rate of change in the output of large scale wind power changes relatively slowly in that timescale, persistence forecast gives a rather good approximation of the production in the next 10-15 minutes. Statistical methods assessing the standard deviation of wind variability, Monte-Carlo simulations using time-steps, and analysis in the frequency domain have been used to assess the required amounts of secondary frequency control reserves [15].

Tertiary frequency control reserves include many different kinds of reserve categories depending on the power system. Usually they are manually activated and have to be fully available in approximately 15 minutes. Upward tertiary reserves are predominantly formed from fast starting power plants that did not get scheduled in the day-ahead UC and downward tertiary reserves are from scheduled power plants able to reduce their output. Some loads can also participate in the tertiary reserves.

Methodologies assessing the tertiary frequency control reserves have included forecast error statistics with and without the consideration of wind power output level, stochastic optimization, time-step Monte-Carlo simulations [16], and risk based methods. The actual increase in the tertiary frequency control reserves has been studied in different systems. Holttinen *et al* [1] summarizes the results from several wind integration studies. It is difficult to make any general conclusions, since the methodologies, assumptions, and power systems vary. Milligan *et al* [15] deals with the secondary and tertiary reserve issues in more detail.

C. Approaches to Unit Commitment

As discussed above, the UC algorithm must take into account the variability and uncertainty that must be managed by the non-wind generator fleet in the commitment stack. This is best accomplished by incorporating the requirements for the various reserves as a constraint into the optimization process. The additional flexibility (which includes ramping and minimum stable generation levels) may already be available as a byproduct of the commitment process. In other cases, however, the traditional UC may not provide enough flexibility; thus the constraints are required to ensure that the commitment stack can perform as needed over the operating period.

There are several alternative formulations and approaches that can be taken to UC. In the next two subsections different methodologies are inspected more closely and after that a categorization is presented.

D. UC in Day-ahead Only

In the literature relating to wind power and UC, much of it assumes that UC will continue to be carried out day-ahead, with the chance to change the commitment of units, particularly slower units such as steam turbines, only being provided once a day. Methods are then developed to determine the best way to commit power plants.

Restrepo *et al.* [17] examine the effect that including a probability distribution of wind power with deterministic UC will have on the day-ahead UC, assuming a prediction error which remains constant throughout the day. It is shown as expected that the amount of wind curtailed can be quite high.

Ruiz *et al* [18] combine stochastic programming methods with increased reserve to examine the impact of wind on the day-ahead UC. It is shown that using stochastic methods combined with a proper amount of reserve reduces wind curtailment and increases the robustness of the day-ahead solutions.

Wu *et al* [19] and Wang *et al* [20] describe a security constrained stochastic UC model which models uncertainty of wind power in the day-ahead time frame. In [20] an algorithm for calculating a day-ahead UC schedule is presented taking network constraints into account and being robust towards wind power forecasts errors.

Bouffard [21] proposes a short-term forward electricity market-clearing problem with stochastic security taking wind power generation into account. This presents an algorithm which can be used to maintain security while costing less than a deterministic solution. An example from a small system illustrates the benefits.

Pappala *et al* [22] also present an algorithm to include wind power uncertainty in UC decisions; again the forecast error increases with time horizon, though the authors point out that the uncertainty does not monotonically increase. It is again shown that stochastic methods can increase the integration of wind power while maintaining power system reliability.

Much of the current methodologies can therefore be seen to use day-ahead UC. The uncertainty over wind power production 24 hours or more into the future means that the realised commitments are far from what would be ideal in the case when wind production were accurately known. If the increased uncertainty is dealt with reserves, then Fig. 6 shows the average replacement reserve (similar to tertiary frequency control reserve in the terminology of this article) that is needed as the time horizon for forecast updates increases for the Irish system with 6000 MW of wind in 2020, taken from [23]. This is determined based on the 90th percentile of forecast error, which was found to correspond to the required 8 hours loss of load expectation [23]. As can be seen, the average amount of required reserve over the year increases when rescheduling due to updated forecasts is done less often.

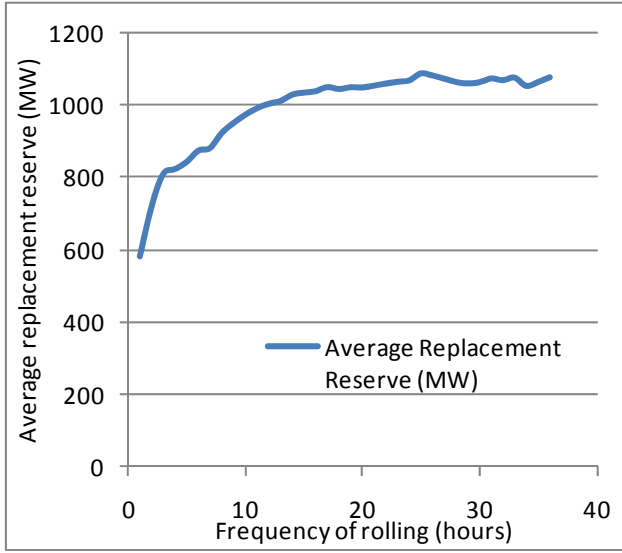


Fig. 6. Increase in reserve requirements as time between forecast updates increases [23].

E. Intra-day UC

Repeating UC in the intra-day would make use of more accurate wind forecasts and this would result in more accurate UC. Generally, repeating UC in the intra-day would still require that a 24 hour or 36 hour UC is carried out to accommodate slower starting units; however these schedules are now updated whenever new information is available. By using newer information, the reserves actually carried on the system can be reduced, as illustrated by Fig. 6.

At present, intra-day recommitment is carried out if there has been a major change to the system, for example a large outage of a transmission interconnection line or generating unit. Markets with significant amount of wind power could have the opportunity to recommit based on updated forecasts as is proposed in [[24]-[26]] and/or trade wind power surpluses or deficits in intra-day markets. These are currently available e.g. in the Nordic system, in Spain and the Netherlands.

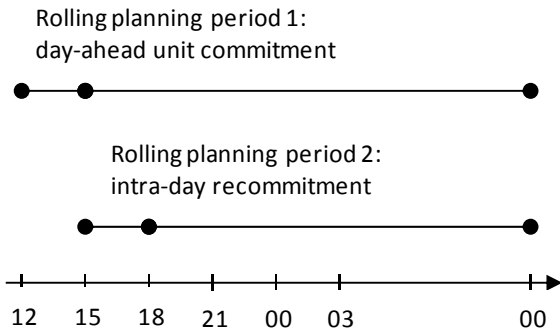


Fig. 7. Illustration of rolling planning

Fig. 7 shows the concept of rolling UC that can simulate the intra-day markets or the behavior of the regulated system operator. As can be seen, the day-ahead schedule is first produced as before, shown by the top line. Then, the system is recommitted when new information becomes available, in this case 3 hours later and UC would be repeated every three hours until the next day-ahead unit commitment. The actual

structure could be different in regards to the time between commitments or the length of the planning period [24].

For intra-day UC certain ‘here and now’ decisions have to be taken at the time of optimization. Some units have to be committed: those that will help to meet demand before the next UC and those whose commitment decision cannot be postponed so that they can provide energy in a later period. The remaining time frame of the UC can be thought of as ‘wait and see’. Here, a provisional commitment schedule for units is produced, which can be changed later when up-to-date information arrives.

F. Categorization of UC methodologies

Based on the previous two subsections, it is now possible to divide the different UC methodologies for wind power studies into categories. The main division depends on the way the information about wind power and demand uncertainty has been handled in the methodology. Another important factor is whether recommitment is possible in the intra-day. Table I shows the categorization.

G. Other Issues

Power flow constraints are not always included in the UC models, as the network calculations are computationally time consuming. In order to simplify the problem many wind power integration studies have not taken power flows into account. Instead they have just used net transfer capacities defined by the TSOs. This could be followed by a detailed load flow analysis using the results from the multi-area UC as input (see [27]). However, for meshed grids a simplified load flow is necessary to achieve realistic results.

UC models usually use mixed integer programming (MIP) to capture the on/off decision variables for the starts and stops of individual units. The recent trend in wind integration studies has been towards simulating larger areas. This is due to the fact that most impacts of wind power can be diminished by using interconnection capacity to neighboring countries. It is also the trend in electricity markets to include several countries and sub-systems. To capture the impacts better, simulation of regions containing all relevant neighboring areas or the whole market area is needed. To reduce the problem size, relaxed mixed integer programming (LP) has been introduced for larger systems (see [28]). It is therefore also of importance to compare the two methods and develop the more simplified LP programming to represent start-up costs, minimum load factor and lead times.

IV. IMPLICATIONS

The implications of significant penetration of wind power for the UC process are manifold. This section discusses intra-day recommitment, the need for better forecasting tools, dynamic reserve allocation, benefits of sharing resources over interconnections, handling very large forecast errors, importance of information about ramp events, and sub-hourly scheduling.

A. Intra-day recommitments

Day-ahead UC of slow starting units without the possibility of intra-day rescheduling increases operational

TABLE I
CATEGORIZATION OF APPROACHES TO UNIT COMMITMENT

One perfect forecast	Perfect information about wind power production and electricity demand in the day-ahead time scale. Can be used as a base case for estimating the cost of uncertainty.		
One forecast	A rule based adder for reserves, either in MW or percentage terms is used to account for uncertainty.	UC only in day-ahead With significant wind power penetration a large tertiary reserve would be required. E.g. [29]	
		Intra-day UC Decreases the required reserve adder and the amount of wind curtailment.	
Pre-processed one forecast	The UC model is deterministic with one forecast, but the data about wind and demand uncertainty has been pre-processed to create a reserve requirement that is based on probabilistics.	UC only in day-ahead With significant wind power penetration a large tertiary reserve would be required. [17] was based on achieving an explicit loss of load probability (LOLP) for each hour of the year.	
		Intra-day UC	Statistical rules Pre-processing is based on statistically derived rules.
			(LOLP) approaches Convolution of various probabilities to arrive at the desired LOLP. These approaches can be either static or dynamic with the latter providing a more robust and economically efficient commitment schedule.
Stochastic	Optimization of UC decisions over several scenarios for possible outcomes of wind and demand. Scenarios cover part or all of the tertiary reserve requirement. E.g. [24], [30], [31]		

costs significantly in power systems with large amounts of wind power. The day-ahead UC schedules are often sub-optimal in the real time operating situation due to the changes between the day-ahead forecasts of net load used in the day-ahead UC and the realized net load. Too little online capacity will be allocated when the realized wind power is less than the day-ahead forecast leading to operation of expensive peak load units, and in the opposite case allocating too much online capacity day-ahead leading to increased amounts of wind curtailment in the actual operating hours.

Intra-day UC would be used by system operators and market parties to ensure there is adequate generation to meet demand, while reducing costs; it would also be used for intra-day balancing markets that are seen as important when integrating wind power [26]. Certain unit constraints may become far more important when using intra-day UC; for example startup times of units, which may be longer than the time between commitments [32]. These questions have to be taken into account in the market design.

Tuohy *et al* [24] show that increasing the frequency of commitment from 6 hours to 3 hours can bring tangible benefits in terms of cost and reliability in the Irish system; however modeling limitations mean that any benefits of decreasing the rolling planning period further are not shown there.

B. Improved forecasts

Improved forecasts would decrease the uncertainty in the wind power output. The benefits of better forecasts are potentially very large in absolute monetary terms in a large power system with lot of wind power. As described in the subsection describing forecast uncertainty, there is lot of ongoing research to improve the wind forecasts.

It was also noted that the forecasts can only be as good as the underlying data. Currently large part of the meteorological data collection takes place at the relatively slow pace of one once or four times per day. In order to increase the accuracy of wind power forecasts, it could be

worthwhile to invest in higher frequency data collection and improved weather observation networks.

C. Dynamic reserve allocation

Traditionally reserves have had a fixed MW target. However, this would suit poorly in a system with lot of wind. The demand for tertiary frequency control reserves is affected by the possible error in the wind forecast. When the forecasted wind output is low, there will not be any need for large upward reserve due to wind power. However, when the forecasted wind output is high, the tertiary frequency control reserve should be comparable to the possible forecast error. The reserve level should depend on the uncertainty of the forecast, which changes depending not just on the wind output but also on the weather situation at large.

D. Cross System Scheduling

Sharing of balancing reserves over an interconnection can reduce the total amount of reserves. The cost of providing these will also decrease as more units can operate at their efficient levels.

Milligan and Kirby [33] review the benefits of larger balancing areas for the integration of variable generation and argue that the benefits are important. The work in [34] and [35] investigated the impact of using cross border scheduling for integration of wind power in the Netherlands. The results indicate clear benefits for sharing of balancing reserves over system borders. The results of the TradeWind study [36] highlighted the benefit of intra-day rescheduling of cross border exchanges compared to day-ahead exchange.

E. Unusual Events not Covered by the Committed Resource Stack

In the description of wind forecast errors, it was brought forth that the probability distribution of wind power forecast has long tails due to unusual weather events. It is therefore important to represent the full supply curve for the various reserve products in the UC phase. Especially beneficial would be different forms of demand response where non-

critical applications could be shut down in the case of very high prices.

However, it can still happen that the committed resource stack is not large enough in some relatively rare circumstances and that it does not necessarily make economic sense to be always fully prepared for them in the UC phase, because the risk may be too small to warrant the costs of keeping up the reserves. In these situations, resulting in either insufficient capacity or over commitment, there are still other options available.

After the stack for tertiary frequency control reserves has been exhausted, it is possible to utilize contingency reserves. However, this should be contrasted against the increased risk of system black out and associated value at risk. A better option might be involuntary loss of load for pre-selected segments of consumption. In the case that transmission interconnections are not re-scheduled in normal operations, it would be possible to use resources from neighboring systems with emergency exports or imports. For the events where there is too much production, wind curtailment should be made possible to alleviate the situation.

Modeling frameworks are developing to incorporate some of these issues, but this evolution is primarily occurring with research models and not the wide-spread commercial production simulation models that are used by the power industry at large.

F. Ramps

In addition to the more pressing issues above, there are other issues in UC that large wind power penetration will also affect. One of them is ramping of wind power generation. Fig. 6 illustrates ramping extremes of wind power production. Will there be enough capacity to move the operational point of power plants fast enough when the ramps get steeper at higher wind power penetrations? The optimization of simultaneous ramping of multiple units is required to ensure this. It can lead to situations where fast units are used to help slower but less expensive units to reach required production levels during a ramp event.

G. Sub-hourly scheduling

To appropriately capture impacts of wind power, unit scheduling should have high enough temporal resolution. Hourly time scale is often considered to be detailed enough. However, large penetration of wind power will also increase the importance of intra-hour scheduling, since ramp rates will get higher. Sub-hourly scheduling, at 10 to 15 minute time steps would better capture the operating time scale of some systems.

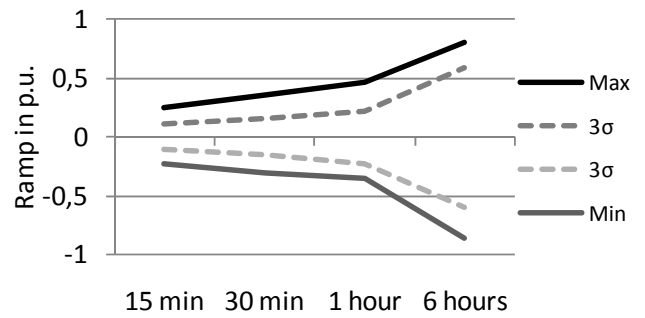


Fig. 6. Extreme ramps in wind power production in different time scales. Data from Netherlands with simulated 7800 MW of wind power [32].

V. CONCLUSIONS

The article has reviewed the new requirements that integrating large amounts of variable and partly uncertain wind power production could bring to UC and power system operations. Unit commitment models can help to understand the impacts of wind power as well as to evaluate new market designs for systems with large amounts of wind power.

It is clear that the quality and timing of wind power forecasts derived from NWP is critical in reducing the uncertainty in the UC and operational planning, which will in turn reduce the operational costs.

The article proposed several ways to limit the required amount of tertiary frequency control reserves due to wind power. Unit commitment and reserve allocation could be performed more often than currently. Usefulness of this would depend on the quality of intraday forecasts and on power system properties – inflexible systems could benefit more. Using stochastic information about the forecasts during the unit commitment would make more robust commitment decisions. Likewise, increasing the market size for tertiary reserves by allowing cross border trading of reserves would help to decrease the joint reserves.

VI. ACKNOWLEDGMENT

This paper is a result of the international collaboration IEA WIND Task 25 Design and Operation of Power Systems with Large Amounts of Wind Power.

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