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Impact of Wind Power on the Unit Commitment and Power System Operations

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Abstract— **The article reviews the new requirements variable and partly unpredictable wind power could bring to unit commitment and power system operations. Current practice is shortly described and contrasted against the new requirements. Literature specifically addressing questions about wind power and unit commitment related power system operations is reviewed. Analyzed issues include forecast errors, dispatch, operating reserves, intra-day unit commitments, and sharing reserves across interconnections. Discussion highlights the most important issues and gaps in the current knowledge.**

Index Terms—**Unit commitment, power system operations, reserve allocation, economic dispatch, ancillary services, wind power**

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) and ancillary services directly related to the UC.

Unit commitment through a market mechanism or by a system operator creates schedules for power plant operation. The convenient convention has been to commit generation units once per day well ahead of the hours of actual operation. 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 operating the system will require more flexibility – more reserves and more committed units. Increased demand for flexibility 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 a point of reference, around 20% penetration led to wind power causing largest part of imbalances in the Danish system [2]. Wind power production is already at that level in Portugal, Spain, Denmark, parts of Germany and Ireland while many more countries have official targets surpassing the 20% mark.

The article shortly 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. Discussion in Section IV highlights the critical issues.

II. UNIT COMMITMENT AND POWER SYSTEM OPERATIONS WITHOUT WIND

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 or retailing power to anticipate their positions in the market. It is also a tool for TSO/ISO/RTOs who need to safeguard the reliable operation of the system and facilitate the market by timely reinforcement and expansion of the transmission network. System operators routinely conduct planning studies to determine whether any network congestion may arise for a variety of future scenarios. UC is an essential tool for predicting the likely generation injections at various nodes in the network depending on the load situation and these together will determine the power flows.

The primary objective of the UC process is to minimize costs while ensuring that sufficient generation is online to meet the load demand 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 a load forecast.

Traditionally, UC has been carried out for units on a day-

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ahead basis [3]. Here, 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 [4]. The rationale for the day-ahead UC is due to the temporal nature of the constraints on 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 [5].

Fig. 1 shows a simplified UC process for a system with no wind. The day-ahead load forecast, plus tertiary frequency control reserves and losses (and perhaps other considerations such as exports and imports) is the commitment target[1]. The commitment stack must be able to manage secondary frequency control (“restores the frequency and the interchanges with other systems to their target values after an imbalance” [6]), tertiary frequency control (“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” [6]), and meet the ramp requirements over all time frames. In addition there is primary frequency control, which is mainly used to cover large disturbances due to power plant or transmission line failure and is here considered separate from the UC.

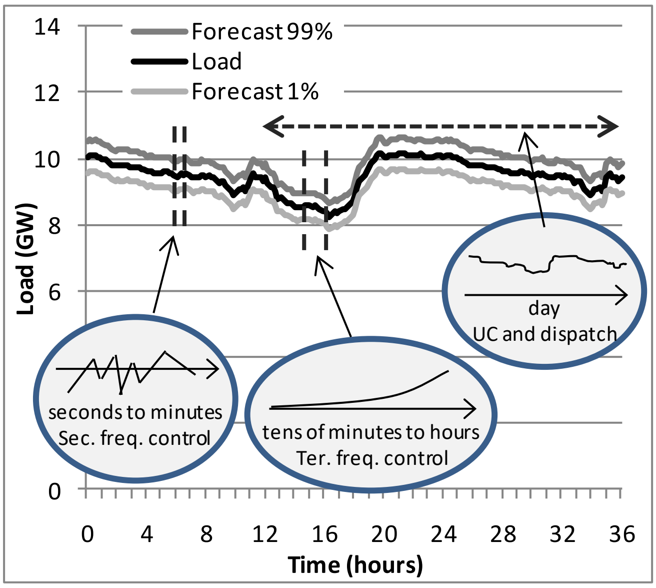


Fig. 1. Time frames of unit commitment and reserves

Secondary frequency control is usually derived from power plants that operate near their optimal operating point, but can change their output within some margins. They automatically react to deviations from the system frequency. However, their reserve is limited, and they must be relieved so that they can react to new changes in the frequency.

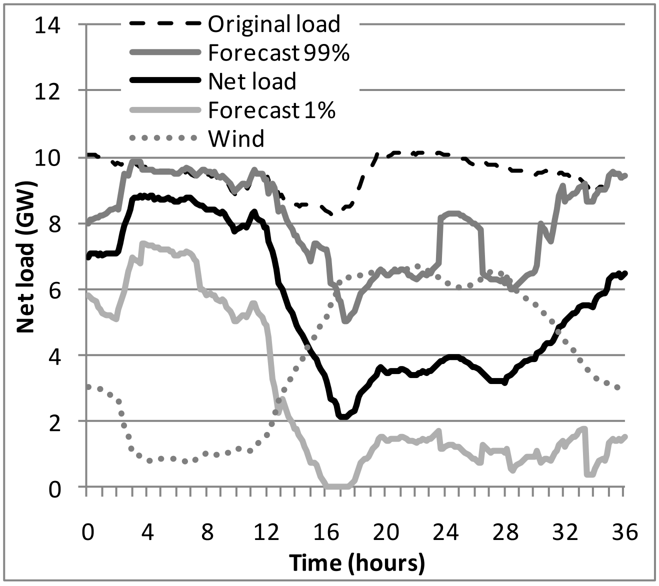
Throughout the day secondary reserves are relieved by the power plants scheduled to come online to meet changes in the load – usually with an hourly resolution. This is not enough, since the load fluctuates in shorter time resolution as well and since the realized load will be different from what was predicted during the day-ahead UC. To mitigate the cumulative errors, tertiary frequency control reserves are also used.

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 power plants that did not get scheduled in the day-ahead market and downward tertiary reserves are from scheduled power plants able to reduce their output. Some loads can also participate in the tertiary reserves. In a market based environment, units willing to provide the service have been bid to a tertiary reserve market after the closing of the day-ahead market. System operator calls the bidders in price order unless system security requires skipping bids. The use of tertiary reserves can be reduced with intra-day markets, in which the original dispatch of slower power plants can be changed.

Load forecast is relatively accurate in the 36 hour time range and therefore a limited amount of tertiary reserves can ensure a reliable system operation. However, tertiary reserves also relieve primary reserves and that needs to be also taken into account.

III. IMPACT OF WIND ON UNIT COMMITMENT AND SYSTEM OPERATIONS

Unit commitment and system operations are more complex 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 load alone. Therefore, there is a need for additional reserve to manage this increase in variability and uncertainty, and this reserve requirement must be taken into account by the UC process. Fig. 2 shows an example, using the same day as Fig. 1.



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[1] The article uses general terms for different frequency related ancillary services as defined by Rebours et al [6].

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

Comparing the load 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 load 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 a 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 some less important issues. The article uses current literature to highlight the challenging aspects.

A. Description of Wind Power Forecast Uncertainty

For the integration of a sizable amount of wind power into a power system, wind power forecasting is indispensable. UC of the other power plants and balancing of supply and demand would be highly inefficient if not impossible without a wind power forecast.

Wind power forecast tools use weather predictions by numerical weather prediction (NWP) models as input, which provide predictions of wind speed, wind direction and other meteorological parameters, usually in hourly resolution for forecast horizons of several days. The accuracy of this input data also determines the accuracy of the wind power forecast to a great extent. (See Fig. 3)

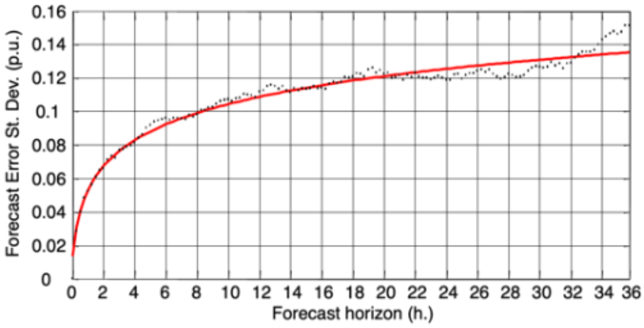


Fig 3. Normalized standard deviation of wind power forecast error for 12 GW installed capacity versus forecast horizon [28].

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 [7]. In most cases the online data is from wind farms, but sometimes also from wind measurements. Current data correlates with the near term production and significantly improves the accuracy of shortest term forecast.

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 area with more wind farms is preferable.

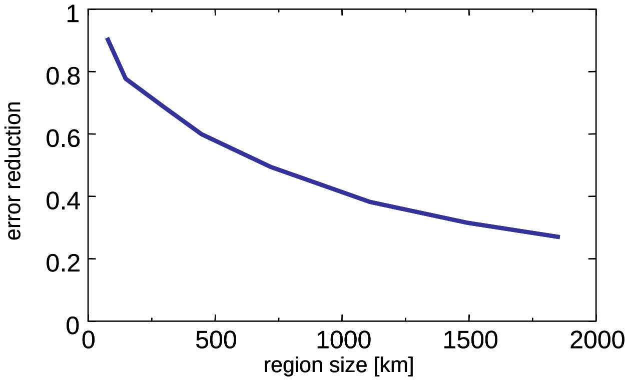


Fig. 4. Decrease of forecast error of prediction for aggregated wind power production due to spatial smoothing effects. Error reduction = ratio between rmse (root-mean-square-error) of regional prediction and rmse of single site, based on results of measured power production of 40 wind farms in Germany.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

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 ‘day-ahead’ wind power forecasts depends solely on the available NWP input data updates, which usually take place between 1 and 4 times per day. If the input data is updated only once per day, it can be almost 24 hours old in the last wind power forecast updates before the arrival of new NWP input data. Additionally, NWP models are computationally very expensive and usually need calculation times of several hours. If the data is 24 hours old, the NWP calculations take 6 hours, and wind power production is forecasted 8 hours into the future, forecasts in the end of the horizon can be based on input data which is 38 hours old. This considerably decreases forecast accuracy compared to an ideal situation.

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. 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 [9]).

Wind power generation for a large amount of installed capacity shows on average a relatively smooth behavior and can usually be forecasted with a high degree of accuracy. However, wind power generation depends via the wind speed on the weather development, which is mathematically described as chaotic rather than stochastic. This leads to an increased probability of large forecast errors in comparison to the mean forecast errors. This can be seen in the probability distributions for the wind power gradients and the forecast error, which do not follow a normal distribution, because they have ‘thick’ tails (Fig. 5).

The second reason for large gradients in wind power generation is the nonlinear relation of the power curve of wind turbines. The power output increases from 10% to 90% approximately in the wind speed interval between 6-12 m/s.

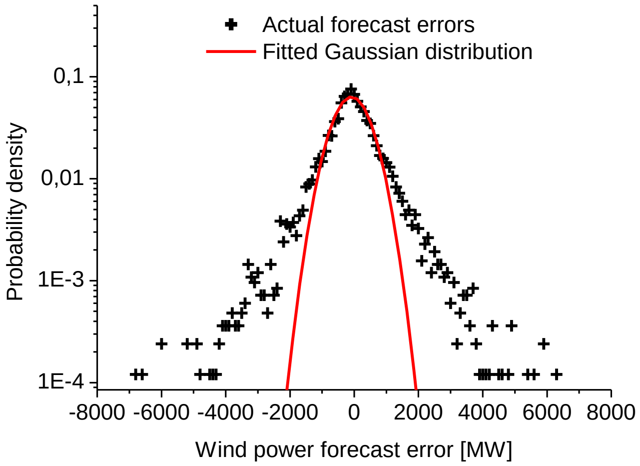


Fig. 5. Probability distribution of wind power forecast errors (from [7]).

Additionally, wind turbines usually shut-down their operation in storm events. If the wind speed exceeds a certain threshold, the turbine stops and power generation drops from full rated power to zero. Depending on the weather situation, the area and the turbine types this can lead to large drops even in large scale power generation. Such events are very difficult to predict for such discreet and seldom events and may therefore lead to large forecast errors.

Wind power forecasts naturally include forecasts of gradients. However, the forecasts are optimized to produce a small mean or root mean square error, not to predict extreme events. One of the most important sources of large errors is the uncertainty in time for weather changes leading to power gradients. Therefore a smoother prediction leads on average to smaller errors, but underestimates large gradients. Therefore, separate gradient forecasts or gradient warnings are performed, which are optimized to forecast gradients or even the probability of the occurrence of certain gradients.

B. Dispatch

Scheduling of power plants in the UC will be affected by the low marginal cost of wind power. In practice only must-run units will take precedence over wind power and in some power systems even those might have to stop operating before wind power due to priority access or production subsidies of wind power that will make the marginal cost for wind power negative.

When wind power forecasts are used, wind power is bid to produce according to the forecasts. When variable wind power replaces generation from conventional units, it is likely to increase the number of conventional unit start-ups as well as their part-load operation. In principle this should work fine within the existing UC frameworks, if they can handle restrictions on ramping, start-up and shut-down times. However, with large scale wind power the operation of some must-run units should be re-evaluated. System security has to be maintained, but it could be possible to replace must-run production with wind power.

C. Reserves

When wind power is added to the system, the uncertainty associated with wind forecasts requires an increase in reserve levels [10][11]. There is a considerable range of approaches that are used to calculate the impact of wind energy on 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 generation control operates. Since large scale wind power changes output 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 for secondary frequency control. Milligan et al [12] deals with the secondary and tertiary reserve issues in more detail.

TABLE I
GENERAL APPROACHES TO UNIT COMMITMENT

Deterministic	The peak commitment target can be augmented by a simplified rule-based adder, either in MW or percentage terms, to account for uncertainty. In systems with significant wind energy, the objective function should be altered to account for not only the peak, but also ramp requirements, and minimum generation levels. For example [14].
Quasi-stochastic *1. Statistical rules*	The commitment process accounts for variations and uncertainties surrounding the load and wind forecasts using a statistically-derived rule. Examples include EWITS and the Minnesota 20% Wind Integration Study. In the U.S., for example, recognition of the Control Performance Standards (CPS1 and CPS2) that require that most variations are met by generation
2. Convolution of probabilities	Loss of load probability approaches – this is an emerging family of methods that account for LOLP or a related metric, and convolve various probabilities such as forecast errors and state transition probabilities to estimate a risk metric that can be used as the commitment target or objective function. These approaches can be either static or dynamic (such as that used by Hydro Quebec), with the latter providing a more robust and economically efficient commitment schedule.
Stochastic	Approach has been implemented in the Wilmar model, and utilized in wind integration studies in Nordic countries [15], Ireland [16], and the United States. The approach builds a scenario tree that accounts for unit outages and forecast errors. The stochastic UC generally leads to a more robust UC schedule, resulting in less curtailed wind.

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, 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. Increase in the need for tertiary frequency control reserves is discussed throughout the rest of the section.

D. 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 turndown 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. Table I provides an overview of general approaches to UC with larger uncertainty due to wind power. In the next two subsections different methodologies are inspected more closely.

E. 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 [19] and Wang [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 practices can therefore be seen to use day-ahead UC. The main drawbacks to the current practices are that there is an increase in reserve demands when a large amount of wind power needs to be accommodated.

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. Fig. 4 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 on the system for the Irish system with 6000 MW of wind in 2020, taken from [16]. This is determined based on the 95th percentile of forecast error, as described in [11]. This value is chosen as it was found to correspond to the current reliability level of the Irish system of 8 hours loss of load expectation per year. As can be seen, the average amount of reserve needed increases as planning is done less often.

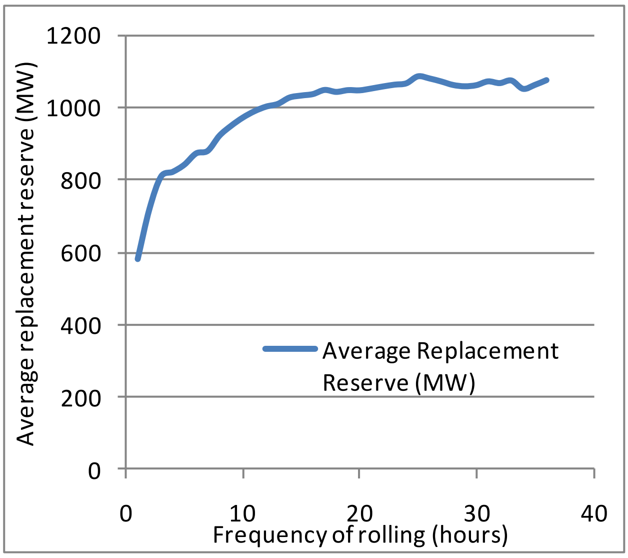


Fig. 4. Increase in reserve requirements as time between forecast updates increases [16].

F. Intra Day UC – Benefits and Limitations

Repeating UC in the intraday would make use of more accurate wind forecasts and this would result in more accurate UC. Generally, repeating UC in the intra-day still means that a 24 hour or 36 hour UC needs to be 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 will be reduced, as illustrated in Fig. 4. At present, intraday 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 should have the opportunity to recommit based on updated forecasts as is proposed in [23-26] 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. 5 shows the concept of rolling UC. 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. The actual structure could be different in regards to the time between commitments or the length of the planning period [23], [26].

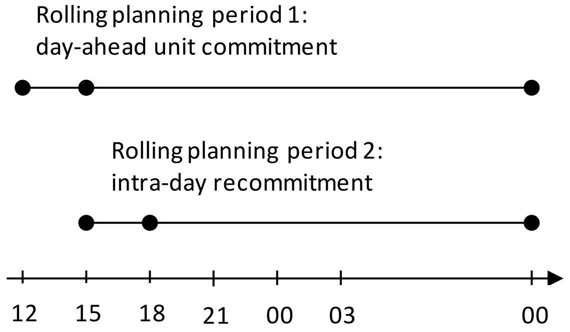


Fig. 5. Illustration of rolling planning

For intraday 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.

Intraday 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 intraday balancing markets that are seen as important when integrating wind power [25]. Certain unit constraints may become far more important when using intraday UC; for example startup times of units, which may be longer than the time between commitments. These questions have to be taken into account in the market design.

Much of the value that can be added by using rolling UC will depend on the flexibility of the units in the system. For those systems with high amounts of flexibility, the benefits of recommitting more often may not be as high. For example, [27] conclude that they could not find significant benefits of updating their Weather Research and Forecast model in intra-day operations in Illinois, US. Tuohy et al [23] 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.

G. Cross Border Scheduling

Connection to other areas and sharing of balancing reserves is often proposed as a good measure to integrate higher shares of variable power into a system, since the per-unit variability and unpredictability are reduced [1]. Furthermore balancing resources can be shared. If areas share reserves, not only does the total amount of reserves decrease, but the cost of providing these will also decrease as more units can operate at their efficient levels.

The work in [28] and [29] investigated the impact of using cross border scheduling for integration of wind power in the Netherlands. Here, two main results were found in relation to how UC and economic dispatch are carried out, as shown in Fig. 6.

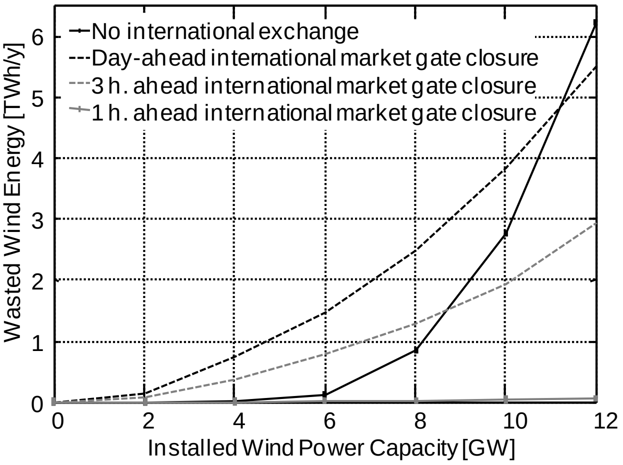


Fig. 6. Wasted wind energy for increased wind power capacity and different methods of interacting with international markets for the Netherlands

Interestingly, a day-ahead or 3 hours ahead international market gate closure time results in larger amounts of wasted wind at smaller wind power capacities than even the Dutch system in isolation. This is the result of the methodology applied for the optimization of international exchange at market gate closure, which is based on the assumption that all feasible international transactions are being made. In case a significant wind power forecast error is present at the moment that these transactions become fixed, already scheduled imports may prevent the integration of unpredicted surpluses of wind power, leading to larger amounts of wasted wind energy. For large wind power penetrations, however, the accuracy of forecasts is improved, and the benefits of international exchange capacity outweigh the disadvantage of forecast errors. The amount of wasted wind becomes negligible when both the wind power forecasts as well as the international exchange schedules are updated hourly.

H. 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. Therefore, it can 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 these situations, resulting in either insufficient capacity or over commitment, there are usually several options available (Table II).

To determine which of these options, or combination of options, should be used one should determine the most cost-effective approach. This requires knowledge of the prices and availability of each of these options. In areas with robust markets for ancillary services, it is therefore important to represent the supply curve for the various reserve products because there may be times of very high forecast errors that result in a high demand for balancing reserve when these reserves may be limited in supply.

TABLE II
OPTIONS WHEN TERTIARY RESERVES ARE NOT ENOUGH

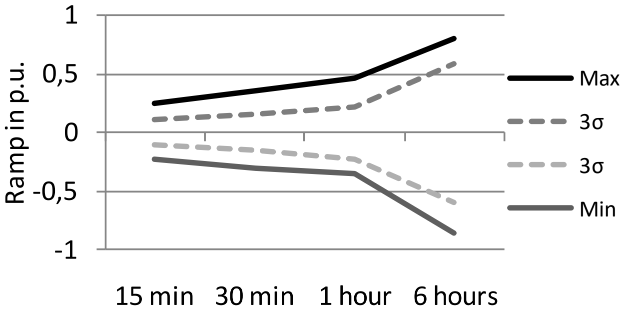
Insufficient capacity (over forecast of wind energy)	**Over commitment (under forecast of wind energy)**
Additional quick start capacity	De-committing units
Out of merit/dispatch if the event is reasonably predicted	Out of merit/dispatch if the event is reasonably predicted
Responsive load	Responsive load
Utilization of contingency reserves to avoid load curtailment	Wind curtailment
Emergency import	Emergency export
Load curtailment	

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.

I. Other Issues

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 generation. Fig. 7 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.

Fig. 7. Extreme ramps in wind power production in different time scales.



Data from Netherlands with simulated 7800 MW of wind power [30].

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. Sub-hourly scheduling, at 10 to 15 minute time steps would better capture the operating time scale of some systems. However, at least so far the benefits of higher resolution have been small compared to the costs in the literature.

Power flow constraints are not always included in the UC models, as the network calculations are computationally time consuming. Inclusion of grid congestion becomes increasingly difficult when the system size increases or stochastic UC is used. Unfortunately, optimizing wind power UC would benefit or even require those approaches. As an approximation, the scheduling problem for larger areas can be divided to multi area tasks, with set transmission limits between the areas. In this case using thermal capacities of lines would give too optimistic results. A better assumption is to use net transfer capacities (NTC) defined by the TSOs, followed by a detailed load flow analysis using the results from the multi-area UC as input (see [31]).

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, linear programming (LP) has been introduced for larger systems (see [32]). It is therefore also of importance to compare the two methods and develop the more simplified LP programming to include at least some implications of start-up costs, minimum load factor and lead times.

IV. 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 NWPs is critical in reducing the uncertainty. Forecasts with smaller probability band will decrease the need for reserves. Since power system operation is expensive, even small improvements can make large absolute savings. Therefore, it could make sense to update weather information gathering systems to enable more up-to-date information for power system operations.

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.

V. ACKNOWLEDGMENT

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VI. REFERENCES

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