Short-Term Energy Balancing With Increasing Levels of Wind Energy

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Short term energy balancing with increasing levels of wind energy

Juha Kiviluoma, Peter Meibom, Aidan Tuohy, Niamh Troy, Michael Milligan, Bernhard Lange,
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Abstract—Increasing levels of wind energy are adding to the uncertainty and variability inherent in electricity grids and are consequently driving changes. Here, some of the possible evolutions in optimal short term energy balancing to better deal with wind energy uncertainty are investigated. The focus is mainly on managing reserves through changes in scheduling, in particular market structure (more regular and higher resolution scheduling), reserve procurement (dynamic as opposed to static) and improved operational planning (stochastic as opposed to deterministic). Infrastructure changes including, flexible plant, increased demand side participation, more interconnection, transmission, larger balancing areas, and critically improved forecasting can also be significant and are dealt with in the discussion. The evolutions are tightly coupled, their impact is system dependent and so no "best" set is identifiable but experience of system operators will be critical to future developments.

Index Terms—Energy balancing, market design, scheduling, reserve allocation, unit commitment, power system operations, wind power

I. INTRODUCTION

Increasing levels of wind energy, which is variable, difficult to predict accurately and increasingly connected via power electronic converters, are changing how electricity grids are planned, designed and operated [1]. For example, the spatially distributed, asynchronous nature of wind energy is driving upgrades in the transmission system, with deployment of high voltage direct current transmission (HVDC) becoming increasingly popular to connect areas with good wind resources to areas with large loads. Systems with high wind penetration are also experiencing dramatic changes to the operating regimes of conventional generators, which must now operate more flexibly in order to accommodate variable wind power. The displacement of conventional generation also impacts power system dynamics as the voltage support and frequency response previously supplied by these units are also displaced [2]-[3].

The increased variability and uncertainty that comes with increased wind energy penetrations exists across multiple time scales and makes energy balancing more challenging. Long term energy balancing is complicated by the fact that the capacity value of wind for a given system can vary significantly from year to year [4]. Optimal short term (minutes to day ahead) energy balancing for systems with high wind penetration, which is the focus here, requires high quality wind forecasts and advanced scheduling methodologies. These advances from the traditional scheduling approach include: dynamic reserve targets, higher resolution scheduling periods, more frequent scheduling and the use of stochastic optimization techniques. The performance of these approaches is heavily influenced by infrastructural and portfolio changes in the power system. In particular, a more flexible portfolio, more demand side participation, increased interconnection, transmission, larger balancing areas and improved wind forecasting [5].

The remainder of the paper is arranged as follows: Section II briefly summarizes how short term energy balancing is currently achieved through the scheduling process and how large scale wind energy penetration may impact this process. Section III describes advancements to the traditional scheduling methodology that are being implemented in industry and/or proposed in the literature. Section IV discusses longer term infrastructural developments in the power system that will impact short term energy balancing with increasing levels of wind energy. Section V concludes.

II. SHORT TERM ENERGY BALANCING AND WIND ENERGY

The primary objective of optimal short term energy balancing is to minimize costs while maintaining the balance between supply and demand at, or above, a desired reliability level. The problem can be studied by modeling Unit Commitment (UC), which determines the commitment schedule of units, in combination with Economic Dispatch (ED), which determines the dispatch level of those units in real time. UC tools commit units, typically day-ahead, based on the demand forecast and requirement for reserves and are subject to both unit constraints (e.g. minimum generation) and system constraints (e.g. transmission capacity). Reserves, with various activation times, ensure sufficient generation is available to meet forecast errors, contingencies

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and variations over shorter time resolutions than the resolution of the UC and dispatch (typically one hour down to 5 minutes). Therefore, committed units need to be able to manage primary, secondary and tertiary frequency control as well as meet the ramp requirements over all time frames. As wind energy increases the most impacted reserve categories are regulating reserves and load following reserves together with supplemental/replacement reserves (see [6] for discussion on reserve terminology). Regulating reserve corrects random movements in a time frame faster than the dispatch interval, while the latter two correct the cumulative forecast error in the minutes to hours timeframe and are jointly termed 'tertiary reserves'. Given that relatively slow moving aggregated wind generation does not change quickly enough to be considered a contingency event, contingency reserves have been shown to be unaffected by increasing wind penetration and hence are not discussed here [7].

The convention has been to commit generating units once per day well ahead of the hours of actual operation [8]. The rationale for the day-ahead UC is due to the temporal nature of the constraints on some of these units. A decision to commit or de-commit a unit must respect units' startup and shutdown times as well as minimum up and down times, which for a large coal or nuclear unit can be lengthy, and so such decisions need to be made well in advance. If necessary, the system operator may recommit units intraday to allow for significant changes in demand or contingencies. Intraday markets perform a similar function where they exist.

Demand follows daily, weekly and seasonal patterns and as such demand forecasts are relatively accurate. Consequently UC optimization approaches have traditionally been deterministic, with uncertainty in demand and power generation being accounted for by provision of reserves. Wind power forecasts by contrast are relatively inaccurate, particularly in the day-ahead time-scale, as error increases strongly with time horizon. This can be seen in Fig. 1 which illustrates wind power forecast error at various time horizons on the 2020 Dutch system. This study used an atmospheric model to generate wind speed forecasts. In the short term (1-6 hours ahead) information from online wind

or wind power measurements have to be used in addition to the numerical weather prediction model data to reach a good performance [9]. Large wind power forecast errors increase system costs and reduce reliability as reserves must be deployed and units re-dispatched.

At low penetrations of wind power, additional reserves can be scheduled to cover the additional uncertainty due to wind power. However, as the wind power penetration grows, it becomes increasingly inefficient to rely on existing methods for reserve quantification and scheduling. The next section explores evolutions to scheduling that are being studied and in some cases applied in industry.
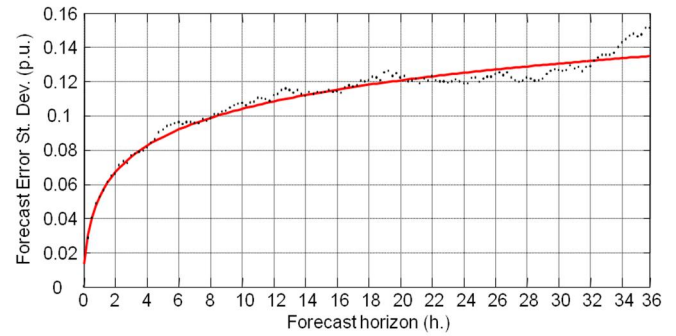

Fig 1. Normalized standard deviation of wind power forecast error for 12 GW installed capacity versus forecast horizon (Source: Netherlands, AVDE tool with data from the atmospheric model HIRLAM [10]). Solid line is a curve fitting.

III. SCHEDULING EVOLUTIONS FOR SHORT-TERM ENERGY BALANCING

Table I summarizes the evolutions in the scheduling methodology that are currently being deployed and/or proposed for short-term energy balancing with high levels of wind energy. Different methods, which can account for the uncertainty of wind power output, are presented in the first column, while the top row categorizes these methods in terms of when they are undertaken, i.e. once per day or more regularly. The different methods can be complimentary. For example, more regular and higher resolution commitment and dispatch can be done in place of, or as part of dynamic reserve procurement. In reality combinations of these different strategies will be employed.

TABLE I
EVOLUTIONS FOR SHORT TERM ENERGY BALANCING WITH INCREASING WIND ENERGY PENETRATIONS

		Scheduling frequency	
	Explanation	Once per day	More regular scheduling
Dynamic reserve procurement	A reserve requirement that is based on dynamic forecast error estimates at different time horizons.	Wind power increases tertiary reserve significantly, but the impact will be more limited when the forecast uncertainty is accounted for dynamically.	The combined impact of more regular UC and dynamic reserve procurement would help to keep tertiary reserve requirement relatively low most of the time.
Stochastic UC	Optimization of UC decisions over several scenarios for possible outcomes of wind and demand.	Improves the reliability and yields more optimal UC.	Reduces tertiary reserve procurement and improves UC optimality further.
Scheduling resolution	Scheduling period is shortened e.g. from hourly to five minutes	Ramps within the scheduling period will be smaller, which reduces regulating reserves. Scheduling accuracy will be improved.	

A. Scheduling frequency

A more frequent UC, ED, and reserve procurement achieves two things: portion of the procured reserves can be released later and less expensive reserves can be used more often. Increased frequency enables the use of more up-to-date forecasts and real system information. By using updated information, the reserves carried on the system can be reduced as the operating period gets closer, as illustrated by Fig. 2. In general, repeating UC and reserve procurement in the intra-day would still require that a 24 hour or longer UC is carried out to accommodate slower starting units and to ensure availability of capacity; however these schedules should then be updated whenever new information is available. In addition, this approach allows commitment decisions for quicker starting units to be made closer to real time, delaying commitment decisions until more accurate forecasts are available. In effect, fewer units need to be scheduled for start-up, which reduces the procurement costs.
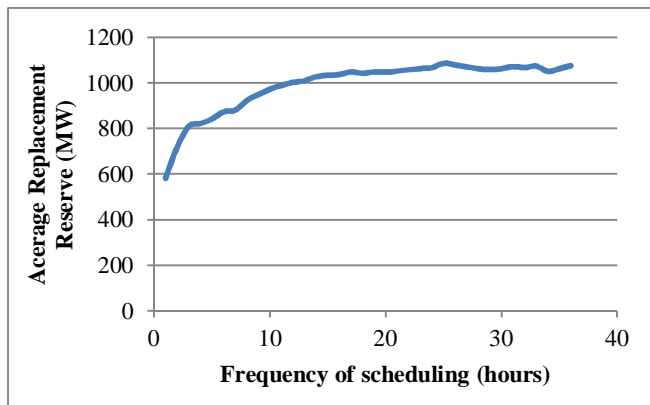

Fig. 2. An example of the trade-off between the reserve requirements and the frequency of commitment [11]. Replacement reserve is similar to the tertiary reserve defined here.

The rationale for more frequent scheduling was proposed by Schlueter *et al.* in 1985 [12], although it was designed for storm events and has not been cited in recent literature. Tuohy *et al.* [13] 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 prevented any benefits of decreasing the planning period further from being quantified. Similarly [14] demonstrates benefits when moving from day-ahead to 3-hour ahead gate closure in the UC.

More regular UC and ED may also cause some additional costs. Operational costs for some power plants may increase due to shorter preparation time. This increases the importance of accurate modeling of certain unit constraints; for example startup times of units, which may be longer than the time between commitments [15].

While research demonstrates benefits for more regular scheduling, in power exchanges the liquidity of the intra-day market has been low – at least in Europe [16]. This hinders the realization of possible benefits from more regular scheduling. One reason is that generators may expect higher

profits in the balancing market and therefore do not bid intra-day [17]. They may also be hindered by bi-lateral contracts. Hence, intra-day has been an expensive method to balance forecast errors. This leads to self-balancing, which is sub-optimal, or to the use of balancing markets, which is on average more expensive due to the shorter response time. The liquidity problem of intra-day markets is something that most modeling studies do not capture, as they assume that all available power plants will bid into the intra-day market. Therefore, the results from these models may overestimate the benefits of more regular scheduling. It remains to be seen whether the liquidity will be sufficiently improved as increasing uncertainty induces more intra-day trading. Another option is to modify current market structures in order to promote liquidity (e.g. auctions instead of continuous trading, bundling of day-ahead and intra-day markets into one real time market), but new market structures will have problems of their own.

Intra-day markets are currently operational in Belgium, Germany, UK, France, Italy, the Nordic system, Spain, Portugal, Poland, Romania, the Netherlands, and the North American ISOs. It is also planned to be a feature of the common European internal energy market, which is to start in 2014 [18].

B. Dynamic reserve procurement

Meteorological conditions govern the probable range of wind power output and wind power forecast errors also tend to vary with these conditions [19]. As a simple example, if the predicted wind power output is low, downward error cannot be large. Therefore, a static reserve level is not appropriate. Rather, dynamic reserve constraints which are functions of the wind forecast error and/or the short term variability of wind power output should be implemented, where the reserve requirement is based on the present level of wind power output, and the expected uncertainty and short term variability of wind. Taking dynamic reserve allocation as a starting point, the influence of wind power on different operating reserve categories has been detailed in [20].

Regulating reserve is used to correct fast changes in energy imbalance under normal operating conditions. The increase in the required regulating reserves depends primarily on the capacity of the wind generation fleet. Fluctuations in wind farm outputs are uncorrelated in such a short time scale and therefore the combined seconds to minutes fluctuation of a large portfolio of wind farms is small [21]. In situations with very high levels of wind generation where the regulating power plants are being displaced, wind power plants need to provide the regulation. The alternative is that wind power plants will have to be curtailed in order to accommodate the minimum generation levels of the regulating power plant.

The longer time frame reserves (several minutes to hours) are strongly influenced also by the geographic spread of the wind power plants. A wide geographic dispersion results in less correlation between turbine outputs and hence less reserves are needed [21].

A simple implementation of a wind forecast is based on

the current output level of wind power plants ('persistence forecast') as in [22]. This can be used as the input for an algorithm to calculate the short-term reserve target (e.g. minutes to an hour ahead). Hence, dynamic reserve requirement can provide cost savings by decreasing spinning reserves compared to a static reserve target [23].

As the time horizon increases, forecast errors become more important. Hence, the required tertiary reserve is highly dependent on the time horizon. Fig. 2 shows the average replacement reserve that is needed as the time horizon for forecast updates increases for the 2020 Irish system with 6000 MW of installed wind capacity [11]. This is based on the 90th percentile of forecast error, which was found to correspond to the required 8 hours loss of load expectation [11]. As can be seen, the average amount of required reserve increases when rescheduling is done less often, particularly in the first 1-10 hours of the forecast.

In power systems with a long lead time for unit commitment (e.g. day-ahead) dynamic reserve procurement can dramatically decrease the need for tertiary reserves. Dynamic reserves have been implemented in recent wind integration studies (e.g. [11], [24] and [25]). In many power systems, tertiary reserves are procured from a real-time balancing market. However, markets do not inherently ensure that the bid stack contains enough capacity to give a high level of reliability if the forecast error happens to be large [8].

Holttinen et al. [1] compare the results from several wind integration studies, where it is shown that the methods and assumptions used to calculate the reserve requirements create important differences between results. Also Milligan et al. [6] discusses how different wind integration studies have analyzed future reserve needs. They also clarify the different reserve definitions across power systems and how they might relate to the increasing share of wind power. The methods to estimate reserve requirements varied widely, including forecast error statistics with and without the consideration of wind power output level [26], time-step Monte-Carlo simulations [27], and risk based methods [7] which convolute probabilities of wind power, demand, and unit availability. In the risk based methods, the probability of violating reserve requirement could be constant throughout the year [28]. It could also aim at maintaining certain probability level over a longer period (e.g. a year), but not force the same probability in each situation as the cost can vary. The latter approach could potentially provide more robust commitments. In [29], [30] and [13] dynamic reserve procurement is combined with a more frequent scheduling.

C. Scheduling resolution

Power systems with a significant amount of wind power could benefit from higher resolution scheduling (e.g. five-minutes instead of one hour). This has been recently implemented in several power systems [31] and in many cases wind power has been at least a partial motivator. Ramps within the shorter dispatch interval will be smaller, which enables a reduction of regulation reserves acting within the scheduling interval [32]. For example [33]

discusses a proposal for an energy imbalance market in the Western Interconnection of the US and compares different market resolutions. In all different scenarios examined ten-minute dispatch interval with a ten-minute gate closure decreased the requirement for regulation reserves by about 70% compared to hourly dispatch interval with a 40-minute gate closure. The impact of moving from hourly dispatch interval to half-hourly dispatch interval with the same 40-minute gate closure was close to 20%. The method calculated the dynamic reserve requirement using variability within the dispatch interval along with the uncertainty. Other reserves were not impacted, since they were assumed to depend on one-hour forecasts.

Another reason to increase scheduling resolution is that with higher ramps, the hourly dispatch may change too much from one dispatch interval to the next. For example, if a large system were experiencing a steep ramp in the net demand and the marginal units happen to be in a smaller system connected with an intertie, the intertie could experience a complete reversal over a short period of time. Higher scheduling resolution could lead to more manageable, gradual changes.

Larger net demand ramps due to both wind generation [34] and higher market resolution will cause higher MW/min ramps to be visible in the UC and ED models. Therefore, it becomes more important to model ramping limitations accurately. Aggregated wind data from Texas, which displays wind generation ramps in one-minute resolution is available in [35]. Ela and O'Malley [36] have developed a model that combines UC, ED, and AGC (automatic generation control) in order to analyze the impact of wind power on the short-term energy balance, considering also the time scale of seconds. According to the test system results, decreasing the dispatch interval helps to decrease control performance standard violations caused by ramping limits and wind power uncertainty.

D. Stochastic UC

Uncertainty can be directly represented in the UC formulation by using a stochastic approach. In one formulation of this method, the UC optimizes the expected cost, subject to constraints, with the expected net demand (demand minus wind generation) given by a distribution of possibilities (Fig 3). In this way the additional reserves may be implicitly carried [29], because the solver will try and meet as much of the distribution as is optimal considering, for example, the value of lost load. If the whole distribution is included, then the stochastic unit commitment approach inherently has a dynamic reserve constraint built in as the distribution of forecasts is an input that is changing with the underlying meteorological conditions.
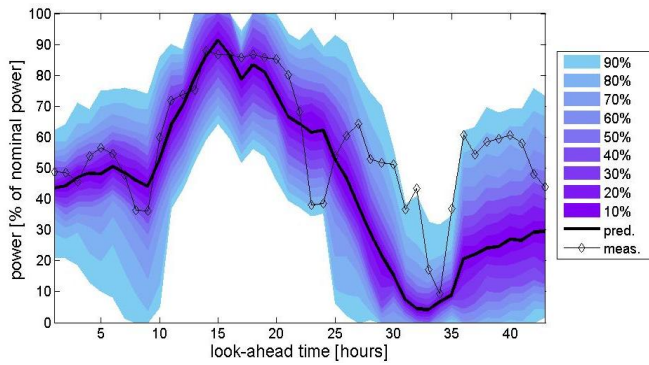
Fig. 3. Probability weighted forecasts [37]

In practice, not all of the stochastic information can be included in UC models. In standard approaches to UC, the distribution is represented by "scenario trees" with branches corresponding to different possible outcomes. Each additional branch included in the optimization will increase the computation time. Fig. 3 is an example of a distribution that considers only the forecast quantiles. A more robust representation would include both a sufficient number of branches for possible output levels, as well as stochastic information about the ramp steepness and ramp timings. If ramp uncertainty is not included in the stochastic scenarios, then ramping capability may have to be provided by a separate ramping reserve constraint, or as an addition to existing reserve categories. Midwest ISO is planning to incorporate a ramping constraint into their market clearing tools, which will incentivize market participants to provide ramping services when needed [38]-[39].

There are several alternative formulations and approaches that can be taken to stochastic UC. These are primarily being investigated in research models and not in the commercial models that are used by the power industry at large. Some of the models reviewed below do not use actual wind forecasts, or even their statistical properties, as input data and therefore their results should be treated with caution although their UC methodologies can be valuable. Restrepo *et al.* [28] examines the effect that including a probability distribution of net demand in a deterministic UC will have on the day-ahead UC, assuming a prediction error which remains constant throughout the day. The probability distribution is rendered into an equivalent mixed-integer form. It is shown, as expected, that the amount of wind curtailed can get quite high. Ruiz *et al.* [40] 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 an appropriate amount of reserve reduces wind curtailment and increases the robustness of the day-ahead solutions. Wu *et al.* [41] and Wang *et al.* [42] describe a security constrained stochastic UC model which models uncertainty of wind power in the day-ahead time frame. In [42] 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 and Galiana [43] propose a short-term forward electricity market-clearing problem with stochastic security capable of accounting for

wind power generation. This algorithm was shown to reduce costs and allow greater wind penetrations compared with a deterministic solution. A simple example from a small system was used to illustrate the benefits of their approach. Pappala *et al.* [44] present a self-adaptive particle swarm algorithm to solve a stochastic UC problem. It is again shown that stochastic methods can increase the amount of wind energy that can be integrated while maintaining power system reliability. Wang *et al.* [45] have included an economic dispatch simulation in a stochastic day-ahead UC model. Both models were run in hourly resolution with no intra-day rescheduling or power flow constraints. The authors evaluate different strategies to apply wind power forecasts and reserve requirements and it was found that stochastic UC with additional static reserve requirement gives the least cost results. Constantinescu *et al.* [30] combine a numerical weather prediction model using ensembles with a stochastic UC. Meibom *et al.* [46] present a stochastic UC model that allows UC schedules for power plants to be dependent on wind power production and demand forecasts, as long as units' start-up times are respected. The stochastic unit commitment model is unique in its combination of a scenario generation methodology, treatment of reserves and frequent scheduling and dispatch driven by updated forecasts. Sturt and Strbac [29] have a similar approach, but without transmission constraints, which decreases computation time. The analysis compares different scenario trees and their impact on the system cost and computation time. Larger trees yield benefits, but at a considerable computational cost. The approaches to stochastic UC are various.

Stochastic UC solution times can be excessive, especially in large systems. The solve time may be increased by an order of 10 or more compared to a deterministic UC. Furthermore, when evaluating impacts of wind power, larger footprints need to be included in the modeled area in order to more accurately represent the interconnected systems that are prevalent around the world and to take spatial smoothing into account. To reduce the problem size, aggregation of units into unit groups, in combination with relaxed mixed integer programming (LP), has been proposed for larger footprints (see [47]). Decomposition schemes in combination with parallel computing facilities also offer promise in handling larger problems sizes [48]. Further work remains to reduce computation times by using more efficient, but still adequate, model formulations and as well as parallel computing facilities.

Stochastic UC may yield lower costs and better performance than a deterministic optimization but the studies so far are not conclusive. However, the stochastic approaches do tend to reduce curtailments which would indicate that as wind penetration rise they will prove advantageous.

While it is possible to integrate uncertainty into optimization models, it will also be important to convey similar information to control rooms, but in a simplified form [49]. Simplification should display expected generation as well as what risks the forecast contains for system security. One such approach would be to use up-to-

date system information to select the most applicable scenario from a set of scenarios produced by an earlier run of stochastic scheduling tool. This would reduce the amount of displayed information and would also take into account the slower running cycle of the stochastic tool.

IV. DISCUSSION

The effectiveness of the scheduling evolutions described in the section above will be dependent on the characteristics of the particular system. As the power system evolves over the coming years there are longer term infrastructural changes that will have a substantial influence on the evolution of short term energy balancing with increasing wind energy penetration.

Market signals related to the pricing of reserve and other frequency-related ancillary services may result in a very flexible generation portfolio where the necessity to forecast out multiple hours may be removed as all units can start at very short notice. In this case the rationale for a day-ahead UC may be unnecessary. Additionally a system with a highly flexible plant portfolio, which can respond rapidly to forecast errors, may not see as much benefit from the robust solutions produced by stochastic unit commitment as an inflexible system would. Some power plant manufacturers have already reacted by developing combined cycle units that are capable of more flexible operation (e.g. Siemens SGT5-8000H, GE FlexEfficiency 50) or reciprocating engines [50]. It is also possible to retrofit old units for more flexible operation [51].

Electrification of the two other major end-uses of energy, transport and heat, could also provide balancing opportunities. Smart charging of electric vehicles could be especially useful for providing contingency reserves and in reducing the impact of wind power forecast errors. However, it is energy-restricted and hence likely to offer only limited resources over periods lasting several hours. On the other hand, converting and storing electrical energy as heat holds large potential in energy terms. With a heat storage, excess wind power generation can be later used for heating or cooling, either in space heating or in industrial applications [52]-[55]. More conventional demand response (see [56]), which might involve shutting down non-critical applications in the case of very high energy or reserve market prices, would be especially useful when large wing forecast errors arise due to unusual weather events. Sioshansi [57] demonstrates that price elastic demand can reduce the monetary impact of wind power forecast errors considerably.

There are also plans for interconnection to reservoir hydro dominated systems to access flexibility. Examples include the planned interconnections between the Nordic system and continental Europe as well as the UK [58]; in North America, new interconnections are planned between the MidWest ISO and Manitoba Hydro, BC Hydro and Western Electricity Council, Hydro Quebec and New York ISO as well as ISO New England.

The construction of more transmission and the development of larger balancing areas[1] will decrease costs from variability and uncertainty. Several studies have found benefits in larger balancing areas [59]-[61]. There are multiple reasons for this. In a larger system, wind power ramps will be less steep per unit, while ramping capability will increase monotonically. Reserves can be provided with fewer and on average more efficient units than before. In addition, forecast errors will be reduced somewhat per unit, thus reducing the need for additional reserves [1].

The most direct infrastructure change that will impact on the effectiveness of the scheduling evolutions for short term energy balancing is better wind forecasts. A survey of Jones [62], based on an international questionnaire to system operators, found that wind power forecasts are vitally important for successful integration of variable generation. Furthermore, 30% of respondents believed that probabilistic forecasts are of 'high' importance and a further 40% believed they are of 'modest' importance in control rooms.

Quantitative analysis is required to determine the best way of achieving optimal short term energy balancing in evolving grids and to help inform future developments. This is highly complex due to several possible trade-offs and hence current literature is only beginning to address the issue. For example Tuohy and O'Malley [63] illustrated the trade-off between better forecasting and the benefits of storage. Similarly the study in [14] shows that in the Netherlands international exchange is a better solution than storage for short term energy balancing with high wind penetrations. These studies coupled with significant learning potential as power system operators gain experience of managing large levels of uncertainty due to wind plants will determine future trends.

V. CONCLUSIONS

Short term energy balancing to manage the variability and uncertainty of wind power is evolving. Scheduling evolutions including scheduling frequency, dynamic reserve procurement, higher scheduling resolution and stochastic UC are being proposed and some are being implemented. Frequent scheduling takes advantage of new data closer to real-time and helps to reduce exposure to uncertainty. With more frequent scheduling the procured reserves can be released later and less expensive reserves can be used more often. Dynamically scheduling reserves reduces the quantity of reserve procurement. Scheduling at higher resolution can reduce the need for reserve, while stochastic scheduling produces solutions which may inherently carry required reserves and are robust against forecast uncertainty. Each of these scheduling evolutions impact on how system operations and decision making can be organized to better manage reserve requirements. Infrastructure developments including increased system flexibility, increased demand

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[1] Area where the system operator is responsible to maintain physical balance in relation to adjacent areas and hence play its role in interconnection wide frequency control. A tight co-operation between balancing areas could achieve similar results.

side management, interconnection, transmission, larger balancing areas and improved wind forecasting will also improve short term energy balancing performance. The scheduling evolutions discussed here are tightly coupled and complimentary to the infrastructure developments, and the overall best solution is system dependent and will be determined by further research and experience.

VI. ACKNOWLEDGMENT

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