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Adequate intraday market design to enable the integration of wind energy into the European power systems

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ABSTRACT

This contribution analyses the European electricity markets with respect to their aptitude to absorb large amounts of wind energy. Thereby in a first step the market designs of the major European power markets in France, Germany, Scandinavia, Spain and UK are reviewed, with a particular focus on liquidity in the spot and intraday markets. Then some key features of the short-term adjustments required by wind energy are discussed and the necessity of sufficient liquidity in intraday markets is highlighted. For the example of the German market subsequently the discrepancy between the physical short-term adjustment needs and the traded volumes on the intraday market is analyzed. This leads to an evaluation of proposals for improving the liquidity on the short-term market, including the use of continuous spot trading like in UK or the use of intraday auctions like in Spain.

1. Introduction

The transmission system operators all over Europe have been confronted with new challenges as a consequence of the liberalization of European electricity markets. Further challenges lie ahead both for system operators and electricity market operators in Europe with the on-going strive for renewable power generation. With wind and solar energy getting increasingly popular as ecological, emission free energy sources, the question is gaining importance, how the inherent fluctuations in their production should be dealt with best at the level of system operation and market design. Without adequate measures being taken, the inherent fluctuations of wind and solar power would obviously make them very poor substitutes of conventional, controllable electricity production from coal, gas, nuclear and other power plants.

In particular, the organization of the continental European and Nordic power markets, based mainly on day-ahead spot markets, induces high demands for balancing services and/or intraday trading to cope with increased amounts of wind power. Therefore, the contribution analyses, how the market design in the European countries could and should be adapted to the new challenges arising from wind energy. The perspective taken focuses on the role of liquidity in intraday markets as one cornerstone to improve the overall efficiency of the market design. This will lower the societal costs of wind integration and in most countries also directly benefit the wind power producers, who otherwise have to bear too high imbalance costs. More generally, the benefits will accrue to the "Balancing Responsible Party", i.e. the entity in charge of handling wind power forecast errors, be it the wind power producers themselves or the grid operator. Hence the subsequent reasoning is basically also valid for countries like Germany, where wind power producers themselves so far are not responsible for the deviations between scheduled and actual wind power infeed. Rather it is the responsibility of the grid operator to handle these deviations and they (or finally the grid customers) will benefit from liquidity and thus efficiency improvements in intraday markets.

The implications of wind energy for prices on the day-ahead and intraday markets have been subject of several papers, including Barth et al. (2006), Weber and Woll (2007), Sensfuß et al. (2008) and Wissen and Nicolosi (2008). Also the question of suitable market design for the integration has been repeatedly discussed, notably by Holttinen (2005), Barth et al. (2008), Maupas (2008), Hiroux and Saguan (2009) and Vandenzande et al. (2009). Yet most of these contributions focus either on the spot market or the balancing energy mechanism. A notable exception is Maupas (2008), who simulates in detail the interplay between the intraday market and the balancing energy mechanism. However Maupas takes the liquidity in the intraday market as given. Hence a major aspect discussed in this paper is the liquidity under different market designs, both for spot and for intraday markets. The overall objective of any reforms in market design should be an improvement of the global efficiency of the markets. Thereby an increase in liquidity will in general be beneficial, since without sufficient liquidity, trading will not occur and hence also an efficient use of production resources will be hindered.

Liquidity is, as stated notably by Amihud (2002), an elusive concept and not directly observable. Generally it is understood to describe the easiness of trading a particular asset and the fact that

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Table 1
Considered markets in Europe.

Country	Grid operator(s)	Market operator	National consumption (2007) (TWh)
France	RTE	Powernext	480
Germany	RWE transportnetz Strom E.ON netz Vattenfall transmission EnBW transportnetz	EEX	556
Nordic countries	Statnett Svenska Kraftnaet Fingrid Energinet.dk	Nordpool	395
Spain	REE	OMEL	268
UK	National grid	APX UK	373 (2006)

Sources: UCTE (2008), own research.

any transactions in the asset will not affect significantly its value. Various definitions have been given, going back at least to Keynes (1930), and different measurement concepts have been proposed (cf. Goyenko et al., 2009). Basically however the easiness of trade is certainly an increasing function of the number of market participants and the number of trades. Therefore a frequently applied indicator for liquidity in financial and energy markets is the trading volume in a market (e.g. EU, 2007). This is easily observable and will therefore also be used in the following for characterizing market liquidity. Yet in the perspective of a market participant, besides the question of being able to find a counterparty for trading also the question of the price impact of a trade is of interest. Specific price-impact indicators for liquidity (cf. Goyenko et al., 2009) could be used here for measurement. However, more directly the slope of the price-demand function (cf. Kempf, 1999; Goyenko et al., 2009) may be used to describe the price impact of liquidity. This will allow later to assess the impact of market liquidity on the integration cost.

In this perspective, liquidity is in fact directly linked to transaction costs. Without sufficient liquidity, any market participant must fear that his purchases (or sales) move the market price and make him pay more (respectively earn less) than the unperturbed market price. In fact, this kind of transaction costs is much more important for energy trade than the pure transaction fees paid to power exchanges or brokers, which usually are far below 1% of the price. Also for larger energy companies, the potential liquidity costs are far more relevant than the internal transaction costs related e.g. to IT systems or trading staff.

The remaining of this paper is organized as follows: in the next section an overview on the market design in major European countries is given with a focus on liquidity and then the needs for short-term adjustments arising from wind energy and other sources are discussed in Section 3. The key issue of liquidity on intraday markets is subsequently investigated in more detail taking as an example the German market in Section 4, whereas the interconnection with the balancing markets (reserves provision and imbalance settlement) are addressed in Section 5. Finally, Section 6 reviews different proposals for improving the functioning and the liquidity on the intraday markets.

2. Market design and liquidity in Europe

In order to assess the necessary steps for improved wind integration, first the current design and functioning of major European electricity markets is reviewed. The focus is thereby on the Nordic, the UK, the German, the French and the Spanish power markets. Major characteristics of these markets are summarized in Table 1. An overview of the sequence of interrelated markets is also given in Fig. 1.

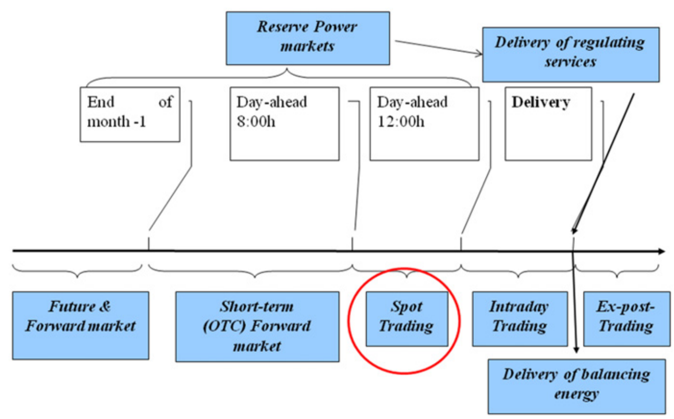

Fig. 1. Typical sequence of electricity trading markets.

A first key point to be made is that none of these markets is run by an Independent System Operator (ISO), similar to the ISO in the Pennsylvania–New Jersey–Maryland (PJM) market or in other US markets. Rather the markets are organized as bilateral, voluntary markets, working at least to some extent independently from the grid management, even though often the Grid operators hold major shares in the power exchanges.

In all countries considered, the power exchanges operate a general market labeled "spot market", which is the main market for physical delivery.[1] Its characteristics will be discussed in detail in Section 2.1. Additionally, for short-term adjustments often intraday markets are operated either by the power exchanges or by other institutions. Their characteristics are reviewed in Section 2.2. In order to have sufficient reserves to handle remaining deviations between scheduled and actual operation, the grid operators moreover mostly operate reserve markets, which are explained in Section 2.3. The sequence of these markets is also illustrated in Fig. 1.

2.1. Spot markets

Trading in the power exchanges has considerably increased during the last years and a comparison of the percentages

[1] In line with common practice in Europe, the term spot market is used to designate day-ahead or similar markets and not real-time markets.

Table 2
Spot markets in the countries considered.

Country	Market operator	Spotmarket gate closure	Exchange traded spot volume (2007) (TWh)	Share of national consumption (%)
France	Powernext	11:00 day-ahead (7 days per week)	44	9
Germany	EEX	12:00 day-ahead (Mo–Fr)	123	22
Nordic Countries	Nordpool	12:00 day-ahead (7/7)	291	74
Spain	OMEL	10:00 day-ahead (7/7)	195	73
UK	APX UK	60 min before delivery (7/7)	10.6	3

Sources: EEX (2008), EU (2007), Nordel (2008), Ockenfels et al. (2008), OMEL (2008), and Powernext (2008), own calculations.

compiled in Table 2 for 2007 to the data used in the EU sector inquiry, which refer to a time period in the years 2004–2005, show partly impressive increases.[2] The share of total consumption traded at the exchange increased in Nordpool by 30 percentage points, in Germany the values are up by 9 percentage points and for France an increase by 6 points compared to the values published in DG Competition's sector enquiry (EU, 2007) is observed. Nevertheless, less than 25% of all electricity consumed is traded at the spot market in the majority of the countries. The situation is however different in the Nordpool market. To some extent, this is certainly due to the long history of liberalization in the Nordic market. But two other factors have also to be considered: first, cross-border (or rather cross-zonal) trade between different zones of the Nordic market is only possible via the Nordpool market (cf. also EU, 2007). Second, the large share of flexible and storable hydropower provides a good basis for hedging and optimizing through the market.

Another market with high liquidity is the Spanish market. Here the volume traded at the exchange-based spot market was in 2007 about 73% of the national consumption. Again institutional arrangements explain this high share: in the past, only electricity traded via OMEL was entitled to receive capacity payments.

By contrast, the British power exchange shows lowest liquidity (cf. Table 2). This is in sharp contrast with the very late gate closure time, which would be expected to increase liquidity. Contrarily to the other markets investigated, the British spot market is not based on a day-ahead auction but rather on continuous trading, which may occur up to 1 h before delivery. EU (2007) invokes as reason for the low liquidity the vertical reintegration of generation and supply businesses after the end of the former pool market. Ockenfels et al. (2008) by contrast give two different arguments, which are more related to the design of the spot market itself: in the continuous trading a pay-as-bid mechanism is applied, which reduces the price transparency of the spot market—a unique reference price for derivative trading is less easily identified under this market design than under simultaneous auctions with marginal pricing as applied in the other markets. A second reason given by Ockenfels et al. (2008) is self-reinforcement: the low liquidity and the limited transparency reduce the confidence of market participants in the power exchange and consequently their willingness to participate.

An additional argument may be put forward for day-ahead auctions: they clearly aggregate liquidity in one unique auction and avoid dispersion across single trades occurring over the whole trading period (two days in UK). This is obviously preferred by the market participants. In fact, EEX offers in advance of its day-ahead auction also a continuous trading window of four hours, where at least peak and base blocks for delivery next day may be traded. Yet while trading volumes in the auctions have continuously increased, liquidity in the continuous trading has decreased. Hence market participants, if given a choice, obviously clearly opt in favor of single auctions. This observation may be at least partly explained by the planning processes in the utilities. Those traditionally have a daily planning cycle, which involves determining day-ahead the expected operation of the units. This planning process, preexisting to liberalization, has been adapted to distinguish between the bid submission to the power exchange and then the planning given power exchange results, yet it still is applied. And the technical interdependencies in power plant operation, such as minimum operation times, start-up costs or lead times make an instantaneous replanning (when a new trade arrives) difficult and/or inefficient.

2.2. *Intraday markets*

In times before liberalization and increasing wind power production, day-ahead plans already had to be updated in the case of new information arrival. One element of new information were plant outages, another one changes in load expectation. With liberalization one would expect markets also to be used for these replanning occasions. Another possible use of intraday markets in competitive environments is to allow for adjustment of infeasible schedules resulting from spot markets with simplified designs (linear bid curves, no block bids, etc.) Indeed in Germany and other European countries there has been a move from inhouse and informal solutions for handling intraday scheduling deviations towards organized markets.

In this context intraday markets may be defined as those markets that are operating between the previously described spot markets and the physical gate closure, i.e. the time after which schedules submitted to the system operator may no longer be changed. Obviously, the market designs in these markets still strongly deviate between countries. Even within the Nordic market, which has a standardized and common spot market since the end of the 1990s, the intraday markets have remained differentiated for a long time. Even today, the intraday market ELBAS is only common to Sweden, Finland and Eastern Denmark. Also in Germany, the intraday market has only been formalized with the new Energy act of 2005. And just since September 2006, intraday trading takes place at the German power exchange EEX. A look at the traded volumes reveals even today very low volumes (cf. Table 3). A total of 1.4 TWh has been traded in 2007, this corresponds to less than 0.3% of the total electricity consumed. In the Scandinavian ELBAS market, the market volume is with 1.6 TWh only slightly higher. These low trading volumes may be related to the market design or to the market structure. Here a closer look is required, yet this is postponed until the market design review has been completed by a look at the balancing markets.

2.3. *Reserve provision, balancing markets and imbalance settlement*

Given that electricity is not storable, the instantaneous equilibration of demand and supply has always been a core concern of Electricity System Operators. Reserves have always been used for this

[2] Note that the EU sector inquiry (EU, 2007) has been published in 2007, yet the data used there are mostly covering the periods 2004–2005.

Table 3
Intraday markets in the countries considered.

Country	Market operator	Gate closure	Intraday trading volume (2007)	Share of national consumption (%)
France	Powernext	60′ before delivery	0.2 TWh (open since 07/11/07)	0.1
Germany	EEX	75′ before delivery	1.4 TWh	0.3
	IntradayS	Even ex-post trades	?	
Sweden, Finland, Denmark East	Nordpool	60′ before delivery	1.6 TWh	0.3
Spain	OMEL	6 auctions per day	25 TWh	8
UK	Not relevant since spot market closes only 1 h before delivery			

Table 4
Reserve categories in the UCTE and NORDEL systems.

Reserves category, by activation type	UCTE	NORDEL
Frequency	*Primary reserve* (time for full activation max 30 s)	*Primary or frequency controlled reserve*, distinguished in • Normal operation reserve • Disturbance reserve
Automatic load flow	*Secondary reserve* (time for full activation max 5 min)	–
Manual	*Tertiary or minute reserve* (time for full activation max 15 min, activation duration max 1 h)	*Secondary or fast active reserves*(time for full activation max 15 min) • Disturbance reserve • Forecast reserve • Counter trading reserve
	Hour reserve (time for full activation 1 h, no provision by TSO)	*Slow active reserves* (time for full activation more than 15 min)

purpose. Even the large internationally interconnected electricity systems have been especially built up to share the burden of reserve provision among a larger number and to benefit of the (weak) law of large numbers. The largest interconnected, synchronized area in Europe is the UCTE system covering continental Europe. Besides, NORDEL (in Scandinavia), UK and Ireland form separate synchronous areas. Each area is characterized by different rules for reserve. Those are primarily technical rules, which indicate how reserves are to be activated and regulated and which quantities have to be foreseen by each participating system operator. Notably the UCTE system distinguishes three reserve categories, whereas in the Nordic market only primary and secondary reserves are distinguished (cf. Table 4).

With market liberalization, the provision of reserves has also been increasingly organized through market mechanisms. Recently, Vandenzande et al. (2009) and others have subsumed reserve provision, use of reserves and imbalance settlement under the term of balancing markets. However, empirically still considerable differences may be found in how reserve markets and imbalance settlement are organized across Europe. Market designs vary from country to country even within one synchronous area. Even within Germany, the four TSOs used different market designs for the purchase of the reserves. Besides these empirical differences across countries, fundamental conceptual differences have to be noted between the balancing markets and the previously discussed day-ahead and intraday markets. Most noticeably, balancing markets are asymmetric by design. Going along with the asymmetry, the three phases market-based reserve procurement, reserve use and imbalance settlement have to be distinguished.[3] The demand on the reserve markets only stems from grid operators, whereas power companies and electricity traders are solely acting on the supply side. The grid operators then use the procured reserves to provide balancing in real time as a service to all grid users. These services are not sold on a separate market place but delivered to all customers simultaneously. After the delivery of balancing services, the costs of the balancing are attributed to the various customers, usually based on their respective imbalances. This is the imbalance settlement. Thereby different models have been developed for the pricing of these balancing services (cf. e.g. Maupas, 2008; Vandenzande et al., 2008, 2009), yet these shall not be discussed in detail here, since the focus of the contribution is on intraday markets.

Obviously the reserves will be used by the Transmission Operators to correct for any imbalances in real time, which have not been previously settled by the market players. As they are the last element in the supply chain, the main issues for the integration of wind energy are: how much is left at the end of the chain? And how much does society or/and wind power operators have to pay for it?

3. Wind power and the need for short-term adjustments

If nothing changed between the day-ahead planning and trading and the real-time operation, there would be no need for any form of short-term adjustments, the plans would just be realised as scheduled. Obviously this is not the case, and the magnitude of adjustments after the closure of the day-ahead market will be assessed in this section. These adjustments may in principle be done both through the intraday and the balancing markets. In an efficient market design, as much as possible of these adjustments would however be done in the intraday market to avoid the use of more expensive flexible resources in real-time balancing. To what extent the intraday market is used for this purpose, will be discussed in the following section by comparing the required short-term adjustments to intraday market liquidity.

Note that also in systems with high wind penetration no need for short-term readjustments arises, as far as changes in wind power infeed are predicted in day-ahead forecasts. Predicted changes in wind power production over the next day (e.g. strong wind in the morning,

[3] One design issue is, whether reserve markets should pay a separate capacity price to reserve providers, or whether the reserves are purely remunerated based on their actual use. In the latter case, favored by Vandenzande et al. (2009), actual energy price would include all opportunity cost, start-up cost, etc. incurred in delivering the energy. Then reserve procurement would mostly sum up in providing a bid platform, where bids for providing balancing energy may be submitted by producers and traders. Such systems have notably been in place in the NORDEL region. One might note however that the Danish TSO energinet.dk has abandoned this pure energy price based system, and has put into place option or capacity payments to ensure sufficient supply of reserves.

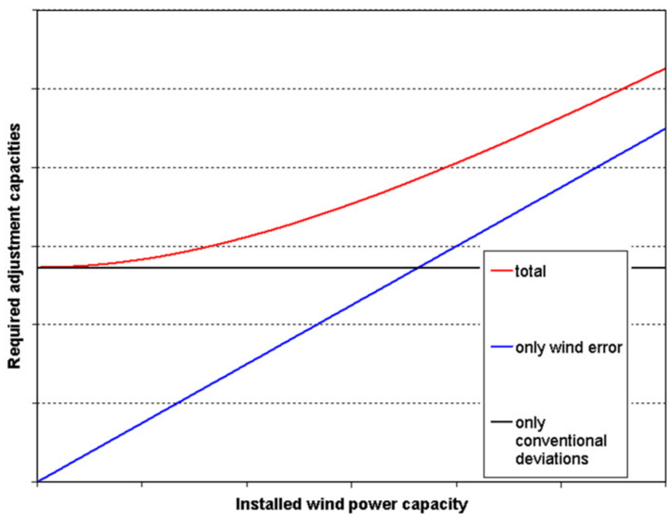

Fig. 2. Required capacities for short-term adjustments as a function of installed wind power capacity.

light breeze in the afternoon) lead to trading activities on the day-ahead market, where wind power producers will sell more for the morning hours and less for the afternoon hours.

Yet, as discussed above, both in the conventional system and with wind energy, there is new information arriving between day-ahead planning and real time. In the conventional system, the most important short-term informations are updates on the (expected) load L, e.g. due to changes in temperature or sunshine, and unforeseen plant outages K. For wind W obviously updated forecasts deliver new information. This new information may either be based on new weather forecasts derived from meteorological models or on a statistical analysis and extrapolation of the current wind power infeed as compared to the forecasts. As discussed e.g. in Lange and Focken (2008), the latter approach is advantageous for the close future, i.e. roughly for forecast horizons below six hours, whereas meteorological models are mostly suitable for longer-term forecasts.

Adaptation to these new informations requires either short-term trading possibilities or the existence of reserves or both. For the system balance it makes no difference, whether the additional (or reduced) power is provided through intraday trading or through pre-contracted reserves. Therefore, we will in a first step just talk about short-term adjustment mechanisms in general, independently whether they consist of intraday markets or activation of reserves.

Given that all three sources of error are prima facie independent, the required total physical adjustment capacity R may be computed through

$$R = N^{-1}(\alpha)\sigma[\Delta_{tot}] = N^{-1}(\alpha)\sqrt{\sigma[L-L_F]^2+\sigma[K-K_F]^2+\sigma[W-W_F]^2} \quad (1)$$

Thereby α is the required reliability level and N^{-1} the inverse of the standard normal distribution, whereas the index F stands for forecasts.[4] As illustrated in Fig. 2, the total adjustment capacities are dominated by the conventional part, as long as the installed wind power capacity is small. But with large wind power capacities, the wind forecast error gets more important and asymptotically the total error converges to the wind forecast error.

[4] The formula does only hold exactly, if all three errors are normally distributed. This assumption is reasonably well satisfied for load and wind forecast errors, yet power plant outages obviously are discrete events with corresponding discrete distributions. Yet as a first approximation and for illustrative purposes the formula still is useful.

Simultaneously, the correlation $\rho_{W,tot}$ between wind and total error increases

$$\rho_{W,tot} = \frac{Cov[W-W_F,\Delta_{tot}]}{\sigma[W-W_F]\sigma[\Delta_{tot}]} = \frac{Var[W-W_F]}{\sigma[W-W_F]\sigma[\Delta_{tot}]} = \frac{\sigma[W-W_F]}{\sigma[\Delta_{tot}]} \quad (2)$$

This is also illustrated in Fig. 3.

Given this increasing correlation, wind energy operators will pay in any market-based short-term adjustment mechanism more for their forecast errors if the wind penetration increases. With a linear price function on the short-term market

$$p_{adj} = p_0 + m\cdot\Delta_{tot} + \varepsilon \quad (3)$$

these additional costs can be assessed explicitly

$$\begin{aligned} C_{adj} &= E[p_{adj}\cdot(W-W_F)] \\ &= p_0\cdot E[W-W_F] + m\cdot E[\Delta_{tot}\cdot(W-W_F)] + E[\varepsilon\cdot(W-W_F)] \\ &= m\cdot Cov[\Delta_{tot},(W-W_F)] = m\cdot\rho\cdot\sigma[\Delta_{tot}]\cdot\sigma[W-W_F] \\ &= m\cdot\sigma[W-W_F]^2 \end{aligned} \quad (4)$$

Hence the adjustment costs are simply a linear function of the variance of the (absolute) wind forecast error. If the relative wind forecast error $E_{rel,Wind}$ does not change with the installed wind power capacity Cap_{Wind},[5] the variance and hence the adjustment cost will increase quadratically with the installed wind power capacity.

$$C_{adj} = m\cdot\sigma[W-W_F]^2 = m\cdot(E_{Wind,rel}\cdot Cap_{Wind})^2 \quad (5)$$

Moreover they linearly depend on the parameter m, which is the slope of the price function. This slope will be the higher the lower the liquidity in the corresponding market is (cf. e.g. Amihud, 2002).

Consequently a key issue for wind integration in a market-based environment is to ensure enough short-term liquidity.[6] A wind power producer facing the choice between selling/purchasing in the intraday market or going for imbalance settlement, will usually opt for the intraday market, given that imbalance prices are typically higher—or at least they should be, cf. Section 5. Whereas on the reserve markets the available bids are substantially predetermined by the reserve quantities contracted by the grid operators, the liquidity on the intraday market is not predetermined but is dependent on market structure and market design and the resulting attractiveness for the power plant operators to enter the intraday market.

From the viewpoint of a power plant operator, there is obviously also a potential tradeoff between entering the intraday market and providing reserves, yet before looking at these interdependencies, the current status of liquidity is assessed on the example of the German intraday market.

4. Key issue: liquidity in intraday trading

The previous discussion has shown that one key issue for efficient integration of wind energy is an efficient functioning of intraday markets[7]. Fig. 4 illustrates that errors in wind power forecasts

[5] For low values of installed wind capacities, geographical dispersion of wind power plants will typically increase with the number of plants installed. In that case, relative wind power forecast errors are likely to decrease with raising wind capacities. Yet for higher penetration rates, such as those reached in Germany, Denmark or Spain, this geographic dispersion effect is no longer likely to occur, since the plants are already widely distributed over the countries.

[6] Other relevant issues, notably linked to the distribution of the integration cost and the pricing of balancing services are discussed e.g. in Holttinen (2005) and Barth et al. (2008).

[7] As noticed by one referee, obviously also other measures may contribute to a more efficient wind integration. Also adequate rules in the balancing markets and

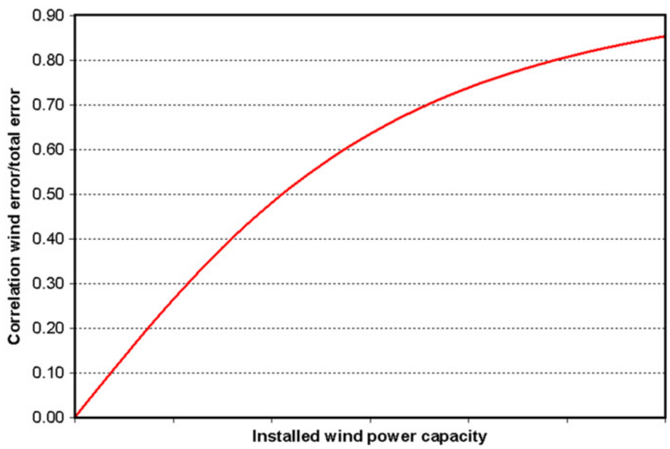

Fig. 3. Correlation between wind and total error as a function of installed wind power capacity.

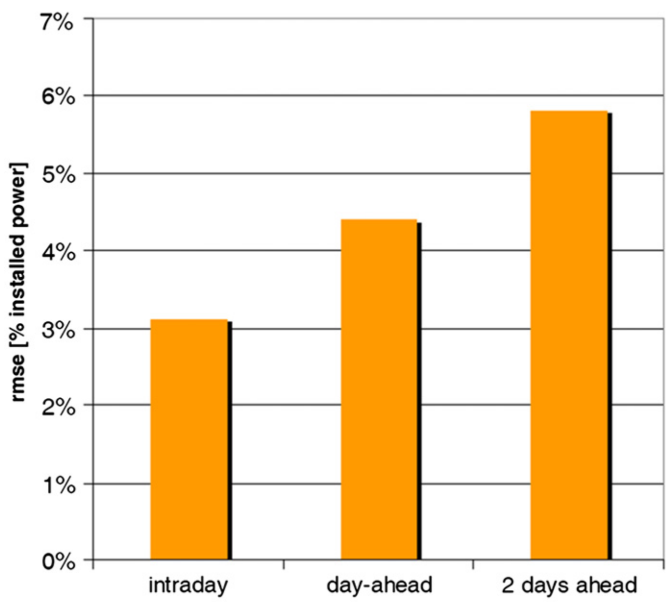

Fig. 4. Relative forecast error for aggregated production of all German wind farms.

decrease considerably when the forecasting horizon is reduced. One has however to be aware that the prediction error is reported here relative to the installed power and not to the actual average power production. Given that German wind power turbines have on average 1600 full load hours, the day-ahead prediction error is more than 20% of the average production.

This error may be reduced by making use of intraday forecasts, yet the reduction is not linear (cf. Fig. 4). Nevertheless the use of information closer to actual delivery will be beneficial.

Hence market design should facilitate an efficient use of this information. In principle, several alternative routes may thereby pursued:

- ensure functioning intraday markets,
- allow for intraday and even real-time internal portfolio optimization within large producers and
- move the entire gate closure time for the spot market closer to delivery and trading then on the spot market.[8]

Since the second alternative raises concerns on market power and the third seems not likely to provide liquidity as shown above in Section 2, the focus in the following is on the intraday markets. Here in a first step for the case of Germany the physical needs for intraday trading are assessed. Those are then compared to the observed trading volumes and the discrepancies are interpreted.

4.1. Needs for short-term adjustments and intraday trading

As discussed in Section 3, three major sources for deviations between day-ahead plans and actual delivery have to be considered in energy systems with high wind penetration:

- Load forecast deviations
- Power plant outages
- Wind forecast deviations.

Since all these are physical or technical phenomena accessible to statistical measurement, the total market volume resulting from these sources may be assessed. This is done in the following for the case of Germany (cf. also Pack, 2007), starting with wind energy, which is the prime focus here.

For wind power, both the day-ahead predictions and the actual (estimated) production are now regularly published by the German TSOs. Based on data from 2006 and 2007, the mean absolute deviation (MAE) is estimated at 600 MW, which is also in line with the above given values—considering that there are about 20,000 MW installed wind power capacity in Germany and that the MAE is lower than the root mean square error (RSME).

For load forecasts, an average forecast error of 2% in day-ahead forecasts (cf. Hufendiek, 2001) provides a total potential of around 1200 MW of aggregate intraday load deviations within Germany.[9] This shows, that despite already high wind penetration in Germany, the load forecast error is still dominating the wind forecast error by about a factor of 2. And under the assumption of stochastical independence of the two forecast errors, additional wind forecast errors increase the required trading or/and reserve volume currently only by less than 50%.[10] Yet this will change with a further increase in installed wind capacities.

The potential for intraday trading resulting from power plant outages is determined by the number of outages per block and year and the duration of these outages. With about 20 outages per

(*footnote continued*)
measures to reduce market power in these markets will be important. This aspect will be taken up in the next section.

[8] As noted by one reviewer, this would ultimately lead to confounding the spot and the intraday market. Another reviewer remarked that this option is very close to the first one. Yet, while there are certainly some commonalities, the first one takes a continuation of the current single day-ahead market auction as given. The latter one, by contrast, implies a move towards continuous or at least repeated trading. In Section 6, the pro and cons of these alternatives are discussed further.

[9] Maupas (2008) indicates even a forecast error below 1% for the French system.

[10] This is an upper bound derived from Eq. (1) by determining the marginal change in reserves for an increase in Wind forecast error $E_{Wind} = N^{-1}(\alpha)\sigma(W - W_F)$:

$$\frac{\partial R}{\partial E_{Wind}} = \frac{N^{-1}(\alpha)}{2\sqrt{\sigma[L-L_F]^2 + \sigma[K-K_F]^2 + \sigma[W-W_F]^2}}\left(\frac{2\sigma[W-W_F]}{N^{-1}(\alpha)}\right) = \frac{E_{Wind}}{R}$$

In the numerical approximation, the power plant outages are neglected for the moment and the previously mentioned figures for wind and load forecast errors are inserted.

unit and year for fossil-fired units[11] and an average duration of 10 h we get for Germany an expected volume of 1700 MW. Given that the electricity for the first hour of an outage cannot be procured at the intraday market and due to a rather skewed distribution of outage durations, it is expected that the actual level is rather on average around 1400 MW.

4.2. Observed intraday trading

Using the relation (1), the potentials for intraday trading mentioned in the previous section may be added up quadratically. This yields a daily trading volume with a standard deviation of more than 2000 MW, corresponding to more than 17 TWh trading volume per year. This is far beyond the 1.6 TWh observed in the German power exchange in 2007. Even if OTC trades, including the specialized Internet platform named IntradayS, are taken into account, a strong discrepancy between the physically expected trading and actual figures appear.

4.3. Reasons for discrepancy

Besides transaction costs and potential trade-offs with the balancing markets (cf. below), a major reason for the discrepancy certainly is the market concentration in the power market. The large producers and suppliers will at least partly find it more advantageous to do a netting of intraday open positions within their own portfolio instead of going through the power exchange.[12] Since similar arguments apply for spot trading, the share of 22% of physical volume reached in the spot market (cf. Table 2) may be taken as a first guess on the relevance of this factor. Applying this percentage to the total estimated volume of 17 TWh (cf. Section 4.2), a realizable market volume of about 4 TWh is derived, which is still far beyond the actual trading. Partly the lack in liquidity may certainly be interpreted as a temporary effect and autonomous increases may be expected in the future. Yet it is questionable whether this alone will be sufficient and alternatives have to be considered. In particular market participants often complain that there are very little opportunities to purchase power in the case of unforeseen events.

5. Interaction with the balancing markets

So far, the focus of the analysis has been on the intraday market as a short-term opportunity for wind power producers to compensate for their forecast errors.[13] Obviously the alternative for these operators is not to compensate the errors through market transactions but rather to use balancing energy provided by the system operator. Which alternative is chosen, depends on the prices on both markets. Also on the supply side, bidding into the reserve market clearly is a substitute for the power plant owners to short-term sales of power on the spot and intraday markets (cf. also Maupas, 2008; Just and Weber, 2008).

Hence the two markets are closely interlinked. From a market design perspective, the two markets and their interaction should thus be designed in a way to provide incentives to all market participants for achieving globally efficient market results. Yet a proposal for an optimal design is beyond the scope of this paper, since it requires the consideration of short- and long-term incentives to all market participants, not only to wind power producers but also to conventional producers, traders, consumers and grid operators. Nevertheless, a few key requirements in view of improved wind integration are discussed in the following.

Given that reserves are even more flexible than quantities sold on the intraday market, their provision should be more complicated and their price should in principle be higher than the price of intraday energy. Hence the wind power producers normally should have clear incentives to avoid using balancing services in real time whereas the power producers would bid flexible units first into the reserve markets. Only those units not accepted in the reserve market or not capable of delivering reserves would consequently be offered in the intraday market, reducing somewhat the liquidity in this market segment. Nevertheless, enough capacities should be available for the intraday market except for some peak hours.

This simple relationship may however be disturbed if the bids on the reserve markets consist of a capacity and an energy bid, as it is notably the case in Germany. Given that they earn a capacity revenue, power plant operators may then offer lower energy prices on the reserve markets than on the intraday market. If the TSOs use those prices for pricing balancing energy, situations may occur, where the balancing energy price is lower than the intraday market price. This obviously creates distorting incentives for wind power producers and other balance responsible entities.[14] This kind of inconsistent incentive particularly occurs, when the reserve power is not procured simultaneously with the spot electricity, as is again the case in Germany. In this case, an additional rule should ensure that prices for positive balancing energy do not undercut spot prices. This would clearly avoid the gaming incentives discussed by Wawer (2007).

An important aspect of imbalance pricing systems is whether a one-price system is used or a two-price system. In the former, there is a uniform balancing energy price at each moment in time—paid by the balance responsible parties who have a balance deficit but at the same time also received by the balance responsible parties with an excess supply. By contrast in a two-price system, deficits are penalized by a higher price than the one paid to positive imbalances. As discussed in Barth et al. (2008) and Vandenzande et al. (2009), one-price systems avoid distortions in the balancing markets and hence facilitate the integration of wind energy. Vandenzande et al. (2009) show that conventional generators tend to undercontract under a two-price system—and similar results are also to be expected for wind power producers, who will equally try to avoid penalties for being short in the imbalance settlement. Hence a two-price system will negatively affect the liquidity of the intraday market, with the further consequence of increasing average prices. Consequently, the use of two-price systems for imbalance pricing should clearly be avoided, both to improve liquidity in the intraday market and to avoid penalization of wind power producers.

Another kind of problem occurs in Denmark and the other Scandinavian countries, where the liquidity of the intraday market is also low. This is at least partly related to the fact, that producers

[11] This figure is given by VGB Powertech (2007) based on statistics for numerous conventional power plants in Germany and Europe.

[12] In Germany, this is especially true for the four large power producers RWE, E.ON, Vattenfall and EnBW, who control about 80% of the total conventional power plant capacities. Ownership for wind power production is far less concentrated. Moreover wind power producers are under the current legal framework not obliged to ensure balancing for their production.

[13] In some markets, notably in Germany and previously in Spain, the wind power producers themselves are not responsible for the deviations between scheduled and actual wind power infeed. Rather it is the responsibility of the grid operator to handle these deviations. However this does not change substantially the subsequent reasoning, since it is focusing on the incentives for the "Balancing Responsible Party", i.e. the entity in charge of handling wind power forecast errors, be it the wind power producers themselves or the grid operator.

[14] Cf. also the work by Wawer (2007) on the distorting effects of the German pricing mechanisms for balancing energy.

can submit bids in unlimited quantities for the so-called balancing power market. Those bids do not receive a capacity price, yet they are included in the short-term merit order list of the grid operators and activated if economically attractive. However this system is not as problematic as it may seem: given the high share of hydro, flexible power capacity usually is not scarce in the Nordic power system. Consequently differences between day-ahead (or intraday) power prices and the balancing power prices are low. This implies that wind operators (provided they see a uniform balancing price) do not incur large losses, if their deviations are settled using balancing energy instead of intraday trade. More problematic is here that all Scandinavian countries except Norway use two-price models when it comes to charging the balancing energy.

The results of Maupas (2008) suggest that it is economically most efficient not to have an intraday market and a balancing energy mechanism in parallel but to rely solely on the balancing markets. The main explanation is that the doubling of markets leads to inefficient planning with the TSO, because he has to adapt to changing trades and plans of the individual operators. Yet Maupas (2008) also clearly indicates that the quantities dealt with in this case by the balancing energy mechanism may get very large. Moreover this market design may facilitate the abuse of market power, given that in many countries only a few companies are dominating the electricity business.

To conclude, the analyses indicate that well-designed balancing markets will contribute to an improved functioning of the intraday market. Yet also the opposite is true. An increase in liquidity in the intraday market reduces the impact of distortions in the balancing markets. With liquid intraday markets, market participants and notably wind power producers will be less obliged to rely on the balancing markets where distortions from market power or penalties imposed are so far rather common in Europe.

6. Key challenge: improved intraday market functioning

In this situation, four principal alternatives may be envisaged to improve the functioning of the intraday market and thus ease the integration of wind energy:

- Change from day-ahead spot auction to continuous spot trading until close to physical gate closure
- Move gate closure time for the spot auction e.g. to 6 p.m. on the day before
- Bundling of liquidity by introducing auctions in the intraday market
- Increase of liquidity by obliging market partners to bid into the intraday market

The intention of all these measures is to facilitate the intraday adjustment for wind power producers and thus to lower the adjustment cost.

At first sight, the first alternative seems advantageous, since it would allow all market participants clearing their open positions as they occur, even just before physical delivery. Yet this argument is only valid if limitations in liquidity are not taken into account. In view of the British experience, this alternative is rather not very attractive. It is likely to go along with rather low liquidity, leading thus to increases of adjustment costs paid by wind power providers.[15]

The second alternative would certainly provide some improvement compared to the current situation, yet is not very compatible with the usual office hours and would hence at least induce some additional transaction costs for increased staff presence etc. It is certainly not problematic in view of providing enough liquidity on the spot market, but the fundamental problem of how dealing with deviations within the day itself is not solved.

The third alternative corresponds to the actual market design of the Spanish and now also Portuguese market. There six auctions during the day of delivery itself are carried out. The total market volume is 25 TWh and thus considerably above the volumes observed in the other markets. Also the distribution of purchases and sales corresponds to the theoretical considerations made above. Almost 75% of all purchases are done by producing units—presumably to compensate for outages. On the sales side even more than 90% of the bids stem from producing units—the consuming units apparently on average underestimate their needs and tend to act as net purchaser in the intraday market. Such a revised market design would certainly induce some additional operational costs (for new IT systems, staff, etc.), yet overall transaction costs are almost certainly lower, since the price risk for trading on the intraday market is lowered. Hence this alternative is an advantageous compromise between providing flexible intraday trading opportunities and bundling liquidity sufficiently in dedicated auctions.

The fourth alternative is problematic given that it would impose constraints on the economic activities of the market participants. Yet at least in one point this would be beneficial for liquidity and also economically sound: so far in Germany, the TSOs have to handle the forecast deviations for wind energy. Since they have not much trading competence by themselves, they tend to outsource this activity and frequently they buy the portfolio management services from the trading company within the same holding. Those traders usually compensate the wind fluctuations with other fluctuations in their portfolio and consequently only put limited amounts for purchase at the stock exchange. By separating these diverse activities, liquidity would obviously be increased. From a liquidity point of view, this proposal thus seems attractive and it may well go along with high flexibility in e.g. continuous trading. Yet the freedom to trade – including the freedom to abstain from trading – is constitutive of market economies. Limitations to this freedom have, therefore, to be well thought through and societal benefits must be high to justify any restrictions in the field. At second sight the benefits of the fourth alternative are however not so clear. In that case, players with combined portfolios, including conventional plants, wind and demand or at least two out of the three, may formally go through the market to net out their imbalances. Yet while fulfilling the formal obligation, they may still put buy and sell bids at identical prices, clearing thus immediately and providing only an apparent liquidity of no use to other market participants. Hence mandatory bids into the intraday market are in themselves probably insufficient to improve the situation for independent wind power producers.

7. Final remarks

The discussion has shown that wind energy will particularly benefit from increased liquidity in the intraday markets—at least once the current status is lifted, where wind power operators in

[15] The even more radical step from an exchange based to a pool based system like PJM, which might allow curing for liquidity issues, is currently hardly conceivable in Europe. This would in fact require a strong pan-European or at least international ISO, which is not in sight.

Germany and elsewhere are not responsible for the schedule deviations, which they are causing. Among the possibilities considered here, the organization of intraday auctions as done in Spain seems to be the most attractive way for increasing liquidity. Yet one has to be careful not to provide inconsistent incentives and gambling opportunities for traders active both in the day-ahead and the various intraday auctions. Also more research is needed to assess the optimal combination of intraday and balancing market designs. Several approaches may be envisaged to address this issue: equilibrium analysis in the vein of Just and Weber (2008) to determine price and quantity patterns in a perfect competition setting, game theoretical modeling to assess potential incentives for excersing market power or simulation studies in the line of Maupas (2008) to investigate possible market outcomes and costs.

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