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Experience and challenges with short term balancing in European systems with large share of wind power

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Abstract—The amount of wind power in the world is quickly increasing. The background for this development is improved technology, decreased costs for the units, and increased concern regarding environmental problems of competing technologies such as fossil fuels. Some areas are starting to experience very high penetration levels of wind and there have been many instances when wind power has exceeded 50 % of the electrical energy production in some balancing areas. The aims of this paper are to show the increased need for balancing, caused by wind power in the minutes to hourly time scale, and to show how this balancing has been performed in some systems when the wind share was higher than 50 percent. Experience has shown that this is possible, but that there are some challenges that have to be solved as the amount of wind power increases.

Index Terms— Wind power, integration, power system, power transmission, frequency control, balancing of wind power.

I INTRODUCTION

The world's total electric consumption is currently around 20,200 TWh per year [1], of which 2.5% [2] is provided by wind power. In 2010 Spain covered 16% [3] of their electric energy demand with wind power. The corresponding figures were 17% for Portugal [4], 13% for Ireland [5] and 25% Western Denmark (2009) [6].

It is important for the development of future power systems to investigate how systems with larger shares of wind power can be operated and designed for efficient integration without violating system security. Experiences from the integration of large amounts of wind power have been studied in several reports [7, 8, 9, 10, 11], but here we collect and analyze data from several power systems facing challenging intra-hour short-term balancing conditions.

In Section II an analysis of measured intra-hour wind power variations in different systems is presented. Section III describes the fundamentals of how to keep the balance in power systems and Section IV provides a description of how this balance was kept in some systems during periods of high wind penetration. A summary and conclusions are presented in Section V.

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II EXPERIENCE OF SHORT TERM WIND POWER CHANGES IN SOME HIGH PENETRATION CASES.

In Ireland, Portugal, Spain, Germany, Denmark and parts of Sweden experience has been gained into the frequency of occurrence of changes in wind power, for a variety of ramp magnitudes. The size of the changes depends on meteorology, the amount of wind power capacity and the distance between wind power installations. The size of the changes also depends on how long a time period one studies; the variation within 30 minutes is larger than variation within 5 minutes. Some statistics from selected places are shown below.

A. –Sweden - Gotland

On the island of Gotland there is 110 MW of wind power installed. The island is connected to the mainland by two High Voltage Direct Current, HVDC cables. In most situations the direction of the power flow is from the mainland to Gotland, but at low load and high wind, the power flows in the opposite direction. This requires a flexible operation of the HVDC lines.

The wind power data studied here consists of a total of 27411 five-minute measurements of both the load and the wind power production on Gotland, during the period of March 12 – June 16, 2011. 85 percent of all wind power production is measured, while 15 percent is estimated from nearby units. The mean wind power production during this period was 26.8 MW, i.e. 24 percent of installed capacity.

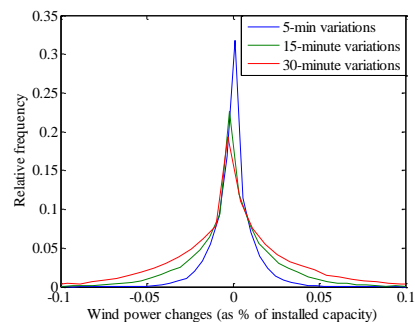


Figure 1: Short term changes (Probability Density Function) within an hour of total wind power production at Sweden-Gotland. A positive value reflects an increase in power and a negative value a decrease

The standard deviation (as percent of installed capacity) for the three studied time periods were 1.41% (5 min), 2.94% (15 min) and 4.48% (30 min). With the assumption of approximate Gaussian distributed changes, 32 % is then outside $\pm \sigma$ and 0.3 % is outside $\pm 3\sigma$. This means, for example, that during approximately 99.7 % of the time, the

wind power changes within 30 minutes are lower than 13.43 % of 110 MW, i.e. lower than 14.8 MW.

The wind power on Gotland is rather concentrated in a small area along the south-west coast of the island. The mean distance between all wind power plants is estimated to 30 km. Gotland is connected to the mainland by HVDC-LCC (Line Commutated Converters) and the reactive power support comes from synchronous compensators on Gotland. During 2010, the wind generation contributed 25% of Gotland's electric energy consumption.

B. 50Hertz Transmission - Germany

50Hertz Transmission is the TSO (Transmission System Operator) responsible for northern and eastern Germany. The installed wind power capacity in this area by mid of 2011 was 11,320 MW. Around 41.1% of the installed capacity within Germany is installed within the 50Hertz Transmission control area.

The wind power data available from this part of Germany consists of 15-minute resolution measurements for the year 2008 (installed wind generation capacity was 9,677 MW as of 12/31/2008), giving a total of 35,136 observations. The power measurements are generated by an up-scaling algorithm in a cycle of seconds and then aggregated to a 15 minute mean value, while the real-time behavior is recorded ex-post based on 15 minute resolution meter data. The minimum and maximum wind power production levels in 2008 were 8 MW and 8,257 MW [19], i.e. 0.083 % and 85.3% capacity factors, respectively. The mean wind power production was 1880.8 MW, amounting to 19.4% of the installed capacity. The probability density functions for the 15 and 30 minute wind variations are shown in Figure 2.

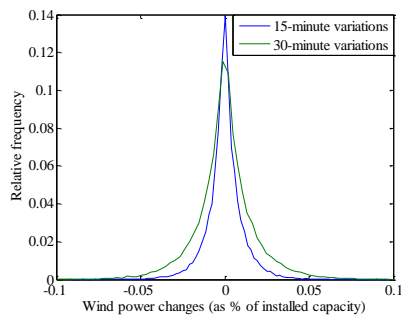


Figure 2: Probability density functions of 15 minute and 30 minute variations of registered wind power from the 50Hertz area in Germany.

The standard deviations (as percent of installed capacity) for the time periods studied were 1.10% (15 min) and 1.84% (30 min).

C. Portugal

By the end of 2009 the wind capacity installed in Portugal was 3,357 MW. All wind power data is collected by the system operator REN at 15 minute sampling values. For this study data for 2009 was used. During that year the wind generation contributed 15% of the country's electric energy consumption (9 TWh) and had a mean wind power production of 1,027 MW.

The probability density function was computed for 15 minute, 30 minute, 1 hour and 4 hour changes in wind power production, for nationwide wind production, as depicted in Figure 3.

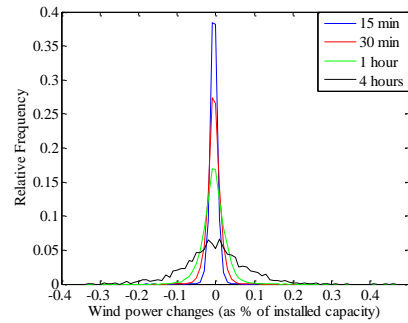


Figure 3: Total wind power changes for the Portuguese system for four different time periods.

The standard deviations (as percent of installed capacity) for the studied time periods were 0.95% (15 min.) and 1.64% (30 min.). Five areas with only a single month's data available have also been studied. The nominal capacities installed in each area are P(A)=65.6 MW, P(E)=382 MW, P(G) = 504 MW, P(I)=105 MW and P(J)=113 MW, details are found in table 4.

The wind power capacity in Portugal is concentrated in the center and north of the country within a maximum distance of 450 km. The mean distance between all wind power plants can be estimated to 133 km.

D. Denmark

In Denmark wind energy is produced by 5,000 wind turbines scattered over the entirety of the country. Of the installed capacity of 3,800 MW, only the four offshore wind farms (700 MW) are connected to the transmission system and the rest is typically connected to the 10 kV network. The Danish TSO, Energinet.dk, has online measurements available for half of the wind power capacity and the remainder is calculated by online estimation. The estimation is carried out for 23 regions and is based on online measurements from selected wind turbines with similar properties as the non-measured.

For the analysis presented here, 1 minute resolution of instantaneous wind power values from each region have been considered for the first six months of 2011. After an initial data cleaning, the changes in wind power over 1, 5, 15, 60 and 240 minutes were calculated for each region. The probability density functions for 15 minute changes for a variety of areas and total Danish wind power are shown in Figure 4.

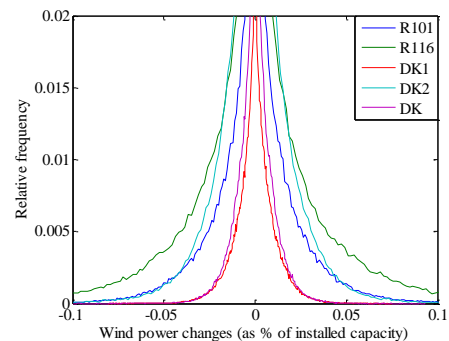


Figure 4: 15 minute changes of total wind power production for different Danish areas. R101 and R116 are from two of the 23 regions, DK1 is Western Denmark, DK2 is Eastern Denmark and DK is whole Denmark

The standard deviations of wind power changes for three of the areas studied, over four time periods studied are shown in Table 1.

Region	R101		DK1		DK	
Wind	251 MW		2,839 MW		3,801 MW	
Distance	30 km		102 km		113 km	
Time	Σ	3σ	σ	3σ	σ	3σ
1 min	0.8	2.4	0.4	1.2	0.3	0.9
5 min	1.4	4.2	0.6	1.8	0.5	1.5
15 min	2.3	6.9	1.1	3.3	1.0	3.0
30 min	3.7	11.1	1.8	5.4	1.7	5.1

Table 1: Short term changes in percent of installed capacity within an hour of total wind power production in Denmark

E. Spain

At the end of 2010, 19635 MW of wind power capacity was installed on the Spanish power system. All wind power data is collected by the system operator, REE (Red Eléctrica de España), as 10 minute mean power production values. Data was measured by the Spanish TSO during 2010 (from January 1st 2010 to December 31st 2010) for the peninsular area (excluding Canary Islands and Balearic Islands). The power production of 98.6% of installed wind farm capacity is measured while the rest (1.4%) is estimated. During this period the mean wind production was 4,877.1 MW, i.e. 25.2 % capacity factor. The minimum and maximum wind power production levels in 2010 were 191 MW and 14,901 MW; 0.99% and 76.14% of the installed capacity, respectively.

The probability density function for 10 and 30 minute wind power production changes, as well as for 1 and 4 hours, for the whole of Spain are shown in Figure 5. The variation in production of nine wind farms spread all over Spain, with a total installed capacity of 282 MW, has also been studied for the year 2007. The results are shown in table 2.

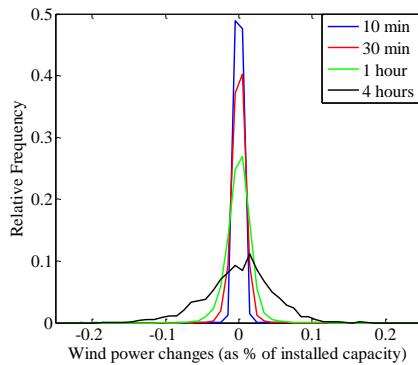


Figure 5: Wind power changes of total wind power production for Spain for four different time periods.

Region	Single farm		Nine Farms		Spain	
Wind	31 MW		282 MW		19,635 MW	
Distance	0.8 km		235 km		289 km	
Time	σ	3σ	σ	3σ	σ	3σ
10 min	4.02	12.1	1.703	5.109	0.449	1.346
30 min	6.43	19.3	2.439	7.317	0.941	2.822
1 hour	-	-	4.068	12.204	1.629	4.886

Table 2: Short term changes in percent of installed capacity within an hour of total wind power production in Spain

The wind power in Spain is spread all over the country. The mean distance between all wind power plants can be estimated to 289 km

F. Ireland

The majority of the 1,539 MW of installed wind capacity, in the Republic of Ireland in 2010, is situated along the 490 km of Atlantic coastline. The mean distance between these wind power plants is approximately 170 km. EirGrid, the system operator, has collected energy data from grid connected wind farms at a resolution of 15 minutes from 1999 to present. 2010 data is employed here to calculate 15, 30, 45 and 60 minute changes in wind power production.

In order to show the effect of spatial diversity, the probability density function for 15 minute changes in normalized wind power production were obtained for three separate areas: total Republic of Ireland production, production in the south west region, and production in Co. Donegal, situated in the north of the country. The results are as shown in Figure 6

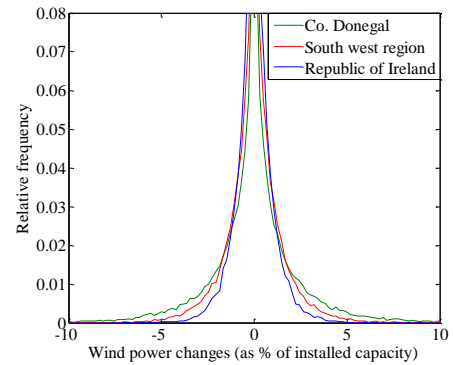


Figure 6: 15 minute normalized wind power changes of total wind power production for Ireland for three different areas in the Republic of Ireland.

The standard deviations of change in wind production are shown in Table 3 for each region and time period studied.

Region	Co. Donegal		South west Region		Republic of Ireland	
Wind	274 MW		747 MW		1539 MW	
Area	4,841 km ²		~24,675 km ²		70,273 km ²	
Time	σ	3σ	σ	3σ	σ	3σ
15 min	2.4	7.3	1.4	4.4	1.0	3
30 min	3.7	11.2	2.4	7.3	1.7	4.9
45 min	4.6	13.8	3.2	9.7	2.2	6.6
60 min	5.4	16.2	3.9	11.8	2.7	8.2

Table 3: Short term changes in percent of installed capacity within an hour of total wind power production in Ireland

G. Summary

In general the greater the geographical spread between wind farms is, the lower the variability should be. This has been shown for hourly changes [11-12] as a function between two individual wind power stations. Here we focus on intra hour variation instead. The standard deviation of changes in wind power for different time frames and a variety of sites are summarized in table 4.

The mean distance between the wind farms are estimated in the following way: wind farms are assumed to be evenly dispersed across a region, which can then be modeled as a rectangle spanned by width a , and height b . The mean distance between wind farms are then assumed to be the mean distance between two random points in a corresponding rectangle.

Country / area	Wind	Standard deviation – σ [percent]			
	MW	5 min	10 min	15 min	30 min
Sweden - Gotland	110	1.41		2.94	4.48
Denmark – 1 region	251	1.4		2.3	3.7
West Denmark	2,839	0.6		1.1	1.8
Denmark	3,801	0.5		1	1.7
Spain – 1 farm	31		4.021	4.62 *	6.43
Spain – 9 farms	282		1.703	1.89 *	2.44
Spain	19,635		0.449	0.57 *	0.94
Ireland – Donegal	274			2.4	3.7
Ireland – SouthWest	747			1.4	2.4
Ireland – ROI	1,539			1.0	1.7
Portugal	3,357			0.95	1.64
Portugal – Zone A	65.6			3.70	4.19
Portugal – Zone E	382			3.78	4.95
Portugal – Zone G	504			1.98	2.57
Portugal – Zone I	105			5.58	7.05
Portugal – Zone J	113			4.76	5.47
Germany	9,677			1.1	1.84

Table 4: Wind power changes of total wind power production for all studied areas and for four different time periods. * 15 minute data for Spain are obtained from linear interpolation using 10 min and 30 min data.

This means that the rectangle should be selected so it seems representative for this use. The mean distance between the two points can be calculated as [13-14]:

$$Mean = \frac{1}{15} \left[\frac{a^3}{b^2} + \frac{b^3}{a^2} + d \left(3 - \frac{a^2}{b^2} - \frac{b^3}{a^2} \right) + \frac{5}{2} \left(\frac{b^2}{a} \ln \frac{a+d}{b} + \frac{a^2}{b} \ln \frac{b+d}{a} \right) \right] \quad (1)$$

where $d = \sqrt{a^2 + b^2}$

With eq. 1 the mean distances for the different studied areas can be estimated as shown in table 5. For the Portuguese subareas the mean distances are D(A)=18 km, D(E)=40 km D(G)=158 km, D(I)=5 km and D(J)=5 km.

Country	a [km]	b [km]	Mean [km]
Sweden - Gotland	80	30	30.2
Denmark – 1 region	65	50	30.1
West Denmark	250	130	101.6
Denmark	250	180	112.9
Spain – 1 farm	2	1	0.8
Spain – 9 farms	540	350	234.8
Spain	640	460	288.7
Ireland – Donegal	87	55	37.5
Ireland – SouthWest	200	125	85.9
Ireland – ROI	450	156	167.7
Portugal	370	100	133.2
50Hertz (Germany)	450	250	186.4

Table 5: Estimated mean distance between the wind power stations in each studied area.

The data from Table 4 and Table 5 can now be plotted and the result is shown in Figure 7.

A least squares fit is applied to the 10 and 30 min. data (dashed and solid lines in Figure 7) according to:

$$\sigma = \sigma_0 \cdot e^{-p \cdot dist} \quad (2)$$

where

σ_0 = standard deviation for wind power in one location

p = parameter

$dist$ = mean distance between the wind power units in km.

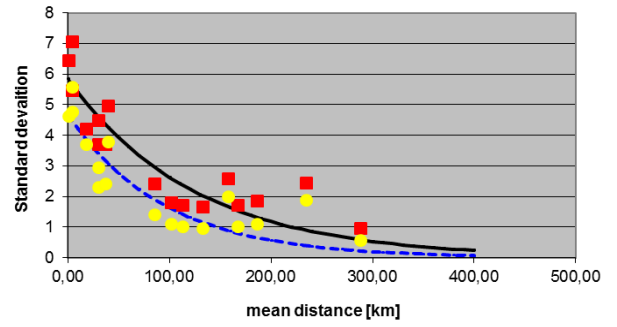


Figure 7: Standard deviation in percent of installed capacity for 10 minute (circles), 30 minute (boxes), 10 min-fitted (dashed), and 30 min-fitted (straight line) change of total wind power as a function of mean distance between all wind power stations. Data are from tables 3-4.

This curve type is selected since it is reasonable that variability exists at mean distances of zero, and that variability decreases as distance increases, but not to zero. With equal weighting of all points in Figure 11, the resulting parameters for the curve drawn in the figure are shown in table 6.

parameter	15 minute	30 minute
σ_0	4,67	5,85
p	0,0106	0,00799

Table 6: Least square parameters for fitting of standard deviations to a decreasing function.

It can, however, be noted in Figure 7 that the fitting is not accurate for all points (e.g. 9 farms in Spain). It is then important to note that the variation within 10 or 30 minutes depends on many local issues such as the topography, the local wind conditions, etc, which means that one cannot expect to get a perfect fitting. The same type of graph with imperfect fitting has also been reported for the standard deviation of hourly mean values, for example [11, 12].

III BALANCING OF WIND POWER IN A POWER SYSTEM

For any power system, regardless of wind power capacity, it is important to operate the system efficiently and to have enough operating reserve margins to maintain high reliability.

When production and/or demand are changing, the primary control reacts automatically and adjusts the production in the primary controlled plants. The equilibrium is restored, but the primary margins are used, so it is then necessary to increase/decrease production in other plants in order to replace the used primary control in preparation for new changes in production and/or consumption. At the same time the reliability of the transmission system has to be maintained. This continuous balancing process is then divided into *primary* (below a minute), *secondary* (up to some minutes) and *tertiary* (more than 10-15 minutes) controls depending on how fast the reaction to changes is.

The details for this process are different for each system as are the reliability criteria and possibilities to trade the required reserves in markets. Furthermore, the arrangements for trading between neighboring systems has a large impact on the efficiency of the process.

In a certain system the challenges depend mainly on:

- lowest consumption level

- possibilities to control other generators and to interchange regulation power among TSOs,
- internal transmission congestion,
- possibilities to trade with neighboring systems

The largest wind variability balancing challenge exists when the share of wind power is high (often in windy low load situations, load \equiv demand), the trading with neighbors is very limited or inflexible and the flexibility of the other power stations in the system is limited [7, 11, 15]. An important factor is also if it is necessary to keep large reserves also for other purposes, such as outages in transmission lines and/or large thermal power stations.

Another important factor is the strength of the interconnections from a system to neighboring systems. To consider this the index “share of wind power” can be used. It was defined in [11] and used in [7].

$$\text{Share of wind power} = \frac{\text{Max wind power [MW]}}{\text{Min. consumption [MW] + possible export [MW]}} \quad (3)$$

IV EXPERIENCE OF BALANCING OF WIND POWER IN SOME HIGH PENETRATION CASES.

Periods of high instantaneous wind power penetrations tend to occur during periods of comparatively low load and high wind output. In these situations there may be a challenge to keep the balance between net demand (the demand not met by wind generation) and generation since, not only is the load varying, but also the output of a large generator.

A. Sweden-Gotland

The island of Gotland is located in the Baltic Sea and is connected to mainland Sweden with a double HVDC cable, with two converters of size 180 MW each. From 2003 one cable changes its direction automatically to export from Gotland when wind power production on the island is 15 MW lower than total consumption. The reason is that one has to keep a margin since each HVDC link cannot operate on a too low level. In 2010 there was 110 MW wind power on Gotland, while the load varied between 30 and 175 MW. This means that in a situation with high wind and low load the wind power may be higher than the load, resulting in a net export from Gotland. During the summer when low load is rather common, the net load on Gotland may be lower than 15 MW, causing one of the links to change its direction. During 2011 the amount of wind power will increase to 165 MW, making exports from Gotland increasingly common. The HVDC lines are bipolar type HVDC links. The hysteresis of one of the links is ± 15 MW, enabling export on this link. The other link always sends power to Gotland for reliability reasons in case of fast load changes.

B. Ireland

The Irish power system consists of the Republic of Ireland system (ROI) and the Northern Ireland system. These two systems are operated synchronously with a 450 MW HVDC link between Northern Ireland and Scotland. This link is scheduled day ahead at an hourly resolution. During 2010, 13 % [5] of the ROI consumption was covered by wind power. The installed wind capacity was 1,539 MW.

The amount of wind power in the ROI system increases

continuously. 25 % of system energy demand was met by wind generation during May 2011, compared to 11.91 % in April 2011 and 7.6% percent during May 2010. This unexpected period of high wind generation was due to unseasonal Atlantic weather fronts which remained over the country for much of the month.

Figure 8 shows the duration curve of instantaneous percentage of system demand served by wind generation for the month of May. The highest instantaneous penetration was allowed to reach 52 percent, which occurred on the 10th of May 2011 at 1.15 a.m. when 1143 MW of wind production was used to meet 2189 MW of demand. The instantaneous system non synchronous penetration (asynchronous generation and imports over HVDC interconnectors) is limited due to concerns that the system may have insufficient online inertia to maintain system reliability in the event of a generator outage [21]. Generation remained above 40 percent of system demand for 2.25 days during the month, and above 30 percent for 10.6 days during the month. At the lowest system demand (1694 MW), wind generation met 25 percent of load, with no curtailment order in place. At the peak system demand of 3567 MW, wind generation met 18 percent of energy required during this specific hour. The 290 MW hydro pumped storage facility was unavailable to operators for the month of May, due to maintenance.

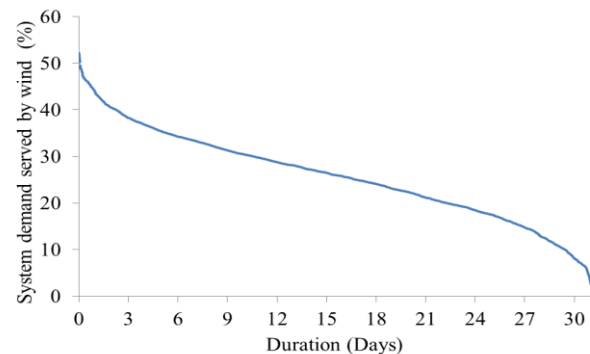


Figure 8: Number of days in May 2011 in Ireland (ROI) with a certain share of wind power

Due to the nature of the Irish system (a small island system with little interconnection), reserve levels are determined with system flexibility in mind. No additional reserve was required during periods of high wind variability. However, frequency and voltage stability concerns have necessitated rules for the number of units which remain online. Three units are required to remain online in Northern Ireland and five are required to remain online in the Republic of Ireland. Furthermore, the TSO, EirGrid, may restrict the instantaneous System Non-Synchronous Penetration (SNSP) to 50% of system demand to maintain system security [16]. SNSP is calculated as the sum of asynchronous generation plus the net import over the HVDC interconnectors divided by the system demand. The SNSP limit is imposed for voltage and stability reasons. Consequently, 7 night time wind constraint orders averaging 370 MW are suggested by wind generation production data. With the construction of a new 500 MW interconnection to Great Britain due to be completed in 2012, this may allow wind to meet up to 75% of system demand when the interconnector is exporting [16].

C. Portugal

Portugal had 4,229 MW of wind power installed as of March 2011. The minimum and maximum demand is 3,380 MW and 9,400 MW respectively and the only interconnection capacity is to Spain, 1200 MW. During 2010, 17 % of the energy consumption in Portugal was covered by wind power [4].

Very high wind penetration conditions have recently occurred in Portugal, as on May 15th, 2011, 6.45 am, when wind power covered 81% of the consumption [14]. Figure 9 shows one example from Portugal, and Table 7 illustrates recent high penetration situations of wind and other sources with no power regulation capability (e.g. run of the river plants, industrial CHP, Combined Heat and Power, with IPP contracts and PV, photo voltaics, power stations).

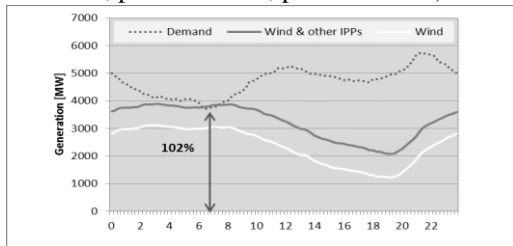


Figure 9: Portuguese load and generation profiles for May 15, 2011

Day	Time	Min. Load [MW]	Min. Load & Pump [MW]	Max. Wind Power [MW]	Max. Non-regul. Power [MW]	Max. Wind Penetr. [%]	Max. Penetr. Non-reg. P [%]
15.Nov.09	7:30	3708	4365	2785	3958	70%	87%
31.Oct.10	2:15	3862	4137	3182	4093	75%	95%
15.May.11	6:45	3727	4206	3115	3811	81%	102%

Table 7: Portuguese recent situations with high share of wind power, data source <http://www.ren.pt>.

During the very wet and windy winter of 2009/2010, on the 15th of November, 2009, the wind generation peaked at 70 % of the total consumption at 7h30. By then several hydro plants with pumped storage and three thermal power plants located in the south of the country, (the main Renewable Energy Sources are located in the North and Center) - were operating. Several small hydro power plants were generating close to nominal power and were maintained in operation. The larger reversible units were put in pumping mode. No operational problems were reported and no curtailments were necessary. Almost a year later, on the 31st October, 2010, the wind penetration reached 75% at 2:15 a.m.. Based on the wind forecasts, the system regulation was achieved by halting almost all of the run-of-river (ROR) plants by 1:30 am. Only two reversible hydro plants were operated (as pumps) during this period. The two larger thermal power plants, closer to the main load centers were kept in operation.

On May 15th, 2011, another extreme penetration period was observed at 6:45 a.m. with wind meeting 81% of the consumption. Most of the hydro plants halted their generation between midnight and 4 a.m.. Close to the wind peak penetration, some hydro plants contributed with generation to balance the wind power fluctuations while the

large reversible hydro centrals were using their full pumping capacity. Although ROR hydro stations do not, formally, participate in the power regulation, their generation may be halted for small periods depending on the technical conditions of each flow. During that night of May, 2009, it was possible to interrupt production at all of them between 0 and 5 a.m.. There was only one gas-fired thermal power station in operation whose production was reduced by 25% (approx.) at around 4 a.m.. Import of electricity (from France through Spain) was substituted by export between 5:45 a.m. and 9:15 a.m.. As before, again in this night of very high wind participation in the energy mix, no problems were reported or wind curtailment needed.

During these periods of high wind penetration the imports of electric energy from France through Spain were halted and substituted by exports of energy. Until recently, the approach followed by the TSO to deal with periods of very high wind generation during low-load hours, as the ones presented here, was to limit the import capacity. The Portuguese regulator is currently analyzing this situation in terms of compliance to market regulations and recommends that counter-trading is applied.

D. Spain

Spain has currently (April 2011) 19,988 MW of wind power installed. The minimum and maximum load during 2010 were 18,176 and 44,127 MW respectively. Interconnection is available to neighboring Portugal (max import(MI) 2200 MW, max export(ME) 2000 MW), France (MI 1200 MW, ME 600 MW) and to Morocco(MI 600 MW, ME 900 MW). During 2010 15.6 % of energy consumption in Spain was met by wind power.

Wind power supplied 20.73 % of the demand during the month of March, 2011, making it the technology with the highest energy production during that month.

The Spanish system has been operated on some days with more than half of its demand covered by wind generation (9th November, 2010 with 54 % of the consumption fed by wind). Maximum wind power in Spain was registered during this day. From 2:10 a.m. to 5:00 a.m., tertiary reserves down were exhausted. Operation staff gave instructions for 2 thermal groups disconnection (403 MW), in order to maintain power system stability. Finally, the Spanish TSO considered, applying its Grid Code, the wind power curtailments detailed in table 8. However, it must be noted that this type of event is unusual in the Spanish power system, around 200 hours during 2010, [18].

Time	Wind power	Wind/Load Percentage	Order Up/Down (MW)
3:39 a.m.	12,252	53.81	-541
5:15 a.m.	11,304	48.76	+230
5:41 a.m.	11,542	49.00	+510

Table 8: Wind power share in Spain, 9th November 2010

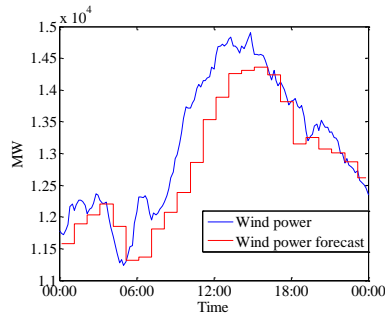


Figure 10: Wind power generation and wind power forecast in Spain during November 9th 2010

Figure 10 shows wind power generation and wind power forecast during November 9th 2010

To guarantee the security of the system, REE requires real-time communication with the generating stations, enabling it to know at all times their conditions and variables of operation, and to issue the necessary instructions relating to production conditions in order for them to be duly fulfilled by these stations. The system operator receives the telemetry of 98.6 % of the wind generation capacity installed, from which 96 % is controllable (are able to adapt their production to the given set-point within 15 minutes). The telecommunication deployment of almost 800 wind farms spread all around Spain has been achieved as a result of the aggregation of all the distributed resources of more than 10 MW. The information is collected from the production units, which in turn is needed for real time operations. Measurements, such as active and reactive power, voltage, connectivity, temperature and wind speed, are taken from wind farms every 12 seconds. In this way Spain has become the first country worldwide to have a control center for all their wind farms of over 10 MW.

Supervising and controlling the wind generation in real time has decreased the number and quantity of curtailments, maintaining the quality and security of the electricity supply at the same time as maximizing renewable energy integration

By the end of 2010, 704 Spanish wind farms have been certified against fault-ride-through capability (19,258 MW and around 95% of the installed capacity). Wind turbines totaling 1,000 MW have been excluded because of their defunct manufactures, small size turbines or prototype turbines design. As a result of this technical adaptation, the problem of significant wind generation tripping has been solved - production curtailments for this reason have not been required since 2008.

E. Denmark

The western part of Denmark is AC connected to the continental European power system, whereas the eastern part belongs to the Scandinavian synchronous area. The two parts of the country were interconnected by a HVDC line in 2010. Table 9 outlines the balancing challenge.

	West [MW]	East [MW]
Wind capacity	2800	1000
Demand max/min	3700/1300	2600/800
HVDC export capacity	1600*	600*
AC export capacity	1500	1700

Table 9: Danish wind power capacity compared to demand and export capacity. *) Excluding the 600 MW HVDC interconnection capacity.

75 % of the Danish wind power capacity is concentrated to the western part of Denmark and therefore the system impact is largest there. Wind power production exceeds the demand in this area for approximately 75 hours per year.

In the early morning of August 25, 2010 the wind production was equivalent to 99 % of the total Danish demand. Typically, high wind power production in Denmark also means high wind power production in the south of Germany. Due to network congestions this means that the interconnection capacity to Germany cannot be fully utilized for exports. In this situation the market price was higher in Norway and Sweden and 1.1 GW was exported to Scandinavia.

Depending on the system conditions, the system operator Energinet.dk requires two or three central power stations in both parts of the country to be online. For high wind situations with low prices where the central power stations are not dispatched by the market, they are currently paid to operate.

This must-run requirement is primarily related to the safe operation of the HVDC-lines and securing sufficient voltage control during power changes on the tie lines. The rule is not specifically related to the wind power.

In the coming years the wind power capacity will increase further. The balancing issues will be tackled by a combination of several different measures. Details can be found in [19].

Several central power stations are expected to be mothballed in the next years which will make it difficult and expensive to meet the current must-run requirement. Based on a socioeconomic evaluation Energinet.dk intends to minimize this dependency by building the required system support into the grid in the form of new synchronous compensators, SVCs and taking advantage of the VSC technology on new DC lines.

VI SUMMARY AND CONCLUSION

In this paper it is shown that the intra-hour variations of total wind power from larger areas varies from 3% (percent of installed capacity, standard deviation) when mean distance between wind power plants are 10 km for 30 min changes down to less than 0.5% for mean distance of 350 km and time horizon 10 minutes.

Country and Date	A: WP as share of load B: WP capacity factor	Short description
Sweden - Gotland	A: 100 % B: 50-90%	Balancing performed outside the area. The main technical challenge is situations with net demand close to zero.
Ireland-ROI	A: 52 % B: 74%	Frequency and voltage stability concerns have necessitated rules for the number of units which remain online
Portugal May 15, 2011	A: 84 % B: 63 %	Including un-controlled hydro the share was 102%. Almost all ROR production was stopped during the wind power peak. Balancing performed outside the area by limiting the import capacity.
Spain	A: 54 %	Tertiary reserves down were exhausted

Nov 9, 2010	B: 44 %	and operation staff gave instructions for 2 thermal groups disconnection (403 MW), in order to maintain power system stability.
Denmark Aug 25, 2010	A: 99 %	From technical point of view this is a rather common situation. In this situation the market price was higher in Norway and Sweden and 1.1 GW was exported to Scandinavia.

Table 10: Summary of reported short term balancing challenges during high share situations in five studied European countries. B: Capacity Factor = share of installed capacity.

Experiences from five systems with with instantaneous wind power production shares from 50% to more than 100% of load are described. Some reported challenging dates and systems are summarized in table 10.

The conclusion is that it is important to consider the internal distance between units when intra-hour wind power variation is to be estimated. Experiences also show that shares of more than 50% of wind power has been experienced and managed in systems with comparatively small exchange capabilities with their neighbors, i.e., Ireland, Portugal and Spain.

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