Wind Power in Denmark, Germany, Ireland, Great Britain, France and Spain

Statistical Survey 2012

Preface

This text supplements *Wind Power and Spot Prices: German and Danish Experience 2006-2008*[1] and Statistical Surveys 2009 to 2011 by adding data for the calendar year 2012.

The evaluations are based on data published by Energinet.dk, by the four German transmission system operators, by Eirgrid and by Elexon Portal. French data has been extracted form the eCO2mix/RTE web site by Hubert Flocard who also extracted Spanish wind power time series. Furthermore data from Norwegian Water Resources and Energy Directorate[2], Statnett[3] and Nord Pool Spot[4] has been used. Evaluations are offered, though with reservations regarding the accuracy of the data.

A selection of the hourly time series used for the statistical analyses in this text is available at http://pfbach.dk/.

Abbreviations:

EEX	European Energy Exchange	DKE	Denmark East	DE	Germany
NP	Nord Pool	N	Norway	ENDK	Energinet.dk
DKW	Denmark West	S	Sweden	IE	Ireland
GB	Great Britain	F	France	E	Spain

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[1] http://www.ref.org.uk/publications/148-spot-price-study-in-germany-and-denmark-
[2] http://nve.no/
[3] http://www.statnett.no/
[4] http://www.nordpoolspot.com/

1. Overview

European perspectives

- The estimated inflow of water in Norway was 134 TWh in 2012 or 22 TWh lower than in 2011. The total content of the hydro storages in Norway, Sweden and Finland was 13 TWh lower at the end of 2012 than one year before.
- The total export from Norway and Sweden to the Netherlands, Denmark, Germany and Poland was 22.9 TWh.
- The main flow of electricity in Europe was from north to south.
- In Germany the flow went partly via Poland and the Czech Republic. Poland has decided to install phase shifting transformers in order to control the transit.
- There have been reports from Germany on curtailment of renewable power due to strained grids in 2012.
- Germany has published ambitious plans for the energy transition (die Energiewende) inclusive plans for reinforcement of the primary grid.

Spot market performance

2012	Average area prices	Spot prices <= 0	Standard deviation
	€/MWh	No of hours	€/MWh
West Denmark (DKW)	36,38	34	16,35
East Denmark (DKE)	37,57	32	18,27
Nord Pool system price	31,11	0	13,79
EEX, Germany	42,66	58	18,60

- The market areas seem to have been well connected in 2012. The Great Belt link has contributed to more uniform conditions for the two Danish bidding areas.
- The spot prices were lower in 2012 than in the previous years. The change has no obvious explanation, but a production surplus in Germany and a different Norwegian operation policy for water storages may have contributed.
- The observations for 2012 confirm previous year’s conclusions: spot prices in Germany and Denmark are closely related. Congestions occur on the Danish interconnections with both Norway and Germany and the average Danish spot prices are between the Nord Pool system price and the German EEX price.
- Nord Pool allowed negative spot prices in Denmark from October 2009. In 2012 most of the negative spot prices occurred simultaneously in Denmark and Germany.

Wind power performance

2012		Denmark	Germany	Ireland	Great Britain	France	Spain
Wind	GWh	10,268	45,817	4,103	12,605	14,105	47,640
Max	MW	3,782	24,020	1,496	4,882	5,927	16,413
Load factor		0.31	0.22	0.31	0.29	0.27	0.33
Share		30.1%	7.8%	16.0%	4.0%	2.9%	17.4%

– The average capacity factors in Denmark were 0.24 onshore and 0.45 offshore[5]. The corresponding duration hours were 2,143 hours onshore and 3,944 hours offshore.

Correlation coefficients Hourly wind power	2012	Spain	France	Great Britain	Ireland	Germany
	Denmark	-0.048	0.157	0.301	0.096	0.663
	Germany	0.022	0.418	0.353	0.178	
	Ireland	0.074	0.251	0.608		
	Great Britain	0.149	0.379			
	France	0.410				

– Wind power has a high positive correlation between Denmark and Germany and between Ireland and Great Britain.
– The recorded minimum wind power output in 2011 was 3.6% of maximum for France and lower than 1% for each of the other countries.
– International aggregation of wind power cannot create a smooth total output, not even for all 6 countries together. The minimum average wind power output for 6 countries during 24 consecutive hours in 2012 was 9.1% of the hourly maximum.

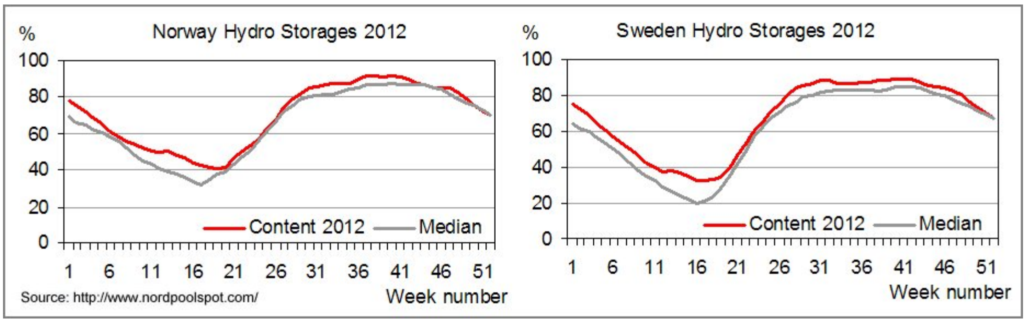
Interconnector performance

2012	Max capacity MW				Trading availability			
	To DKW	From DKW	To DKE	From DKE	To DKW	From DKW	To DKE	From DKE
Norway	950	1.000			90,3	87,7		
Sweden	680	740	1.300	1.700	93,2	84,4	95,1	87,0
Germany	1.500	1.780	600	585	57,4	44,4	93,6	92,9
DKW			590	600			92,2	92,4

– The trading capacity across a border can be reduced due to technical faults at the interconnector or due to operational limits in the interconnected AC networks.
– The average trading availability for all Danish interconnectors for the years 2006-2012 is 82% which is well below typical planning assumptions for interconnectors.
– Operational limitations and wind power variations seem to be equal important as reasons for congestions and market problems.

[5] The capacity factor is based on **installed capacity** for wind turbines operating throughout the year. The load factor is based on the **maximum total production** for wind turbines in a country.

2. Scandinavian and German energy perspectives 2012



	Consumption		Production		Net export		Hydro storage ult.	
GWh	2011	2012	2011	2012	2011	2012	2011	2012
Norway	123,141	128,245	126,516	146,341	3,374	18,096	65,722	56,597
Sweden	139,215	141,721	146,734	161,635	7,519	19,913	25,955	21,829
Finland	81,917	82,863	68,314	65,706	-13,603	-17,158	3,459	3,951
Denmark	34,980	33,776	33,749	28,678	-1,231	-5,098		
Total	379,253	386,606	375,313	402,360	-3,941	15,755	95,136	82,377
Source: http://www.nordpoolspot.com/								

The inflow of water in Norway was 107 TWh in 2010, 156 TWh in 2011 and 134 TWh in 2012. The net export from the four Nordic countries in 2012 was 20 TWh higher than in 2011 and the content of the hydro storages at the end of the year fell by 13 TWh in 2012.

In 2012 the import from Russia to Finland was 4.4 TWh. The total export from Norway and Sweden to the Netherlands, Denmark, Germany and Poland was 22.9 TWh.

The German data for 2012 is preliminary.

A growth of renewable generation has counterbalanced the falling nuclear production.

The gross consumption of electricity has decreased since 2010. This may have contributed to the German surplus of electricity in 2012 in spite of the closure of 8 nuclear units (8.4 GW) in 2011.

Germany Production	2010 TWh	2011 TWh	2012 TWh
Fossil fuel	358.1	351.8	356.0
Nuclear	140.6	108.0	99.5
Renewables	103.4	123.5	136.1
Other	26.7	25.6	26.0
Total production	628.8	608.9	617.6
Net export	17.7	6.3	23.1
Gross consumption	610.9	602.6	594.0
Source: http://www.ag-energiebilanzen.de/			

The energy balance in Europe can be very different from year to year. The inflow of water in the Nordic countries is an important factor and has contributed to the flow of electricity from north to south in 2012.

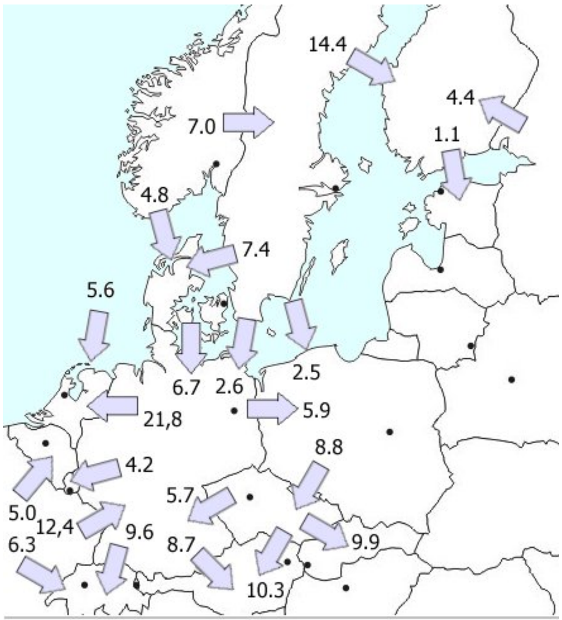
Net exchanges 2012			
Exporters	TWh	Importers	TWh
Germany	22.7	Finland	17.6
Sweden	19.9	Denmark	5.4
Norway	17.2	The Netherlands	17.2
Czech Rep.	17.1	Italy	42.4
France	43.5	Belgium	9.8
Source: ENTSO-E			

This leads together with the increasing share of non-dispatchable generation with high variability to intense electricity transports and increasingly strained grids in Europe. This is particularly the case for the German grid which serves as a European backbone.

The net exchanges can give an impression of the movements of electricity in 2012.

There is a concentration of wind power in the northern part of Germany. It creates together with the import from north a surplus of electricity which must be moved to the west and to the south.

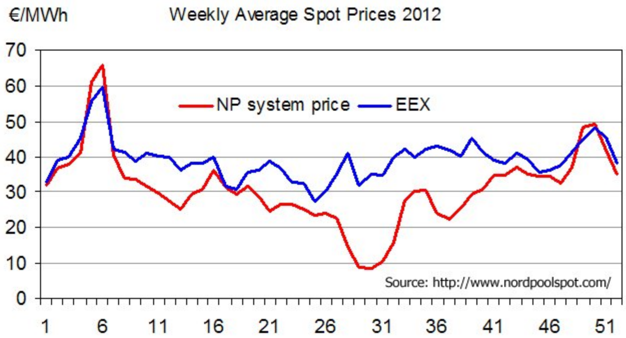
A part of the southbound traffic uses parallel paths in Poland and the Czech Republic. This transit is considered to be a threat to the operational security in these countries. Therefore Poland has decided to install phase shifting transformers in order to control the transit. The result can be a further pressure on the German grids.



Net electricity exchanges (TWh) 2012
Data provided by ENTSO-E

The Nordpool system prices reflect the energy surplus during the summer season. Apart from a couple of peaks the German EEX spot price was quite stable during 2012.

The difference between the Nordpool system price and the German EEX price is a driving force behind the electricity export to Germany. Other regions in Europe had higher or lower spot prices in 2012 to determine the direction of the electricity flow.



The complex transport pattern demonstrates the importance of efficient electricity markets and efficient market couplings. The performance of the European electricity markets should be carefully monitored and continuously improved.

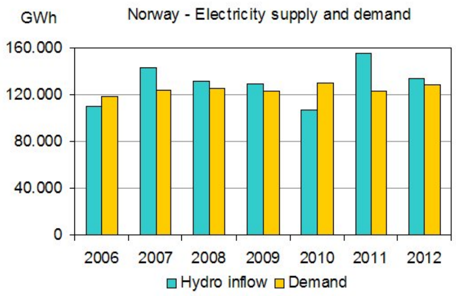
3. Trends 2006-2012

3.1 Hydrology and nuclear availability

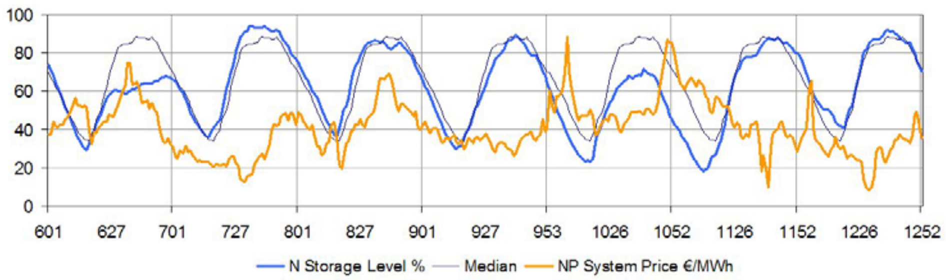
The Nordic energy balance depends on the hydro power systems in Norway and Sweden and on the availability of nuclear power in Sweden and Finland. This is demonstrated by a few charts with data form Norway and Sweden.

The inflow of hydro energy in Norway is irregular and has considerable variations from year to year. Inflow was preferred for this chart instead of production.

The variations are offset by international exchanges, by using the hydro storages (84.3 TWh) and from 2009 by thermal generation on the gas-fired Kårstø power station (440 MW).

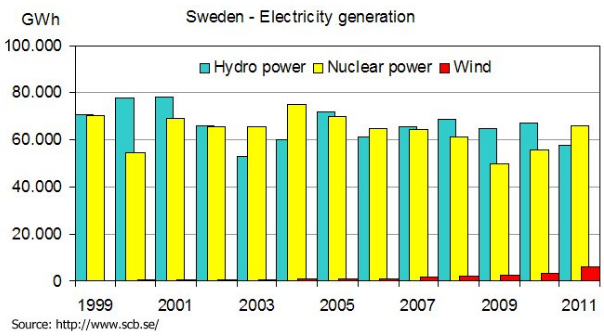


The content of the hydro storages follows an annual pattern. The very low spot price in the summer 2012 was the result of storage content above the median level:

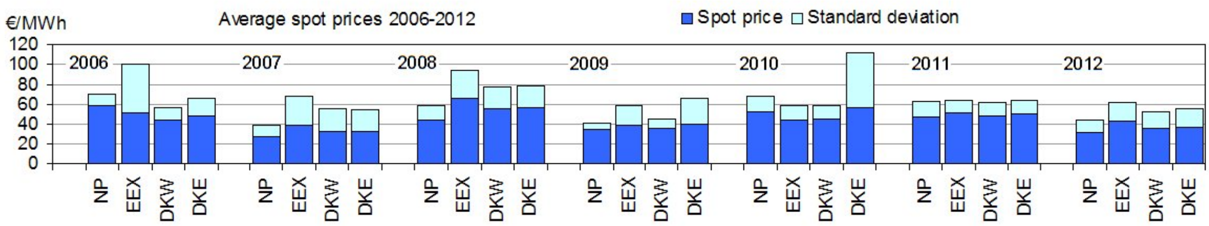


Similar variations can be observed in Swe-den. The Swedish hydro production was 78 TWh in 2001 and 53 TWh in 2003. The nu-clear production was 75 TWh in 2004 and 50 TWh in 2009.

The Swedish aggregated hydro and nuclear production was lower in 2009 than in any other year since 1999.



3.2 Spot prices



Average spot prices change from year to year and between price areas depending on local balances between supply and demand. The lowest average price, 27.80 €/MWh, was observed for the Nord Pool system price in 2007. The following year the German EEX price had an average value over 60 €/MWh.

The standard deviations reflect the price volatility. A high standard deviation indicates a less stable spot market. The reasons may be different, but in most cases bottlenecks in the grid play a decisive role.

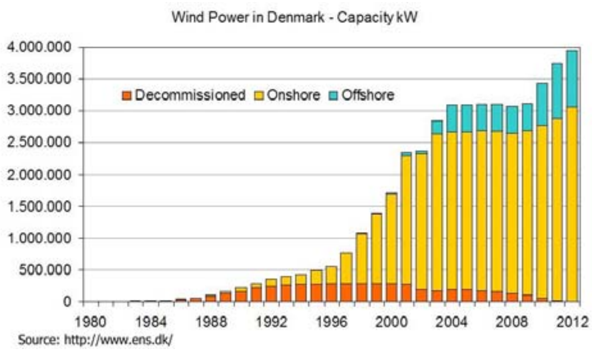
Number of hours	2006	2007	2008	2009	2010	2011	2012
	Spot price <= 0						
West Denmark (DKW)	28	85	28	55	12	18	34
East Denmark (DKE)	5	30	9	4	6	17	32
Nord Pool system price	0	0	0	3	0	0	0
EEX, Germany	10	28	35	73	12	16	58
Balancing power	Downwards price <=0						
West Denmark (DKW)	229	194	80	159	301	166	68
East Denmark (DKE)	45	53	25	30	4	144	56

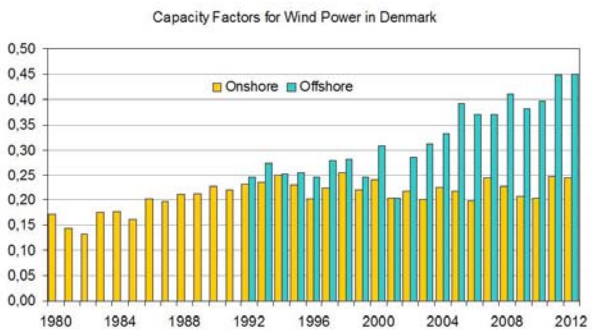
The magnitude of the overflow problem due to Danish wind power can be indicated by the number of hours with spot prices and downwards balancing prices equal to or below zero. When the price of balancing (or regulating) power is below 0 the system operator must pay for export of energy. Nord Pool introduced negative spot prices in October 2009.

3.3 Wind energy

Wind energy	Denmark		Germany		Ireland		Great Britain		France		Spain	
	TWh	Share	TWh	Share	TWh	Share	TWh	Share	TWh	Share	TWh	Share
2006	6.1	17%	39.5[6]	-	1,6[7]	-	-	-	-	-	-	-
2007	7.2	20%	40.0	-	2.0	-	-	-	-	-	-	-
2008	7.0	19%	43.0	-	2.4	-	-	-	-	-	-	-
2009	6.7	19%	37.7	7%	2.9	-	-	-	-	-	-	-
2010	7.8	22%	36.1	7%	2.6	10%	-	-	-	-	-	-
2011	9.8	28%	43.0	8%	4.3	17%	9.7	3%	11.2	2%	-	-
2012	10.3	30%	45.8	8%	4.1	16%	12.6	4%	14.1	3%	47.6	18%

Capacity factors have been calculated for Danish wind turbines. Only wind turbines which have been in service during the whole year are included.

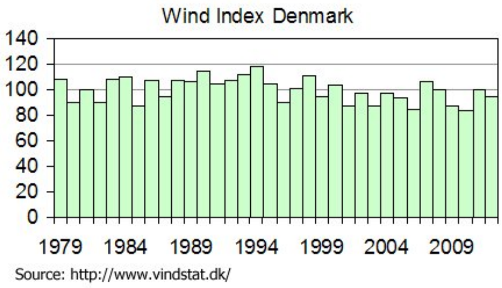




Like hydro power wind energy has variations from year to year. For the years 1983 to 2012 the wind energy index varies between 85% and 119%.[8]

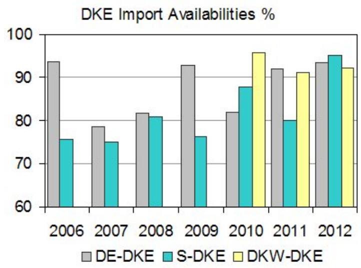
[6] http://www.wind-energie.de/de/statistiken/
[7] http://www.seai.ie/
[8] http://www.vindstat.dk/Hovedtabel.htm (in Danish)

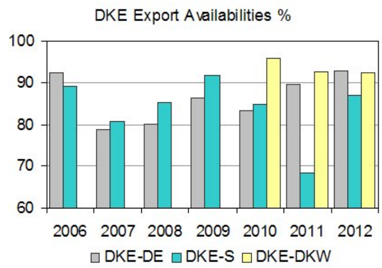
In 2012 it has been discussed internationally if the capacity factor for wind turbines is generally deteriorating with age. The Danish observations above seem not to support this hypothesis. There has been a slightly decreasing wind energy index over a number of years which may have contributed to the view.



3.4 Interconnector availability

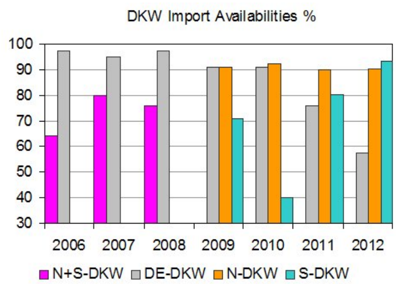
It is an essential result of the collection of data since 2006 that the average availability of the interconnectors is much lower than usually assumed.

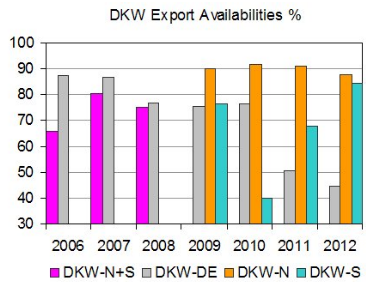




The reasons can be outages due to technical breakdowns or capacity reductions due to problems elsewhere in the grid. It could be interesting to know the unavailability for each of the two possible causes, but the available data do not support such quantification.

For the years 2006-2008 data for the HVDC interconnections between West Denmark and Norway and Sweden were aggregated as for one interconnector. Therefore the chart shows a common value for the first three years for the Skagerrak and the Konti-Skan interconnections.





An interconnection is supposed to have at least 90% availability every year. Long outages may occur, but should be rare.

The fact that most interconnectors have a worse availability in most years in one direction or the other indicates a need for a careful rethinking of the capacity planning for the international grid. Bottlenecks are serious problems in European grids. According to the EWIS report[9] the congestion problems will be worse within the next few years.

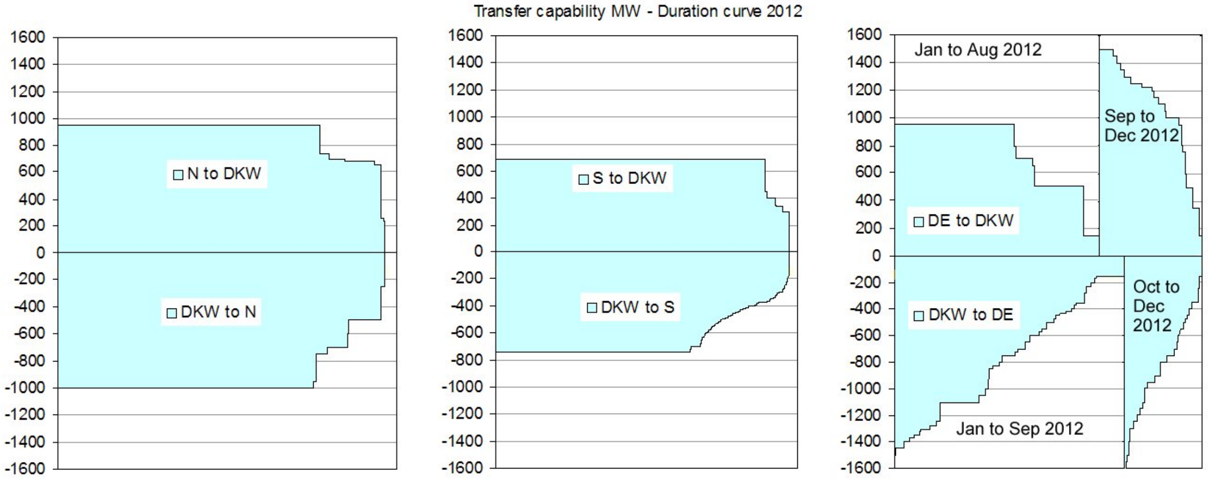
4. Interconnector Performance 2012

The electricity market is the modern tool for optimizing power system operation across national borders. Sufficient transport capacity is a decisive factor for both reasonable system security and an efficient market service.

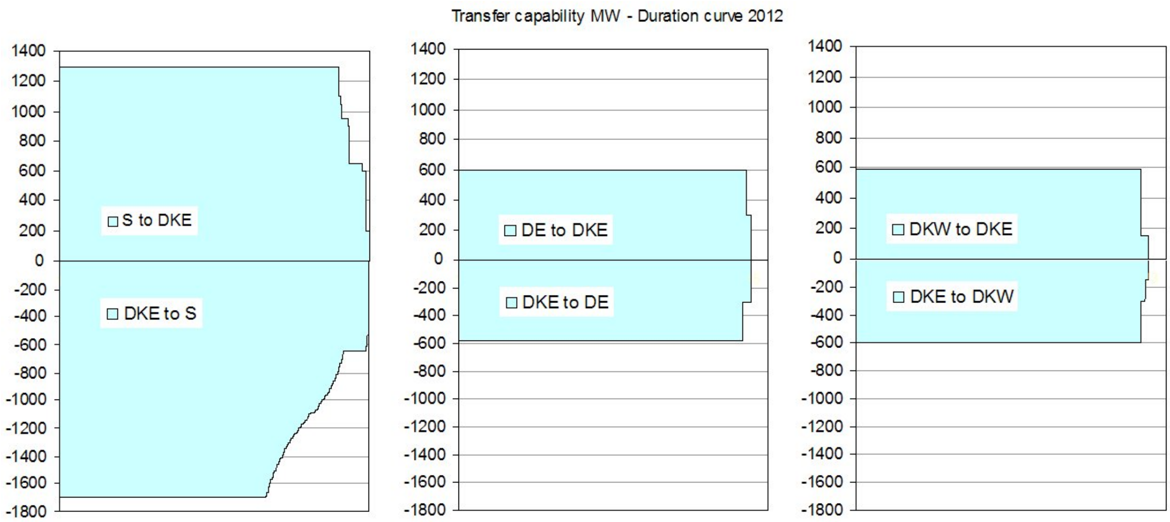
Availabilities of Danish interconnectors can be shown because Energinet.dk publishes hourly trading capacities. The trading capacity across a border can be reduced due to technical

[9] European Wind Integration Study: EWIS Final Report, 31 March 2010

faults at the interconnector or due to operational limits in the interconnected AC networks. Unfortunately the statistics cannot separate the two reasons.



The AC interconnections between West Denmark and Germany and between East Denmark and Sweden are main life lines for the Danish power systems. Energinet.dk has announced an increase of transfer capability between Germany and West Denmark in 2012. From 1 September 2012 the import capacity to Denmark should be changed from 950 MW to 1500 MW. From 1 October 2012 the maximum export capacity should be increased from 1500 MW to 1780 MW. Therefore the duration curves for this border have been split up. They indicate some improvement for import from Germany to Denmark, but practically no improvement and still very low availability for export from Denmark to Germany.



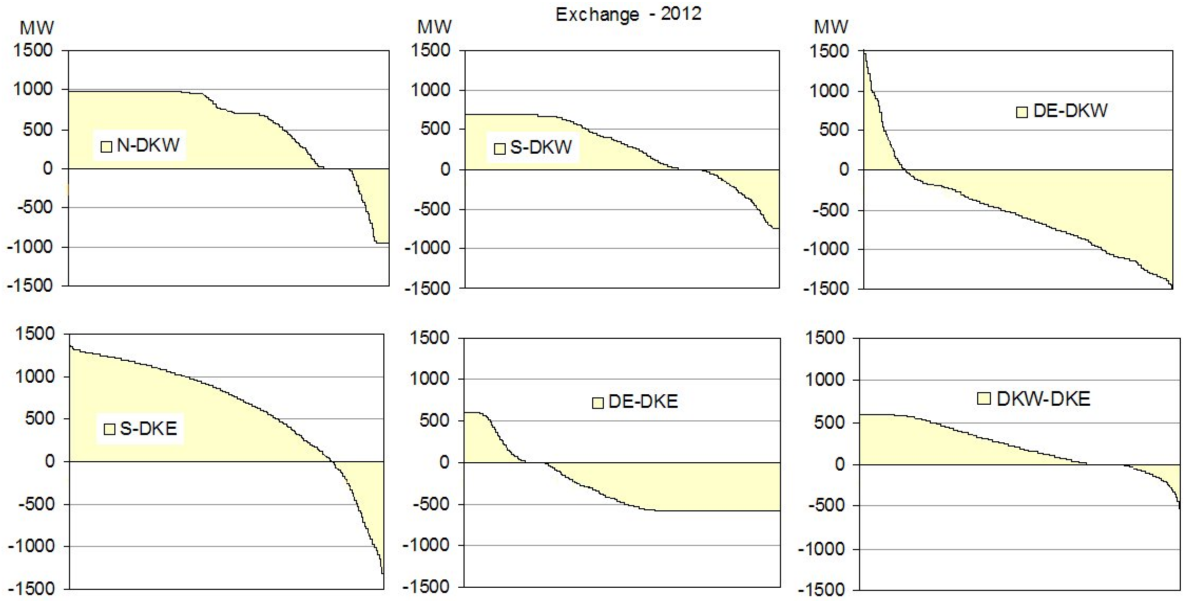
It is important to use realistic availabilities in the long term planning.

However, interconnections are often supposed to have nearly 100% availability. The Danish observations from the period 2006 to 2012 demonstrate that the practical availabilities are much lower.

2012	Average availabilities of interconnections			
%	To DKW	From DKW	To DKE	From DKE
Norway	90,2	87,7		
Sweden	93,2	84,5	95,1	87,0
Germany	57,3	44,5	93,6	92,8
DKW			92,2	92,4

Interconnections can help smooth spot price oscillations due to intermittent generation (particularly wind power), but, obviously, this is only true if there is sufficient capacity available for this purpose.

The following charts give an impression of the amounts exchanged on each interconnection in 2010:



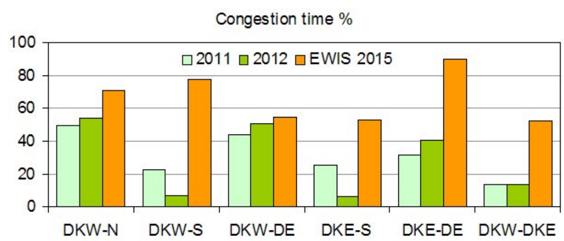
The table shows transferred volumes of energy. The transfer of energy in 2011 between Norway and Sweden via West Denmark was 1499 GWh eastbound and 156 GWh westbound.

2012	→ GWh	← GWh	Total GWh
DKW-N	673	5,455	6,128
DKW-S	734	2,884	3,618
DKW-DE	5287	703	5990
DKE-S	837	6202	7.039
DKE-DE	3112	615	3.726
DKW-DKE	2127	257	2.384

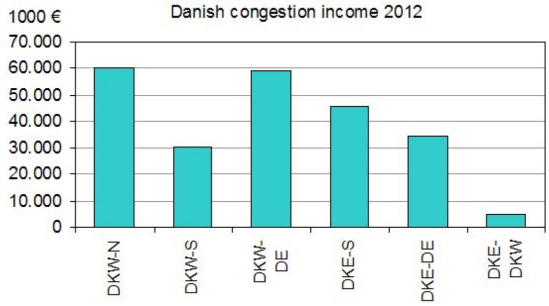
The charts indicate low levels of congestion, but the impression is misleading. Due to the operational limitations there is more congestion than suggested by the charts. In the following table the number of hours with import, export and congestion in 2012 is shown for each of the six Danish interconnectors.

2012 Hours	Export	Congest.	Import	Congest.	Total	Congested
DKW-N	1194	4	7265	4735	8784	54.0%
DKW-S	2519	246	6034	363	8784	6.9%
DKW-DE	7610	4405	1174	82	8784	51.1%
DKE-S	1457	133	7327	415	8784	6.2%
DKE-DE	6575	3201	1724	399	8784	41.0%
DKW-DKE	6325	1011	2232	222	8784	14.0%

The congestion time in 2012 exceeds 40% for the link between Norway and West Denmark and for both links between Germany and Denmark.

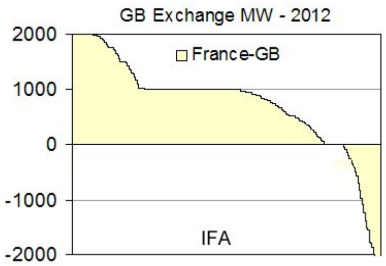


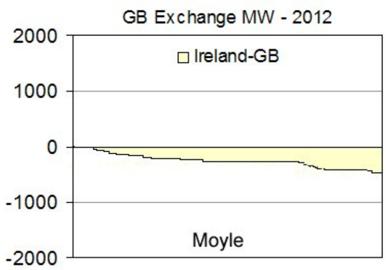
This chart compares the observed congestion times in 2011 and 2012 with estimated values for 2015 from the EWIS study[10]. The comparison suggests careful consideration of the future need for interconnector capacity in order to maintain reasonable function of the international electricity markets.

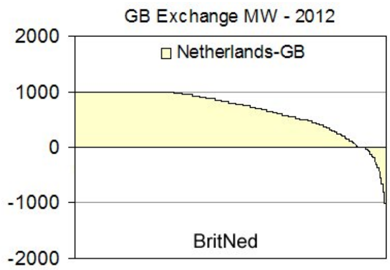


The congestion income is another indicator for the demand for more transfer capacity. According to Energinet.dk the total Danish congestion income in 2012 was 234 million €.

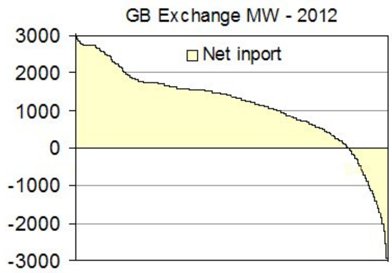
The British data include exchanges for four interconnectors. Duration curves for 2012 are shown below for three of them.







The new East-West interconnection between Wales and Ireland had very small exchanges in 2012 and seems not yet to be operating commercially.



The Moyle interconnector is a 500 MW dual pole HVDC link, but in normal operation the trading capacity will be limited to between 300 MW and 450 MW due to security constraints in the two interconnected AC grids[11].

Availabilities can be calculated from outage plans published by National Grid. For the IFA interconnector the availability in 2012 was 0.647. The reduction due to planned outages was 0.225. The reduction due to unplanned outages was 0.128.

The calculation must be made manually because the outage plans are not available as spreadsheets.

The table shows the exchanged volumes. The net import to Great Britain was 9.9 TWh in 2012 against 4.8 TWh in 2011.

GWh	Import	Export	Net import
EW	23	136	-113
IFA	7.601	1.166	6.435
Moyle	1	2.180	-2.179
Britnet	5.987	229	5.758
Total	13.612	3.712	9.900

The observations on British data for 2012 seem to confirm that the average trading capacity of interconnectors can be considerably lower than the nominal capacity.

[10] European Wind Integration Study: EWIS Final Report, 31 March 2010
[11] http://www.mutual-energy.com/The_Moyle_Interconnector/Role_in_the_Electricity_Market.php

5. European Wind Power Performance 2012

5.1 National Wind Power Output

Time series have been collected for Ireland, for Great Britain, for France, for Spain, for the two parts of Denmark (west and east) and for the four German transmission system operators (Amprion, TenneT, 50hertz and EnBW Transportnetze).

National time series for Denmark and Germany have been created by adding the two Danish time series and by adding the four German time series.

The wind power main characteristics of the five countries are:

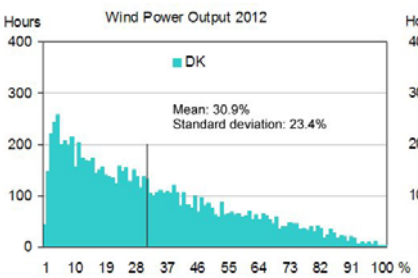
2012		Denmark	Germany	Ireland	Great Britain	France	Spain
Wind	GWh	10,268	45,817	4,103	12,605	14,105	47,640
Max	MW	3,782	24,020	1,496	4,882	5,927	16,413
Min	MW	6	134	1	0	211	118
	Load factor	0.31	0.22	0.31	0.29	0.27	0.33
	Share of load	30.1%	7.8%	16.0%	4.0%	2.9%	17.4%

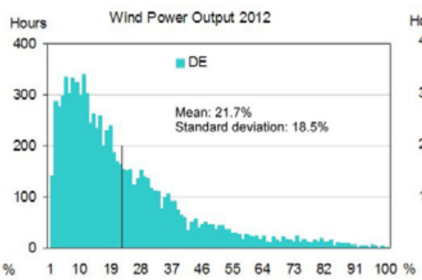
The German share of wind energy has been based on an estimated total electricity gross consumption of 590 TWh. It is remarkable that no hour in 2012 had less than 211 MW wind power production in France (4% of maximum wind power output).

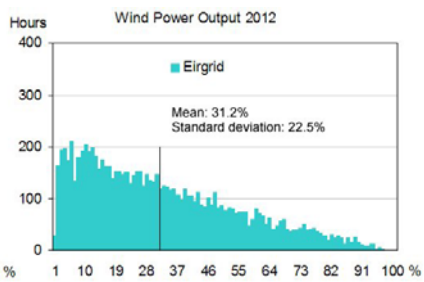
The installed wind power capacity in Denmark in service throughout 2012 was 3,938 MW of which 871 MW was offshore capacity.[12] The installed capacity in Germany at the end of 2012 was 31,308 MW of which 280 MW was offshore capacity.[13] On the island of Ireland 2054.9 MW of wind power was installed on 11 April 2012.[14]

Statistical distributions can be used for characterizing the time series. The charts below show the number of hours recorded for 1% steps of maximum production. The mean values of the distributions are identical with the load factors.

In this paper **load factors** are related to the highest observed hourly production. A **capacity factor** would refer to the installed capacity which for wind power usually changes during the year. Therefore wind power capacity factors are less well defined unless calculated for a group of wind turbines with a full year's service.



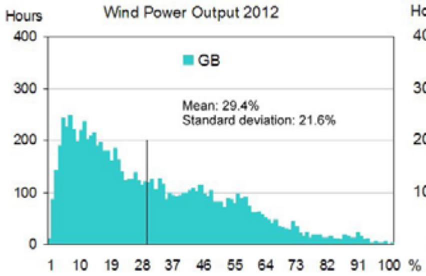


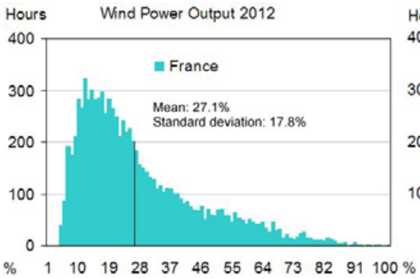


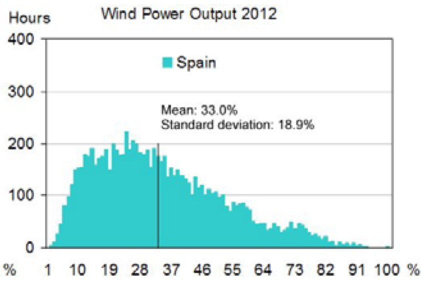
Wind power has a lower output per installed MW than most other power sources. Therefore the observed distributions are left-skewed. The difference between the countries indicates

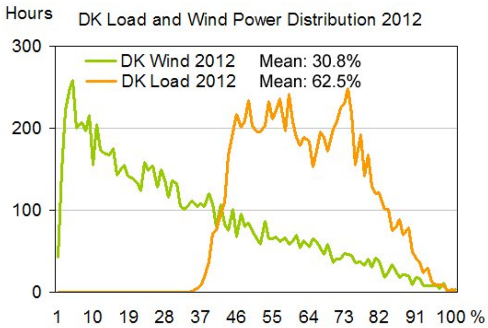
[12] http://www.ens.dk
[13] http://www.wind-energie.de/infocenter/statistiken
[14] http://www.iwea.com/index.cfm/page/windenergyfaqs?#q21

better wind conditions in Spain, Denmark and Ireland than in Germany. Ireland is known to have excellent wind conditions and Denmark has a considerable share of offshore wind power.



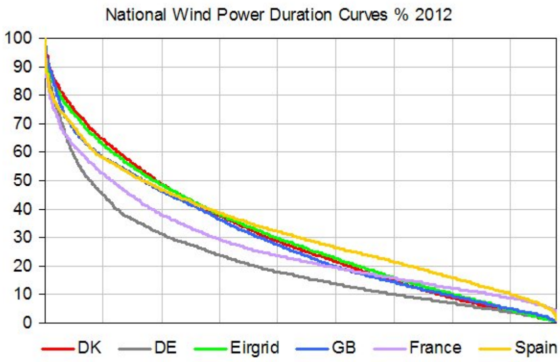






The wind power distribution curves are much different from load distribution curves. The mean value of a typical load distribution curves exceeds 60%. The very different distributions are among the reasons why the integration of a large share of wind power is quite challenging.

The duration curve is another way for illustration of national wind power output profiles. The wind power output has been normalized to percent of the highest observed hourly production. The chart reflects the different national wind conditions.



The irregular **variability of wind power** may cause two types of problems. When there is a low output of wind power there is a risk of shortage of power which must be prevented by mobilization of suitable amounts of reserve power. A high output of wind power may cause overflow of power. Overflow is mainly an economic problem. Curtailment of wind power implies loss of energy and should therefore be minimized.

In order to quantify the two types of problems periods with very low and very high wind power production will be identified.

The **national minimum and maximum wind production** in 2011 has been identified:

2012	One hour	Denmark	Germany	Ireland	Great Britain	France	Spain
Minimum	MW	6	134	1	0	211	118
	Share of max	0.2%	0.6%	0.1%	0.0%	3.6%	0.7%
	Date	11 Oct	24 Oct	21 Jul	29 May	15 Nov	11 Sep
	Hour	11-12	16-17	02-03	10-11	15-16	12-13
Maximum	MW	3,782	24,020	1,496	4,882	5,927	16,413
	Date	23 Dec	3 Jan	18 Dec	30 Dec	27 Dec	18 Apr
	Hour	07-08	16-17	23-24	13-14	15-16	17-18

The average wind power output has been calculated for 12, 24, 48 and 96 consecutive hours. The following **minimum and maximum average production levels** have been found:

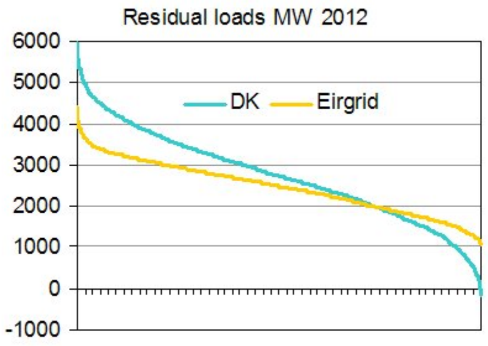
2012	Consecutive hours	Denmark		Germany		Ireland		Great Britain		France		Spain	
		MW	%	MW	%	MW	%	MW	%	MW	%	MW	%
Minimum	12	23	1	198	1	8	1	26	1	260	4	401	2
	24	44	1	270	1	12	1	59	1	323	5	681	4
	48	98	3	566	2	13	1	69	1	358	6	971	6
	96	158	4	1,254	5	58	4	167	3	448	8	1,602	10
Maximum	1	3,782	100	24,020	100	1,496	100	4,882	100	5,927	100	16,413	100
	12	3,652	97	23,094	96	1,352	90	4,658	95	5,417	91	15,647	95
	24	3,403	90	22,283	93	1,260	84	4,538	93	5,133	87	14,529	89
	48	3,095	82	21,729	90	1,238	83	4,370	90	4,762	80	13,856	84
	96	2,939	78	18,638	78	1,111	74	4,154	85	4,381	74	12,283	75

This table indicates that sustained low wind power output is more common that sustained high wind power output. France and Spain have more wind power output during low winds than the other countries.

The **residual load** is the difference between gross electricity demand and wind power output. The profile of the residual load is interesting because it must be supplied by more traditional sources. The following characteristics have been extracted for Denmark and Ireland:

	Denmark			Ireland		
	GWh	Max MW	Min MW	GWh	Max MW	Min MW
Load	34,135	6,215	2,085	25,623	4,553	1,617
Residual load >0	23,861	5,962	-570	21,470	4,405	967
Residual load <0	10			0		
Difference	10,284	253	2,655	4,153	148	650

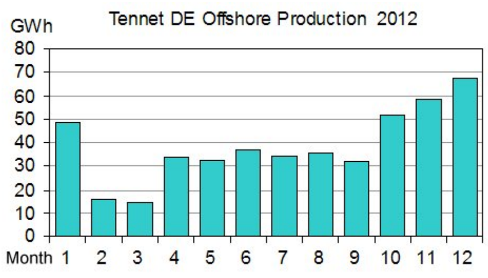
Wind power impact
- The energy balance was improved by 30% in Denmark and by 16% in Ireland
- The contribution to peak capacity was only 4% in Denmark and 3% in Ireland



In Denmark the very low minimum residual load causes export of electricity because the CHP systems need electricity demand and a certain production on large thermal units is required in order to maintain the operational security.

5.2 Offshore wind

The German transmission system operator, TenneT, is responsible for connecting German North Sea wind parks to the grid. TenneT has published a time series for offshore wind in 2012. The production was 459 GWh in 2012 with a maximum output at 163 MW. The annual load factor was 0.32. The offshore data for 2012 is insufficient for real comparisons with the



national time series, but with a suitable production volume the separate offshore data can be a very interesting source in the future.

5.3 International aggregation of wind power

It is difficult to quantify the smoothing effect of aggregating wind power across a larger geographical area. The following combinations will be considered: Denmark/Germany, Ireland/Great Britain and Denmark/Ireland. The latter combination has the purpose to evaluate the effect of a long distance from west to east.

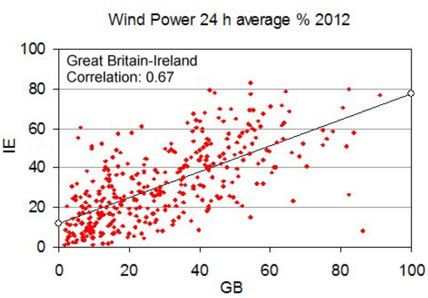
The first approach will be based on statistical methods.

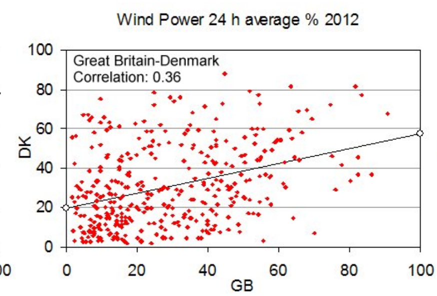
Correlation coefficients have been calculated for all combinations based on hourly wind power data.

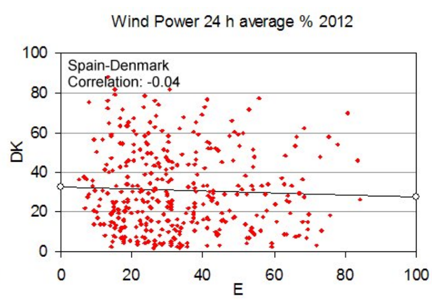
Correlation coefficients Hourly wind power	2012	Spain	France	Great Britain	Ireland	Germany
	Denmark	-0.048	0.157	0.301	0.096	0.663
	Germany	0.022	0.418	0.353	0.178	
	Ireland	0.074	0.251	0.608		
	Great Britain	0.149	0.379			
	France	0.410				

Two variables can have closely connected variations, either in the same direction (correlation near 1) or in the opposite direction (correlation near -1). For two independent variables the correlation is about 0.

The strongest correlations are found between Denmark and Germany and between Ireland and Great Britain. The weakest correlations are found between Spain and Denmark and between Spain and Germany. Three cases based on daily average wind power productions for three pairs of countries have been selected as an illustration.





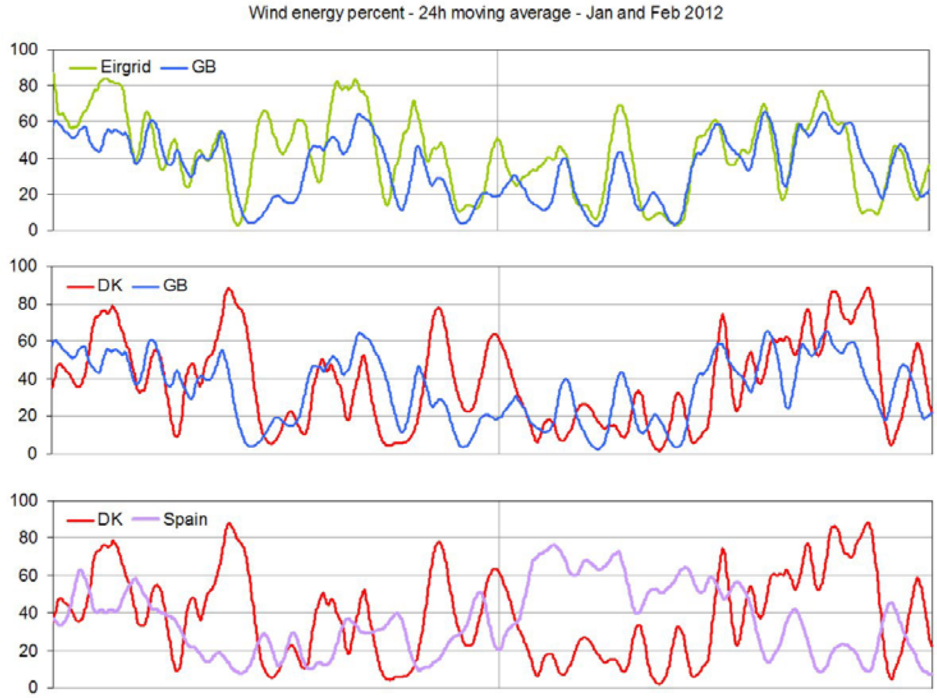


It is obvious from the results that there is a high degree of co-variation of wind power in Ireland and Great Britain. The co-variation of wind power in Denmark and Great Britain is less significant and wind power productions in Denmark and Spain are practically independent.

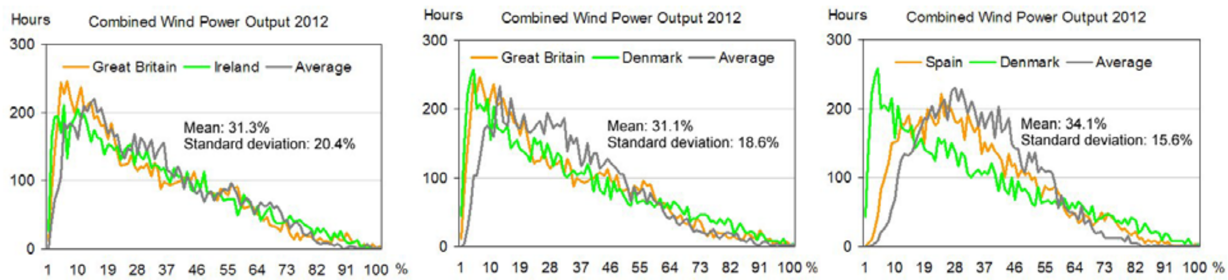
Noise from the hourly time series can be reduced by the use of 24 hour moving averages. The correlation coefficients (based on hourly data) are slightly higher for the moving average and for daily averages:

2012	Observations	Correlation coefficients		
		Ireland-Great Britain	Denmark-Great Britain	Denmark-Spain
Raw data	8784	0.61	0.30	-0.05
24 h moving average	8784	0.67	0.36	-0.04
24 h daily average	366	0.68	0.37	-0.04

Extracts from the time series can visually demonstrate the different correlation levels.



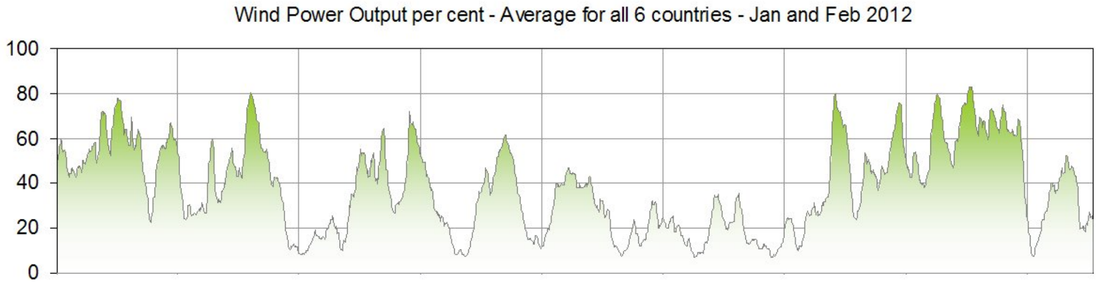
The **combined wind power output** for two countries can be analysed either by just adding them together or by calculating an average. The following results are based on the latter method because it eliminates the effect of different magnitudes of the national wind power fleets.



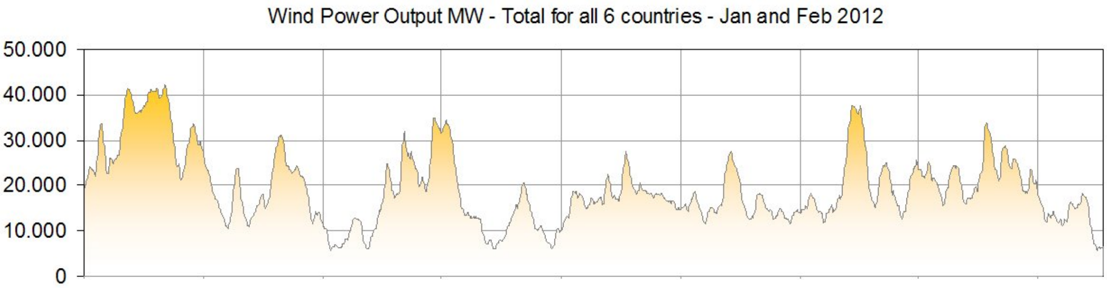
The average distribution for all six countries has a mean value of 37.7% and a standard deviation of 16.5%.

While the Danish-Irish average wind power distribution has a different shape, creating average distributions for Denmark and Germany and for Ireland and Great Britain does not change the shape of the distribution significantly. However, the distribution is still very left-skewed. The result will not be a smooth output of power.

The average time series are used for evaluation of the sustainability of wind power in system operation.



The average hourly wind power output for the five countries eliminates some peaks and valleys at each country's production profile. However, with a standard deviation of 16.7% the variability is still high, and the aggregated wind power production cannot be considered as a reliable source of power.



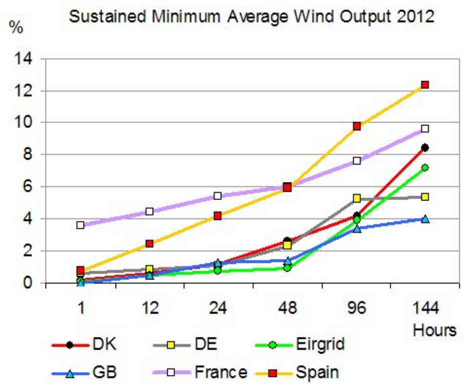
Adding national wind power in MW outputs instead of calculating average in % gives a slightly different profile. The mean value is 34.3% instead of 37.7% while the standard deviation is practically unchanged (16.0% instead of 16.5%). Thus the variability of the two distributions is the same. The lower mean value reflects a higher influence of the German data.

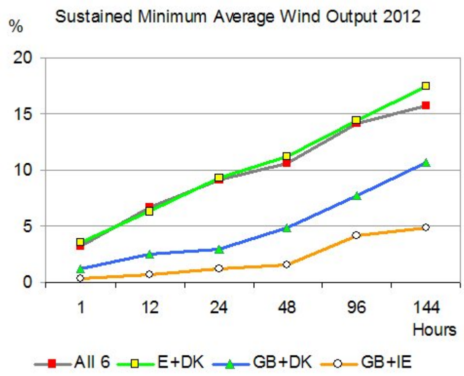
The minimum aggregated wind power output can be presented in a more systematic way. Periods with minimum and maximum production have been analysed for the following combinations of average wind power output:

2012	Consecutive hours	GB+IE		GB+DK		DK+E		All 6	
		MW	%	MW	%	MW	%	MW	%
Minimum	12	48	0.76	198	2.47	1162	6.27	2988	6.72
	24	77	1.23	241	2.99	1716	9.26	4065	9.14
	48	96	1.54	393	4.89	2085	11.25	4718	10.60
	96	264	4.22	625	7.77	2667	14.39	6299	14.16
Maximum	1	6247	100.0	8372	100.0	18539	100.0	44493	100.00
	12	5959	95.39	7772	92.83	17950	96.83	41864	94.09
	24	5682	90.97	7384	88.20	16772	90.47	40784	91.66
	48	5381	86.14	7244	86.53	15380	82.96	39258	88.23
	96	5151	82.47	6687	79.87	13678	73.78	35728	80.30

The table shows for example that the minimum average aggregated wind power output of the six countries in 2011 for 24 consecutive hours has been 6.72% of the aggregated maximum value. The maximum average aggregated output for 24 consecutive hours has been 94.09%.

The following charts summarize the minimum results by comparing national results with aggregated results:





The left-hand chart demonstrates the exceptional characteristics of French and Spanish wind power. The lowest hourly French production values in 2012 are about 4%. The reason could be that the installed wind power in France has two gravity centres, one in the North West depending on Atlantic winds and one in the southern part of France depending on Mediterranean winds.

The four north European countries in this study are supposed to be dominated by Atlantic winds.

The Spanish one hour minimum production has the same magnitude as in the four north European countries, but the 48 hours sustained minimum production in both France and Spain is significantly higher than in the northern countries.

International combinations of wind power during high wind periods have also been analysed but the results seem to be unchanged compared with the national data.

5.4 Wind power capacity credit

The minimum observed sustained average wind power outputs in 24 hours in 2011 were (in % of maximum hourly output):

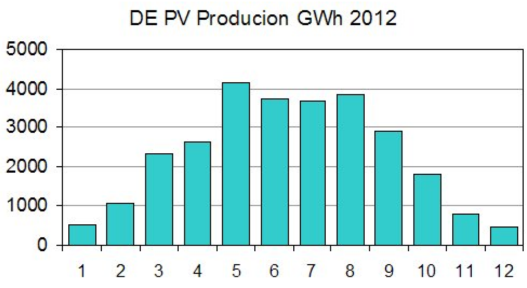
Denmark	Germany	Ireland	Great Britain	France	Spain
1.16%	1.12%	0.78%	1.21%	5.44%	4.15%

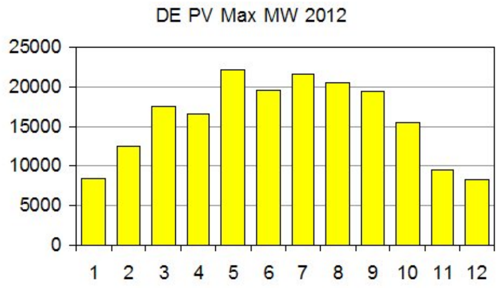
A capacity credit can be calculated for a fleet of wind turbines by use of statistical methods, and capacity credits between 6 and 10% of the installed wind power capacity have been proposed.

However, it should be noted that the capacity credits for adjacent areas cannot be added. Wind power plants do not operate in a stochastically independent manner, because they all depend on a common and related source, the wind.

6. Photovoltaics 2012

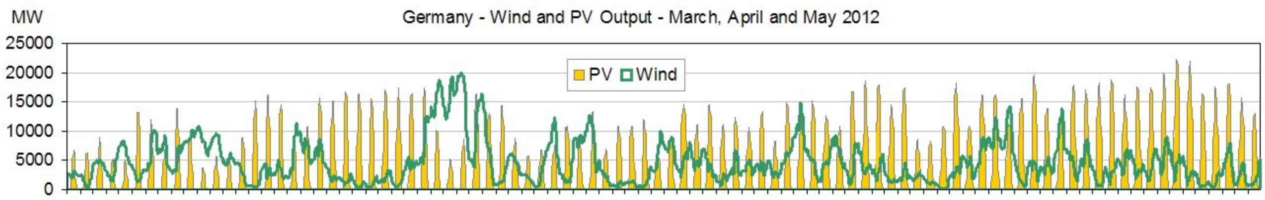
Photovoltaic (PV) has gained considerable importance in Germany. In 2012 all four German transmission system operators have published estimated hourly production data. The total production in 2012 was 27,866 GWh with a maximum output of 22,150 MW. The corresponding load factor is 0.14.





So far none of the other countries has published time series for PV production.

The variability of PV is different from the variability of wind power. It can be argued that the daily variations could make PV more useful than wind power. The question is if PV can make the shape of the residual load smoother.



Unfortunately an hourly time series for the total German electricity demand has not been available and PV time series for other countries are not yet available.

The increasing grid problems in Germany are not only caused by the variability of wind power and PV but also by moving production capacity from south to north in Germany. More and better publicly available data will be a condition for more thorough analyses.

A theoretical study for Denmark[15] has demonstrated the operational interaction between wind power, PV and CHP. From an operational point of view the best combination seems to be three parts wind energy to one part PV energy.

The CHP system can provide necessary flexibility for balancing the variations in wind power and PV.

[15] http://pfbach.dk/firma_pfb/pfb_balancing_wind_pv_and_chp_2012_11_18.pdf

7. Main characteristics of Danish power systems in 2012

7.1 Annual key figures

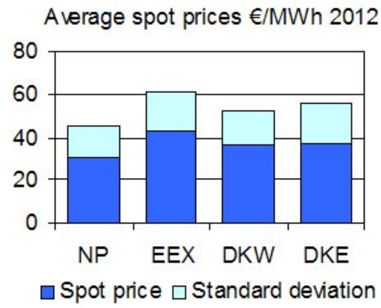
The following table is based on market data from Energinet.dk:

2012	Gross demand			Thermal	Wind		Hourly net exchange	
	MWh	Max MW	Duration Hours	Generation MWh	Generation MWh	% of de-mand	Export MWh	Import MWh
DK West	20.438.155	3.676	5.559	12.332.513	7.605.345	37,2	2.252.742	2.727.318
DK East	13.696.859	2.559	5.353	6.273.137	2.662.512	19,4	132.217	4.872.431
DK (total)	34.135.015	6.215	5.492	18.605.650	10.267.858	30,1	1.619.939	6.834.729
Source: Energinet.dk								

The duration hours have been calculated as annual energy demand divided by maximum load. They tell the same story as the load factor (duration hours divided by the number of hours in the year). The year 2012 had 8,784 hours.

The average market conditions are summarized in this table:

2012	Area price €/MWh	St.Dev. €/MWh		Spot price €/MWh	St.Dev. €/MWh
DK West	36,38	16,35	NP	31,11	13,79
DK East	37,57	18,27	EEX	42,66	18,60



The standard deviation is an indicator of the price volatility.

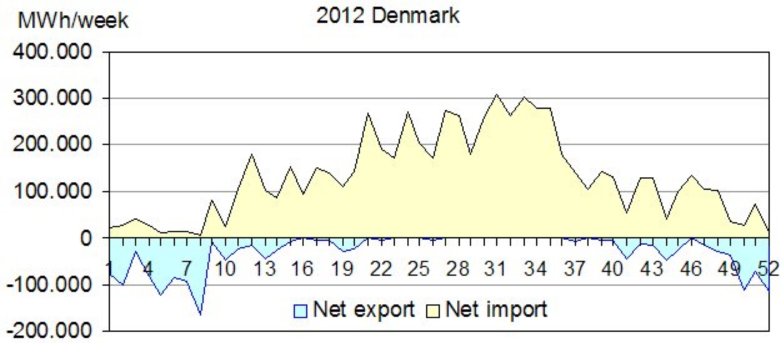
The Great Belt link between East and West Denmark has contributed to the equalization between the two parts of Denmark.

The magnitude of the overflow problem due to Danish wind power can be indicated in a table with number of hours with spot prices less than or equal to zero and downwards balancing prices equal to or below zero.

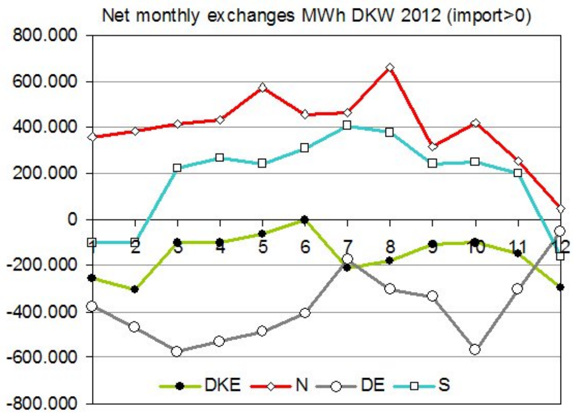
No of hours	Spot price <= 0	Spot price >100	Bal. price <= 0	Bal. price >100
DK West	34	46	68	213
DK East	32	74	56	328
Nord Pool	0	52		
EEX	58	60		

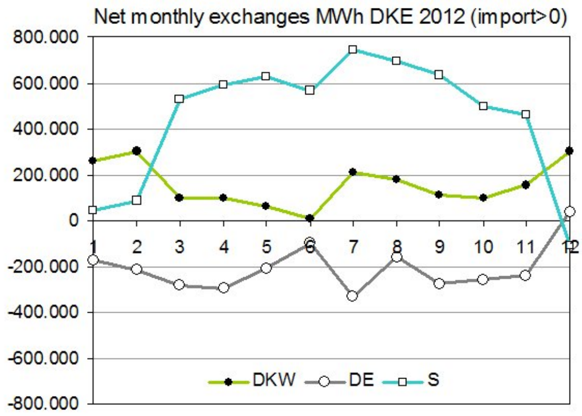
When the price of balancing (or regulating) power is below 0 the system operator must pay for export of energy. Nord Pool introduced negative spot prices in October 2009.

7.2 Weekly and monthly averages



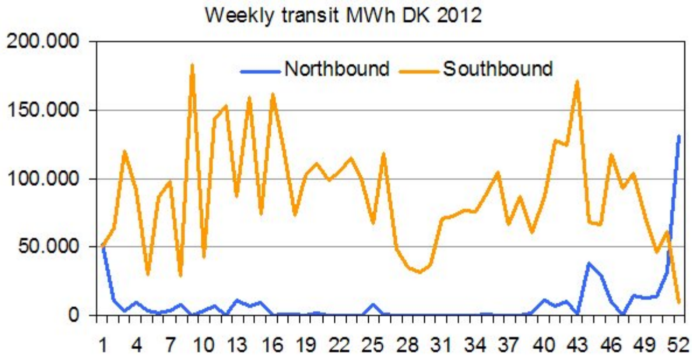
Net exchanges have been accumulated weekly per hour for Denmark (above) and monthly for each border (below). The pattern reflects the variation of the Danish balance of electric energy during the year.



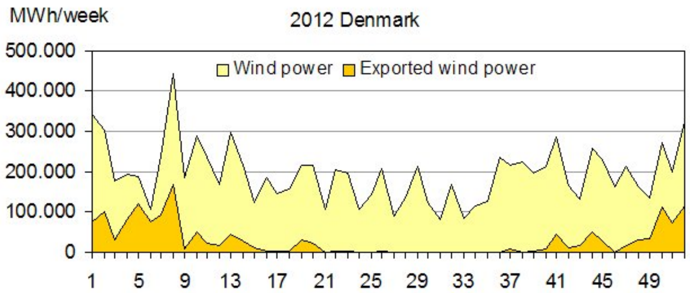


The charts clearly demonstrate two trends: a net import to Denmark in 2012 and a transit from north to south throughout the year. The Great Belt link transferred energy from west to east throughout the year.

The transit has been calculated hour by hour. The total transit through Denmark was 0.5 TWh northbound and 4.6 TWh southbound. The net transfer from West to East Denmark was 1.9 TWh.



The generation of wind energy varies considerably from week to week.



The wind energy is divided into an export share (the light brown area) and a share used locally (the light yellow area). The estimate of exported wind energy is a sensitive matter because it raises doubts about the beneficiary of subsidised Danish renewable energy. In this context the *wind energy export* has been defined for each hour as the smaller value of generated wind energy and net export. The chart indicates that the share of exported wind energy is high during the cold seasons when increased demand for heat entails high electricity production from the CHP plants. It cannot be denied that there is not sufficient demand in Denmark for electricity from both CHP and wind power during the winter season. According to this estimate the export of wind energy was 1.6 TWh in 2012 or 15% of the wind energy production.

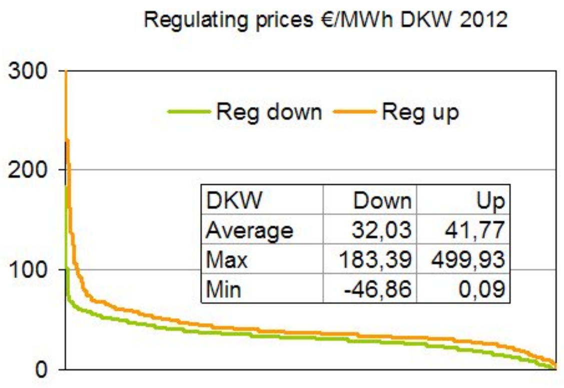
8. Regulating Power 2012

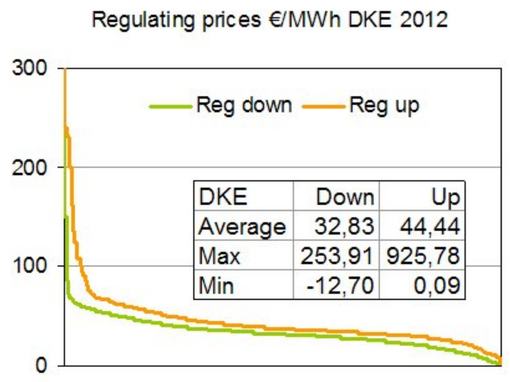
Nord Pool Spot is a wholesale market for buyers and sellers, the gate closure being for the following day at noon. Therefore its spot prices are based on expectations 24 to 36 hours before real time, and day-ahead wind power forecasts are very inaccurate.

The Nord Pool ELBAS market offers market players access to intra-day trade until 1 hour before delivery.

The Nordic system operators use the Nordic regulating power market for real time balancing. Market players are bidding in advance, and the system operators can activate the bids when needed. In Denmark there are different prices for regulating upwards and downwards.

Dispersed regulating prices are a first warning of unsatisfactory market stability.





Negative prices for regulating power occurred in 166 hours in West Denmark and 144 hours in East Denmark.

No of hours	Downwards		Upwards	
€/MWh	<-100	<=0	>100	>200
DK West	7	68	213	55
DK East	7	56	328	119

Since 2011 the difference between west and east in Denmark was practically eliminated. This is probably another effect of the Great Belt link.

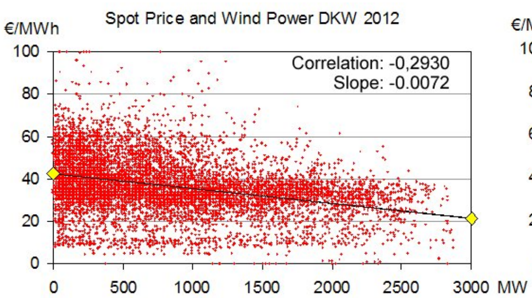
9. Wind Power and Spot Markets 2012

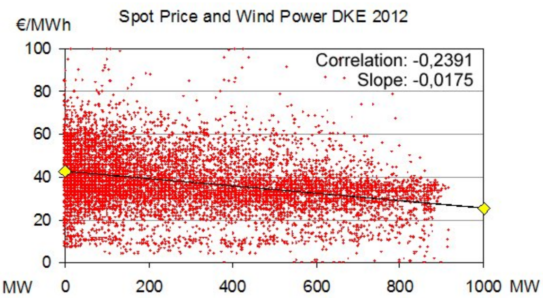
Wind power has an impact on market prices in two ways:

- increasing wind generation may cause reduced prices
- the volatility of wind power may cause price volatility

On 1 November 2011 Sweden was divided into four bidding areas. The decision was made by Svenska Kraftnät after legally binding commitments from Svenska Kraftnät to the European Commission.

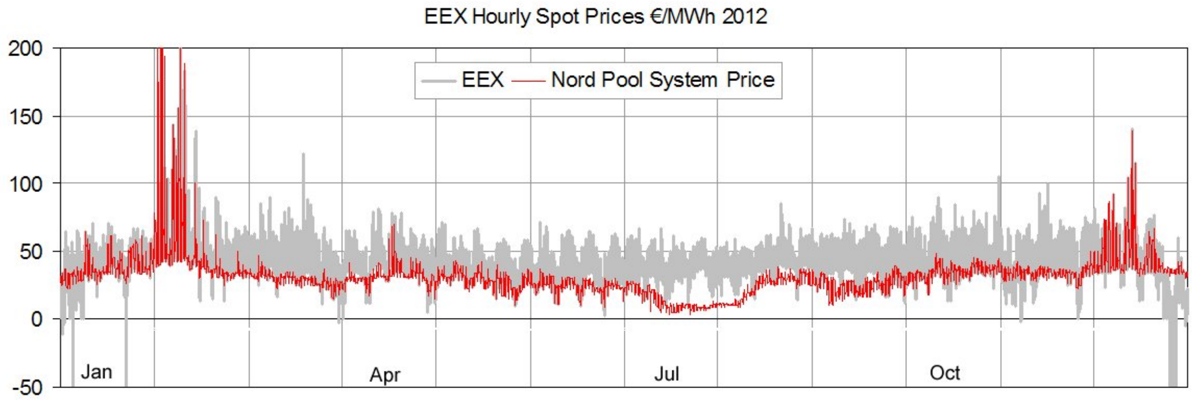
The following diagrams show local hourly spot prices and wind power for the entire year 2012. The correlations are surprisingly low. The reason is that several other factors than wind power have an impact on market prices.





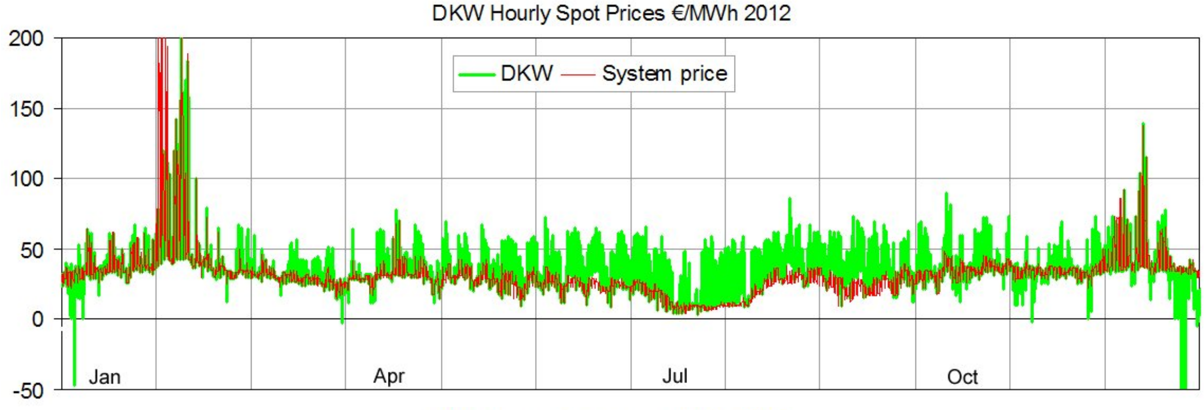
The two distributions are rather much alike due to the new Great Belt Link.

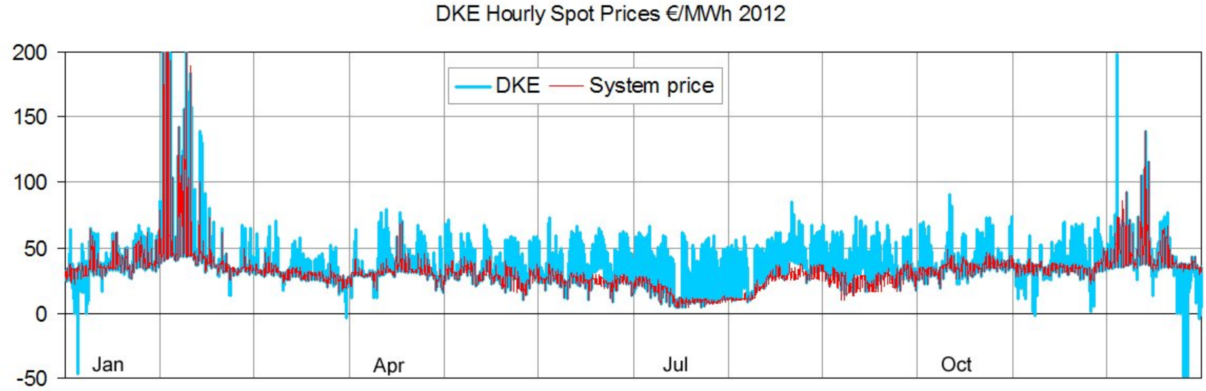
A time series with hourly spot prices can be used for the identification of some characteristic periods.



The chart above compares the EEX spot price with the Nord Pool system price. The average price level and the volatility is slightly higher for EEX than for the Nord Pool system price. This is in accordance with the transit through Denmark in 2012 from north to south.

The following charts for the two Danish price areas seem to indicate that the Danish spot prices are closer related to EEX prices than to Nord Pool prices.

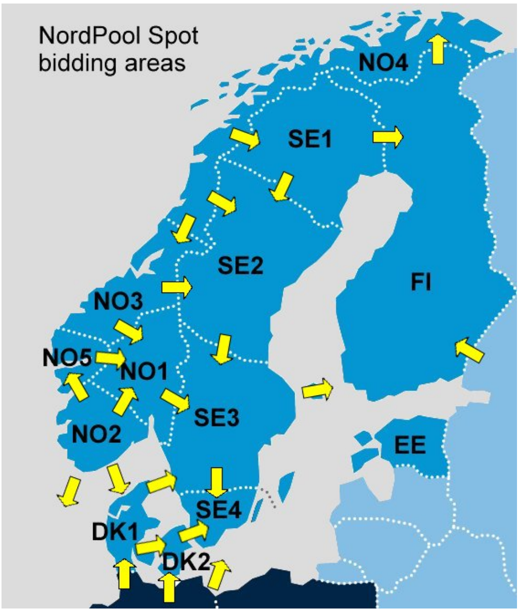




The market reports from Energinet.dk have been essential sources of information on operational conditions. From January 2012 the publication of market reports was stopped. Therefore this section will be significantly reduced compared with previous years

9.1 February 2012: Capacity shortage in Sweden and Finland

The very high spot prices 1 to 3 February are remarkable. The hydrological conditions cannot explain a power shortage. In order to create an overview the prevailing flow directions during the three days are shown on the map (source: www.nordpoolspot.com).



There seems to have been a shortage of power in southern Sweden and in Finland. The reasons are unknown.

From the southern part of Norway power flows to the Netherlands, to Denmark and to Sweden. German power flows to both parts of Denmark and to Sweden. In this case Denmark serves as a transit area from Germany and Norway to Sweden.

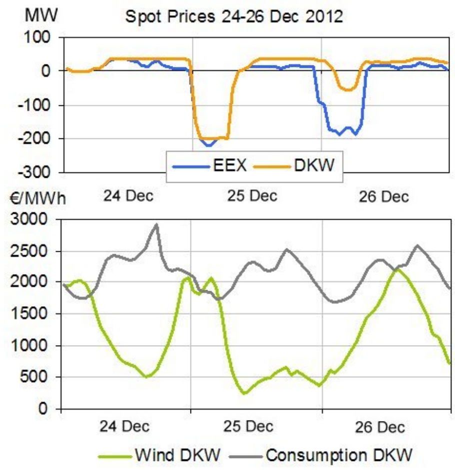
The case demonstrates that power shortage can occur in the Nordic area even when the hydrological situation is comfortable.

9.2 First half of December 2012: Capacity shortage again

The power flows in this period were similar to the flows shown in the previous section and the troubled areas seem once more to have been south Sweden and Finland.

9.3 24-26 December 2012: Wind Power Peak and Low Consumption

The very low spot price on 25 December 2012 is a typical Christmas case.



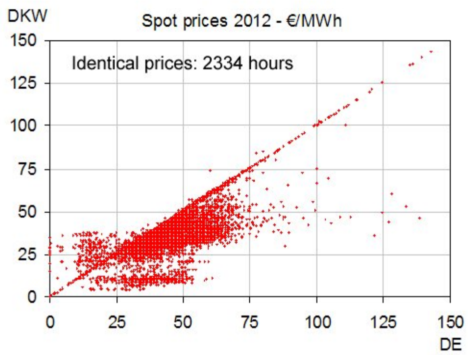
It is demonstrated above that normally the coupling between wind power and spot prices is rather weak. However, a strong spot price response is possible when wind power peaks occur simultaneously with low electricity demand.

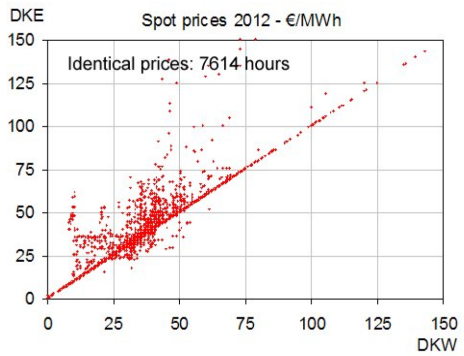
The grid is an important stabilizing factor. However, it should be noticed that Danish and German wind power are closely interrelated and that the coupling between the two markets is increasingly efficient.

Therefore the future spot price volatility will depend on European grid reinforcements which must at least follow the wind power development.

9.4 Effect of Market Coupling

After initial problems the Danish-German market coupling was re-launched by the European Market Coupling Company on 9 November 2009. Market coupling is a process where two or more energy exchanges cooperate on utilizing the available trading capacity between two or more regions during every hour of operation to secure that the energy flows from the low-price towards the high-price area. A comparison of spot prices demonstrates the effect:





In 2012 Germany and Western Denmark had identical spot prices for 27% of the hours. East and West in Denmark had identical spot prices for 87% of the hours. Price differences indicate hours with either physical congestion or poor market function. The sign of the difference shows that most unserved transfer is from west to east in Denmark and from Denmark to Germany. Chapter 4 shows that the available capacity of the AC interconnection DKW-DE has been continuously fine-tuned. This indicates that the transfer capability across the border is insufficient.

10. CO_2 Emission from Danish Electricity Production 2012

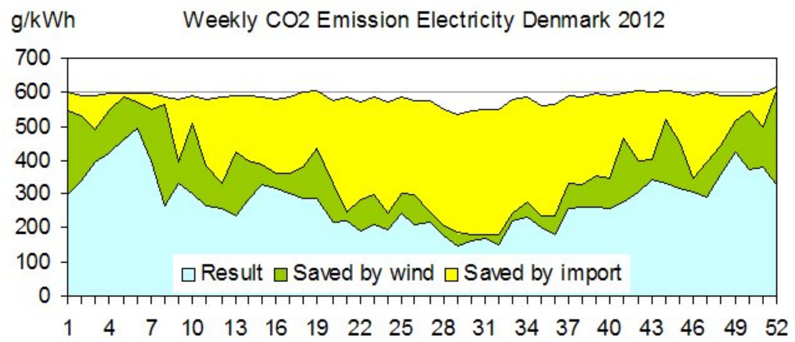
Since 15 February 2011 Energinet.dk has published daily text files with hourly CO_2 forecasts (in Danish)[16].

The first forecast for a day is published on the day before about three o'clock p.m. The forecast is updated during the day every 15 minutes. The final version is based on actual combination of power plants, fuels, emission data and productions. Information on how the CO_2 burden is distributed between electricity supply and heat supply is missing.

Specific Carbon Emission Type of production	g/kWh
Large power plants	700
Local power plants	300
Wind turbines	0
Sweden	40
Norway	0
Germany	500

Energinet.dk calculates the hourly emission based on actual production schedules and the observed average emission figures in the table. For hours with a net export of electricity it is assumed that export and consumption in Denmark have the same specific emission of CO_2. For hours with net import the carbon emission of imported electricity depends on the exporting country. An average emission value for imported electricity and electricity produced in Denmark is used for the consumption in Denmark. Transit of electricity is common in Denmark. For hours with net import the same average emission value is used for Danish consumption and for export.

The calculated weekly specific carbon emission from the Danish thermal power production is quite stable between 535 and 617 g/kWh throughout the year 2012. It is assumed that the thermal production capacity is sufficient for covering all Danish electricity demand with the same specific emission.



The table above demonstrates the importance of the transit direction of the international trade. In 2012 there has been a predominant transit from north to south and a considerable net import. The yellow area shows that this combination has caused a remarkable reduction in CO_2 emission.

The green area is the effect of Danish wind energy production. The light blue area is the calculated CO2 emission attributed to Danish electricity consumption. The resulting average value for 2012 is 289 g/kWh.

In a theoretical reference case without import and without wind power the average carbon emission for 2011 would have been 588 g/kWh. Import and wind power have contributed with 194 and 105 g/kWh to the resulting 289 g/kWh.

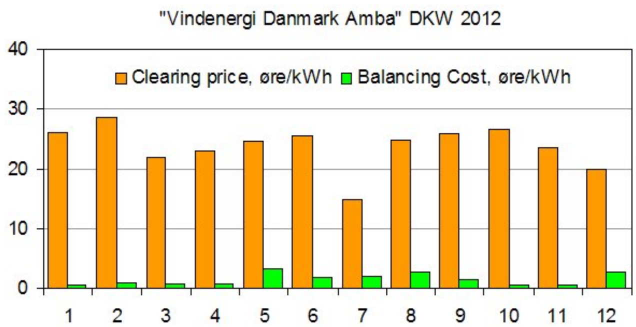
It is not known if other countries report their CO_2 emissions after similar and consistent procedures. Common international guide lines for the calculations would be useful.

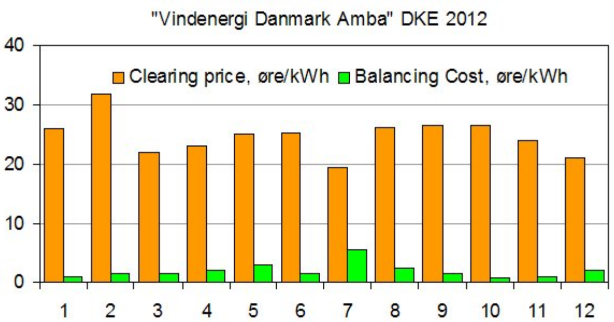
[16] http://energinet.dk/DA/El/Engrosmarked/Udtraek-af-markedsdata/Sider/CO2-prognoser.aspx

11. Wind Energy Trading 2012

One of the important traders of wind energy in Denmark is “Vindenergi Danmark Amba”, which is a co-operative of owners of wind power plants, who must sell wind energy commercially. The web site, www.vindenergi.dk, presents the following trading statistics for 2012 (with my translations, but in Danish currency):

	Jan	Feb	Mar	April	May	June
West Denmark						
Installed capacity, MW	1.583	1.573	1.601	1.614	1.627	1.641
Production, GWh	394	327	393	260	264	276
Clearing price, øre/kWh	26,2	28,6	21,8	23,2	24,5	25,5
Balancing cost., øre/kWh	0,6	1	0,8	0,7	3,2	1,7
East Denmark						
Installed capacity, MW	308	312	319	322	322	342
Production, GWh	78	64	64	45	48	48
Clearing price, øre/kWh	26	31,8	22	23	25,1	25,2
Balancing cost., øre/kWh	0,9	1,4	1,4	1,9	3	1,6
Total						
Installed capacity, MW	1.891	1.885	1.919	1.937	1.949	1.982
Production, GWh ,	472	390	457	305	312	324
	Jul	Aug	Sep	Oct	Nov	Dec
West Denmark						
Installed capacity, MW	1.645	1.680	1.686	1.697	1.705	1.725
Production, GWh	209	176	324	298	302	396
Clearing price, øre/kWh	15	24,8	25,8	26,5	23,5	20
Balancing cost., øre/kWh	1,9	2,7	1,5	0,6	0,5	2,7
East Denmark						
Installed capacity, MW	342	342	344	348	349	349
Production, GWh	36	31	63	60	59	72
Clearing price, øre/kWh	19,5	26,2	26,4	26,4	24,1	20,9
Balancing cost., øre/kWh	5,4	2,4	1,5	0,7	1	1,9
Total						
Installed capacity, MW	1.987	2.022	2.030	2.045	2.054	2.074
Production, GWh	245	207	387	358	361	468



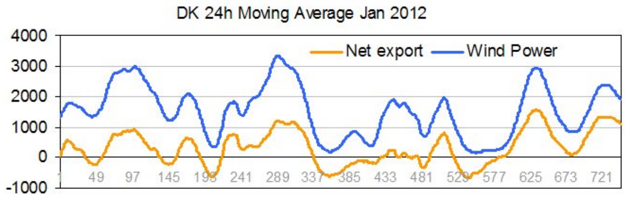


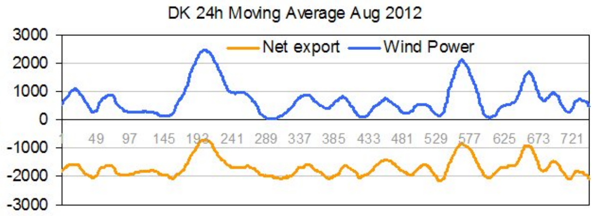
12. Danish wind power and export of electricity

The previous statistical surveys presented an estimate of the export share of the Danish wind energy. The *wind energy export* was defined for each of the two Danish price areas and for each hour as the smaller value of generated wind energy and net export.

The same algorithm was used in the CEPOS study, “Wind Energy – The Case of Denmark” (September 2009). The claim that a considerable share of the Danish wind energy was exported caused persistent scientific criticism. The main argument was that the export was due to competitive Danish thermal power plants and that the exported electricity was dispatchable thermal energy rather than wind energy.

The discussion of the *origin* of the exported electricity may be an interesting academic matter. But the *variations* of wind power and electricity export can easily be compared. The following charts show 24 hours moving average for Denmark in January and August 2012:





This seems to be convincing evidence that waves of wind energy cause corresponding waves of electricity exchange. The use of CHP (combined heat and power) in Denmark explains the difference between winter and summer. Therefore a correlation analysis for the entire year will give misleading results.

The estimated export share of wind energy in 2012 was 1.6 TWh or 15% of the Danish wind energy production. Most of the export can be observed for the cold seasons. The reason is simple. There is not sufficient electricity demand in Denmark for both CHP and wind power.

It is irrelevant if wind energy or CHP electricity has been exported, but adding new wind power to the power system without adding new electricity demand will cause growing electricity export. An increasing dependency on foreign balancing services would be in conflict with the intentions behind the new wind power. Therefore the development of domestic measures should be encouraged and supported in order to facilitate parallel commissioning of new wind turbines and new flexible electricity demand.