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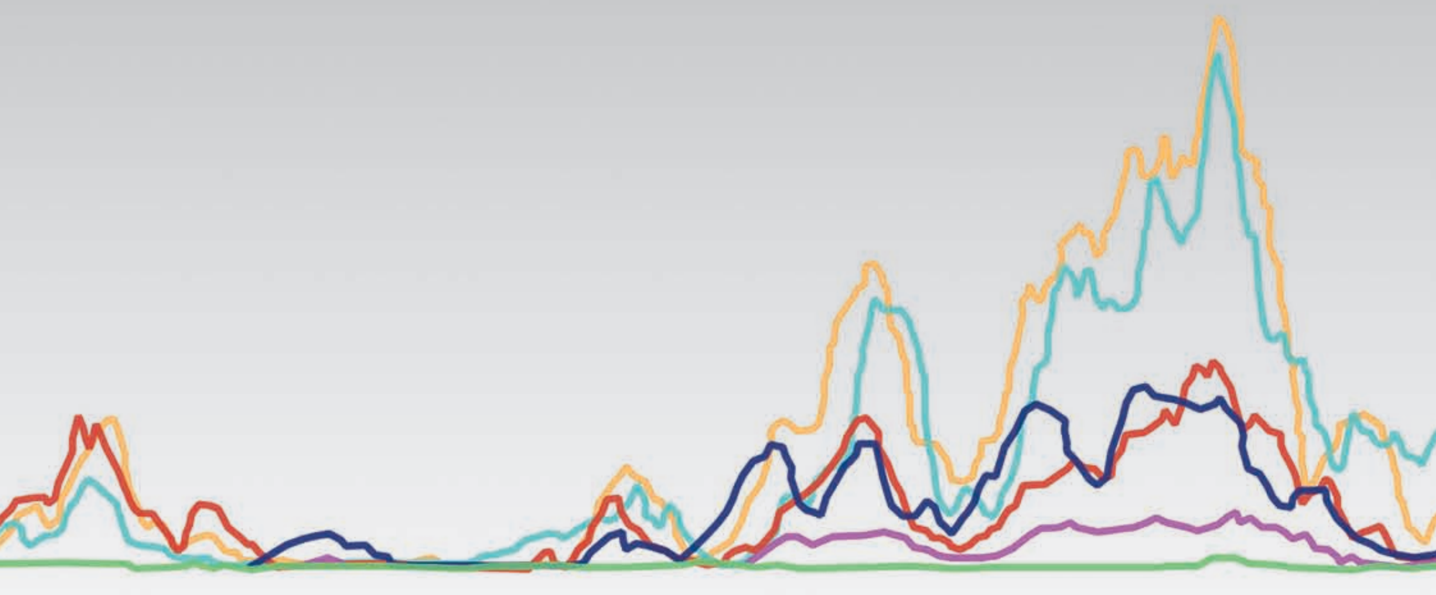
PAUL-FREDERIK BACH

The Variability of Wind Power

Collected Papers 2009–2010

With a preface by Michael Laughton



PAUL-FREDERIK BACH

THE VARIABILITY OF WIND POWER

Paul-Frederik Bach

Paul-Frederik Bach has more than 40 years' experience in power system planning. He worked with grid and generation planning at ELSAM, the coordinating office for West Danish power stations, until 1997. As planning director at Eltra, Transmission System Operator in West Denmark, he was in charge of West Denmark's affiliation to the Nordic spot market for electricity, Nord Pool, in 1999. Until retirement in 2005 his main responsibility was the integration of large amounts of wind power into the power grid in Denmark. He is still active as a consultant with interest in safe and efficient integration of wind power, particularly prevention of disturbances by advanced system control measures.

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The Renewable Energy Foundation's Research Monographs on Energy *are a new series publishing technical analysis and information relating to the energy sector, with a particular emphasis on renewable and alternative energy.*

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Preface

The electricity supply of the future will become ever more dependent on renewable energy sources. That much is clear from consideration of many global requirements and factors, such as the need to reduce greenhouse gas emissions, the inevitably finite nature of oil, gas and coal deposits, and – although this is not often mentioned – the moral responsibility to conserve hydrocarbon resources for the various chemical, as distinct from energy, needs of future generations. Most prominently, of course, growing environmental awareness and in particular the determination to limit carbon dioxide emissions has led to national and international legislation and agreements that either directly or indirectly focus on the development of sources of renewable or alternative energy.

Generally speaking, and whatever its original form, renewable energy is converted most easily into electricity, so the direct connection of such sources to the electricity supply system has appeared as the obvious first solution to seek, though other possibilities will probably emerge in due course. While national policies have been formulated and enacted, a widespread misunderstanding of the scientific and technical nature of the requirements of electrical power system operation has unfortunately resulted in targets and time-scales being set without reference to reality, at least as seen from the engineer's perspective.

As a result, it is possible and perhaps likely that environmental and political idealism combined with technical naivety will come into conflict with the more complex realities of electrical power supply, resulting in disappointment and consequent damage to the perceived need for more renewable generation. Notably, high economic costs to the consumer, caused by excess generation capacity and operational subsidies, could be paradoxically combined with an increasingly weak security of supply, leading to political disenchantment. This should be avoided, but doing so will require candour and courage.

In practice, electricity is supplied as two commodities: energy, that has a clear and well understood market value; and power, that does not, but nevertheless 'keeps the lights on'. It is the absence of proper consideration of 'power', *strictu sensu*, in current energy policies that is at the root of much difficulty.

The present work by Paul-Frederik Bach works towards rectifying this deficit by offering a detailed examination of power output from wind powered generators in Denmark. Mr Bach frequently emphasizes the importance of having fine-grained publicly available data for the actual performance of wind generation, for without such information debate concerning the contribution of wind, or any other renewable source of energy, it is not possible at present to evaluate the effects of policies and, importantly for wind, to open the discussion as to how best to compensate for its variability.

The development and use of renewable energy depends inescapably on geography, and this study foregrounds the special nature of the Danish situation. Denmark has only been able to achieve a proportionately high penetration of wind power on its system due, firstly, to the relatively small size of the Danish power system compared to the larger power systems with which it is linked, and, secondly, to the strong transmission links to surrounding countries, namely the HVDC undersea cables to Norway and Sweden, and especially the 400 kV AC interconnection between West Denmark and Germany. (At the time of writing there is no fully operational link between East and West Denmark, though a new connection is undergoing testing and scheduled for opening in September 2010.) With a strong grid, plus responsive power plants – in this case Norway and Sweden's hydroelectric plants (and Norway is 99% and Sweden 40% hydro), able to balance the stochastic variations in wind power – the task of integration is made much easier. In their absence it becomes harder.

The outstanding major concern in the work reported here, and one with very serious implications – especially for the United Kingdom with its predominantly island system with inadequate international interconnection capacity – is the extent to which subsidized wind power can, in practice, be used within the system without needing to be constrained off: in other words wasted, or exported at whatever market prices, perhaps disadvantageous ones, prevail elsewhere.

There has been much discussion of the export question in Denmark, and in 2009 a report was commissioned from the Danish think tank CEPOS by the Washington-based Institute for Energy Research, a not-for-profit organization that conducts intensive research and analysis on the functions, operations and government regulation of global energy markets. Among other conclusions the report, *Wind Energy – The Case of Denmark,*[1] established that on average wind power production in Denmark converts to just over 19 per cent of electrical energy consumption in Denmark, but that variations in wind power output lead to significant variations in power *exports*, primarily to Norway and Sweden and also to Germany.

Matching these variations in wind power and export power, the report concluded that significant quantities of Denmark's wind power output are transmitted to other systems. Indeed, on average over the past five years just under 10 per cent of electric power consumption in Denmark actually came from wind power, a much smaller quantity than is superficially apparent.

If true, the implications are highly significant, both economically and politically. A reasonable concern, at least within Denmark, is the degree to which government-mandated subsidies paid for by Danish consumers end up simply lowering prices in neighbouring countries. The CEPOS report suggested that subsidy is exported along with wind power to the tune of about 110 billion euros per year. While the report doesn't give full details for the calculation – and it is hard to assess its reliability – the topic raised is an important one, and cannot easily be dismissed.

The CEPOS report is, for the most part, serious and methodical, and it certainly contributes to an understanding of wind power in Denmark. However, electricity flow is not

1 http://www.cepos.dk/fileadmin/user_upload/Arkiv/PDF/Wind_energy_-_the_case_of_Denmark.pdf

a traceable commodity, so the work inevitably provoked controversial reaction, for example, the recent report *Danish Wind Power – Export and Cost*,[2] published by Aalborg University and partly financed by the CEESA (Coherent Energy and Environmental System Analysis) Research Project. This response maintained that wind energy replaces energy from Danish thermal power stations in the Danish market and that, depending on the market situation, these thermal power plants in Denmark are either closed down or choose to produce for export.

In his analysis of the nature of Danish wind power Mr Bach, however, remarks that:

> While the amount of exported wind energy is a matter of interpretational definition, and is dependent on perspective, it is clearly evident from the data that the irregular variations of Danish wind power are reflected in the exchange of electricity with the neighboring countries. This much cannot be denied; the facts are clear.

In turn, he considers the assumptions and conclusions in the CEESA report; these are analysed and found to be incorrect, and negated by the examination of actual Time Series data rather than the use of a general economic theory of merit order scheduling. In particular, he notes that the electricity output from thermal power plants in Denmark depends mainly on the demand for heat for district heating and on market prices.

Thermal power plants are also used for system regulation and as operating reserves. If high wind power output causes lower spot prices in Denmark then the thermal production will be lower. From the data revealed in the Time Series describing plant output, on the other hand, Danish wind power has normally only a little influence on spot prices; thus, this indicates that thermal power plants in Denmark, with few exceptions, are operated practically independently of wind power output.

It follows that the levels of power exported vary directly with the levels of wind power, a conclusion in good agreement with the observed power exchanges. Thus, to assume that that all or most wind-produced Danish electrical energy is used within Denmark is mistaken, and it is therefore erroneous to conclude that the Danish development of wind power is a leading example for other countries. As noted in the text:

> Maintaining the myth of the successful Danish integration of wind power may be good public relations, but refusing to face realities is self-deception.

Mr Bach correctly emphasizes, however, that this is more than a fault-finding analysis. The principal concern is to understand what is required if wind is to be integrated successfully into the Danish power system, and the author's qualifications are excellent. Until retirement Paul-Frederik's main responsibility at Eltra was the integration of substantial quantities of wind power into the Danish electricity grid, and he has unparalleled first-hand experience and knowledge of the practical problems faced. The results published here, and the associated methods used to obtain them, are a valuable contri-

2 http://www.energyplanning.aau.dk/Publications/DanishWindPower.pdf

bution to a subject where so much is obscured by idealism or vested interests both intellectual and financial.

The Renewable Energy Foundation – a charity founded to publish data, including performance records, in the public interest, for those wishing to invest in the renewables industry, including wind – is to be commended for supporting the investigation recorded in this book.

There is much in this report of interest and value relevant to the future UK situation if the planned wind generation capacity both on and offshore materializes. It appears that the United Kingdom must consider significant regulatory and technical changes to grid operation if security of supply is to be guaranteed and costs to the consumer kept under reasonable control.

First and foremost, however, this study's use of large publicly available databanks concerning the operation of the European grid shows that there is a pressing need for similar energy sector data transparency in the United Kingdom. Bluntly, at present we could not attempt to replicate Mr Bach's work here; the data is simply not available. That has to change.

M. A. Laughton, FREng.

Wind Power and Spot Prices in Denmark and Germany: Statistical Survey 2009

1. Preface

This text is both an update and extension of my previous study, *Wind Power and Spot Prices: German and Danish Experience 2006–2008*.[1] Comprehensive data survey for the calendar year 2009 is provided, and the study now covers hourly wind data from all four German control areas.

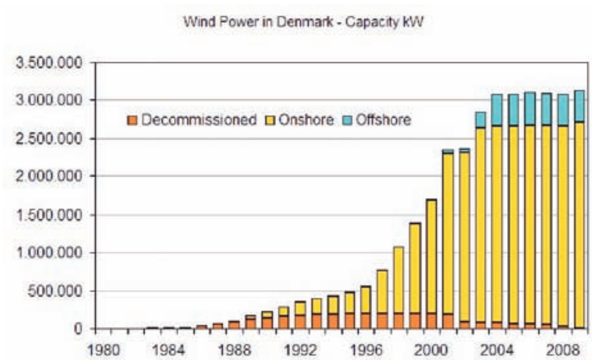
The data employed is published by Energinet.dk, and by the four German transmission system operators, the sources being identified by the following abbreviations:

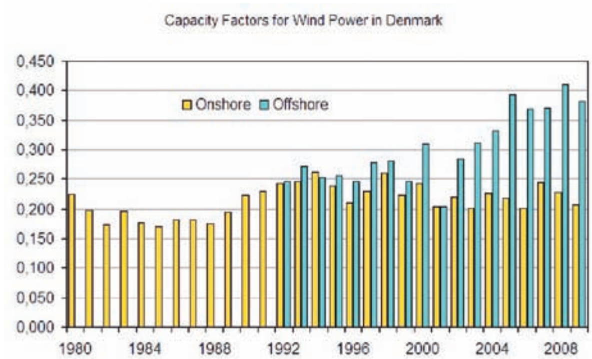
EEX	European Energy Exchange	**DKE**	Denmark East	**DE**	Germany
NP	Nord Pool	**N**	Norway	**ENDK**	Energinet.dk
DKW	Denmark West	**S**	Sweden		

2. Overview

Wind power performance

- In 2009 the energy produced by Danish wind power was 87.9% of that expected in a normal wind year.
- The total energy production from wind power in 2009 was 6.7 TWh for Denmark and 37.7 TWh for Germany.
- The average capacity factors in Denmark were 0.21 onshore and 0.37 offshore, in other words there were 1,820 full load hours onshore and 3,343 offshore.
- The production of wind energy was equivalent to 19.4% of the electricity demand in Denmark in 2009.





1 Paul-Frederik Bach, *Wind Power and Spot Prices: German and Danish Experience 2006–2008* (Renewable Energy Foundation: London, 2009). (http://www.ref.org.uk/PublicationDetails/53)

- For Denmark and Germany together the share of wind energy has been estimated as equivalent to 7.6% of the aggregated demand.
- There is a high positive correlation between German and Danish wind power energy flows.
- Calm periods with low wind power output occur simultaneously in Denmark and Germany. The minimum average wind power output during 24 consecutive hours in 2009 was 0.23% of the maximum hourly production for Denmark, and 1.61% for Denmark and Germany together.

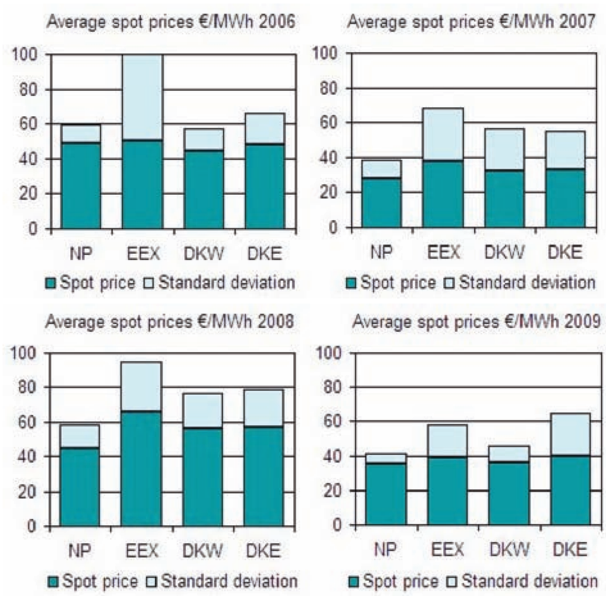
Interconnector performance

- The Danish interconnections had low availability for trade in 2009 due to outages of interconnector equipment, and the limited capacity of adjoining transmission grids.

2009	Average availabilities of interconnections			
%	To DKW	From DKW	To DKE	From DKE
Norway	90.9	90.0		
Sweden	70.9	76.3	76.3	91.6
Germany	90.9	75.4	93.0	86.5

Market performance

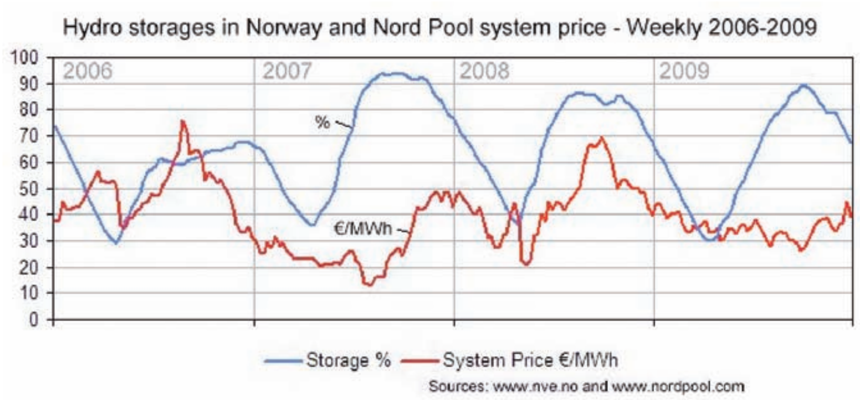
- Average spot prices were low in 2009, with NP, EEX and the two Danish areas exhibiting similar prices.
- Low standard deviations indicate good spot price stability, but do not exclude the occurrence of extreme prices.
- The German spot market seems to be responding to changing conditions with an increasing number of extreme spot prices.

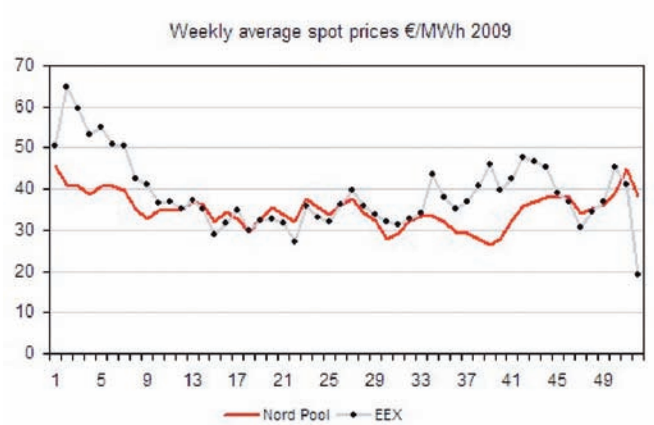


	2006	2007	2008	2009
No of hours	Spot price = 0	Spot price = 0	Spot price = 0	Spot price <= 0
West Denmark (DKW)	28	85	28	55
East Denmark (DKE)	5	30	9	4
Nord Pool system price	0	0	0	3
EEX, Germany	10	28	35	73

- 71 hours with negative spot prices have been observed in Germany in 2009.
- The Nord Pool market allowed negative spot prices in Denmark from October 2009, and 9 hours with negative spot prices occurred in west Denmark in December of that year.
- Periods with price spikes have been observed for east Denmark, particularly during the autumn of 2009, the main reason being the limitations placed on the interconnection with Sweden (Øresund). The consequences of the Swedish congestion policy are demonstrated for selected cases.
- Regardless of causes, it is clear that in 2009 the Nordic electricity transmission system was unable to provide a reasonably functioning market in east Denmark.

3. Neighbouring countries in 2009





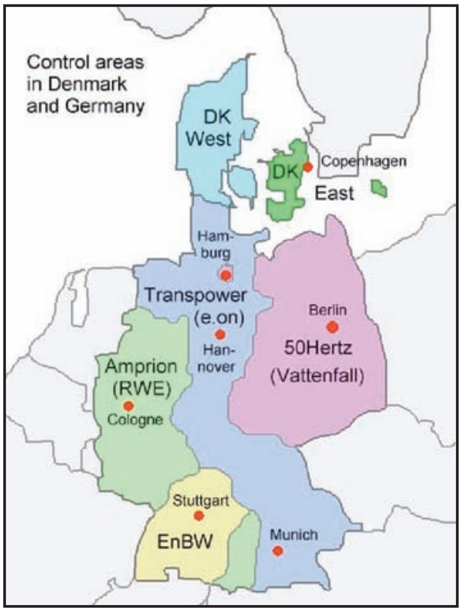
The water storage levels in Norwegian hydro and the Nord Pool spot price indicate stability and normal conditions.

Furthermore, Germany and the Nordic area have had similar average spot price levels during most weeks in 2009. Based on this observation only a limited transit of power should be expected.

In the present study hourly wind power data has been downloaded for all four German control areas, rather than E.on Netz (now Transpower) only, as in previous studies.

The recorded vertical German demand seems to be incomplete, and therefore this set of data had to be ignored in the present report. IndexMundi estimates that German electricity consumption in 2009 was 549 TWh.

The German system operators are: Transpower (formerly E.on Netz), Amprion (formerly RWE), EnBW, and 50Hertz (formerly Vattenfall Transmission).



4. Main characteristics of Danish power systems in 2009

4.1. Annual key figures

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

	Demand	Net Exchange		Wind Generation		Wind Energy Export		
	MWh	Export MWh	Import Mwh	MWh	% of demand	MWh	Hours	% of wind generation
DK West	20,550.012	3,171.098	982,890	5,123,249	24.9	2,476.214	5,683	48.3
DK East	14,049.905	376,231	2,898,132	1,586,727	11.3	278,179	1,972	17.5
DK (total)	34,599.917			6,709,976	19.4			

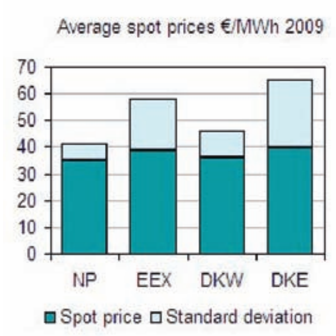
Net export has been calculated hour by hour as the total of all exchange from each of the two Danish systems. In this context the *wind energy export* has been defined for each system and for each hour as the smaller value of generated wind energy and net export.

The full load 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 2009 had 8,760 hours.

Demand	Max	Duration
	MW	Hours
West	3,677	5,588
East	2,614	5,374
Denmark	6,287	5,503

The average market conditions are summarized in this table:

	Area Price	St.Dev.		Spot Price	St.Dev.
	€/MWh	€/MWh		€/MWh	€/MWh
DK West	35.95	10.14	NP	34.90	6.26
DK East	39.76	25.50	EEX	38.78	19.40



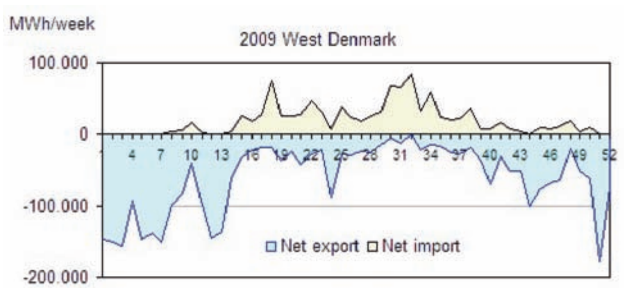
The standard deviation is an indicator of price volatility, and the possible reasons for the differences observed here will be discussed subsequently.

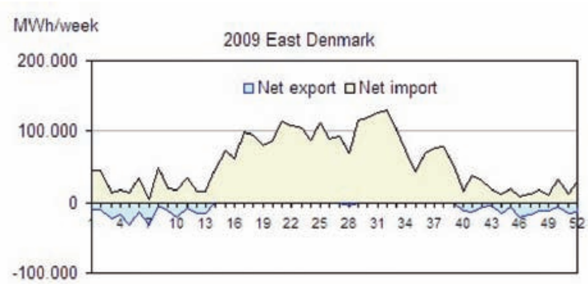
The magnitude of the overflow problem due to Danish wind power can be indicated in a table with number of hours with spot prices equal to zero, and downwards balancing prices equal to or below zero. When the price of balancing (or regulating) power is below zero the system operator must pay for the export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

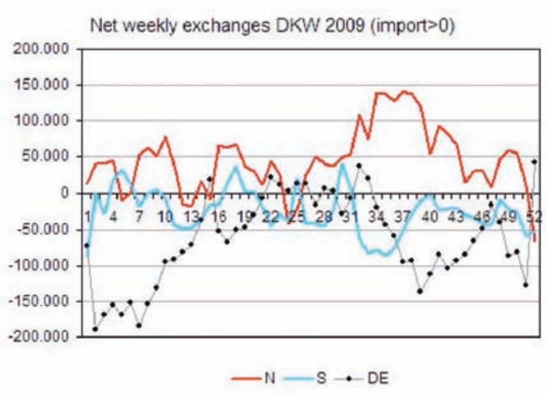
No of hours	Spot price <=0	Spot price >100	Bal. price <=0	Bal. price >100
DK West	55	4	159	77
DK East	4	98	30	319
Nord Pool	3	4		
EEX	73	45		

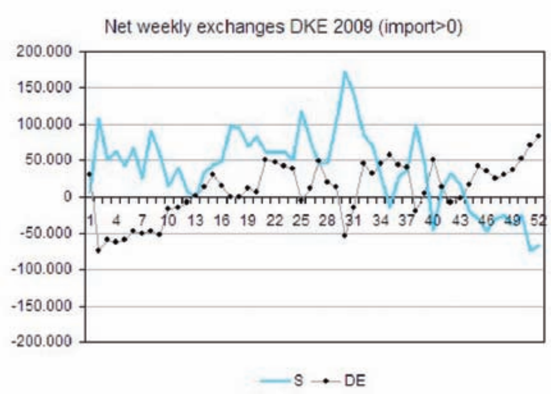
4.2. Weekly averages

Net exchanges per hour have been accumulated for each of the two Danish control areas and for each border. The charts show that Western Denmark has significant surpluses of electricity during the cold seasons.



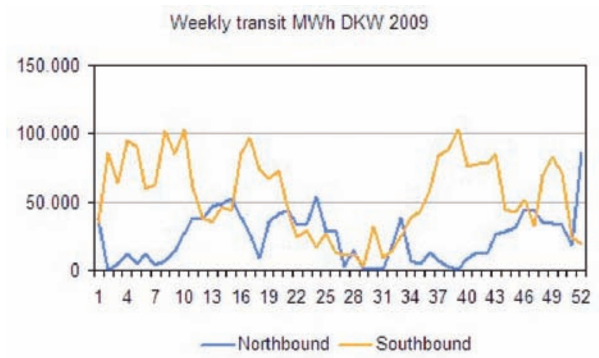


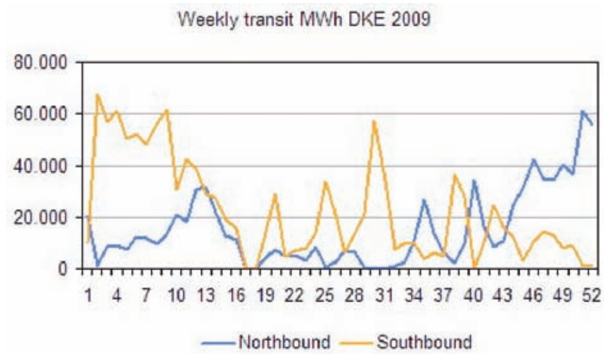


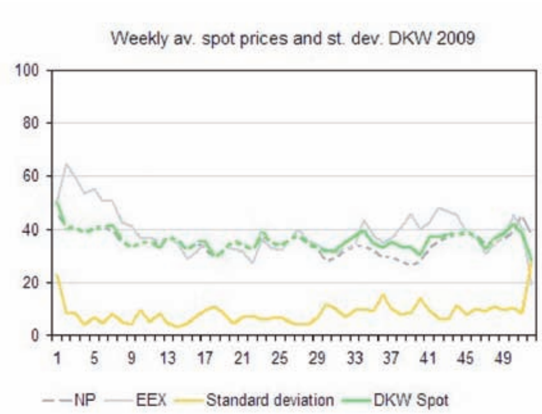


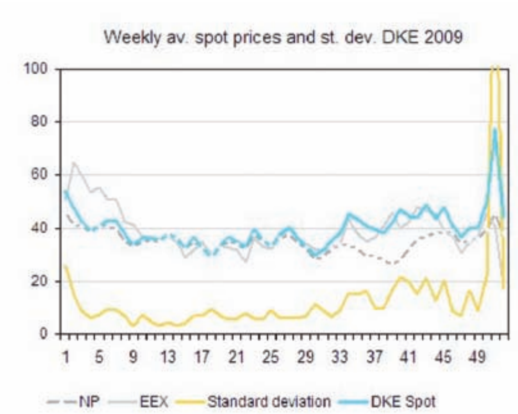
Transit has been calculated hour by hour. In accordance with the spot price profile (Section 2) there is a mainly southbound transit during the first ten weeks, but no predominant direction during the summer.

During transit periods congestion on one of the interconnectors is common, with the spot prices for the two Danish systems following either Nord Pool or EEX depending on which interconnector is congested.





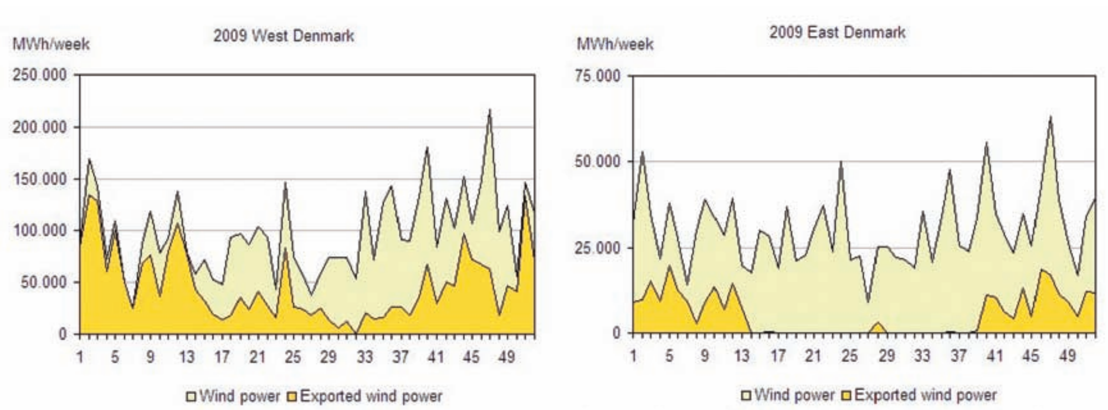




The chart suggests congestion on the borders between Denmark and Germany during the first ten weeks and congestion between Eastern Denmark and Sweden during weeks 33 to 45. In Section 5 we will evaluate the situation in Eastern Denmark in week number 51.

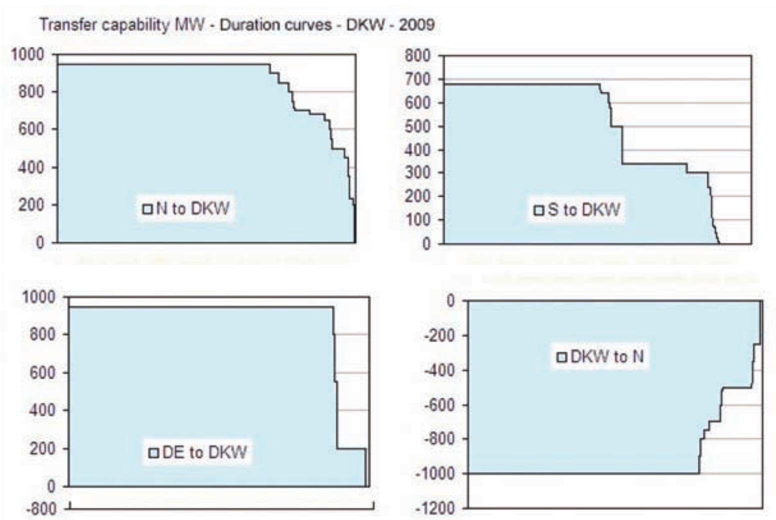
The generation of wind energy varies considerably from week to week.

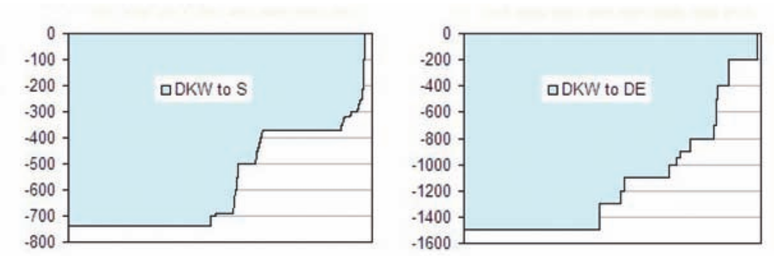
Following the definition in 4.1 the wind energy is divided into an export share (the light brown area) and a share used locally (the light yellow area). The estimate of exported wind energy is a sensitive matter because it raises doubts about the beneficiary of subsidized Danish renewable energy. The 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.



4.3. Interconnector Performance

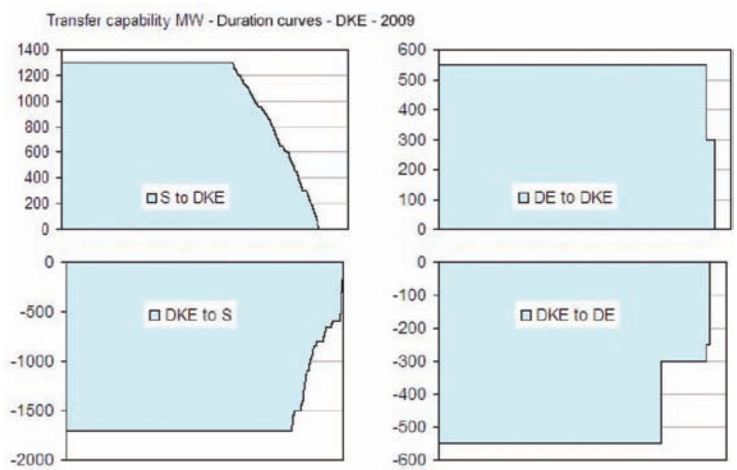
The electricity market optimizes power system operation across national borders, and so sufficient transport capacity is a decisive factor for both reasonable system security and an efficient market service. However, the trading capacity on the 400 kV AC interconnection between West Denmark and Germany depends on stability limits of the interconnected AC networks.





The duration curves above for West Denmark show that the HVDC links to Norway and Sweden continued to suffer from severe hardware faults during 2009, the transfer capability from West Denmark to Germany being more or less reduced for nearly half of 2009.

Interestingly, the capacity reductions on the AC interconnection between Denmark East and Sweden reflect Swedish congestion policy. The Nordic system operators use different methods for the handling of internal bottlenecks, with Norway being divided into areas with different area prices in case of congestion, whereas it is the Swedish policy to maintain the same spot price for all parts of the country. Therefore internal bottlenecks are transferred into reduced trading capacity on interconnectors.

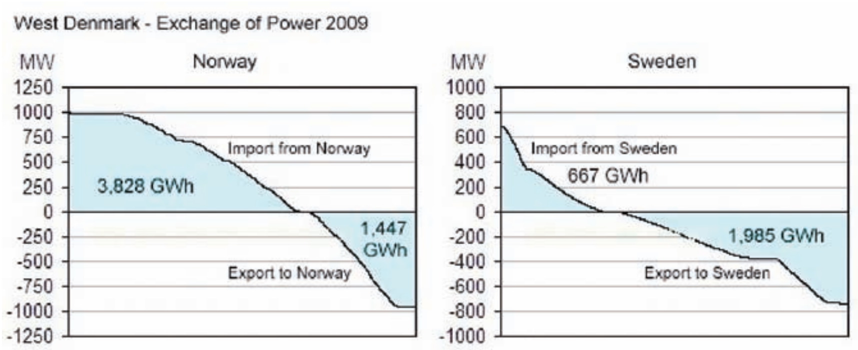


Studies of interconnection and its utility as a means of integrating renewable energy often assume nearly 100% availability. However, Danish observations from the period 2006 to 2009 demonstrate that the in practice availabilities are much lower.

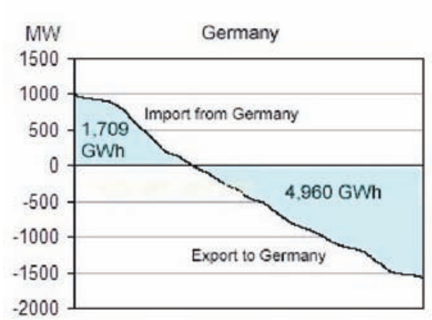
2009	Average availabilities of interconnections			
%	To DKW	From DKW	To DKE	From DKE
Norway	90.9	90.0		
Sweden	70.9	76.3	76.3	91.6
Germany	90.9	75.4	93.0	86.5

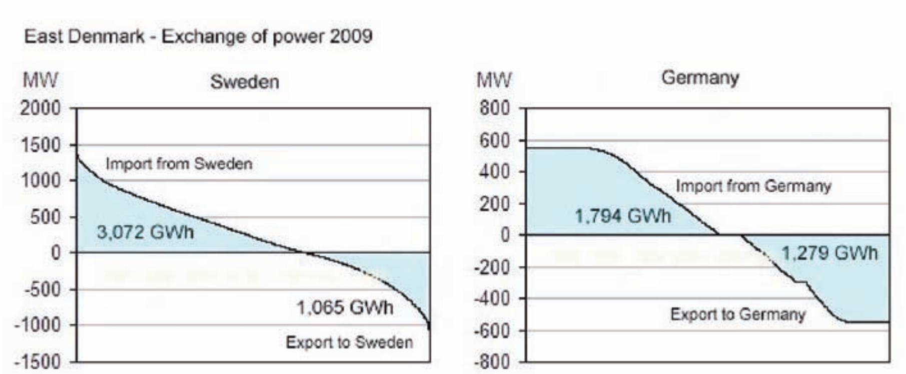
The significance of this point is obvious; interconnections can help smooth spot price oscillations due to intermittent generation (particularly wind power), but this is only true if there is capacity available for this purpose.

The following charts give an impression of the amounts exchanged in 2009:



The distribution suggests a clear transit from Norway to Sweden, with 1,009 GWh being transferred via Denmark during 3,793 hours in 2009.





In the following table the numbers of hours of import, export and congestion are shown for each of the five interconnectors.

Hours	Export	Congest.	Import	Congest.	Total	% congestion
DKW-N	2,725	11	5,989	2,625	8,760	30.1
DKW-S	5,925	927	2,604	214	8,760	13
DKW-DE	5,806	2,351	2,952	353	8,760	30.9
DKE-S	3,085	32	5,674	673	8,760	8
DKE-DE	3,595	1,067	4,696	1,391	8,760	28.1

4.4. Wind Power Properties

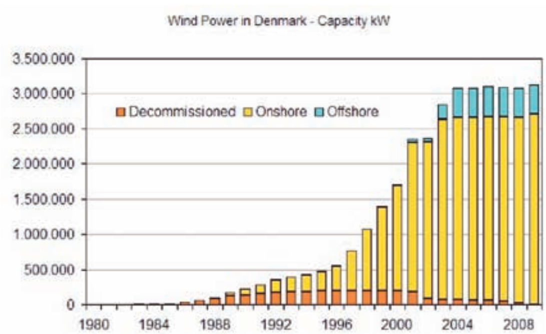
Downloading hourly wind power output for Germany allows us to study the wind power profile for a larger geographical area than Denmark, and is particularly interesting as a means of evaluating whether the smoothing effect can eliminate the occurrence of sharp peaks and periods of zero production.

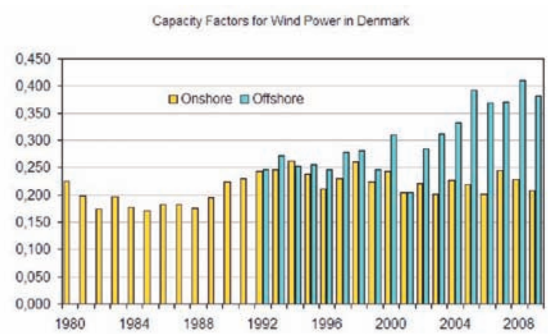
2009		Transpower	Amprion	EnBW	50Hertz	DE total
Wind	GWh	15,437	6,479	453	15,369	37,738
Max	MW	8,383	3,678	349	8,888	20,349
Min	MW	0	21	0	1	159
Duration	Hours	1,841	1,762	1,297	1,729	1,854
Share	%	-	-	-	-	6.9

The calculation of German wind energy share has been based on an estimated total electricity consumption of 549 TWh.

2009		DKW	DKE	DK total	DE/DK total
Wind	GWh	5,122	1,586	6,708	44,446
Max	MW	2,262	669	2,877	21,678
Min	MW	0	0	1	223
Duration	Hours	2,265	2,372	2,331	2,054
Share	%	24.9	11.3	19.4	7.6

At the end of 2008 the installed wind power capacity in Denmark was 3,085 MW, of which 423 MW was offshore capacity,[2] while that in Germany was 23,903 MW.[3] The first German offshore wind farm, the 60 MW Alpha Ventus, was completed in 2009.[4]





Note that these charts include only those wind turbines which have been in operation during the entire year.

The maximum simultaneous wind power production for Denmark and Germany was 21,678 MW in 2009, or 89.5% of the sum of the six local *peak* productions (24,229 MW).

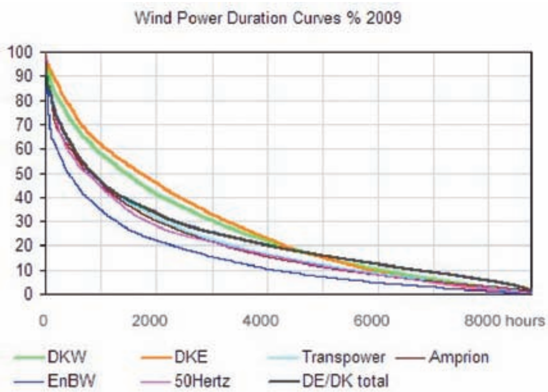
2 http://www.ens.dk

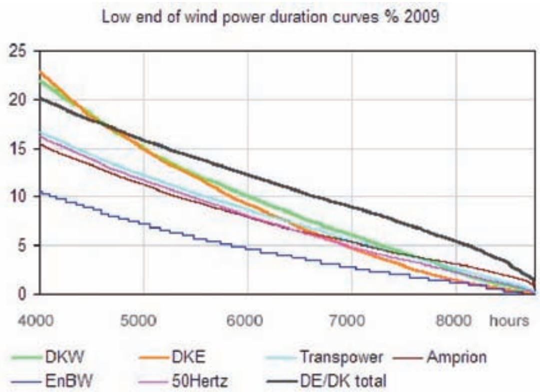
3 http://www.wind-energie.de/de/statistiken/datenblatt-2008/

4 http://www.monstersandcritics.com/news/business/news/article_1513628.php/Germany-completes-construction-of-first-offshore-wind-farm

The wind power duration curves have been calculated as a percentage of the annual maximum production in order to facilitate comparisons. The curves have different profiles reflecting different wind resources and different shares of offshore wind power.

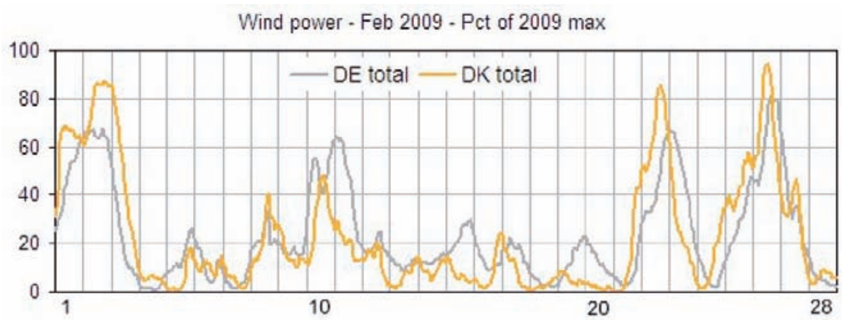
The close-up on the lower end of the duration curves demonstrates the smoothing effect for periods with low wind power output. In this range the aggregated curve shows higher values than each of the six control area curves.





The maximum aggregated wind power output for the six areas is 21,678 MW, or 89% of the sum of the maximum productions for each area. The total installed wind power capacity in Denmark and Germany at the beginning of 2009 was about 27,000 MW, so the average installed capacity in that year was probably slightly higher.

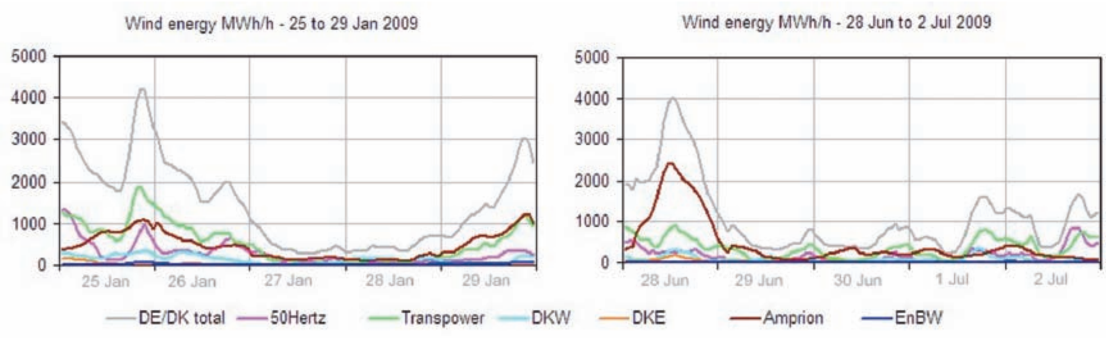
It is possible to demonstrate that the wind power variations in Denmark and Germany are quite closely synchronized, as in the following example (in per cent of the year's maximum aggregated output for each of the two countries).



The minimum aggregated wind power output is of interest from an operational perspective.

2009	Wind power minimum average sustained output in % of annual hourly maximum								
	DKW	DKE	Transpower	Amprion	EnBW	50Hertz	DK total	DE total	DE/DK total
Hours	%	%	%	%	%	%	%	%	%
1	0.00	0.00	0.00	0.57	0.00	0.01	0.04	0.78	1.03
12	0.16	0.01	0.30	1.00	0.00	0.13	0.33	1.12	1.47
24	0.23	0.10	0.71	1.37	0.25	0.58	0.39	1.28	1.61

Several consecutive days with combined Danish and German wind power output below 1,000 MW have been observed in January and June 2009.



A capacity credit can be calculated for a fleet of wind turbines by use of statistical methods, and a capacity credit between 6 and 10 per cent of the installed wind power capacity has been proposed. However, it should be noted that the capacity credits for adjacent areas cannot be added in a simple fashion. Wind power plants do not operate in a stochastically independent manner, because they all depend on a common and related source, the wind.

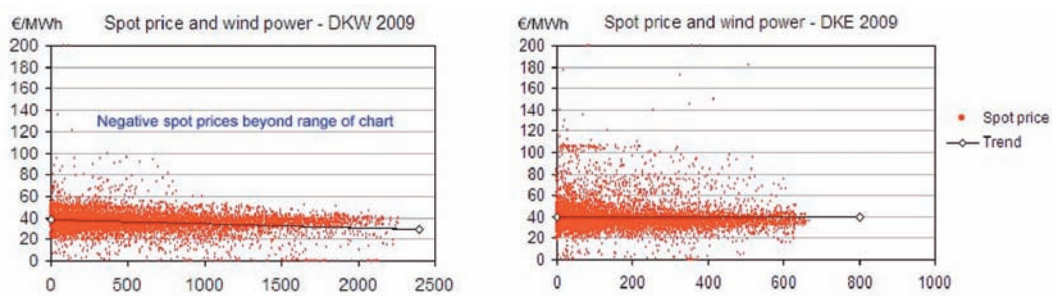
In the determination of the necessary reserve capacity for Denmark and Germany the wind power fleet should therefore be considered as one unit. The security criteria for the operation must be based on the minimum sustained capacity of the total wind fleet which seems to be less than 1% of the installed capacity for 1 hour and less than 1.5% for 24 hours.

5. Wind Power and Spot Markets

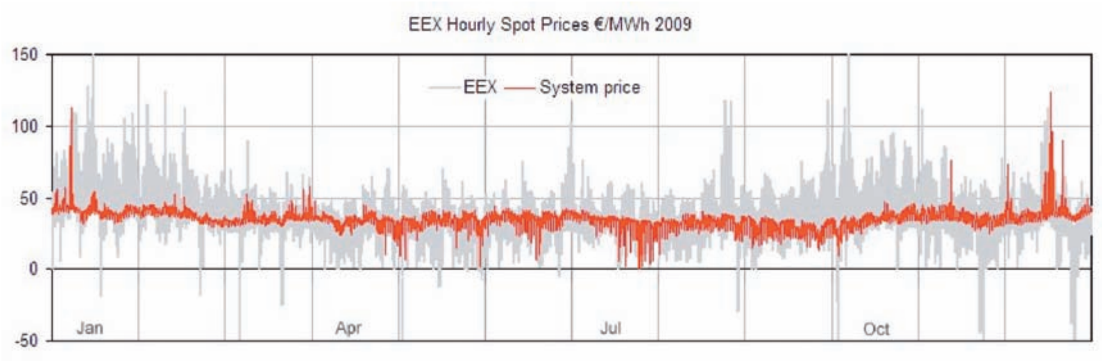
Wind power has an impact on market prices in two ways:

- Increasing wind generation may cause reduced prices.
- The volatility of wind power may cause price volatility.

The following diagrams show local spot prices and wind power for the entire year 2009. The correlations are surprisingly low, and it seems reasonable to conclude that factors other than wind power have a significant impact on market prices. Nord Pool allowed negative spot prices in Denmark from 1 October 2009, and a few cases have been observed. The new price floor is -200 €/MWh.

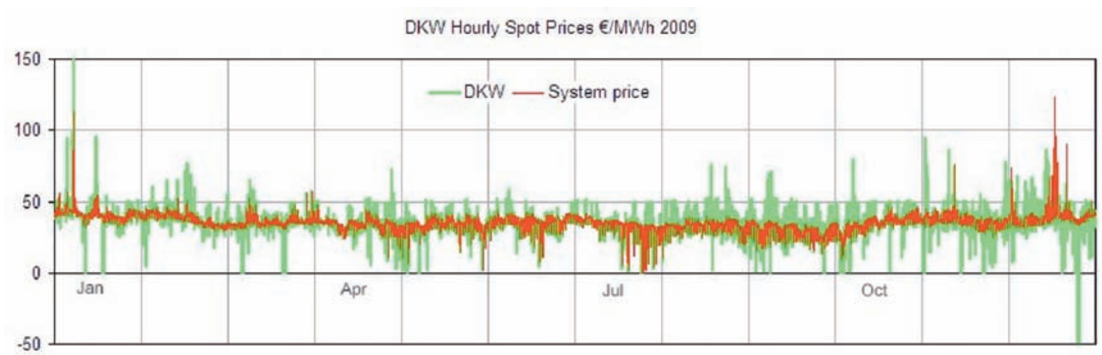


A time series with hourly spot prices can be used for the identification of some characteristic periods.

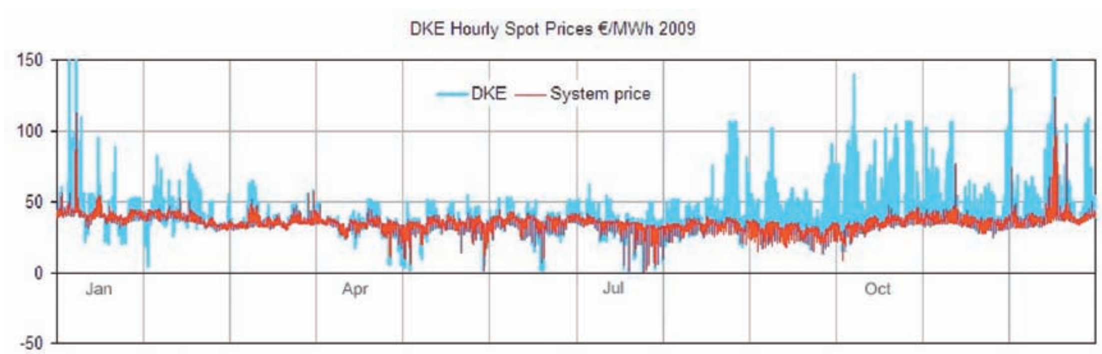


The chart above compares the EEX spot price with the Nord Pool system price. The high volatility and the negative spot prices in the German market are obvious, but it should be noted that even the system price has a slightly higher volatility than in previous years.

In the following chart several cases of zero spot prices in Western Denmark are visible, and the first negative spot prices are observable in December.



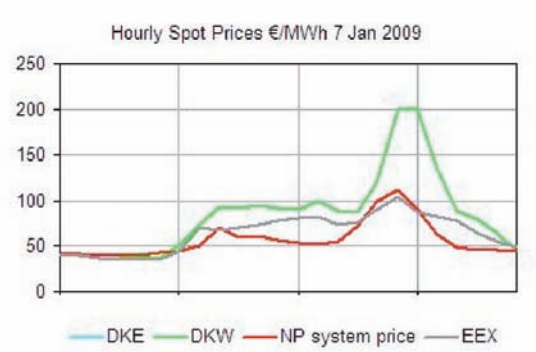
Only a few cases of zero prices have been observed in Eastern Denmark, but a series of high prices during the autumn can be seen in the subsequent chart:

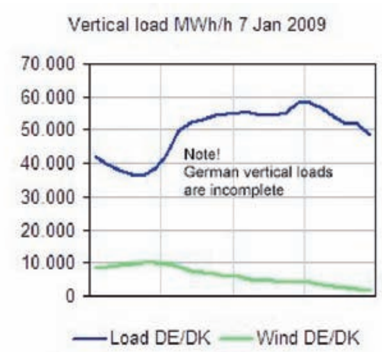


The following observations from these charts have been selected for examination:

5.1: 7 January 2009: Denmark isolated from other spot markets
5.2: 26 July 2009: Zero prices in all Nordic countries
5.3: Energinet.dk: “Nordic electricity prices hit rock bottom”
5.4: Price spikes in DKE during autumn
5.5: December 2009: Positive and negative price spikes

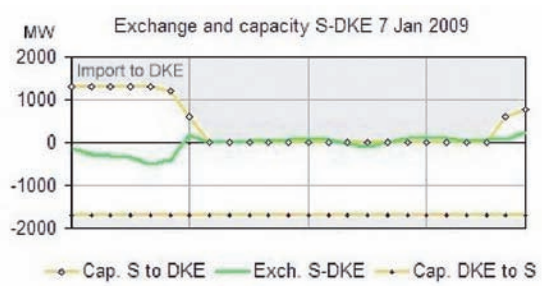
5.1. 7 January 2009: Denmark isolated from other spot markets

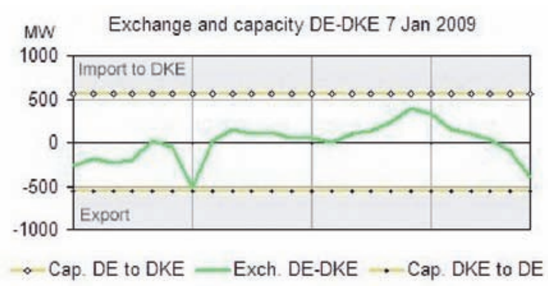




The spot price curves are interesting because the Nord Pool system price and the EEX spot price are at the same level during the evening peak, while the two Danish area prices are higher and identical throughout the day.

Price spikes in Germany and Denmark due to increasing demand and falling total wind power output during the day are not surprising, but the isolated nature of the Danish price curves calls for an explanation.



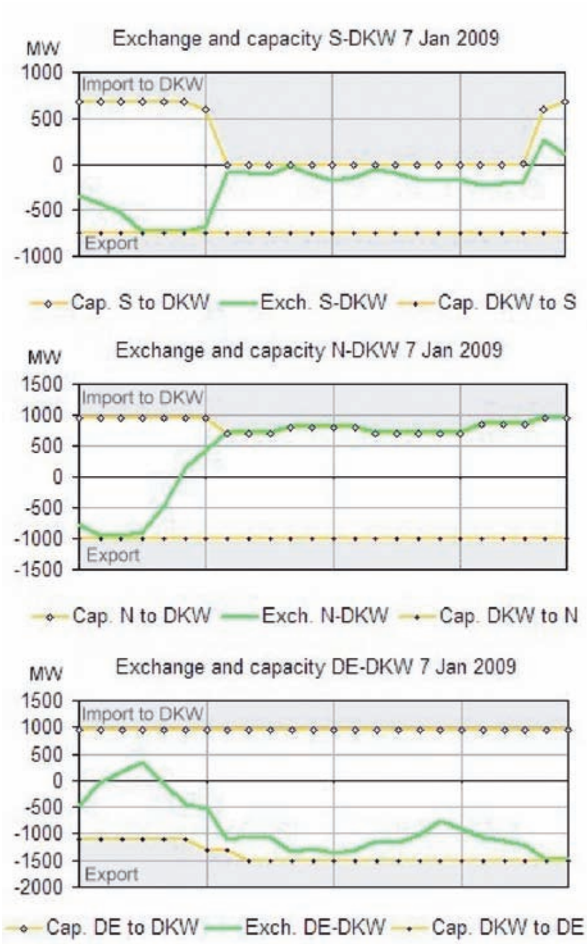


The transfer capability from Sweden to Eastern Denmark was reduced to zero throughout the day, which explains the price difference between Eastern Denmark and Sweden.

However, the exchange between Eastern Denmark and Germany has not been constrained, and the missing market coupling between Denmark and Germany may account for the price difference.

Interconnectors from Norway to the Netherlands and from Sweden to Germany bypass Denmark, and they may have connected the Nordic and the continental markets and caused a consistency between the Nordic system prices and the EEX prices.

On 7 January 2010 from 7 to 22 the spot markets in the two Danish price areas were disconnected from spot markets in the neighbouring countries. The identity of spot prices in the two Danish price areas is remarkable and suggests inefficient competition in the spot market.

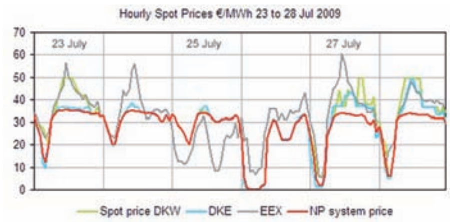


The market in Western Denmark has also been effectively isolated from the Nordic market due to grid constraints. Typically, there has been an export to Germany of about 1,000 MW throughout the day, a flow which runs against strong price signals and indicates inefficient market arrangements across the border.

The 2009 spot price study tried to confirm a hypothesis relating to the correlation between wind power and spot prices, but found more complex explanations. In line with observations from the previous three years this case demonstrates that volatile spot prices are caused by a combination of several circumstances, such as grid congestion, inefficient market arrangements, *and* shortage of generation. Abuse of market power could also be a contributing factor. Wind power is a factor, but it is not the sole factor.

5.2. 26 July 2009: Zero prices in all Nordic countries

In July 2009 the Nord Pool spot price was more volatile than usual, and during the night of 26 July zero spot prices are recorded for all four Nordic countries.



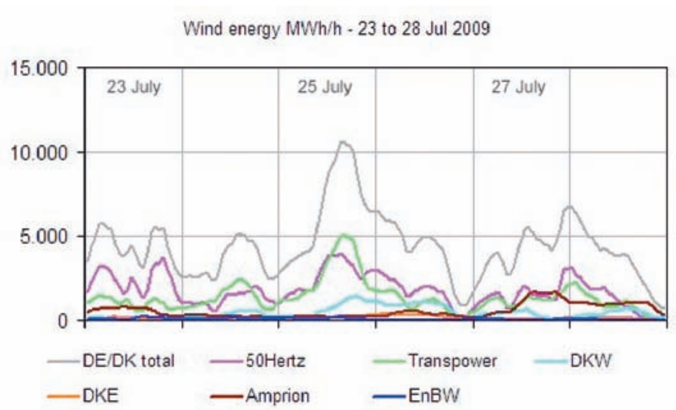
During five of the six days on the chart the EEX price was higher than the Nord Pool system price.

The Energinet.dk Market Report for July 2009 has the following explanations:

> In July, the water level in the Nordic hydro reservoirs started out below the norm for the time of the year, and although the water level rose during the month, it never reached normal levels.
>
> The price fall in the Nordic market was therefore mainly the result of seasonal fluctuations in the demand. Due to the small increase in the coal price, the average spot price at the EEX in Germany rose from DKK 247/MWh in June to DKK 265/MWh in July.
>
> The night of Sunday, 26 July 2009, zero prices were observed for four hours in all the Nordic countries except for the central and northernmost Norwegian price areas. The zero prices were caused by high wind-power generation in the Danish areas and ample water supply in the other Nordic countries. Furthermore, sales opportunities were limited because consumption in the Nordic countries had hit a record low. Both the area prices and the system price, which expresses the theoretical market price without congestion, were DKK 0/MWh – a phenomenon never seen before in the Nordic market.

Low electricity demand in July seems to have been the main reason for low spot prices, and the influence of wind power was probably limited.

The average wind power output in Germany and Denmark for the 6 days was less than 20% of the installed capacity. On 25 July there was a modest peak of wind power reflected in the EEX spot price.



The collapse of the Nordic spot prices during the night of the 26th is still surprising. Contributing reasons could be misjudgment by market participants and inefficiencies of market functions such as the missing market coupling between Nord Pool and EEX.

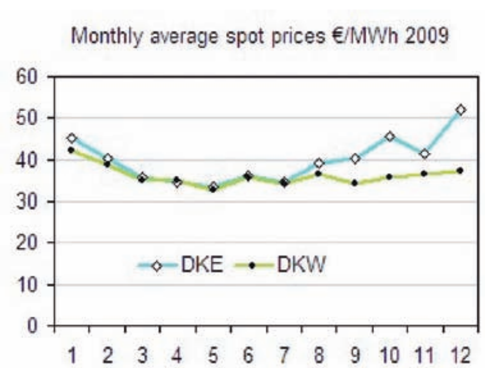
5.3. Energinet.dk: "Nordic electricity prices hit rock bottom"

According to Energinet.dk's market report for September 2010 low electricity demand and rising water level in the Nordic hydro storages caused a continuing falling level of electricity prices.

The following quotation from the market report gives a fair overview of the conditions on the Nordic electricity market:

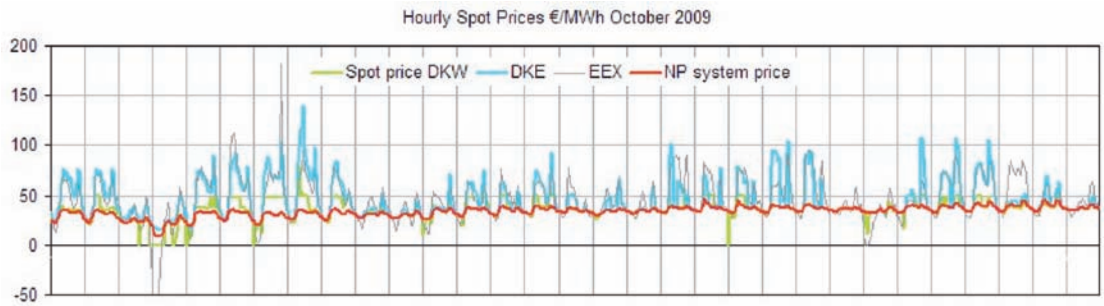
> In Western Denmark, the average electricity price dropped by almost DKK 20/MWh during September to an average of DKK 253/MWh. The largest fall in the remaining Nordic countries was seen in Southern Norway where the electricity price decreased by more than DKK 50/MWh on average per month to an average of DKK 170/MWh in September. This price fall is caused by the rising water level in the Nordic hydro reservoirs, especially in Norway where the water level is close to the norm for this time of the year.
>
> In Eastern Denmark, the spot price increased by almost DKK 10/MWh on average in September compared to August, and Eastern Denmark was the only price area in the Nordic countries which saw price increases. In September, the average spot price in Eastern Denmark was DKK 301/MWh. This increase was a result of Svenska Kraftnät's limitations on the Øresund Link caused by internal congestion in the transmission grid in Sweden. During the hours of Svenska Kraftnät's limitations on the Øresund Link, Eastern Denmark is in fact only connected to the remaining Nordic market through the Kontek cable to Germany.
>
> Despite a slightly increasing tendency in the East Danish electricity price in September, the electricity prices in both of the Danish price areas are almost half the prices of last year; and the market situation shows clear signs of the electricity price in the Danish price areas being strongly influenced by import from the remaining Nordic countries. Furthermore, the general economic downturn and the consequent decreasing electricity consumption also put a downward pressure on the electricity price.

5.4. Price spikes in DKE during autumn

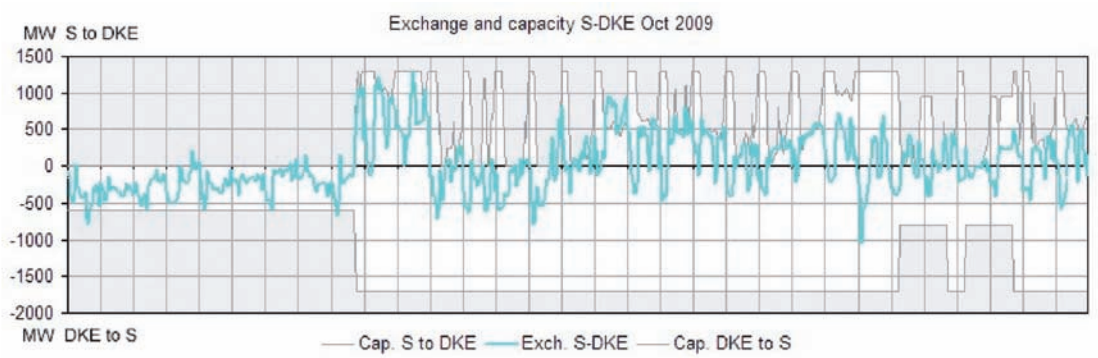


Swedish-imposed limits on the interconnectors between Sweden and East Denmark have caused a slightly higher price level in East Denmark than in West Denmark, particularly during the last months of the year. Indeed, the average spot price in East Denmark is 27% above the price in West Denmark in October and 40% higher in December.

The spot price curves for October show how DKE spot prices have by and large followed the German market, an observation that demonstrates a dependency on the German market and suggests serious bottlenecks between Sweden and East Denmark.



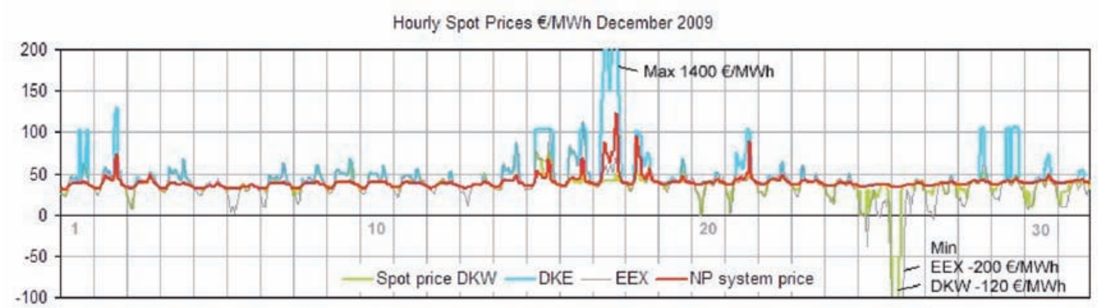
The following chart confirms this assumption, the white area showing the range which has been available for exchange:



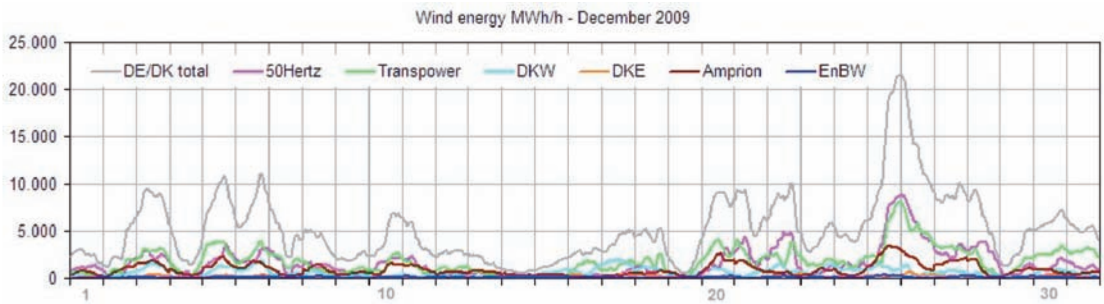
Svenska Kraftnät may have good reasons for these limitations, but the European Court will decide if Swedish market participants have enjoyed protection that is in conflict with the rules of competition.

In any case, it is a fact that the Nordic electricity transmission system is insufficient to provide reasonable market service, and the higher spot price level in East Denmark indicates that insufficient transmission system capacity has had significant economic consequences for electricity consumers.

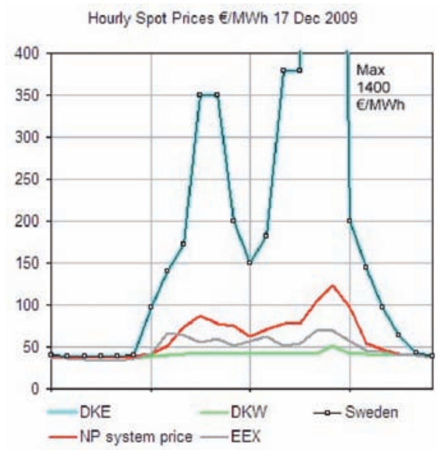
5.5. December 2009: Positive and negative price spikes



The most striking observations based on the spot prices in December are the very high prices on the 17th in DKE and the negative prices on the 26th in DKW. EEX had low night prices in several cases. It is reasonable to ask how these observations are related to wind power.



It would appear that the wind power peak on 26 December may have contributed to the negative prices at that same time. Apart from this peak the wind energy output has been rather low in December; it is interesting to observe that wind power did not exceed 15% of the installed capacity in Germany and Denmark for a five-day period in December. Nevertheless, this cannot be the only reason for the price spikes.

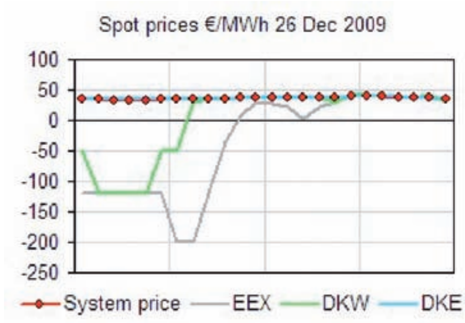


On 17 December a combination of circumstances caused very high spot prices in Sweden and East Denmark, and the spot price chart suggests that an interconnection between west and east in Denmark might have been very helpful in this case.

The DKE peak price on 17 December was a very striking 1,400 €/MWh; the Energinet.dk market report explains the background:

> On 17 December, the East Danish electricity price reached the highest level this year with DKK 10,418/MWh for two hours. The high level was caused by outage of the nuclear power plant Ringhal unit 3 in Sweden and high consumption in the Nordic countries caused by low temperatures. In Sweden and Finland, similar high price levels were recorded. Furthermore, the largest East Danish CHP, Asnæsværket unit 5, was out of operation a couple of days earlier which also contributed to the price increase. In Finland and Sweden the emergency procedure for failure to achieve clearing prices had to be activated in the spot market, and also the system operator's power reserve had to be activated.

On the night of 26 December an unfavourable combination of low electricity demand and a large inflow of wind energy created a surplus of electricity in Germany and West Denmark. Negative spot prices were recorded in Germany and West Denmark, but not in East Denmark.

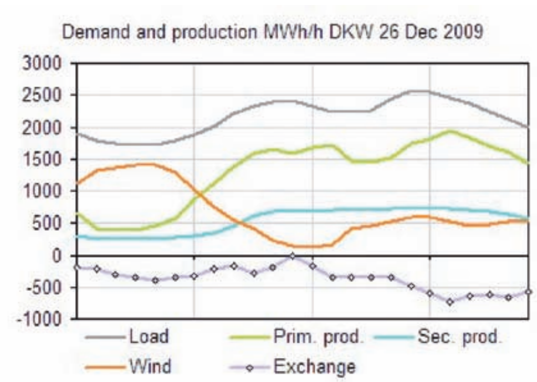


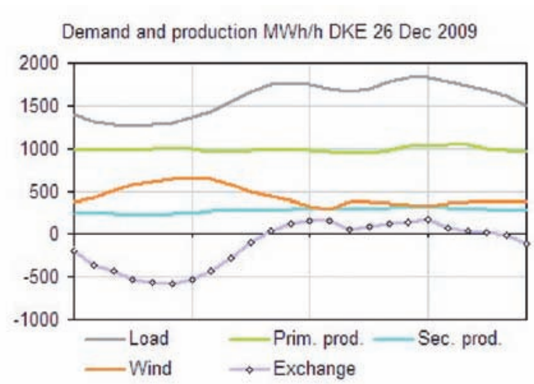
These large differences of behaviour in the two Danish control areas require explanation. The Energinet.dk market report says:

> At the end of December, negative electricity prices were seen for the first time in Western Denmark. The negative electricity prices were caused by low consumption, high wind power generation in Western Denmark as well as in Germany, and low temperatures activated heat load-determined electricity production at combined heat and power plants. For a couple of hours the electricity price dropped to a level of approx. DKK -890/MWh in both Western Denmark and in Germany. In Germany, the spot price continued descending on the European Energy Exchange (EEX) and reached a level of approx. DKK -1488/MWh for the succeeding two hours, during which full utilization of the connection to Western Denmark provided the price difference between the West Danish price area and Germany.

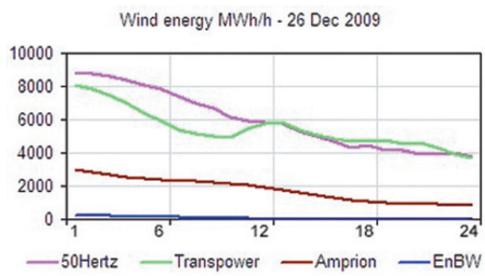
East Denmark had imported the maximum possible (550 MW) from Germany, but plenty of capacity was available in both directions on the Øresund interconnection to Sweden, and therefore East Denmark was able to follow the Nord Pool system price.

In West Denmark the wind power curve was a mirror image of the electricity demand, and all three interconnectors were operated very close to capacity limits. The market had to push thermal generation downwards. The result was identical spot prices in West Denmark and Germany from 01:00 to 05:00 when falling wind power output relieved the situation in West Denmark.





The same night at 01:00 the system operator in East Germany, 50Hertz, had to deal with 4,594 MW demand and 13,841 MW production. Wind power contributed with 8,776 MW and other renewables with 849 MW.



The share of wind energy in the 50Hertz control area is well above the German average, and therefore the rest of the German control areas are obliged to receive 4,650 MW, the so-called HoBA (Horizontaler Belastungsausgleich or horizontal equalization of load).

The export to East Denmark was 550 MW.

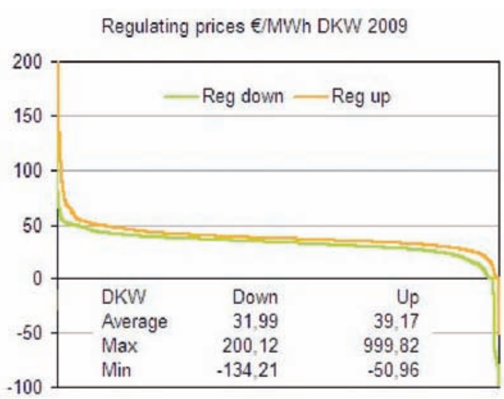
In spite of maximum use of all available options 50Hertz had to demand that production was reduced by 1,000 MW from 01:00 to 04:00. In such cases in Germany the system operator is obliged to publish a report with an explanation of the reasons for the intervention. Another report was published by 50Hertz in 2009 on the conditions on 23 March.

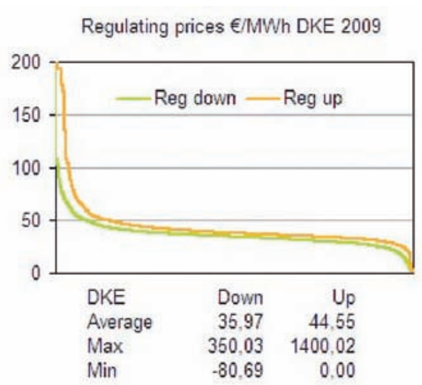
6. Regulating Power

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 one hour before delivery.

The Nordic system operators use the Nordic regulating power market for real time balancing. Market players bid in advance, and the system operators can activate these bids when needed. In Denmark there are different prices for regulating upwards and downwards, and dispersed regulating prices are, consequently, a first warning of unsatisfactory market stability.



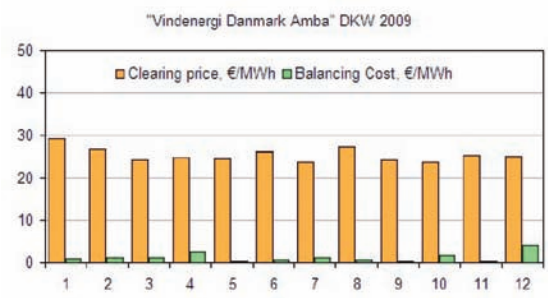


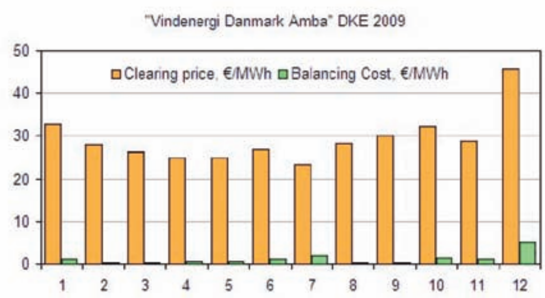
Different rules apply for balancing within Nordel and UCTE, which is probably the reason why the need for regulating power is higher in West Denmark then in East Denmark. Negative prices for regulating power occurred in 194 hours in West Denmark and 53 hours in East Denmark.

7. Wind energy trading

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 2009 (with my translations):

	Jan	Feb	Mar	April	May	June
West Denmark						
Installed capacity, MW	881	889	899	907	915	932
Production, GWh	167	108	160	83	158	135
Clearing price, øre/kWh	29.3	26.8	24.4	24.9	24.7	26.3
Balancing cost., øre/kWh	0.7	1.2	1.1	2.4	0.2	0.5
East Denmark						
Installed capacity, MW	262	264	265	194	194	195
Production, GWh	43	38	42	21	30	29
Clearing price, øre/kWh	32.9	28.0	26.3	24.9	25.0	26.9
Balancing cost., øre/kWh	1.2	0.4	0.2	0.5	0.5	1.1
Total						
Installed capacity, MW	1,143	1,153	1,164	1,100	1,108	1,127
Production, GWh	211	146	202	104	187	165
	July	Aug	Sep	Oct	Nov	Dec
West Denmark						
Installed capacity, MW	954	967	976	991	1,030	1,060
Production, GWh	116	134	176	183	252	152
Clearing price, øre/kWh	23.8	27.2	24.4	23.9	25.3	25.2
Balancing cost., øre/kWh	1.0	0.5	0.2	1.7	0.4	4.0
East Denmark						
Installed capacity, MW	197	197	196	196	199	202
Production, GWh	21	23	31	33	43	26
Clearing price, øre/kWh	23,3	28.3	30.1	32.3	28.8	45.6
Balancing cost., øre/kWh	2.0	0.4	0.4	1.3	1.2	5.0
Total						
Installed capacity, MW	1,150	1,164	1,173	1,187	1,229	1,262
Production, GWh	137	157	207	216	295	178


"Vindenergi Danmark Amba" DKW 2009
Clearing price, €/MWh
Balancing Cost, €/MWh
50
40
30
20
10
0
1 2 3 4 5 6 7 8 9 10 11 12


"Vindenergi Danmark Amba" DKE 2009
Clearing price, €/MWh
Balancing Cost, €/MWh
50
40
30
20
10
0
1 2 3 4 5 6 7 8 9 10 11 12

Wind Power Variability: Observations and Analysis[1]

1. Geographic dispersion and wind power variations

It is well known that wind power is highly variable in output, and that output from a single location cannot be a reliable source of electricity. However, it is, or has been, widely believed that the aggregated generation of a number of dispersed locations will have significantly more manageable properties due to the so-called "smoothing" effect. Simply, it is hoped that the variety of weather conditions across regions will result in a more constant and less sharply variable *aggregate* output.

There is an intense discussion in the UK on this matter, but a conclusion is unlikely to be reached since data which could shed light on the matter is not publicly available.

In other countries with substantial wind power capacities the hourly wind energy output is published by the transmission system operators; indeed Denmark has published such data since the year 2000, and in Germany it has been required by statute since 2004. The Danish dataset is telemetrically reported from all generators, while the German data are estimates based on metered values for selected wind power plants. Such information offers an opportunity to replace assumptions by observations, and is highly desirable in the United Kingdom, for planning purposes, not least because its grid is less heavily interconnected than others and thus it faces more critical system balancing problems, with both economic and physical aspects.

2. The Spot Price Study

It was lack of UK market data that motivated the Renewable Energy Foundation (London) in 2008 to ask me to analyze the correlation between wind power and spot prices in the Danish price areas of the Nord Pool spot market for the years 2006 to 2008.

In the initial phases of the work it became obvious that the spot markets in Denmark and Germany were closely synchronized, even though the two countries have different market operators, that in Germany being operated by European Energy Exchange (EEX) in Frankfurt, and the Danish system by Nord Pool Spot in Oslo. In view of this relationship it was decided to extend the study with wind power data for one of the four German control areas, which was then operated by E.on Netz (now Transpower).

One main conclusion of the report, which was published in May 2008, was that the power markets in Germany and Denmark are so closely related that it is misleading to

1 This article was first published in *New Power* 14 (March 2010), 7–10.

say that Denmark has successfully integrated 20% wind energy (by MWh); instead we should say that these two countries have *together* absorbed about 7%.[2]

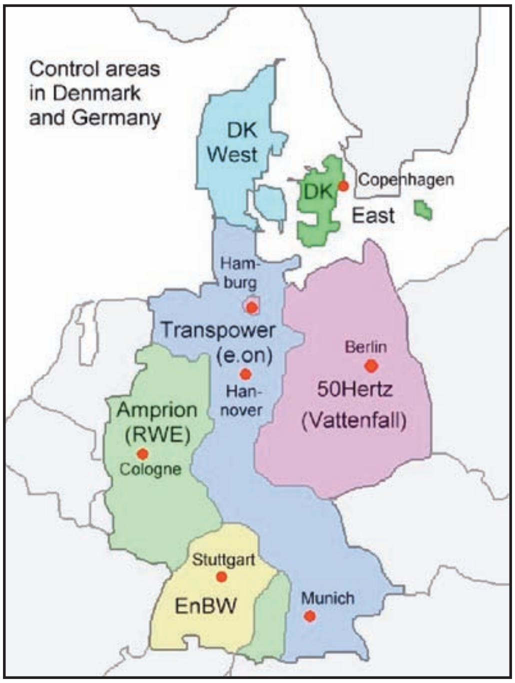
Another observation was that even the simultaneous wind power output in the two countries is positively correlated, and the variability of the aggregate wind power is high. Crucially, there are frequent periods with very low, and indeed very high, wind power output in both countries.

3. Low Winds in December 2007

The most significant calm period in the three-year observation period occurred in December 2007, when wind power generation was low for two consecutive weeks. This combined with a high demand for electricity and caused a power shortage with high spot prices in both Denmark and Germany.

It has been argued by some that the results of my study are irrelevant to the UK because "Britain and its seas are a huge area compared to Western Denmark".

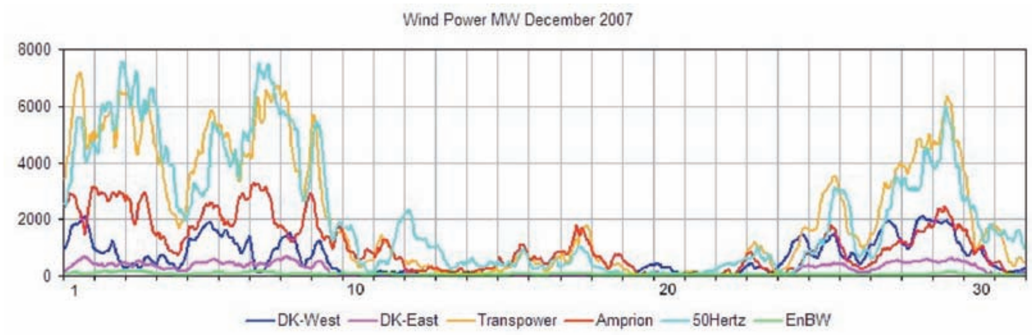
In order to test this argument data for December 2007 were downloaded for the remaining three German control areas, Amprion, EnBW and 50Hertz. The extent of the two Danish and the four German control areas is about 600 km from west to east and 1,150 km from north to south.



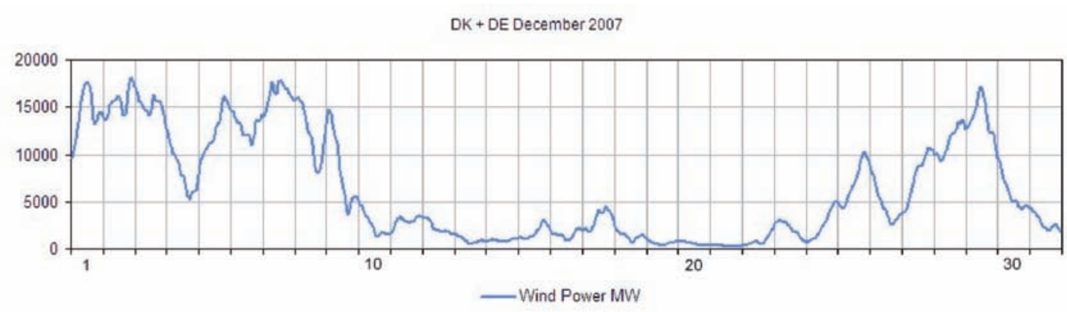
The extent to which the conclusions from this extended area can be applied to the UK may depend to some degree on meteorological conditions beyond the scope of this article. However, it seems reasonable to suppose that the behaviour of wind power in these countries will have some relevance to that anticipated in the United Kingdom.

It is obvious from the observations that the two-week calm affected wind power in all six control areas.

2 Paul-Frederik Bach, *Wind Power and Spot Prices: German and Danish Experience 2006–2008* (Renewable Energy Foundation: London, 2009). (http://www.ref.org.uk/PublicationDetails/53)

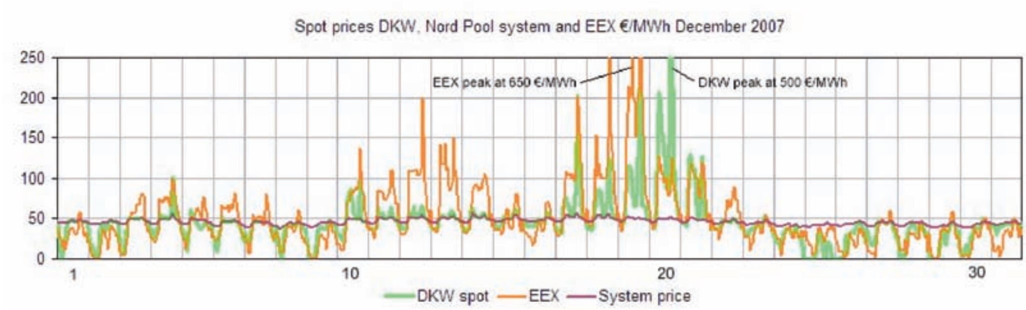


Aggregating these outputs we can chart the simultaneous wind power generation in Denmark and Germany in December 2007:



While it is correct to observe that there is some smoothing, the degree is obviously limited in significance.

During this month the spot markets clearly responded to the wind power variations. Very low prices were recorded during periods with abundant wind power. Conversely, German spot prices were high during both weeks with low wind power output, and in Denmark high spot prices were also observed, particularly during the second of the two weeks. It should be noted that congestion on the interconnections between Sweden and Denmark and loss of a large thermal unit were contributing but not predominating factors. The following chart shows the spot prices in West Denmark (DKW Spot),[3] and Germany (EEX), and the system price for Nord Pool, and should be read in relation to the aggregate wind power chart above. Note that the peak prices (€650/MWh and €500/MWh) exceed the displayed vertical axis.



3 The spot price in East Denmark is not shown because it was practically the same as the price in West Denmark during December 2007.

It is remarkable that the Nord Pool system price is much more stable than the spot prices in West Denmark and Germany. One conclusion that can be drawn is that wind power can have a significant effect on the spot markets in Germany and Denmark.

4. Capacity credit

The total installed wind power capacity in Germany and Denmark in December 2007 is estimated to have been between 23 and 26 GW. The sum of the individual wind power peak productions in the six control areas in December 2007 was 21,042 MW. However, the simultaneous or aggregate production peak was 18,028 MW, or 14% lower than the sum of the peaks in the individual areas.

The recorded minimum simultaneous, aggregate, wind power production was 252 MW, or about 1% of the installed capacity.

It is generally assumed, in Germany at least (UK sources are sometimes more optimistic), that the magnitude of capacity credit for wind power is about 6% of the installed capacity. Such an assumption is not necessarily in conflict with the observations reported here, since capacity credit is a statistical term. Though the capacity credit of a thermal power plant can be much higher than 6%, the power system must be prepared for operation without this particular unit at any time according to the so-called N-1 principle. Thus, the system should be ready for the loss of the largest single generating unit in the portfolio. The basic condition of such a precautionary reasoning is that outages of thermal units are stochastically independent; the failure of one does not indicate an increased likelihood that another will fail.

However, wind power plants do not operate in a stochastically independent manner, because they all depend on a common and related source, the wind. Consequently, for planning and analytic purposes the entire fleet of wind power plants should be considered as one unit. Therefore while a 6% capacity credit for wind power might be justifiable in certain senses, nevertheless the power system must be prepared for operation without any contribution from wind power, even in large areas such as Germany and Denmark combined.

5. Paving the way for additional wind power

Some might consider that the presentation of these observations is just fault-finding. My own view is that, on the contrary, it is only by facing possible problems following a high penetration of wind power that we can hope to inspire the development of solutions for a successful utilization of renewable energy.

A straightforward solution to the wind power variability problem would be to install thermal reserve capacity for all the wind power, with reference to the N-1 principle. However, while engineerable and available, this approach would be very expensive and inefficient, perhaps unacceptably so.

Alternatively, when an increasing share of the generating capacity cannot be controlled by a dispatcher, new flexible elements, both in generation and demand, could be introduced in order to maintain the necessary balance between the consumption and production of electricity.

The new power system architectures being designed for this purpose, the so-called "smart grids", are supposed to mobilize flexibility in our energy systems and provide innovative services to all users and better overall efficiency. Various promising options have been identified, and both the EU and several national governments support the development of smart grids. An example is the Ecogrid project in Denmark, on which the present author worked.[4] However, while environmental problems and shrinking supplies of fossil energy call for new energy solutions, the difficulties presented by renewable generators are not trivial. Doubtless, wind power will make a contribution, but it must be supported by other measures, some of which are yet to be engineered or even conceived. Ignoring the fundamental character of this problem would be both irresponsible and counterproductive; no solutions will be forthcoming unless we admit that they must be found.

6. An ongoing debate

The ready availability of empirical data in Germany and Denmark has allowed this paper to demonstrate and discuss an instance of sustained low wind power output in those countries, and much further data is available to researchers minded to study the wind power properties in greater depth. While this material is drawn from an area of the same extent as the UK, and has probable relevance to the British case, it is regrettable that the discussion of wind power integration in the United Kingdom cannot be based on empirical observations made in that specific geographical area. It would be of enormous assistance to researchers, and clearly in the public interest, if the relevant UK authorities were to publish time series data of observed wind energy output, from both the transmission and distribution connected installations.

4 See: www.ecogrid.dk

Wind Power Variations Are Exported

Can we make better use of Danish wind energy?

The installation of new wind turbines in Denmark has been seen as an essential step towards meeting the targets in climate and energy policy, but there has been little or no attention to the actual use of the wind energy produced. The output profile of wind power is very different to that for electricity demand; sometimes demand is high and wind power low, and sometimes wind power is high and demand low. Therefore, it is not obvious that wind power added to the Danish power system will be useful to *Danish* consumers.

Building wind turbines – and Denmark has developed sophisticated machines and installed about 3,000 MW of wind power – is one thing, but the process of adapting a power system to absorb a significant share of wind energy, the so-called the *integration* of wind power, is quite another, and so far comparatively little and certainly insufficient research has been focused on this necessary second phase.

The Danish think tank CEPOS recently opened up debate on this subject by publishing a report, *Wind Energy – The case of Denmark*.[1] The study is based on the observation that the profile of the net export of electricity from Denmark has a remarkably close relation with the wind power generation profile, particularly for the west Danish power system. This leads CEPOS to the assumption that the export is caused by the wind power.

One reaction to this work is the recent *Danish Wind Power – Export and Cost*,[2] published by Aalborg University and partly financed by the CEESA (Coherent Energy and Environmental System Analysis) Research Project.

The CEESA report claims that, contrary to the CEPOS analysis, wind energy replaces energy from Danish thermal power stations, and that, depending on the market situation, these thermal power plants in Denmark are either closed down or choose to produce for export.

Both viewpoints are defensible. Electricity cannot be traced; we cannot tag electrons as “wind” or “coal” generated. No absolutely definitive argument can be given in support of either, though evidence of varying strengths may be adduced in support of both. Of course, the viewpoints are very different, and would probably lead to different conclusions regarding the need for initiatives for the better integration of wind power. The purpose of a debate about the evidence should be to find a reasonable balance.

However, the CEESA report claims to present the “truth” and seems to hope that the scientific weight of the list of authors will close the debate before it ever started. The language is somewhat dogmatic and allows no alternative opinions.

1 http://www.cepos.dk/fileadmin/user_upload/Arkiv/PDF/Wind_energy_-_the_case_of_Denmark.pdf

2 http://www.energyplanning.aau.dk/Publications/DanishWindPower.pdf

It is surprising that the CEPOS study, which after all is simply empirical information on the export of wind energy and some related interpretation, should cause so much anger. It is furthermore very disappointing that a group of group of highly qualified Danish scientists should feel moved to employ dubious arguments that can only divert attention from the need for better integration of wind energy in Denmark. This is not in the public interest.

While the amount of exported wind energy is a matter of interpretational definition, and is dependent on perspective, it is clearly evident from the data that the irregular variations of Danish wind power are reflected in the exchange of electricity with the neighbouring countries. This much cannot be denied; the facts are clear.

Maintaining the myth of the successful Danish integration of wind power may be good public relations, but refusing to face realities is self-deception and may have economic and other consequences.

The purpose of this note is to question the statistical methods and conclusions presented in Chapter 1 of the CEESA Report. Hopefully it will demonstrate that nobody has a monopoly on truth.

The main arguments in Chapter 1 of the CEESA report

The CEESA report claims that the charts in the CEPOS report do not support the following conclusion:

> …the coincidence of so much wind output with net outflows makes the case for claiming that there is a large component of wind energy in the outflow, indisputable.

The CEESA report uses linear regression analyses of hourly plots of electricity production and exchange of power to demonstrate that the correlation between wind power and net export of electricity is of the same nature as the correlation between thermal generation and net export and that the charts therefore cannot justify any conclusion related to wind power. However, linear regression is not a suitable tool for comparisons of time series, and consequently this method cannot support CEESA's conclusion.

Due to the merit order of suppliers in the international electricity market all thermal production (down to a minimum level determined by security reasons) are to be curtailed before wind power. Therefore, CEESA concludes, the exported surplus of power is supposed to be thermal power. This is a coherent view, but it is not necessarily the only coherent view.

Misleading statistical arguments

The CEESA report refers to the plot of wind power and export shown on page 15 and 16 in the CEPOS report, **but ignores completely the time series shown on the previous pages**.

In figure 1 the CEESA report shows a plot of hourly wind power and net export for west Denmark in 2008. The dispersed cloud of dots suggests that high wind power output may be connected with high net export.

Figure 2 in the CEESA report shows a similar chart for the primary production of electricity (the large power plants). In this case the cloud suggests that high thermal production may be connected with high net export.

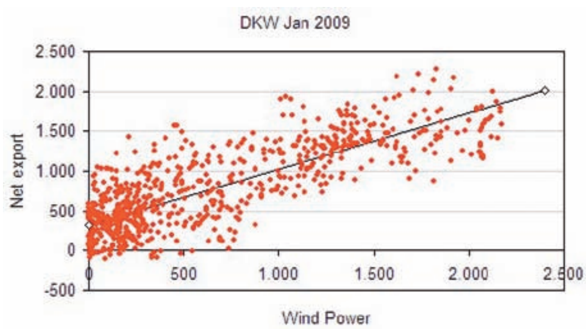
The CEESA report rightly concludes that the correlation is low in both cases and that the charts cannot justify conclusions on the causal relations.

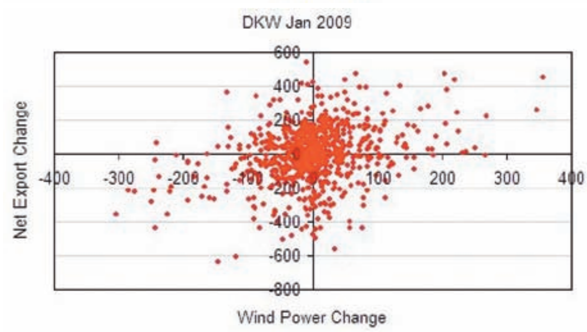
However, instead of studying the time series the CEESA report looks for causal relations by plotting changes from hour to hour of production and export (Appendix 2). The results are clouds of dots without useful information. The purpose of this diversion seems to be to demonstrate the lack of relations between wind power and net export.

The correlation coefficients are then calculated by use of linear regression. These calculations are based on the assumption that there should be the same linear correlation between production and net export throughout the year. But this is not the case.

In this note January and July 2009 will be used for demonstration of the difference.

The upper chart suggests some connection between wind power and net export. The linear correlation coefficient is 0.81. As a contrast it is hard to see how useful information could be extracted from the lower chart (corresponding to Appendix 2 in the CEESA report).

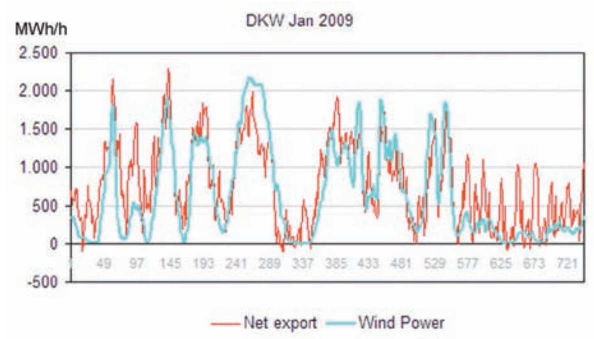


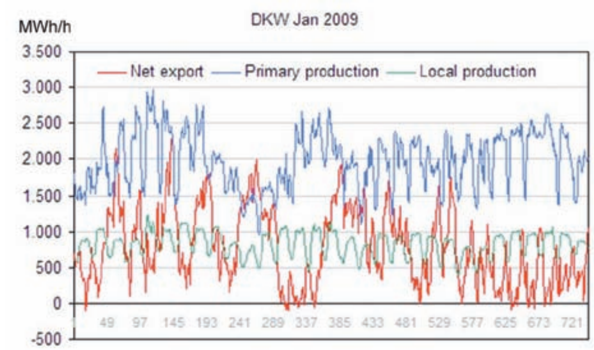


The time series tell different stories.

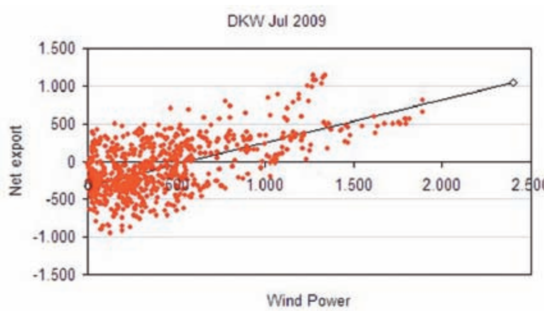
The upper chart suggests that there might be some sort of relation between wind power output and net export, but such relations are not obvious on the lower chart which compares net export with primary thermal production.

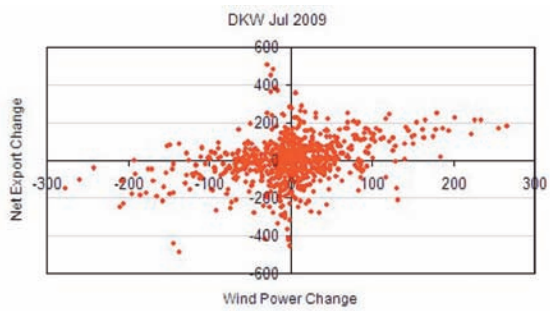
Therefore I cannot agree with the CEESA report that there is no real difference between the ways that wind power and thermal power relate to net export. There is a clear difference in the time series charts.





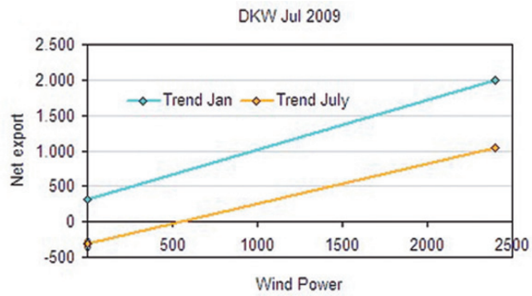
The upper chart also shows that a wave of wind energy is typically longer than one day. Therefore a plot of hourly changes cannot indicate if there are relations between power production and export or not, and it is difficult to see any merit in the calculations in Appendix 2 in the CEESA report.





July is different from January, there being much less wind power output. Indeed, the average was 412 MW in July and 649 MW in January. However, the linear correlation with net export is less obvious, with the correlation coefficient being 0.60 in July and 0.81 in January.

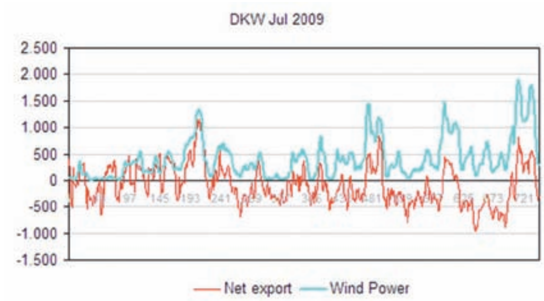
Of particular importance is the difference between the trend lines.

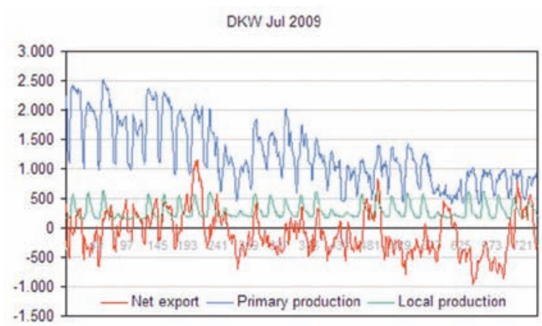


The practical reason for the difference is the high production of the combined heat and power plants during the cold season in order to meet the demand for heat in the district heating systems.

Due to this difference a linear regression analysis for the entire year is not useful. The correlation will inevitably be poor and the results cannot be interpreted in a meaningful way.

Once again, the time series are much more informative.





The wind power variations are reflected in the net export, even in July, while practically no co-variation between thermal generation and net export can be identified.

So on the one hand I agree with the CEESA report that the linear regression analyses do not support the identification of causal relations between wind power and export. On the other hand **a time series analysis indicates a relation between wind power and export which cannot be coincidental and which the CEESA report has ignored**. (See Annex 1 to 3 for complete time series for 2009.) In other words, linear regression analysis is not the correct tool for examining the causal relations between wind power and export.

An exhaustive time series analysis might have shed more light on this interesting issue, but it is far beyond the scope of this note.

Misleading market arguments

The core of the market argument in the CEESA report seems to be the following:

> From a market perspective, it is generally the most expensive production in Denmark which is exported, as any cheaper production would already have replaced more expensive production operating to cover the Danish demand.

Already? The argument seems to be based on the understanding that the market is operated in two steps: In the first step domestic supply is determined and in the second step agreements on export are made. But this is not how the markets work.

The most important market prices for electricity in Denmark are the local area prices of the Nord Pool spot market.

In Denmark market participants must send their bids for the following day to Nord Pool every day before gate closure at 12:00. After gate closure Nord Pool aggregates all bids into two curves, a demand curve and a supply curve. The two curves determine a system price for each hour. In case of congested interconnections local area prices are calculated.

Owners of combined heat and power plants can offer their electricity output at quite low prices due to the high efficiency of the combined production. Therefore Danish power plants are very competitive during the cold seasons.

Even wind power is traded in the spot market. Normally wind energy is offered at very low prices, because the operators of wind turbines cannot control the time and level of their output. The resulting spot price is used for settlement.

For each supplier, production is determined by the area price, and supplies for purchasers are determined accordingly. As a result of the process exchanges across the borders are also determined. There is no special reservation for domestic consumers. **Therefore section 1.2 in the CEESA report is based on a misleading assumption.**

The outcome of the spot market is a plan for the following day. Deviations from the plan are handled by other market arrangements, which will not be discussed in this note.

As noted above, electricity cannot be traced to its source. Therefore the destination of the wind energy can never be objectively determined. But the observations from the time series suggest some significant influence of wind power on net export. This is the background of the estimation of wind energy export in the CEPOS report.

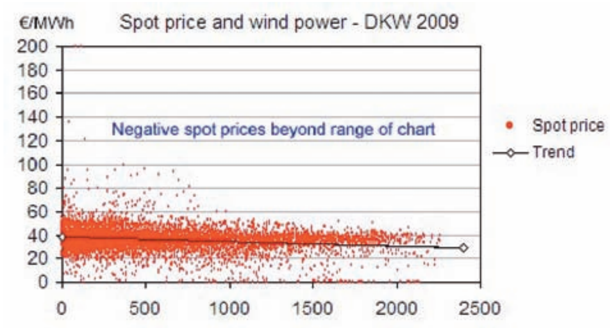
The authors of the CEESA report are entitled to try to see the matter from a different perspective, but the arguments in their report are not valid, and they cannot justify their claim to know objectively what is right and wrong in this matter. The perspective of the CEPOS study is also coherent. When two or more perspectives are possible, we select them according to the understanding they yield and the assistance they give in solving problems. In what follows I shall argue that the CEPOS perspective is helpful if we are to plan for high levels of wind power, while the CEESA view is less constructive.

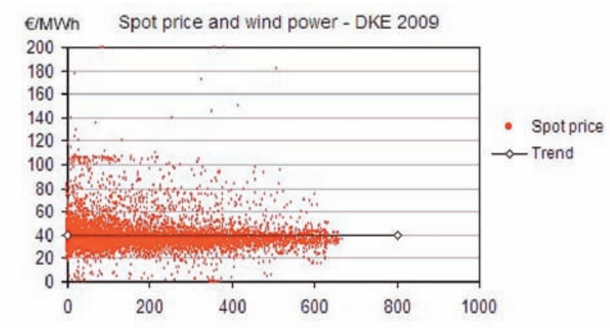
How wind power variations affect exchange of power

The variability of wind power does not fit with the profile of the electricity demand, and therefore a successful integration of wind power requires new types of electricity demand which can be satisfactorily served by wind power.

However, wind power was added to the Danish power systems without a corresponding adaptation of the electricity demand, and as a result we see the wind power variations reflected in the net export of electricity (see Annex 1 to 3).

From this we can conclude that wind energy has replaced more expensive energy somewhere, but not necessarily in Denmark.





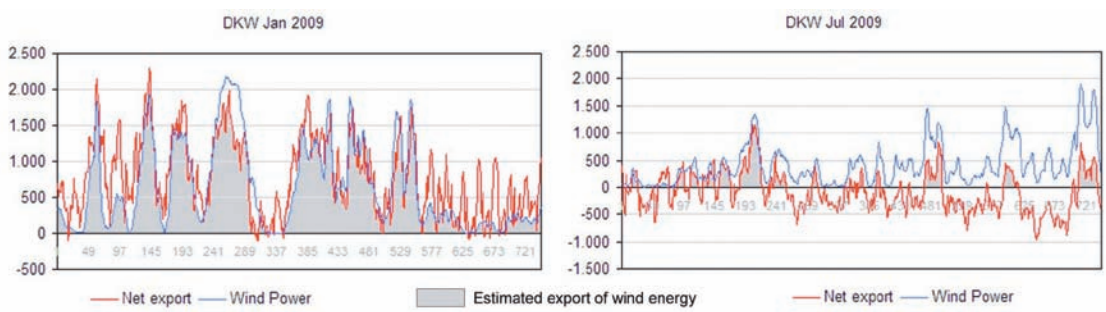
The output from thermal power plants in Denmark depends mainly on the demand for heat for district heating and on the market prices. Thermal power plants are also used for system regulation and as operating reserves.

If high wind power output causes lower spot prices in Denmark the thermal production will be lower. However, Danish wind power normally has little influence on spot prices.

We can conclude that this is an indication that thermal power plants in Denmark, with few exceptions, are operated practically independently of the wind power output.

Therefore more wind results in more export and less wind results in less export. This is the simple causal relation and in good agreement with the observed exchanges of power, and this has been the background for the calculation of wind energy export.

The calculation is based on the simple rule that the smaller of either a) wind power output or b) net export of electricity for each hour, is considered as wind energy export.



The reader should note that this is not a scientific law. It is a rule grounded in engineering and logic which aims to describing the possible consequences of adding wind power to a power system **without at the same time implementing proper integration measures**.

Better integration of wind power is a common interest

The CEESA report claims that it is a theoretical possibility to operate the Danish power system without export of electricity. This would probably be very disturbing to the Danish combined heat and power production, which is also an essential part of Danish energy policy. Therefore this situation cannot be considered as a successful integration.

In 2009 the Renewable Energy Foundation in London published my study *Wind Power and Spot Prices: German and Danish Experience 2006–2008.*[3] The original purpose was to determine how wind power output affected the spot prices in Denmark. The surprising observation was that the correlation between wind power and spot prices is quite low. On the other hand close relations were observed between wind power output in Germany and Denmark and between the electricity markets in those two countries.

Based on these observations it could be said that Germany and Denmark together have solved the integration problems for about 7% wind energy, but only due to the common access to the regulation capabilities of the other Nordic countries, notably hydro power in Norway.

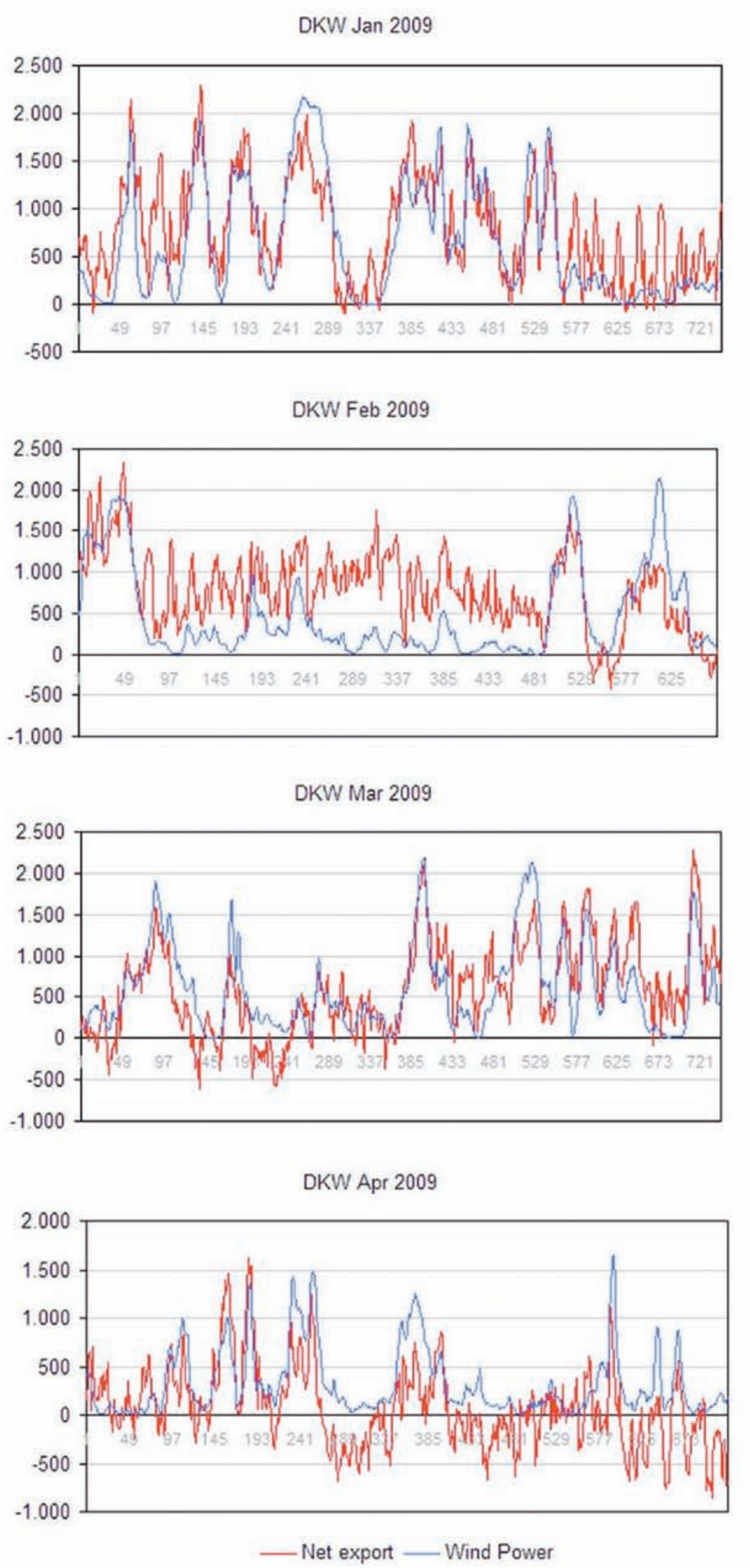
Both Germany and Denmark have ambitious targets for the development of wind power, and it is important that the general public as well as politicians and engineers **realize the magnitude of the necessary integration effort in order to go from 7% to 50% wind energy**.

I consider the Danish integration of 20% wind energy as incomplete. Therefore I do agree with the CEESA report about the need for the measures described in section 1.3.

If we attempt to achieve a level of wind energy in Denmark corresponding to 50% of the demand for electricity there is an urgent need to intensify the development of measures to facilitate the use of wind power, that is to say to integrate it. Hopefully a more constructive debate focusing on these essential integration measures will develop. But this will not happen if legitimate and constructive debate is closed down, as the CEESA report seems to intend.

3 Paul-Frederik Bach, *Wind Power and Spot Prices: German and Danish Experience 2006–2008* (Renewable Energy Foundation: London, 2009). (http://www.ref.org.uk/PublicationDetails/53)

Annex 1


DKW Jan 2009
2.500
2.000
1.500
1.000
500
0
-500
49 97 145 193 241 289 337 385 433 481 529 577 625 673 721
DKW Feb 2009
2.500
2.000
1.500
1.000
500
0
-500
-1.000
49 97 145 193 241 289 337 385 433 481 529 577 625
DKW Mar 2009
2.500
2.000
1.500
1.000
500
0
-500
-1.000
DKW Apr 2009
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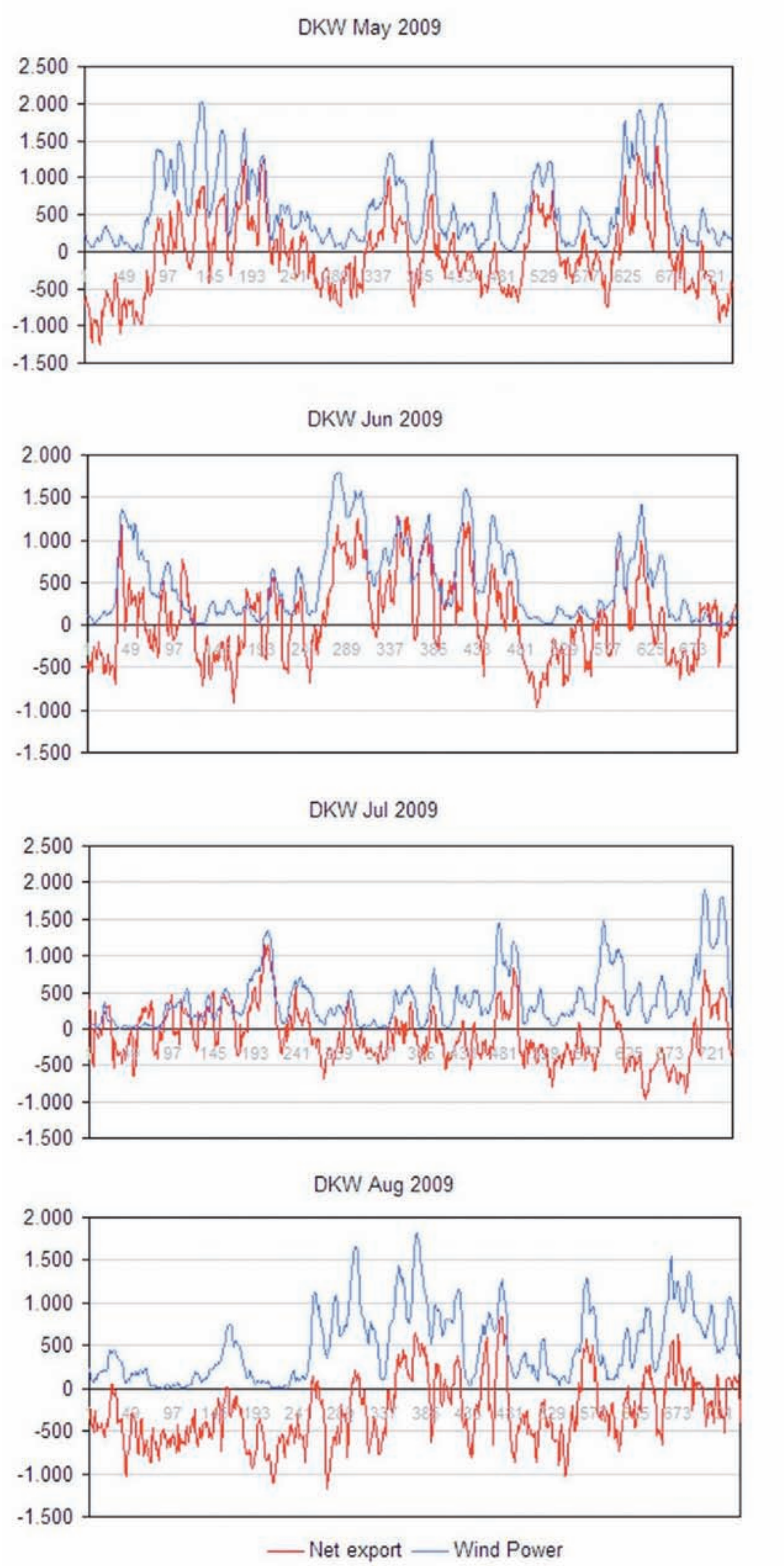
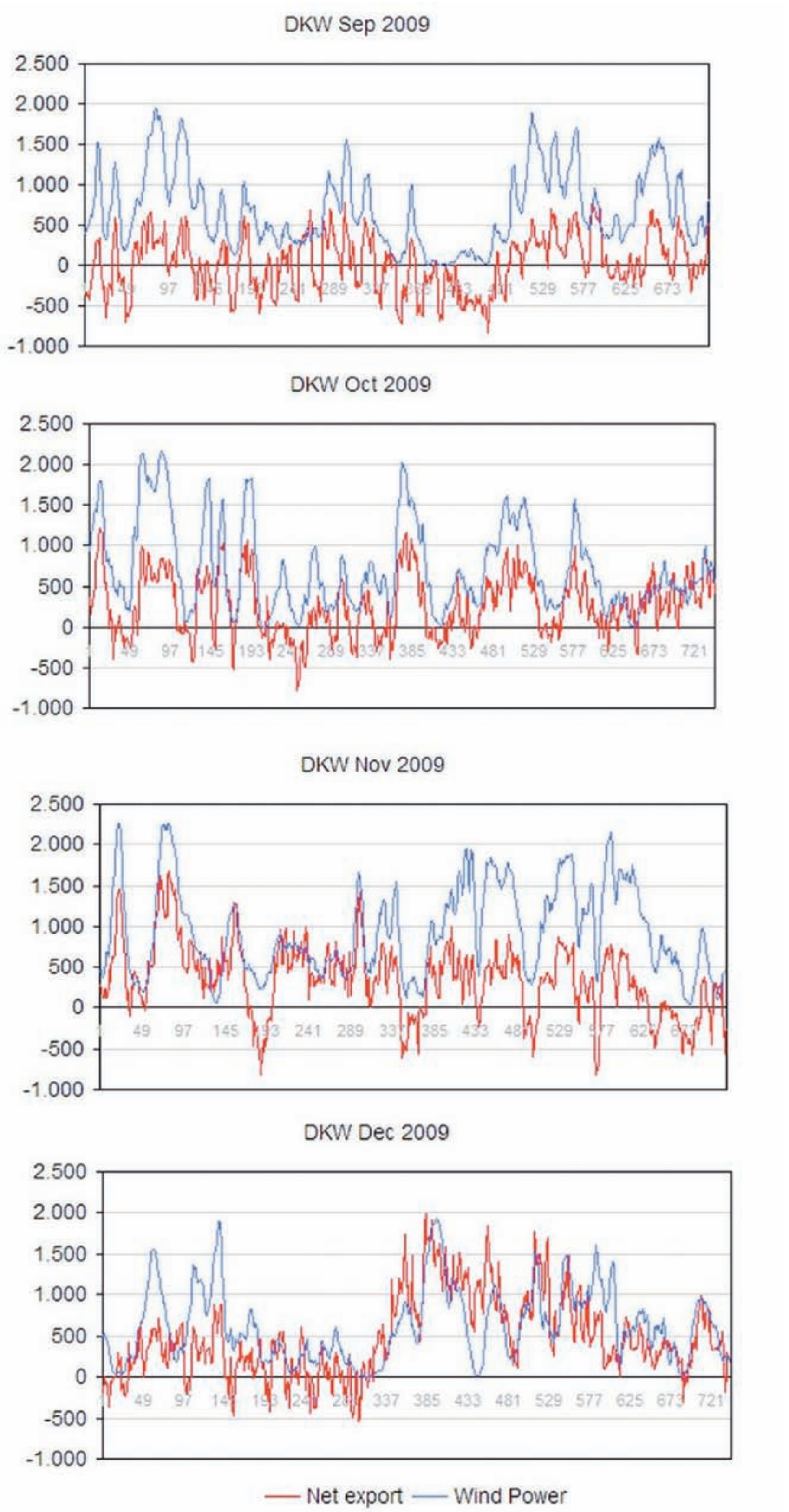
1.000
500
0
-500
-1.000
Net export
Wind Power

Annex 2


DKW May 2009
DKW Jun 2009
DKW Jul 2009
DKW Aug 2009
Net export
Wind Power

Annex 3


DKW Sep 2009
2.500
2.000
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1.000
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97
529
577
673
DKW Oct 2009
2.500
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DKW Dec 2009
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721
Net export
Wind Power

Geographical Distribution and Wind Power Smoothing

Observations from Denmark, Germany and Ireland suggest that in spite of widespread geographical distribution of wind and extensive interconnection the smoothing effect will be only moderate, opening up a remarkable opportunity for those able to mitigate the remaining balancing problems. However, such novel solutions will not come about unless much more time series market data is made freely available to innovative and experimental engineers.

Previous studies have demonstrated that wind power output in Denmark and Germany is synchronized to a significant degree, and that aggregating the two Danish and the four German control areas results in only a weak smoothing of volatility. Indeed, the behaviour of the electricity markets in both countries now reflects this close relationship, confirming the strength of the effect. However, it has been suggested that aggregating wind power along an east-west axis could give much better results, and this article reports on forthcoming technical work employing time series data for Irish wind power in 2009 in order to test this hypothesis.

While a still larger data set would be desirable, few European countries make full electricity market information conveniently available. Denmark, indeed, is something of an exception and has been a frontrunner in publishing hourly data, including spot prices from the European Energy Exchange (EEX).[1] Fortunately for present purposes wind power output in Germany is also available through the four German transmission system operators,[2] and Irish market and system data can be obtained from Eirgrid.[3] Such openness is commendable, and we can hope that it is a growing trend.

1 http://www.energinet.dk/en/menu/Market/Download+of+Market+Data/Download+of+Market+Data.htm

2 http://www.transpower.de/pages/tso_en/Transparency/Publications/Network_figures/Actual_and_forecast_wind_energy_feed-in/index.htm

http://www.50hertz-transmission.net/cps/rde/xchg/trm_de/hs.xsl/SetWebsiteLanguage.xml?languagevariantid=ENG&lang=en&targetPage=153.htm

http://www.amprion.de/en/wind-data-according-to-17-stromnzv

http://www.enbw.com/content/de/netznutzer/strom/download_center/eeg/windprognose/index.jsp

3 http://www.eirgrid.com/operations/systemperformancedata/downloadcentre/

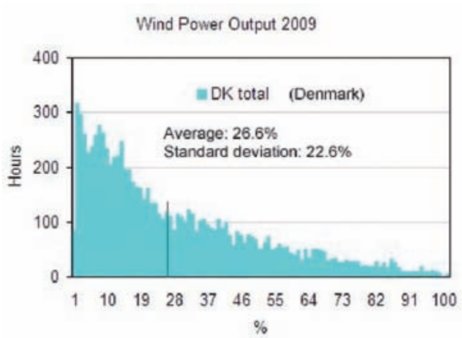
Statistics

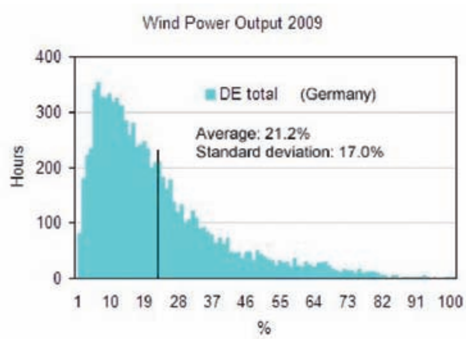
Previous comparisons between Germany and Denmark employed units of energy (MW, MWh), which is a reasonable choice due to the strong interconnections and the close operational relationship between the two countries. In fact, the results demonstrated that the two countries responded to the variations of wind power as one power system. However, since the purpose of analyzing time series for wind power in Denmark, Germany and Ireland is to compare smoothing effects north-south and east-west, the three locations must be given the same weight, and therefore the time series for the three countries have been normalized by converting them into a percentage of that year's maximum value.

The following overview of the three systems can be extracted from the time series in 2009:

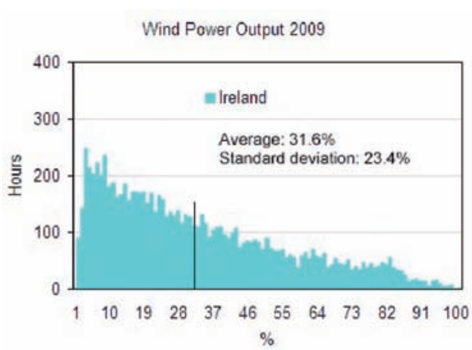
	Denmark	Germany	Ireland
Wind output (GWh)	6,708	37,738	2,886
Wind max output (MW)	2,877	20,353	1,043
Duration (Hours)	2,331	1,854	2,741
Load factor	0.27	0.21	0.31

As can readily be observed, the three wind power systems are different in size and wind intensity, and these differences can be further explored by considering the distribution functions.

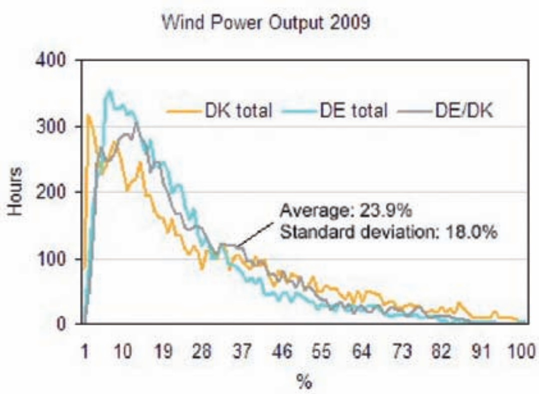


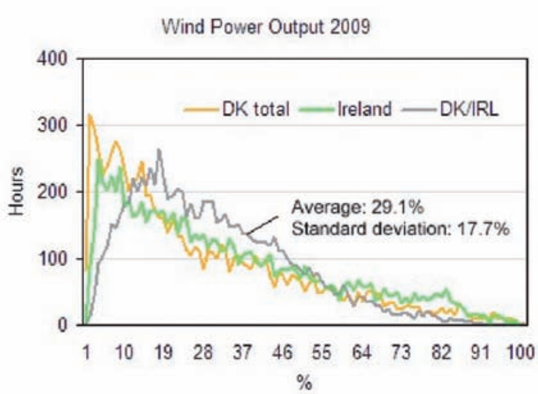


We find that while Denmark has an average of 26.6% and a standard deviation of 22.6%, Germany has an average of 21.2% and a standard deviation of 17%. Due to its larger area Germany has fewer hours with either very low or very high total output. By contrast, the wind intensity at Irish sites is greater than in Denmark and Germany, producing an average output of 31.6% and a standard deviation of 23.4%.



By producing average time series for Denmark and Germany, and for Denmark and Ireland we can quantify and compare the smoothing effects north-south and east-west:



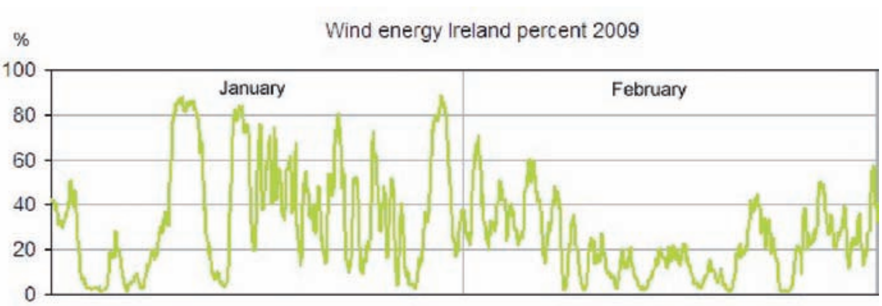


The left hand chart shows that only modest improvements can be obtained by combining Denmark and Germany. However, by combining Denmark and Ireland a different distribution function appears, and if we count the numbers of hours with output lower than 10% and higher than 60%, these limits being arbitrarily chosen, we can calculate the following:

Number of hours	Denmark	Germany	Ireland	DE/DK	DK/IRL
Output < 10%	2,447	2,392	1,733	1,999	1,019
Output > 60%	901	390	1,289	456	528

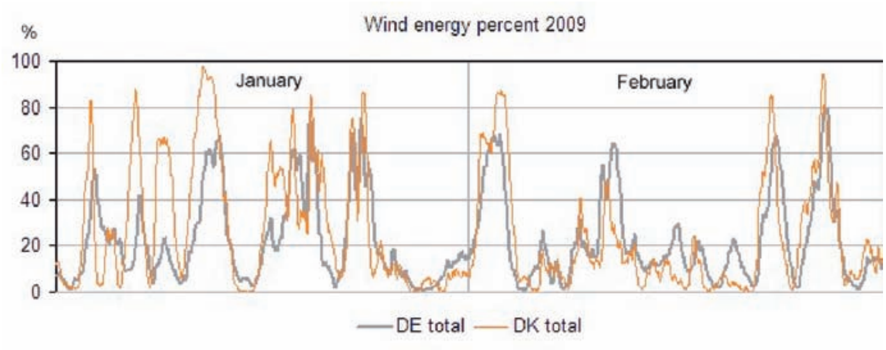
Evidently, combining Irish and Danish wind power reduces the number of hours of extreme output, but the operational significance of this effect can only be evaluated from the resulting time series power output.

The following chart shows the relative wind power output in Ireland in January and February 2009:

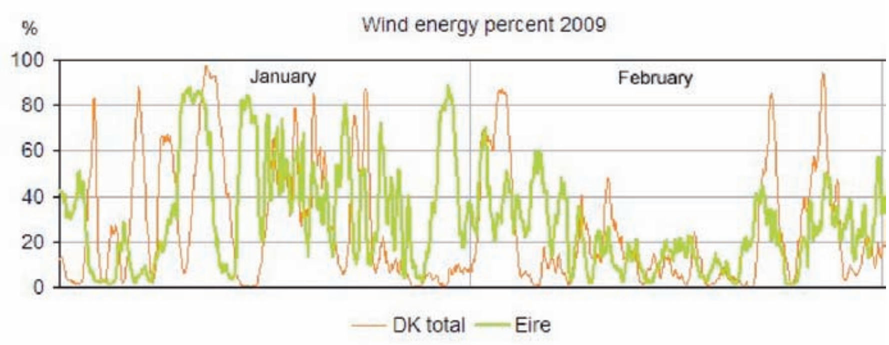


There appear to be some oscillations with higher frequency than are observed in Denmark and Germany, the reasons for which are unknown.

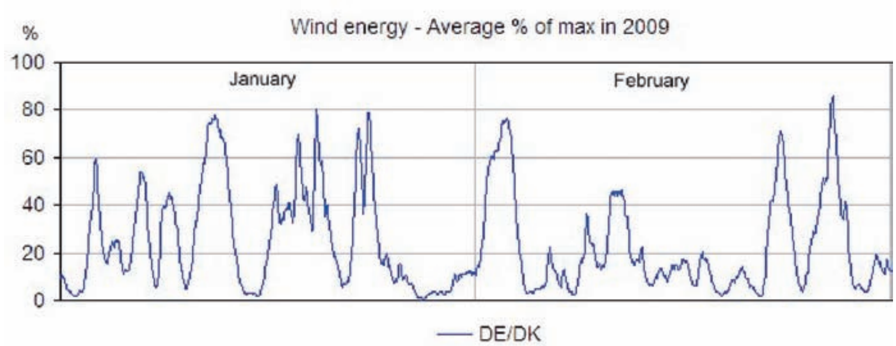
As previously noted, Danish and German wind shows a clear synchronism:



However, Denmark and Ireland differ to a greater degree, as can be seen in the following chart:

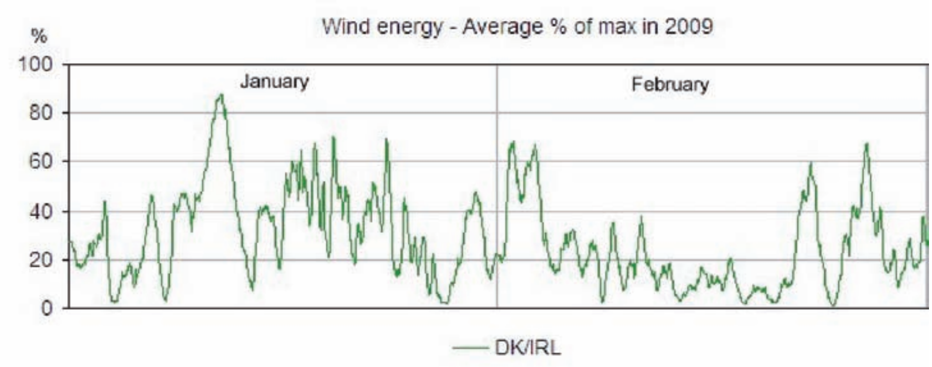


Combining the average time series allows visual inspection of the smoothing effect, the following chart showing the merged Danish and German data:



The chart clearly shows the volatile and random nature, even for the average wind power output for Germany and Denmark. The duration of typical wind power waves is between two and four days, and though the peaks are slightly lower than for each individual country, there are still periods with very low generation and several days with less than 20% energy output.

The combination of the Irish and Danish data yields similar results:



That is to say, though there is some degree of smoothing from an operational point of view there are still random and rapid variations of great magnitude, with sharp peaks and significant periods of low energy output. While the addition of UK data would probably eliminate the rate of some of the variations – which seem to be due to local Irish conditions – and the volatility might be further damped, it is clear that the global characteristics, the output peaks and periods of calm, would remain.

Conclusion

The combination of wind power in Denmark, Germany, and Ireland produces a statistical smoothing effect, with the most significant smoothing observed for the Danish-Irish combination. This is to be expected since typical weather fronts move from west to east, and there is a greater distance between the Danish and Irish wind fleets than between those of Denmark and Germany. However, the effect is not strong, and even assuming market interconnections which are perfect in a physical and regulatory sense there would still be extreme peaks and troughs in wind output for both the north-south and the east-west combination.

That is to say, while better market coupling across borders through stronger grids and interconnections can pave the way for a solution, current data suggests that such interconnection will not in itself be sufficient. However, the necessary supplementary technologies, including novel kinds of demand and demand management, do not yet exist, and there will be remarkable opportunities for investors willing to support the innovative engineering needed. An important, indeed a critical, step towards exploring and encouraging these innovations is convenient access to market data time series for additional European countries. This is particularly true for the almost islanded United Kingdom grid, which has one of the most ambitious wind power programs in Europe and thus needs these solutions more than almost any other state.

The European Wind Integration Study Final Report

After a 36-month working period European Wind Integration (EWIS) has published its report on integration of wind power in 2015. This study was supported by the EU and hosted by ENTSO-E (European Network of Transmission System Operators for Electricity). This work is comprehensive and ground-breaking. Several points should be highlighted:

- The study includes nearly 30 European countries.
- The *EWIS market model* calculates flows across borders for an entire year.
- The market model results were used for selection of points-in-time snapshots for closer analyses.
- The *EWIS network model* was used for the analysis of steady state power flow in the European grid for the selected snapshots.
- System security was evaluated by transient stability analyses.

Furthermore, different wind development scenarios for 2015 have been considered:

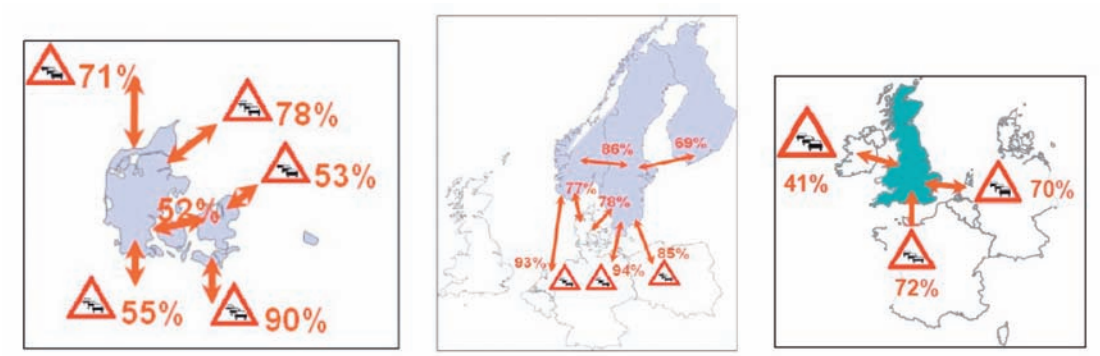
- *Reference:* Wind generation capacity across Europe at about 70 GW (2008 level)
- *Best estimate (BE):* About 140 GW across Europe
- *Optimistic wind (OW):* About 185 GW across Europe

Clearly, this is an extremely ambitious study.

Essential results

Congestion:

According to the market model simulations the interconnections will be congested for a considerable part of the year in 2015. The following excellent charts refer to best estimate wind and expected grid reinforcements:



For each interconnector the congestion is defined as the number of hours with congestion divided by the total number of hours.

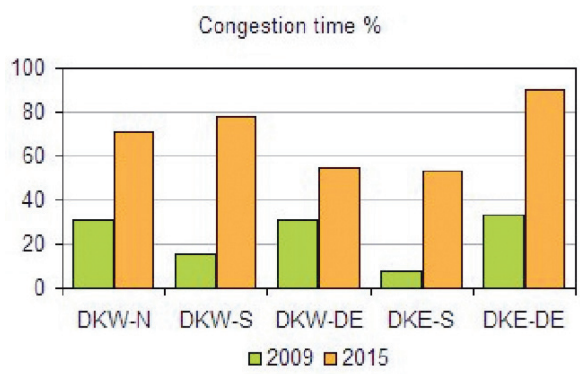
Observations from the period 2006 to 2009 have demonstrated that the available transfer capability of each interconnector is considerably below the nominal capacity due to outages of equipment and security restrictions. It is not clear to which degree these limitations have been considered in the EWIS study.

The simulated results can be compared with observations from 2009:

Hours	Export	Congest.	Import	Congest.	Total	% congest.	Simulated %
						2009	2015
DKW-N	2725	11	5989	2625	8760	30,1	71
DKW-S	5925	927	2604	214	8760	13,0	78
DKW-DE	5806	2351	2952	353	8760	30,9	55
DKE-S	3085	32	5674	673	8760	8,0	53
DKE-DE	3595	1067	4696	1391	8760	28,1	90

The results demonstrate that congestion time is expected to increase considerably within a few years.

The report does not discuss impact on market prices, but an increased price volatility will be a most likely consequence. It is a question if the market participants can be properly served in 2015.



Power flow:

Snapshots with low demand and high wind power output were selected for point in time analyses because they are particularly challenging. The results show lines with critical load and loop flows in the central parts of Europe.

There is a particular risk at the German-Polish border that flows could exceed security limits. Without appropriate technical measures the trading capacities must be substantially reduced.

System security:

The statements do not seem to be very clear, as can be seen in this quotation from the executive summary:

> To exploit improved dynamic line ratings, EWIS has found that improvements in stability performance may be required (for example by improving the speed of protection operation and by enhancing system voltage profiles). Even with such improvements stability may remain a limit to power transfer capability such that

it will need ongoing assessment, especially as power transfers are increased on existing lines.

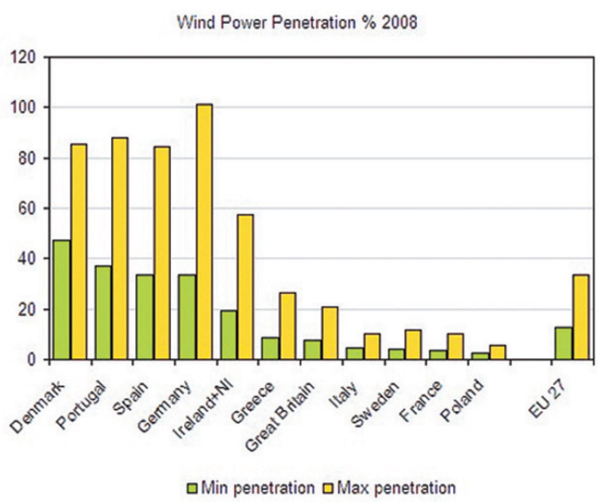
Voltage dip during a three phase short circuit in the German grid

The fault in the figure above is supposed to cause disconnection of 2,600 MW wind power. The fault will be very challenging to the west Danish power system and is therefore of particular interest to the present author.

The voltage at Dollern (a few kilometres to the west of Krümmel) is supposed to be 40% for 150ms. Obviously, the fault-ride-through capability of the fleet of wind power plants will be decisive to the stability of the entire system.

Missing quantification of wind energy penetration

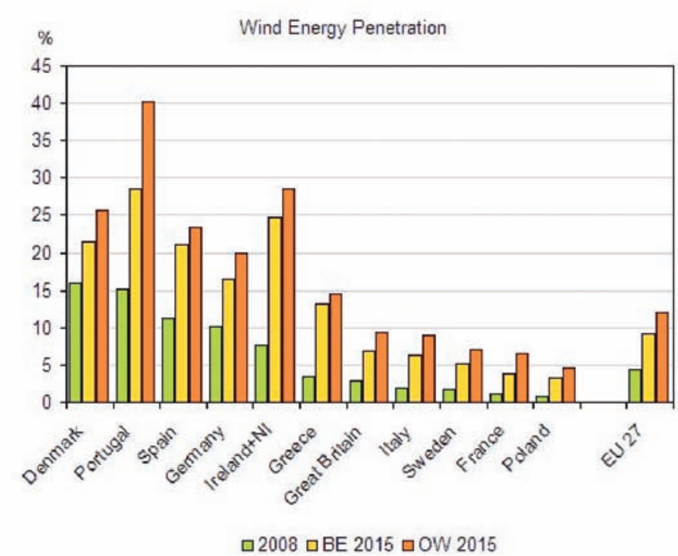
The EWIS report presents results of comprehensive calculations but, unfortunately, very little data has been published in the report.



The minimum and maximum wind power penetrations are presented as installed wind power capacity as percent of peak demand and minimum demand. The wind power penetration chart is based on data for selected countries from table 2.1 and fig. 2.1 in the EWIS-report.

The capacity penetrations give an important impression of the magnitude of the operational challenges caused by wind power. In Germany the installed wind power in 2008 exceeded the minimum load giving a maximum penetration at 101%.

However, *energy* penetration is also interesting, because it is an indicator of the environmental effect of the wind power expansion. Data from other sources than the EWIS-report was necessary in order to compile the next chart.



The wind energy estimates are based on a common capacity factor, 0.25, which is that observed in Denmark in 2009. Better estimates are desirable, but so far not available.

The energy penetration in 2015 will vary a lot between countries. For Europe as a whole the wind energy penetration in 2015 is estimated at 9% for best estimate wind and at 12% for the optimistic wind estimate, figures that indicate a modest ambition for the future European share of renewables.

This is useful information. EWIS has suggested grid reinforcements, improved system control and harmonized market arrangements in order to meet the challenges identified for 2015, and while these are important measures, they are not necessarily sufficient, and for further increased wind energy penetrations other measures entailing the direct participation of end-users of energy should be anticipated.

The German DENA study 2005

In order to pave the way for an ambitious wind power program the German government commissioned a comprehensive analysis of grid security and integration cost, the study being coordinated by DENA (Deutsche Energie Agentur). The targets were 12.5% wind energy penetration by 2010 and at least 20% penetration by 2020.

The study was published in February 2005, but without results for 2020. The summary in English remarks:

> During the preparation of the study it became clear that within the given framework conditions of the study it would only be possible to draft technical solutions for the integration of renewable energy sources into the existing power system

> up to a share of approx. 20% in electric power generation (5% offshore-wind, 7.5% onshore-wind, and 7.5% other renewable sources). A further major increase in geographically concentrated offshore wind farms in Northern Germany, as it is planned after 2015, would require a more extensive investigation to develop viable technical solutions.

Consequently analyses for 2020 were postponed to a later Part II of the study and only results of analyses up to 2015 were published. The wind energy penetration in 2015 was supposed to be 15%.

However, in the light of the plans for a joint European wind power integration study the DENA study Part II was abandoned and one of the German TSOs, Transpower, undertook the responsibility as coordinator of the EWIS study.

As the DENA study has already stressed, short circuits in Northern Germany might cause disconnection of 3,000 MW wind power in Germany and on top of that another 1,000 MW in Denmark. Such a case is of obvious relevance to Denmark, and deserves careful study.

A continuation of the EWIS study is urgently needed

In certain respects the EWIS work can be welcomed, since a study including all EU countries is a significant step forward, and the amount of data and calculations involved are clearly large. In other regards it is less satisfactory. For example, tables with essential basic data such as assumed electricity consumption per country and wind energy output per country are not provided here, and must be supplied in the next EWIS report to facilitate validation.

But most importantly, five years after the DENA study, results considering the situation beyond 2015 are still missing. Given the very ambitious targets for renewable energy currently entertained in EU policy, and in national policies, this failure of nerve of deeply regrettable, and there is an urgent need for a continuation of the EWIS study so that future problems can be anticipated and either avoided or remedial actions planned and executed.

REF
RENEWABLE ENERGY FOUNDATION

PAUL-FREDERIK BACH

The Variability of Wind Power

Collected Papers 2009–2010

With a preface by Michael Laughton

The Renewable Energy Foundation is a registered charity encouraging the development of renewable energy and energy conservation whilst emphasizing that such development must be governed by the fundamental principles of sustainability.

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