# Quantifying Exports and Minimising Curtailment: From 20% to 50% Wind Penetration in Denmark

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## Abstract

Denmark is frequently held up as a case study of a grid successfully integrating a wind penetration of 20%. Conversely, claims are made that Denmark exports “most” or “almost all” of the electricity generated by its wind turbines, although more specific claims refer to 57%, 1% or 0.1% of wind power being exported.

Analysing hourly power data from 2000-2010, hourly price data from 2006-2010, and minute-by-minute data from the last twelve months, this paper critiques the methods behind each of these claims, and compares them to known features of electricity markets. Although electrons do not carry labels of origin, and a method to assign exports to specific generation sources will carry some subjectivity, it is possible to put some meaningful limits on such claims about exports.

Based on that analysis, the paper then assesses the likely impact on exports of Denmark’s proposal to move to 50% wind penetration. Mixed-economy market structures and infrastructure options are set out that will enable such penetrations to be manageable, while minimising need for curtailment of wind production, and without increasing the likelihood of loss of load.

# Introduction

Denmark has become world-famous for achieving 20% of its electricity generation by wind, and for its ambition to proceed to 50% from wind by 2025. It has consequently become the subject of controversial interpretation between different sides in the energy debate, with attention focussing on the amount of wind energy that could be attributed to exports.

In 2009, the Houston & Washington DC-based Institute for Energy Research commissioned the Danish free-market think-tank CEPOS ("Center for Policy Studies") to produce a report on the Danish wind industry: Hugh Sharman and Henrik Meyer wrote that report (Sharman & Meyer, 2009), with analysis of Danish exports by Paul-Frederik Bach. Its argument about export built on an earlier paper by Hugh Sharman, which had claimed that Denmark had integrated wind by exporting most of the power it generated, based on correlations between wind power and exports (Sharman, 2005). The 2009 CEPOS report argued that the correlations between wind and exports show causality, and that a very high proportion of wind power is exported.

In response, members of the Coherent Energy and Environmental System Analysis (CEESA) Research Project, lead by Henrik Lund, published a detailed rebuttal (Lund et al., 2010). The CEESA report looked at some of the economics of the argument, including the merit order effect, and examined the economics of two points in 2008. It found that Danish exports of wind amounted to less than 1% of wind power generated, equivalently 0.2% of demand, and supported the claims that Denmark met around 19% of its demand from wind power.

Further exchanges between Paul-Frederik Bach (Bach, 2010) and CEESA (Lund, Hvelplund, Østergaard, Möller, & Mathiesen, 2010), with a contribution from Bertel Lohmann Andersen (Andersen, 2010), showed the changes in wind output at the hourly level are mirrored by changes in export in some months, but not in others. The relevance of these correlations to the question of causality remained a subject of dispute. Andersen dismisses the economic arguments based on the merit order effect as being "incomprehensible to the layman". However, in this paper I extend the economic approach, to explore causality and not just correlation.

The question of how much wind power Denmark currently exports, is significant because Denmark intends to increase its wind penetration from around 19% to 50%. If the penetration of 19% has been achieved by exporting a large proportion of its wind energy, then higher penetrations will require frequent curtailment of wind output, as the interconnectors reach their maximum export capacity, which will increase the average cost of wind power in the future. If current wind exports are low, then curtailment will not necessarily be a major issue for Denmark.

This paper reviews the export arguments within those reports, by adding analyses of variations in exports, generation and demand at the minute-by-minute level; it takes a detailed look at the impact of the merit order effect on exports, by comparing the effect of using three different algorithms; it looks at the market prices and energy moved, at the hourly scale, when Denmark is a net importer, and a net exporter, of electricity. It then reviews the consequences for the future.

## Claims

First, a quick look at some of the claims that have been made on this subject:

> "Almost all of Denmark's wind power is exported to its European neighbours"
> (MacKay, 2009)
>
> "Denmark is exporting most of its wildly fluctuating wind power to larger neighbours"
> (Sharman, 2005)

> “wind power has recently (2006) met as little as 5% of Denmark’s annual electricity consumption with an average over the last five years of 9.7%” (Sharman & Meyer, 2009)
>
> “Over the last eight years West Denmark has exported (couldn’t use), on average, 57% of the wind power it generated and East Denmark an average of 45%.” (Sharman & Meyer, 2009)

Can any of these claims be substantiated? This paper examines the evidence.

## Context

### *Policy*

The global oil crises of the 1970s made an interventionist approach to energy policy welcome in many countries, Denmark included (Lauersen, 2008). Denmark’s high energy taxes grew from energy-saving imperatives in the 1970, and were maintained even after the end of 1980s when O&G prices fell (Odgaard & Jørgensen, 2005). As a result, even though Denmark has median pre-tax domestic energy prices, and some of the lowest pre-tax industrial energy prices, in the EU, it has some of the most expensive post-tax domestic energy prices in the EU (Lund et al., 2010). Partly as a result of this, Danish energy consumption has been almost unchanged since 1980, a period in which the Danish economy has grown by 78% (Danish Energy Agency, 2010).

Denmark became self-sufficient in energy in 1997 (Odgaard & Jørgensen, 2005), largely thanks to its deposits of oil and natural gas. Continuation of its centralised energy strategy, coupled with active financial support for both public sector and private sector research and development, has accumulated economic benefits and ensure continuing public support for its mixed-market approach, standing it apart from the wave of deregulation that swept across much of the industrialised world’s energy industries.

The country had a brief flirtation with a market-centred approach in 2000-2004: a flirtation which brought about uncertainty in the investment environment, and consequently a significant slowing in the delivery of new clean power generation. After 2004, the political landscape shifted back, with the emphasis returning to one of a central strategy being developed by the government and the nationalised grid company, Energinet.dk; the market plays a tactical role. A cross-party concord in 2008 paved the way for a more certain investment environment for renewables, with the result that Danish wind expansion has now recommenced, with offshore wind farms being tendered on lowest-fixed-tariff basis, for the first 50,000 full-load hours (covering approximately the first 14 years of generation), working towards a target of 50% wind penetration by 2025.

### *Electricity generation in Denmark*

This paper works with the three generation categories used for statistical reporting by the Danish transmission system operator Energinet.dk: *Wind generation* covers onshore and offshore wind. *District* plant covers local power stations which supply combined heat and power [CHP]: heat to District Heating schemes, and power to the grid. These plants were, until recently, controlled locally rather than by central dispatch. *Central* plant is controlled by central dispatch; some central power is generated as CHP, some in condensing mode. In 2000, 52% of electricity came from CHP, split evenly between district and central plant (Odgaard & Jørgensen, 2005).

Denmark has two separate grids: Western Denmark and Eastern Denmark.

Eastern Denmark is synchronised to Sweden, with 1900 MW of AC connectors. It also has a 600MW DC connector to Germany.

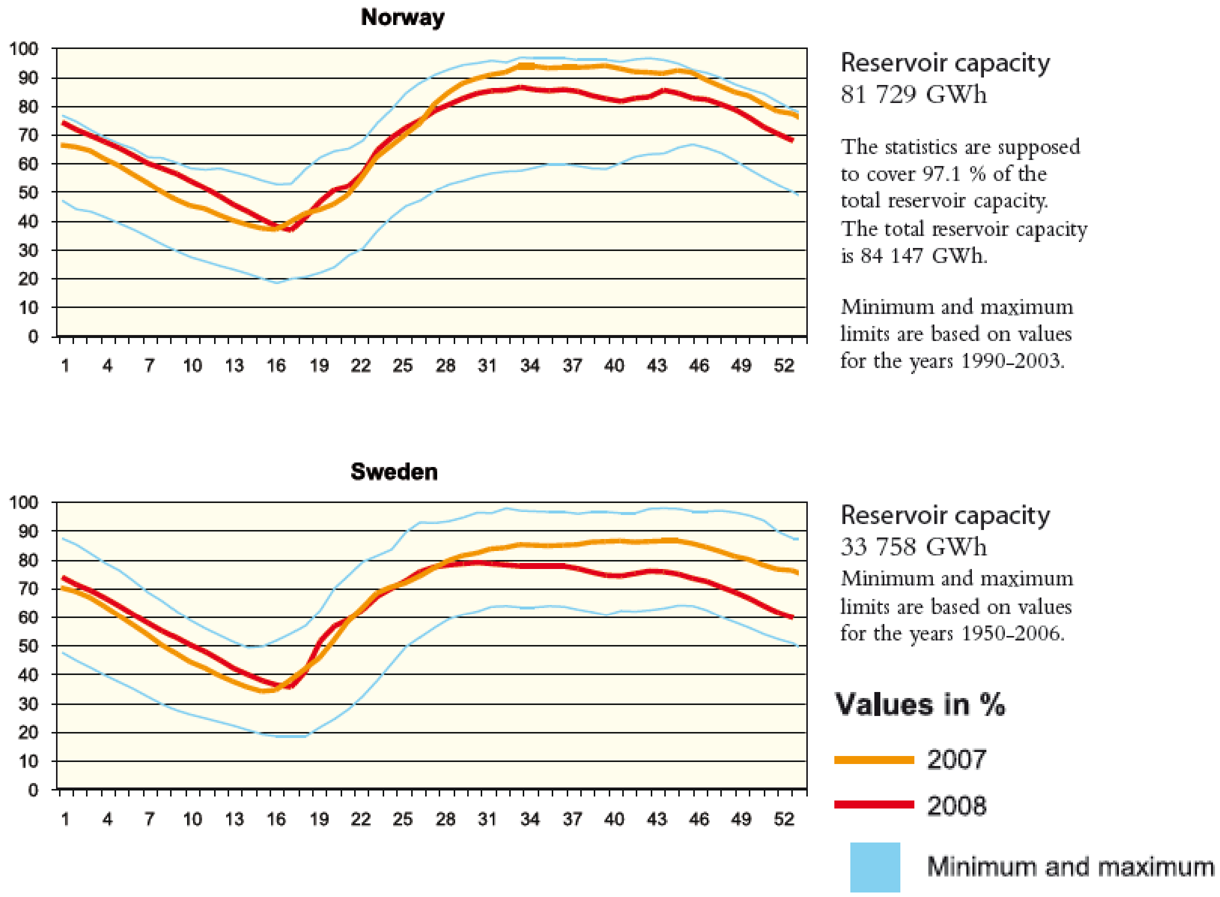
Western Denmark is synchronised to Germany and the continental grid (formerly UCTE) via AC connectors that can export at 1500MW and import at 950MW. It also has 740MW of DC connectors to Sweden, and 1040MW of DC connectors to Norway.

The first interconnector between West and East Denmark, a 600MW DC link, was commissioned in July 2010.

## Denmark's trading partners for electricity

Norway and Sweden have *seasonal* storage hydro. These run on an annual cycle, with the reservoir varying between 60-100% capacity in weeks 31-43, dropping to its minimum around week 16, at 20-50%. Hydro generation forms 98% of all Norwegian power, and 47% of Swedish power (Nordel, 2008).

Figure 1 Annual patterns of reservoir levels for storage hydro in Norway and Sweden (Nordel, 2008)




Together with 5,530 GWh of storage in Finland, the collective storage is an immense 121 TWh. The average electricity demand across Denmark, Norway, Sweden and Finland is collectively 47GW, peaking at 61GW (Nordel, 2008) (these figures are broadly comparable to average and peak demands in Britain). The energy stored in Scandinavia's hydro represents 2568 hours, i.e. 107 days, of average consumption.

Denmark is also the transmission corridor from Germany to Norway and Sweden, each of which has much larger demand than Denmark; consequently, Denmark's interconnectors, although small relative to German, Norwegian and Swedish demand, are large relative to Danish demand. International exchange of electricity with its connected neighbours represents a significant role for Danish transmission infrastructure. Exports to, and imports from, each of these countries, are shown below, together with wind generation and other (district and central thermal plant) Danish generation.

Figure 2 Danish generation, and exports to and imports from its neighbours

| TWh | Denmark | | Norway | | Sweden | | Germany | |
|---|---|---|---|---|---|---|---|---|
| | wind | other | export | import | export | import | export | import |
| 2006 | 6.1 | 36.8 | 2.3 | 1.1 | 5.5 | 1.6 | 5.8 | 3.9 |
| 2007 | 7.2 | 29.9 | 1.2 | 4.0 | 2.4 | 4.9 | 7.8 | 1.4 |
| 2008 | 7.0 | 27.7 | 0.4 | 4.8 | 1.8 | 6.6 | 9.1 | 1.3 |
| 2009 | 6.7 | 27.6 | 1.4 | 3.8 | 3.1 | 3.7 | 6.2 | 3.5 |
| 2010* | 4.3 | 17.9 | 2.8 | 0.8 | 2.7 | 2.4 | 1.7 | 4.1 |
| all | 31.2 | 139.9 | 8.1 | 14.6 | 15.4 | 19.3 | 30.6 | 14.2 |

*to 20 August 2010

### *CHP and Heating*

As a result of three decades of mixed-market planning and national legislation, District Heating [DH] is supplied to 61% of homes (Danish Energy Agency, 2010), and 80% of the heat is generated by CHP.

Annual space and water heating demand is 220 PJ (Odgaard & Jørgensen, 2005), equivalent to a mean thermal power of 61 TWh per year or 7.0 GW.

The law on heat supply determines that heat can only be charged at gross cost – i.e. not for profit. Compulsory connection to DH where available (or where zoned for) became law in 1982. The ban on installing electric heat in new build was implemented in 1988, and extended, in 1994, to a ban on replacing water-based central heating with electric heaters in existing buildings (Odgaard & Jørgensen, 2005).

The Energy Agreement of 13 March 1990 made compulsory the conversion of DH plants to CHP, with conversions happening between 1990 and 1998. After conversion, running as cogeneration was compulsory. By 2002, this meant electricity production was being sold at a loss to neighbouring countries; so as of 1 July 2003, CHP were exempted from the cogeneration obligation: so that electricity would be generated when the price is favourable, and heat when there is demand. Until end of 2004, district plant has been on a fixed-tariff regime for electricity (three-tier fixed price determined by time-of-day). From 1 Jan 2005, generation pricing on plants over 5MW has been at market rate, incentivising them to become responsive to market conditions.

This change in regime is significant, for the question at hand: after 2004, district plant becomes more responsive to market conditions; therefore, from 2005 onwards, its production has been able to respond to changes in prices in the international market.

## Merit order

As an underlying economic principle, generation sources with the lowest marginal cost (in this case, wind), come top of the merit order, with the most expensive coming last. If the explicit costs do not include pollution prices, then one might nominally internalise the externalities such as greenhouse-gas emissions and other pollutants, in which case this would reinforce wind's position at the top of the merit order

(Sharman and Meyer 2009) briefly describe in a footnote the method that Hugh Sharman & Paul-Frederik Bach used to calculate their figures:

> "an algorithm that quantifies and records the wind energy export as the smaller value of generated wind energy and net export for each hour."

That algorithm embeds the assumption that wind must come at the bottom of the merit order, and that the assumed component of exports that comes from wind is always maximised. This paper examines the effect of that assumption, and compares it to its alternatives.

The merit order is used by the CEESA paper (Lund et al., 2010) in its calculation of wind exports.

## *Summary of CEESA export calculations*

> "The large power units currently in the energy system cannot go below a certain technical minimum. In 2008, there were hours during which the large units in western Denmark were operated at only 415 MW and in eastern Denmark only 181 MW. Consequently, it could be argued that the system *technically* can be operated with such minimum production, and that everything above this is due to economic and market based optimisation." (Lund et al., 2010)

However, taking data for 2000-2010, it is clear that these figures are over-estimates, with each area of Denmark having hours when the large units operated well below these levels.

> "The grid requires a certain minimum ratio between power production on large central plants and wind power in order to remain stable. In 2008, hours can be found during which the grids were operated, for the western and eastern Denmark respectively, with a wind power of 3.53 and 3.03 times the production on the large power units. Consequently, it can be argued that the system can operate with such minimum shares of production on the large units, meaning that they can reduce production to this level without compromising the system stability."

Similarly, with the 2000-2010 data, there are occasions where the ratio of wind power to large power units exceeds these factors.

Consequently, the CEESA algorithm is conservative, relative to the same algorithm calibrated against longer time series.

> "By using the above principles, one can identify hours during which the wind power plus a production on large units of a minimum of 415 MW and a minimum of 1/3.53 of the wind power exceed the demand. Such excess production can then be defined as wind power being exported while the rest is export due to the decision to increase production on the power plants for financial reasons …By using such principles, the wind power export in 2008 was 61 GWh equal to less than 1 percent of the wind power production (or less than 0.2 percent of the demand)."

This method thus over-estimates demand, because the "minimum output" figures used for thermal plant, and minimum ratio for wind:thermal plant, are both too conservative. However, as the CEESA estimate gives an estimate of the exported wind power at less than 1% of wind power production, or 0.2% of total demand, further refinement cannot make a significant difference to the results.

## *Merit order methods*

The CEESA paper (Lund et al., 2010) broadly takes wind at the top of the merit order, although some thermal plant is allocated as "must run", coming above wind in the merit order. The CEPOS paper (Sharman & Meyer, 2009) takes wind at the bottom of the merit order. This paper takes three algorithms, and compares their estimates of wind outputs:

**A.** Wind at the bottom of the merit order: take the lesser of wind produced, and net exports. That is to say that all export by default is assumed to be wind power; export, when present, is by default wind power. This is the algorithm used by Paul-Frederik Bach and Hugh Sharman in the CEPOS paper (Sharman & Meyer, 2009).

**B.** Wind below district plant in the merit order, but above central plant. Take wind produced, plus electricity generated by district plants, minus consumption. The export figure is set with a lower bound of zero (wind exports cannot be negative), and an upper bound of total wind produced, so if district-generated electricity were to exceed consumption, then all wind generation would be classified as exports. This is a more conservative version of the algorithm used by CEESA in (Lund et al., 2010).

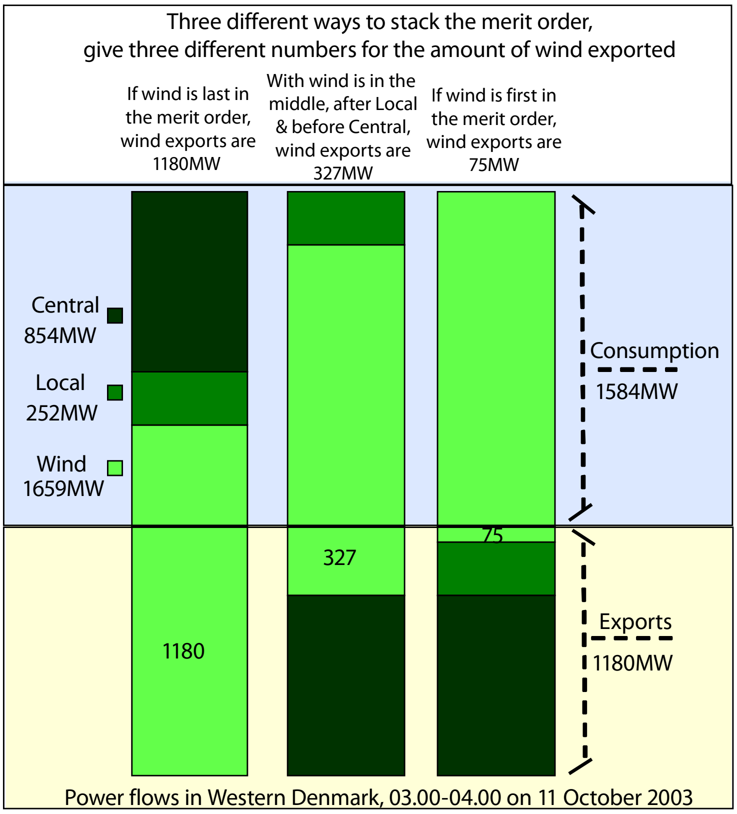
**C.** Wind at the top of the merit order. If wind production is less than gross consumption within a particular hour, wind exports are zero; otherwise, wind exports are wind generation minus gross consumption.

In any given hour, the estimate of wind exports will be highest by method A (which assumes that all exported power is wind, by default), and lowest by method C (which assumes that all exported power is thermal plant, by default).

## Example calculations

To illustrate these three methods, a sample hour, 03.00-04.00 on 11 October 2003, is taken; this was selected purely because it shows how significant the differences in a single calculation *can* be, rather than being representative of most hours, (which it is not).

Figure 3 Three different algorithms compared for a single hour's output




Local consumption was 1584 MW, exports were 1180 MW, meaning that 2764 MW is drawn from the Danish grid in total; 1659 MW of this came from wind, 252 MW from district plant, and 854 MW from Central plant (with 1MW rounding error).

Using algorithm A, 1180 MW of wind power is exported: by taking wind last in the merit order, then the 252 MW of district CHP plus 854 MW from central plant is assigned to consumption, leaving a remainder of 478 MW of consumption to be met by wind: the remaining 1180 MW of wind power is assigned as export.

With algorithm B, 327 MW of wind power is exported: taking district plant first, then wind, then central plant, the 252 MW of district CHP and 1332 MW of wind are allocated against Danish consumption, leaving the remaining 327 MW of wind and all of the 854 MW of Central plant allocated to exports.

With algorithm C, 75 MW of wind is exported: putting wind at the top of the merit order, then demand is met solely by 1584MW of wind generation. 75 MW of wind, together with all 252 MW of district CHP and 854 MW of Central plant are assigned to export.

## *Conclusion of Analyses*

Here, three different methods for calculating the proportion are set out, and the validity of each is discussed.

Figure 4 Proportion of Danish demand met by wind: and proportion of wind energy exported: results of three algorithms compared

**All Denmark**

| | % of Danish consumption met by wind | | | | % of wind energy exported | | |
|---|---|---|---|---|---|---|---|
| | | C | B | A | C | B | A |
| | % of elec from wind, raw | Wind at top of merit order | District at top, wind 2nd, in merit order | Wind at bottom of merit order | Wind at top of merit order | District at top, wind 2nd, in merit order | Wind at bottom of merit order |
| **2000** | 12.2% | 12.2% | 12.2% | 7.2% | 0.0% | 0.2% | 41% |
| **2001** | 12.3% | 12.3% | 12.2% | 5.7% | 0.0% | 0.8% | 53% |
| **2002** | 14.0% | 14.0% | 13.8% | 5.3% | 0.0% | 1.5% | 62% |
| **2003** | 16.0% | 16.0% | 15.6% | 2.9% | 0.1% | 2.5% | 82% |
| **2004** | 18.8% | 18.7% | 18.4% | 8.3% | 0.0% | 1.7% | 56% |
| **2005** | 18.7% | 18.6% | 18.3% | 12.3% | 0.1% | 1.9% | 34% |
| **2006** | 17.0% | 17.0% | 16.9% | 4.7% | 0.1% | 0.6% | 72% |
| **2007** | 19.9% | 19.8% | 19.7% | 10.9% | 0.1% | 0.8% | 45% |
| **2008** | 19.3% | 19.3% | 19.2% | 12.2% | 0.1% | 0.9% | 37% |
| **2009** | 19.4% | 19.4% | 19.3% | 11.5% | 0.1% | 0.6% | 41% |
| **2010*** | 19.2% | 19.2% | 19.1% | 12.6% | 0.0% | 0.6% | 34% |

* to 20 August 2010

Detailed results for Western and Eastern Denmark are presented in the appendix.

Algorithm C, taking a merit order with wind at the top, inevitably gives the highest proportion of wind contributing to demand, with 0.0-0.1% of wind being exported, and wind meeting 17-20% of demand in recent years. This algorithm most closely represents the market conditions operating from 2005 onwards.

Algorithm B, which takes district plant to be "must run" plant, that operates regardless of the economics of doing so, matches the regulatory environment that these plants operated in, prior to

2005. From 2005 onwards, these plants were paid on a market tariff rather than a three-stage fixed tariff, and so became responsive to market conditions. Algorithm B is therefore a reasonable estimate of wind exports for the period 2000-2004.

Algorithm A, as used in (Sharman & Meyer, 2009), which puts wind bottom of the merit order behind all thermal plants, assumes that central plants are never switched on to make from export. No evidence was found to support this algorithm, which contradicts what is known about the price of wind as a fuel, relative to coal and biomass.

No valid algorithm can produce the "high export" figure, and that valid methods suggest that the proportion of wind that is exported of the order of 0.1-2.5%, depending on the individual year, with an average of 0.1-1.2% for the decade 2000-2009.

## Correlations, balancing and causality

Sharman writes of the correlation between the shape of exports over time, and the shape of wind generation (Sharman, 2005) (Sharman & Meyer, 2009). The correlation exists, and here I present a brief quantitative analysis, together with a description of underlying causality.

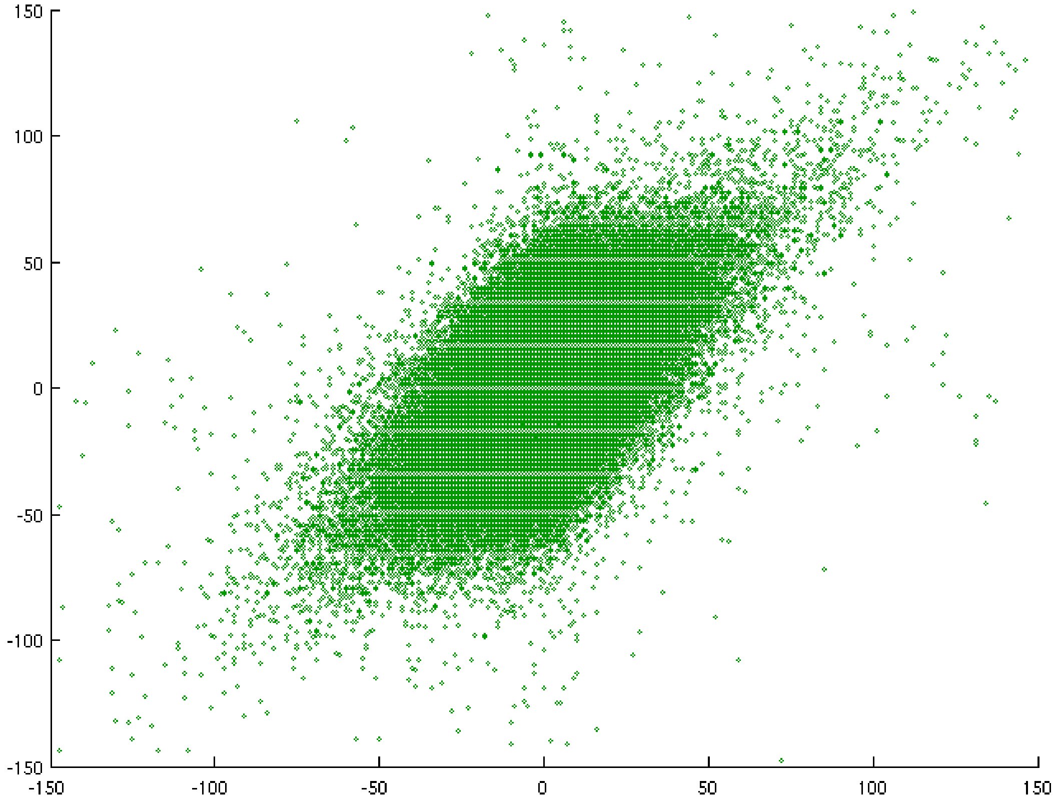
### Minute by minute balancing

I analysed the minute-by-minute *values* for generation, demand and net export, and the minute-on-minute *changes* in generation, demand and net export, for the period September 2009 to August 2010.

Both wind generation and central plant generation correlate with exports, each with a correlation of 0.60 – that is to say, when exports are high, then both wind and central plant generation tend to be high. (Lund et al., 2010) also reported that both wind and central plant correlate with exports to a similar extent as each other, and notes that correlation does not imply causality.

*Changes* in wind generation, at the level of minute-to-minute *variations*, correlate well with variations in net exports.

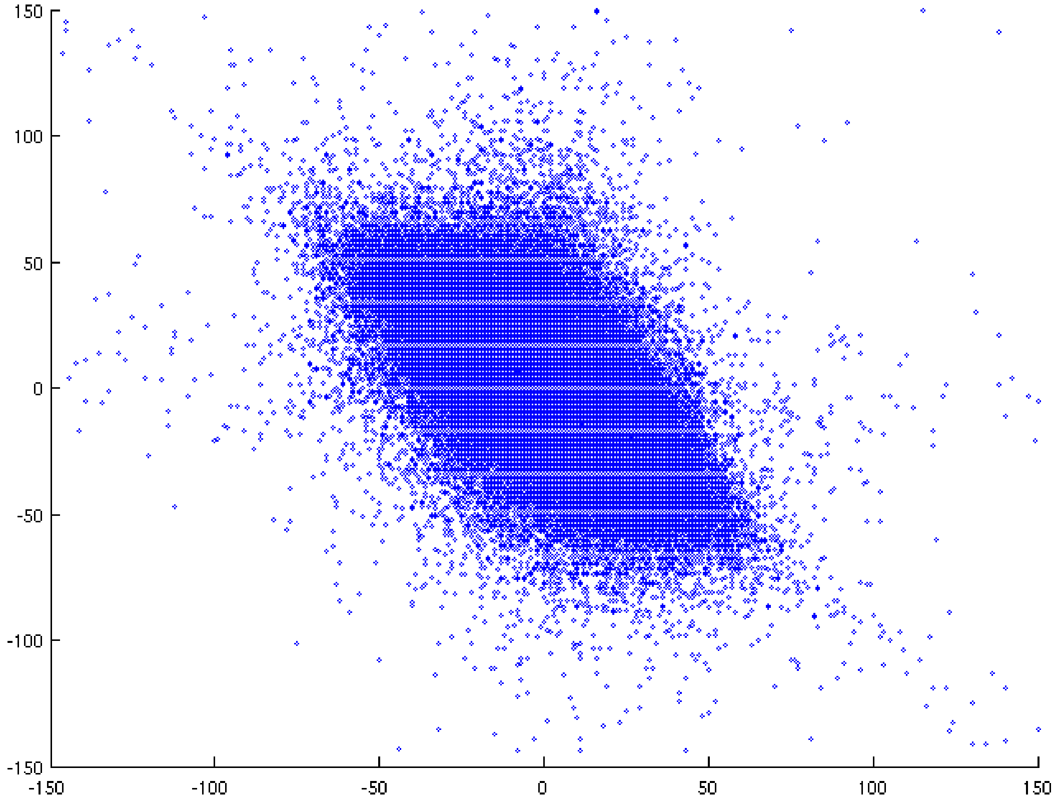
Figure 5 plot of minute-on-minute *changes* in wind output (x-axis) against *changes* in net exports (y-axis), Sep 2009-Aug 2010




In those periods when wind generation increases, minute-on-minute, then the amount of net exported power increases. (correlation=0.69, p<0.01)

Minute-on-minute variations in demand are also reflected in minute-on-minute variations in net exports: as demand increases from one minute to the next, exports decrease. (correlation=-0.47, p<0.01)

Figure 6 plot of minute-on-minute *changes* in demand (x-axis) against *changes* in net exports (y-axis), Sep 2009-Aug 2010




So there is some correlation in variation at the minute-by-minute level. In the case of exports and demand, causality is clear: the grid must balance at each second, which means that supply must meet demand; any difference between Danish generation and Danish consumption must be balanced exactly by imports and exports.

Denmark is using its high-capacity interconnectors to smooth variations in wind generation, and variations in demand.

So, Denmark exports a large proportion of the *variations* in its wind power, and the variations in its demand: it could balance it with responsive demand, or by varying thermal central plant output. However, historically, the lowest-cost way to smooth those variations has been to export them to Norway and Sweden, where large-capacity fast-responding storage hydro plant can easily absorb these variations.

> “Hydropower output can be adjusted very rapidly as the highly variable wind power flows through the interconnectors.” (Sharman 2005)

This, however, is a different argument to the one that claims that Denmark exports its wind power: variations in power are not the same as power itself.

## Exporting wind variations: a synthetic case study

Are these correlations of minute-on-minute changes, relevant to the discussion of size of exports?

Take, as a small excursion from the discussion of observed data, a synthetic situation where supply is just sufficient to meet demands, and with spare export capacity on the interconnectors. If, at that time, prices in neighbouring countries are higher than the marginal cost of running plant in Denmark, then it is profitable for that Danish plant to operate, even though it is not needed to meet Danish demand. The shape of exports won't change, but the whole graph will move up, and exports increase.

To take some fictitious numbers to illustrate this point: assuming a two-country system, Denmark and Norway, with the former having a constant demand of 2,500 MW, and the latter having a constant demand of 10,000 MW. If Denmark only has wind generation, then it must balance its grid by importing or exporting the difference between demand and wind to Norway. For Norway to balance its section of the grid, its hydro must vary to complement variations in Danish wind. Hence, Denmark exports its wind variations, even when it is only importing power, and not exporting it.

Figure 7 Synthetic numbers illustrating export of Danish variations, even when no power is exported

| | | | | |
|---|---|---|---|---|
| Danish demand | 2500 | 2500 | 2500 | 2500 |
| Wind | 1500 | 1000 | 1800 | 2400 |
| Danish exports<br>Norwegian imports | -1000 | -1500 | -700 | -100 |
| Norwegian demand | 10000 | 10000 | 10000 | 10000 |
| Norwegian hydro | 11000 | 11500 | 10700 | 10100 |

Throughout this time period, Danish imports are positive: that is to say, no power is exported *to* Norway; power is only imported *from* it. However, something *is* exported to Norway: with a constant Norwegian demand, the output from Norwegian hydro would also be constant; but adding in the varying additional output needed to meet exports to Denmark, the variations in its hydro output must complement the variations in Denmark's wind generation. Hence, the export of variations is entirely distinct from the export of power: variations in power are exported, whether power itself is imported or exported.

We can extend this synthetic case study with the introduction of thermal power into our synthetic Denmark. If the price on international markets is low, as they would be if Norway has had a particularly rainy year, and its reservoirs are high, then there is no financial incentive for Danish plants to generate lots of electricity. However, if prices on the Norwegian part of the grid are high, then Danish thermal plant can earn a profit by operating beyond what Danish demand requires. The figures from the example above are repeated below, together with a constant output of 1,500 MW from Danish thermal plant.

Figure 8 Synthetic numbers illustrating export of Danish variations when power is exported

| | | | | |
|---|---|---|---|---|
| Danish demand | 2500 | 2500 | 2500 | 2500 |
| Wind | 1500 | 1000 | 1800 | 2400 |
| thermal plant | 1500 | 1500 | 1500 | 1500 |
| Danish exports<br>Norwegian imports | 500 | 0 | 800 | 1400 |
| Norwegian demand | 10000 | 10000 | 10000 | 10000 |
| Hydro | 9500 | 10000 | 9200 | 8600 |

Notably, the variations from wind are still exported, as they were previously. But now, Denmark also exports power to Norway, where it meets Norwegian demand; Norwegian hydro, as a result, can operate at lower power levels, though its variations still reflect variations in Danish wind generation. The correlation between Danish wind generation, and Danish exports, is identical in each case: variations in export (or, in the first case negative exports, i.e. imports), are closely correlated to variations in wind generation, and this applies as much to the first case as the second.

So, even in a synthetic case where all variables can be controlled, and Danish thermal plant is running, deterministically, with the explicit purpose of supplying external demand, variations in Danish exports still correlate perfectly to variations in Danish wind generation. Hence, correlations in variation provide no information as to the source of energy that is being exported.

## *The dry years: 2003 and 2006*

Moving from synthetic data, back to real data, 2003 and 2006 are cited by Sharman in the CEPOS report as being years of exceptionally high exports of wind energy from Denmark. Reservoir levels in Norway and Sweden were low, resulting in high prices there. Both countries required imported power.

> "2003 (especially) and 2006 were dry years. In both years, Norway and Sweden were not as self-sufficient as normal and were forced to import quite large amounts of thermal power from Denmark and Finland. During 2003, thermal generation in West Denmark exceeded Danish demand while 5 TWh, a quarter of West Denmark's normal consumption, was exported northwards." (Sharman & Meyer, 2009)

In 2003, West Denmark wind production was 4.36TWh out of total production 27TWh, and demand was 20TWh (Sharman, 2005).

Denmark was well-placed to meet this demand from its Northern neighbours, with its high-efficiency central plants:

> "Fifteen of these [central plants] are … among the world's most thermodynamically efficient steam turbine power stations" (Sharman & Meyer, 2009)

and its high combined-efficiency CHP plants:

> "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." (Bach, 2010)

This would seem to establish the cause-and-effect behind high Danish exports of thermally generated power in those years. And yet Sharman, using Bach's export algorithm, comes to a very different conclusion:

> "It is a notable finding of this study that wind power exports during the dry years of 2003 and 2006 were very high being 72% and 84% from East and West Denmark respectively during 2003 and 77% and 71% respectively from East and West Denmark during 2006." (Sharman & Meyer, 2009)

Figure 9 : total generation, net and gross exports, and exports by generation source

| West | | | | | | A Wind at top of merit order | | B District at top, wind 2nd, in merit order | | C Wind at bottom of merit order | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | local demand | Thermal | Wind | exports netted yearly | exports netted hourly | Thermal exports | wind exports | Thermal exports | wind exports | Thermal exports | wind exports |
| **2003** | 2,357 | 2,581 | 498 | 722 | 730 | 729 | 0.4 | 714 | 16.1 | 310 | 419 |
| **2006** | 2,443 | 2,430 | 527 | 514 | 545 | 544 | 0.4 | 541 | 3.9 | 173 | 372 |
| **East** | | | | | | | | | | | |
| **2003** | 1,618 | 1,735 | 137 | 254 | 314 | 314 | 0 | 314 | 0 | 215 | 99 |
| **2006** | 1,664 | 1,772 | 170 | 278 | 319 | 319 | 0 | 319 | 0 | 188 | 131 |

(An expanded version of the above table, with figures for all years 2000-2010, is given in the appendix)

In each of the dry years, thermal plant runs extremely high. Even assuming that district plant works on a "must run basis", ahead of wind (merit order algorithm B), gives very low estimates for wind export: in other words, it is the large central plants that are running very high in the dry years, to meet Norwegian and Swedish demand. Only by assuming that those central plants come above wind in the merit order is it possible to assign high export values to wind in these years. Such an assumption contradicts what is known about the economics of generation in those years.

## *Relative Prices of Imports and exports*

To examine the empirical evidence for the hypothesis that during the periods when Denmark is a net exporter of energy, prices are sufficiently high for thermal plant to make a profit by running at higher levels than required by Danish demand, the detailed hourly Energinet.dk market data, which is available for the period 2006 to present, was divided into two groups.

1. Hours when Denmark was a net exporter of electricity; from this group, the volume-weighted average prices of *exports* to each country were calculated, using the Elspot market price.
2. Hours when Denmark was a net importer; similarly, from this group, the volume-weighted average prices of *imports* from each country were calculated, again using the Elspot market price.

There are two further groups of imports and exports that are excluded from these calculations: the imports into Denmark in those hours when Denmark is a net exporter; and the exports from Denmark in those hours when it is a net importer, are both excluded.

The trade volumes, and volume-weighted average prices, for each of the three countries that Denmark trades electricity with, are shown below, for each of those two groups. In most cases, Denmark was exporting power at a higher price than importing it. The two exceptions are highlighted in the table: Norway in 2006, and Sweden in 2008.

Figure 10 Volume-weighted average prices, and trade volumes, from Denmark to its neighbours

| Danish electricity trade | Norway | | | | Sweden | | | | Germany | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | export | | import | | export | | import | | export | | import | |
| | TWh | € | € | TWh | TWh | € | € | TWh | TWh | € | € | TWh |
| 2006 | 2.1 | 48.7 | 49.2 | 0.2 | 5.0 | 49.3 | 47.6 | 0.4 | 5.1 | 70.2 | 36.1 | 0.7 |
| 2007 | 1.1 | 31.6 | 16.7 | 2.9 | 1.9 | 33.1 | 26.1 | 3.8 | 3.6 | 56.5 | 18.4 | 0.5 |
| 2008 | 0.4 | 42.7 | 40.0 | 3.1 | 1.1 | 46.1 | 52.0 | 5.1 | 4.3 | 77.0 | 39.9 | 0.7 |
| 2009 | 1.0 | 34.2 | 32.5 | 2.4 | 1.6 | 38.9 | 36.0 | 2.2 | 3.5 | 51.2 | 23.2 | 1.8 |
| 2010* | 1.9 | 51.4 | 49.9 | 0.7 | 2.4 | 71.5 | 44.4 | 2.0 | 0.5 | 51.9 | 35.0 | 1.6 |
| all | 6.5 | 44.1 | 31.9 | 9.3 | 12.0 | 49.4 | 40.8 | 13.5 | 17.0 | 64.6 | 30.3 | 5.2 |

*to 20 August 2010

As discussed earlier, 2006 was a very dry year for Scandinavia, resulting in very high exports to Norway (2.1 TWh) and Sweden (5.0 TWh). Prices in those markets were exceptionally high because of the shortage of stored energy in their seasonal hydro, which meant that the high volumes of exports to them were very profitable, averaging €48.7/MWh to Norway, and €49.3/MWh to Sweden. This bears out the merit-order explanation that Danish thermal plants were running unusually high in 2006 because of the significant import demand from Norway and Sweden.

Consequently, given the high prices and local generation shortages in Norway, Danish imports from there were very low, and relatively expensive: in those hours when Denmark was a net importer, it imported a total of 0.2 TWh from Norway at €49.2/MWh.

In 2008, exceptionally high prices in Germany meant that Danish thermal plant could make good profit by exporting there; there were atypically low exports to Sweden, where prices were much lower.

All of these figures support the hypothesis that Danish thermal plant was running surplus to Danish demand because it could make money from exports.

## The Future

So, what does this all mean for the future, as Denmark looks to integrate 50% wind generation into the grid by 2025?

As the preceding analysis shows, the claims that Denmark currently exports a large proportion of its wind power do not bear scrutiny: the only way to make such a calculation is to put aside all economic reality and to assume that wind has the highest short-run marginal cost, (i.e. is a more expensive "fuel" than coal or biomass) on the grid.

Therefore, the issue of exported energy is not a barrier to further wind integration.

Denmark has to date, as we saw above, used its interconnectors to smooth variations in demand, as well as variations in wind generation. As wind penetration increases, it will be necessary to broaden the balancing mechanisms deployed at the level of seconds to minutes, to smooth the greater variations in wind that might be expected.

As the Ecogrid study (Trong et al., 2009) notes, when examining scenarios for 50% wind power in 2025:

> "The experts' general conclusion is that penetration of 50 % wind energy in Denmark is possible, but will require profound changes in the power system architecture … All four scenarios described in WP 3 show that it is unlikely that Denmark can rely on international markets to provide operating reserves and sufficient balancing capacity to the same extent as today in a power system with 50 % wind power

These changes to the power system architecture will require top-down leadership and strategy development. The traditional Danish mixed-market model, of a state-owned transmission company that coordinates the commissioning of new infrastructure on a least-cost basis, and develops long-term strategy in liaison with central government, has already delivered one such transformation already, moving Denmark's grid from being dominated by oil-fired central plant to widely distributed CHP plant and wind power. The next step is to integrate all the distributed players in the market, on both the supply and demand side, to meet future balancing needs.

One such source of balancing is the country's extensive heat storage capacity in the Danish district heating systems:

> "As a rough estimate between 20 and 30 GWh energy can be stored as useful heat." (Trong et al., 2009)

30 GWh of heat storage, in a grid with up to 5 GW of wind capacity installed, will provide a valuable sink for peaks of wind energy generation, allowing the entire country's wind farms to run for many hours meeting both electricity demand and filling district heating storage, thus minimising curtailment.

## Demand-side response

To date, little balancing has been done on the demand-side: as we saw in the analysis of minute-by-minute flows, international trade is used to smooth variations in demand as well as variations in wind generation. The traditional wisdom is that electricity demand is price-inelastic in the short term, hindering the demand-side from providing balancing services.

But is electricity demand price-inelastic in the short term?

There are two groups of customers:

1) There are industrial customers with large individual blocks of demand. Because a few of these can make up a large chunk of demand, the transactional costs on negotiating interruptibility with them are low, relative to the potential gains. So, they get interruptible contracts. The problem is that these are industrial users with very inelastic demand for energy; high fixed costs means that their marginal cost of downward regulation is very high.
2) There are many customers each with very low individual demand. The transactional cost of contracting them for regulation has been very high. However, a lot of their energy demand is not time-sensitive (refrigeration, heating, laundry, dishwashers), so spot elasticities can be much higher. And accumulated together, they do have high demand.

So, demand is not elastic – this has been an artifice of the market, and of high transactional costs for balancing services with a high number of small consumers.

Demand-side response increases responsiveness in the market, and wireless communications, mobile phone data networks and low-cost switching makes this viable, by reducing those transactional costs.

To manage the greater demands on balancing, the Ecogrid project recommends greater use of demand-side response, not just in district heating, but electric vehicles and domestic use, requiring a smart grid to reduce the barriers and transaction costs for customers to supply balancing capacity.

Again, this requires central co-ordination, and Ecogrid recommends a multilateral strategy task force, consisting of representatives from Energinet, government, academia, industry, customers, distribution, retail service providers, and generation companies (Trong et al., 2009).

The mixed-market model looks set to continue to transform Danish energy industries, preparing it for 50% wind penetration by 2025, by combining effective central strategising with market-led lowest-cost implementation.

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# Appendix – Detailed results

Figure 11 Western Denmark: estimated exports, and proportion of wind exported, results of three algorithms compared

| West Denmark | | | | MW exports | | | % of wind energy exported | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | C | B | A | C | B | A |
| | Demand (MW) | Wind (MW) | % supplied by wind | Wind at top of merit order | District at top, wind 2nd, in merit order | Wind at bottom of merit order | Wind at top of merit order | District at top, wind 2nd, in merit order | Wind at bottom of merit order |
| **2000** | 2,346 | 387 | 16% | - | 1 | 170 | 0.0% | 0.3% | 44% |
| **2001** | 2,353 | 388 | 16% | - | 4 | 233 | 0.0% | 1.0% | 60% |
| **2002** | 2,343 | 437 | 19% | 0.01 | 8.4 | 295 | 0.0% | 1.9% | 67% |
| **2003** | 2,357 | 498 | 21% | 0.40 | 16.1 | 419 | 0.1% | 3.2% | 84% |
| **2004** | 2,374 | 555 | 23% | 0.30 | 12.9 | 347 | 0.1% | 2.3% | 63% |
| **2005** | 2,398 | 573 | 24% | 0.70 | 14.1 | 215 | 0.1% | 2.5% | 37% |
| **2006** | 2,443 | 527 | 22% | 0.37 | 3.9 | 372 | 0.1% | 0.7% | 71% |
| **2007** | 2,465 | 635 | 26% | 0.72 | 6.8 | 298 | 0.1% | 1.1% | 47% |
| **2008** | 2,462 | 591 | 24% | 0.52 | 7.2 | 252 | 0.1% | 1.2% | 43% |
| **2009** | 2,346 | 585 | 25% | 0.45 | 4.4 | 282 | 0.1% | 0.7% | 48% |
| **2010*** | 2,358 | 595 | 25% | 0.27 | 4.7 | 205 | 0.0% | 0.8% | 34% |

* to 20 August 2010

Figure 12 Eastern Denmark: estimated exports, and proportion of wind exported, results of three algorithms compared

| East Denmark | | | | MW exports | | | % of wind energy exported | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | C | B | A | C | B | A |
| | Demand (MW) | Wind (MW) | % supplied by wind | Wind at top of merit order | District at top, wind 2nd, in merit order | Wind at bottom of merit order | Wind at top of merit order | District at top, wind 2nd, in merit order | Wind at bottom of merit order |
| **2000** | 1,618 | 98 | 6% | - | - | 28 | 0.0% | 0.0% | 28% |
| **2001** | 1,662 | 105 | 6% | - | - | 30 | 0.0% | 0.0% | 28% |
| **2002** | 1,636 | 120 | 7% | - | - | 50 | 0.0% | 0.0% | 42% |
| **2003** | 1,618 | 137 | 8% | - | - | 99 | 0.0% | 0.0% | 72% |
| **2004** | 1,623 | 195 | 12% | - | - | 70 | 0.0% | 0.0% | 36% |
| **2005** | 1,649 | 182 | 11% | - | - | 42 | 0.0% | 0.0% | 23% |
| **2006** | 1,664 | 170 | 10% | - | - | 131 | 0.0% | 0.0% | 77% |
| **2007** | 1,657 | 184 | 11% | - | - | 72 | 0.0% | 0.0% | 39% |
| **2008** | 1,648 | 203 | 12% | - | - | 43 | 0.0% | 0.0% | 21% |
| **2009** | 1,603 | 181 | 11% | - | - | 32 | 0.0% | 0.0% | 18% |
| **2010*** | 1,614 | 169 | 10% | - | - | 56 | 0.0% | 0.0% | 33% |

* to 20 August 2010

Figure 13 All Denmark: estimated exports, and proportion of wind exported, results of three algorithms compared

| All Denmark | | | | MW exports | | | % of wind energy exported | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | C | B | A | C | B | A |
| | Demand (MW) | Wind (MW) | % supplied by wind | Wind at top of merit order | District at top, wind 2nd, in merit order | Wind at bottom of merit order | Wind at top of merit order | District at top, wind 2nd, in merit order | Wind at bottom of merit order |
| **2000** | 3,964 | 485 | 12% | - | 1 | 198 | 0.0% | 0.2% | 41% |
| **2001** | 4,015 | 493 | 12% | - | 4 | 263 | 0.0% | 0.8% | 53% |
| **2002** | 3,979 | 557 | 14% | 0 | 8 | 345 | 0.0% | 1.5% | 62% |
| **2003** | 3,975 | 635 | 16% | 0 | 16 | 518 | 0.1% | 2.5% | 82% |
| **2004** | 3,997 | 750 | 19% | 0 | 13 | 417 | 0.0% | 1.7% | 56% |
| **2005** | 4,047 | 755 | 19% | 1 | 14 | 257 | 0.1% | 1.9% | 34% |
| **2006** | 4,107 | 697 | 17% | 0 | 4 | 503 | 0.1% | 0.6% | 72% |
| **2007** | 4,122 | 819 | 20% | 1 | 7 | 370 | 0.1% | 0.8% | 45% |
| **2008** | 4,110 | 794 | 19% | 1 | 7 | 294 | 0.1% | 0.9% | 37% |
| **2009** | 3,949 | 766 | 19% | 0 | 4 | 314 | 0.1% | 0.6% | 41% |
| **2010*** | 3,972 | 764 | 19% | 0 | 5 | 262 | 0.0% | 0.6% | 34% |

* to 20 August 2010

Figure 14: total generation, net and gross exports, and exports by generation source

| | | | | | | A Wind at top of merit order | | B District at top, wind 2nd, in merit order | | C Wind at bottom of merit order | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **West** | local demand | Thermal | Wind | exports netted yearly | exports netted hourly | Thermal exports | wind exports | Thermal exports | wind exports | Thermal exports | wind exports |
| **2000** | 2,346 | 1,993 | 387 | 34 | 223 | 223 | 0.0 | 222 | 1.1 | 53 | 170 |
| **2001** | 2,353 | 2,215 | 388 | 250 | 404 | 404 | 0.0 | 400 | 3.8 | 170 | 233 |
| **2002** | 2,343 | 2,205 | 437 | 299 | 433 | 433 | 0.0 | 424 | 8.4 | 138 | 295 |
| **2003** | 2,357 | 2,581 | 498 | 722 | 730 | 729 | 0.4 | 714 | 16.1 | 310 | 419 |
| **2004** | 2,374 | 2,208 | 555 | 389 | 506 | 505 | 0.3 | 493 | 12.9 | 158 | 347 |
| **2005** | 2,398 | 1,892 | 573 | 67 | 240 | 239 | 0.7 | 226 | 14.1 | 25 | 215 |
| **2006** | 2,443 | 2,430 | 527 | 514 | 545 | 544 | 0.4 | 541 | 3.9 | 173 | 372 |
| **2007** | 2,465 | 2,033 | 635 | 203 | 357 | 357 | 0.7 | 351 | 6.8 | 59 | 298 |
| **2008** | 2,462 | 1,987 | 591 | 117 | 305 | 305 | 0.5 | 298 | 7.2 | 54 | 252 |
| **2009** | 2,346 | 2,011 | 585 | 250 | 362 | 362 | 0.5 | 358 | 4.4 | 80 | 282 |
| **2010** | 2,358 | 2,018 | 595 | 256 | 390 | 390 | 0.3 | 385 | 4.7 | 184 | 205 |
| **East** | | | | | | | | | | | |
| **2000** | 1,618 | 1,411 | 98 | -109 | 62 | 62 | 0 | 62 | 0 | 34 | 28 |
| **2001** | 1,662 | 1,373 | 105 | -184 | 76 | 76 | 0 | 76 | 0 | 46 | 30 |
| **2002** | 1,636 | 1,453 | 120 | -63 | 172 | 172 | 0 | 172 | 0 | 122 | 50 |
| **2003** | 1,618 | 1,735 | 137 | 254 | 314 | 314 | 0 | 314 | 0 | 215 | 99 |
| **2004** | 1,623 | 1,366 | 195 | -62 | 123 | 123 | 0 | 123 | 0 | 54 | 70 |
| **2005** | 1,649 | 1,244 | 182 | -223 | 64 | 64 | 0 | 64 | 0 | 23 | 42 |
| **2006** | 1,664 | 1,772 | 170 | 278 | 319 | 319 | 0 | 319 | 0 | 188 | 131 |
| **2007** | 1,657 | 1,379 | 184 | -94 | 135 | 135 | 0 | 135 | 0 | 64 | 72 |
| **2008** | 1,648 | 1,163 | 203 | -282 | 67 | 67 | 0 | 67 | 0 | 24 | 43 |
| **2009** | 1,603 | 1,138 | 181 | -284 | 43 | 43 | 0 | 43 | 0 | 11 | 32 |
| **2010** | 1,614 | 1,197 | 169 | -248 | 110 | 110 | 0 | 110 | 0 | 53 | 56 |