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Table of Contents

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Abstract

For reasons of mainly climate change mitigation, many countries are increasing their shares of domestically exploitable renewable energy resources. One of the most economically feasible renewable energy sources, wind power, is gaining higher and higher penetrations in electricity supply world wide and increasing 21 % from 2003 to 2004 (Windpower Monthly 2004). With growing wind power penetrations, however, grid and system integration becomes more and more important issues, and at a 20% penetration in Western Denmark, the issue is pertinent here.

This article analyses the potential economic benefit of selling excess electricity production on the *Nord Pool* power pool in relation to the required grid expansion. This is done through energy systems analyses, transmission grid modelling, analyses or the required transmission grid investments and analyses of the Nord Pool price variations. The analyses are done for varying degrees of wind power penetrations ranging from 20% of the West Danish electricity demand up to 100% of the demand.

The analyses demonstrate, that while there is an economic potential for some expansion in some years, in most cases the added investment proves unfeasible and either reduction of the wind turbines production under excess generation situations or other uses is more profitable unless the wind penetration very high.

Introduction

Since the oil crises of the 1970s, Denmark has pursued an active energy policy of reducing dependency on imported fossil fuels (Danish Ministry of Trade 1976; Danish Ministry of Energy 1981). This policy was given added focus and a slight change of direction towards renewable energy sources with the establishment of a very early national carbon dioxide emission reduction target of a 20% reduction from 1988 to 2005 in line with the recommendations of the Montreal Accord (Danish Ministry of Energy 1990; Danish Ministry of Energy 1993) well as the Kyoto protocol requirement adapted by Denmark (Danish Ministry of Environment and Energy 1996), exploitation of renewable energy sources has played an important role in the pursuit of these policies of self-sufficiency and climate change mitigation. Over-all energy efficiency improvements have also come from an extensive exploitation of cogeneration of heat and power (CHP) for the purpose of district heating generation as planned already in the first energy plan of 1976. The results are also apparent: With 20% wind penetration and a share of local non-dispatchable CHP at 26% in e.g. Western Denmark in 2004 (Eltra 2004), a very fuel efficient energy system has been established.

While a shift to a more market-based pricing system for wind power supplied to the grid has more or less halted Danish expansion of land-based wind turbines, political agreement was reached in 2004 regarding the establishment of two new 200 MW off-shore farms (Danish Government, 2004). This is an expansion of approximately 16% compared to the present level in terms of capacity but in terms of production it is closer to a 30% expansion due to more annual full-load operating hours off-shore.

Denmark is split up into two non-connected dispatch areas. This article addresses Western Denmark, which holds about 55% of the Danish population and has the highest shares of wind power and local CHP. In 2004, wind power constituted at its peak 118% of the entire demand in this area and small-scale non-dispatchable CHP came to a maximum share of 64%. The two combined had a maximum share of 148% of the demand (percentages based on statistical analyses of production and consumption data from (ELTRA A)).

This is of course not during peak demand but does indicate the significant weight of non-dispatchable production. Adding to that generally high shares indicated in Figure 1 and the fact that the large centrally-dispatchable power plants also have to operate for reasons of grid stability and in order to generate district heating for large urban areas, the result is that there are times, where there are large excess productions. In normal thermal or hydro-based systems, there is not such a high non-dispatchable production however the opposite is the case here. At many points in time throughout the year, there is thus a necessity to export electricity.

Western Denmark does have a relatively strong grid (Figure 2) with strong electric connections abroad totalling approx 2900 MW (Eltra 2004). A large share of 1200 MW however, is to Germany which itself has 14609 MW (Winpower Monthly 2004) of wind power mainly in the Northern länder and thus limited possibilities of picking up excess power generation from Denmark during periods of high wind velocities which will concur with periods of high wind velocities in Germany.

Scope of article

With much of the power generation being non-dispatchable, export is utilised for integration of wind power today however this option is limited by transmission capacity. The transmission capacity may be expanded to alleviate this or other strategies may be employed including a) improved control of the small-scale CHP plants, see e.g. (Østergaard 2006), b) moveable loads (including heat pumps, electrolytic converters or battery storages in vehicles), see e.g. (Lund 2005; Østergaard 2005; Østergaard 2003). Expansion and the two alternative strategies change the timing of either load or production or the geographic area in which the wind power is integrated however potentials and not the least costs differ greatly between the options.

This article analyses whether it is economically feasible to expand the domestic transmission system as well as export capacity from Western Denmark to Norway and Sweden based on added in -come from selling additional export on the Nord Pool power exchange at higher wind pene-trations.

The energy systems' analyses are based on relatively simple extrapolations and calculations based on empirical data whereas the transmission grid analyses are more analytically-based being founded on a transmission grid description and a load-flow model of the grid detailing geographic distribution of demand and supply in order to determine transmission line loads.

Energy system scenario

The analyses take their point of departure in actual hourly values of demand, wind power generation, import, export and available export capacity for five years in Western Denmark. The five years are all with annual wind energy contents (wind index) at or below average (see figure 3). Largest exports would naturally occur under above average wind conditions, however, data were not available for such years.

In these analyse, wind power is modelled at levels from the current level of approximately 20% and up to a wind penetration of 100%. These percentages are in shares of the demand in Western Denmark however without taking into consideration whether the timing of wind power fits the timing of the demand. As these will naturally not follow the demand, even at 100% wind penetration, demand surpass wind power generation approximately half the time and the reverse will also happen approximately half the time. Some thermal production is hence required even at 100% wind penetration but this is not addressed in detail in these analyses. Furthermore, some degree of production on large synchronous generators is typically required to supply required ancillary services (Østergaard 2006), though requirements will probably decrease in the future as distributed generating technologies improve performance and stability.

For each hour of the five years, installed wind power capacity is modelled expanded up to 100% wind penetration by simple extrapolation. Over the period of years indicated in Figure 3, installed wind capacity has grown. This is compensated in the modelling so all are referred to year 2004 levels.

Available export capacity is the physical export capacity minus momentary export plus imports where the physical capacity is the approximately 1700 MW minus temporary reductions due to e.g. maintenance and line faults. Import and export of course does not take place at the same time - at least not in a physical sense but maybe in economic terms. Import is therefore included in the calculations as import in an hour may be perceived as an additional available export capacity. Additional capacity may subsequently be added and the additional momentary export be determined by comparing with the available momentary wind power. Figure 4 and 5 show available export capacity for two weeks in 2004. It should be noted that the week numbers are not coinciding with the European week numbering system but rather, the first seven days of the year is defined as week number one.

It is clear from the two figures that available export capacity changes considerably over the day and the week as an indication of the use of these connections.

Non-controllable electricity sources are typically not able to trade very actively on the power pools. With no control of the production, the only possible market option is using he sport market. If a high number of wind turbines such as the entire Western Danish stock were to be traded together, predictions would of course improve and thereby possible enabling wind turbines to trade better, however in these analyses, it has been assumed, that this is not the case.

Spot market prices on the Nord Pool power exchange vary considerably over time, but there is no immediate correlation with momentary wind power as indicated in Figures 6 and 7 showing pool prices for Western Denmark along with momentary wind input. These prices are used to determine the value of additional export caused by expansion of wind power.

There is though some correlation between wind power and spot market price. That, however, is beyond the requirements for these analyses). At high wind expansions there could be a higher corre-lation between momentary wind power and pool-prices however Danish electricity consumption and generation is very modest compared to the Norwegian and Swedish con-sumptions, so a concurrent expansion of transmission capacity between Denmark and Norway/Sweden will lower this correlation.

Expansion of export capacity is modelled in the form of a 600 MW HCDC line at a total cost of 1350 million Danish Kroner (DKK); approx 200 million € (Eltra 2002). Calculated as an annuity over 30 years at 3% discount rate and adding 2% operation and maintenance (O&M) costs annually (Jørgensen 2003), this comes to approximately 70 million DKK per year.

Domestic grid expansions are determined by load-flow analyses of the Western Danish grid using the energyPRO GRID model (Andersen & Mæng 2004; Lund & Østergaard 2000) and databases established for the Mosaic project (Østergaard et al. 2004) for all hours in the year. In the modelling, the over-loads in the transmission system are identified assuming an otherwise intact grid and reinforcements are priced. These costs are subsequently calculated as an annuity over 30 years at a discount rate of 3% as for the HVDC lines, 2% O&M is added and the total is summed for domestic lines as well as HVDC lines.

The analyses have not looked into possibly required reinforcements in the receiving end, and such costs are hence not included

The total grid costs may lastly be deducted from the added income of selling electricity on the Nord Pool thereby revealing the potential income from expansion of export capacity. It should be noted that it is not an analysis of the potential income of expanding wind power; turbine costs are not considered. It should also be duly noted that it is under an assumption of “must take” i.e. the transmission and system operator (TSO) is obliged to take electricity from producers at a price regardless of whether needed in the system or not.

Results of the analyses

Additional export varies from year to year in the models as shown in Figure 8 with a tendency that high-wind years also have higher additional exports. It is however interesting comparing years 2001 and 2002. In spite of a significant difference in annual wind energy contents, additional exports are more or less identical demonstrating that the timing is very important. The average diurnal variation does not change much from year to year however seasonal variations in wind energy contents do manifest themselves as indicated by Figure 8.

Adding an extra 600 MW export facility gives an additional export as indicated in Figure 9. Again, in spite of 2001 having by far the lowest annual wind energy contents, additional exports this year are among the highest due to the prices of this year.

Applying the momentary Nord Pool prices for the momentary additional exports at higher installed wind capacities gives the incomes in Figures 10 and 11 where the difference shown in Figure 12 thus reveals the economic benefit of the added export capacity without taking the grid expansion costs into account though.

Calculating the grid expansion needs give the results listed in figure 13. It is quite clear that the most important investment is in the international HVDC cables whereas domestic expansions at low wind penetrations is more of less negligible. At higher penetrations this becomes more important though never at a level comparable to the HVDC line.

Adding these costs as previously outlined gives the over-all income of expanding the transmission system and HVCD export capacity to Norway/Sweden. These results are given in Figure 14.

It is clear from the figure that the economic viability of expanding the transmission system and export connections vary considerably from year to year. If the timing of the excesses is wrong compared to the pool price (as in the year 2000) a strong expansion of wind power is required in order to make the investment feasible. In most of the other years, expansion is only feasible at a wind power penetration around 35-40% though in one year (2003), only a modest expansion compared to the present approx. 20% penetration is required.

Expansion with an additional 600 MW HVDC capacity to a total of 1200 MW is feasible in some of the years but generally only at very high wind penetrations above 50-60%. These analyses are not detailed further here as other issues become more pertinent at such high levels.

Conclusions

Expansion of grid connections from Western Denmark to neighbouring countries is feasible if Denmark pursues a path of wind power expansion. While not relevant under present circumstances, added export capacity becomes economically favourable when wind penetration reaches and surpasses 35-40%

Capacity expansion to even higher levels – 1200 MW in these analyses – are only feasible at very high wind penetrations.

The analyses are done using statistical data for five years however these five years were in fact comparably low-wind years. Higher wind velocities would naturally increase the utility of added transmission capacity domestically and internationally.

Acknowledgements

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Figures

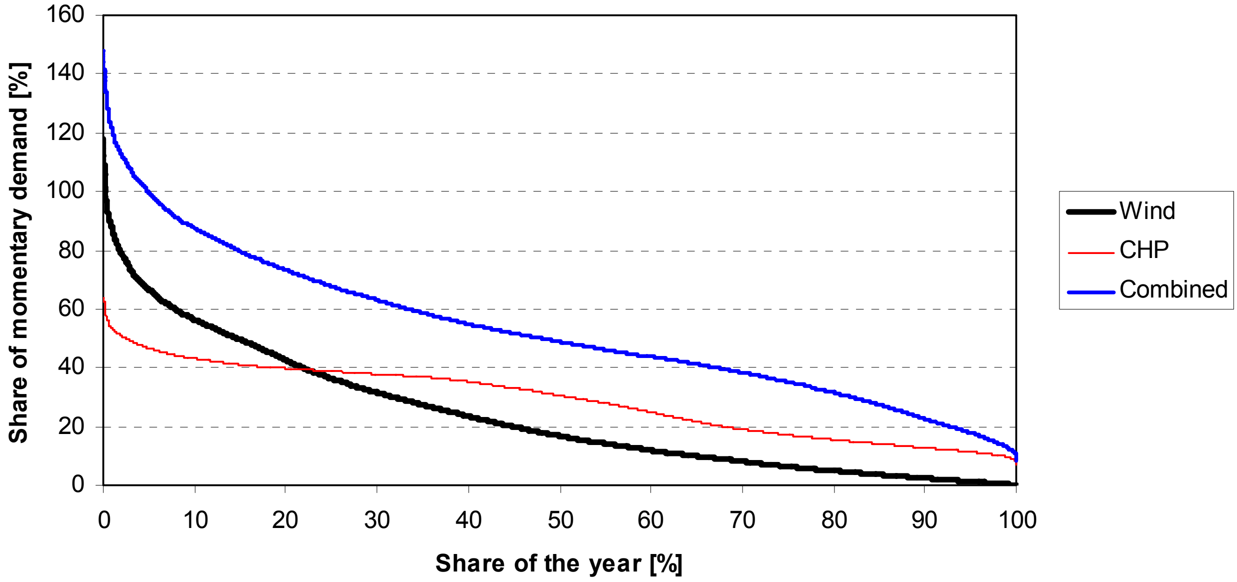

Figure 1: Duration curves for wind power and small-scale (local) CHP in Western Denmark in 2004. Based on data from Eltra A.

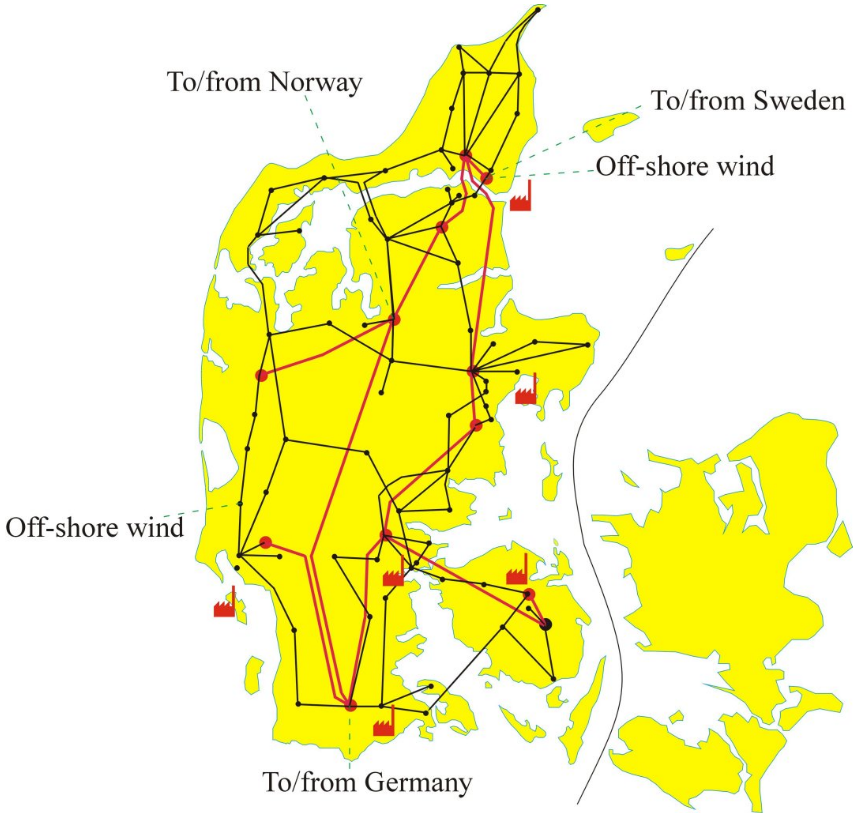

Figure 2: The transmission grid in Western Denmark.

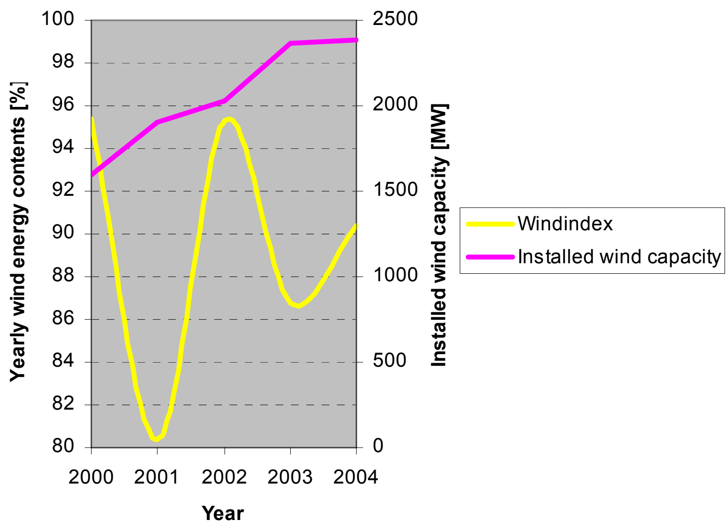

Figure 3. Installed wind capacity and relative wind energy contents in the five years modelled. Sources Eltra B and EMD.

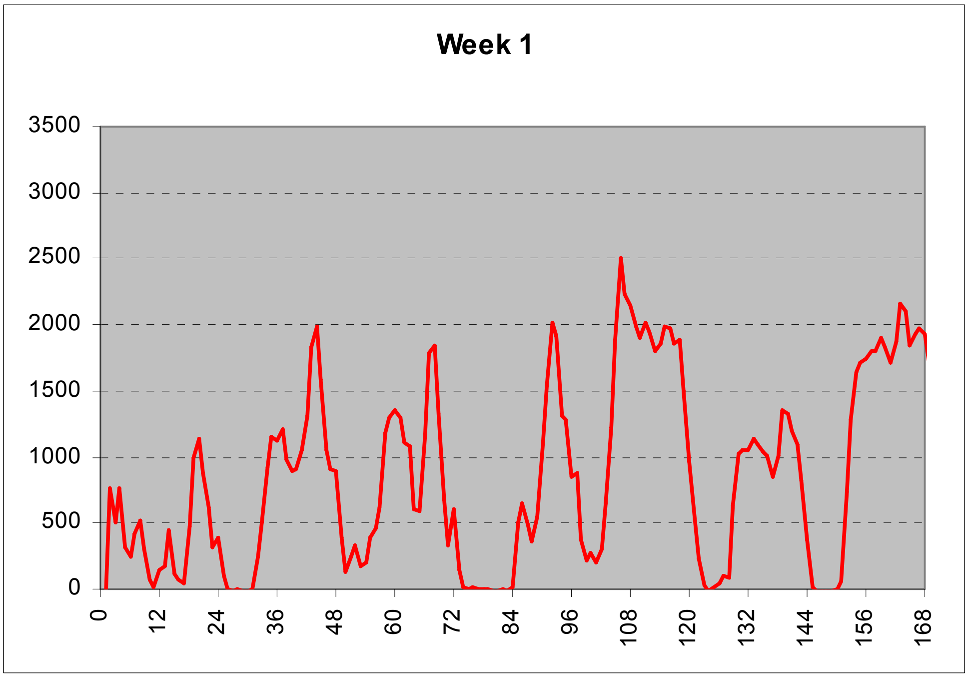

Figure 4: Available export capacity to Sweden and Norway without additional capacity added – a winter week, based on data from Eltra B.

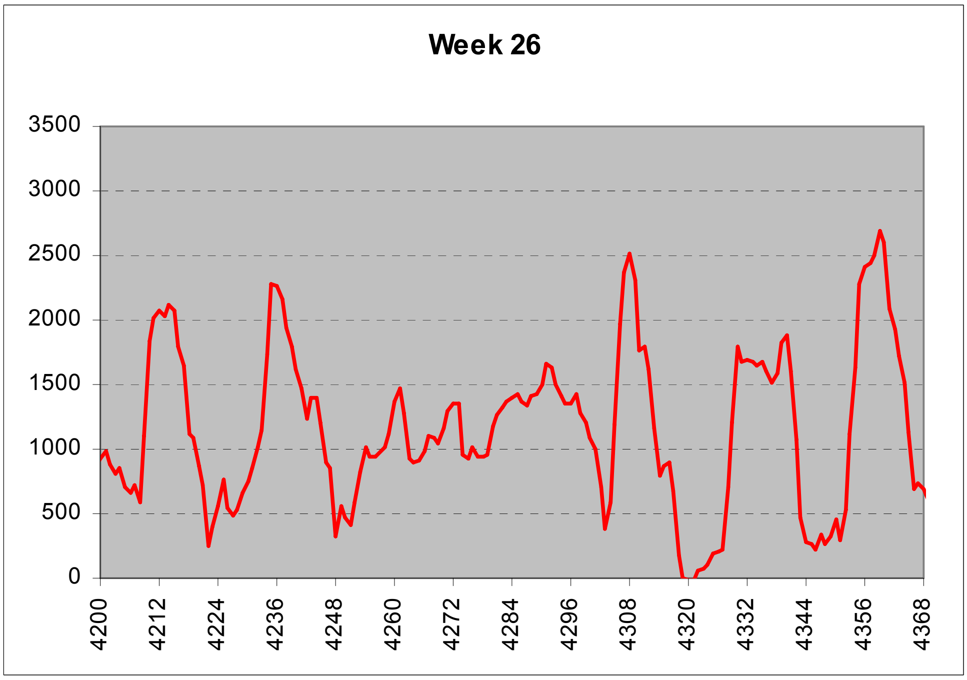

Figure 5: Available export capacity to Sweden and Norway without additional capacity added – a summer week, based on data from Eltra B.

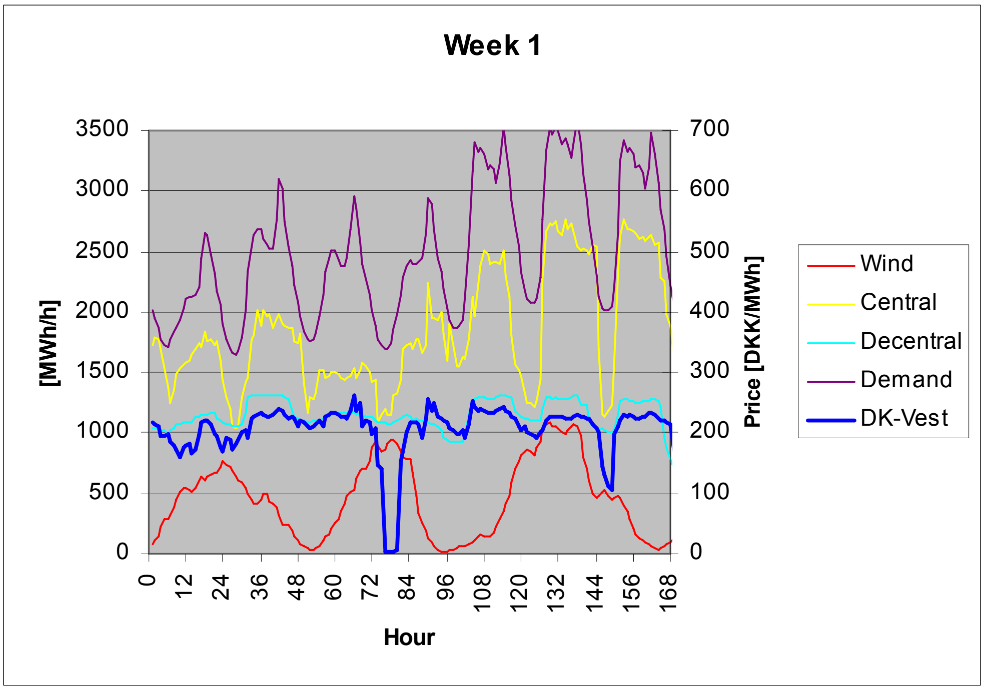

Figure 6: Production, demand and spot market price in a winter week of 2004, based on data from Eltra B.

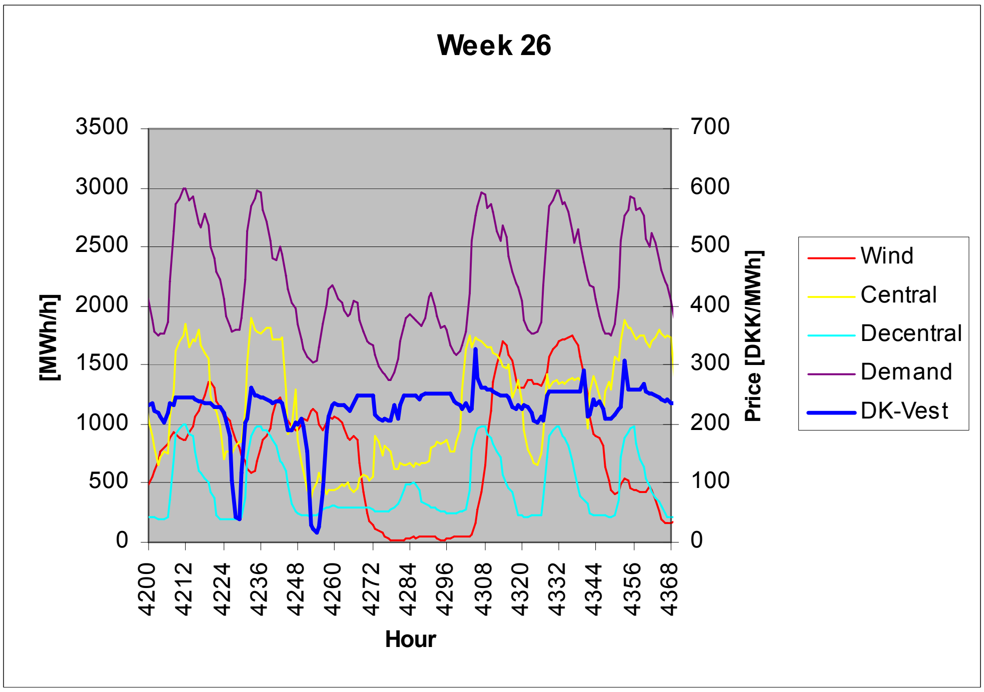

Figure 7: Production, demand and spot market price in a summer week of 2004, based on data from Eltra B.

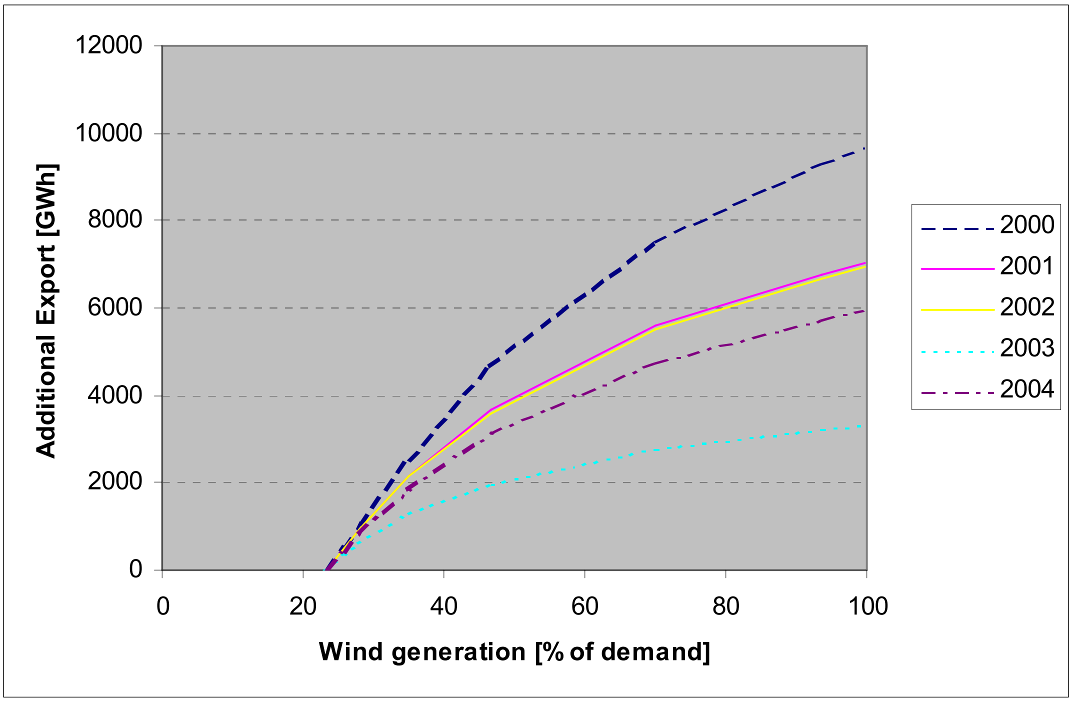

Figure 8: Additional export using available export capacity, based on 2004 data.

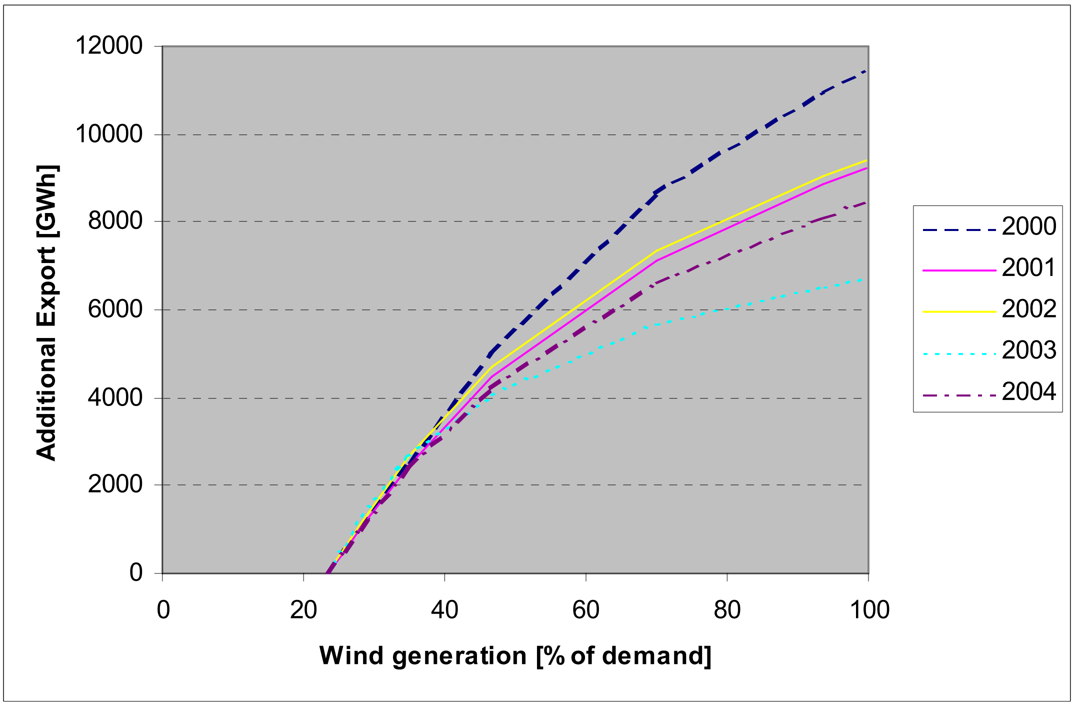

Figure 9: Additional export using available export capacity plus an additional 600 MW, based on 2004 data.

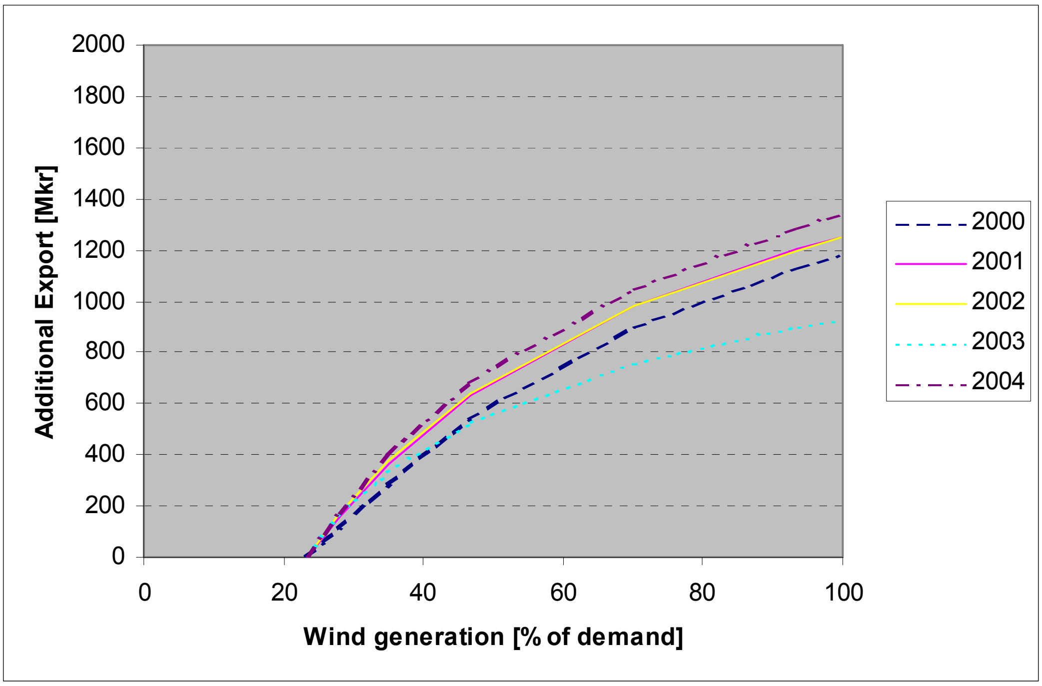

Figure 10: Additional income without added export capacity.

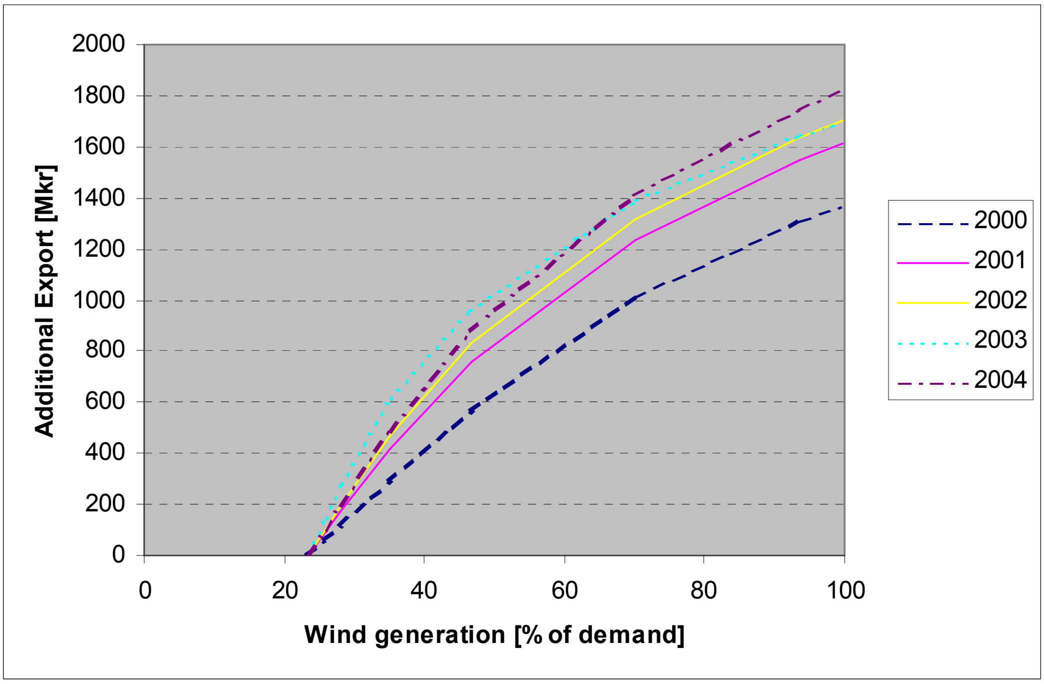

Figure 11: Additional income with 600 MW added export capacity.

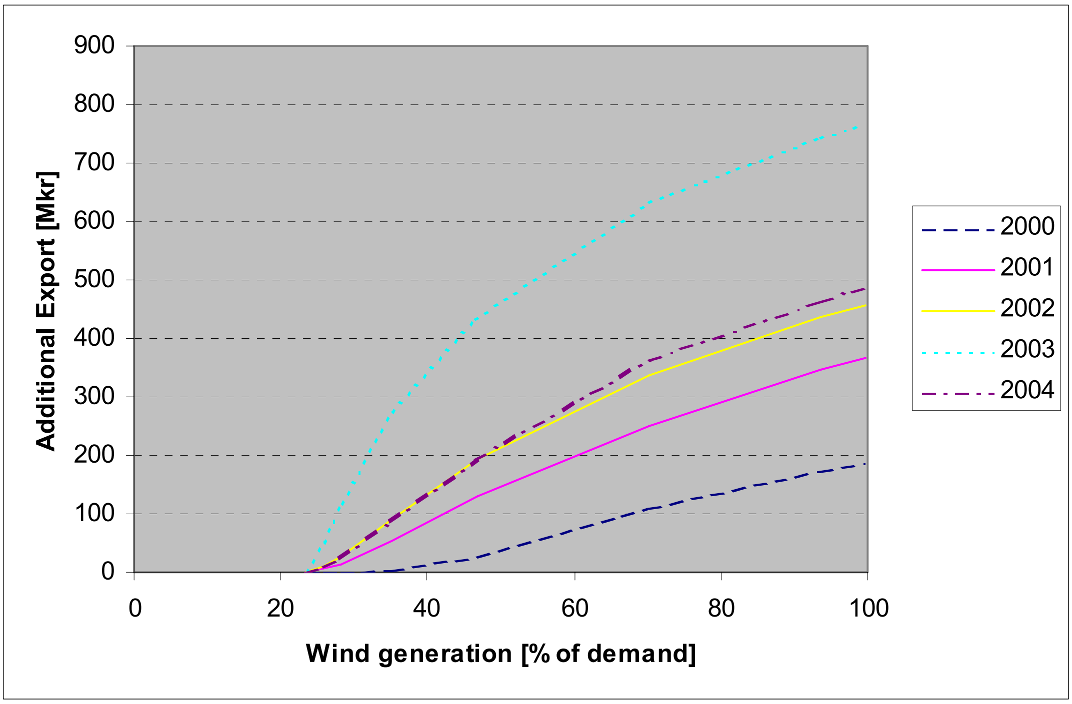

Figure 12: Marginal income from investing in 600 MW export capacity – grid costs not included.

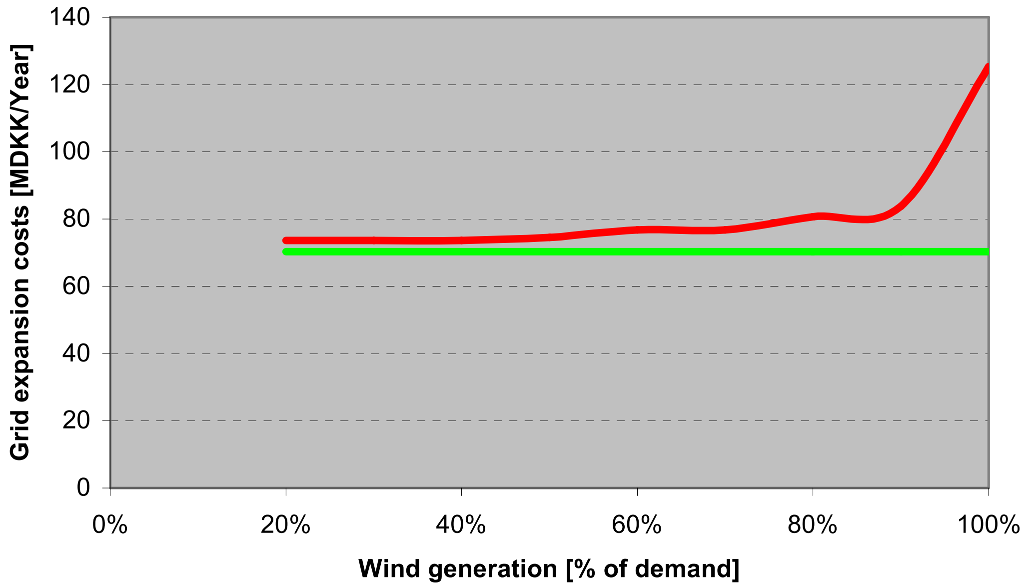

Figure 13: Grid expansion costs. The lower line is for HVDC connection alone; the upper line is including domestic transmission capacity expansion.

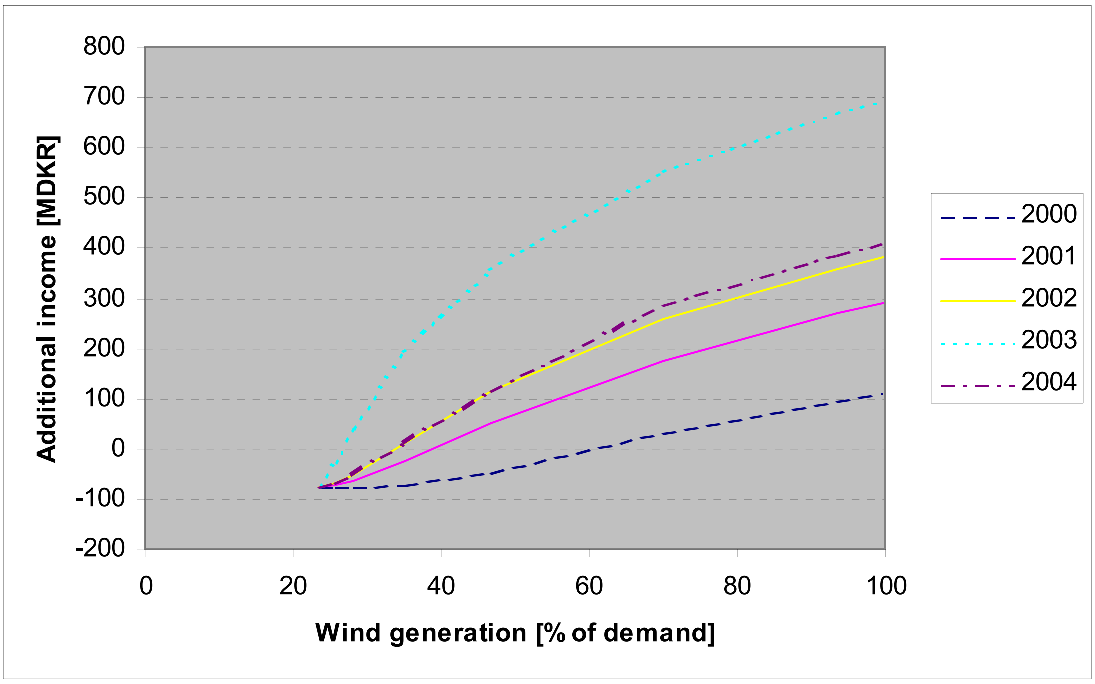

Figure 14: Added income from investing in transmission and export capacity expansion and selling excess wind power generation on the Nord Pool power exchange.