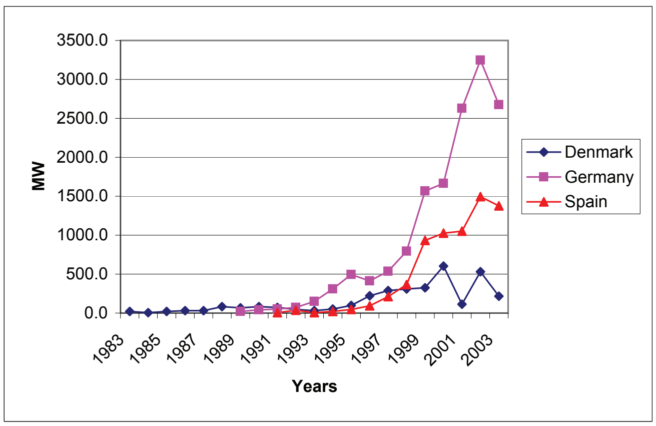
The Economics of Wind Power

By Poul E. Morthorst*

Within the last 10 to 15 years wind power, globally, has developed incredibly fast. In 1990 total installed capacity of wind power in the world amounted to approximately 2.0 MW – by the end of 2003 this capacity has increased to more than 40 GW, equalling an annual growth rate of more than 25%. And the rate of growth is still high - in 2002 global installed capacity increased by 30% and by approximately 26% in 2003. European countries dominate the wind power scene. In 2003 approximately 65% of total installed wind turbine capacity was established in Europe, and the only major contributors outside Europe were the United States with a total installed capacity of approximately 6.4 GW and India with 2.1 GW (BTM-consult, 2004).

Figure 1
Annual Increase of Installed Wind Power Capacity in Germany, Spain and Denmark



But even within Europe, a few countries denominate: Germany, Spain and Denmark accounted for more than 75% of the growth in European installed wind turbine capacity in 2003, and correspondingly these three countries together have installed more than 80% of the total accumulated capacity in Europe. Germany has had an especially rapid development. In 1991 total accumulated capacity in Germany was approximately 100 MW; today the annual capacity increase is approximately 2700 MW and total installed wind power capacity is almost 15 GW. Similar developments are found in Denmark and Spain, although not to the same extent. Denmark had a total installed capacity of almost 3.1 GW and a growth rate of approximately 8% in 2003, while Spain had installed 6.4 GW with a growth rate of more than 25% in 2003. Other contributors in Europe worthy of mention are the Netherlands (0.9 GW), Italy (0.9 GW), UK (0.8 GW), Greece (0.5 GW), Sweden (0.4 GW) and Austria (0.4 GW), (BTM-consult, 2004).

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Policy Conditions for Wind Power

The main reason behind the development in Germany, Spain and Denmark is a fast improvement in the cost-effectiveness of wind power during the past ten years (Redlinger et.al.,1998), combined with long-term agreements on fixed feed-in tariffs (at fairly high levels), altogether making wind turbines one of the most economically viable renewable energy technologies today. The national policies of fairly high buy-back rates and substantial subsidies from governments to a certain extent reflect the need for a development of renewable energy technologies to cope with the greenhouse gas effect. According to the Kyoto protocol the European Union has agreed on a common greenhouse gas (GHG) reduction of 8% by the years 2008-12 compared with 1990. All the three above-mentioned countries have adopted a policy of GHG-limitation in accordance with the agreed burden sharing in the EU.

That the development of renewable energy resources is expected to play an important role in the implementation of these GHG-targets is reflected in EU policy as well. In its White Paper on a strategy for the development of renewable energy the EU Commission launched a goal of covering 12% of the European Union's gross inland energy consumption by the year 2010 by renewable sources; that is mainly by biomass, hydro power, wind energy, and solar energy. Next to biomass, wind energy is seen as the main contributor (European Commission, 1997). Moreover, the European Commission has agreed on the promotion of renewable energy technologies, including a proposal on the share of renewables in the individual member states in 2010, based on the percentage of each country's consumption of electricity (European Commission, 2000). Although not binding these targets are generally accepted by the EU member states. Thus the directive signals the need to include renewable energy technologies as one of the serious options in achieving the targets for GHG-reductions.

In parallel with the implementation of the Kyoto GHG-commitments a number of countries are liberalising their electricity industry. The cornerstone in liberalisation is opening of the electricity markets for trade, within the country and among countries. To generate efficient competition unbundling of the power industry might be necessary: splitting existing companies into independent ones for production, transmission and distribution of electricity. Finally, to handle dispatch of electricity an independent systems operator is needed, and establishing a power exchange might facilitate and increase transparency in trading.

This process towards liberalised electricity markets has been going on for some years. The EU-directive on common rules for the internal market in electricity, states that each member state has the right of access to the electricity and distribution grids, thus opening the concept of free electricity trade in Europe. A number of countries already have or are in the transition phase of liberalising their electricity industry. Electricity exchange markets are being developed to facilitate electricity trade and now exist in several countries, among them England, Germany, Norway, Sweden, Finland

and Denmark. In 1996 Norway and Sweden established the first inter Nordic electricity exchange market (NordPool). Through collaboration with the existing Finnish electricity exchange, El-Ex, in 1998, Finland was included in the market. In the summer of 1999 the western part of Denmark joined the exchange, while the eastern part became a member in 2000.

How wind power is to be integrated into the competitive electricity market is still an open question. At present most renewable energy technologies are not economically competitive with conventional power producing plants. Thus it can be expected that if renewables must compete on pure market conditions this will halt the development of new renewable capacity. One model of generating additional payments to renewable technologies is to develop a separate green market. This model will facilitate the integration of renewables into the liberalised market and at the same time make it possible for these technologies to be partly compensated for the environmental benefits they generate compared to conventional power production.

A number of EU member states, Holland, Belgium, the UK, Italy and Sweden, already have or are presently aiming at introducing tradable green certificate systems (TGC's). The main objective of a TGC-scheme is to increase the penetration of renewable electricity production into the electricity market by stimulating demand. Green certificates are generated by renewable producers, which receive a certificate for each unit of production sold to the electricity grid (Voogt et.al., 1999). The TGC-systems in the EU appear to be quite different, however. For example, Holland has a voluntary scheme, Italy places the obligation on the power producers, while Sweden sets a quota on electricity consumers. Thus, no common EU TGC-system seems to be underway.

In 1999 the Danish Parliament agreed to phase out the existing feed-in tariff system and replace this with a green certificate market (Morthorst, 2000). Uncertainty about how the new certificate system would work stalled the development of Danish wind power in 2001 (only 115 MW was established), Finally the government decided to postponed the certificate market until 2004-5, mainly due to resistance from Danish wind organisations and wind manufacturers. Whether a green certificate system will ever be put in place in Denmark is doubtful, This will probably happen only if a common European-wide system is established. But as mentioned, there are at present no signs within the EU of developing a common green market for renewables. Germany and France have chosen to continue with the well proven feed-in tariff system.

Economics of On-land Sited Wind Turbines

Wind power is used in a number of different applications, including both grid-connected and stand-alone electricity production, as well as water pumping. This section analyses the economics of wind energy, primarily in relation to grid-connected turbines which account for the bulk of the market value of installed turbines.

The main parameters governing wind power economics include the following:

- Investment costs, including auxiliary costs for foundation, grid-connection, etc.
- Operation and maintenance costs
- Electricity production / average wind speed
- Turbine lifetime
- Discount rate

Of these, the most important parameters are the turbines' electricity production and their investment costs. As electricity production is highly dependent on wind conditions, choosing the right turbine site is critical to achieving economic viability.

The following sections outline the structure and development of land-based wind turbines' capital costs and efficiency trends. Offshore turbines are gaining an increasingly important role in the overall development of wind power, and thus an overview is given in a separate section.

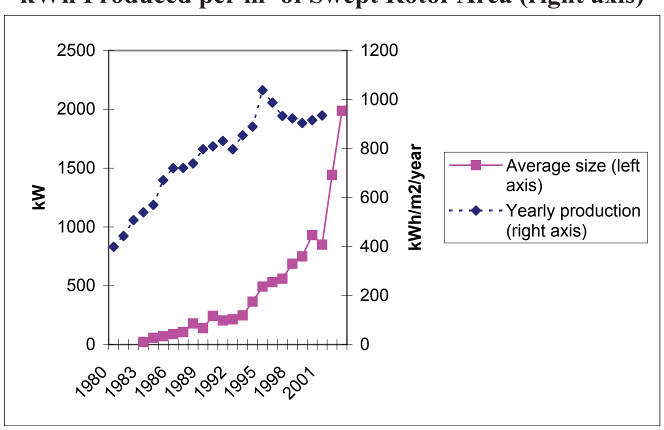
In general, two trends have dominated grid-connected wind turbine development:

1) The average size of turbines sold on the market has increased substantially
2) The efficiency of production has increased steadily.

Figure 2 shows the average size of wind turbines sold each year using the Danish market as a proxy. As illustrated in Figure 2 (left axis), the average size has increased significantly, from less than 50 kW in 1985 to almost 2 GW in 2003. In 2003 the best-selling turbines in the world market had a rated capacity of 750-1500 kW and more than a 50% share of the market. But turbines with capacities of the 1.5 MW and up had a share of 35% and are increasing in market share. At the end of 2003 turbines with a capacity of 2 MW and above were getting increasingly important, even for on-land sitings.

Compared with other countries, the Danish market is at the upper level in the development of the average size of turbines sold. The average size sold in Denmark in 2003 was almost 2 MW; influenced to a high degree by the development of a large offshore farm equipped with 2.2 MW machines. Germany was a little below with an average size of 1650 kW,

Figure 2
Development of Average Wind Turbine Size Sold in the Danish Market (left axis) and Efficiency, Measured as kWh Produced per m^2 of Swept Rotor Area (right axis)



while the average in the UK was almost 1.8 MW and Sweden was approximately 900 kW. In Spain the average was 870 kW and in the United States approximately 1400 kW.

The development of electricity production efficiency is also shown in Figure 2, measured as annual energy production per swept rotor area (kWh/m^2 on the right axis). Measured in this way, efficiency has increased by almost 3 percent annually over the last 15 years. This improvement in efficiency is due to a combination of improved equipment efficiency, improved turbine siting, and higher hub height. The decrease in efficiency shown in Figure 2 is due to a lower average wind speed at those sites available for the latest established turbines[1].

Capital costs of wind energy projects are dominated by the cost of the wind turbine itself (ex works)[2]. Table 1 shows a typical cost structure for a 1 GW turbine in Denmark. The turbine's share of total cost is approximately 82 percent, while grid-connection accounts for approximately 7 percent and foundation for approximately 5 percent. Other cost components, such as control systems and land, account for only minor shares of total costs.

Table 1
Cost Structure for a 1 GW Wind Turbine (year 2001 €)

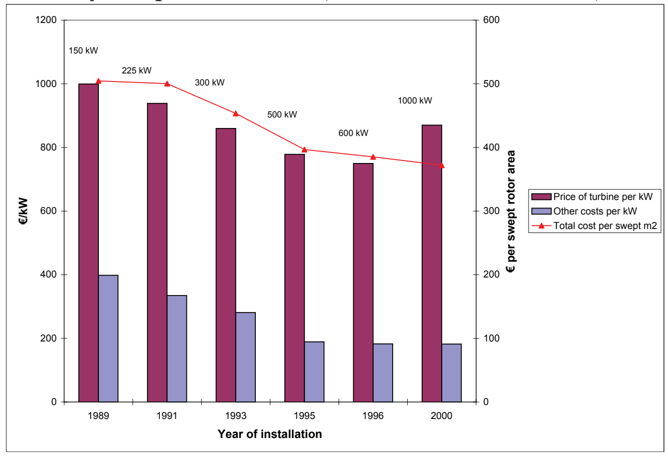
	Investment (1000€)	Share (%)
Turbine (ex works)	748	81.9
Foundation	44	4.8
Electric installation	10	1.1
Grid-connection	60	6.6
Control systems	2	0.2
Consultancy	8	0.9
Land	27	2.9
Financial costs	8	0.9
Road	7	0.7
Total	914	100.0

Note: Based on Danish figures for a 1 GW turbine, using average 2001 exchange rate 1€ = 7.45 DKK.

Figure 3 shows changes in capital costs over the years. The data reflect turbines installed in the particular year shown. All costs at the left axis are calculated per kW of rated capacity, while those at the right axis are calculated per swept rotor area. All costs are converted to 2001 prices. As shown in the figure, there has been a substantial decline in per-kW costs from 1989 to 1999. In this period turbine costs per kW decreased in real terms by approximately 4 percent per annum. At the same time, the share of auxiliary costs as a percentage of total costs has also decreased. In 1987 almost 29 percent of total investment cost was related to costs other than the turbine itself. By 1999 this share had declined to approximately 20 percent. The trend towards lower auxiliary costs continues for the last vintage of turbines shown (1000 kW), where other costs amount to approximately 18 percent of total costs.

A little surprisingly, investment costs per kW have increased for this last-mentioned machine compared to a 600 kW turbine. The reason is to be found in the dimensioning of the turbine. With higher hub heights and larger rotor diameters the turbine is equipped with a relative smaller generator

Figure 3
Left axis: Wind Turbine Capital Costs (ex works) and other costs per kW Rated Power (€/kW in constant 2001 €). Right axis: Investment Costs Divided by Swept Rotor Area (€/m2 in constant 2001 €)



although it produces more electricity. This is illustrated in Figure 3 at the right axis, where total investment costs are divided by the swept rotor area[3]. As shown in this figure, the cost per swept rotor area has decreased continuously for all turbines considered. Thus, overall investment costs per swept rotor area have declined by approximately 3 percent per year during the period analysed.

The total cost per produced kWh (unit cost) is calculated by discounting and leveling investment and O&M costs over the lifetime of the turbine, divided by the annual electricity production. The unit cost of generation is thus calculated as an average cost over the turbine's lifetime. In reality, actual costs will be lower than the calculated average at the beginning of the turbine's life, due to low O&M costs, and will increase over the period of turbine use.

Figure 4 shows the calculated unit cost for different sizes of turbines based on the above-mentioned investment and O&M costs, a 20 year lifetime, and a real discount rate of 5 percent per annum. The turbines' electricity production is estimated for roughness classes one and two, corresponding to an average wind speed of approximately 6.9 m/s and 6.3 m/s, respectively, at a height of 50 meters above ground level.

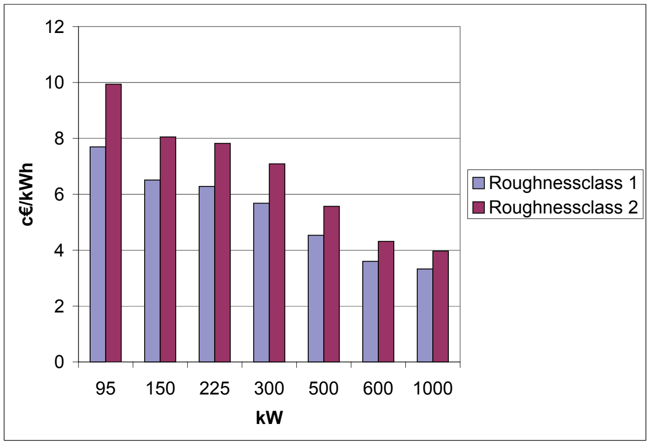
Figure 4 illustrates the trend towards larger turbines and improved cost-effectiveness. For a roughness class one site (6.9 m/s), for example, the average cost has decreased from over 7.7 c€ /kWh for the 95 kW turbine (1985) to under 3.4 c€ /kWh for a new 1000 kW machine, an improvement of more than 50 percent over a time span of 15 years (constant 2001 prices).

The discount rate has a significant influence on electricity production costs and hence on wind projects' financial viability. For a 1000 kW turbine, changing the discount rate from 5 to 10 percent per year (in real terms) increases the production cost by a little more than 30 percent.

Future Development of the Economics of On-land Turbines

In this section the future development of the economics of wind power is illustrated by the use of the experience

Figure 4
Total Wind Energy Costs per unit of Electricity Produced, by Turbine Size. (c€/kWh, constant 2001 prices)



curve methodology. As is well known, the experience curve approach was developed back in the 1970s by the Boston Consulting Group. The main feature is that it relates the cumulative quantitative development of a product with the development of the specific costs (Johnson, 1984). Thus, if the cumulative sale of a product is doubled, the estimated learning rate tells you the achieved reduction in specific product costs.

The experience curve is not a forecasting tool based on estimated relationships. It is merely pointing out that if the existing trends continue then we might see the proposed development. It converts the effect of mass production into an effect upon production costs, other casual relationships are not taken into account. Thus changes in market development and/or technological break-throughs within the field might considerably change the picture.

In a recently EU-project, EXTOOL, with the participation of Lund University in Sweden, ISET in Germany, and Risø National Laboratory in Denmark, the concept of the experience curve was investigated and applied to wind power. The following section is essentially based on the results from this project as presented at a workshop in Paris (Extool, 2003).

For Denmark an experience curve using data from the beginning of the 80s until now has been estimated. Using the specific costs of energy as a basis (costs per kWh produced) progress ratios in the range of 0.83 to 0.87 are found, corresponding to learning rates of 0.17 to 0.13. That is, when total installed capacity of wind power is doubled the costs per produced kWh for new turbines are reduced between 13 and 17%. In this way both the efficiency improvements and embodied and disembodied cost reductions are taken into account in the analysis.

The consequences of applying the above-mentioned results for wind power are illustrated in Figure 5. At present the cumulative installed capacity of wind power world-wide is increasing by almost 30% per annum. Thus, within three years time the total installed capacity is expected to double, and according to the experience curve, the costs per kWh wind produced power could fall by approximately 13-17% in that period. If growth in installed wind power continues, within 5-7 years the costs of wind produced power should, according to the experience curve approach, be within a range of approximately 2.3 c€/kWh to 3.0 c€/kWh.

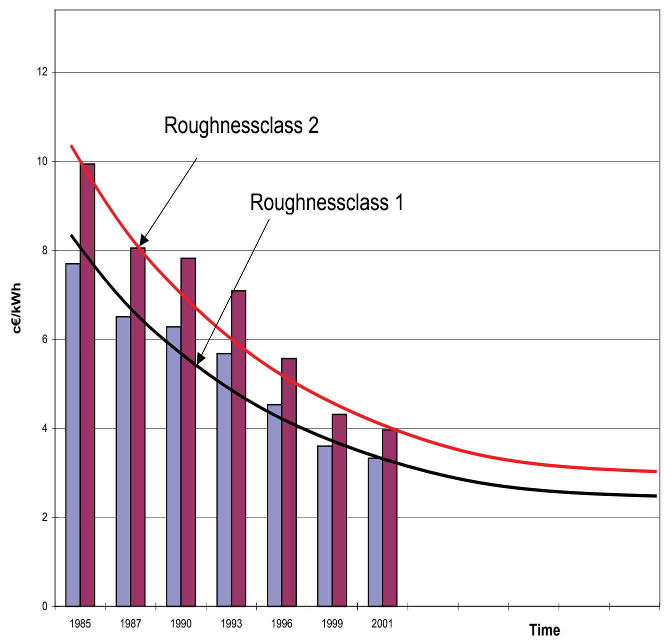
What then are the production costs of the competing conventional power producers? At present the price of power at the Nordic power market, NordPool, has an average of approximately 3.0 c€/kWh. However, at the Nordic market no major new investments in power capacity have been undertaken in the time period when Denmark has taken part in the market. And the Nordic organisation for TSOs, Nordel, expects a shortage of power capacity within the next 3-4 years (H.H.Lindboe, 2002). Thus, it is expected that the price will rise to induce new investments in conventional power plants. According to Danish power companies, the most promising technology to chose is a natural gas fired combined cycle power plants, which will produce at a cost of 3.3 c€/kWh to 4 c€/kWh[4] (ELSAM, 2002).

As shown in Figure 5 this implies that within 5-7 years wind power should be fully competitive with new conventional produced power, if the existing trends continue.

Development of Offshore Wind Turbines

In a number of countries offshore turbines are playing an increasingly important role in the development of wind power, particularly in the north-western part of Europe. Without doubt the main reasons are that on-land sitings are limited

Figure 5
Using Experience Curves to Illustrate the Future Development of Wind Turbine Economics



in number and the utilisation of these sites, to a certain extent, is exposed to opposition from the local population. This, seen in relation to an unexpected high level of energy production from offshore turbines compared to on-land sitings (based on the experiences gained until now), has paved the way for a huge interest in offshore development.

At present a number of offshore wind farms are in operation in the northern part of Europe, the largest ones in Danish waters. The worlds largest offshore wind farm is situated on the West Coast of Denmark; Horns Reef, situated approximately. 20 km west of the coast of Jutland was established in 2002 and has a total capacity of 160 MW, consisting of 80 2 MW turbines. The Nysted project at Rødsand, close to the isle of Lolland in Denmark, was finalised in 2003. Nysted has a total capacity of approximately 160 MW consisting of 72 2.2 MW turbines. Middelgrunden (Denmark) east of Copenhagen was put in operation in 2001. The total capacity is 40 MW consisting of 20 2 MW turbines. Finally, Samsø offshore wind farm (Denmark) situated south of the isle of Samsø was put in operation in 2002 and consists of 10 2.3 MW turbines.

Moreover, in a number of countries offshore wind power projects are in the planning and implementation phase. Notable among these are Germany, Ireland, the Netherlands, and UK.

An important concern for the Danish Government is to ensure that the future offshore development is based on market conditions in an economically efficient way. The government, therefore, has investigated the possibilities and conditions of tendering future offshore wind farms in Danish waters. By applying a tendering procedure, competition among bidders will be ensured and the most cost-effective offshore turbine developments will be undertaken. As part of the governmental investigations a scenario was worked out for the future development of a new offshore wind farm at Horns Reef consisting of 3 Mw turbines compared with the 2 MW turbines, which are utilised at the existing Horns Reef wind farm. The economic consequences of this scenario is summarised below:

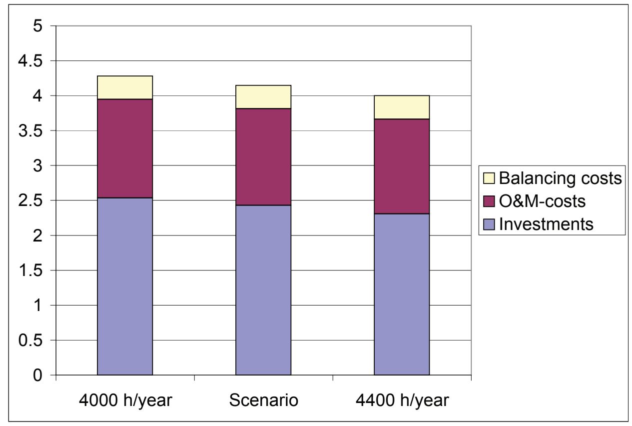
In the scenario, the number of full load hours is assumed to be 4190 h/year and investment and O&M-costs are modified to a 3 MW-farm, using cost data from the existing 2 MW farm as a starting point. As shown in Figure 6, in the scenario total production costs are calculated to approx. 4.2 c€/kWh, including 1.4 c€/kWh as O&M-costs and 0.3 c€/kWh for balancing the power production at the market. Not unexpectedly the assumption on full load hours is important. If the assumed utilisation time is reduced to 4000 h/year, costs will increase to 4.3 c€/kWh, while a utilisation time of 4400 h/year corresponds to a cost of only 4.0 c€/kWh.

The above costs are calculated as simple national economic ones using a real discount rate of 5% p.a. and, therefore, they will not be the costs of a private investor, who will have higher financial costs, require a risk premium and eventually a profit. How much a private investor will add on top of the simple costs will depend, among other things, on the perceived technological and political risk of establishing the offshore farm and, finally, on the competition in the bidding process for such an offshore farm.

Conclusions

Wind power is one of the most promising new renewable technologies, undergoing a rapid technological development

Figure 6
Calculated Production Costs in the Scenario Based on 3 MW Turbines, including Sensitivity Analyses on Numbers of Full Load Hours.



and possessing environmental characteristics that make it well suited to contribute to a future sustainable development. This paper has addressed the market and economic development of wind power. The following issues are highlighted:

- On a global scale wind power is developing rapidly, showing growth rates of installed capacity of more than 25% annually. Nevertheless, the development is vulnerable, because it is dominated by a few countries: Germany, Spain, United States and Denmark. A number of EU members states have established green markets, but still there are no signs of a common EU green certificate market.
- The size of the average turbine sold at the market place is continually increasing. In 2001 the best-selling turbines had a rated capacity of 750-1500 kW and a market share above 50%. At the end of 2002 turbines with a capacity of 2 MW and above were getting increasingly important, even for on-land sitings.
- Within the last 15 years there has been a continuous trend towards larger and more optimised turbines and thus towards more cost-effective machines. For a coastal location, for example, the average cost has decreased from over 7.7 c€ /kWh for the 95 kW turbine (1985) to under 3.4 c€ /kWh for a new 1000 kW machine (2001), an improvement of more than 50 percent over a time span of 15 years (constant 2001 prices).
- If growth in installed wind power continues, within 5-7 years the costs of wind produced power should, according to the experience curve approach, be within a range of approximately 2.3 c€/kWh to 3.0 c€/kWh. At the Nordic power market a natural gas fired combined cycle power plants to be constructed and on-stream within 5-6 years will produce at a cost of 3.3 c€/kWh to 4 c€/kWh. This implies that with in 5-7 years on-land sited wind turbines should be fully competitive with new conventional produced power, if the existing trends continue.
- Offshore wind power is getting an increasingly important role in the development of wind power and a future offshore farm equipped with 3 MW turbines could

produce at a cost of approx. 4.2 c€/kWh, including 1.4 c€/kWh as O&M-costs and 0.3 c€/kWh for balancing the power production at the market.

Footnotes

[1] The efficiency measure is based upon Danish turbine statistics and sites available for new turbines are increasingly getting more limited in number.

[2] 'Ex works' means that no site work, foundation, or grid connection costs are included. Ex works costs include the turbine as provided by the manufacturer, including the turbine itself, blades, tower, and transport to the site.

[3] Swept rotor area is a good proxy for the turbines' power production.

[4] Depending on the number of full load hours the plant is expected to produce. At the high cost an utilisation time of 4000 hours is assumed, while the low costs implies an utilisation time of approximately 6500.

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