WIND POWER:
Status and Development Possibilities

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Introduction

With in the last 10 years wind power has on a global scale developed incredible fast. In 1990 total installed capacity of wind power in the World amounted to approx. 2.0 MW – by the end of 1999 this capacity has increased to 13.9 GW. An increase of almost sevenfold, equalling an annual growth rate of almost 25%. And the rate of growth is increasing - in 1998 global installed capacity increased by 33 % and by more than 37% in 1999. But European countries dominate the wind power scene. In 1999 approx. 85% of total installed wind turbine capacity was established in Europe, and the only major contributors outside Europe were the US with a total installed capacity of approx. 2.5 GW and India with 1.0 GW [2].

But even within Europe a few countries are the dominant ones: Germany, Spain and Denmark accounts for more than 85% of the growth in European installed wind turbine capacity in 1999, and correspondingly these three countries together has installed more than 80% of the total accumulated capacity in Europe. Especially Germany has had a rapid development. In 1991 total accumulated capacity in Germany was approx. 100 MW; by now the annual capacity increase is approx. 1600 MW and total installed wind power capacity is above 4.4 GW. Similar developments are found in Denmark and Spain, although not to the same extent. Denmark by now has a total installed capacity of more than 1.7 GW and a growth rate of more than 20% in 1999, while Spain in total has installed 1.8 GW with a tremendous growth rate more than doubling the installed capacity in 1999. Other contributors in Europe to be mentioned are the Netherlands (0.4 GW), UK (0.35 GW), Italy (0.3 GW) and Sweden (0.2 GW).

The main reasoning behind the development in these three above-mentioned dominant countries in Europe (i.e. Germany, Spain and Denmark) is a fast improvement of the cost-effectiveness of wind power during the past ten years [3], combined with long-term agreements on fixed feed-in tariffs (at fairly high levels), altogether making wind turbines some of the most economically viable renewable energy technologies today [4]. And 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. And all the three above-mentioned countries have adopted a policy of GHG-limitations in accordance with the agreed burden sharing in 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 the EU policy as well. In its recent White Paper on a strategy for the development of renewable energy the EU-Commission has 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 foreseen to be the main contributor with regard to future importance [1].

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: To split 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 these England, Norway, Sweden, Finland and Denmark. In 1996 Norway and Sweden together 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 a specific pricing area has been established for the western part of Denmark, and the eastern part of Denmark is expected to join mid 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 economic competitive to 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 making it possible for these technologies partly to be economically compensated for the environmental benefits, that they generate compared to conventional power production.

Holland was the first country to explore the possibilities of the green market. A voluntary green certificate market, called the Green Label, was started in January 1998 with the main objective of increasing 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. On a voluntary basis electricity consumers have a minimum target to be covered by green electricity. In the Green Label system, each electricity distribution company has a minimum quota for renewable electricity to be covered by the year 2000[1].

In Denmark a green market to a certain extent comparable to the Dutch is on the way. Recently a comprehensive electricity reform has passed Parliament, covering the future organisation and opening of the electricity market, including the development of a separate green market for renewable generated electricity.

Economics of Wind Energy[2]

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

[1] The Dutch system is in more detail described in [5].
[2] This section is mainly based on [3].

the vast 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, and so on.
- 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 they are thus treated in detail 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 1 shows the average size of wind turbines sold in the Danish export market each year. As illustrated in Figure 1 (left axis), the average size has increased significantly, from roughly 50 kW in 1985 to 600 kW in 1997. In late 1999, the best-selling turbine had a rated capacity of 750 kW, but turbines with capacities as high as 2000 kW had already entered the market.

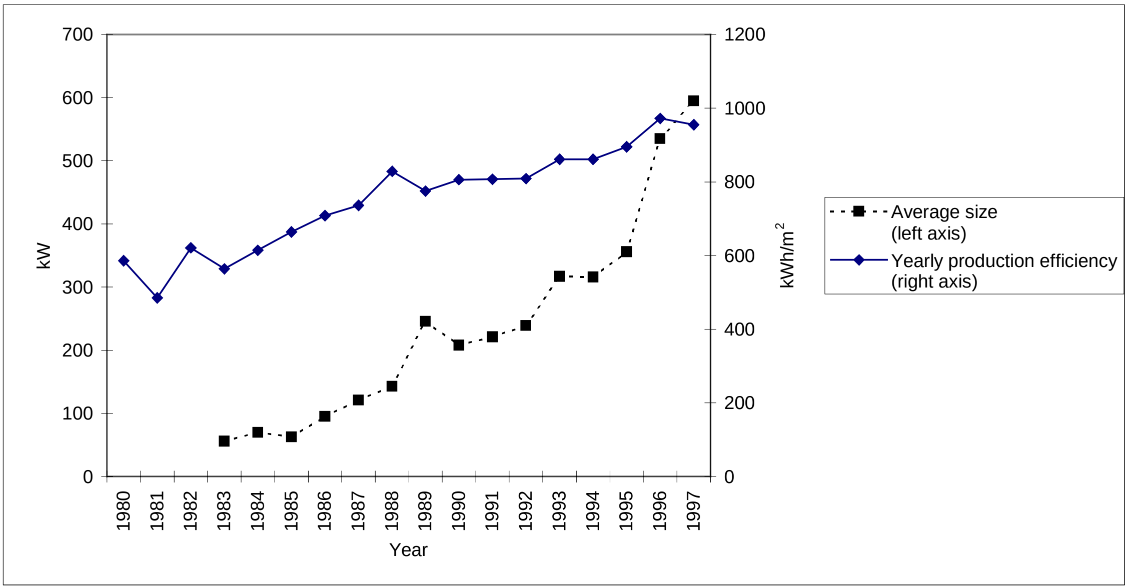

Figure 1. Development of average wind turbine size sold in the market (left axis) and efficiency, measured as kWh produced per m^2 of swept rotor area (right axis). Source: Danish Wind Turbine Manufacturers Association.

The development of electricity production efficiency is also shown in Figure 1, 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.

Capital costs of wind energy projects are dominated by the cost of the wind turbine itself (ex works)[3]. Table 1 shows a typical cost structure for a 600 kW turbine in Denmark. The turbine's share of total cost is approximately 80 percent, while grid-connection accounts for approximately 9 percent and foundation for approximately 4 percent. Other cost components, such as control systems and land, account for only minor shares of total costs.

Table 1. Cost structure for a 600 kW wind turbine (1997 US$)

	Investment (1000 US$)	Share (%)
Turbine (ex works)	483	80
Foundation	23	4
Electric installation	9	2
Grid-connection	53	9
Control systems	2	-
Consultancy	6	1
Land	10	2
Financial costs	8	1
Road	7	1
Total	**601**	**100**

Note: Based on Danish figures for a 600 kW turbine, using average 1997 exchange rate 1US$ = 6.608 DKK.

Figure 2 shows changes in capital costs over the years. The data reflect turbines installed in the particular year shown. All costs are per kW of rated capacity and have been converted to 1997 prices. As shown in the figure, there has been a substantial decline in per-kW costs. From 1989 to 1996, 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 1989 almost 29 percent of total investment costs were related to costs other than the turbine itself. By 1996 this share had declined to approximately 20 percent. Thus, overall investment costs per kW have declined by more than 5 percent per year during the analysed period.

[3] '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.

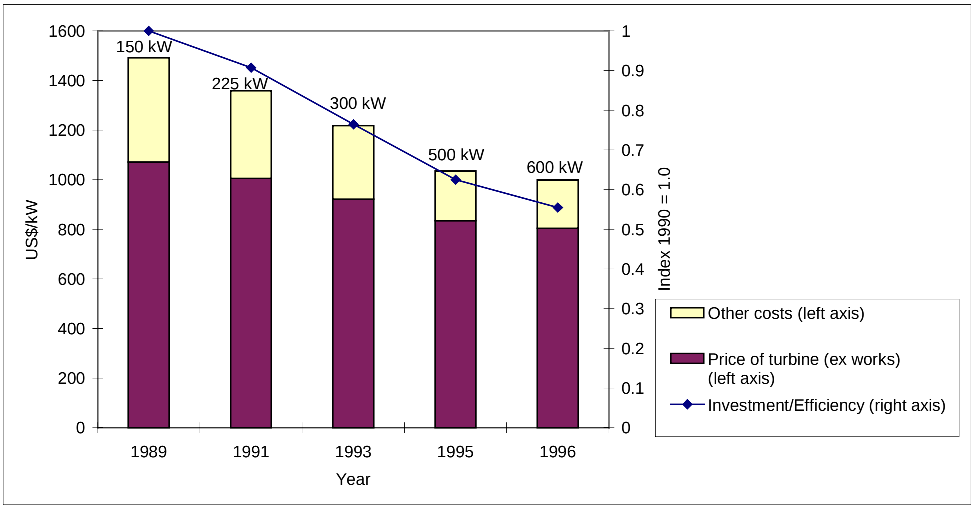

Figure 2. Left axis: Wind turbine capital costs (ex works) and other costs (US$/kW in constant 1997 $). Right axis: Investment costs divided by efficiency (Index 1990 = 1.0).

Reductions in capital costs are expected to continue for the foreseeable future. EPRI [6], for instance, predicts that capital costs per swept area ($\$/m^2$) should decline by 23 percent between 1997 and 2000, and by a further 10 percent between 2000 and 2005.[4]

Combining the efficiency improvement shown in Figure 1 and the decline in investment costs per kW shown on the left axis of Figure 2, one can calculate the ratio of total investment to annual production efficiency ($/kW divided by kWh/m^2), shown on the right axis of Figure 2. This ratio provides a rough indication of total investment costs divided by annual electricity production, assuming a close relationship between turbine capacity and swept rotor area. This ratio has improved by more than 45 percent between 1989 and 1996, or more than 8 percent per annum in real terms. This improvement reflects not only declining turbine costs and improved efficiency, but improved turbine siting as well.

Wind energy project capital costs as reported by the International Energy Agency [7] show substantial variation between countries, due to factors such as market structures, site characteristics, and planning regulations. According to the IEA, total wind project capital costs vary between approximately US$ 900/kW and US$ 1500/kW in different countries. Caution should therefore be exercised in making cross-country cost comparisons, particularly as currency exchange rates also significantly impact apparent costs in any given country.

The total cost per produced kWh (unit cost) is calculated by discounting and levelising 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 3 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.

[4] Because output capacity (kW) changes in approximate proportion to swept area, a decline in $\$/m^2$ cost is a rough indicator of a similar decline in $/kW.

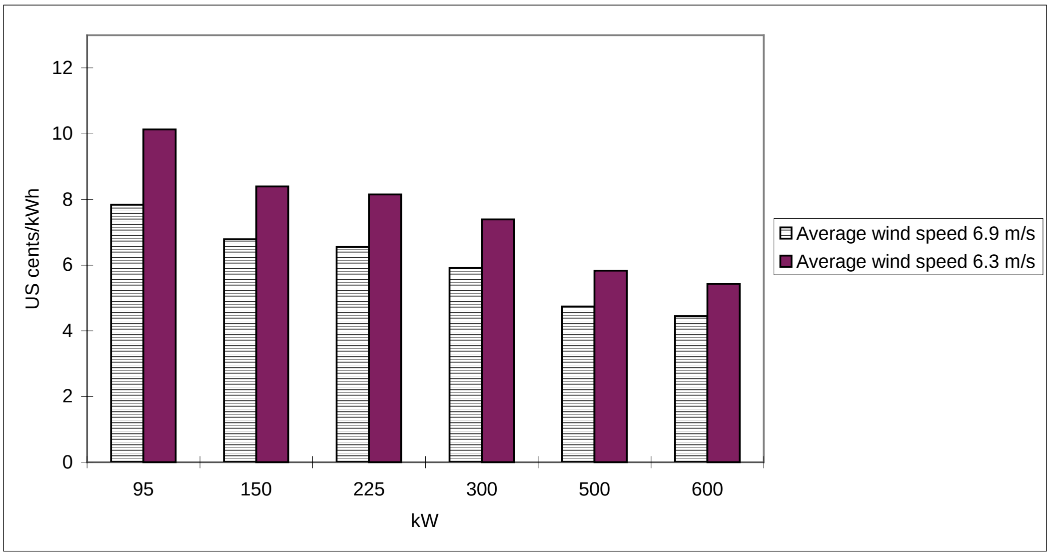

Figure 3. Total wind energy costs per unit of electricity produced, by turbine size, based on hub height of 50 meters. (US cents/kWh, constant 1997 prices).

Figure 3 illustrates the trend towards larger turbines and greater cost-effectiveness. For a roughness class one site (6.9 m/s), for example, the average cost in 1997 US dollars has decreased from over 7.8 cents/kWh for the 95 kW turbine to under 4.5 cents/kWh for a new 600 kW machine, an improvement of almost 45 percent over a time span of 9-10 years.

The discount rate has a significant influence on electricity production costs and hence on wind projects' financial viability. For a 600 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.

The development of offshore turbines in Denmark

In a number of countries offshore turbines are getting an increasingly important role in the development of wind power, particularly in the northwestern part of Europe. Without doubt the main reasons are that on-land sitings are limited in number and that the utilization of these sites to a certain extent is exposed to opposition from the local population. More over, there seems to be fewer restrictions on the utilization of offshore sitings. 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, especially in Denmark.

A number of different interest groups are struggling for rights to the sea. Among these can be mentioned: the fishing industry, the navy, nature conservancy associations and marine archaeologists. To select an area for wind turbine sitings and at the same time meet the most important claims of the other parties, the Danish Government set up a committee to define the main areas in Danish waters suitable for establishing offshore wind farms. In total an area of approx. 1000 square kilometers has been pointed out, corresponding to the siting of 7000-8000 MW wind turbines. Most of the areas are located at a distance from the coast of 15-30 kilometers, and at a water depth of 4-10 meters [8]. In total four areas are identified.

In a collaboration between the Danish Utilities and the Danish Energy Agency the possibilities for utilizing these areas for offshore turbines were evaluated and an action plan put forward. The plan states that 750 MW of wind power has to be established before 2008 with the Danish utilities as the main entrepreneur. If the wind farms are equipped with 1.5 - 2 MW turbines, it will be possible to achieve a production cost for electricity of approx. 4.7 to 5.1 cEUR per kWh, thus ranging at the same level of production costs as an on-land siting with average wind conditions [10].

At present two offshore wind farms are in operation in Denmark:

- The Tunø Knob wind farm located east of Jutland with a total capacity of 5 MW
- The Vindeby wind farm located northwest of the isle of Lolland with a total capacity of 4.95 MW

A new one – Middelgrunden east of Copenhagen – has just been approved. It will be equipped with 20 2 MW machines. The project is undertaken in collaboration between a cooperative and a utility. And more offshore wind farms are on the way.

To illustrate the economics of offshore wind turbines, a typical wind farm (Tunø Knob located in Denmark) is chosen as an example. The farm consists of 10 turbines each with a rated capacity of 500 kW (total capacity 5 MW) and it is located 6 kilometers from the coast, at a depth of sea of approx. 3.1-4.7 meters. Each turbine has its own foundation (concrete), which is placed at the sea bottom. Through a transmission cable the turbines are connected to the high voltage grid at the coast. The farm is operated from a power plant nearby, and no staff is required at the site. The investment costs related to this farm are shown in Table 2 [8].

Table 2: Investment costs related to the Tunø Knob wind farm (1996- prices)

	Investments Mill. US$	Share %
Turbine ex work	4.8	40
Transmission cable (sea)		
- to the coast	1.5	12
- between the turbines	0.6	5
Transmission cable (land)	0.4	3
Electricity systems	0.5	4
Foundations	2.8	23
Operating and control systems	0.2	2
Environmental analysis	1.3	11
Total	12.1	100

Note: Exchange rate per May-1997 1 US$ = 6.45 DKK.

Compared to land-based turbines the main differences in the cost structure are related to 2 issues:

- Foundations are considerably more costly for offshore turbines. The costs depend on both the sea depth, and the chosen principle of construction. For a conventional turbine sited on land, the share of the total cost for the foundation normally is approx. 8-9%. In the Tunø Knob project this percentage is 23% (cf. Table 2), and thus considerably more expensive than for on-land sitings. It must be mentioned, however, that developing foundations for Tunø Knob was a pilot project, and therefore not optimized.

- Sea transmission cables. Connections between the turbines and from the turbines to the coast generate additional costs compared with on-land sitings. For Tunø Knob wind farm the cost share for sea transmission cables is 17%, (cf. Table 2).

Finally, a number of environmental analysis were carried out in relation to the Tunø project. These include investigation of the sea bottom especially concerning materiel left behind from military activities, a project for clarifying the impact of the wind farm on birdlife and, finally, one visualizing the wind farm itself. The cost share for environmental analysis at the Tunø Knob farm is 11%, but part of these costs are related to the pilot character of this project and is not expected to be repeated next time an offshore wind farm will be established.
The total electricity production from the Tunø Knob wind farm has turned out to be higher than expected, showing a utilisation time of almost 3100 hours. Using this production, the above-mentioned investment costs, a real interest rate of 5% and a lifetime of 20 years, the production costs per kWh amounts to approx. 6.5 cEUR [5].

Recently, a number of projects have been carried out in Denmark, especially in relation to minimising the cost of foundations for off-shore turbines. Based on [7], the most important findings will be stated briefly in the following:

- Using a 1500-kW wind turbine as reference, foundation costs are in general estimated to be only slightly higher (approx. 30%) than experienced for the 500- kW turbines at Tunø Knob wind farm. The main reason for this is that the newly developed foundations are made of steel rather than concrete, as used in the Tunø Knob project.

- Although, of course, the foundation cost increases with sea depth, this increase is less than linear. Depending on type of construction and the analysed locality, when the sea depth is increased from 5 to 11 meters the foundation cost goes up only 12 to 34%.

- Three types of foundations are analysed in [7]: Mono-pile, Gravity and Tripod. The cost estimates are found to be remarkably close for all three types, with a maximum variation of approx. 12% at the same location.

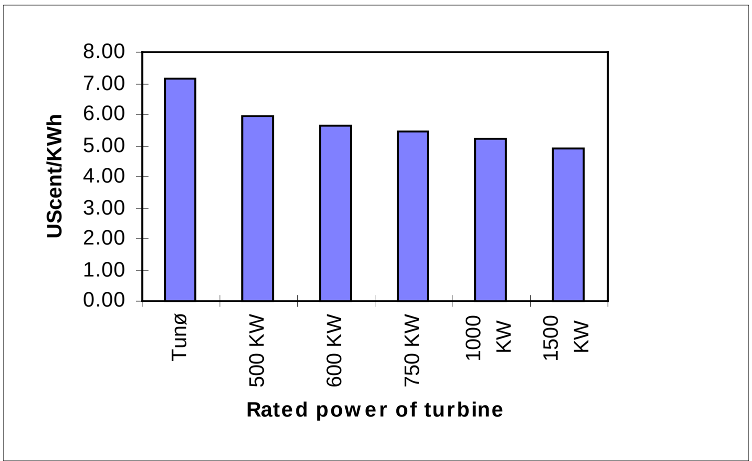

Figure 4. The cost of electricity produced as a function of the rated power of an off-shore wind turbine

The consequences for the electricity production costs of moving towards larger turbines in the sea are illustrated in Figure 4. As reference is shown the electricity production cost at the Tunø Knob wind farm, which is compared with the production cost for turbines with a higher rated capacity. The turbines are assumed to be located at the same distance from the coast and at a sea depth of approx. 5-6 meters. As shown in Figure 4 the cost per kWh produced is expected to decrease from approx. 7.5 US cent (Tunø Knob 500-kW turbine) to approx. 4.7 US cent for a 1500-kW turbine.

The closer the wind farm is located to the coast and the higher the energy production from the farm, the lower will be the cost to the sea transmission cable per unit of electricity produced. How these two parameters affect electricity production is illustrated in Figure 5. To establish Figure 5, data is collected for three sizes of wind farms: a small one of 7.5 MW (comparable to Tunø Knob), a medium-size farm of approx. 30 MW (which at present is fairly close to be implemented in Denmark) and a large wind farm of 100-200 MW. All are equipped with 1.5 MW turbines.

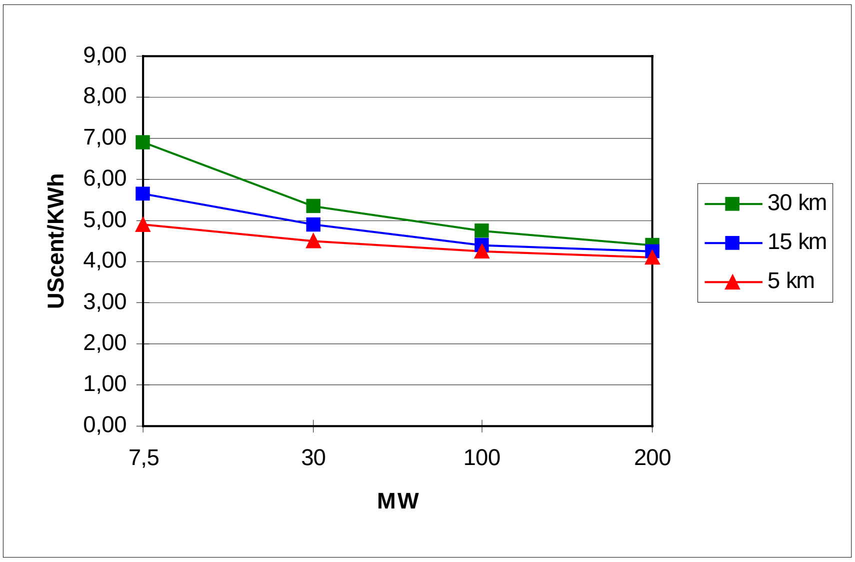

Figure 5. The cost of electricity production as a function of distance to the coast and the capacity of the wind farm

The distance to the coast has a substantial impact for small farms especially on coast. As shown in Figure 5 the production cost rises from 4.9 to 6.9 US cent, when the distance to the coast goes out from 5 to 30 kilometres. Increasing the capacity of the wind farm lowers the cost per unit of electricity produced significantly. When the distance to the coast increases from 5 to 30 kilometres the electricity production cost for a 200 MW wind farm increases from only 4.1 to 4.4 US cent.

A green certificate market – the Danish model

In Denmark a comprehensive restructuring of the legislation for the electricity and the energy industry has just been completed (the Danish electricity reform, [11]). The electricity reform is an agreement between the Danish government and most political parties in the Danish Parliament and it covers the future organisation and opening of the electricity market and the fulfilment of international environmental commitments. Thus it states the framework of how the power supply industry including renewable energy producers can operate within the context of a liberalised electricity market.

In relation to the development of renewable technologies the most important new issues in the agreement are the following [11]:

1) The Danish power industry (including producers of renewable electricity) is being fully liberalised and a full opening of the Danish electricity market shall be carried through before the end of 2002.

2) Tradable CO_2 permits are being introduced in the power industry (if the quotas are exceeded the power companies have to pay a penalty).

3) A separate green certificate market for electricity generated by renewable energy technologies is being developed.

The main objectives of introducing a separate green electricity market in Denmark is to secure a cost-effective development of renewable energy technologies to help ensuring that Denmark can comply with the commitments on GHG-reductions in the Kyoto-protocol. But public budget considerations are important, too. Presently in Denmark, wind power is purchased according to long-term agreements on (almost) fixed feed-in tariffs, and these feed-in tariffs are fixed at fairly high levels. Approx. half of the tariff is a governmental production subsidy and in 1998 more than 100 million Euro was paid out of the public budget only subsiding wind turbines [12]. In the green certificate model the renewable production subsidy is converted from being paid out of the public budget to be paid directly by the Danish electricity consumers. Thus, almost as important as the environmental aspects is the release of the Government from the pretty heavy burden of subsiding renewable technologies, although this could be achieved by other means than the introduction of a green certificate market.

The main characteristics of the Danish proposal for a green certificate market are the following:

- All consumers of electricity in Denmark are obliged to buy a certain share of electricity generated by renewable energy technologies. A major part will be covered by the electricity distribution companies, which will buy the green electricity on behalf of their consumers. Large companies (or other consumers) trading directly with power suppliers will have to cover an equivalent share of their consumption with green electricity

- All renewable energy technologies, including wind power, biomass and biogas plants, photovoltaics, geothermal and small hydro plants, will be certified for producing green electricity. Per unit of electricity produced they will get a green certificate, which can be sold to distribution companies or other electricity consumers with the obligation to cover a certain share of their electricity consumption.

The demand for green certificates will thus be given by distribution companies and other consumers, who have to cover their share on an annual basis. The Danish Energy Authorities will determine this share, presumably for a number of years in advance. At the end of each year a volume of green certificates corresponding to the quota will be withdrawn from the market by the authorities. According to the Danish electricity reform agreement a share of 20% of the total electricity consumption has to be covered by the end of 2003 (for all renewable technologies). It might be expected, that as a starting point the quota will be fixed at a lower level, gradually approaching the 20% target in 2003. Supply will be determined by the production of electricity from the above-mentioned renewable energy technologies. At present approx. 12% of the total electricity consumption in Denmark is covered by wind power and 1-2 % by other renewables.

The market will function solely as a financial market, only restricted by the upper limit of green certificates, which cannot exceed the amount of electricity produced by the renewable technologies.

A simplistic illustration of the functioning of a green certificate market on an annual basis is shown in Figure 6 below.

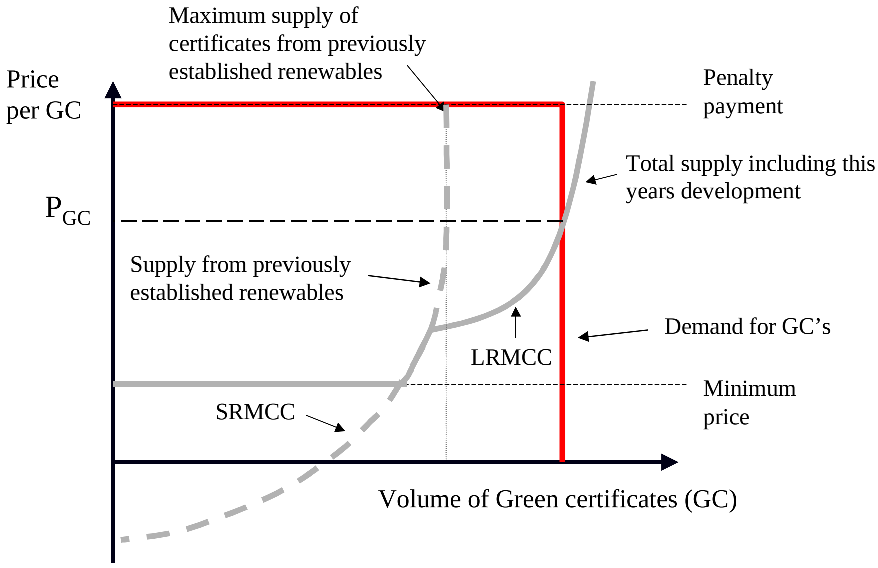

Figure 6: Demand and supply at a green certificate market

On an annual basis the demand for green certificates is given by the obliged demand covering the quota of domestic electricity consumption as required by the energy authorities. This is shown as the vertical demand curve in Figure 6– on an annual basis almost totally inelastic. If demand exceeds supply and electricity consumers cannot fulfill their obligations, they will have to pay a penalty price according to the unfulfilled part. This penalty price will in reality become the maximum price at the green certificate market (the upper horizontal stippled line in Figure 6). If the price is above this maximum limit, consumers will prefer to pay the penalty instead of buying certificates although they are available, and this establishes a horizontal continuation of the demand-curve at the level of the maximum price. In the Danish green certificate model a minimum price is required as well (the lower horizontal stippled line in Figure 6). According to the electricity reform the minimum price of green certificates will be equivalent to 0.10 DKK/kWh (1.3 cEUR) and the maximum price to 0.27 DKK/kWh (3.6 cEUR). The lower end of this interval is equal to the present carbon tax, while the upper end is equal to the sum of the production subsidy and the carbon tax.

The supply of green certificates can be split into two parts: One part supplied by those renewable plants, that at the start of the year are established already– the shape of the supply curve will depend on the short run marginal cost of certificates (SRMCC) and the annual electricity production from these plants. SRMCC is equal to the short run marginal cost of the plant (SRMC) less the spot market price for electricity. This is shown in Figure 6 as the stippled curve. If SRMCC is lower than the minimum price (it might even become negative if the spot market price is higher than SRMC) the supply curve is equal to the minimum price. The other part will be supplied by those renewables that are developed within the specific year - the shape of the supply curve will depend on the long run marginal certificate costs for new plants (LRMCC) and electricity produced from these new plants. LRMCC is equal to the long run marginal cost for new renewable capacity less the spot market price for electricity. Adding this part to the supply curve for the already existing plants the total supply curve is established (shown in Figure 6 as the full drawn curve). The price of the green certificates is determined by the intersection of the total supply curve and the demand line (P_{GC} in Figure 6).

To get an optimal development of new capacity the realized price of green certificates has to be somewhere between the minimum price and the penalty payment. Thus an important task for the energy authorities will be to specify the quota in such a way, that an appropriate development of new renewable capacity will take place. If the quota is too narrow, the realized price on green certificates might be too low to secure a development of new capacity at all. On the other hand, if the quota was too wide and the realized price hits the upper limit, the optimal capacity development would be lower than prescribed by the quota. Thus there would not be enough green certificates and electricity consumers would have to pay a penalty for the unfulfilled part, although it was impossible for them to fulfill the quota.

But other obstacles exist before a green certificate market is considered to be well-functioning. In the Danish system a considerable part of the supply of green certificates will be related to electricity production from wind turbines. Using empirical data for Denmark it is estimated that the maximum variation of the annual wind-generated electricity is approx. +/- 20% with a standard deviation of approx. 10% [14]. High variations in the annual production from wind power will imply high variations in the supply of green certificates and thus – due to the inelastic supply- and demand-curves – a highly volatile price-determination at the green market. Finally, it can be mentioned that there will be a considerable time lag in the development of new renewable capacity from the initial investment decision to when the plant is on stream. For some renewable energy technologies, the construction will take at least 3-4 years, and even for wind turbines it might take 2-3 years including planning procedures etc. This time lag, of course, will tend to increase irregularities of supply and make the long-term determination of demand quotas even more important. Obstacles like these are important to address before a well-functioning green certificate market can be established.

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