

Wind power is often criticized as being economically 'uncompetitive'. Yet the real cost of wind power has decreased dramatically – by 50% over 15 years – and that trend is set to continue. **Poul Erik Morthorst and Hugo Chandler** present the numbers.

**W**ind power is undergoing rapid development, from a European as well as a global perspective. Within the past 10 years, the global installed capacity of wind power has increased more than tenfold. This has seen it rise from approximately 2.8 GW, as of 1993, to just under 40 GW at the end of 2003, with an annual growth rate of about 30%. However, at present there are only a few sites with high wind speeds where wind power can compete economically with conventional power production.

This article looks at the cost of wind power. It first examines investment costs – both in terms of megawatts installed and square metres of swept rotor area – then takes a brief look at operation and maintenance costs, then at the overall costs of production, and, finally, explores the way in which costs are likely to develop in the future.

The main parameters governing wind power economics are:

- investment costs, including auxiliary costs for foundations, grid-connection and so on
- electricity production/average wind speed
- operation and maintenance (O&M) costs
- turbine lifetime
- discount rate.

Of these, the most important parameters are investment costs and electricity production costs – as electricity production is highly dependent on wind conditions, choosing the right site is critical for economic viability.

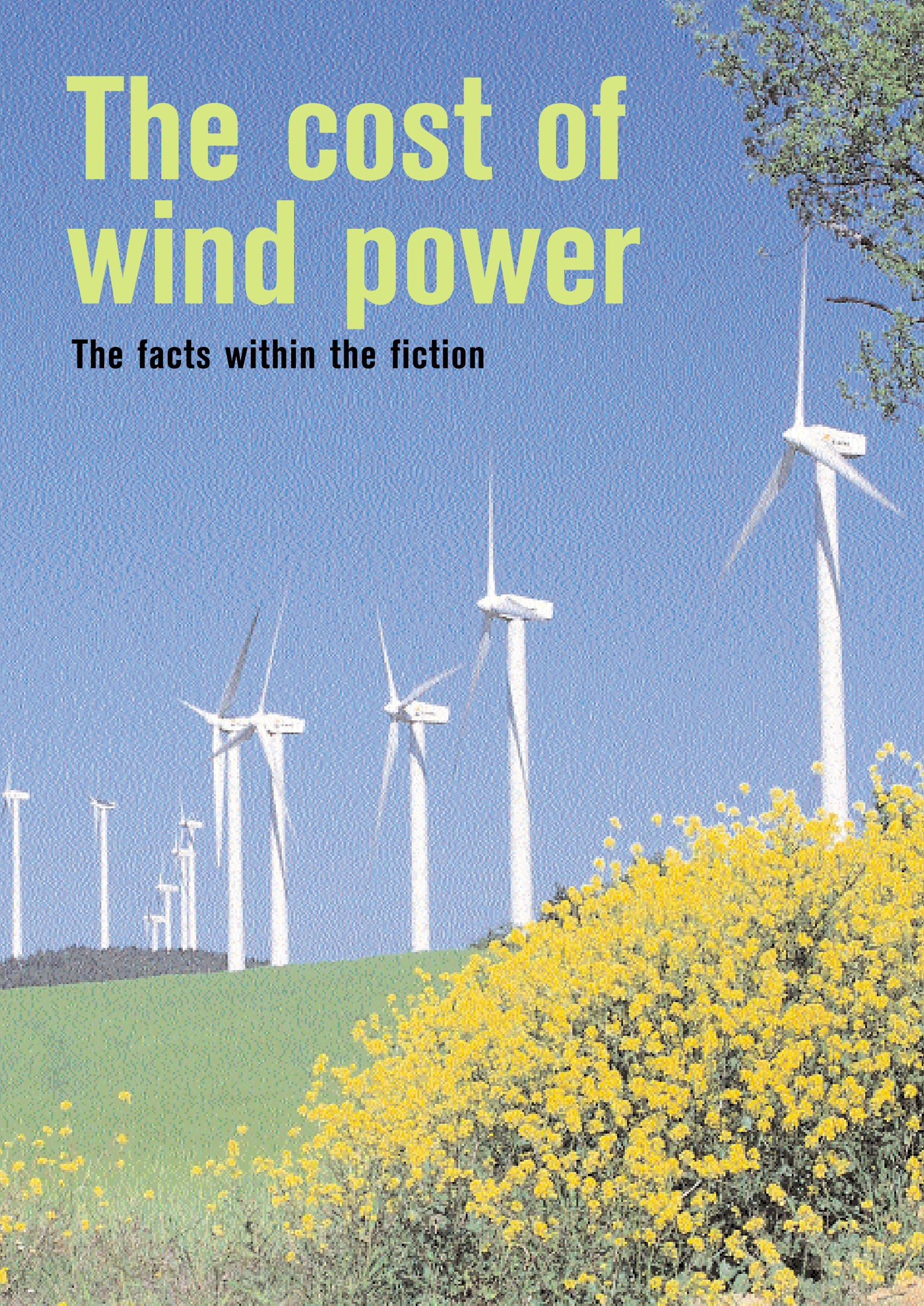
**Within the past 10 years, the global installed capacity of wind power has increased more than tenfold**

Clear skies at a wind farm in the Izco hills, Navarre, Spain: thinking on wind power should not be clouded by myths, but grounded in the facts EHN



# The cost of wind power

**The facts within the fiction**





**'WIND ENERGY - THE FACTS'**

Half-truths and opinions have cast a fog about the reality of wind energy, the youngest of mainstream electricity generation technologies. Some claims, both positive and negative, are patently absurd. Others persist under cover of convincing-sounding statistics, and such fallacious claims must be quashed by hard facts and sound methodologies. With this in mind, the European Wind Energy Association, in collaboration with the European Commission, has produced *Wind Energy - The Facts*, to provide solid ground in the whirl of fiction that surrounds wind energy.

Expert authors have compiled five volumes on technology, costs and prices, industry and employment, environment, and markets. These constitute a powerful defence against the number-one weapon of wind energy's opponents - ignorance among the general public and politicians. *The Facts* is a 'catch-all' document that covers the whole range of issues surrounding wind energy, although it is not exhaustive. Many issues, such as storage, remain little touched upon, and scope remains for further work.

Further information on *Wind Energy - The Facts* is available at [www.ewea.org](http://www.ewea.org)

Three major trends have dominated the development of grid-connected turbines in recent years.

- Turbines have grown larger and taller. By the end of 2002, turbines with a capacity of 2 MW and above were becoming increasingly important. The hub height of the turbine is a significant factor in terms of power production (along with the wind regime and efficiency of production).
- The efficiency of turbine production has increased steadily. As a function of improved hardware efficiency, improved turbine siting and higher hub height, overall efficiency has increased by 2%-3% annually over the last 15 years.
- Investment costs per kilowatt have decreased, as outlined below.

Larger turbines are becoming increasingly important: the Bouin wind farm saw the first multi-megawatt turbines installed in France NORDEX



**CAPITAL COSTS**

Capital costs of wind energy projects are dominated by the cost of the turbine itself, described as 'ex works'. (This simply means that no site work, foundation, or grid connection costs are included; 'ex works' costs include the turbine as provided by the manufacturer - the turbine itself, blades, tower, and transport to the site.) Table 1 shows the cost structure for a medium-sized turbine (850 kW - 1.5 MW) sited on land, based on a limited selection of data from the UK, Spain, Germany and Denmark. The turbine's share of total cost is typically a little less than 80%, but, as is shown in Table 1, considerable variations do exist, ranging between 74% and 82%.

**TABLE 1. Cost structure for a typical medium-sized wind turbine (850 kW - 1.5 MW). Based on data from Germany, Denmark, Spain and UK for 2001-02**

| Cost component        | Share of total cost (%) | Typical share of other costs (%) |
|-----------------------|-------------------------|----------------------------------|
| Turbine (ex works)    | 74-82                   | -                                |
| Foundation            | 1-6                     | 20-25                            |
| Electric installation | 1-9                     | 10-15                            |
| Grid connection       | 2-9                     | 35-45                            |
| Consultancy           | 1-3                     | 5-10                             |
| Land                  | 1-3                     | 5-10                             |
| Financial costs       | 1-5                     | 5-10                             |
| Road construction     | 1-5                     | 5-10                             |

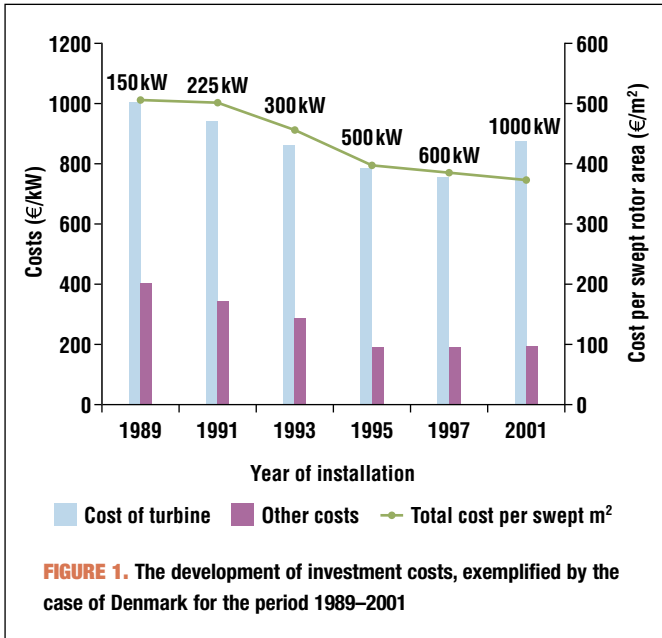
Figure 1 shows how investment costs developed in Denmark over the period 1989-2001. Swept rotor area is a good indicator of the turbine's power production, and this measure is a relevant index for cost development per kilowatt-hour. As shown in Figure 1, there has been a substantial decline in costs per unit of swept rotor area for all turbines. Overall investment costs by swept rotor area have declined by almost 3% per annum during the period analysed, corresponding to a total reduction in cost of approximately 30% over the past 12 years.

Looking at the cost per rated capacity (kW), the same kind of reduction is found in the period 1989-1997. Perhaps surprisingly, investment costs per kilowatt are shown to have increased from the 600 kW machine to the considerably larger 1 MW turbine. The reason for this is the dimensioning of the turbine: with higher hub heights and larger rotor diameters, turbines are equipped with a relatively smaller generator - although it produces more electricity. Thus the price per kW installed is higher in the larger machine, though the price per kWh generated is lower. It is particularly important to be aware of this when looking at turbines constructed for use in areas with low to medium wind speeds, where rotor diameters are often considerably larger than the standard model.

A further reason for the perceived increase in investment cost is that, in 2001, the 1 MW machine was still fairly new. It is expected that, with economies of scale, a reduction in price will be seen over time.

**OPERATION AND MAINTENANCE COSTS**

Operation and maintenance (O&M) costs constitute a sizeable share of the total annual costs of a turbine.



Over the lifetime of the turbine, O&M costs might easily have an average share of approximately 20%–25% of the total, levelized cost per kWh produced. While the turbine is fairly new, the share might constitute 10%–15%, but can increase to at least 20%–35% by the end of its life – up to 20 years later.

O&M costs are related to a limited number of cost components:

- insurance
- regular maintenance
- repair
- spare parts
- administration.

Some of these cost components can be estimated with relative ease. For insurance and regular maintenance, it is possible to obtain standard contracts covering a considerable portion of the turbine’s total lifetime. On the other hand, costs for repair and related spare parts are much more difficult to predict. Although all cost components tend to increase over time, costs for repair and spare parts are particularly influenced by turbine age, starting low and increasing over time.

Due to the youth of the wind energy industry, only a limited number of turbines have existed for their expected 20-year lifetime, and most of these are of low capacity and were constructed using outmoded design criteria. Some cost data can be gleaned from existing older turbines, but estimates about O&M costs should nevertheless be taken with a pinch of salt, especially towards the end of the turbine lifetime.

Based on experiences from Germany, Spain, the UK and Denmark, O&M costs are estimated to be approximately 1.2–1.5 Eurocents/kWh of generated wind energy over the total lifetime. Data from Spain indicate that a little less than 60% of this amount goes on straight O&M and installation costs (half of this proportion goes on spare parts, and the rest is equally distributed between labour costs and fungibles). The remaining 40% is almost equally split between insurance, rental of land and overheads.

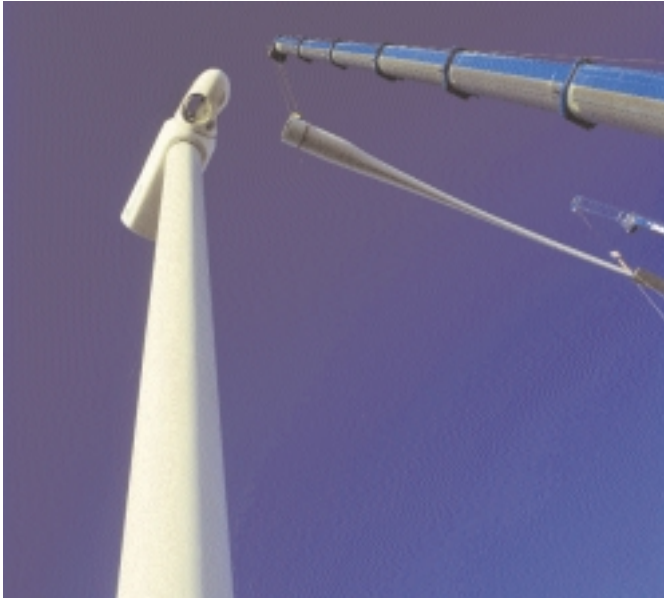
## WIND POWER PRODUCTION COSTS

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

**Power production is the single most important factor in calculating the cost per kWh**

Power production is the single most important factor for calculating the cost per kWh; turbines sited at good wind locations are likely to be profitable, while those at poor locations may run at a loss. In this section, the cost of wind-generated energy will be calculated based on a number of assumptions. Due to the importance of power production, this parameter will be treated on a sensitivity analysis basis (the analysis of how sensitive outcomes are to changes in the assumptions they are based upon). Assumptions include:

- the calculations relate to a new, land-based turbine of 850 kW – 1.5 MW capacity



Putting it all together: power production is the most important factor in calculating the cost of generated energy ECOTÈCNIA

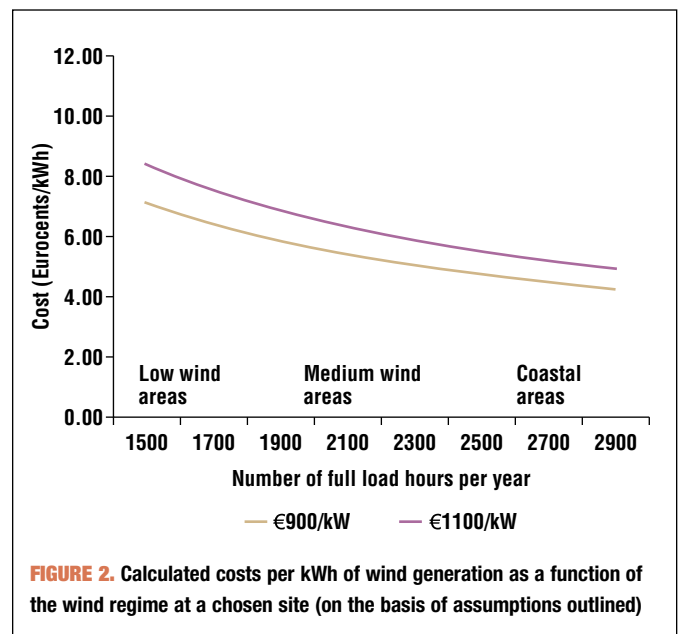
- investment costs reflect the range given above, with a cost per kW of €900-1100/kW (these costs are based on data from Spain, UK, Germany and Denmark)
- O&M costs are assumed to be 1.2 Eurocents/kWh, averaged over the lifetime of the turbine
- the lifetime of the turbine is 20 years, in accordance with most technical design criteria

- the discount rate is assumed to vary within an interval of 5%-10% a year. In the basic calculations, an annual discount rate of 7.5% is used, and a sensitivity analysis of the importance of the interest range is performed
- economic analyses are carried out as simple national economic ones; factors such as taxes, depreciation and risk premiums are not taken into account, and everything is calculated at fixed 2001 prices.

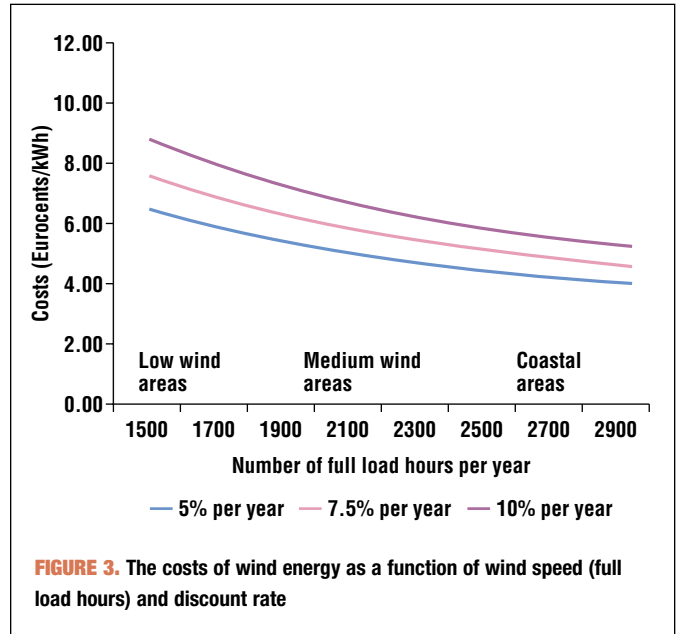
The calculated costs per kWh as a function of site wind regime are indicated in Figure 2. As it shows, costs range between 6-8 Eurocents/kWh at sites with low average wind speeds, and 4-5 Eurocents/kWh at good coastal positions. In Europe, coastal positions such as these are mostly to be found in the UK, Ireland, France, Denmark and Norway. Medium wind areas are generally found at inland locations in Central and Southern Europe, in Germany, France, Spain, the Netherlands and Italy, but also at inland sites in Sweden, Finland and Denmark. In many cases, local conditions significantly influence the average wind speed at the site, and so strong fluctuations in the wind regime are to be expected, even in neighbouring areas.

Approximately 75% of the total wind power production costs are related to capital costs, that is, the costs of the turbine itself, foundations, electrical equipment and grid-connection. This means wind power is a so-called 'capital-intensive' technology compared with conventional natural gas-fired plant, for example (in which as much as 40%-60% of total costs are related to fuel and O&M costs). For this reason, the cost of capital (discount or interest rate) is an important factor for calculating the cost of wind power; cost of capital varies substantially between individual EU member states. In Figure 2, the costs per kWh of wind energy are shown as a function of the wind regime and the discount rate, the latter varying between 5% and 10% a year.

As is shown in Figure 3, costs range from approximately 5-6.5 Eurocents/kWh at medium wind locations, indicating that a doubling of the interest rate induces an increase in production costs of 1.5 Eurocents/kWh. In low wind areas, the



**FIGURE 2.** Calculated costs per kWh of wind generation as a function of the wind regime at a chosen site (on the basis of assumptions outlined)



**FIGURE 3.** The costs of wind energy as a function of wind speed (full load hours) and discount rate

costs are significantly higher, at 6.5–9 Eurocents/kWh, while production costs in coastal areas range from 4 to 5.5 Eurocents/kWh.

### THE IMPROVING ECONOMICS OF WIND POWER

The rapid development of wind power capacity, both in Europe and globally, has had a strong influence on the development of wind power costs over the past 20 years. To illustrate the trend of reducing power production costs, an historical case study has been included showing the production costs for different sizes and vintages of turbines. (Due to limited data, it has only been possible to construct this case study for Denmark, though a similar trend was observed in Germany at a slightly slower pace.)

Figure 4 shows the calculated unit cost for different sizes of turbines based on the same assumptions as used above. (A 20-year lifetime and an annual discount rate of 7.5% is assumed for all turbines in the analysis. All costs are converted into constant 2001 prices.)

Electricity production is estimated for two wind regimes: a coastal location and an inland location with medium wind speed. The starting point for the analysis is the 95 kW machine that was installed mainly in Denmark during the mid-1980s, followed by successive turbines (150 kW, 225 kW and so on), and ending with the 1 MW turbine typically installed around year 2000. It should be noted that turbine manufacturers, as a rule of thumb, expect the production cost of wind energy to decline by 3%–5% for each new generation of turbines that they add to their product portfolio. Further cost reductions are therefore likely to have occurred with the production of turbines over 1 MW. Note that the calculations are performed for the total lifetime (20 years) of the turbines, which means that calculations for the old turbines are based on track records of up to 15 years (average figures), while newer turbines might have a track record of only a few years. Thus the newer the turbine, the more uncertain the calculations.

Figure 4 illustrates the economic consequences of the trend towards larger turbines and improved cost-effectiveness.

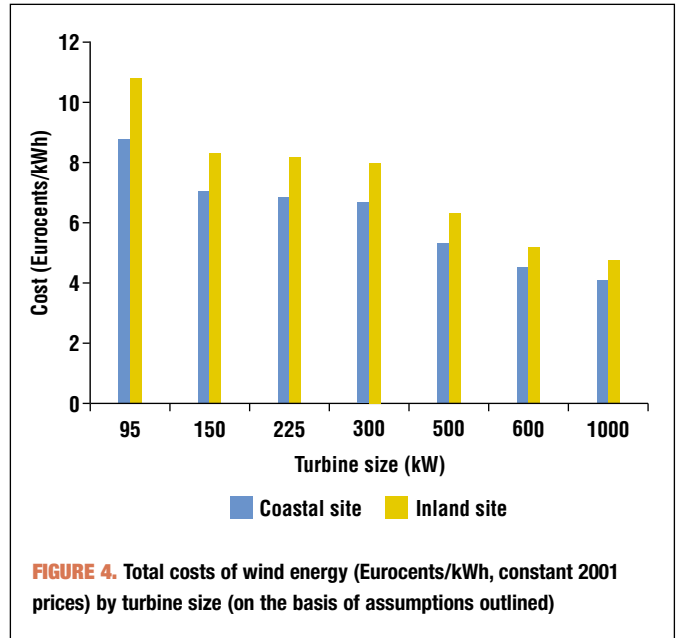
**Turbine manufacturers expect the cost of wind energy production to decline 3%–5% for each new generation of machine**

For a coastal location, for example, the average cost has decreased from approximately 8.8 Eurocents/kWh for the 95 kW turbine, to approximately 4.1 Eurocents/kWh for a 1 MW machine – an improvement of more than 50% over a 15-year period (at constant 2001 prices).

**FUTURE EXPECTATIONS**

The future development of wind power economics is illustrated by the use of experience curve methodology. The experience curve approach was developed during the 1970s by the Boston Consulting Group: its main feature is that it relates the cumulative, quantitative development of a product with the development of its specific costs. Thus, if the cumulative sale of a product is doubled, the estimated experience curve (or learning rate) can provide the achieved reduction in specific product costs.

The experience curve is not a forecasting tool based on estimated relationships. It merely points out that if existing trends are to continue, then we might see the proposed development. It converts the effect of mass production into an effect on production costs, but other causal relationships are



not taken into account. Thus, changes in market development and/or technological breakthroughs within the field may considerably alter the picture.

Different experience curves have been estimated for a number of projects, but unfortunately, most have used different specifications. Consequently, direct comparisons cannot be made. To get the full value of the experience gained, not only should the price reduction of the turbine (€/kW) be taken into



New wave: turbines recently installed at Powergen's Scroby Sands offshore wind farm NEWSCAST

account, but so should the improvements in turbine production efficiency. The latter requires the use of an energy specification (€/kWh) which excludes many of the reference cases (Neij, 1997 and Neij *et al.*, 2003). Thus, using the specific costs of energy as a basis (costs per kWh produced), the estimated progress ratios in these publications range from 0.83–0.91, corresponding to learning rates of 0.17–0.09 – that is, when the total installed capacity of wind power is doubled, the costs per kWh produced for new turbines fall by between 9% and 17%. In this way, both the efficiency improvements and direct and indirect costs are taken into account in the analysis.

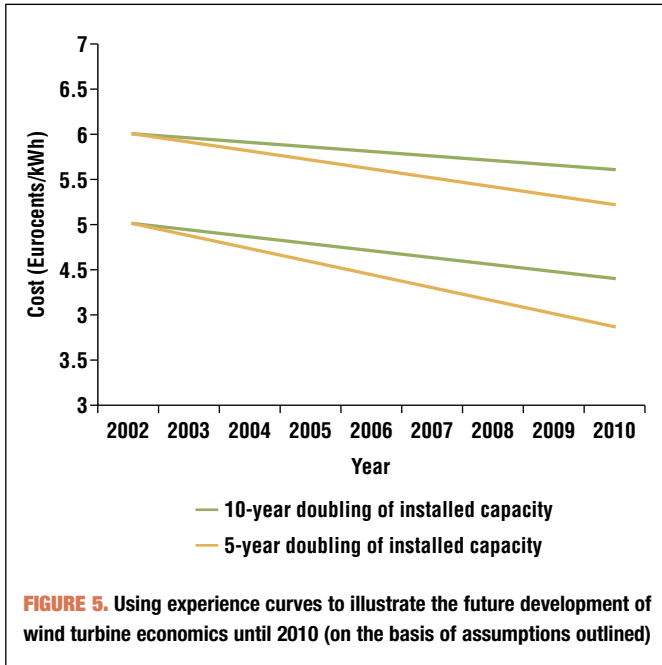
Figure 5 shows the effect of learning rates on wind power production costs up to 2010, based on the following assumptions:

- a learning rate between 9% and 17% is assumed, implying that each time the total installed capacity is doubled, the costs per kWh of wind energy is reduced by 9%–17%
- the growth rate of installed capacity is assumed to double the cumulative installations every fifth, and every tenth year for the 9% and 17% rates, respectively
- the starting point for the development is the cost of wind power as observed today – that is, in the range of 5–6 Eurocents/kWh produced for an average medium-sized turbine (850 kW – 1.5 MW) sited at a medium wind regime (average wind speed of 6.3 metres/second at a hub height of 50 metres).

On average, over the past 10 years wind power capacity has grown at 30% per year and has thus doubled every three years.

At present, the production costs for a medium-sized turbine (850 kW – 1.5 MW) installed in an area with a medium wind speed are approximately 5–6 Eurocents/kWh energy generated. Assuming a 10-year doubling time for total installed capacity, the cost range in 2010 would be approximately

**The costs per kWh produced in 2010 could be as low as 3.1–4.4 Eurocents/kWh**



4.4-5.6 Eurocents/kWh. A doubling time of only five years would imply a cost range of 3.9-5.2 Eurocents/kWh in 2010. If the turbine is located in a coastal area with a higher wind speed (an average of 6.9 metres/second at a height of 50 metres), the costs per kWh produced in 2010 could be as low as 3.1-4.4 Eurocents/kWh (if total installed capacity doubles every five years).

This article has demonstrated the steady fall in wind energy costs seen over the last ten years, and touched on some hopes for the future. It paints a positive picture of wind energy – although, if anything, its outlook is conservative. Nonetheless, wind power costs are still, for the time being, marginally higher than conventional power technologies such as coal and natural gas. While it is generally appreciated that wind energy and other renewables have environmental benefits not shared by conventional electricity generation, until these benefits are fully reflected in market prices further cost reductions of wind power will be essential for continued growth.

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