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INTRODUCTION TO VOLUME 1 - TECHNOLOGY

Electricity can be generated in many ways. In each case, a fuel is used to turn a turbine which drives a generator which feeds the grid. The turbines are designed to suit the particular characteristics of the fuel. Wind generated electricity is no different. The wind is the fuel – unlike fossil fuels it is both free and clean, but otherwise it is just the same. It drives the turbine which generates electricity into a grid.

The politics and economics of wind energy have played an important role in the development of the industry and contributed to its present success. Engineering is, however, pivotal. As the wind industry has become better established, the central place of engineering has become overshadowed by other issues. This is a tribute to the success of the engineers and their turbines. This volume addresses the key engineering issues:

- The turbines – their past achievements and future challenges – a remarkable tale of technical endeavour and entrepreneurship.
- The wind – its characteristics and reliability – how can it be measured, quantified and harnessed?
- The wind farms – an assembly of individual turbines into wind power stations or wind farms – their optimisation and development.
- The grid – transporting the energy from remote locations with plentiful wind energy to the loads – the key technical and strategic challenges.

This volume provides an historical overview of turbine development, describes the present status and considers future challenges. This is a remarkable story starting in the nineteenth century and then accelerating through the last two decades of the twentieth century on a course very similar to the early days of aeronautics. The story is far from finished but it has certainly started with a vengeance.

Wind must be treated with great respect. The speed of the wind on a site has a very powerful effect on the economics of a wind farm; it provides both the fuel to generate electricity and the loads to destroy the turbine. This volume describes how it can be quantified, harnessed and put to work in an economic and predictable manner. The long-term behaviour of the wind is described as well as its short-term behaviour. The latter can be successfully forecast to allow wind energy to participate in electricity markets.

In order for wind to live up to its raw potential promise, individual turbines must be assembled into wind farms or wind power stations. The design and operation of the different types of wind farms are discussed and examples provided.

Finally, the key strategic issue for the future is addressed: How can the windy parts of Europe, both onshore and offshore, deliver power for the industrial loads and population centres. This goal is achieved through the local, national and international grids. The way in which the grid is used and constrained is a key political and technical issue. The technical and regulatory constraints are described and some challenges for the future are raised.

This volume explores how this new, vibrant and rapidly expanding industry exploits one of nature's most copious sources of energy – the wind.

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1 TURBINE TECHNOLOGY

1.1 Evolution of Commercial Wind Technology

The extent of Europe's wind resource will be established in the following chapter. The engineering challenge to the wind industry is to harness that energy and turn it into electricity – to design an efficient wind turbine (WT). In this chapter the evolution of WT technology is discussed, its present status described, and future challenges identified.

The evolution of modern turbines is a remarkable story of engineering and scientific skill, coupled with a strong entrepreneurial spirit. In the last 20 years turbines have increased in power by a factor of 100, the cost of energy has reduced, and the industry has moved from an idealistic fringe activity to the edge of conventional power generation. At the same time, the engineering base and computational tools have developed to match machine size and volume.

This is a remarkable story, and it is far from finished. Many technical challenges remain and even more spectacular achievements will result. Serious investment is needed to maximise potential through R&D.

The use of technical jargon in this section has been kept to a minimum but technical terms inevitably arise. These are explained in the glossary provided at the end of the book.

1.1.1 ACHIEVEMENTS

Modern commercial wind energy started in earnest in the early 1980s following the oil crises of the 1970s when issues of security and diversity of energy supply and, to a lesser extent, long-term sustainability, generated interest in renewable energy sources.

However, wind power sceptics raised questions about:

- reliability
- noise
- efficiency
- grid impact
- visual and general environmental impact
- potential for serious contribution to a national energy supply
- cost

Initially, none of these issues could be dismissed lightly, but gradually all have been addressed.

- In larger projects with proven medium sized turbines, availability of 98% is consistently achieved. The latest large machines are also approaching that level of availability.
- Some of the early turbines were noisy – both aerodynamically and mechanically – and noise was a problem. Today, mechanical noise is practically eliminated and aerodynamic noise has been vastly reduced.
- WTs are now highly efficient with less than 10% thermal losses in the system transmission. The aerodynamic efficiency of turbines has gradually risen from the early 1980s with the coefficient of performance rising from 0.44 to about 0.50 for state-of-the-art technology. The value of 0.5 is near to the practical limit dictated by the drag of aerofoils and compares with a theoretical limit of 0.59 (known as the Betz limit).
- It was often suggested that there would be major problems of grid stability with penetrations of wind energy above 10%. Now, a much more complex picture has emerged. Benefits of capacity credits, local reinforcement of grids and the ability of variable speed turbines to contribute to grid stability counteract concerns about variability of supply, mismatch with demand and the need for storage in the electrical system. In typical grid systems there may be an adverse economic impact for penetration levels above 20%, but there is no overriding technical difficulty that would limit wind energy penetration to very low values.
- Visual and environmental impacts require sensitive treatment but, Europe-wide, public reaction to operational wind farms is generally positive.
- A dismissive view of the possibility of nationally significant wind energy contributions was prevalent in the 1980s. With penetration levels of over 17% in Denmark, and around 5% in both Germany and Spain, this view is belied. Moreover, growth of the offshore market, a resource large enough to supply all of Europe's electricity, will further reinforce the significance of wind energy in the European energy supply.
- Costs of turbines per unit capacity have reduced greatly since the 1980s. This cost reduction has been achieved through both technical improvements and

also through volume. Wind energy is now sometimes commercially competitive with new coal or gas power plant on good, windy sites.

1.1.2 THE CHALLENGE

The concept of a wind driven rotor is ancient, and electric motors were in profusion domestically and commercially in the latter half of the twentieth century. Making a WT can seem simple but it is a big challenge to produce a turbine that:

- Meets specifications (frequency, voltage, harmonic content) for standard electricity generation with each unit operating as an unattended power station.
- Copes with wind variability (mean wind speeds on exploitable sites range from 5 m/s to 11 m/s, with severe turbulence in the Earth's boundary layer and extreme gusts up to 70 m/s).
- Competes economically with other energy sources.

The traditional "Dutch" windmill (Figure 1.1) had proliferated to a peak of around 100,000 machines throughout Europe by the late nineteenth century. These machines preceded electricity supply and were indeed "windmills" used for grinding grain, for example. They were always attended, perhaps inhabited and, largely, manually controlled. They were integrated within the community, designed for frequent replacement of certain components and efficiency was of little importance.

In contrast, the function of a modern power-generating WT is to generate high quality, network frequency electricity. Each turbine must function as an automatically controlled independent "mini power station". It is unthinkable for a modern WT to be permanently attended, and uneconomic for it to need much maintenance. The development of the microprocessor has played a crucial role in realising this situation, thus enabling cost-effective wind technology. A modern WT is required to work unattended, with low maintenance, continuously for more than 20 years.

Figure 1.1: Traditional "Dutch" Windmill

1.1.3 A UNIQUE TECHNOLOGY

Stall

WTs have little respect for engineering conventions. Most aerodynamic devices (aeroplanes, gas turbines, etc.) avoid stall. Stall, from a functional standpoint, is the breakdown of the normally powerful lifting force when the angle of flow over an aerofoil (such as a wing section) becomes too steep. This is a potentially fatal event for a flying machine, whereas WTs can make purposeful use of stall as a means of limiting power in high wind speeds.

For a further discussion of stall, see sections 1.1.5. and 1.2.3.

The design requirements of stall regulation have led to new aerofoil developments and also the use of stall strips, vortex generators, fences, Gurney flaps and other devices for fine-tuning rotor blade performance.

Fatigue

The power train components of a WT are subject to highly irregular loading input from turbulent wind conditions, and the number of fatigue cycles experienced by the major structural components can be orders of magnitude greater than for other rotating machines. Consider that a modern WT operates for about 13 years in a design life of 20 and is almost always unattended. A motor vehicle, by comparison, is manned, frequently maintained and its design life of about 150,000 kilometres is equivalent to just four months of continuous operation.

Thus, in the use rather than avoidance of stall and in the severity of the fatigue environment, wind technology has a unique technical identity and R&D demands.

1.1.4 RUN UP TO COMMERCIAL TECHNOLOGY

An early attempt at large-scale commercial generation of power from wind was the 53 m diameter, 1.25 MW Smith Putnam WT erected at Grandpa's Knob in Vermont, USA in 1939. This design brought together some of the finest scientists and engineers of the time (aerodynamic design by von Karman, dynamic analysis by den Hartog). The turbine operated successfully for longer than some multi-MW machines of the 1980s.

It was a landmark in technological development and provided valuable information about quality input to design, machine dynamics, fatigue, siting sensitivity, etc.

The next milestone in WT development was the Gedser turbine. With assistance from Marshall Plan post-war funding, a 200 kW, 24 m diameter WT was installed during 1956-57 on the island of Gedser in the south-east of Denmark. This machine operated from 1958 to 1967 with a capacity factor of around 20%.

In the early 1960s, Professor Ulrich Hütter developed high tip speed designs which had a significant influence on WT research in Germany and the US.

1970 - 1990

In the early 1980s, many issues of rotor blade technology were investigated. Steel rotors were tried but rejected as too heavy, aluminium was deemed too uncertain in the context of fatigue endurance, and the wood-epoxy system developed by the Gougeon brothers in the US was employed in a number of small and large turbines. The blade manufacturing industry has, however, been dominated by fibreglass polyester construction which evolved from a boat building background and became thoroughly consolidated in Denmark in the 1980s.

By 1980 in the US, a combination of state and federal, energy and investment tax credits had stimulated a rapidly expanding market for wind in California. Over the period 1980-95 about 1,700 MW of wind capacity was installed, more than half after 1985 when the tax credits had reduced to about 15%.

Tax credits attracted an indiscriminate overpopulation of various areas of California (San Gorgonio, Tehachapi and Altamont Pass) with many ill-designed WTs which functioned poorly. However, the tax credits created a major export market for European, especially Danish, WT manufacturers who had relatively cost-effective, tried and tested hardware available. The technically successful operation of the later, better designed WTs in California did much to establish the foundation on which the modern wind industry is built. The former, poor quality, turbines conversely created a poor image for the industry which it has taken a long time to shake off.

1990 - Present

The growth of wind energy in California was not sustained, but there was striking development in European markets with an installation rate in Germany of around 200 MW per annum in the early 1990s. From a technological standpoint, the significant outcome was the appearance of new German manufacturers and development of new concepts, with the introduction of innovative direct drive generator technology being particularly noteworthy. Subsequently, a huge expansion of the Spanish market has occurred, including wind farm development, new designs and new manufacturers.

There have been gradual, yet significant, new technology developments in direct drive power trains, in variable speed electrical and control systems, in alternative blade materials and in other areas. However, the most striking trend in recent years has been the development of ever larger WTs leading to the current commercial generation of MW machines with a new generation of multi-MW offshore turbines now appearing.

1.1.5 DESIGN STYLES

Significant consolidation of design has taken place since the 1980s, although new types of electrical generators have also introduced further diversification.

Vertical Axis

Figure 1.2: Darreius Type Vertical Axis Wind Turbine

Due to their expected advantages of omni-directionality and having gears and generating equipment at the tower base, vertical axis designs were considered. However, they are inherently less efficient (because of the variation in aerodynamic torque with a wide range in angle of attack over a rotation of the rotor). In addition, it was not found to be feasible to have the gearbox of large vertical axis turbines at ground level because of the weight and cost of the transmission shaft.

The vertical axis design also involves a lot of structure per unit of capacity taking account of cross arms in the H type design. The Darreius design (Figure 1.2) is more efficient structurally. The blade shape is a so-called catenary curve and is loaded only in tension, not in bending by the forces caused as the rotor spins. However, it is evident that much of the blade surface is close to the axis. Blade sections close to the axis rotate more slowly and this results in reduced aerodynamic efficiency. These disadvantages have caused the vertical axis design route to disappear from the mainstream commercial market. FlowWind, the main commercial suppliers of vertical axis turbines, stopped supplying them over a decade ago.

Number of Blades 1,2,3, Many?

Small-scale multi-bladed turbines are still in use for water pumping. They are of relatively low aerodynamic efficiency but, with the large blade area, can provide a high starting force able to turn the rotor in light winds which suits pumping duty.

Most modern WTs have three blades although, in the 1980s and early 1990s, some attempt was made to market one- and two-bladed designs.

The single-bladed design (Figure 1.3) is the most structurally efficient as all the installed blade surface area is in a single beam. It is normal to shut down (park) WTs in very high winds in order to protect them structurally. This is because they would experience much higher blade loads and tower loads if they continued to operate. The one-bladed design allows unique parking strategies – with the blade acting as a wind vane or downwind behind the tower – which may minimise storm loading impact. However, there are a number of disadvantages with single-blade turbines, such as added mass to provide a counterweight to balance the rotor statically, reduced aerodynamic efficien-

Figure 1.3: Single-Bladed Wind Turbine

cy due to the higher tip loss of a low aspect ratio single blade and complex dynamics requiring a blade hinge to relieve loads. The designs of Riva Calzoni, Messerschmidt and others were of too high a tip speed to be acceptable in the modern European market from an acoustic point of view. High tip speed is not an intrinsic requirement of the single-bladed concept, but is required to optimise the design.

The two-bladed rotor design (Figure 1.4) is technically on a par with the established three-bladed design. For the benefit of a potentially simpler and more efficient rotor structure with more options for rotor and nacelle erection, either higher cyclic loading must be accepted or a teeter hinge introduced. The two-bladed rotor is a little less efficient aerodynamically than the three-bladed.

In general, there are some small benefits from increasing blade number, relating to minimising losses that take place at the blade tips. In aggregate, these losses are less for a larger number of narrow blade tips than for fewer wides ones.

Figure 1.4: Two-Bladed Wind Turbines of Carter Wind Turbines Ltd.

In rotor design, an operating speed or operating speed range is normally selected first, having regard to issues such as acoustic noise emission. With the speed chosen it then follows that there is an optimum total blade area for maximum rotor efficiency. The number of blades is, in principle, open, but more blades imply more slender blades for the fixed (optimum) total blade area. This summarises the broad principles affecting blade numbers.

It is a complete misconception that doubling the number of blades will double the power of a rotor. Instead, if the rotor is well designed, it will reduce the power.

In the overall cost benefit, it is hard to discriminate between the two- and three-bladed designs. It is generally wrong to suppose that the two-bladed design saves on the cost of a blade, as the two blades of a two-bladed rotor do not equate with two blades of a three-bladed rotor. Two-bladed rotors generally run at a much higher tip speed than three-bladed rotors so most historic designs would consequently have noise problems. There is, however, no fundamental reason for the higher tip speed, and this should be discounted in an objective technical comparison of the design merits of two versus three blades.

Thus, the one-bladed rotor is, perhaps, more problematic technically whilst the two-bladed rotor is basically acceptable

technically. The decisive factor in eliminating the one-blade rotor design from the commercial market and in almost eliminating the two-bladed design has been visual impact. The apparently unsteady passage of the blade(s) through a cycle of rotation has often been found to be objectionable.

Pitch Versus Stall

The two principal means of limiting rotor power in high operational wind speeds - stall regulation and pitch regulation - are now discussed.

Stall was introduced in Section 1.1.3. Stall regulated machines require speed regulation. As wind speed increases, providing the rotor speed is held constant, flow angles over the blade sections steepen. The blades become increasingly stalled and this limits power to acceptable levels without any additional active control.

For this to work, the speed of the WT rotor must be held essentially constant and this is achieved through the connection of the electric generator to the grid. In this respect, the grid behaves like a large flywheel holding the speed of the turbine nearly constant irrespective of changes in wind speed.

Stall control is a subtle process both aerodynamically and electrically and is hard to explain in simple terms. Briefly, a stall regulated WT will run at approximately constant speed in high wind, not producing excessive power and yet achieving this without any change to rotor geometry.

The main alternative to stall regulated operation is pitch regulation. This involves turning the blades about their long axis (pitching the blades) to regulate the power extracted by the rotor. In contrast to stall regulation, pitch regulation requires changes to rotor geometry. This involves an active control system to sense blade position, measure output power and instruct appropriate changes of blade pitch.

The objective of pitch regulation is similar to stall regulation, namely to regulate output power in high operational wind speeds.

Variable Speed versus Fixed Speed

Initially, most WTs operated at fixed speed when producing power. In a start-up sequence the rotor may be parked (held stopped) and on release of the brakes would be accelerated by the wind until the required fixed speed was reached. At this point, a connection to the electricity grid would be made and the grid would, through the generator, hold the speed constant. When the wind speed increased beyond the level at which rated power was generated, power was regulated in either of the ways previously described by stall or by pitching the blades.

Subsequently, variable speed operation was introduced. This allowed the rotor speed and wind speed to match so the rotor could maintain the best flow geometry for maximum efficiency. The rotor could be connected to the grid at low speeds in very light winds and would speed up in proportion to wind speed. As rated power was approached, and certainly after rated power was being produced, the rotor would revert, essentially, to constant speed operation with the blades being pitched as necessary to regulate power. An important difference between this kind of variable speed operation and conventional fixed speed operation is that moderate speed variations are still permitted. This reduces loads on the drive train and reduces the amount of pitch activity required for power regulation.

The design issues of pitch versus stall and degree of rotor speed variation are evidently connected.

In the 1980s, the classic Danish, three-bladed fixed speed, stall regulated design was predominant. Aerodynamicists outside the wind industry (helicopter, gas turbine, etc.) were shocked by the idea of using stall. Yet because of the progressive way in which stall occurs over the WT rotor, it proved to be a thoroughly viable way of operation, making use of, rather than avoiding, stall. It is one of the unique aspects of wind technology.

Active pitch control is the term used to describe the control system in which the blades pitch along their axis like

a propeller blade. This approach superficially offered better control than stall regulation, but it emerged through experience that pitch control of a fixed speed WT in high operational wind speeds above rated wind speed (minimum steady wind speed at which the turbine can produce its rated output power) could be quite problematic. The reasons are complex but in turbulent (constantly changing) wind conditions it is demanding to keep adjusting pitch to the most appropriate angle; high loads and power can result whenever the control system is "caught out" with the blades in the wrong position.

In view of such difficulties, which were most acute in high operational wind speeds (say 15 m/s to 25 m/s), pitch control in conjunction with a rigidly fixed speed became regarded as a "forbidden" combination. Vestas initially solved this problem by introducing OptiSlip – essentially a degree of variable speed with about 10% speed variation using a high slip induction generator. Speed variation helps to regulate power and reduces demand for rapid pitch action.

Variable speed had some attractions but also had costs and reliability concerns. It was seen as the future with expected cost reduction and performance improvements in variable speed drive technology. To some extent this has been realised. There was never a clear case for variable speed on economic grounds with small energy gains being offset by extra costs and also additional losses in the variable speed drive. The current drive towards variable speed in new large WTs relates to greater operational flexibility and concerns about power quality of stall regulated WTs. Two-speed systems emerged during the 1980s and 1990s as a compromise improving energy capture and noise emission characteristics of stall regulated WTs. The stall regulated design remains viable, but variable speed technology offers better output power quality to the grid and this is now driving the design route of the largest machines. Although some experiments are underway with a combination of variable speed and stall regulation, variable speed combines naturally with pitch regulation. For reasons related to the methods of power control, an electrical variable speed system allows pitch control to be effective and not overactive.

Another significant impetus to the application of pitch control and, specifically, pitch control with independent pitching of each blade, is the acceptance by certification authorities that this allows the rotor to be considered as having two independent braking systems acting on the low speed shaft. Hence, only a parking brake is required for overall machine safety.

1.1.6 DESIGN DRIVERS FOR MODERN TECHNOLOGY

The main design drivers for current wind technology are:

- low wind and high wind sites
- grid compatibility
- acoustic performance
- aerodynamic performance
- visual impact
- offshore expansion

Although the existing offshore market in terms of installed capacity is only 0.4% of the world's land-based installed capacity, the latest developments in wind technology are primarily driven by the emerging offshore market. This means that the technology development focus is on the most effective ways to make very large turbines. Specific considerations are:

- low mass nacelle arrangements
- large rotor technology and advanced composite engineering
- design for offshore foundations, erection and maintenance

Of the other main drivers, larger rotor diameters (in relation to rated output power) have resulted in order to enhance exploitation of low wind speed sites. Reinforced structures, relatively shorter towers and smaller rotor diameters in relation to rated power are employed on extremely high wind speed sites.

Grid compatibility issues are inhibiting further development of large WTs employing stall regulation. Acoustic performance regulates tip speed for land-based applications and requires careful attention to mechanical and aerodynamic engineering details. Only small improve-

ments in aerodynamic performance are now possible (relative to theoretical limits), but maximising performance without aggravating loads continues to drive aerodynamic design developments. Visual impact constrains design options that may fundamentally be technically viable, as is the case with two-bladed rotors.

1.1.7 GROWTH OF WIND TURBINE SIZE

Modern wind technology is available for a range of sites - low and high wind speeds, for desert and arctic climates. European wind farms operate with high availability, are generally well integrated with the environment (Figure 1.5) and accepted by the public.

In spite of repeated predictions of a levelling off at an optimum mid-range size, and in spite of the irrefutable logic that WTs cannot get larger indefinitely, turbine size at the centre of commercial production has increased year on year (Figures 1.6 and 1.7).

Figure 1.5: Modern Wind Technology

Figure 1.6: Growth in Size of Commercial Wind Turbine Designs

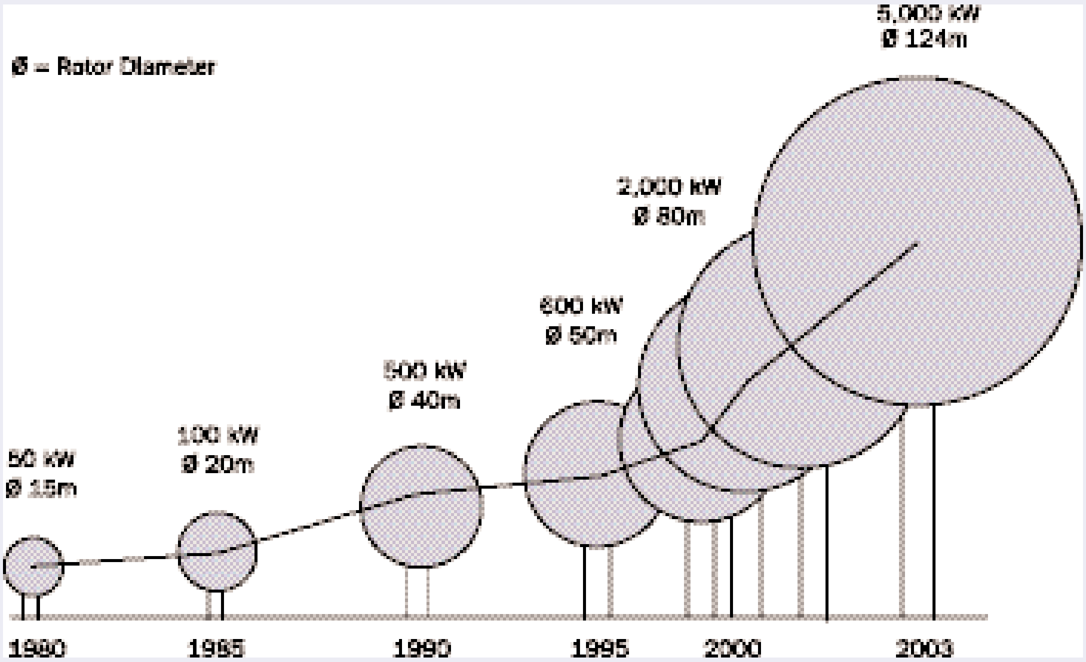
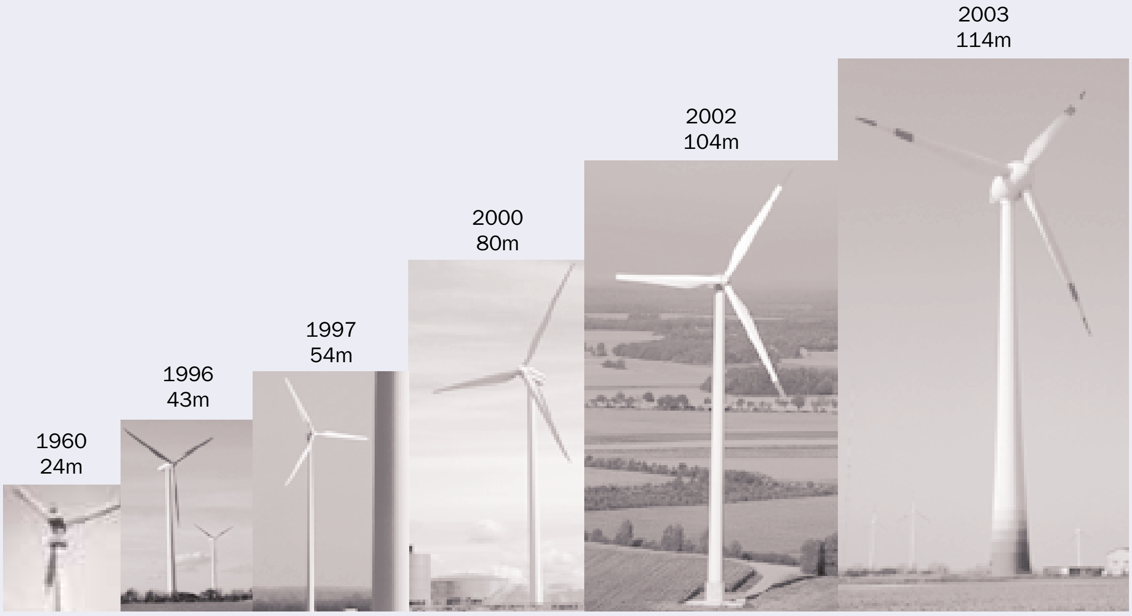


Figure 1.7: Growth in Size of Commercial Wind Turbine Designs



The size of commercial WTs has steadily increased with units of 20-60 kW appearing in the early wind farms in California of the 1980s, up to the latest multi-MW machines with rotor diameters over 100 m. The photo-collage of Figure 1.7 shows turbines from the Gedser prototypic Danish design (1958-67) through a set of commercial turbines up to 2003. The largest is the Enercon E112 a land-based prototype, but of a design targeted at the developing offshore market.

In large offshore projects, it is clear that almost all the balance of plant costs associated with foundations, electrical interconnection, access and maintenance will be reduced (per installed kW of wind farm capacity) if the unit capacity in a wind farm is increased and hence the number of units reduced. Many technological factors indicate that it will be very challenging to develop economically viable turbines above 5 MW rating, based on the current architecture. The single most important factor is that turbine costs intrinsically increase more rapidly with diameter than with energy output. New concepts may emerge to provide generating units larger than 5 MW capacity for offshore projects. This is the latest challenge for the wind industry.

Figure 1.8: Spanish Wind Turbines

The growth of machine size has been paralleled by the growth of markets and manufacturers. The German market is the largest in the world and German WT designs are well represented in this chapter. There has also been a huge growth in the Spanish market (Figures 1.8 and 1.9) in recent years which has combined elements of licensing, technology transfer and independent manufacture (as with Vestas and Gamesa), development of established turbine manufacturers (such as Ecotecnia and Made), as well as the Spanish aerospace industry (MTorres) and integrated developer/manufacturers (EHN).

Figure 1.9: Spanish Wind Turbines

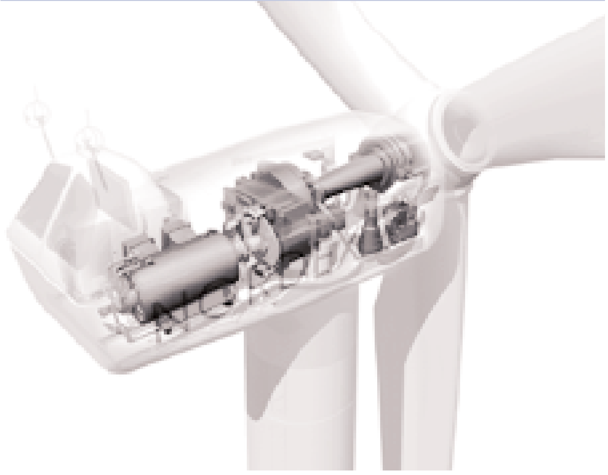
1.1.8 ARCHITECTURE OF A MODERN WIND TURBINE

Many developments and improvements have taken place since commercialisation of wind technology in the early 1980s, but the basic architecture of the mainstream design is little changed. Most WTs have upwind rotors and are actively yawed to preserve alignment with wind direction.

The three-bladed rotor proliferates and, typically, has a separate front bearing with a low speed shaft connected to a gearbox which provides an output speed suitable for a four-pole generator. This general architecture is evident in the Nordex N54, for example (Figure 1.10). Commonly, with the largest WTs, the blade pitch will be varied continuously under active control to regulate power at the higher operational wind speeds. For future large machines there appears to be a consensus that pitch regulation will be adopted.

Support structures are most commonly tubular steel towers tapering in some way, both in metal wall thickness and in diameter from tower base to tower top. Concrete towers, concrete bases with steel upper sections and lattice towers are also used but are much less prevalent. Tower height is rather site-specific and turbines are commonly available with three or more tower height options.

Figure 1.10: Typical Nacelle Layout of a Modern Wind Turbine



The drive train shows the rotor attached to a main shaft driving the generator through the gearbox. It is in the area of the gearbox that significant developments in basic design architecture are now appearing, in the form of direct drive generators. The gearbox is removed and the aerodynamic rotor drives the generator directly. Hybrid arrangements involving a single stage gearbox and multi-pole generator are also appearing. These developments are discussed in Section 1.3. It is far from clear which of the configurations is optimum. The effort to minimise capital cost and maximise reliability continues – the ultimate goal is to minimise the cost of electricity generated from the wind.

1.1.9 ERECTION OF LARGE WIND TURBINES

Erection of wind farms and systems for handling ever larger components have progressed since the early commercial projects of the 1980s. For a period up to the mid 1990s, the allowable mass of components to be lifted to hub height was determined by available cranes. Subsequently, there has been a shift, indicative of the maturity and growth of the wind industry, where crane manufacturers are producing designs specially suited to wind farm installation.

Figure 1.11 shows typical stages in the erection of land-based wind turbines. Often, complete rotors are lifted on to nacelles. Sometimes, hub and blades are lifted individually. As the wind industry becomes more consistent the supporting industries will develop to supply its demands. The advent of large cranes in sufficient numbers to support developments in Germany is a good example.

Figure 1.11: Typical Erection Procedures for Land-Based Wind Turbines

1.2 Technology Trends

This section investigates various design trends. As turbines have grown larger and larger, the way in which important design parameters change with size can be demonstrated and used to predict how turbines may develop in the future. For various design parameters these trends can be used to establish key challenges for the industry.

1.2.1 LARGER DIAMETERS

Diameter in relation to power rating has generally increased in recent years. This is clearly illustrated in Table 1.1 which shows the various 1.5 MW turbines which have been available in the market over the last few years. A remarkable increase from 65 m to 69 m to almost 74 m in average diameter of 1.5 MW turbines has taken place for the years 1997, 2000 and 2003 respectively. The diameter, or rather the square of the diameter, determines how much energy a WT can produce. The rating, the maximum power that the rotor is allowed to produce, plays an important part in determining system loads. Balancing the diameter and the rating is therefore a key task in WT design.

This is partly due to the optimisation of designs to maximise energy capture on comparatively low wind speed sites, but there is growing interest in better load management through more intelligent control systems as a means of realising relatively larger rotors and increasing energy capture. Understanding, predicting, controlling, and thereby limiting the loads, is a vital part of WT development.

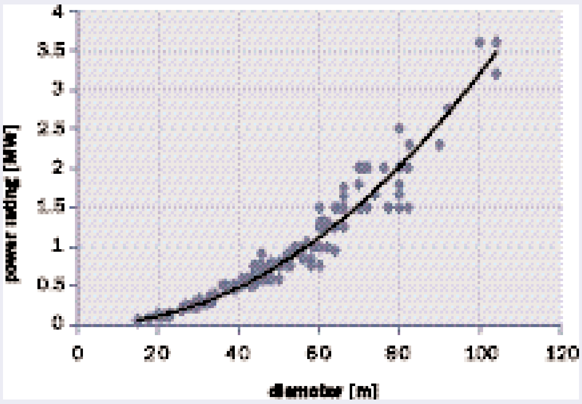
Considering the range of wind turbine sizes, the increase in diameter to rating ratio of the latest turbines has been a consistent trend. In the early 1990s, rated power typically varied as diameter, $D^{2.4}$. This parameter is important because as the turbine increases in diameter it also increases in height. There is a relationship between diameter and rating as wind shear causes wind speed to increase with height. The exponent of 2.4 is exactly what would be expected for a land-based site with the nominal wind shear exponent of 1/7. Power would be as D^2 at any given hub height, but as hub height increases with turbine size, power can be expected to vary as $D^{(2 + 3x1/7)}$ (i.e. approximately as $D^{2.4}$).

For WT designs in 2003, the exponent has decreased from 2.4 to nearly 2 (Figure 1.12 and Table 1.2).

Table 1.1: Diameters of 1.5 MW Wind Turbines

Year	Design	D (m)
	NEG MICON 64C/1500	64.0
	FUHRLANDER FL MD70	70.0
	PWE 1570	70.0
	REPOWER MD 70	70.0
	SUDWIND S70	70.0
	TORRES TWT 1500	70.0
	GEWE 1.5s	70.5
	NEG MICON 72C/1500	72.0
	FUHRLANDER FL MD77	77.0
	GEWE 1.5sl	77.0
	REPOWER MD 77	77.0
	SUDWIND S77	77.0
	PWE 1577	77.4
	GAMESA G-80 1500	80.0
	NEG MICON 82/1500	82.0
2003	**AVERAGE**	**73.6**
	NEG MICON 64C/1500	64.0
	ENERCON E-66/15.66	66.0
	WINDTEC 1566	66.0
	JACOBS MD 70	70.0
	SUDWIND S70	70.0
	TACKE TW 1.5s	70.5
	TACKE TW 1.5sl	77.0
2000	**AVERAGE**	**69.1**
	NTK 1500/64	64.0
	TACKE TW 1.5	65.0
	ENERCON E-66/15.66	66.0
1997	**AVERAGE**	**65.0**

Figure 1.12: Rating versus Diameter of Presently Available Wind Turbine Designs, $Pr=0.000195D^{2.155}$



The largest designs are intended for offshore where there is reduced wind shear and reduced turbulence. The reduction of the exponent of diameter in relation to rated power fits that context.

Matching the power rating and the diameter is a key cost determinant. Different combinations will appear on different markets.

Table 1.2: Diameter Exponent of Rated Power

Year	Exponent
1996	2.320
1997	2.290
1998	2.250
1999	2.122
2000	2.147
2001	2.119
2002	2.115
2003	2.075
Overall	**2.073**

1.2.2 TIP SPEED - OFFSHORE AND LAND BASED DESIGNS

The tip speed of a turbine is the product of the rotational speed and the radius of the blade. Noise increases very sharply with tip speed and hence high tip speed turbines are very much noisier than slow tip speed turbines. For a given power, a fast turning turbine exhibits lower torque (drive train load) than a low speed turbine and hence has a lower drive train cost. There is therefore a trade-off to be made between drive train load and noise. For the onshore market, noise is the major constraint.

Table 1.3: Tip Speed Trends – Land Based and Offshore Technology

Wind Turbine Design	Power (MW)	Dia (m)	Tip Speed (m/s)	Offshore to Onshore Ratio
BONUS 600kW	**0.60**	**44.0**	**62.2**	
BONUS 1MW/54	**1.00**	**54.0**	**42.6**	
BONUS 1.3MW/62	**1.30**	**62.0**	**61.7**	
BONUS 2MW/76	**2.00**	**76.0**	**67.7**	
BONUS 2.3MW/82	**2.30**	**82.4**	**71.6**	**1.26**
De Wind D4	0.60	48.0	73.4	
De Wind D6/1000	1.00	62.0	67.2	
De Wind D6/62	1.00	62.0	81.8	
De Wind D6/64	1.25	64.0	83.1	
De Wind D8/2MW	**2.00**	**80.0**	**86.7**	**1.14**
ENERCON E-58	1.00	58.0	72.9	
ENERCON E-66	**1.80**	**70.0**	**80.7**	**1.11**
GEWE 1.5s	1.50	70.5	73.8	
GEWE 1.5sl	1.50	77.0	73.8	
GEWE 3.6s offshore	**3.60**	**104.0**	**83.3**	**1.13**
NEG Micon NM 750/48	0.75	48.2	55.5	
NEG Micon NM 1000/60	1.00	60.0	56.6	
NEG Micon NM 1500/82	1.50	82.0	61.8	
NEG Micon NM 1500C/64	1.50	64.0	58.0	
NEG Micon NM 2000/72	**2.00**	**72.0**	**67.9**	
NEG Micon NM 92/2750	**2.75**	**92.0**	**75.2**	**1.23**
Nordex N50	0.80	50.0	62.2	
Nordex N54/1000	1.00	54.0	60.8	
Nordex N60	1.30	60.0	60.3	
Nordex N62	1.30	62.0	60.3	
Nordex N80	**2.50**	**80.0**	**80.0**	
Nordex N90	**2.50**	**90.0**	**79.6**	**1.31**
LAGERWEY LW 52/750	**0.75**	**50.5**	**71.4**	
LAGERWEY LW 58/750	**0.75**	**58.0**	**63.8**	
LAGERWEY LW 70/1500	**1.50**	**70.6**	**70.2**	
LAGERWEY LW 72/2000	**2.00**	**71.2**	**89.5**	**1.31**
Vestas V47/660 Vari slip	0.66	47.0	64.0	
Vestas V52/850kW	0.85	52.0	70.8	
Vestas V66	1.65	66.0	65.7	
Vestas V80	**2.00**	**80.0**	**79.6**	**1.19**

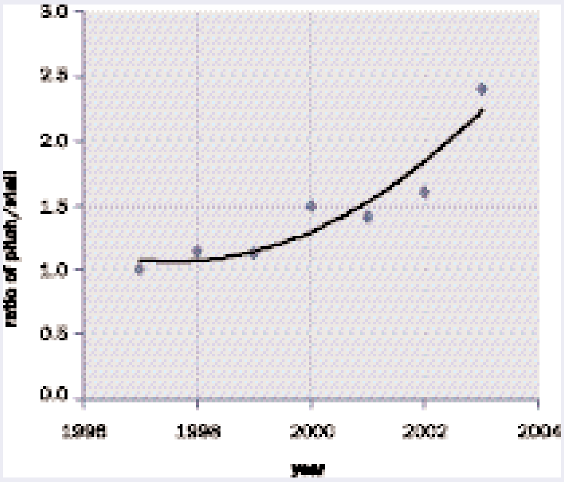
Tip speed trends of some larger scale designs are summarised in Table 1.3. The largest turbines (2 MW rating or more, highlighted) usually target the offshore market. Comparing the tip speed of the offshore design of each manufactures with the average tip speed of the designs targeted at land based applications, a very significant increase in tip speed ranging approximately from 10% to 30% is evident.

This makes sense given that less sensitivity to acoustic noise is expected for offshore sites, which may be up to 30 km from land. The increased tip speed reduces the torque associated with any given power level and allows useful mass and cost reductions in the power train.

1.2.3 PITCH VERSUS STALL

There has been an enduring debate in the wind industry about the merits of pitch versus stall regulation. This was discussed in Section 1.1.5.

Figure 1.13: Ratio of Pitch Regulated to Stall Regulated Designs of ≥ 1 MW Rating



Until the advent of MW-scale WTs in the mid 1990s, stall regulation predominated. However, pitch regulation is now the favoured option for the largest machines (Figure 1.13). There are now more than twice as many pitch regulated turbines on the market than stall regulated versions. This is due to a combination of factors. Overall costs are quite similar for each design type, but pitch regulation offers potentially better output power quality (this has been perhaps the most significant factor in the German market), and pitch regulation with independent operation of each pitch actuator allows the rotor to be regarded as two independent braking systems for certification purposes. There has been some concern, particularly for the largest machines, about stall induced vibrations (vibrations which occur as the blade enters stall). There has, in fact, been little evidence of these vibrations occurring on a large scale, although there have been specific problems of edgewise vibration of stall regulated rotor blades associated with loss of aerodynamic damping in deep stall. However, this has been addressed by introducing dampers in the rotor blades.

1.2.4 SPEED VARIATION

Operation at variable speed offers the possibility of increased "grid friendliness", load reduction and some minor energy benefits. It is thus an attractive option. Among wind turbines over 1 MW rating, out of 52 distinct models of 20 different manufacturers, only three were fixed speed, 12 had two speed systems and 37 employed variable speed. This shows that it is almost mandatory for MW-scale turbines to have some degree of speed variation and that continuously variable speed is the predominant choice.

Variable speed operation is realised in many ways, each differing in significant details. Direct drive systems have a natural capability for a very wide speed range although, even here, some restriction on minimum speed may reduce the cost of power electronics. The "conventional" variable-speed concept using a geared drive train connects the generator to the network through a power electronic converter and enables systems that may have wide or narrow speed ranges. The electrical energy is generated at variable frequency – a frequency related to the rotational speed of the rotor – and then converted, by the converter or inverter (both power electronic devices) to the frequency of the grid. There are several possible configurations, based on both synchronous and induction generators.

The preferred system now is the DFIG (doubly-fed induction generator), also called the wound rotor induction

generator (WRIG). This provides almost all the benefits of full-range variable speed drives, but only a proportion, perhaps a third, of the power passes through the converter. The power converter is thus approximately a third of the size and cost of a conventional variable speed drive, and its losses are reduced by a similar proportion. In this concept, the stator of the electrical machine is connected directly to the network, and the rotor circuit is connected via the power converter. This is a modern version of the classical Kramer or Scherbius system. The DFIG has a more limited speed range than the conventional variable-speed drive (approximately 1.5 or 2:1, compared to 2.5:1 or more). This speed range, however, is sufficient to provide the benefits listed above. The conventional option of a power converter with the same rating as the generator is unlikely to compete with the DFIG until the cost of power electronic converters falls substantially and their efficiency improves. There is evidence that this point may have been reached, with some manufacturers moving over to fully rated converters.

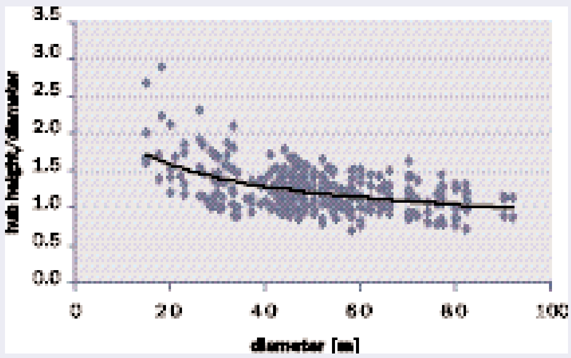
Other novel generator configurations have been proposed for WT applications, including the switched reluctance (SR) (also known as variable reluctance) machine. All rely on full-size power converters, and are therefore also at a disadvantage relative to the DFIG. The DFIG configuration used at present requires slip-rings to transfer power to and from the rotor circuit. There is an alternative method which in effect transfers the rotor power magnetically, called the brushless doubly-fed induction generator (BDIG) which avoids the use of slip-rings. However, at least one generator manufacturer has concluded that such machines are inherently larger and more expensive than the slip-ring option. No commercial turbine uses the BDIG. As the experience of DFIG with slip-rings is good in WTs, this remains the preferred option. Slip-ring maintenance intervals of six months are achieved, and may be stretched to yearly. Of the 37 mentioned variable speed designs one, the Gamesa 80, is high slip (7%) and all others have speed ratio ranges (maximum steady rated speed/minimum operating speed) from 1.5 to 3.3.

There were four designs with speed ratios above 2.2 and 24 with speed ratios in the range 1.8 to 2.2. This is an area of WT design which is quite complicated. There are several alternative approaches which are being investigated. All rely to some degree on power electronics. The cost of power electronics is falling as a result of activity unconnected with the wind industry, but the industry is profiting directly from it. The result will be a reduction in the cost of the inverters and hence in the capital cost of the variable speed drives and, finally, in the resulting electricity.

1.2.5 HUB HEIGHT

The choice of hub height is site dependent. There is a trade-off between the benefits of the extra energy which may result from placing the rotor in the higher wind speeds to be found at higher levels above the ground against the extra cost of making the towers larger. Hub height equal to diameter is a good description of the average trend of the largest turbines. There is always great variation in tower height for any given size of rotor, with high towers suiting low wind speed sites. There is generally low wind shear offshore and less benefit from high towers not withstanding the extra costs in materials and WT erection. It is therefore expected that large offshore turbines will have a tower height possibly less than or equal to diameter and set at a level to provide adequate blade tip clearance in extreme wave conditions. The distribution of hub height and diameter is shown in Figure 1.14.

Figure 1.14: Hub Height Trends, $H=3.8786D^{-0.3}$



1.2.6 ROTOR MASS

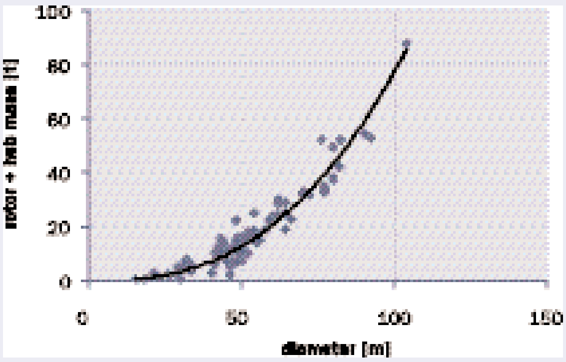
The rotor accounts for approximately 20% of the cost of the turbine. Blade manufacturers have naturally sought to reduce material volume and mass, especially in the largest

blades. The way in which design principles change with blade size is therefore very important. If blade stress is kept constant as the size increases (a reasonable design assumption) then the blade loads and required blade strength will both scale as the cube of diameter, implying that geometric similar blades are feasible in a given material and that blade mass will then also scale as cube of diameter.

As the blade turns it has to support its own weight and thus bending becomes a dominant loading if inappropriate materials are used. This scaling is then defeated. In that case, the blade bending moment will scale as the diameter to the power of four.

Also, the higher tip speeds of large offshore rotors imply reduced solidity (solidity is essentially the ratio of blade projected area to rotor swept area) and hence slimmer blades. The reduced blade area will only allow reduced blade mass if materials of sufficiently high specific strength are available. Again, this fits in with the increased prominence of carbon fibre reinforcement in large blade design. As designs evolve with increasing attention to mass reduction, an overall picture of rotor mass scaling as less than cubic is apparent (Figure 1.15).

Figure 1.15: Rotor Mass Trends, $M_{rotor} = 0.000486D^{2.6}$



It will be a challenge to maintain this trend (of less than cubic scaling through improved design concepts and materials) if rotors continue to get larger. If the power exponent increases as it will naturally tend to do, then the optimum size of the rotor will reduce. It is therefore in this area that the search for appropriate materials will focus.

1.3 Recent Developments

1.3.1 DIRECT DRIVE GENERATORS

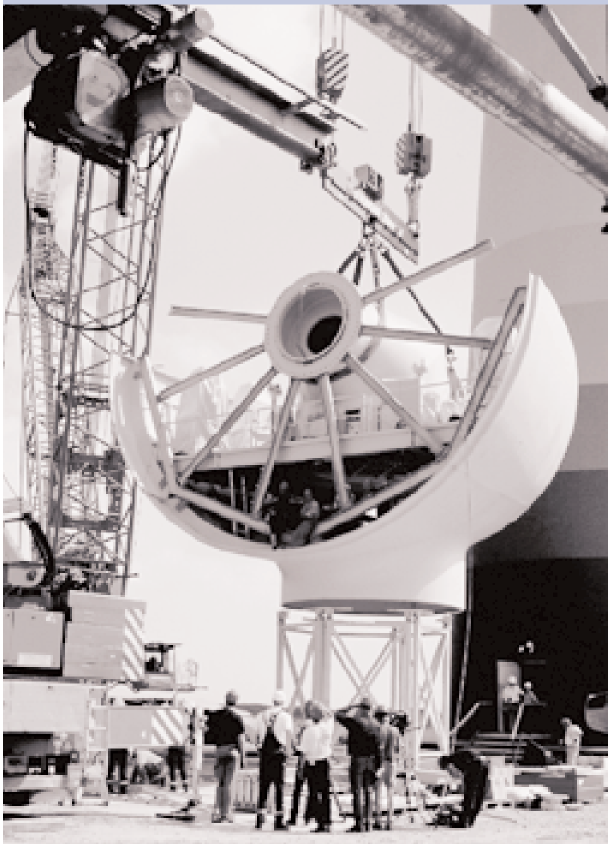
Direct drive transmission systems for WTs, avoiding the gearbox as a cost and maintenance item, are of increasing interest. Historically, gearboxes have presented challenges; hence their removal through the direct drive concept may seem desirable. It is, however, possible that mechanical difficulties are simply replaced by electrical ones. As yet, there is no clear answer, but the issue may prove to be important for the future development of the industry.

Direct drive generators operate at the rotational speed of the WT rotor and are directly coupled without need for a gearbox. The expected advantages are reductions in capital cost, drive train losses, downtime and maintenance cost. The simplicity of the system and the avoidance of a gearbox as a maintenance item are definite advantages of the direct drive system. To date, direct drive systems are generally heavier than conventional drive trains and the cost comparison is unclear. Enercon has undoubtedly been the most high profile wind energy company to commit to direct drive technology almost since the start of its significant market presence in the early 1990s.

Figure 1.16: Wind Farm of WTs at Borssum

The Enercon designs, now in production at 1.8 MW and with a prototype E112 at 4.5 MW (Figure 1.17 shows the build of the E112 making apparent the large diameter of the direct drive generator), employ direct drive generators with wound rotors.

Figure 1.17. Assembly of the E112



These are, in principle, conventional synchronous machines with rotor slip-rings and a rotor excitation circuit. The other direct drive machines, in production and in development, use permanent magnets on the rotor.

However, the mass and size of direct drive generators are intrinsically large. In particular, the large diameter of the generator has implications for nacelle layout and transport, especially for onshore turbines.

The diameter is large for two reasons:

- The power output is proportional to rotor length times rotor diameter squared, while the active mass (electrical steel and copper) is related to rotor length times diameter. Therefore, larger diameter implies higher power output per unit mass.
- To keep the output frequency in a reasonable range for normal electrical machine design (approximately 20 Hz in Enercon machines), the number of poles on the generator rotor should be kept high. There are difficulties in making poles with small dimensions, which therefore implies that circumference should be kept large if possible.

Figure 1.18: The Zephyros LW72 Wind Turbine

The Dutch manufacturer, Lagerwey, markets WTs of 52m and 58m in diameter with direct drive generators. The LW52 and LW58 are wound rotor synchronous machines like Enercon's. A related design, the Zephyros LW 72 (Figure 1.18 shows the first installation at a site in the Netherlands, south of Rotterdam), uses permanent magnet generators and generates at medium voltage (3-4 kV).

A four quadrant insulated gate bi-polar transistor (IGBT) rectifier is used at 690 V for the LW52 and LW58. The LW72 works with an integrated gate commutated thyristor (IGCT) rectifier at 3 kV (18 rpm, 1,500 kW output) and, with higher rotor speed, at 4 kV (24 rpm, 2,000 kW). The higher speed version is intended for offshore use where noise is not an issue. An IGCT converter is considered to be more reliable because it has fewer and more robust elements. This is the main difference between the LW52 and LW58, 750 kW turbines and the LW72. The LW58 and LW72 have generator diameters close to 4 m which is favourable for transport costs, whereas the LW52 (an older design) has a generator diameter of over 5m diameter.

It is clear that the direct drive generator with fully-rated power converter concept is commercially viable. It may be particularly suitable for the offshore market where its potential high reliability may be an advantage and its large diameter is not a significant transport restriction. Jeumont Industries has also developed a direct drive permanent magnet generator system, employed in the J48 750 kW turbine.

In addition to the standard drive train at MW-scale with a three stage gearbox and four- or six-pole generator, or the gearless drive train with multi-pole direct drive generator, an intermediate solution has been considered with a single stage of gearing and multi-pole generator.

1.3.2 HYBRID – SINGLE STAGE OF GEARS AND MULTI-POLE GENERATOR

It may be that the optimum WT design will be the one with the minimum tower head mass since, in mature production, mass may broadly equate to cost. The pursuit of minimum mass is therefore a common goal.

The term “hybrid” is adopted to describe a new type of power train in which a gearbox is used to increase speed, but not to the level at which standard generators of up to eight-poles can be used. It can thus be considered as a compromise between the fully direct drive and the fully conventional solution. The generator is multi-pole and essentially similar to direct drive designs, but is more compact, being of relatively higher speed and lower torque. A concept described as “Multibrid” was initially proposed by the German consultancy company, Aerodyn. The idea was to have a single stage of gearing (6:1 is about the ratio limit achievable in a single stage) driving a medium speed multi-pole generator. The aim was to avoid the complexity of a multi-stage gearbox but also have a lower system mass with a more efficient and compact nacelle arrangement than is possible with a large diameter direct drive generator. The Multibrid design concept is now being pursued by Pfleiderer Wind Energy and WinWinD.

The Finnish company WinWinD has developed the WinWinD (Figures 1.19 and 1.20), a 1.1 MW, 56 m diameter WT. A single stage of planetary gearing (ratio 5.7:1) is coupled with a low speed (40-146 rpm) multi-pole PMG. The nacelle arrangement is very compact. The PMG uses rare earth magnets and is water cooled. The nacelle structure consists of a simple steel cylinder welded to a stub cylinder abutting at right angles which contains the slewing ring.

Figure: 1.19: A Hybrid Design

The WinWinD design employs variable speed with individual blade pitching. This WT system is of similar mass to conventional designs and has a simple and compact nacelle layout (see Figure 1.20).

Figures 1.20: The WinWinD 1.1 MW Wind Turbine

Historically, gearbox problems are divided equally with the low speed (planetary) stage and high speed stages. Thus, the hybrid design is a trade-off between improved gearbox reliability and reduced gearbox cost and increased generator mass and cost (compared to a conventional high speed generator). Taking account of component costs (capital and maintenance) and layout issues impacting on structure costs, there is no fundamental reason why there should not be an optimum configuration mid-way between the power train with high speed generator and the power train with direct drive. As yet, however, it is unclear whether the hybrid design route is simply a viable alternative on a par with other options or if it has a definite advantage.

1.3.3 ROTOR BLADE DEVELOPMENTS

General Rotor Blade Development

The vast majority of WT blades are made from glass polyester or glass epoxy. Although there is some automation involved in the process it is labour intensive with the procedures still traced back to their boat building origins. Modern blade manufacturing and testing is illustrated in Figures 1.21 to 1.23. Rotor diameters in excess of 100 m are now being designed, manufactured and tested for offshore applications. LM Glasfiber in Denmark has dominated the independent blade market.

Many manufacturers want to secure component supply by setting up their own blade manufacturing capability. Vestas has long been in this position, as has Enercon. Bonus Energy A/S is now manufacturing blades using glass epoxy with resin infusion technology. NEG Micon owns NEG Micon Rotors, the UK plant where wood epoxy blades are produced. In most cases, the aim is not necessarily to meet all blade demand from in-house supply, but rather to have options for technical and commercial security. Thus, these manufacturers and others have also purchased many blades from independent suppliers.

Lightning can cause serious damage to blades and blade tips and all leading manufacturers can offer lightning pro-

tection systems usually with metallic tip inserts and down conductors embedded in the blades. Lightning is a complex and unpredictable natural phenomenon, but high voltage testing helps to prove design solutions. Testing is of prime importance for new blade designs and ultimate testing and fatigue testing are now routine (Figure 1.21).

With the need for higher dimensional quality, higher specific strength and mass reduction of large blades, the industry is being weaned from the basic "boat building" technology of the lower grades of glass fibre combined with polyester resin that has served it well over several decades. For the larger blades, all established manufacturers switched from polyester to epoxy resin infusion some years ago and all new manufacturers use epoxy resin based systems.

The spar and shell design, both manufactured using prepregs, is particularly favoured by Vestas. It has advantages in realising fast production with good quality control and suits the manufacture of lightweight, flexible blades. These advantages are somewhat offset by a premium in the material components.

Figure 1.22: NEG Micon Blade Manufacture

Figure 1.21: NEG Micon Blade Testing

Figure 1.23: Bonus Blade Manufacture

© NEG Micon E/S

The design of a blade starts with the aerodynamic shape. The aerodynamic properties are principally determined by the choice of aerofoil. Considerable efforts have been made to design aerofoils specifically for WT use. The requirements of a WT aerofoil are significantly different to those of more conventional aeronautical applications and hence this has been a particularly demanding task. Even within the WT discipline, stall and pitch regulated rotors have different design parameters with pitch regulated aerofoils closer to conventional applications. Various “families” of aerofoil have now been developed. Further computational efforts may be expected to bear some fruit.

Rotor Aerodynamic Devices

For stall regulated designs a more pragmatic approach is needed and a variety of aerodynamic devices is used to fine-tune the performance of stall regulated rotors. These include vortex generators, stall strips, fences, dinotails and Gurney flaps. Vortex generators can inhibit flow separation and increase lift before stall. Sometimes this will improve the power curve so increasing output power in wind speeds just below rated when a rapid development of stall regulation is then desirable. Stall strips may be used to induce an earlier stall in the outboard blade sections of a blade that is producing too much power around rated wind speed. The “dinotail” is an interesting development of Bonus A/S in which a serrated trailing edge – similar to the back tail plates of a stegosaurus, hence dino(saur) tail, was tried out to modify vortex shedding and reduce acoustic emissions. It was found to reduce drag generally and hence improve power performance.

1.3.4 SINGLE BEARING ARRANGEMENT

Some WT designs have sought to achieve a lower weight and more integrated power train by using the gearbox input bearing as the main rotor bearing (e.g. designs of Zond Energy Systems and Wind Energy Group, neither company is now trading). Such a bearing has higher friction than a smaller diameter bearing and may be appreciably more expensive, but it can also realise very significant economies in avoiding a low speed shaft and in reducing nacelle weight and space demands.

1.3.5 OFFSHORE TECHNOLOGY

Offshore Wind Farm Installations

Currently, offshore installations only constitute a very small part of the WT market, but offshore wind is set to develop in a significant way and the potential offshore market is the main driver for large turbine technology development.

Table 1.4: Operational Offshore Wind Farms

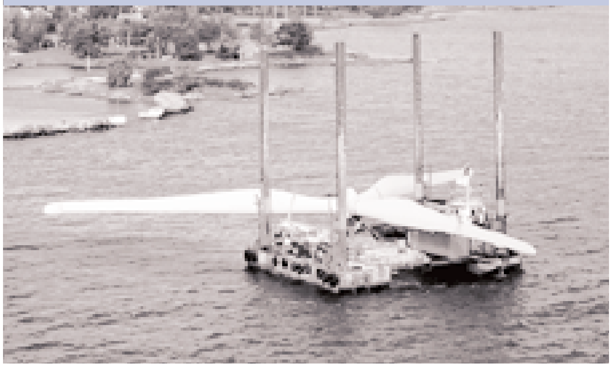
Location	Capacity (MW)	Turbines	Year of installation
Vindeby, Denmark	5	11 Bonus 450kW	1991
Lely, The Netherlands	2	4 NedWind 500kW	1994
Tunø Knob, Denmark	5	10 Vestas V39 500 kW	1995
Dronton, The Netherlands	17	28 Nordtank 600kW	1997
Bockstigen-Valor, Sweden	3	5 Wind World 500kW	1998
Blyth, UK	4	2 Vestas 2MW	2000
Middelgruden, Denmark	40	20 Bonus 2MW	2000
Utgrunden, Sweden	10	7 GE Wind 1.425MW	2000
Yttre Strengund, Sweden	10	5 NEG Micon 2MW	2001
Samsø, Denmark	23	10 Bonus 2.3MW	2003
North Hoyle, UK	60	30 Vestas 2.0MW	2003
Horns Rev, Denmark	160	80 Vestas V80 2MW	2003
Nysted, Denmark	158.4	72 Bonus 2.2MW	2003
Arklow Bank, Ireland	25	7 GEWE 3.6MW	2003
Total Offshore Installed Capacity	**522.4**		**2003**

Table 1.4 indicates that 522.4 MW of offshore wind have been installed in European waters, and at the time of writing, there are declared plans for about 3.5 GW of offshore wind up to a horizon of 2007. About 10 years ago, the technology started with a “toe in the water” approach to test turbine operation in the offshore environment. The turbines were “marinised” with some extra protection, in some cases de-humidified nacelle space, but otherwise were essentially the same as the land-based technology.

The largest WTs now being designed primarily for offshore use reveal design changes, mainly higher tip speeds (as discussed in Section 1.2) and built-in handling equipment in the nacelle. With turbines now available of 2 MW rating and above and two projects (Horns Rev + Nysted) of over 150 MW capacity each, the commercially viable offshore wind farm is at hand.

Logistics of Offshore Wind Farms

Figure 1.24: Blade Handling for Transport by Sea



Ironically, given that the offshore environment is generally considered hostile, for WTs offshore conditions are often more benign than many onshore sites. Design issues, constraints and drivers are different. The ultimate goal, as always, is low cost and reliable electricity. The two new considerations are access and construction. The former will play a vital role in determining the energy produced and the latter a large part in determining the capital cost.

The logistics involved in manufacture, transport, erection and maintenance of offshore multi-MW WTs is a severe challenge and on a commercial scale is likely to involve integrated dockyard assembly facilities. In the case of blades which may be more than 50 m in length, direct access to the sea from the manufacturing plant is highly desirable if not essential.

Technology for Offshore

Typical stages in the establishment of offshore wind farms are illustrated in Figures 1.25 and 1.26 which are composite images from various projects.

Figure 1.25: Erection of Offshore Wind Farms

Figure 1.26: Erection of Offshore Wind Farms

© Elsam A/S

It is unlikely that there will be any consensus on offshore erection methods in the near future. Some issues are very site-specific and a variety of craft and handling tools will be tried. In some cases, wholly assembled rotors or tower top systems may be handled. In others, the assembly is much more piecemeal, as with land-based sites.

Offshore Foundations

It is well recognised that the balance of plant and maintenance costs will be critical for the viability of offshore wind. On land, machine costs may be about 75% of total costs with the balance of plant hardware plus lifetime maintenance costs accounting for the remainder. Offshore, this split may well be reversed and much attention is being given to regulating such costs by design.

Table 1.5: Summary of Foundation Concepts

Foundation Type/Concept	Application	Advantages	Disadvantages
Mono-piles	Most conditions, preferably shallow water and not deep soft material. Up to 4 m diameter. Diameters of 5-6 m are the next step.	Simple, light, versatile. Of lengths up to 35 m.	Expensive installation due to large size. May require pre-drilling a socket. Difficult to remove.
Multiple-piles (tripod)	Most conditions, preferably not deep soft material. Suits water depth above 30 m.	Very rigid and versatile.	Very expensive construction and installation. Difficult to remove.
Concrete gravity base	Virtually all soil conditions.	Float-out installation.	Expensive due to large weight.
Steel gravity base	Virtually all soil conditions. Deeper water than concrete.	Lighter than concrete. Easier transportation and installation. Lower expense since the same crane can be used as for erection of turbine.	Costly in areas with significant erosion. Requires a cathodic protection system. Costly compared with concrete in shallow waters.
Mono-suction caisson	Sands, soft clays.	Inexpensive installation. Easy removal.	Installation proven in limited range of materials.
Multiple suction caisson (tripod)	Sands, soft clays. Deeper water.	Inexpensive installation. Easy removal.	Installation proven in limited range of materials. More expensive construction.
Floating	Deep waters – 100 m.	Inexpensive foundation construction. Less sensitive to water depth than other types. Non-rigid, so lower wave loads.	High mooring and platform costs. Excludes fishing and navigation from most areas of farm.

Particular attention is being given to developing cost effective foundations and a variety of concepts are under consideration. To date, the mono-pile is the most favoured solution, but much depends on wave loading, ice loading, water depth and seabed conditions. According to Milborrow (2003), at least a 20% reduction in foundation costs is expected by 2012.

A summary comparison of foundation concepts is presented in Table 1.5.

Some of the foundation concepts discussed in Table 1.5 are illustrated in Figures 1.27 and 1.28. In general, it would appear that fewer larger foundations will be more economically constructed and installed than many small ones. This is a significant driver to develop offshore turbine units of very large capacity.

Future of Offshore Wind Technology

Up to 1990, the general economic view of offshore wind was rather negative. Two to four times the unit generating cost compared to land-based installations was typically projected.

Figure 1.27: Monopile, Tripod and Gravity Based Foundations

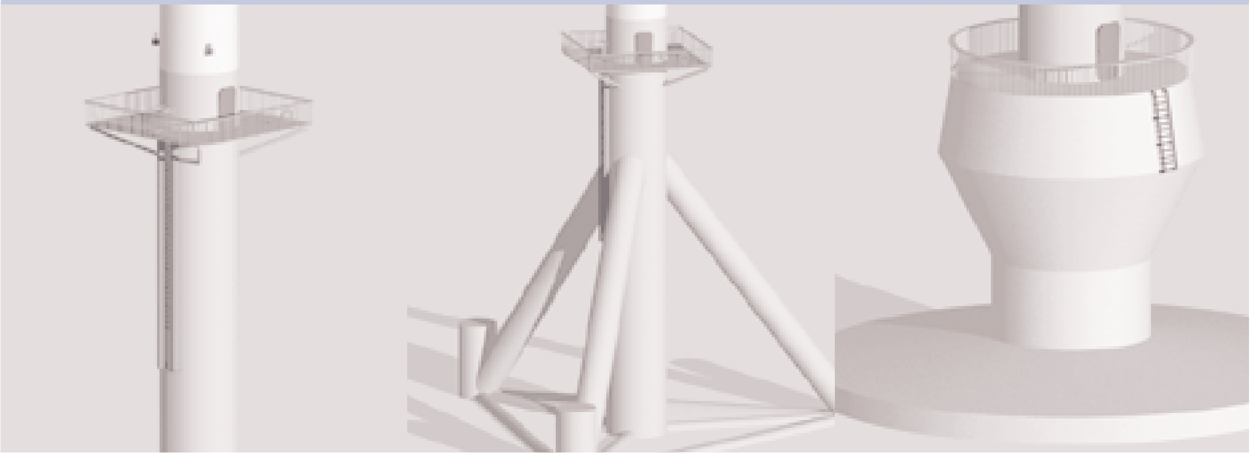
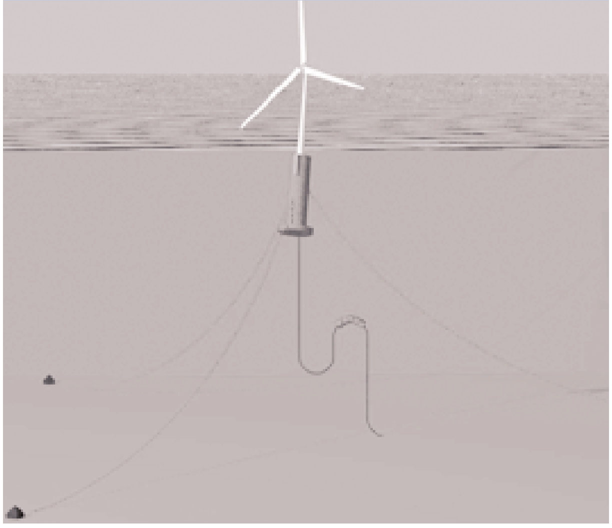


Figure 1.28: Floating Support



These projections ignored various factors that are now evident with the advent of commercial offshore wind:

- Perhaps most significantly, higher mean wind speeds are often available at the offshore sites that would compete with land-based sites to serve a given population area.
- There is excellent offshore resource near centres of consumption (south east England and Long Island New York, for example) where little land-based development is feasible.
- Although infrastructure costs are necessarily much higher, there is some mitigation of turbine machinery costs. With relaxation of acoustic noise constraints, higher tip speeds are feasible, so reducing drive train torque and cost. Also, there is generally reduced wind turbulence offshore compared to land-based sites.

Figure 1.29: Wind Farm at Horns Rev

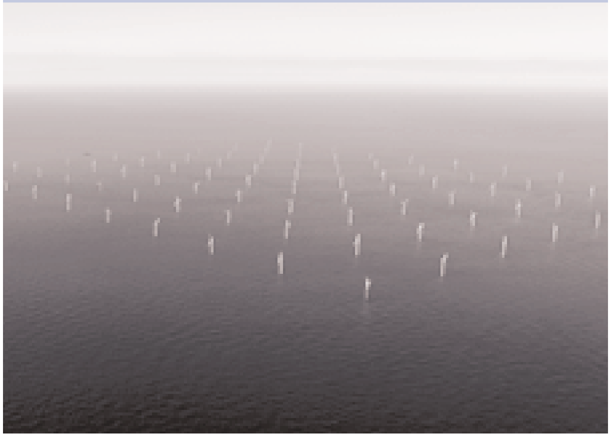


Figure 1.29 shows the development at Horns Rev, Denmark.

It is expected that the wind industry will continue to develop with an ever sharper focus on the specific needs of offshore technology. Some of this development is seen in the turbines themselves, in the tendencies towards increased tip speed and specific maintenance aids. Although the use of helicopters for installation and maintenance operations may be prohibitively expensive, and helicopters are very limited in lift capacity, some manufacturers provide helipads on the nacelle of their offshore turbines to increase access opportunities for maintenance engineers. Some offshore turbines have in-built cranes whilst others have provision for winches to be brought to the turbine in order to exchange components.

Although a mature European offshore industry exists in the context of oil and gas recovery, the demands of offshore wind farms are quite specific and ongoing development is expected in the areas of foundations, access, wind farm electrics, transportation and erection. In the oil and gas industry, maintaining production is of overriding importance and justifies high capital cost solutions. In the wind industry, production is also vital, but so also is minimisation of capital costs. Oil rigs are massive one-off constructions whereas quantity production issues will figure in the installation and maintenance of a large offshore wind farm which may have hundreds of turbine units. This implies that while the existing offshore industry may have knowledge and experience of considerable value to the wind industry, it may not have off-the-shelf equipment that is optimum for wind farm establishment.

Optimal design for access in testing sea-states and optimal strategies for maintenance will be some time in evolving. There is undoubtedly much work ahead in cost optimisation of offshore wind farm technology with regard to all the issues of infrastructure (foundations, erection and maintenance technology and logistics especially), but the European wind industry has clearly accepted the challenge.

1.4 Technology Status

1.4.1 OVERALL DESIGN TRENDS

How has WT technology evolved since the early 1980s?

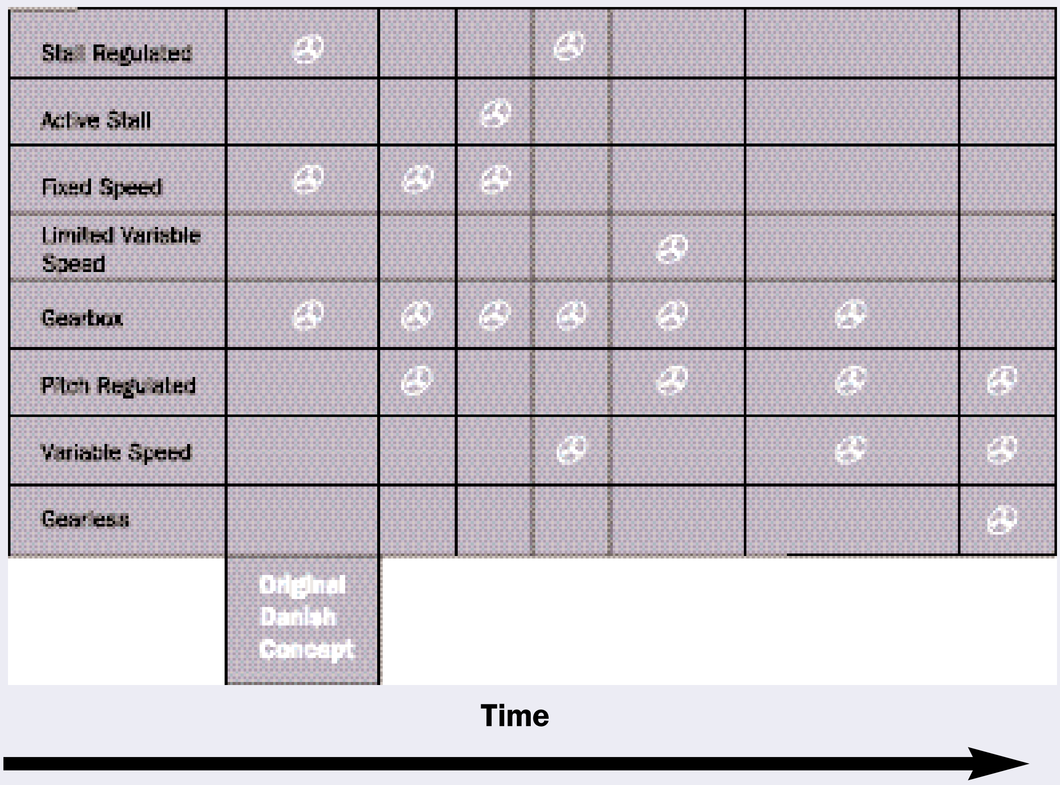
Although there has always been a wide variety of designs on the margins of commercial technology, in the early days the Danish, three-bladed, single fixed speed, stall regulated turbine dominated the market at rated power levels of generally less than 200 kW. Blades were almost invariably manufactured from glass-polyester resin.

In 2003, the focus of attention is on technology around and above 1.5 MW rating and commercial turbines now exist with rotor diameters in excess of 100 m. Designs with variable pitch and variable speed predominate while direct drive generators are becoming more prevalent.

Epoxy-based resin systems predominate in blade manufacture and carbon fibre reinforcement is increasingly used in big blades. Some manufacturers produce wholly carbon blades and many use carbon in cap spars. One company has developed means of effectively combining carbon with wood laminate. If the trend towards increasing use of carbon continues, and the offshore market develops substantially, the wind industry could lead world demand for quality carbon fibre, so driving further cost reductions for carbon fibres and prepregs.

Figure 1.30 shows the evolution from the original mainstream architecture, stall regulated, fixed speed and with geared transmission to the present, pitch regulated, vari-

Figure 1.30: Technology Trends



able speed and with direct drive transmissions appearing, along with continued use of gearbox transmissions.

These design changes are not in any significant degree a path to cost reduction. Variable speed may offer a little more energy capture but this is largely offset by added cost. The design changes have largely been driven by market demands - better acoustic noise regulation, better output power quality, reduction of gearbox problems, etc.

Since the initial commercialisation of wind energy in the early 1980s, there have, of course, been huge cost reductions and this is a direct consequence of the dramatic growth in the market.

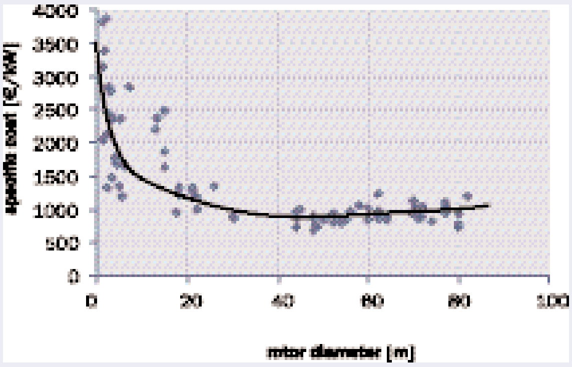
Thus, modern WTs are more sophisticated and adaptable than their predecessors on account of technology development and are also much cheaper (discounting inflationary factors) on account of market expansion. Market expansion has, of course, promoted incremental technology improvements in design, materials, processes and logistics that have contributed very significantly to cost reductions. There are significant technological gains from advances in WT engineering, but no significant cost reduction has come from the most visible changes in mainstream technology direction - variable speed, direct drive and pitch regulation.

1.4.2 SIZE LIMITATIONS

Frequently, the wind energy industry is asked: “Is there an optimum size for a wind turbine?” The answer is a complex mixture of economics and technology, and is not well defined. All predictions show very shallow minima for most parameters; hence the answer will be very sensitive to the assumptions made and, ultimately, to the practicalities of turbine manufacture. The overall trend in price per kW is presented in Figure 1.31. Note that this figure reflects pub-

lished price data and project prices are, in general, significantly lower. Very small turbines are extremely expensive per kW. They require disproportionately tall towers to clear boundary layer obstacles and their control systems represent a relatively high proportion of total cost.

Figure 1.31: Trends in List Price

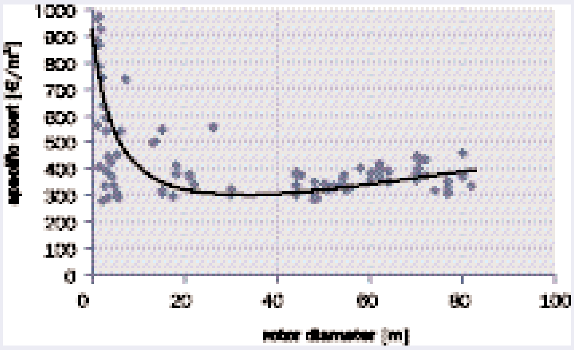


At larger sizes these factors diminish and costs reduce. However, the cost (net manufacturing cost of turbine ex-works) rises gradually for rotor diameters in excess of about 50 m. Taking account of land utilisation, infrastructure costs and maintenance costs, there is, however, still a net cost benefit in larger turbines for energy production rather than for capital cost and this is accentuated offshore where infrastructure costs dominate.

Energy capture improves with increasing hub height, but the biggest machines are justified for offshore application and the wind shear effect (which is typically an increase of average wind speed with height) is less offshore than at landbased sites. It is often asserted that component mass and costs increase less than cubically with scale. However, the underlying physics is often confused with the effects of technology development and the influence of volume on production cost. Often different design concepts are used in large-scale projects, e.g. for gearboxes or in materials technology, so reducing the specific mass of very large blades.

The latest and largest offshore designs benefit from increased tip speed ratio and hence are in a different class from earlier designs. There is a hint of this in Figure 1.32.

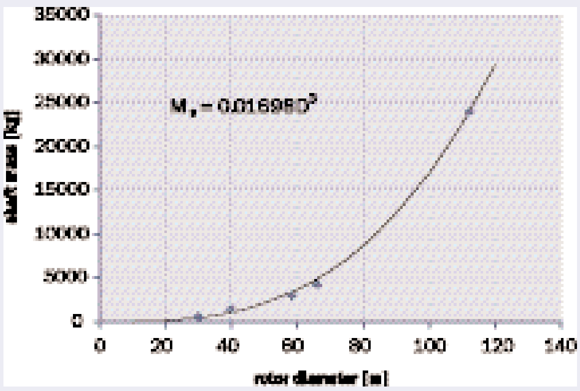
Figure 1.32: Price Trends of Large Wind Turbines



The specific cost could readily be interpreted as constant above 40 m diameter. However, excluding the largest offshore machines (75 to 80 m plus) which, having higher tip speeds, form a separate new class on a lower cost curve, the general trend is suggestive of a rising cost curve.

In general, design loads increase cubically with rotor diameter and for constant design stress, cubic increase in component size will accommodate this trend. This is exemplified with clarity in Figure 1.33 where the mass of a series of Enercon main shafts over a wide size range follow an almost perfect cubic curve. It should also be noted that, from a fracture mechanics stand point, design for constant stress independent of scale may not be acceptable at very large sizes as the probability of a critical flaw existing in any given material sample increases with sample size.

Figure 1.33: Main Shaft Mass – Enercon Designs



It is easy to find data suggesting less than cubic scale-up of WT components. On a sound basis it can be argued that control system mass or costs will not scale-up cubically. Generators and electrics will scale only as power (diameter squared) if, unlike the input speed provided to the gearbox, the generator shaft speed is held constant. However, this is just a trade-off between mass and cost in gearbox or generator which can vary between the conventional geared transmission, the system with a single stage of gearing and direct drive.

A power law fit to the data of Figure 1.34 would give an exponent of about 1.3, significantly less than cubic.

However, design development with time is being confused with inherent physical scaling. Old, relatively heavy, blades are mixed with new ones where great effort and the benefit of longer manufacturing experience have contributed to significant specific mass reduction.

Thus, blade mass can *appear* to scale with increasing blade size by a power law that is much less than cubic. This is principally because:

- the large blades of 40 m length or more are very substantial structures and particularly focus development effort to reduce mass and cost;
- the largest blades are the most recent and at the most advanced stage of manufacturing technology.

Figure 1.34: Blade Mass Trends Based on Blade Manufacturers' Data

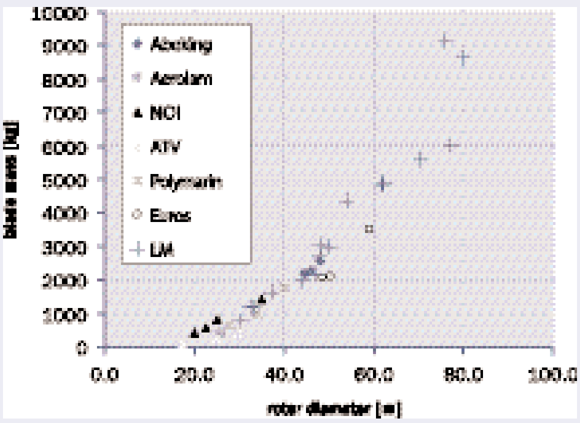


Table 1.6: Blade Mass versus Diameter Trend Line Exponents

Manufacturer	Exponent
NOI	2.05
ATV	3.07
Polymarin	2.76
Euros	2.92
LM Glasfider	2.30

A different picture emerges when the data of Table 1.6 are considered.

There is further clarification of blade mass trends in Figure 1.34 where blade mass data from manufacturers' data sheets are presented. It is apparent from this figure that the small carbon blades of ATV (A Tout Vent) are very light for their size, as would be expected with CFRP as the principal material. The wood epoxy blades of NEG Micon Rotors (Aerolam in the legend of Figure 1.34) are also of low specific mass.

Table 1.6 corroborates the comments explaining why blade mass apparently increases as less than cubic. Trend line equations (not shown in Figure 1.34 to avoid undue complication) in the form of best fit power law curves were determined for the data of each manufacturer. In the case of ATV who has a consistent technology for small blades and Euros who are new entry manufacturers with little development time behind them, the power law exponents are close to the predicted cubic relationship. The other manufacturers LM, NOI (formerly Aerpac) and Polymarin have been trading for a long time, their technology has gone through major developments and the power law exponents appear to be less than cubic. It is logical that the lowest exponent of all applies to NOI since their blade range includes small Aerpac blades originally manufactured with polyester resin in a wet lay-up process, whereas all recent designs of large blades are based on resin infusion using epoxy resin.

Scaling of WTs is inevitably more complex than can adequately be addressed here. Technology developments will confront the up-scaling problems, as is now happening with increased focus on mass reduction of MW-scale systems.

To a certain extent, whether turbine-specific cost rises appreciably with up-scaling is controversial and the cost-optimum turbine size remains uncertain (and is properly a secondary issue to the overall cost factors applicable to specific projects). However, the industry is faced with an important issue, to look much more carefully at scaling trends in order to identify an economic size limit of conventional turbine technology and consider new concept development for very large-scale offshore units.

This is not a make or break issue as world market growth can be well satisfied with turbines within the compass of present technology, i.e. up to about 5 MW, but it is nevertheless of some importance in striving for the best economics in future offshore projects.

1.4.3 THE SUCCESS OF WIND TECHNOLOGY

Figure 1.35 shows the reduction in turbine cost with time. It is based on sales prices provided by Bonus and has been adjusted for inflation. It is valuable to have data from a single manufacturer where there is consistency of design and cost evaluation. The decrease in turbine price is very evident.

Figure 1.35: Wind Turbine Price Reduction

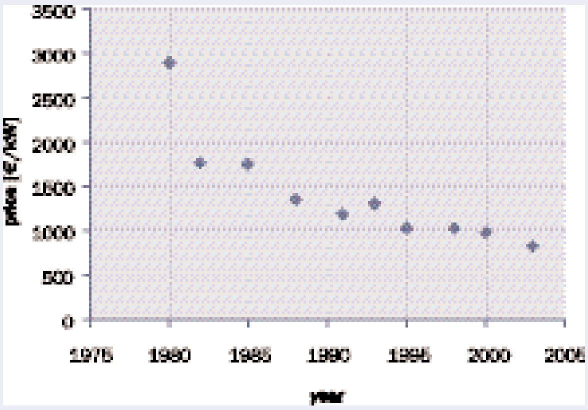


Figure 1.36: Typical Availability for a Large Wind Farm Since Erection

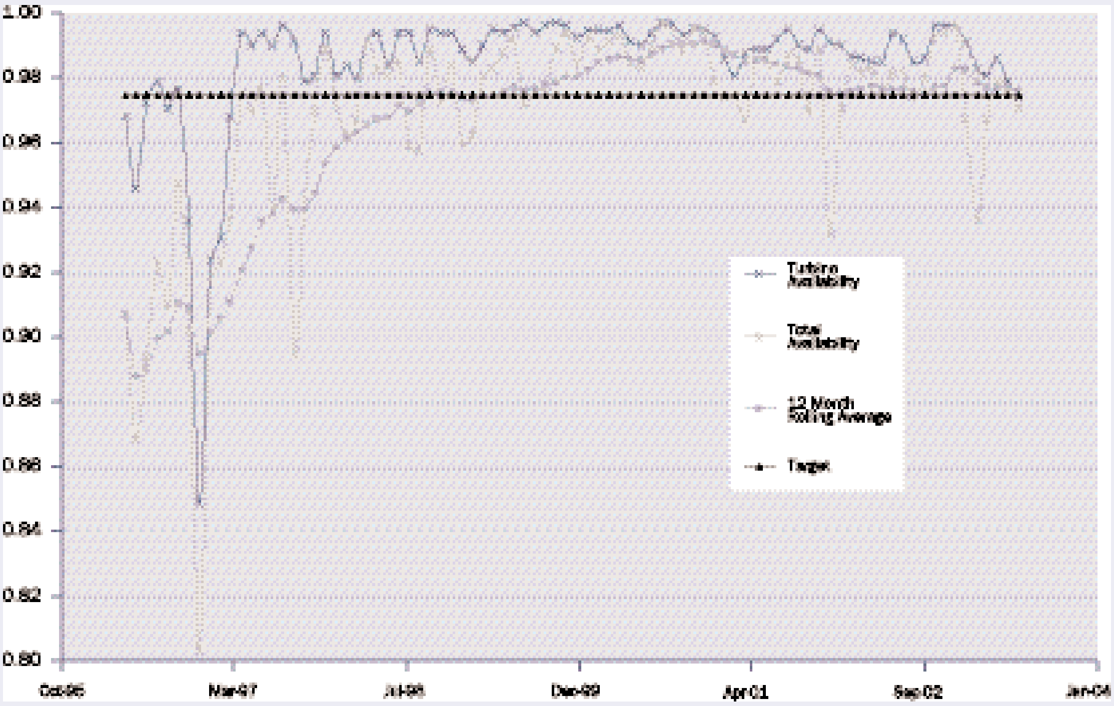


Figure 1.36 shows a time history of availability from a large European wind farm. It demonstrates that the availability in mature operation is in excess of 98%. It also shows the way in which the availability climbs as the turbines "run in". This project was built and commissioned in three phases. These phases can be seen coming online during the first two years. In conjunction with decreasing cost, performance has risen. Aerodynamic design improvements and variable speed operation have realised small energy gains. But above all availability, which reflects the operational reliability of the product, has risen (Figure 1.36) to average levels generally above a target of 97.5%; this compares very favourably with all other electricity generating technologies.

1.5 CONCLUDING REMARKS AND FUTURE R&D

The development of WTs is a remarkable success story which is not yet complete. The wind industry is now poised at a stage where it is regarded by some as a mature technology and able to stand on its own commercially. While that status is a great achievement, it is important to realise the potential for yet greater growth that can best be furthered by continuing vigorous R&D efforts. Much of the current R&D focus will be on supporting the new drive towards offshore technology. The design drivers are always reduction in cost and increased reliability. A WT is a complicated integrated structure - all its elements interact and each will play its part in the optimisation. Whilst Chapter Five will deal in greater detail with R&D requirements, a short indicative list is presented here to give a broad view of future R&D demands.

- More intelligent control systems with additional sensors measuring system vibrations.
- Advanced adaptable rotor concepts.
- Aerofoil design targeted at control of loads.
- Higher tip speed designs for offshore.
- Rotors making increasing use of carbon reinforcements.
- Low solidity, downwind, flexible rotor designs.
- Direct drive PMG technology including rare earth magnets and alternative electrical machine topologies.
- Special designs of systems and components for erection, access and maintenance of offshore turbines.
- Design studies of systems rated above 5 MW for offshore including possibly multi-rotor systems.
- Variable speed DC or AC HV generation for offshore.
- Offshore meteorology - hardware for measurements and modelling issues.
- Integration of support structure design for offshore turbines.
- Improved access methods for offshore turbines.
- Condition monitoring of critical components.
- SCADA for offshore - development for remote intervention.
- Development of alternative and deep water foundation structure arrangements
- Floating turbines.

There are also many issues around standards, development of manufacturing processes and computer design tools. This list is not comprehensive and does not suggest any priorities but rather gives a flavour of the many areas where R&D support can benefit the wind industry.

2 WIND RESOURCE ESTIMATION

2.1 Introduction

Wind is the fuel for wind power stations. Small changes in wind speed produce large changes in the commercial value of a wind farm. For example, a two-thirds increase in the wind speed might be expected to double energy production over the lifetime of a wind farm.

This chapter explains why knowledge of the wind resource is important for each and every stage of the development of a wind farm, from initial site selection right the way through to operation.

Europe has an enormous wind resource. It can be considered on various levels. At the top level, the potential resource can be examined from a strategic standpoint:

- Where is it?
- How does it compare to EU and national loads?
- Which regions and areas offer good potential?

At the next level, it is necessary to understand the actual wind resource on a site in detail:

- How is it measured?
- How will it change with time?
- How does it vary over the site?
- How is it harnessed?

It is at this stage that commercial evaluation of a wind farm is required and accurate estimates must be provided which are bankable. Once the wind speed on the site has been estimated, it is then vital to make an accurate and reliable estimate of the resulting energy production from a wind farm which might be built there. This requires wind farm modelling and detailed investigation of the environmental and ownership constraints.

As the contribution of wind energy to electricity production increases, in the context of liberalised energy markets, new questions are beginning to emerge, which are critically linked to the nature of the wind:

- How can wind energy be consolidated, traded and generally integrated into conventional electricity systems?
- Will an ability to forecast wind farm output help this integration?

These questions, and more, are addressed in this volume. The first section looks at strategic "raw" resource issues, while the following sections provide a detailed step-by-step evaluation of the assessment process. A worked example of a real wind farm is provided in Appendix C and, finally, some recommendations are made on the key issues that need to be tackled in the near future to help wind energy reach its full potential.

2.2 Regional Wind Resources

Naturally, wind energy developers are very interested in the energy that can be extracted from the wind, and how this varies by location. Wind is ubiquitous; in order to make the choice of development site both an affordable and a manageable process, some indication of the relative size of the "wind resource" across an area is very useful. The wind resource is usually expressed as a wind speed or energy density and, typically, there will be a cut-off value below which the energy which can be extracted is not sufficient to merit a wind farm development.

On-site Measurement

The best, most accurate, indication of the wind resource at a site is through on-site measurement using an anemometer. This is, however, a fairly costly and time-consuming process.

Computer Modelling

On a broader scale, wind speeds can be modelled using computer programs which describe the effects on the wind of parameters such as elevation, topography and ground surface cover. These models must be primed with some values at a known location; usually, this role is fulfilled by local meteorological station measurements or by other weather-related recorded data.

Typically, these wind-mapping programs will derive gridded or contour values for a specified height to create a "wind atlas." Wind atlases have been produced on a very wide range of scales, from the global down to a local government region. They represent the best estimate of the wind

resource across a large area. They do not substitute for anemometry measurements; rather, they serve to focus investigations and indicate where on-site measurements would be merited.

As a further stage in investigations, theoretical wind turbines (WTs) can be placed in a chosen spacing, within a geographical model containing wind speed values as a gridded dataset. This is usually computed in a geographical information system (GIS). Using assumptions about the technology conversion efficiency to units of energy, it is possible to derive an energy estimate which corresponds to a defined area. This is typically expressed as region X having a wind energy potential of Y units of energy.

Constraints

Most wind energy resource studies start with a top-level theoretical resource, which is progressively reduced by including so-called constraints. These are those considerations which will tend to reduce the actual area available to the wind energy developer. They can be geographically-delineated conservation areas, for instance, or areas where the wind speed is not economically viable, or areas of unsuitable terrain. These areas are then sequentially removed from the area over which the energy resource is summed.

Different estimates of the potential energy resource can be calculated according to assumptions about the area which will be available for development. The resource without constraints is often called the "theoretical" resource. Consideration of technical constraints results in the estimation of a "technical" resource and, finally, considerations of planning, environmental and social issues results in the estimation of a so-called "practical" resource.

There are, inevitably, limits to which these modelling exercises can reflect reality – data availability is the main limitation, but also some constraints simply cannot be modelled accurately. Such studies are useful in estimating upper bounds on deployment, the effects of known constraints, interactions between constraints and likely patterns of development. A GIS also helps visualise the scale of the development. Because technology undergoes progressive development, and the nature of constraints will evolve as solutions are found and new constraints emerge, energy resource estimates tend to be valid only for a limited time.

2.3 Wind Atlases

2.3.1 ONSHORE

Figure 2.1 shows the onshore wind energy resource as computed on a broad scale for the 1989 *European Wind Atlas*. The map shows wind speeds at a height of 50 m above ground level, which reflects the height of WTs at that time. Because wind speeds increase with height, and because higher wind speeds mean that much more energy can be extracted (this is discussed in more detail in later sections), the average height of WTs has shown a steady increase in the past decade. So, wind speeds experienced by today's commercial technology are higher than those shown in Figure 2.1.

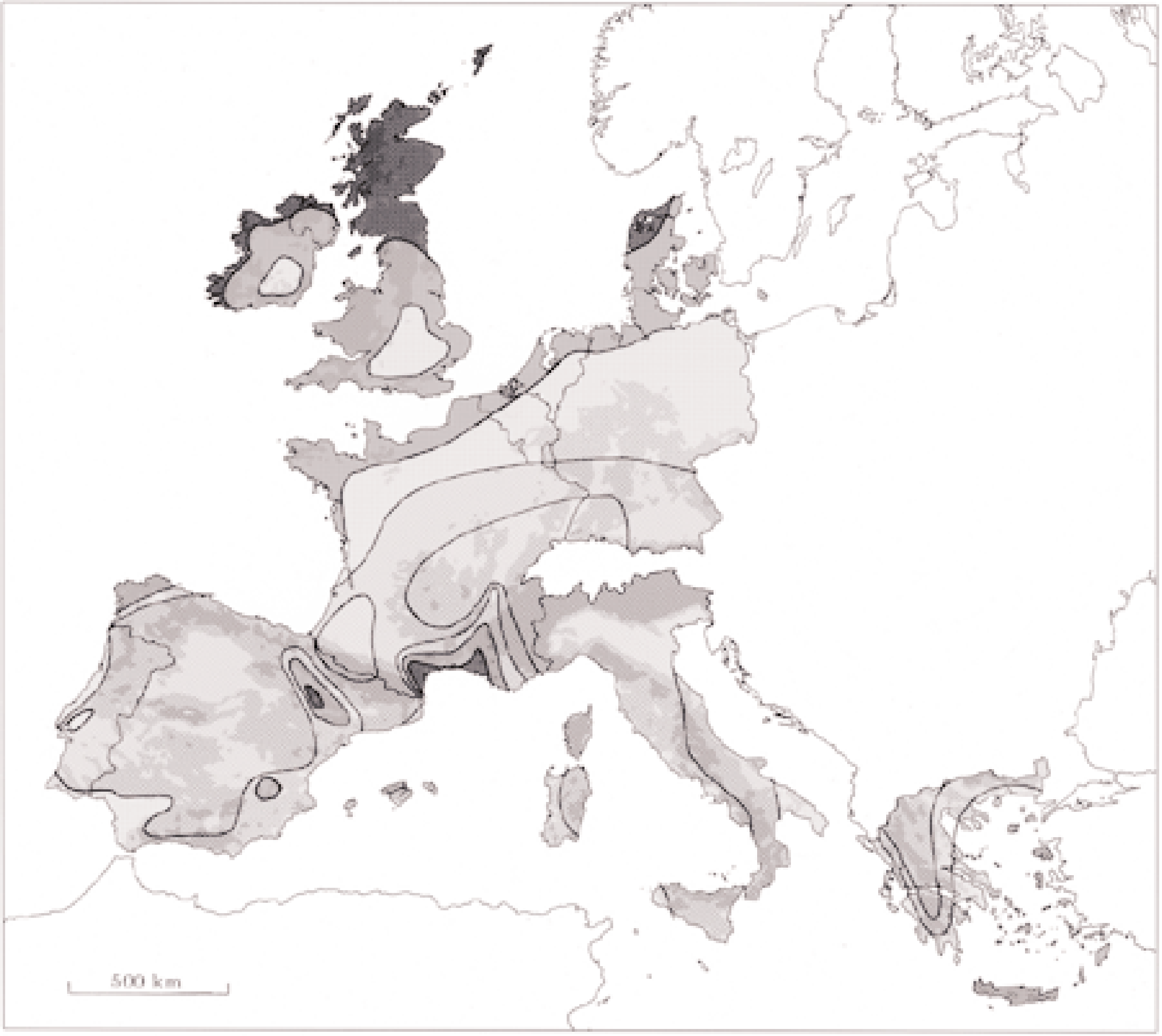
The wind speed above which commercial exploitation can take place varies according to the specific market conditions. While countries such as the UK and Ireland clearly have exceptional potential, every European country has an exploitable wind resource.

The *European Wind Atlas* employs meteorological data from a selection of monitoring stations, and shows the distribution of wind speeds on a broad scale. It has been used extensively by developers and governments to estimate the size of the wind resource and regional variations. It is possible to map wind speeds at a higher resolution using, for instance, more detailed topographical data and a larger sample size of meteorological data, in order to show more local variations in wind speed; these can be used by developers looking for sites in a particular country.

There are far too many examples of national, regional and local wind atlases, for Europe and the rest of the world, to mention them all here. When investigating a particular region or country for its wind development potential, one of the first questions is – "Is there a wind atlas for this area?"

A review of national wind atlases for European countries has been undertaken for this edition of *Wind Energy – The Facts*, the results of which are shown in Table 2.1. Where permission has been granted, map reproductions are contained in Appendix A. The *European Wind Atlas* resulted in the development of a wind-mapping tool called WAsP which is used widely for both broad-scale wind mapping and more site-specific applications. Table 2.1 distinguishes between the use of WAsP and other wind mapping methods.

Figure 2.1: European Wind Atlas, Onshore (EU-12)



Wind resources at 50 metres above ground level for five different topographic conditions

	Sheltered terrain		Open plain		At a sea coast		Open sea		Hills and ridges	
	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}
	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0- 8.5	400- 700
	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

Source: Risø National Laboratory, Denmark. See Appendix A for colour version.

Table 2.1: Wind Atlases in the EU-25

Country	Coverage in the European Wind Atlas	Other WAsP Application	Other Model
EU-15			
Austria		✓ [1]	
Belgium	✓		
Denmark	✓	✓ [2]	✓ [3]
Finland		✓ [4]	
France	✓		
Germany	✓	✓ [5]	
Greece	✓		✓ [6]
Ireland	✓	✓ [7]	✓ [8]
Italy	✓		✓ [9]
Luxembourg	✓		
The Netherlands	✓		
Portugal	✓		
Spain	✓		
Sweden		✓ [10]	
UK	✓		✓ [11]
New Member States			
Cyprus			
Czech Republic		✓ [1]	
Estonia		✓ [13]	✓ [14]
Hungary		✓ [1]	
Latvia		✓ [13]	
Lithuania		✓ [13]	
Malta			
Poland			✓ [15]
Slovakia		✓ [1]	
Slovenia		✓ [1]	
Others			
Armenia			✓ [16]
Croatia		✓ [1]	
Norway			✓ [12]
Russia		✓ [17]	

1 Dobesch and Kury (1997)
2 Risø (1999)
3 Petersen *et al.* (1981)
4 Tammelin (1991)
5 Traup and Kruse (1996)
6 CRES (2001)
7 Watson and Landberg (forthcoming)
8 TrueWind Solutions (2003)
9 Podesta *et al.* (2002)
10 Krieg (1992, 1999)
11 Burch and Ravenscroft (1992)
12 Vector (2001, 2003)
13 Rathman (2003)
14 Steinrücke, *et al.* (1996)
15 Sander *et al.* (2003)
16 Elliott *et al.* (2003)
17 Starkov *et al.* (2000)

2.3.2 OFFSHORE

There are two published offshore wind maps for Europe. One is an extension of the onshore *European Wind Atlas* (see Figure 2.2). Note that wind speeds are provided for a range of heights. The 100 m height values are the most appropriate for current offshore turbines. There is also a 1995 European Commission-funded study (Garrad Hassan, Germanischer Lloyd, Windtest, 1995), which produced offshore wind maps for each of the (then) EU countries (reproduced for each country in Appendix B). Another European offshore wind map is forthcoming from the POWER project, also funded by the European Commission.

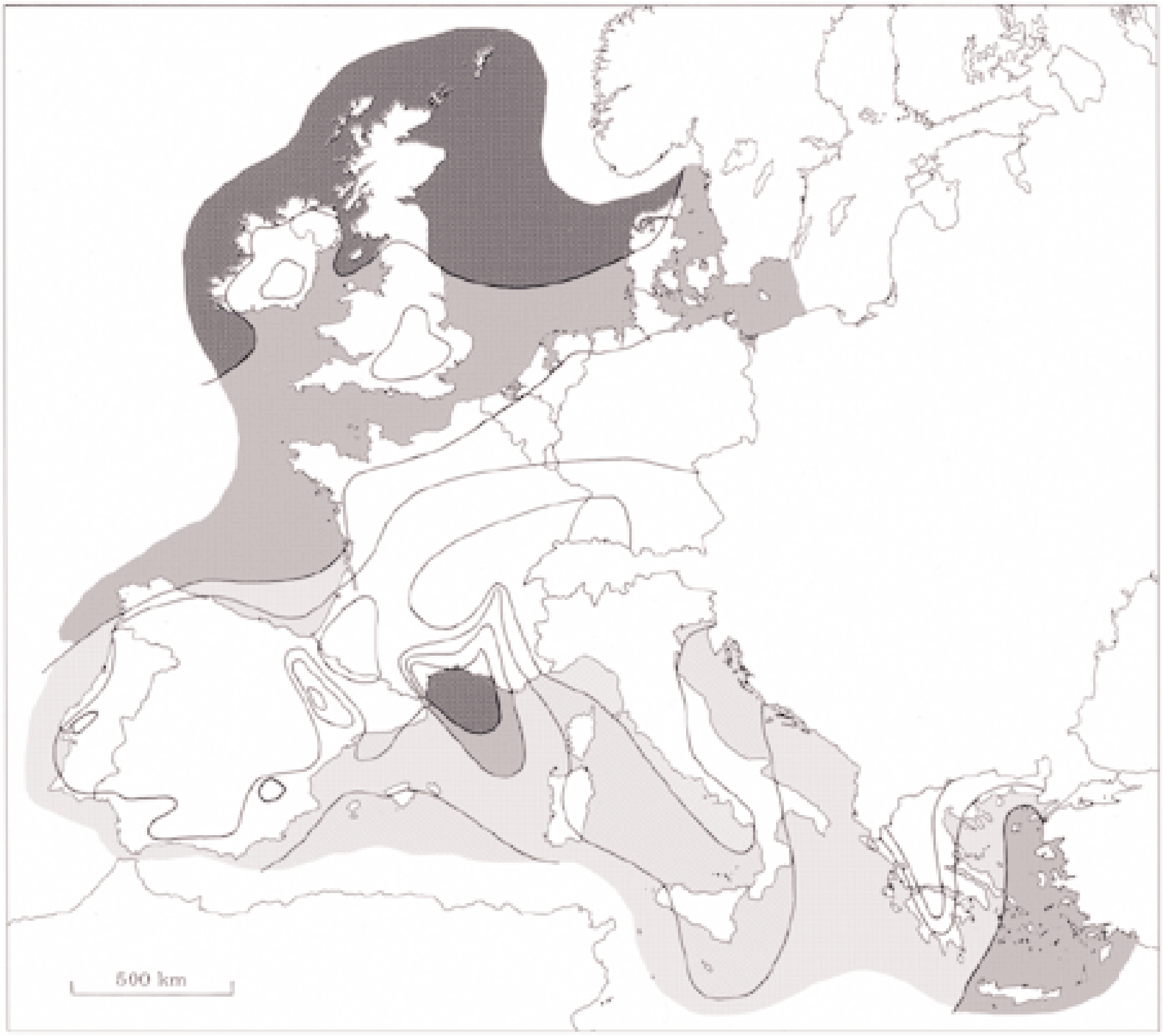
2.4 Energy Estimates

2.4.1 ONSHORE

There are very few estimates of the onshore wind energy potential for the whole of Europe, and those that do exist make assumptions which are, given today's technology, conservative. *Employing wind data* (Grubb and Meyer, 1993) made one of the first worldwide estimates of onshore wind energy potential. For Western Europe, they estimated a gross potential of 31,400 TWh/year and a "second order" potential of 4,800 TWh/year, the latter employing constraints based on population density. Corresponding estimates for Eastern Europe and the Soviet countries were 106,000 and 10,600 TWh/year. At the time the estimates were made, Grubb and Meyer predicted future turbines would reach a height of 50 m.

A 1993 assessment of the technical onshore wind resource for OECD countries (van Wijk and Coelingh, 1993) and referenced in the first *Wind Energy - The Facts* publication (1999), remains the only European-wide estimate of onshore wind potential which gives a comparable estimate for each country. The study presents figures for the "meteorological" potential, which is expressed as the land area on which wind speeds of 5.1 m/s and over are experienced, as well as the "site" potential, which is the former land area minus land considered to be unsuitable for terrain or climatic reasons. It then estimates a "technical" wind energy potential, which further reduces the site potential by

Figure 2.2: European Wind Atlas, Offshore



Wind resources over open sea (more than 10 km offshore) for five standard heights										
	10 m		25 m		50 m		100 m		200 m	
	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}
	> 8.0	> 600	> 8.5	> 700	> 9.0	> 800	> 10.0	> 1100	> 11.0	> 1500
	7.0-8.0	350-600	7.5-8.5	450-700	8.0-9.0	600-800	8.5-10.0	650-1100	9.5-11.0	900-1500
	6.0-7.0	250-300	6.5-7.5	300-450	7.0-8.0	400-600	7.5- 8.5	450- 650	8.0- 9.5	600- 900
	4.5-6.0	100-250	5.0-6.5	150-300	5.5-7.0	200-400	6.0- 7.5	250- 450	6.5- 8.0	300- 600
	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 6.0	< 250	< 6.5	< 300

Source: Risø National Laboratory, Denmark. See Appendix B for colour version.

assuming that only 4% of the land could be used as a result of practical and social constraints. An energy estimate is derived assuming 8 MW/km^2. The technical potential is reproduced in Table 2.2 below, together with figures for total electricity production and wind energy production (expressed in TWh and as a percentage of the van Wijk and Coelingh technical potential).

While updated assumptions on both the technology (larger machines) and constraints would increase van Wijk and Coelingh's technical potential (Table 2.2) is nonetheless instructive in two key respects. It shows that even with conservative estimates of technical potential, only Germany has managed to exploit its wind resource to anything approaching the potential estimated in 1993. It also demonstrates very clearly that those countries with the biggest resources are not necessarily those which have exploited them most effectively.

Table 2.2: EU-15 and Norway, Technical Onshore Potential

Country	Yr 2002 Consumption (TWh)[1]	van Wijk & Coelingh Technical Potential (TWh/yr)	Wind Energy Production (TWh, 2002)[2]; and % of Technical Potential	
Austria	60.15	3	0.24	8
Belgium	81.73	5	0.088	2
Denmark	34.01	29	5.28	18
Finland	79.64	7	0.08	1
France	431.83	85	0.20	0.2
Germany	531.78	24	18.49	77
Greece	48.60	44	0.65	1
Ireland	22.14	44	0.27	1
Italy	295.08	69	1.18	2
Luxembourg	5.65	0	0.048	-
The Netherlands	105.81	7	1.36	19
Portugal	42.55	15	0.39	3
Spain	221.42	86	11.95	14
Sweden	138.16	41	0.66	2
UK	349.20	114	1.45	1
Norway	114.94	76	0.26	0.3
TOTAL	2,562.69	649	42.60	6.6

[1] Extrapolated from 2001, using IEA data from "Electricity Information 2003".
[2] Estimated from installed capacity, using capacity factors derived from year 2000 Eurostat production data.

The European Bank for Reconstruction and Development (EBRD) has recently commissioned a series of renewable energy assessments in its countries of operation (Black and Veatch, 2003). This included an estimate, for each country, of the realisable wind energy potential (in MW capacity) by 2020, and a figure for currently installed/under construction wind energy capacity. Both of these estimates have been converted to energy, using a capacity factor of 30% – the same as that employed by the study to derive the MW estimates (see Table 2.3). The wind energy potential estimates were based on previous estimates for the USSR in a 1989 publication *Master Plan of Wind Power Development in the USSR until 2010*, and other supporting information gathered by the study team.

Table 2.3: Eastern European Countries, Onshore Potential, EBRD

Country	Yr 2001 Net TWh Consumption[1]	EBRD Assessment (TWh/yr)	Wind Energy Production (TWh); and % of EBRD Assessment	
New Member States[2]				
Czech Republic	55.6	5.8	0.06	1
Estonia	6.2	1.3	0.02	2
Hungary	35.1	1.3	0.01	1
Latvia	6.0	1.4	0.06	4
Lithuania	8.7	1.3	0	0
Poland	118.8	10.5	0.19	2
Slovakia	24.4	0.7	0	0
Slovenia	13.8	0.3	0	0
Other EBRD				
Albania	5.9	0.1	0	0
Armenia	5.8	1.1	0.09	8
Azerbaijan	16.6	3.9	Negligible	0
Belarus	26.7	0.5	Negligible	0
Bosnia/Herzegovina	8.1	0.1	0	0
Bulgaria	32.5	8.9	0	0
Croatia	14.3	2.6	0	0
Georgia	7.6	6.0	0	0
Kazakhstan	48.4	21.0	0	0
Krgyzstan	10.5	3.9	0	0
FYR Macedonia	6.1	0.1	0	0
Moldova	3.2	1.3	0	0
Romania	46.1	7.9	Negligible	0
Russia	773.0	157.7	0.01	0.006
Tajikistan	14.5	2.6	0	0
Turkmenistan	8.5	26.3	0	0
Ukraine	152.4	13.1	0.11	0.8
Uzbekistan	47.1	2.6	0	0
FR Yugoslavia	32.4	0.3	0	0

[1] From US Department of Energy.
[2] Those not covered by the EBRD assessment are not included.

2.4.2 OFFSHORE

The only publicly available, consistent, energy estimates for the offshore wind resource are from the previously mentioned European Commission study (Garrad Hassan, Germanischer Lloyd, Windtest, 1995). These are reproduced in Table 2.4. The Commission-funded CA-OWEE project (Concerted Action on Offshore Wind Energy in Europe, Delft University *et al*., 2001), collated estimates provided by each member state, and these are also shown in Table 2.4. These estimates are based on a variety of source material.

Table 2.4: Offshore Wind Energy Estimates, Europe

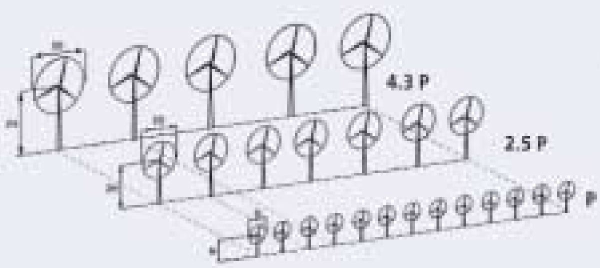
Country	Yr 2002 Consumption (TWh)	GH-GL Study (TWh/y)	CA-OWEE Survey (TWh/y)
Belgium	78.0	24	4
Denmark	37.2	550	26
Finland	71.9		20
France	533.3	477	44
Germany	543.5	238	45
Greece	48.9	92	5
Ireland	22.9	184	11
Italy	270.3	154	10
The Netherlands	92.4	137	33
Portugal	44.1	48	2 - 3
Spain	216.3	140	7
Sweden	143.4		22.5
UK	361.5	986	230 - 334
Total	**2,463.7**	**3,030**	**459.5 - 564.5**

2.4.3 UPDATING RESOURCE POTENTIAL

An estimate of the potential wind energy resource is not a fixed quantity. It changes over time as the technology develops and as more is learned about its performance and about the technical, environmental and social considerations which influence the density and location of turbine deployment. This changing quantity is not unique to the wind industry - it is an established concept in the oil and gas industry, where estimates of recoverable oil and gas reserves are continually being revised as the technology improves and as new discoveries are made.

Figure 2.3 explains the upward trend in turbine size. For line configurations of wind parks, the installed power per unit of length increases at a rate greater than linearly with diameter which would be expected from simple considerations.

Figure 2.3: Relationship between Power and Turbine Dimensions



P: installed power (kW)
D: rotor diameter (m)
H: tower height (m)

Source: ECN (2003).

As an example of how more up-to-date assumptions can change resource estimates, Table 2.5 compares estimates for the UK's onshore wind resource published in 1994 and later revised in 1997 (Brocklehurst, 1997). The same underlying wind data were used for both studies. Principal differences were in the "typical" technology assumptions made in 1994 and 1997 – 300 kW and 25 m hub height in 1992 compared with 600 kW and 45 m in 1997 – and in the availability and use of constraints data. The latter has no effect on the technical or "feasible" resource, but allows a more sophisticated and thorough estimate of the practical resource.

Table 2.5 shows data for the so-called feasible, accessible and practical resource. The practical resource is significantly greater in 1997 than in 1994 due largely to the increase in machine size. The accessible resource is slightly smaller in 1997, due to assumptions on protected areas. The practical resource is greater in 1997 due to a combination of factors relating to technology, deployment and economic factors.

Table 2.5: UK Onshore Resource Estimates			
	Feasible (TWh)	Accessible (TWh)	Practical (TWh)
1994	204.120	343.730	37.407
1997	660.787	317.854	57.627

2.4.4 CONCLUDING REMARKS

This brief section has collected together the available wind energy estimates for the EU-15 and the new member states. There is no complete integrated report which can be drawn upon to provide a single estimate of the wind energy resource in the EU-25. It would seem an appropriate and useful task to develop a single common approach so that the wind energy potential for an enlarged EU can be assessed. Plans can then be made to promote wind energy as widely as possible. The real future for wind is through large-scale integration and hence this approach would have both technical and strategic merit.

2.5 Local Wind Resource Assessment and Energy Analysis

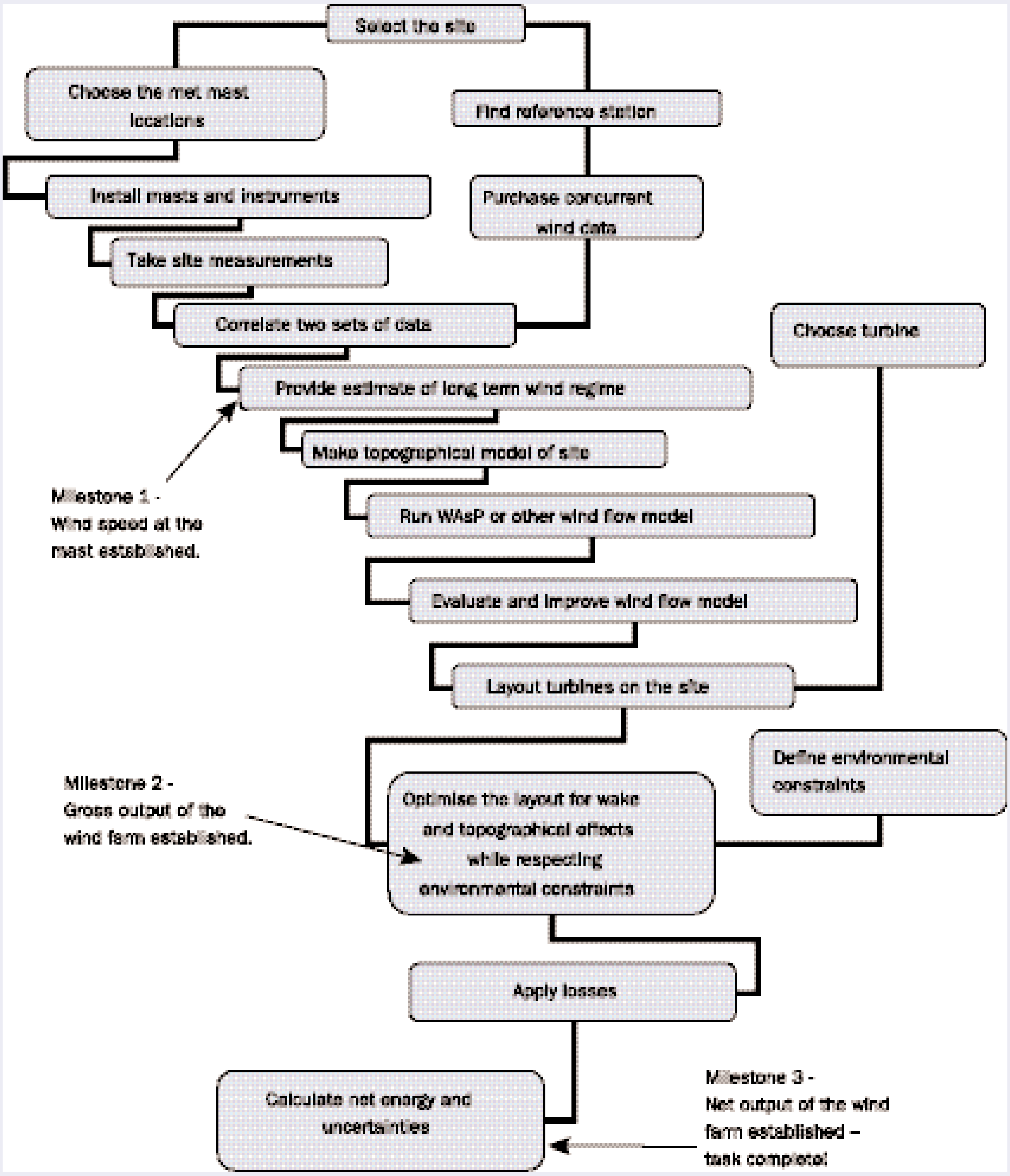
2.5.1 INTRODUCTION

The previous section has presented wind maps for Europe and has considered the wind resource at a strategic level. The purpose of this section is to consider the resource assessment and modelling at a local, wind farm, level. To the wind farm developer, regional wind maps are valuable tools for site finding, but will not be of sufficient accuracy to justify the financing of a development. The single most important characteristic of a site is its wind speed, and the performance of a wind farm is very sensitive to uncertainties and errors in the basic wind speed estimate.

For the majority of prospective wind farms, the developer must carry out a wind resource measurement and analysis programme. This must provide a robust prediction of the farm's expected energy production over its lifetime. This section discusses the issues which are pertinent to recording an appropriate set of site wind data and the methodologies which can be used to predict the expected long-term energy production of a project.

Figure 2.4 provides an overview of the whole process. The sections below describe this process step-by-step. Appendix C provides a worked example of a real wind farm which has been operational for a year and for which these techniques were used to estimate its long-term energy production.

Figure 2.4: Overview of the Energy Prediction Process



2.5.2 THE IMPORTANCE OF THE WIND RESOURCE

Wind energy has the attractive attribute that the fuel is free and will continue to be free for the project's lifetime and beyond. The economics of a project depend, crucially, on the site wind resource. At the start of the project development process, the long-term mean wind speed at the site is not known. To illustrate the importance of this measurement, Table 2.6 shows the energy production of a 10 MW project for a range of long-term annual mean wind speeds.

It can be seen that when the long-term mean wind speed is increased by 67% from 6 m/s to 10 m/s, energy production increases by 134%. This range of speeds would be typical of Bavaria at the low end and Scotland or Ireland at the high end. As the capital cost does not strongly depend on wind speed, the sensitivity of the project economics to wind speed is clear. Table 2.6 illustrates the importance of having as accurate a definition of the site wind resource as possible. The sensitivity of energy yield to wind speed variation varies with the wind speed. For a low wind speed site the sensitivity is greater than for a high wind speed site. For example, at a low wind speed site a 1% change in wind speed might result in a 2% change in energy, whereas at a high wind speed site the value might be only 1.5%.

Table 2.6 illustrates long-term mean wind speeds at different sites. The same comments apply at an individual site. The commercial value of a wind farm development depends on its energy yield which, in turn, is highly sensitive to wind speed. A change in wind speed of just a few per cent makes an enormous difference financially.

In summary, the single most important characteristic of a wind farm site is the wind speed. Every effort should be made to maximise the length, quality and geographical coverage of the data collected. However, measurements are undertaken at the very beginning of a project and some compromise is therefore inevitable.

2.5.3 BEST PRACTICE FOR ACCURATE WIND SPEED MEASUREMENTS

These results illustrate the importance of having an accurate knowledge of the wind resource. A high quality site wind speed measurement campaign is therefore essential to reduce uncertainty in the predicted energy production of a proposed project. The goal for a wind measurement campaign is to provide information to allow the best possible estimate of the energy on the site to be provided. The question then arises of how many masts to use and how high they should be.

Number and Height of Meteorological Masts

For a small or medium sized wind farm site it is likely that one meteorological mast will be sufficient to provide an accurate assessment of the site's wind resource. For large wind farms, say in excess of 20 MW, located in complex terrain, it is likely that more than one mast will be required to give an adequate definition of the wind resource across the site. In simple terrain, and where there is already a lot of experience at neighbouring wind

Table 2.6: Sensitivity of Wind Farm Energy Production to Wind Speed

Wind Speed (m/s)	Wind Speed Normalised to 6 m/s (%)	Energy Production of 10 MW Wind Farm (MWh/annum)[1]	Energy Production Normalised to 6 m/s site (%)	Capital Cost Normalised to 6 m/s site (%)
5	83	11,150	63	100
6	100	17,714	100	100
7	117	24,534	138	102
8	133	30,972	175	105
9	150	36,656	207	110
10	167	41,386	234	120

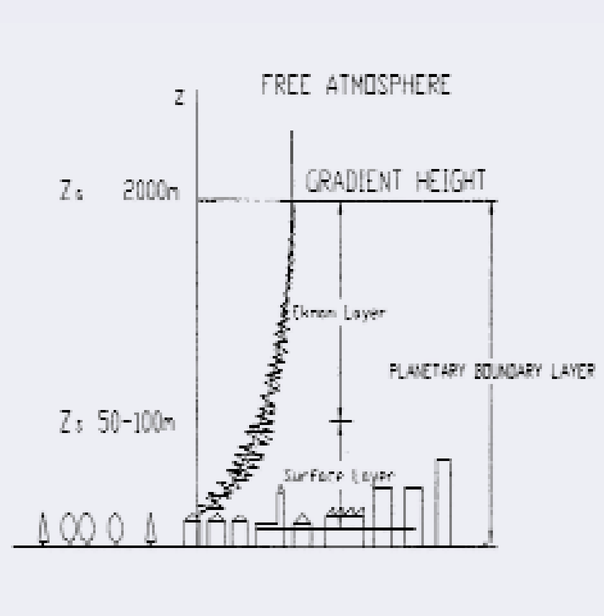
[1] Assumes typical turbine performance, air density of 1.225 kg/m^3, total losses of 12 % and Raleigh wind speed distribution.

farms, the performance of these wind farms can be used in lieu of a measurement campaign. A great many turbines have been sited in this way in North Germany and Denmark. However, great caution must be exercised in extending this approach to more complex areas.

The locations and specifications of the mast or masts need to be considered on a site-specific basis but, in general terms, if there are significant numbers of turbines more than one kilometre from a meteorological mast in terrain which is either complex or in which there is significant forestry, it is likely that additional masts will be required. In such circumstances, discussion with the analyst who will have responsibility for assessing the wind resource at the site is recommended at an early stage.

The wind speed generally increases with height, as illustrated in Figure 2.5.

Figure 2.5: The Atmospheric Boundary Layer Shear Profile



The figure shows, schematically, the way in which the wind speed grows. This characteristic is called "shear" and the shape of this profile is known as the "wind shear profile". Given the discussion above about the importance of accurate wind speed measurements, it is clear that it will be important to measure the wind speed as near to the hub height of the proposed turbine as possible. If a hub height measurement is not made then it will be necessary to estimate the shear profile. This can be done, but it produces uncertainties. Commercial wind turbines often have hub heights in excess of 60 m. Just five years ago, a typical hub height was 30 to 40 m.

A 40 m meteorological tower can be erected by a small crew of experienced people and is relatively cheap at approximately €20,000. Higher masts are much more expensive to erect, around €100,000, and also more awkward to handle. Given the cost sensitive nature of this stage of the development there is a compromise to be made between expensive accurate measurements at hub height or cheaper measurements at a lower height which will be subject to more uncertainty. Often early prospecting is undertaken with a short mast and further higher masts are added if the site appears promising.

Specification of Monitoring Equipment and Required Signals

A typical anemometry mast will have a number of anemometers (devices which measure wind speed) installed at different heights on the mast and one or two wind vanes (devices which measure wind direction). These will be connected to a data logger at the base of the mast via screened cables. It is unusual for there to be a power supply at a prospective wind farm site, so the whole anemometry system is usually battery operated. Some systems have battery charging via a solar panel or small wind turbine (WT). For some systems, particularly in cold climates, temperature measurement is important to detect icing of the anemometers. In such circumstances, the use of heated or "ice free" anemometers is beneficial; however, their use without an external power source is usually impractical. Measurement of the atmospheric pressure at the site is desirable, but often not essential.

Signals which would typically be recorded for each sensor with a 10-minute averaging period are:

- Mean wind speed
- Maximum three second gust wind speed
- True standard deviation of wind speed
- Mean wind direction
- Mean temperature
- Logger battery voltage

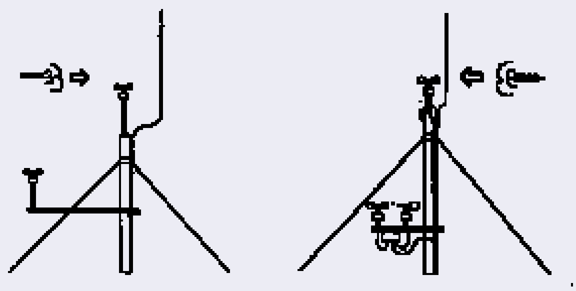
In recent years, it has become increasingly common to download data via modem. This approach has made managing large quantities of data from masts on a range of prospective sites significantly more efficient than manual downloading. It also has the potential to improve data coverage rates.

Recommendations provided by the International Electrotechnical Committee (IEC), the International Energy Agency (IEA) and MEASNET (IEA Annex XI edition 1999, IEC 6-1400 Part 12, www.measnet.com) provide substantial detail on minimum technical requirements for anemometers, wind vanes and data loggers. It is strongly recommended that anyone intending to make "bankable" wind measurements should refer to these documents. Historically, a notable deviation from best practice as defined in the IEC and IEA documents is the use of anemometers which have not been individually calibrated for the assessment of the wind resource at the site. Each sensor will have a slightly different operational characteristic as a result of variations in manufacturing tolerances. The use of individually calibrated anemometers has a direct impact on reducing the uncertainty in the predicted wind speed at a site and is therefore to be recommended.

Over the past decade, perhaps the most significant shortcoming of wind speed measurements at prospective wind farm sites has been poor sensor mounting arrangements. There has been an increasing body of measured data which has demonstrated that, if the separation of anemometers from the meteorological mast, booms and other sensors is not sufficient, then the wind speed recorded by the sensor is not the true wind speed since it is influenced by the presence of the other objects.

It is important to be aware of the potential influence of the support structure on the measured data. Detailed guidance is provided in IEA Annex XI edition 1999, IEC 6-1400 Part 12, (www.measnet.com) on specific separation distances which are required to reduce the influence of the support structure on the measurement to acceptable levels. Illustrative examples which demonstrate good and poor mounting arrangements are presented in Figure 2.6.

Figure 2.6: Summary of Good Practice (left) and Poor Practice (right) Mounting Arrangements



If the guidance presented above is followed, a high quality set of wind data should become available, in time, from a prospective site. The absolute minimum requirement is one year to ensure that any seasonal variation is properly captured. In addition to specifying and installing appropriate equipment, vigilance is required in the regular downloading and checking of data to ensure high levels of data coverage are achieved. It will be necessary to demonstrate, either internally or externally, the provenance of the data on which important financial decisions are being made. Therefore, it is important to keep accurate records regarding all aspects of the specification, calibration, installation and maintenance of the equipment used.

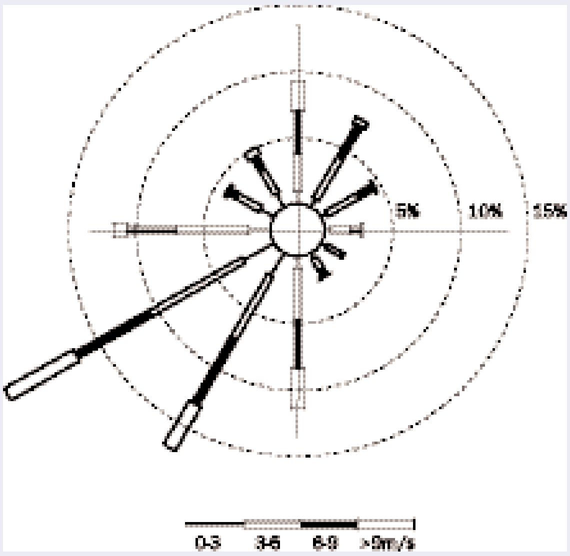
2.5.4 THE ANNUAL VARIABILITY OF WIND SPEED

"Wind rose" is the term given to the way in which the joint wind speed and direction distribution is displayed. An example is given in Figure 2.7. The wind rose can be

thought of as a wheel with spokes spaced, in this example, at 30˚ intervals. For each sector the wind is considered separately. The length of time that the wind comes from this sector is shown by the length of the spoke and the speed is shown by the thickness of the spoke.

The design of a wind farm is sensitive to the shape of the wind rose for the site. In some areas, particularly where the wind is driven by thermal effects, the wind rose can be very unidirectional. For example in Palm Springs, USA the wind comes from a sector 10˚ wide for 95% of the year. At this type of site, the WTs will tend to be arranged in tightly packed rows perpendicular to the wind with large spaces downwind. In Northern Europe, the wind, although predominantly from the south west, also comes from other directions for a significant part of the time and hence the WTs will tend to be more uniformly spaced in all directions.

Figure 2.7: Wind Rose



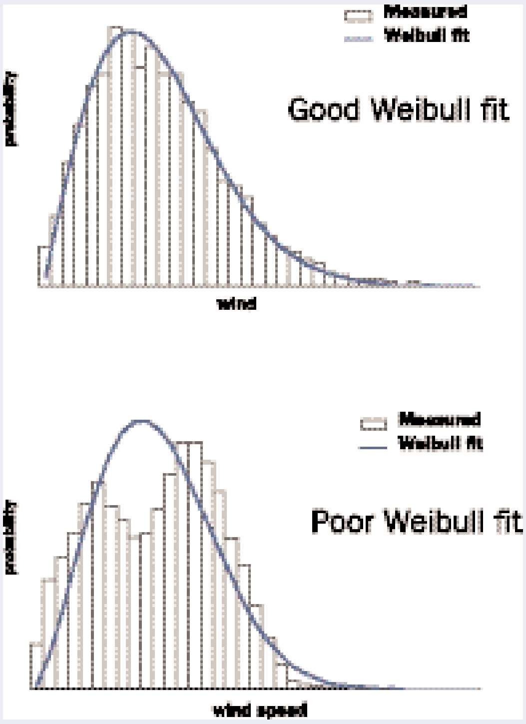
The description above has concentrated on the wind speed and wind rose. The other important parameter which determines the output of a wind farm is the wind speed distribution. This distribution describes the amount of time on a particular site that the wind speed is between different levels. This characteristic can be very important and is often inadequately treated. It is the combination of the wind speed distribution and the power curve of the proposed turbine which combine together to determine the energy production.

Consider, as an example, two sites, A and B, both with a mean wind speed of 9 m/s. At one extreme, Site A, the wind blows at 9 m/s all the time and the wind farm would be very energetic. At the other extreme, Site B, the wind blows at 4 m/s (below cut-in wind speed for a typical WT) for one-third of the time, at 26 m/s (above cut-out wind speed for most turbines) for one-third of the time and at 9 m/s for one-third of the time. The mean wind speed at Site B would be (1/3) x (4 + 9 + 26) = 13 m/s, much higher than Site A, but the energy yield at Site B would be only one-third of that at Site A.

Although this example is unrealistic, it serves to illustrate a point; that wind speed alone is not adequate to describe a site's potential energy yield. Some more realistic site wind speed distributions are shown in Figure 2.8 where the actual wind speed distribution is also shown as a "Weibull fit" to the distribution. The Weibull distribution is a mathematical expression which has been found to provide a good approximation to measured wind speed distributions. This empirical curve fit is therefore used to characterise a site. Such a distribution is described by two parameters: the Weibull "scale" parameter which is closely related to the mean wind speed; and "shape" which is a measurement of the width of the distribution parameter. This approach is useful since it allows both the wind speed and its distribution to be described in a concise fashion. However, as can be seen from this figure, care must be taken in using a Weibull fit. It is often a very good likeness but it can be misleading.

The annual variability in wind rose and wind speed frequency distribution are also important in assessing the uncertainty in the annual energy production of a wind farm, and are described in detail in a later section of this chapter. For illustrative purposes, only the variation in annual mean wind speed is considered, as the other factors usually have a secondary effect.

Figure 2.8: Some Example Wind Speed Distributions



Variability of One Year Periods

As discussed above, annual wind speed variability has a strong influence on the analysis methodologies developed for the assessment of the long-term wind resource at a site and the uncertainty in such predictions. Before describing some typical methodologies, an example is used to illustrate typical levels of annual variability of wind speed. The example seeks to answer the following questions:

- *If there is one year of wind data available from a potential wind farm site, what error is likely to be associated with assuming that such data are representative of the long term?*
- *If, instead, there are three years of data available from the site, how does the picture change?*

Figure 2.9a: The Annual Mean Wind Speed Recorded at Malin Head, Ireland

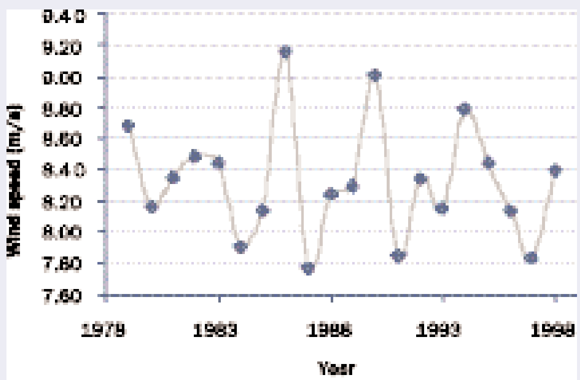


Table 2.7: Wind Speeds and Energy Production for the Average, Lowest and Highest Wind Speed Year in the Period 1979 to 1998 Based on a Nominal 10 MW Wind Farm at Malin Head

	Annual Mean Wind Speed (m/s)	Percentage of Average Year (%)	Energy Production (MWh/annum)	Percentage of Average Year (%)
Lowest wind speed year (1987)	7.77	93.3	29,491	89.8
Average year	8.33	100.0	32,847	100.0
Highest wind speed year (1986)	9.16	110.0	37,413	113.9

Figure 2.9a presents the annual mean wind speed recorded at Malin Head meteorological station over a 20-year period. It can be seen that there is significant variation in the annual mean wind speed, with maximum and minimum values ranging from less than 7.8 m/s to nearly 9.2 m/s. The standard deviation of annual mean wind speed over the 20-year period is approximately 5% of the mean.

Table 2.7 presents the average and annual maximum and minimum wind speeds. As an illustration, the equivalent annual energy productions for the example 10 MW wind farm case described above are also presented.

Figure 2.9b: Annual Mean Wind Speed at Malin Head over a 20-Year Period – Three Year Rolling Averages

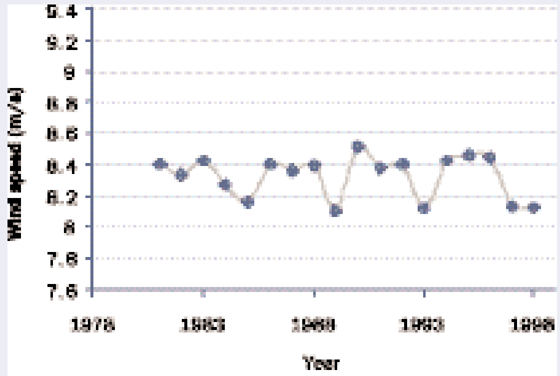


Table 2.7 shows that, had wind speed measurements been made on the site for just one year, and this one year had been assumed to be representative of the long term, then the predicted long-term wind speed at the site could have been in error by 10%. It is often the case that little on-site data is available and hence this situation can arise. In terms of energy production it is evident that the predicted figure could be in error by some 14% if the above assumption had been made. For a lower wind speed site, a 10% error in wind speed could easily have a 20% effect on energy production owing to its higher sensitivity to changes in wind speed at lower wind speeds.

Variability of Three-Year Periods

Figure 2.9b illustrates the same data as in Figure 2.9a, but applying to a three-year rolling average. It is immediately apparent that the variability in the mean wind speed over the three-year period is substantially reduced compared with the one year period.

The results presented in Table 2.7 are reproduced in Table 2.8, this time based on the highest and lowest three-year averages.

Table 2.8: Wind Speeds and Energy Production for the Average, Lowest and Highest Three Year Periods within the Period 1979 to 1998

	Annual Mean Wind Speed (m/s)	Percentage of Average Year (%)	Energy Production (MWh/annum)	Percentage of Average Year (%)
Lowest wind speed year (1989)	8.10	97.2	31,540	96.0
Average year	8.33	100.0	32,847	100.0
Highest wind speed year (1990)	8.51	102.2	33,871	103.1

Table 2.8 illustrates that, if three years of data are available from a site, the maximum deviations of the wind speed and energy production over these periods from long-term averages is substantially reduced. The deviations of 10% and 14% in wind speed and energy for the analysis based on one-year data sets reduces to deviations of 3% and 4% respectively when three-year periods are considered.

While the results presented here are site-specific, they are broadly representative of any wind farm in Europe. The reliability of long-term data and the consistency of the wind is central to the commercial appraisal of a wind farm.

Some substantial work has been undertaken (Raftery, 1997) to try and identify the key characteristics of long-term behaviour of the wind. This effort consisted of identifying reliable long-term data sets from around the world and attempting to tease out some common characteristics. One of the results of this approach is illustrated in Figure 2.10. Data sets of at least 30 years in duration have been assembled for each site. The mean of the 30 annual figures was calculated, together with their standard deviation. The ratio of the standard deviation to the mean was then calculated and it was found that this varied very little from location to location. This same trend was observed all over the world, in Australia, Japan and the US, as well as Europe. This finding is useful in order to determine the expected variation in long-term wind behaviour.

In summary, this work indicates that the annual variability of long-term mean wind speeds at sites across Europe tends to be similar and can reasonably be characterised by a normal distribution with a standard deviation of 6%. This result plays an important role in assessing uncertainty in the prediction of wind farm energy production.

Figure 2.10: Wind Map of Europe – Inter Annual Variation Shown as Standard Deviation as a Percentage of Mean

2.5.5 ANALYTICAL METHODS FOR THE PREDICTION OF THE LONG-TERM WIND REGIME AT A SITE

From the above, it is clear that the key element in assessing the energy production of a proposed wind farm site is the prediction of the long-term wind regime at the site mast or masts. The outcome of the analyses described in this section is a long-term wind speed distribution together with the wind rose. Other meteorological inputs to the energy production analyses are the long-term site air density and site turbulence intensity - a measurement of the “roughness” of the wind - which, while important, are of secondary influence to the energy production of the wind farm; their derivation is not therefore considered in detail here. It should be noted that the turbulence intensity is very important in determining the loading on a WT and hence its expected operational lifespan.

Overview

There are essentially two methods which can be used for the prediction of the long-term wind resource at a site where on-site measurements are available. These are:

1 Correlate on-site wind data with wind data recorded at a long-term reference station.
2 Use only on-site wind data.

Unless a long-term data set is already available for a site, it is desirable to use Method 1 for predicting the long-term wind resource at a site. Typically, a reliable result can be obtained with as little as one year of site data. As illustrated by the example presented for Malin Head above, if Method 1 cannot be used and Method 2 is used with only one year of data, the uncertainty caused by the assumption that the year of data recording is representative of the long term is substantial.

It is therefore normal practice to find a suitable source of longer term data in the vicinity of the wind farm site. This allows a correlation analysis to be undertaken and, if only relatively short data sets are available from the site itself, is likely to result in an analysis with a significantly lower uncertainty than that which would result from use of the on-site data alone. However, before a data set from a

long-term reference station can be used in an analysis, it is vital that thorough checks on its validity are carried out.

Before discussing the details of this approach it may be helpful to consider the broader picture. It would be ideal if every site benefited from a long-term data set of, say, 10 years. Now and again this happens, but it is very rare. It is therefore necessary either to use limited on-site data or to try and use other data to gain a longer term view. The correlation approach can be thought of in the following way. Data are gathered on the site using good quality calibrated equipment. These data provide absolute measurements of the wind speed on the site during the measurement period. If it can be established that there is a close relationship (a good correlation) between these site data and a reference mast, then it will be possible, by using the mast's long-term reference data, to re-create the wind speeds on the site. Thus, it is possible to "pretend" that long-term wind speed records exist for the site. If a good correlation exists, this is a very powerful technique but, if the correlation is weak, it can be misleading and hence should be used with caution.

Necessary conditions for an off-site wind data set to be considered as a long-term reference are set out below:

- The reference data set includes data which overlaps with the data recorded on site.
- It can be demonstrated that the data have been recorded using a consistent system over the period of both the concurrent and longer term data. This should include consideration not just of the position and height of the mast and the consistency of equipment used, but also potential changes in the exposure of the mast. For example, the construction of a new building at an airport or the erection of a wind farm near an existing mast will corrupt the data. The absolute values recorded at the reference station are not important, but any changes in either process or the surrounding environment, will render it useless as a reference site. This investigation is therefore very important and is usually done by a physical visit to the site, together with an interview with site staff.
- The exposure of the reference station should be good. It is rare that data recorded by systems in town centres, or where the mean wind speed at the reference station is less than half that of the site, prove to be reliable long-term reference data sets.
- The data are well correlated with those recorded at the site.

Where there have been changes in the consistency at a reference long-term data source, or where a reliable correlation cannot be demonstrated, it is important that the use of a prospective source of long-term data is rejected. If no suitable reference meteorological station can be found, then the long-term wind resource can only be derived from the data recorded at the site itself. It is likely that longer data sets of two or more years are required to achieve similar uncertainty levels to those which would have been obtained had a high quality long-term reference data set been available.

Experience of wind energy project analysis across Europe indicates that the density of public sources of high quality wind data is greater in northern than in southern Europe. This observation, combined with the generally more complex terrain in much of southern Europe, often leads to analyses in southern Europe being based only on the data recorded at the wind farm site or other nearby wind farm sites. In contrast, for analyses in northern Europe, correlation of site data to data recorded at national meteorological stations is more common. Clearly, this statement is a generalisation and there are numerous exceptions to it. However, the establishment of a good set of long-term reference masts specifically for wind energy use in areas of Europe where wind energy projects are likely to be developed would be an extremely valuable asset. An EU-wide network of this sort would be highly beneficial.

Correlation Methodologies

Some detailed discussion about different correlation techniques is provided in Appendix D.

The process of comparing the wind speeds on the site with the wind speeds at the reference station and using the comparison to estimate the long-term wind speed on the site is called measure correlate predict (MCP). This process is also described in some detail in Appendix D.

Once the MCP process has been completed, an estimate exists of the long-term wind speed on the site.

This stage – shown as Milestone 1 on Figure 2.4 - is a very important one, since it marks the point at which reliable information on the site's long-term wind speed behaviour at a single point (or points if there are multiple masts) becomes available. This estimate will contain both the mean long-term expected value and the uncertainty associated with that value. So far, however, we know nothing of the distribution of the wind speed across the site and neither have we considered the way in which the energy values can be converted into energy.

2.5.6 THE PREDICTION OF THE ENERGY PRODUCTION OF A WIND FARM

In order to predict the energy production of the wind farm it is necessary to undertake the following tasks:

- Predict the variation in the long-term wind speed over the site at the hub height of the machines based on the long-term wind speeds at the mast locations.
- Predict the wake losses which arise as a result of one turbine operating in front of another.
- Calculate or estimate other losses.

Information Required for an Analysis

In addition to the wind data described in the earlier sections, inputs to this process are typically as follows:

- Wind farm layout and hub height.
- Turbine characteristics, including power curve (the curve which plots the power output of a turbine as a function of the wind speed) and thrust curve (the equivalent curve of the force applied by the wind at the top of the tower as a function of wind speed).
- Predicted long-term site air density and turbulence intensity (the turbulence intensity is the "roughness" of the wind).
- Definition of the topography over the site and surrounding area.
- Definition of the surface ground cover over the site and surrounding area.

Energy Production Prediction Methodologies

Typically, the prediction of the variation in wind speed with height, the variation in wind speed over the site area, and the wake interaction between WTs are calculated within a bespoke suite of computer programs which are specifically designed to facilitate accurate predictions of wind farm energy production. The use of such tools allows the energy production of different options of layout, turbine type and hub height to be established rapidly once models have been set up. Such programs are commonly termed wind farm design tools (WFDT).

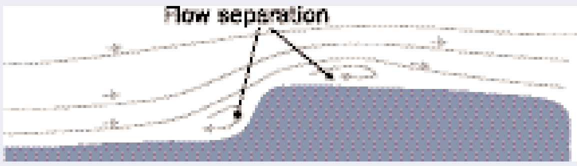
Within WFDTs, site wind flow calculations are commonly undertaken using the WAsP model (Troen and Petersen, 1989) which has been widely used within the industry over the past decade. Other commercial models which are physically similar to WAsP are also sometimes used. This area of the wind farm energy calculation is in need of the greatest level of fundamental research and development. Flow models for use in commercial wind farm development have to be quick to execute and be both reliable and consistent. At present, the industry opts for simple but effective tools. More rigorous and much more time consuming tools may be adopted in the future if they can be made cost effective and not too sensitive to modelling assumptions.

The challenge is to take a topographical map and, for any point on it, determine the long-term wind rose. This information is then used to calculate the long-term wind speed at all the points on the map where it is intended to place WTs.

The WAsP model does have shortcomings under certain topographical and flow conditions. It needs to be used with care and experience and not as a "black box". In particular, it does not include "viscous effects" which cause the wind to "separate" as it flows over a sharp change in topography. The WAsP model will follow the terrain whereas the real wind will behave as shown in Figure 2.11.

There is an enormous amount of work in progress in all aspects of engineering, quite distinct from the wind energy industry in which developments are being made in the

Figure 2.11: An Example of Flow Separation over a Hill



numerical prediction of complicated flows. Most notably, these efforts centre on aerospace problems – accurately predicting flow over aircraft wings and fuselage for example, or predicting internal flows in turbo-machinery. Efforts are now being made to apply such models to the arbitrary terrain which defines a wind farm. There is still a long way to go before these models can be considered either reliable or commercially feasible for wind farm design. The energy estimate is only as good as its weakest link and hence its accuracy is largely defined by this step – the topographical wind model. Data sets now exist which can be used for the validation of new codes and further developments are expected. The task is, nevertheless, a demanding one and accurate calculation of wind flow over steep terrain is still some way off. At present it is necessary to use a mixture of computation and human insight.

Once the topographical effects on the flow have been computed, it is necessary to determine how the individual turbines affect one another (the wake effects). If a turbine is working downstream of another (i.e. in its wake) then the turbine will come into contact with less wind than it would if it were in the free stream. For some types of wind rose and wind farm design this effect needs to be carefully calculated as it can be significant – of the order of 15% in lost energy. The models which estimate this loss are knows as "wake models". Different complexities of wake model are used in the various commercially available WFDTs. These tools are now well validated for a variety of different types of wind farm layout. However, it is well known that they do not work well for very tightly packed wind farms, such as those described above at Palm Springs, and further fundamental work is required to improve modelling in this area.

It is important to appreciate that, as the distance of the turbine from the meteorological mast increases, the uncertainty in the prediction also increases. This increase in uncertainty is typically more rapid in complex than in simple terrain. Experience of the decrease in accuracy with distance from the mast when using models such as WAsP are inherent in making recommendations regarding the appropriate number of meteorological masts for a wind farm site, as discussed above. WFDTs also allow environmental constraints to be included – areas of the site which may not be used because of noise, visual intrusion, shadow flicker, land ownership, presence of protected flora and fauna, etc. These considerations are discussed in more detail below.

The ability of WFDTs to provide an integrated model of a wind farm also allows them to be used to optimise wind farm design. This task is performed automatically. The tool positions the turbines to achieve the best possible balance between exploiting maximum wind speed and minimising wake losses. This process can be successfully undertaken at the same time as observing the environmental and ownership constraints. The emergence of WFDTs has been a significant development in wind farm design. The successful completion of an energy calculation using a WFDT may be considered as Milestone 2 in Figure 2.4.

Wind Farm Energy Loss Factors

When WFDT calculations have been undertaken, potential sources of energy loss must be considered on a site-specific basis. Specific sources of energy loss other than those associated with wake effects are described below.

Turbine Availability

A figure is assumed for turbine availability based on data from modern operational wind farms. However, availability may be a matter of warranty between the owner and the turbine supplier and the assumed figure should be reviewed when the terms of that warranty are clear. In some circumstances it is appropriate to consider a time varying value of availability.

Electrical Transmission Efficiency

The electrical transmission efficiency from the terminals at the base of the turbine tower to the wind farm metering point will depend on the site's detailed electrical design. A formal calculation of the electrical loss should be undertaken when the electrical system has been defined. Some of the WFDTs described above may be used for such calculations.

Turbine Icing and Blade Degradation

This factor reflects losses associated with icing of the turbine, temporary "fouling" of the turbine blades by dirt or insects and long-term degradation of the blade. It needs to be considered on a site-specific basis.

High Wind Hysteresis

This is caused by the turbine cut-in and cut-out control criteria for high wind speeds. The magnitude of the loss is influenced by three factors:

1 The turbine will cut-out when the mean wind speed exceeds a maximum level and it will not cut-in again until the mean wind speed is lower than the cut-out mean wind speed.
2 The turbine will cut-out if the instantaneous gust wind speed exceeds a maximum level and the turbine will not cut-in until the wind speed drops.
3 The accuracy of the calibration of the instruments that determine the wind characteristics at the turbine.

These three effects will cause the turbine to lose production for some proportion of high mean wind speed occurrences. This is clearly a site-specific issue which is more significant for high wind speed sites than low wind speed sites.

Substation Maintenance

The wind farm substation will require maintenance which is likely to be at a time which is outside the control of the wind farm owner and, therefore, a small loss may be experienced.

Utility Down Time

The wind farm will be unable to export energy if the grid is not available. This needs to be considered on a site-specific basis with suitable historic information supplied by the grid operator.

Power Curve Adjustment

Power curve adjustment to the energy prediction accounts for variations in the actual turbine performance in comparison to the supplied power curve. An example of such an adjustment is provided in Appendix C.

Columnar Control Loss

If turbine spacing is close, the site conditions may exceed the wind conditions within the WT certification criteria. In these circumstances it may be necessary to shut down turbines which are closely spaced when the wind direction is parallel to the line of turbines. The turbine supplier should indicate whether such a strategy is required at the time of a tender.

These losses can combine to a significant total – often between 9% and 12% of the gross energy yield. Applying these additional losses to the gross energy is represented by Milestone 3 in Figure 2.4.

2.5.7 DEFINITION OF UNCERTAINTY IN PREDICTED ENERGY PRODUCTION

The uncertainty analysis is an important part of any assessment of the long-term energy production of a wind farm. Although an uncertainty analysis needs to be considered on a site-specific basis, the process can be shown as follows:

- Identify the different inputs to and processes within the analysis.
- Assign an uncertainty to each of these elements both in terms of the magnitude of the uncertainty and the shape of the distribution.
- Convert each of the uncertainties into common units of energy.

- Combine the various uncertainties to define a total uncertainty for the entire prediction.
- Present uncertainty statistics at requested levels.

Research work reported by Raftery *et al*. (1999) defined a comprehensive risk register for wind power projects and included detailed Monte Carlo based analysis techniques to assess the uncertainty in the results obtained. Based on the results of this work, use of an uncertainty analysis with a number of simplifying assumptions can be justified. The main simplifying assumptions are that it is reasonable to consider a relatively small number of key uncertainties and that these individual uncertainties can be assumed to be normally distributed. Making these assumptions, it is possible to define energy production levels with a defined probability of exceedance.

It is common to present uncertainty results for both a long future period of, say, 10 years and also for a shorter period of one year. It is now normal practice for banks and financial institutions to be presented with such figures, in parallel with central energy production estimates, when wind farm financing is being arranged.

The uncertainty analyses presented within energy assessments typically assume that the turbines will perform exactly to the defined availability and power performance levels. The power performance and availability levels are usually covered by specific warranty arrangements and hence any consideration of the uncertainty in these parameters needs machine-specific and contract-specific review which is generally outside the scope of a "standard" energy analysis.

Uncertainty in the energy estimates is a vital part of the result.

2.6 Offshore Wind Farm Design and Resource Estimation

This section describes the differences in wind flow monitoring and data analysis offshore compared with onshore.

2.6.1 FUNDAMENTALS

Onshore, topographic effects are one of the main driving forces of the wind regime. With no topographic effects offshore, other factors dominate wind behaviour.

The surface roughness (a parameter used to describe the roughness of the surface of the ground) is low, which results in a steeper boundary layer profile. The different values are illustrated in Table 2.9. Offshore, the surface roughness length is typically assumed to be 0.001 m or less. This assumption is reasonable for relatively calm weather, but it does not take into consideration the effect of wind speed on wave size. However, calculating this parameter is complex as the sea surface does not present fixed roughness elements in the same way as trees, hills and buildings. Low surface roughness also results in low turbulence intensity.

Table 2.9: Typical Values for z_o

Type of Terrain	z_o(m)	α
Mud flats, ice	0.00001	
Smooth sea	0.0001	
Sand	0.0003	0.10
Snow surface	0.001	
Bare soil	0.005	0.13
Low grass, steppe	0.01	
Fallow field	0.03	
Open farmland	0.05	0.19
Shelter belts	0.3	
Forest and woodland	0.5	
Suburb	0.8	
City	1	0.32

The coastal zone, where the properties of the boundary layer will be changing, extends away from the shore for varying distances, and this can result in variations in wind speed and boundary layer profiles across the wind farm.

2.6.2 MEASUREMENT OFFSHORE

Turbines for offshore wind farms are larger than those onshore. Their size presents several issues including the need to understand the characteristics of the boundary layer up to and above heights of 150 m. Measurements offshore are expensive. A typical mast will cost some €750,000, some 50 times that required for equivalent onshore work. Monitoring towers offshore are un-guyed and therefore need to be wider, which can mean that measurements is more susceptible to wind flow effects from the tower.

If monitoring equipment is not available, there are other sources of information which can be used to determine the approximate long-term wind regime at the offshore location. For example, there are some offshore databases for wind data including light vessels and observation platforms. None of these is suitable for a bankable report, however.

2.6.3 WIND ANALYSIS OFFSHORE

Depending on the amount of data available, different analytical methods can be employed. A feasibility study can be carried out based on available wind data in that area. WAsP can be used from coastal meteorological stations to give a prediction offshore, aided by its latest tool, the coastal discontinuity model (CDM) (Bartholemie, 2003). Existing offshore measurements can also be used. There are problems associated with using long distance modelling, especially around the coast, due to the differences in predominant driving forces between onshore and offshore breezes, and variation in the coastal zone in between.

For a more detailed analysis, measurements offshore at the site are necessary. MCP from a mast offshore to an onshore reference station can be used. With several measurement heights more accurate modelling of the boundary layer will help extrapolate to heights above the monitoring mast. Given the absence of topography, offshore measurements from such a mast can be considered representative of a much larger area than would be possible onshore.

2.6.4 ENERGY PREDICTION

This step is essentially the same as for onshore predictions. There is generally only minor predicted variation in wind speed over a site. For large offshore sites, wake losses are likely to be higher than for many onshore wind farms. Such losses are increased due to the lower ambient turbulence levels since offshore wind is much smoother. There is, therefore, less mixing of the air behind the turbine, which results in a slower re-energising of the slow moving air, meaning that the wake lasts longer. Recent research has, for the first time, validated wake modelling techniques offshore (Risø National Laboratory, 2002).

Offshore machines are likely to experience more down time than those onshore, due to difficulties associated with access. If a turbine has shut down and needs maintenance work, access to it may be delayed until there is a suitable window in the weather. This aspect of offshore wind energy is likely to be the most important element in determining real cost.

2.6.5 OTHER EFFECTS TO CONSIDER OFFSHORE

Tidal rise and fall effectively shifts the location of the turbine in the boundary layer. Over a 12-hour period, this can cause variation in mean wind speed and also impact on the shear across the turbine rotor itself. Taking the UK as an example, tidal heights vary significantly, with Avonmouth having mean spring tides of 12.2 m in height, the largest range in the UK.

Temperature driven flows due to thermal inertia of the sea initiate localised winds around the coastal area. The sea takes longer to heat up and cool down than the land. During the day, as the land heats up, the warmer air rises and is replaced by cooler air from over the sea. This creates an onshore wind. The reverse effect can happen during the night, resulting in an offshore wind. The strength and direction of the resulting wind is influenced by the existing gradient wind which in some situations may be cancelled out by the sea breeze, leaving an area of no wind.

2.7 Forecasting

So far, this chapter has only considered the wind industry's ability to estimate long-term energy production from a wind farm. Usually this is the most important task since, to date, most of the power purchase agreements are "take or pay", meaning that the utility or other customer is obliged to buy *all* the energy produced by the wind farm. As the penetration of wind power generation in the overall energy mix increases, it will cause the fluctuations in energy output caused by variations in wind speed to be more visible. The independent system operators (ISOs) working to balance supply and demand on regional or national grid systems will need to predict and manage this variability to avoid balancing problems. The point at which this is required changes from system to system.

As the level of penetration of wind energy into individual grids increases it will be necessary to forecast over short to medium time scales (one hour to two days) how much energy will be produced. In some countries, forecasting is already required. New wind farms in California are required to "use best possible means available" to forecast the output and send such estimates to the California ISO. In European countries where there is already a high level of penetration - Spain, Germany and Denmark - operators and managers are routinely forecasting output from their wind farms. These forecasts are used to schedule the operations of other plant, but are also used for trading purposes.

Forecasting wind energy production will increase in importance as the level of installed capacity grows. The wind industry must allow ISOs to use wind energy to its best effect, by forecasting output from wind farms as accurately as possible. In the UK, where the market is already deregulated, energy traders are using crude forecasts to trade wind energy on the futures market.

At the same time as improving the predictability of the output of wind energy plant through improvements in forecasting techniques, awareness of the true behaviour of conventional plant should be considered. In order to provide the best mix of plant and technologies it will be important for all the different energy forms to be considered on an equitable basis. Proper, formal statistical analysis of both renewable and conventional plant is therefore necessary. This task should be considered as an essential element of a wind energy development strategy.

As a result of its strategic importance, forecasting has been the focus of considerable technical attention in recent years. A good source of general review materials, as well as detailed papers, can be found in Landberg *et al*. (2003). Although there is a variety of different techniques being used, they all share similar characteristics. It is therefore possible to provide a generic description of existing techniques, whereby data is provided by a weather forecast and production data is provided by the wind farms. The two sets of data are combined together to provide a forecast for future energy production.

To integrate wind energy successfully into an electricity system at large penetration levels, it will be necessary to predict wind energy production as accurately as possible.

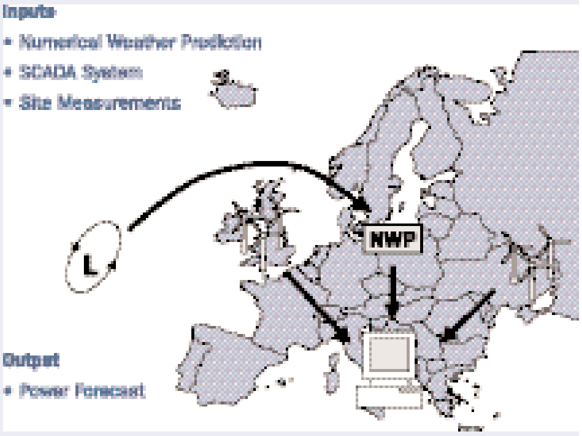
The numerical weather predictions (NWP) models run by national institutes are typically of continental, if not global, scale. Consequently, their resolutions tend to be too coarse for wind energy needs. For example, the model run by the UK Meteorological Office for north-west Europe has a minimum horizontal resolution of approximately 12 km.

The methods of achieving the transformation between coarse NWP forecasts and site-specific ones are varied. Despite this variation, they can largely be grouped into two main types - physical and statistical models.

Physical models primarily aim to improve the resolution of the "original" NWP model. The models used to achieve this can include:

- Simple linear-flow models, such as WAsP.
- Fine resolution NWP models. These are essentially local (nested) meso-scale versions of the original NWP model and are often termed "storm-scale" or "convective-scale". They aim to model local thermal and terrain effects that are not apparent at the coarse-scale.

Figure 2.12: A Schematic Representation of a Forecasting Approach



There are aspects of the physical model approach which need to be considered:

- Skill: The implementation of local meso-scale models requires the skill and competency of a meteorologist. There is always the possibility of a poorly formed model introducing further errors.
- Computational requirements: The formulation and execution of the models is computationally expensive.

2.7.1 OVERVIEW OF THE METHOD

There are several groups working in this area and they all have slightly different approaches (see, for example, Landberg *et al*., 2003). All, however, create power output forecasts through a two-stage process. First, there is the creation of site-specific meteorological forecasts (for some pre-defined reference point, such as a site meteorological mast). These meteorological forecasts are then transformed, via site-specific power models, to power output forecasts. This process is shown schematically in Figure 2.13.

To enable the meteorological model to be both auto-regressive and adaptive, feedback data from the site is also required. In other words, the method needs to know what is happening at the site where the predictions are being made so it can "learn" and adjust the forecasts accordingly. An example time series plot is shown in Figure 2.14. This shows how well the model transforms the initialising NWP forecasts (dotted line) to represent what is actually happening at the site. The example shown is for a T+12 hour (12 hours ahead) forecast horizon, for a meteorological mast on a wind farm situated in complex terrain.

Figure 2.13: Method Overview

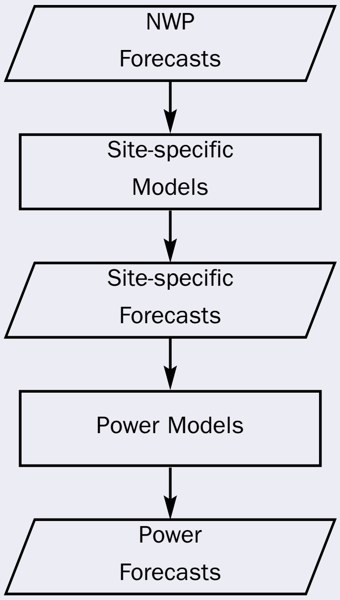
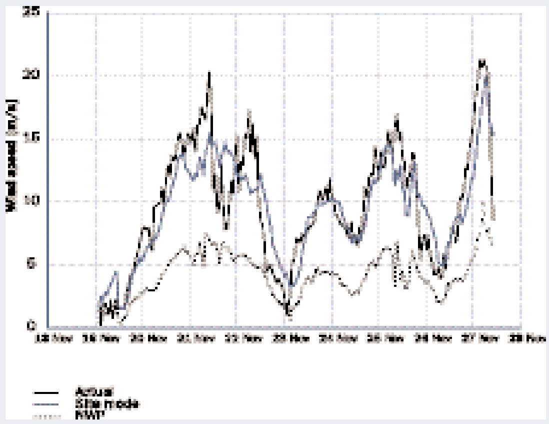


Figure 2.14: Example Time Series of Wind Speed Forecast, T+12h



The time series starts on 19 November with the site model having been initialised on 1 November. Therefore, the model has adapted to this accurate transformation in less than three weeks.

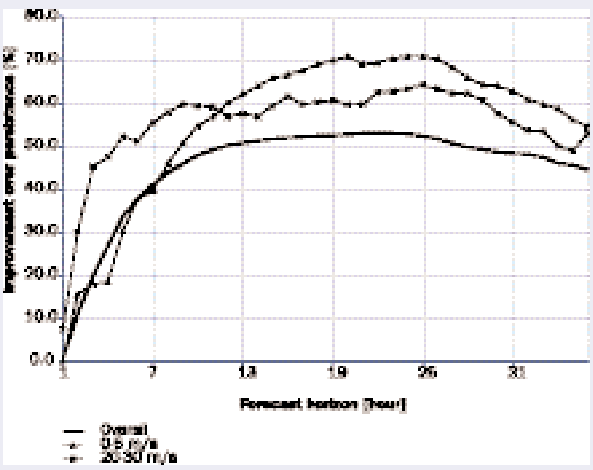
2.7.2 IMPROVEMENT OVER PERSISTENCE

Persistence is the rather grand name given to the crudest of forecasting techniques: the wind speed will stay the same as it is now! For short time scales, as common sense would suggest, it works well. It is often used as a standard yardstick against which to evaluate other more sophisticated forecasting techniques. The improvement in uncertainty (based on reduction of standard deviation of errors), over the basic persistence method, is presented in Figure 2.15 for the same site. The evaluation was undertaken over a total period of two months (November and December). Three lines are shown:

- Overall (line only).
- Low wind speeds (line with triangle).
- High wind speeds (line with star).

Typically, the evaluation of forecasting methods is presented as the "overall" case. However, it is clear that the spread of improvement is not uniform across all wind speed ranges. In this particular example, the crucial low (cut-in) and high (cut-out) wind speed forecasts show significantly greater improvements than the overall case. The cut-out prediction is particularly important since for a small increment in wind speed, say from 24.5 m/s to 25 m/s, the whole plant will shut down. These performance differences can have significant effects on the value of the forecasting tool, depending on its specific application.

Figure 2.15: Improvement over Persistence

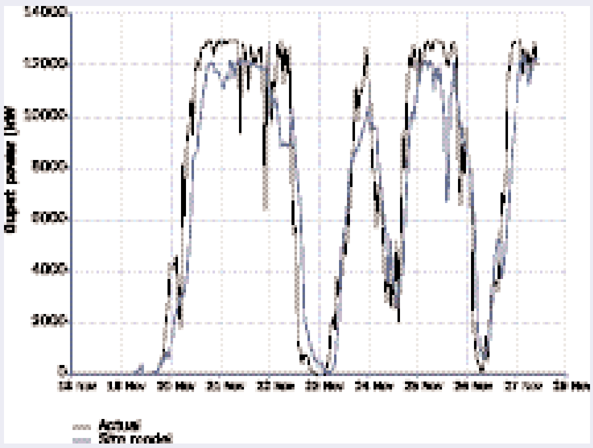


2.7.3 POWER OUTPUT

The next stage of the process is to convert the meteorological forecasts to forecasts of power output. This transformation is typically achieved via a wind farm power matrix, using multiple direction and wind speed bins to represent the power output of the wind farm. It should be stressed that the method of producing this power matrix is crucial if this stage is not to introduce further uncertainty into the forecasts.

The meteorological forecasts shown previously were converted to power using a less than optimal power matrix. The resulting time series is shown in Figure 2.16.

Figure 2.16: Time Series of Power Forecast, T+12h



To an "engineering eye" this prediction looks good; the forecast has captured the shape of the profile rather well. The maximum power level could certainly be improved, but that is a matter of fine tuning. To the "commercial eye", however, the situation is not as good. The fact that the phase of the forecast and the actual power are different is crucial. For example, on 20 November, the steep rise in power is lagged by the prediction so although the shape is good the absolute error on an hourly basis will be large. For hourly trading purposes such a prediction would then be very poor. Whether or not the forecast is "good" or "bad" therefore depends very strongly on its precise purpose. For scheduling plant maintenance it is acceptable, whereas for hourly trading

it is poor. The purpose of the forecast needs to be very carefully defined. This is a strategic as well as a technical issue.

2.7.4 PORTFOLIO EFFECTS

As the geographical spread of an electricity system increases, the wind speeds across it become less correlated. Some areas will be windy, some will not. Some areas will have rising power output, others will have falling power output, etc. The effect of aggregation on wind farm power fluctuations, and on capacity credit issues, has been looked at by several analysts, and forecasting of the output of large numbers of wind farms for the ISO is now commonplace in both Denmark and Germany.

For certain sizes of weather system, the effect of aggregation will certainly be to smooth the output of the wind farms as a whole. This effect is powerful and can be used, subject to further analysis and validation, to dispel the argument that 100 MW of wind requires 100 MW of conventional generation to back it up. The level of backup needed will depend on the geographical disparity of the wind farms, the size of the weather systems and the size of the interconnected system. This matter is an important topic for further work which will allow the robustness of the European wind resource to be properly quantified.

2.7.5 CONCLUSIONS

The present status of forecasting techniques may be summarised as:

- The statistical meteorological model has proven adaptable, transferable and accurate. Improvements in uncertainty (over the basic persistence method) of up to 70% can be forecast 12 hours ahead and beyond.
- Knowledge, interpretation and mitigation of forecast uncertainties are all of primary importance when it comes to the application of a forecast. This is closely linked with the nature of the market in which the forecasts are being used. One very effective way of reducing the overall forecast uncertainty is to aggregate the forecasts from several wind farms.
- Improving forecasting techniques will greatly enhance the commercial and strategic value of wind energy in Europe. It will be necessary to determine the scale at which this work is required - local, national or European. Different techniques will be needed for different scales. The work is now well established but certainly has greater potential than is presently realised. Improvements in forecasting will be derived from within the wind energy industry and also from the great strides being made in numerical weather forecasting generally.

2.8 Future Developments

Wind speed and energy prediction is, and will remain, the most critical part of the development of a wind farm. Enormous investments are made based on the estimates provided. The confidence of lenders and investors must be maintained or boosted. Improvement in these techniques is therefore an important part of European wind energy development. Below is a list of important topics for future development:

- Continued improvement in the quality and quantity of wind data recorded at wind farm sites.
- Consideration should be given to the establishment of a network of reference masts in the new member states to help “kick start” their wind energy activity.
- Some more sophisticated flow modelling tools are starting to be used for the prediction of wind flow over wind farm sites. While further validation work and development is required before such models can be extensively used for the assessment of wind farm projects, it is considered that such models have the potential to significantly improve the modelling of the flow at wind farm sites, particularly in complex terrain. Initially, these models may be useful for investigating sites in complex terrain as well as wind farms located close to mature forestry. Application of existing CFD tools to the complex topography of wind farm sites would be a rewarding activity if it could be proved that such tools can be used both efficiently and reliably. This is an area where future endeavour would be well worthwhile. It offers the possibility of applying sophisticated tools developed elsewhere (e.g. the aircraft industry) to the wind business.
- Remote sensing techniques look promising for making measurements at hub height of large machines and

have possible applications offshore. If they could be made both robust and reliable, and their validity demonstrated by working in parallel with conventional means, then their application would be highly beneficial. The development of accurate Sodar or Lidar techniques have the potential to improve the quality of measured wind data at a wind farm site and may also be useful in the future for undertaking power performance tests. To date, however, it is not considered that these methods are sufficiently accurate to replace conventional measurements. Again this topic would prove a fruitful R&D exercise.

- The wind speed on a potential wind farm site will remain by far the most important parameter to determine the viability of the development. It is the key parameter for lenders and they are becoming increasingly sophisticated in their demands in the analysis of the uncertainty often estimates as well as the long term consistency. The effect of climate change on wind speed has not been covered in this work. It is, however, becoming a common question for lenders and should be addressed.
- The improvement of forecasting techniques is vital to allow wind to compare with conventional plant. Significant investment in fine-tuning these tools would return a good reward and help wind realise its full potential in Europe.
- A unified wind resource map for the new member states combined with the EU-15 does not exist and would be a very useful strategic tool.

3 WIND FARM DESIGN

3.1 Introduction

Previous chapters have discussed the turbines and the wind resource. This chapter presents a brief summary of the design of a wind farm as a whole.

3.2 Preliminary Layout Design

Once a site has been identified and the decision has been taken to invest in its development, the wind farm design procedure commences. This is inevitably an iterative process. The first task is to define the constraints on the development:

- Maximum installed capacity (due to grid connection or power purchase agreement terms).
- Site boundary.
- Set backs from roads, dwellings, overhead lines, ownership boundaries, etc.
- Environmental constraints.
- Location of noise sensitive dwellings if any and assessment criteria.
- Location of visually sensitive viewpoints if any and assessment criteria.
- Turbine minimum spacings as defined by the turbine supplier.
- Constraints associated with communications signals such as microwave link corridors, if any.

These constraints may change as discussions and negotiations with various parties progress.

When an idea of the likely constraints is known, a preliminary design of the wind farm can be produced. This will allow the size of the development to be established. For the purpose of defining the preliminary layout it is necessary to define approximately what sizes of turbine are under consideration for the development, as the installed capacity achievable with different sizes of turbine may vary significantly. The selection of a specific turbine model is often best left to the more detailed design phase when the commercial terms of the various suppliers are known.

The wind resource at the site is the key parameter in determining its economic viability. To assess the energy for a project it is necessary to install anemometry equipment at the site. The preliminary layout allows the wind measurements to be made in appropriate locations. The preliminary layout also allows more detailed discussions to be held with relevant parties to better define the constraints.

3.3 Detailed Layout Design

A key element of the layout design is the minimum turbine spacing used. In order to ensure that the turbines are not being used outside their design conditions, the minimum acceptable turbine spacing should be obtained from the turbine supplier and adhered to. The appropriate spacing for turbines is strongly dependent on the nature of the terrain and the wind rose at a site. If turbines are spaced closer than five rotor diameters (5D) in a frequent wind direction, it is likely that unacceptably high wake losses will result. For areas with predominantly uni-directional wind roses, such as the San Gorgonio Pass in California, or bi-directional wind roses such as Galicia in Spain, greater distances between turbines in the prevailing wind direction and tighter spacing perpendicular to the prevailing wind direction will prove to be more productive. Tight spacing requires approval by the turbine supplier if warranty arrangements are not to be affected.

With the wind farm constraints defined, the layout of the wind farm can be optimised. This process is also called wind farm "micrositing". The aim of such a process is to maximise the energy production of the wind farm whilst minimising the infrastructure and operating costs. For most projects the economics are substantially more sensitive to changes in energy production than infrastructure costs. It is therefore appropriate to use the energy production as the dominant layout design parameter.

The detailed design of the wind farm is facilitated by the use of commercially available wind farm design tools (WFDTs). Once an appropriate analysis of the wind regime at the site has been undertaken, a model is set up which can be used to design the layout, predict the energy production of the wind farm, and address economic and planning related issues.

For large wind farms, it is often difficult to manually derive the most productive layout. For such sites a computational optimisation using a WFDT may identify a layout for which substantial gains in predicted energy production are achieved. Even a 1% gain in energy production from improved micrositing is worthwhile. The computational optimisation process will usually involve many thousands of iterations and can include noise and visual constraints. WFDTs conveniently allow many permutations of wind farm size, turbine type, hub height and layout to be considered quickly and efficiently, so increasing the likelihood that an optimal project results. Financial models may be linked to the tool so that returns from different options can be directly calculated, further streamlining the development decision-making process.

In many countries the visual influence of a wind farm on the landscape is an important issue. The use of computational design tools allows the zone of visual influence (ZVI), or visibility footprint, to be calculated to identify from where the wind farm will be visible. The tools may also be used to provide visualisations, to facilitate the production of photomontages and to predict the noise and shadow flicker from a proposed development. These are often key aspects of the project's environmental impact assessment.

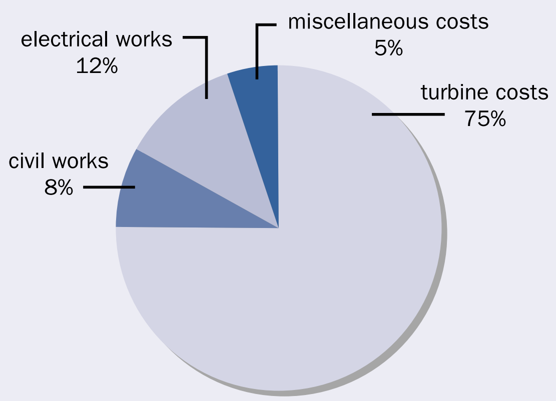
In conclusion, the design of a wind farm is a compromise between high energy, easy access, easy permitting and commercial viability.

3.4 The Infrastructure

The energy output of a wind farm is the key determinant for success. Without adequate wind resource a wind farm cannot be economic. The previous chapters in this volume have described the process of wind assessment in great detail. It is clear that a reliable, economic wind turbine (WT) must be used – a topic which has also been discussed in detail. In addition to these basic principles, it is important to devote adequate attention to the infrastructure needed to support the turbines and to extract the energy and transmit it to the grid.

For a typical onshore wind farm, the cost of the turbines is approximately 75% of the total cost of the farm. This infrastructure is often called the "balance of plant". There are three essential elements of the balance of plant: the foundations; the electrical grid; and the supervisory, control and data acquisition (SCADA) system which links all the turbines to a central computer and acts as the wind farm's "nerve centre". A typical cost breakdown is shown in Figure 3.1.

Figure 3.1: Typical Cost Breakdown for an Onshore Wind Farm



3.4.1 CIVIL WORKS

The foundations must be adequate to support the turbine under extreme loads. Normally, the design load condition for the foundations is the extreme, once-in-50-year wind speed. In Europe, this wind speed is characterised by a three-second gust which would probably lie between 45 and 70 m/s. At the lower end of this range it is likely that the maximum operational loads will be higher than the loads generated by the extreme gust and would therefore govern the foundation design. The first step towards the proper design of the foundations is the specification of a load. The turbine supplier would normally provide a complete specification of the foundation loads as part of a tender package.

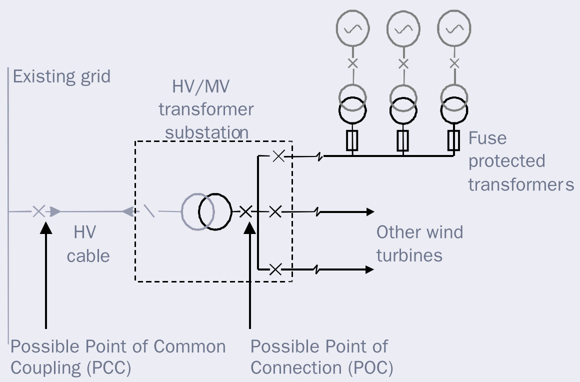
Once the specification has been prepared in detail, design of the foundation structure can be undertaken. Although extremely important, this process is a relatively simple

civil engineering task. A typical foundation would be, perhaps, 13m across a hexagonal form and one to two metres deep. It would be made from reinforced concrete cast into an excavated hole. The construction time for such a foundation, from beginning to end, is normally less than a week.

3.4.2 ELECTRICAL WORKS

The turbine generator voltage is normally classed as “low” and is often 690 V although some more large modern turbines generate at 10-12 kV. For the vast majority of onshore wind farms, the low voltage output of the turbine generator is connected to a pad mount transformer which steps the voltage up to a level used by the internal grid – usually between 10 and 20 kV. The transformer is either mounted on a plinth beside the turbine foundation or, for bigger turbines, is contained within the base of the tower. The individual transformers are then connected to underground cables in an internal grid which takes the power to a substation or interconnector. A typical layout is shown in Figure 3.2. The substation usually contains another transformer which steps the voltage up from the internal grid level to the distribution or transmission level. This final level will depend on the local utility grid. It can be anywhere in the range from 10 kV upwards; a typical level would be 20 to 50 kV. The metering for the wind farm will usually be located at the substation. It can be at the medium or at the high voltage level.

Figure 3.2: A Typical Electrical Layout



The design requirements for the internal grid will be in two parts: the losses must be kept to a minimum (usually less than 2.5% of annual energy); and the design must allow the turbines to connect safely to the utility grid and satisfy both the local grid requirements usually in the form of a “grid code” and also the turbine specifications.

The most cost-effective way in which to develop a wind farm is to find a location which is close to the grid. For some large developments, however, it may be necessary to build an interconnecting line. Such connections are very expensive.

3.4.3 SCADA AND INSTRUMENTS

In addition to the essential equipment needed for a functioning wind farm - the turbines and associated balance of plant - it is also advisable, if the project size can warrant the investment, to erect permanent anemometry. This equipment allows the performance of the wind farm to be carefully monitored and understood. If the wind farm is not performing to budget, it is important to find out whether this is due to poor mechanical performance or less than expected wind resource. Without good quality wind data, it is not possible to make this determination. Large wind farms therefore usually contain a permanent meteorological mast which is installed at the same time as the turbines.

A vital element of the wind farm is the SCADA system which connects the individual turbines, the substation and meteorological stations to a central computer. This computer and the associated communication system allow the operator to supervise the behaviour of all the WTs and also the wind farm as a whole. It records activity every 10 minutes and allows the operator to determine what corrective action, if any, to take. It also records energy output, availability and error signals which will act as the basis for any warranty calculations and claims.

3.5 Construction

A wind farm may be a single turbine or it may be a large number – possibly many hundreds. The design approach and the construction method will, however, be almost identical whatever the size. The record of the

wind industry in the construction of wind farms is very good. Few wind farms are delivered either late or over budget.

Newcomers to the wind industry tend to think of a wind farm as a power station. There are, however, some important differences between these two types of power generation. A conventional power station is one large machine which will not generate power until it is complete. It will often need a substantial and complicated civil structure, and construction risk will be an important part of the project assessment. New lenders will, therefore, always wish to make a careful assessment of the construction risk. However, the construction of a wind farm is more akin to the purchase of a fleet of trucks than it is to the construction of a power station. The turbines will be purchased at a fixed cost agreed in advance and a delivery schedule will be established. In a similar way, the electrical infrastructure can be specified well in advance - again probably at a fixed price. There may be some variable costs associated with the civil works, but this cost variation will be very small compared to the cost of the project as a whole. The construction time is very short compared to conventional power; a 10 MW wind farm can easily be built within a couple of months.

3.6 Costs

Wind farm costs are largely determined by two factors: the complexity of the site and the likely extreme loads. The site may be considered complex if the ground conditions are difficult – hard rocks or boggy, for example - or if access is a problem. A very windy site with high extreme loads will result in a more expensive civil infrastructure as well as higher turbine specification. Typical installation costs for 2001 are reported in Volume 2 as between 900-1,150 €/kW. In 2003, the installed cost for a large wind farm was between €850 and €1,100 per kilowatt installed.

3.7 Commissioning and Operation

Once construction is complete, commissioning will begin. Commissioning of an individual turbine takes little more than two days. The long-term availability of a commercial wind turbine is usually in excess of 97%. This means that, for 97% of the time, the turbine will be available to work if there is adequate wind. This value is superior to values quoted for conventional stations. It will usually take a period of some six months for the wind farm to reach full commercial operation; during that period availability will increase from around 90% immediately after commissioning to the long-term level of 97% or more.

Commissioning tests will usually involve standard tests of the electrical infrastructure and the turbine, and inspection of routine civil engineering quality records. Careful testing at this stage is vital if a good quality wind farm is to be delivered and maintained.

It is normal practice for the supplier of the wind farm to provide a warranty for between two and five years. This will often cover lost revenue, including downtime to correct faults and a test of the power curve of the turbine. If the power curve is found to be defective then reimbursement will be made through the payment of liquidated damages. For modern wind farms there is rarely any problem in meeting the warranted power curves, but availability, particularly for new models, can be lower than expected in the early years of operation. During the first year of turbine operation some “teething” problems are usually experienced. For a new model this effect is more marked. As use of the model increases, these problems are resolved and the availability rises.

After commissioning, the wind farm will be turned over to the operations and maintenance (O&M) crew. A typical crew will be two people for every 20 to 30 WTs installed. For smaller wind farms there may not be a dedicated O&M crew but arrangements will be made for regular visits from a regional team. Typical routine maintenance time for a modern WT is 40 hours per year. Non-routine maintenance may be of a similar order.

There is now much commercial experience with modern WTs and high levels of availability are regularly achieved. Third party operations companies are well-established in all of the major markets and it is likely that this industry subsector will develop very much along the lines associated with other rotating plant and mechanical/electrical equipment.

The building permits obtained in order to allow the construction of the wind farm may have some ongoing environmental reporting requirements, for example the monitoring of noise, avian activity or other flora or fauna interest. Similarly, there may be, depending on local bye-laws, regulatory duties to perform in connection with the local utility. Therefore, in addition to the obvious O&M activity, there is often a management role to perform in parallel. Many wind farms are the subject of project finance and hence will also be reporting to lenders.

3.8 Concluding Remarks

This chapter has briefly outlined the physical activities required to design, build and operate a wind farm and has shown how the principles described in previous chapters are put into practice. It has been demonstrated that a wind farm has different challenges and demands from a conventional power station. It is quick to build and operates using free fuel. Its operational demands are simple but must be thoroughly exercised in order to obtain the long life required for economic success.

4 TRANSMISSION AND DISTRIBUTION NETWORKS

4.1 Introduction

In other chapters of this volume, the amount of raw energy available in the wind has been discussed and the ways in which it can be measured and assessed have been described in detail. The WTs, which convert the raw energy into electricity, have also been described. In order to be useful, this electricity has to be transported from the source – the wind farm – to the load, which may be a long distance away. It also has to be integrated with electricity from other generators. These two aims are achieved through the grid – local, national and international.

The raw wind resource is vast. Technological improvements can be made to the turbines, but they already work very efficiently on a large scale. Therefore, the key strategic element which will determine the degree to which wind energy may realise its potential is its interaction with, and integration into, the European grids. For Irish wind to power the German Ruhr is feasible. Whether or not it happens depends on the grid – technical, economic, regulatory and, ultimately, political considerations about the use and purpose of the grid will govern the outcome.

In this section, the constraints and opportunities offered by the grid for large-scale wind energy integration are discussed. The detailed electrical engineering of grid connection is also described in detail in Appendices E and F. The tasks which face the engineering and regulatory arms of the system operators and the industry as a whole are outlined.

4.2 Setting the Scene

4.2.1 LARGE INTERCONNECTED NETWORKS

An essential element of establishing wind energy is to ensure that the electricity generated can feed into the grid system, and so reach electricity consumers. The electricity grid, or network, exists to accept output from all generators and to transfer power to consumers. There are several key features of this arrangement which have driven the design and operation of large electricity systems:

- Generators, especially large ones, are often distant from centres of demand. This necessitates transmission of electricity across large distances.
- Generation and demand must be balanced at any point in time across the network. There is little energy storage in large power systems compared to the energy being consumed. There is, of course, substantial hydro capacity in many European countries (approximately 16% of EU generating capacity). Some of this can act as storage in principle but there is very little which is actually intended for that purpose, i.e. pump storage (5% of EU generating capacity). This is for economic reasons: energy storage technologies are relatively expensive, both in capital cost and in energy losses.
- There is a culture of operating the system to serve demand, i.e. electricity consumers are uncontrolled, or are controlled only by season, time of day or other price signals. The generators are expected to meet their requirements (a “predict and provide” strategy).

So electricity systems, as we traditionally know them in Europe, consist of large thermal and nuclear generators (with hydro where available), and extensive networks to transmit the power long distances to consumers. The demand is variable, and generation responds to this by increasing and decreasing its output. The larger the electricity system, the smaller (in relative terms) the variations in consumer demand are, due to geographical diversity. This is one of the factors that favour large, highly-interconnected systems over smaller isolated ones. The other such factor is the ability of large systems to cope better with the failure of any one element.

Because of this reduction in variability in large systems, some generators can operate as so-called “baseload” generation, i.e. they operate continually at a constant output. Typically, these are nuclear generators, which cannot readily alter output, or the largest thermal generators. To cope with the daily variability in demand, other generators (“mid-merit” plant) will operate throughout the day but shut down or reduce output during the night. Then there is “peaking” plant, to cope with the short-term peaks in demand, typically in the morning and evening. Hydro generation and pumped-storage plants may be suitable for this task, due to their short start time.

Within these general principles there are wide variations across Europe, depending on availability and cost of fuels, population density, location of centres of population and fuel sources, climate and other factors. The liberalisation of the electricity supply industry in each country also has a major effect.

Liberalisation has tended to move large electricity systems from central planning to a market system where the rules of the market determine the behaviour of all parties.

There are also technical factors which are changing the situation. The major ones are:

- Electronic equipment, consumer and industrial, is less forgiving of poor "power quality" and supply interruptions than old fashioned heavy industrial plant.
- Communications technologies mean that, in principle, customers can become more responsive to price signals.
- Gas-fired generation plant is available with cost benefits.
- Renewable energy technologies are emerging, particularly wind generation.
- Smaller generators are connected to the lower levels of the electricity network, perhaps even in domestic customers' premises.
- New energy storage technologies may become available.

The expansion of wind energy poses a number of issues for electricity systems and their development which can be referenced back to the defining features of wind generation:

- Wind energy output fluctuates. To an extent, this can be controlled and/or predicted, but sometimes it cannot, or only with short notice. This is an added complication for grid operators. It will be demonstrated that it is important to distinguish clearly between predictability and variability – terms which are often confused.
- Wind energy can be in locations remote from demand and/or remote from existing conventional generators. This means that there need to be changes in the grid infrastructure. This may be required earlier than would have been the case for simply replacing assets.
- The technical characteristics of wind generation do not match the technical characteristics of conventional forms of generation, around which the existing electricity systems have evolved.

When aiming to increase wind energy's contribution to electricity supply the key questions are:

- Is it feasible to overcome the technical issues and at the same time maintain the quality of supply that we presently experience and expect to continue?
- Is it realistic to expect these issues to be overcome? If so, what are the costs, including the costs of development and operation of the electricity system?
- How can the costs of the various potential solutions to reducing environmental emissions be objectively compared?

The following sections provide a more detailed description of the situation outlined above, provide some answers to these key questions, and indicate what needs to be done to achieve complete answers.

4.2.2 SMALL ISOLATED NETWORKS

This chapter is mainly concerned with the connection of wind generation to large electricity networks, because this task is required in order for wind energy to make a major contribution to achieving European environmental and energy policy goals.

The vast majority of electricity consumers in Europe are connected to large networks. Both policy goals and economic factors will tend to encourage further interconnection, as small isolated networks generally have higher costs, lower reliability and/or higher atmospheric emissions.

However, small isolated networks will continue to play their part, and there may well be other policy reasons for encouraging the use of wind generation in these circumstances, particularly because such systems are often located in rural or peripheral areas. Therefore, it should be noted that most of the issues discussed in this chapter for large systems are also applicable in some form for smaller isolated systems.

The integration of wind energy into smaller networks is technically more complex, due to:

- Less geographical averaging of the variability of the output of the wind generation.
- Less averaging of the variability of consumer demand.

For these reasons the management of variability becomes particularly important on such systems.

4.3 Electricity Networks

Electricity networks can be split into two major subsections: the transmission network and the distribution network.

The transmission network consists of high voltage power lines designed to transfer bulk power from major generators to areas of demand. In general, the higher the voltage, the larger the transfer capacity. Only the very largest customers are connected to the transmission network. Transmission network voltages are typically above 100 kV. They are designed to be extremely robust, i.e. they can continue to fulfil their function even in the event of several simultaneous failures of the network. Failure of a single element, such as a transformer or transmission line, is referred to as an "N-1" event, and transmission systems should be capable of withstanding all such events. More complex cases of simultaneous failures of multiple elements (for example, the failure of a transmission line when a parallel line has been disconnected for maintenance) can be termed "N-2" or similar. Transmission systems should also be capable of withstanding all such credible combinations.

Transmission systems are operated by transmission system operators (TSOs) or independent system operators (ISOs). Responsibility for constructing or owning the network may belong to other organisations.

Transmission systems are actively managed through grid control centres. Balancing the power entering and leaving the high voltage network, and reconfiguring the network to cope with planned and forced outages is a 24-hour activity. Figure 4.1 shows the transmission network across Europe.

Distribution networks are usually below 100 kV and their purpose is to distribute power from the transmission network to the customers. At present, little generation is connected to distribution networks, but it is growing rapidly. Generation connected to distribution networks is often termed "embedded generation".

Distribution networks are less robust than transmission networks and their reliability decreases as voltage level decreases, e.g. a connection at 33 kV could expect to lose only a few minutes of connection per year on average, whereas a low voltage connection at 230 V for an individual domestic consumer in a rural area would, on average, expect to lose at least an hour.

There is very little so-called "active" management of distribution networks. Rather, they are designed and configured on the basis of extreme combinations of circumstances (for example, maximum demand in conjunction with high ambient temperatures, which reduce the capacity of overhead lines), to ensure that even in these extreme circumstances the network conditions experienced by customers are still within agreed limits.

The addition of embedded generation to these networks creates challenges, for the following principal reasons:

- The embedded generation adds a further set of circumstances (full generation/no generation) with which the network must cope, without negatively affecting the quality of supply seen by other customers.
- The direction and quantity of real and reactive power flows change, which may affect operation of network control and protection equipment.
- Design and operational practices are no longer suitable and may need modification.

To set against these challenges, embedded generation also brings benefits to distribution networks, including:

- Reduction in network losses, in many situations.
- Deferring or avoiding network reinforcement otherwise required to achieve standards for quality of supply.

To address these issues, distribution networks may become more "actively managed". This implies cost, and requires the development of suitable equipment and design principles.

Figure 4.1: The European Transmission Grid

4.4 Considerations for Wind Energy

There are three broad categories of issue which are relevant when considering connection of wind generation to the grid.

First, there is securing the immediate **connection**, which normally falls to the developer to negotiate with the relevant network operator. This involves establishing whether there is sufficient capacity, and what effect the connection will have on the network and other customers in the area. Second, there are considerations for **operating** the network. These relate principally to the intermittent nature of wind energy and ensuring that this does not impact adversely on the operation of the network. Third, there are wider "strategic" considerations in **planning** for large amounts of new generation.

4.4.1 CONNECTIONS

Wind farm developers, like any other sponsor, wish to find the best point of connection for their development. "Best" often means "cheapest", but could, in some circumstances, mean "least risky" or "fastest to construct". In some cases, the capacity of the available network connection will decide the maximum capacity of the generator.

The majority of wind farms in Europe are connected to distribution systems, but proposals for larger onshore and offshore farms suggest that connection to transmission systems will increasingly be sought.

Similar issues arise when connecting to the transmission or distribution networks, although their relative importance changes. Most of the experience is at the distribution level. Here, the key influences are the preponderance of connected consumers, and hence the need to maintain power quality within acceptable levels, and the fact that these networks are not actively managed.

Distribution networks are currently designed for power to flow downwards from the transmission network to the customers. Embedded generation, including wind farms, changes the magnitude and sometimes the direction of power flow, and this can cause technical issues to arise.

This historical characteristic also has a strong influence on the grid "culture". Literally, how do the operators of the grid "feel" about the connection of load in this way? For some grid engineers this change in approach is difficult to accept.

The capital cost of high-voltage equipment means that a transmission system connection is only considered for the largest wind farms, or where the transmission system is much closer to the site than the distribution system. While the issues are similar to those for distribution networks, problems are less likely to occur, due to the greater strength of transmission systems.

In addition, wind projects can be built much faster than conventional plants and, in particular, faster than the transmission system can be modified or reinforced.

Appendix E provides a full commentary on the technical and other issues which arise when seeking to connect a wind farm to a grid.

All are considerations for any generation project. For wind energy, problems arise perhaps more commonly for the following reasons:

- It is a new technology, and practices developed for earlier technologies (principally synchronous generators) are generally not applicable.
- Its output is variable and less predictable.
- Capacity factors are lower than other forms of generation so it is harder to absorb the costs of network connection, which are primarily capacity-related.
- The project location is often far from stronger sections of the network.

In some cases, the network operators are unused to dealing with embedded generation and, in particular, intermittent generators like wind farms. The requirements and design rules of network operators are not written with wind generation in mind, and the application process for a network connection is often not transparent. It will be shown later that regulatory issues will be important in allowing wind to realise its full potential. On the other hand, wind farm developers are sometimes reluctant to commit money to undertaking studies, or even to decide

upon the turbine type, the size of the wind farm or its layout. This can complicate the development process and lead to friction between the wind farm developer and network operator.

4.4.2 OPERATION

"Operation" means the day-to-day management of the network. Distribution networks are not usually actively managed, so this section is more relevant to transmission networks. However, there are pressures (due to embedded generation and other factors) to increase the management of distribution networks, and so this is expected to become more relevant in the future.

Transmission systems are conventionally operated and planned on the basis of a relatively small number of large generating plants, whose output can be varied at will. Wind generation, on the other hand, takes the form of larger numbers of smaller plant, whose output is variable and less predictable. The science of prediction and forecasting has been covered in Chapter 2 and it is clear that this area is likely to develop significantly in the near future, and will play an important role in the integration of wind power, but will not provide a complete solution.

Balancing of Large Systems

Large electricity systems operate with hardly any energy storage, as storage is expensive and the process results in significant energy losses. Therefore, at any second, the supply (output from all generators) has to be controlled to meet customer demand.

In addition, the electricity system must be extremely reliable and robust, able to continue in the event of concurrent failures. For these reasons, system operators and planners have to estimate demand and supply on time-scales of minutes to years. Given the size and complexity of the plant this is a remarkable fact.

The national economic consequences of complete failure of the electricity system, even for only a few hours, are so great that it is worth network operators spending a great deal of money and effort to reduce the risk. Recent events in the US, the UK, Scandinavia and Italy have also served to make this point.

Wind generation is sometimes regarded as negative load, since it can, to a degree, cancel out the demand for power at the point at which the transmission system supplies the distribution system. For the purpose of matching demand and supply of a large electrical system it is not possible to consider wind generation purely as a negative load, however. Therefore, if there is a substantial proportion of wind generation on the system, this adds another variable to the calculations that system operators must perform in order to balance demand and supply. For this reason, wind generation may be seen as increasing risk, and this perceived increased risk is often resisted by the system operators. This resistance needs to be addressed in order to increase the rate at which wind energy can be deployed on a large scale.

It is important when discussing the intermittent nature of wind generation to distinguish between two different concepts: *variability* and *predictability*.

Variability

Even if the output of wind generation were completely predictable, the variability of that output would increase the difficulties of matching supply and demand. Setting aside for the moment the issue of predictability, the variability of wind generation is often seen as a problem. However, analysis of data from operating wind farms and meteorological measurements from locations typical of wind farms produces the following conclusions:

- For a large individual WT, the variation in the output power is small for time-scales of less than a few seconds, due to the averaging of the wind field across the rotor and the filtering effect of the turbine inertia (this is particularly true for variable-speed WTs operating at rated power).
- For an individual wind farm, the variation in the total output power is small for time-scales of tens of seconds, due to the averaging of the output of individual turbines across the wind farm.
- For a number of wind farms spread across a large area, such as a national electricity system, the variation in

the total output power of all wind farms is small for time-scales from minutes or less, up to tens of minutes. This is termed "geographic diversity".

System operators only need to deal with the net output of large groups of wind farms, and so the issue is what variability needs to be planned for and on what time-scales. Analysis of available data allows estimates to be made of the worst-case variation in net power output that can be expected for a given time period, i.e. over 10 minutes or over one hour. This form of analysis should continue to be developed with high resolution data (i.e. sub-hourly periods) from larger numbers of wind farms, as suitable data becomes available. As a starting point, see EWEA (2000) and Commission for Energy Regulation/Office for Electricity Regulation NI (2003).

This type of information can be used by system operators to determine the level of reserve to maintain.

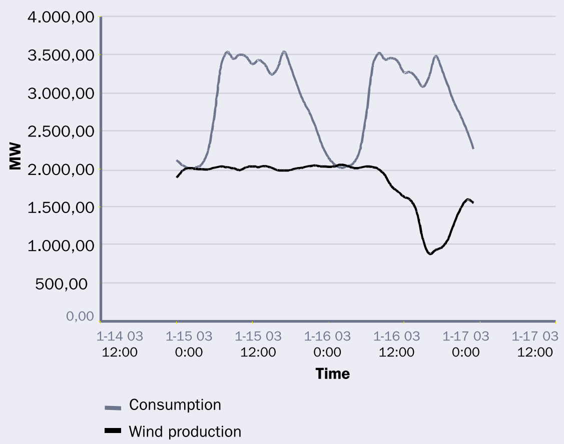
An extreme example of the variability of wind generation is illustrated in Figure 4.2 below, which shows two days in early 2003 on the Eltra system (Denmark), which shows that wind power can maintain almost constant output over prolonged periods. The wind then falls in the evening just when the evening demand peak is approaching. This fall is then followed by a rise in wind output at a time when demand is falling steeply. The coincidence of the steeply falling wind supply and the steeply rising load requirement makes the event extreme in nature.

Note that the wind generation is approximately equivalent to the minimum demand (overnight).

The example given in Figure 4.2 is an extreme case, shown here to highlight the important issues. The majority of days do not exhibit this extreme situation. The counter example is the growing use of wind energy as a source of spinning reserve, as a benefit from the very rapid response times of wind turbines.

Conventional techniques available to system operators for such situations include keeping other generation operating at low output, and making use of interconnections to neighbouring systems. Alternatively, these extreme variations may be controlled at critical times by measures such as setting a temporary cap on the output of all wind farms, or by limiting the maximum rate of change of output (see below). For example, it is known from operational experience in northern Germany and Denmark that the passage of a storm front may produce very severe changes in wind generation output, as WTs shut down from full power due to excessively high winds. This effect can be limited by reducing the output power gradually over several hours in advance of the storm front.

Figure 4.2: Example of Wind and Demand over Two Days (Winter 2003, Eltra System)



Clearly, limiting the output of wind generation wastes "free" energy and should only be done when other means have been exhausted.

Predictability

Important developments have been made in recent years with tools to aid in the forecasting of energy output from wind farms. Details have been provided in Chapter 2 of this volume. It has generally been found that over short time frames, and with good data about the historic wind regime at a site, it is possible to predict wind farm output using a correlation with forecasted meteorological data from nearby weather stations. Although these tools are still in a relatively early stage of development, it is now possible to provide vital forecasting information, which in some cases is a requirement of the project's power pur-

chase agreement. This information can then be used by the system operator in balancing the generation with demand in their system, and significantly reduces the level of uncertainty to which wind generation has historically been attributed.

The system operator can also undertake its own forecasts, perhaps using as an input the current and forecast output of each wind farm, as well as large-scale meteorological forecasts.

This unpredictability can be dealt with by the system operator assuming a forecast level of wind generation into the future (typically for up to 24 or 48 hours ahead). The operator then applies a forecast error to calculate the amount of wind generation in future hours which can be treated as "firm". It has been found in several studies that the forecast error increases with look-ahead time. For example, if the output of all wind generators is forecast to remain constant for the next 24 hours, the firm contribution of that generation will be assumed to decrease over that period.

Improved forecasting will allow the forecast error to be both specified and reduced, thus allowing more wind energy to be treated as firm.

Grid Codes

Grid code documents set the requirements for users of the transmission or distribution system, including generators. These codes cover issues that are important for operation of the system, although some aspects are also relevant to system planning.

These codes have evolved to suit conventional generation: substantial modifications are required in order to apply them to new forms of generation, particularly wind. Such modifications have been produced, or are in the process of being developed, in many European countries.

Typical requirements of grid codes for wind generation, published or in draft, are summarised in Appendix F.

Some difficulties in the process of modifying these codes are listed below:

- The dominant WT technology at present, the doubly-fed induction generator (DFIG) is not well understood by network operators.
- The important characteristics of wind farms relevant to network operators are not well defined, i.e. there is a lack of a common vocabulary for discussing these issues and comparing characteristics of alternative WT types.
- There are some functions that are desirable, but the cost-to-benefit trade-off to provide them is not clear.
- The existing grid codes grew up around synchronous generators so it is difficult to rewrite them from a generic or functional viewpoint.
- There may be some valuable functions currently provided by conventional generation which have not been formally identified in grid codes.
- There may be some functions that would now be better provided by a market rather than by an obligation on all generators.
- It is desirable that all grid codes are similar but there may be some real technical differences between systems.

Because of the expected expansion of wind energy, time is pressing and the need for rapid solutions to the problems conflicts with the need for widespread consultation among all interested parties. This task requires immediate action.

4.4.3 STRATEGIC PLANNING CONSIDERATIONS

As total wind generation capacity increases, its effects on large electricity systems (national scale) will eventually become significant. Both the transmission system and the existing generators could be affected. This section discusses these strategic issues.

The effect of wind generation on an electricity system depends on the "penetration". Two different definitions are often used:

- Wind energy penetration: annual production (GWh) of wind generation as a fraction of total consumption.

- Wind capacity penetration: wind generating capacity (GW) as a fraction of total generating capacity.

Both issues are important when considering the effects of large amounts of wind generation.

Displacement of Conventional Generation

Wind energy to date has tended to displace the output of conventional plant, reducing the conventional plant's consumption of fuel. This is effectively the rationale for its promotion on environmental grounds. In some EU countries, it displaces imported conventional fuels and uses a national sustainable energy source in their place. It does, however, raise some policy issues in the form of economic questions for the owners and financiers of conventional plant.

The costs of conventional generation can increase due to the following causes:

- If forced to run at lower output, conventional generation may operate at a lower thermal efficiency, thus consuming more fuel per MW hour of electricity production and producing more pollution per MW hour of electricity production.
- Due to the variability of wind generation, conventional generation will be called upon to start, stop and change output more frequently. This also incurs costs.

In addition, if a generating plant has been financed on the basis of some assumed annual output, and that annual output can no longer be achieved, the plant may become uneconomic and may be closed. Those who financed the plant may want compensation.

Such effects are not addressed in detail as part of this discussion, but they are central considerations for policy-makers, developers or financiers and can be expected to precipitate important political debate.

Losses

New wind generation can, depending on its location relative to the main loads, increase or decrease the electrical losses within the network. This raises questions about who should pay or be paid for this change in losses. This is a market issue. Several solutions are possible and, indeed, different approaches may be suitable for different electricity systems. All that it is necessary to say at this point is that any system of allocating costs of losses should be able to allow for the contribution, positive or negative, of intermittent generation, particularly embedded generation.

Benefits of Interconnected Systems

Experience has shown the benefits of combining a diverse mix of demand and supply types, via interconnected transmission systems, enabling greater wind generation to be connected.

This is demonstrated by way of example. Table 4.1 shows the characteristics of two contrasting electricity systems.

Table 4.1: Comparison of the Eltra and Crete Systems

Item	Eltra System, DK (2001)	Crete System (2001)
Total conventional generation capacity [MW]	4,724	570
Total wind capacity [MW]	1,932	70
Installed wind capacity penetration	29 %	11 %
Wind energy penetration	16 %	10 %
Transmission capacity to other networks [MW]	2,640	0

The island of Crete is completely isolated from all other electricity systems. Wind energy penetration had already reached the level of 10% by 2001, and continues to increase. For technical reasons it has been found necessary to keep large amounts of conventional generation operating during periods of low demand, even when there is high wind generation. This means that a substantial amount of the wind energy has to be curtailed.

In comparison, the Eltra system has an even higher level of wind energy penetration but has not (yet) needed to curtail wind output. This is because it is highly interconnected to the Nordpool system of the Scandinavian countries to the north and to northern Germany to the south. The

Eltra system has, however, been subject to situations where the generating output exceeds demand, particularly overnight when there is high wind generation. In these circumstances, the system operator has had to sell energy cheaply to the other networks to which it is connected. This highlights the important point that the technical feasibility of high wind penetration is a separate issue to the economic effects.

There are two particular features of the Eltra system that are worth noting:

- At present, the system operator must accept all wind generation that wishes to generate at any time, in preference to generation from conventional sources.
- The same also applies to the output of district heating plants and combined heat and power plants. A large proportion of these plants are so-called "heat-led", i.e. their electricity production is determined by their heat production; therefore, when temperatures are low and there is a high heat demand, their electricity production is also high.

The Nordpool system to which the Eltra system is connected is highly suitable for connection to networks with large amounts of wind generation as it contains large amounts of hydro generation which provides very fast, low loss storage capacity. On the other hand, the north German networks to the south of Denmark have themselves a large proportion of wind generation, so when there is surplus wind in Denmark it may be of little value as there is also likely to be surplus wind in the north of Germany.

Interconnection of electricity systems with wind energy therefore brings benefits, and these can be characterised as being due to the ability to reduce the effect of the variability of wind.

However, other means are available to provide similar benefits. Some of these are:

- Curtailment of wind generation output.
- Energy storage (hydro generation, pumped-storage plant, or new forms of storage).
- Demand management.
- Reducing the costs of operating conventional generation in a more variable regime, such as start up costs, costs of rapid changes in output, and costs of operating away from peak thermal efficiency.
- Providing other generation such as open-cycle gas turbines which have low capital cost and high fuel cost, and which can start, stop and change output very rapidly.

It is not at all clear how these alternatives compare to increased interconnector capacity. It is instructive to note that, even over significantly large geographical areas, output from all of the wind farms in the region could be very low as a result of common weather systems (anticyclones). This is certainly the case for areas the size of the UK, for example. This is of particular concern in winter when anticyclones are accompanied for several days by clear cold conditions and electricity demand can be expected to be high.

Therefore, in order to replace wind generation in an area covered by an anticyclone by wind generation outside that area, transmission system reinforcement for distances of several hundred km will be necessary. The wind generation capacity factor of this new transmission reinforcement would be in the order of, say, 25% to 35%. As transmission reinforcement costs are dominated by capital costs, transmission system reinforcement for the purposes of transfer of wind energy appears to be less attractive than transmission system reinforcement for conventional purposes.

This assumes, of course, that sufficient transmission system capacity does not already exist. However, as transmission systems are built in response to existing patterns of generation and demand, this assumption seems generally to be justified.

A key parameter for the successful large-scale penetration of wind into the European grid will therefore be the size of the interconnected system relative to the size of a large anticyclone. This point is demonstrated graphically in Figure 4.3 which might be subtitled *Wind from Spain and Ireland powers the Ruhr*. The interconnected grid will have to be large enough to make sure that wind is available to meet the required load at all times.

Figure 4.3: A Large Weather System over Europe

Generation Adequacy and "Capacity Credit"

"Generation adequacy" means the likelihood that available generation capacity will be insufficient to meet demand. Detailed probabilistic calculations are carried out to determine the probability of this occurring. If the result is below the accepted requirement then something has to be done. The traditional solution was to build more generating capacity, but this is harder to arrange in a deregulated or liberalised system. The system is designed to cope with failures of the transmission system and individual generators, but wind generation has the additional risk that all wind generation may shut down at the same time due to low winds over a large area, as discussed above.

Formal probabilistic assessment studies show wind does provide some contribution to reducing this risk of inability to meet demand with supply; for example, see Transmission System Operator Ireland, *Generation Adequacy Report 2003-2009* (2002), which calculates a "capacity credit" of approximately 20% depending upon circumstances. This capacity credit means that, in principle, less conventional generation need be built. If capacity or availability payments are made to generators for their contribution to generation adequacy (which is not common) then, in principle, payments should also be made to wind generation.

4.5 Issues for High Wind Penetration in Europe

The key questions defined at the start of this chapter are repeated here for reference:

1 Is it technically feasible to overcome the technical issues and, at the same time, maintain the quality of supply that we presently experience?

2 Is it realistic to expect these issues to be overcome? If so, what are the costs, including the costs of development and operation of the electricity system?

3 How can the costs of the various potential solutions to reducing environmental emissions be objectively compared?

For the first question, it is clear that it is technically feasible to have very high wind penetration on the European electricity systems, without affecting the quality of supply.

For example, a combination of large-scale transmission reinforcement, new interconnector capacity, new energy storage capacity (probably hydro generation and pumped storage), and wind curtailment would, in principle, allow 100% of Europe's electricity consumption to be provided by wind energy if sufficient land and sea area were made available for wind farms and energy storage. This is a hypothetical case, as the cost of reaching this 100% figure would be very high, and would almost certainly not be the optimum means to achieve such a large reduction in emissions from conventional generation.

However, a major part of this cost would be for the energy storage capacity required to supply the electricity system through periods of several days or weeks of low wind. This would not be economically justifiable; it would be cheaper to provide that "storage" by storage of fuel for suitable conventional generators, possibly gas turbines, or by using other renewable technologies.

A strengthened European grid would reduce the need for storage. Development of sustainably produced hydrogen and superconducter technology may also play a role.

As more conventional generation is added to the above scenario, the cost of such a system will reduce, and atmospheric emissions will rise.

The second question cannot be answered fully at present, as the costs of operating an electricity system with high wind penetration (say above 30%) are not yet clearly understood. The *sources* of these increased costs are, however, becoming more clearly understood, as are means to mitigate them.

There have been several studies (EWEA, 2000; Commission for Energy Regulation/Office for Electricity Regulation NI, 2003; Dany *et al*., 2003; UK Department of Trade and Industry, 2002), on this issue which provide some illumination. It is necessary to continue such studies at higher wind penetrations than have so far been envisaged, updated with operating data from large numbers of wind farms.

The answer to the third question is also not clear at present, principally because the second question cannot be fully answered. This is, of course, also partly due to the uncertainty in the costs of other renewable technologies: in particular, whether they are able to achieve the same major benefits from volume production that the wind industry has achieved. However, it is clear that a major part of the additional cost borne by electricity systems with high wind penetration is due to the variability and unpredictability of wind. The latter cost is set to reduce as prediction techniques improve. Therefore, other renewable technologies which do not have these characteristics will have an advantage at high wind penetrations.

The above questions have helped to identify the important issues for achieving high wind penetration in the electricity networks of Europe. These issues can be summarised as follows.

Technical Limits to Wind Energy Penetration

In principle, there are no technical limits. Very high wind energy penetrations appear achievable. The additional costs appear to be low at the local high penetrations currently achieved, and are expected to rise proportionately faster than energy penetration. It is more important to establish what the costs are, in order to compare them against the costs of competing options. These costs will depend on the generation mix, the level of interconnection and forecasting ability.

Variability

Because of the major benefits (for system operators) of geographical diversity, the variability of wind generation is not as severe as is often perceived. Variability can also be damped by relatively simple measures such as capping or ramp rate control of wind farms during critical periods. However, it remains a major disadvantage that becomes more important at high penetrations, principally because it increases the amount of reserve that an operator must carry on the system, and/or requires some other solution such as curtailment of wind generation or increased interconnector capacity.

It is important to gain experience of system operation with wind generation, and system operators should be encouraged to record data from their systems which will allow these issues to be studied.

Predictability

As for the issue of variability, the unpredictability of wind generation requires system operators to carry additional reserve or possibly force curtailment of wind generation.

Significant improvements in wind output forecasting are anticipated through work currently in progress.

Technical Requirements for Wind Generation

Grid codes for distributed generation and wind generation are being developed. It is expected that the wind industry, given sufficient evidence of a continuing market, will develop technical solutions to meet these requirements, at costs which will not be significant in the context of overall project costs. If suitable solutions do not appear (which seems highly unlikely), then it is possible that this issue could slow the rate of expansion of wind generation.

It is important that these requirements are formalised as soon as possible, consistent with adequate consultation with interested parties.

It appears that it will not be possible to develop one set of requirements for all electricity systems in Europe. For example, it appears that requirements in the UK and Ireland for transient stability may be more onerous than on the European mainland, due to their island nature. However, this does not appear to cause any particular problems for WT manufacturers.

System Operation Costs

The additional costs imposed on operators of electricity systems are not clear, as noted above. The costs at high penetrations (above 30%) are particularly unclear.

Further work in this area is required, making use of operational data from systems with distributed wind farms as it becomes available.

Curtailment of Wind Generation

It appears that the variability and unpredictability of wind adds to system operational costs principally by introducing "extreme" events such as storm fronts. These extreme events happen rarely (a few times per year) and therefore coping with them by capital-intensive means such as building additional fast-response generating plant, or similar means, appears to be less attractive than curtailing wind generation by capping it or controlling ramp rate. Any further studies of system costs should take these options into account.

Capacity Credit and "Back Up" Generation Sources

This issue is now becoming important, with a belief among opponents of wind generation that 100 MW of wind generation requires an additional 100 MW of new conventional generation to back it up during calm spells. Further work in this area is required, preferably based on analysis of the probability of failing to meet generation adequacy targets, and using several years of operating data from distributed wind farms.

In this context, it can be noted that no form of generation is completely reliable; all require the electricity system to carry some reserve, in the form of additional generation that can start up or increase its output rapidly. Therefore, the point at issue is how much this level of reserve needs to be increased to cope with wind generation.

It is also generally true that the energy production of wind generation is expected to grow more rapidly than electricity demand. Therefore, the existing conventional generation can expect to be in use less often: it is expected that any increase in reserve requirements due to increased wind generation will not lead to an overall increase in the total capacity of conventional generation.

4.6 Concluding Remarks

When considering the connection of wind generated electricity to the grid, the starting point often seems to be why it *cannot* be done rather than how it *can* be done. This starting point will prove crucial in the successful integration of large amounts of wind. If a political goal is set, as it has been at both European and national levels, then the challenge is to allow that goal to be met in a systematic and rigorous fashion. It is possible to meet environmental policy objectives *and* keep the lights on, but to do so requires some imaginative thinking and new research. It is this aspect which will either allow wind energy to fulfil its promise or leave it as a marginal player.

The grids have been designed for large-scale central generation, whose power is transported outwards through the transmission and distribution systems. They were not designed for, and is operated with, substantial distributed generation. That requirement is coming, not just as part of the introduction of renewable energy, but also as a result of a much increased interest in smaller scale commercial generation as the electricity industry is liberalised. A change in attitude and operation will be required to accommodate this change.

The grid codes were written with conventional generation in mind and also, in particular, with synchronous generators in mind. Thus, it is historical precedent rather than

pure technical necessity for the preclusion of large-scale wind generation from the grid codes. These codes should be revised, not in a bid to compromise the security of the system through relaxation of the terms, but rather to recognise that new types of generator and new sources of energy are available. The grid codes should be optimised to allow the best possible mix of generation rather than to prefer one particular category.

Geographical averaging is a powerful tool to smooth the variations in wind energy output on all time-scales. It also increases the extent to which power system planners can rely on wind energy to meet future demand – the so-called capacity credit. It can only do so if the size of the interconnected system is large enough to compensate for the effect of the weather systems likely to occur over Europe. Systematic investigation of the relative size of the weather and electrical systems will provide a valuable insight into the strategic value of wind energy and the cost of security of supply.

Grid operators must be educated to recognise that although the wind is variable it is also predictable and hence it can, when considered in significant aggregated capacity, be scheduled at a time-scale which is commensurate with conventional plant.

The level of penetration which can be achieved by wind is essentially limited by cost rather than by some fundamental technical considerations. Investigation of the cost-penetration relationship merits serious investigation. This relationship will be system-specific, as it depends on factors such as the other forms of generation available. Interconnection is not the only solution; careful curtailment of energy production during predictable extreme events may well lead to a more cost-effective approach.

Rigorous work on the establishment of the real capacity credit which should accrue to wind generation is well overdue and is amenable to systematic investigation.

5 RESEARCH AND DEVELOPMENT

5.1 Wind Industry Research and Development Overview

Early R&D was technology driven but, as the industry expanded, other issues came to light, such as public attitudes, noise levels, environmental impacts and wind energy financing. Furthermore, the technology emphasis has sometimes been superseded by a strong market push - to bring larger machines with greater output into circulation as soon as possible. Consequently, some more fundamental, promising options in design have not been implemented. This is not always the case however, direct drive turbines being a good example, but it is certain that the need for technology driven research is still important, and support for it is needed.

This chapter provides an overview of the different fields related to R&D in the wind power industry. Some key needs are highlighted, but it must be stressed that this chapter does not prioritise specific needs. The Wind Energy R&D Network provides further information on R&D issues (see below).

Objectives

A principal objective of wind industry R&D is to meet the levels of wind penetration described in the EWEA feasibility study *Wind Force 12 – A Blueprint to Achieve 12% of the World's Electricity by 2020* (EWEA, 2003c).

To achieve this goal, the industry needs to:

- continue making cost reductions.
- enable increased penetration of wind power.
- minimise environmental and social impacts.

During the last two decades, R&D programmes have been a pre-condition for the successful development of the wind power industry to date. In its 2001 report *Long Term Research and Development Needs for Wind Energy for the Time Frame 2000 to 2020* the IEA states:

> *"Thanks in large part to successful R&D, the wind energy market is in a state of rapid development. R&D has been an essential activity in achieving the cost and performance improvements in wind power generation to date."*

European R&D programmes over the last 15 years have been at the forefront of today's industry. Results of such programmes include the development of large MW turbines, the first European wind atlas, and funding demonstration and pilot projects, such as the first offshore wind farm. It is essential that this R&D continues with the support of EU research programmes, such as FP6 and its successors. As the IEA puts it:

> *"In order to achieve a 10 to 20% part of the worldwide energy consumption provided by wind, major steps have to be taken…it is for this objective that there is a need for long-term R&D."*[1]

It is interesting to note that wind technology has been influenced by, and exerts influence on, other industry sectors, such as, for example, aerofoil design in the aeronautics industry, and in the shipping industry where the requirements of the offshore wind power industry has lead to nautical R&D to provide suitable craft for erecting wind turbines (WTs).

Wind Energy R&D Network

The Wind Energy R&D Network, coordinated by EWEA, is formulating a strategy for R&D in the European wind industry. It brings together actors from across the wind energy sector and enables dialogue between industries and other stakeholders with the common goal of substantially increasing the share of wind energy technology in global electricity markets. Finalisation of the strategy is set for 2005[2].

Priority R&D Areas

The Wind Energy R&D Network has established priority R&D areas as below:

- Economic, Policy and Market Issues:
  for example, assessment affecting wind farm investments and market barriers.
- Environmental and Social Impacts.
- Wind Turbine and Component Design Issues:
  for example, basic research in aerodynamics, structural dynamics, structural design and control.
- Testing, Standardisation and Certification:
  for example, common accepted certification procedures for WTs and wind farms.

- Grid Integration, Energy Systems and Resource Prediction: for example, forecast of wind resource.
- Operation and Maintenance (O&M): for example, advanced condition monitoring.
- Location of Wind Farms: for example, in complex terrain and remote areas where satellite technology can be used, among others, in the formulation of wind atlases – showing the wind resource.
- Offshore Wind Technology: for example, research into the control and efficiency of very large wind farms and more cost effective foundations, transport and installation techniques.
- Megawatt and multi-megawatt Wind Turbines: for example, application of new materials with improved strength-mass ratio and development of lighter components.

Underlying these research areas is the drive to increase economic efficiency through reduction of uncertainties in fields ranging from resource prediction to improvements in component reliability. Reducing uncertainties in assessing technical risks will reduce the cost of services provided by finance and insurance companies and allay fears relating to security of supply. These uncertainties are:

- Resource assessment and wind speed measurement.
- WT reliability.
- Performance predictions.
- Prediction of O&M costs.
- Increased maintainability of machines.
- Lifetime design methods.
- Grid assessment.

5.2 Socio-Economic, Policy and Market Issues

There is an overall need for research into methods of cost reduction and risk management that can increase the value of wind energy. Milestones towards cost reduction need to be defined.

As turbines become larger and more powerful, requiring more advanced technology, expertise and refinement, greater development costs, such as increased engineering hours, become apparent. Increasingly complex control requirements due to the complex design of WT systems and farms also contribut to increased development costs.

Reductions in project costs can be expected through rigorous technical and economic standardisation, facilitating the specification of components, and their certification. This means greater transparency and increasing competitive pressure leading to greater efficiency in the market place.

5.2.1 TRANSPARENCY

Despite EU efforts to remove legal barriers between member states, many country-specific regulations remain, hampering transparency and the free market. Greater European-wide harmonisation is vital if a future internal market in wind power is to be developed.

R&D Objectives

- Categorisation of turbine types on the basis of manufacturer data; further use of ISO/IEC and CEN/Cenelec standards; and development of new standards.
- Development of a risk assessment standard for wind turbine projects.
- Certification of standards for wind energy projects addressed to financiers and insurance companies.
- Increased transparency in respect of weather related issues on the one hand, and with regard to operational damage on the other, taking into account the perspective of the insurance industry.
- A continuously updated web based database of member state rules and regulations: policy instruments, planning and construction regulations, permit and environmental issues, tax law, corporate law, etc.

5.2.2 INCREASING THE VALUE OF WIND POWER

At present, value is not only determined by the avoided fuel cost of fossil-fuelled plants through installed wind capacity. Increasing predictability in power output, and an increase in capacity factor has further raised the value of wind electricity. Equally relevant are cost components in electricity production, such as environmental benefits and consumer preference for green electricity, which are not at present internalised in electricity prices. As the cost/value ratio is optimised, the economic drive to realise wind energy plants will grow.

R&D Objectives

- Development of output forecasting models.
- Improved controllability of large wind farms.
- Effective quantification of external benefits of wind energy; and development of methods to quantify the cost/value ratio.

5.2.3 EDUCATION AND HUMAN RESOURCES DEVELOPMENT

1.8 million job-years will be required to meet the Windforce 12 target of 12% wind electricity worldwide in 2020. Education and training are required in both technical and non-technical capabilities in order to provide a skilled workforce to satisfy future demand. In 2003, the European Academy of Wind Energy was established with the aim, inter alia, of providing for this demand. Visit www.eawe.org for further details.

R&D Objectives

- Establish where skill shortages will occur along the growth curve.
- Joint international R&D programmes in universities.
- Develop training schemes to supplement work-based training.
- Establish specialised professorships at universities.
- Develop educational material for primary and secondary schools.

5.3 Environmental and Social Impacts

It is essential to express continually to the general public the predominately positive social and environmental aspects of wind energy, in order to maintain and improve its support for wind power. R&D efforts should aim to increase public involvement, and to further minimise social impacts.

Social R&D Objectives

- Development and verification of public participation models.
- Assessment of the positive social effects of wind energy, such as local employment, investment, taxes, etc.; and the creation of local networks to express these local benefits.
- External costs: an accepted methodology for the assessment of environmental savings through the use of wind energy is needed, to establish a quantifiable and cogent benefit.
- Clear understanding of the external social and environmental costs of conventional power generation, as well as of possible external costs of large wind penetration, is needed so accurate comparisons may be drawn.

Environmental R&D Objectives

- Recommendations for limits on stroboscopic effect/shadow flicker (taking into account seasonal variations) in residential areas and other sensitive areas.
- Methods should be developed to integrate turbines visually into the landscape on an individual turbine and wind farm basis. This may be approached in two ways: through design of individual turbines; and their effective siting in the landscape, with the use of camouflage and stealth techniques.
- The reduction of noise impacts to decrease the minimum required distance between turbines and residential areas. This would increase the potential for wind energy utilisation in populated areas. Methods to predict the noise level generated by turbine blades, gearboxes, generators and transformers need to be improved through more fundamental R&D, leading to the production of low noise blades, gearboxes, and generators.
- Turbine interference on telecommunications/radar needs to be quantified. At present, large areas with high wind potential are restricted by the military. Real dialogue is needed among industry and the military, to establish an acceptable level of understanding in relation to national defence.
- The identification of areas where potential impacts exist on bird populations, habitats & flight paths, as well as ways of mitigating such impacts.
- A standard for turbine design involving the use of life cycle analysis to identify recyclable materials, and to specify how to dispose of non-recyclable elements, e.g. stand alone systems involving the use of batteries.
- Identification of potential cumulative environmental impacts of increased numbers of wind farms, across the EU.
- Decommissioning alternatives.

5.4 Turbine and Component Design Issues

This section discusses design issues related to turbines and their components, but it should be noted that other sections in this chapter are also concerned with such issues with regards to a specific application such as offshore or multi-MW scale turbines, or O&M.

All categories of turbines are, to a varying degree, on the frontier of technology research. Enormous progress has been made to date in increasing efficiency, and reducing the cost of turbine production. R&D into the manufacturing process is key to further cost reductions. For example, an assembly line approach to WT construction would to lead to benefits through economy of scale. Continued R&D efforts are needed in order to improve the technical and economic efficiency of WTs and their components.

New turbine models are increasingly complex, yet once a turbine is deemed ready for market, little time is dedicated to prolonged testing. This is due to market pressure for new, larger turbines. As a result, new preventive features that might help reduce O&M requirements are not always integrated in new designs. Turbine cost reductions of 15-20% may be realised through the implementation of such research results. R&D must be combined with market driven development, and a doubling of accumulated capacity to achieve this cost reduction.

Horizontal integration between the manufacturing sector and research institutes is at present limited. The two are arranged on different time-scales and there is a need for further incentives for cooperation. Within the European Research Area, a wider network for manufacturers, sub-suppliers and research institutions should be encouraged, yielding integrated, active research and aggressive implementation of research findings.

R&D Objectives

- External design conditions (wind climate assessment etc.), aerodynamic and aeroelastic design, structural design, loads and safety.
- New materials with higher strength as well as higher internal damping.
- Advanced manufacturing technologies.
- Feasibility studies of new wind turbine concepts and innovations, e.g. flexible blades & hubs, and variable speed generator systems, to display potential for reducing cost per kWh.

- Methods of reducing O&M costs in the design phase.
- Reliability models leading to higher wind farm availability – particularly relevant regarding offshore turbines.
- Development of more efficient testing and verification methods to both shorten turbine development periods, and improve the quality of verification process.
- Integration of demand side requirements in the design of turbines, e.g. electrical control system interaction with grid requirement.
- Fundamental R&D into site-specific control of turbines to cope with variations in external conditions, e.g. high turbulence levels. One solution is to build in methods for fine tuning the aerodynamic and structural performance of rotor blades and associated fast field diagnosis instruments. E.g. if prohibitive vibrations appear during operation, control systems can be used to actively damp vibrations after the turbine is put in operation.
- Component design, such as longer blades, and electrical components.

5.5 Testing, Standardisation, Certification & Safety

Also discussed in the section on Socio-economic, policy & Market issues, standardisation, testing and certification are themselves the potential results, or indeed overall objectives, of the R&D process; they are essentially R&D results applied to specific areas. Standardised certification and testing techniques lead to increased transparency in the wind power market, and thereby reduce costs. For example, a certification system covering not only power-curves, but the entire turbine and project development process, along the lines of ISO 9000, would increase the insurability of the entire sector. Existing design certification might be supplemented by requiring testing of components under specific test protocols, as is the case with blades under the Danish approval scheme. Project certification can be done to a degree under the IEC-CAP standard, however, the CAP standard is not sufficient as it stands.

High quality and efficient standardisation and certification are vital given the number of turbine types. Low quality turbines on the market would hamper the wind industry's reputation; as the market is sensitive to negative reporting. Standards designed for one market segment can be inappropriate in another, and standards across the segments should normally be limited to essential operating and safety standards.

R&D Objectives

- Identification of standards lacking, and initiation of appropriate actions for new standards and background research.
- Background R&D into a standard for service and maintenance concepts, including labour safety.
- Guidelines and standards describing the steps in project development, according to sector (deep/near offshore; mountainous/isolated/coastal onshore, etc).
- Development of turbine type categories on the basis of ISO/IEC and CEN/Cenelec standards.
- Co-ordination of system development & testing programmes in place in major European R&D centres, with the full involvement of the manufacturing industry.
- Background R&D into standards for project performance testing (production verification).

5.6 Grid Integration, Energy Systems and Resource Prediction

European utilities are increasingly seeing wind power as a viable and reliable source of energy in the grid's supply portfolio. However, there is a reluctance to implement wind capacity, and further understanding of the total capacity of wind generation that can be absorbed locally and regionally by grids is required.

Wind farms must not only ensure efficient operation in varying meteorological conditions, but have also to answer the requirements of the transmission and distribution (T&D) networks to which they are connected - requirements such as high power quality and steady output. These requirements often do not take into account the distributed nature of wind power generation as T&D systems are developed for large, centralised fossil fuel and nuclear power plants.

R&D Objectives

- Development of scenarios for redesign of the EU T&D grid, with high wind penetration.
- Development of tools to enable grids to cope with large-scale wind power.
- Increased predictability of system output. To develop electrical output prediction tools (meteorological fore- cast) to predict output 24-48 hours in advance for wind farms.
- Longer-term forecasting.
- Increased accuracy in pre-installation prediction of electricity output via tools such as anemometry, terrain calibration, and the translation of power wind speed curves from test sites to installation sites.
- Energy management and storage systems for stand-alone applications.
- Develop demand side management tools to encourage consumers to focus their electricity use during high electricity output periods.

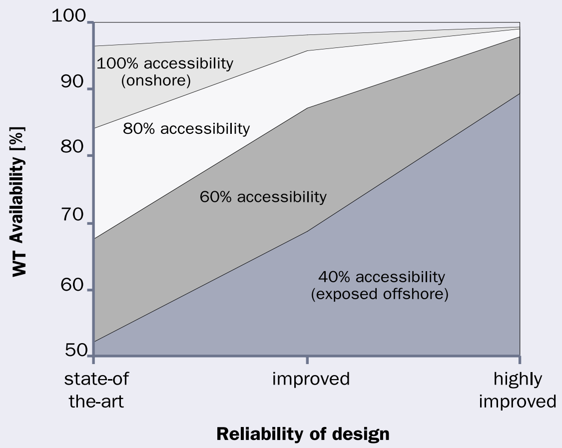
An increase in predictability of wind farm output will reduce requirements for spinning reserve. Improved levels of grid interconnection among European countries will also reduce the need for spinning reserve, as intermittency becomes less of an issue with increased geographical spread. Analysis of spinning reserve requirements and intermittency should be conducted on the basis of the requirements of the entire electricity system rather than on a technology-by-technology basis, to achieve optimal economic and technological solutions. Distribution network operation should be remodelled taking wind farms into account as large-scale as well as decentralised contributors to total electricity production, rather than considering wind as an element to be considered in isolation.

The fact that WTs are clustered into bigger units requires specific R&D into the performance of large wind farms. On the one hand, national grids must be able to absorb large amounts of varying electricity output while on the other, wind energy plants must meet targets in terms of the amount of reactive power produced, harmonic distortion, predictability and controllability of power output.

5.7 Operation and Maintenance

O&M requirements are driven by site conditions, quality of components and turbine design. Costs and electricity output depend on availability and, therefore, on the reliability and accessibility of the WT installation. Figure 5.1 describes availability as a function of reliability and accessibility. In particular, WTs located in offshore locations and in mountainous terrain are subject to potentially very high costs due to availability losses through potentially avoidable O&M.

Figure 5.1: Availability as a Function of Reliability and Accessibility



Source: Delft University, *et al.*, (2001)

In this respect, fast development of early failure detection systems is essential. Data describing the properties of WTs should be gathered and used as inputs for improving the reliability of turbine design. Statistical data on the machine performance and component outage events are necessary as a basis for maintenance optimisation. Much research is needed regarding early failure detection and condition monitoring to establish trends to assist in predicting part failure.

R&D Objectives

- Accelerated development of early failure detection and condition systems.
- Cross industry analysis of turbine and component performance and maintenance statistics.

- Resolution of confidentiality issues.
- Increased understanding of the drivers behind O&M costs in offshore sites.
- Developments in preventative maintenance.
- Standardisation of components and turbine documentation for ease of replacement.
- Harmonised methods and certification of O&M companies to a high standard.
- Certification of service and maintenance concepts.
- Better techniques for assessing wind turbine and wind park performance in situ.

5.8 Location of Wind Farms

Already, in some densely populated countries with a high level of installed wind capacity, the best sites, in terms of available wind resource, are being exploited. Space is limited also by the requirements of other activities (e.g. nature conservation, agriculture, military).

In densely populated coastal countries, offshore sites are the "new" option, while in mountainous land-locked countries, sites are found in complex terrain, such as funnels, hills and mountains. Other areas include those with cold and icing climates and, possibly, built up areas.

R&D Objectives

- Offshore resource assessment, also showing exclusion zones: shipping lanes, grids, pipelines, military, flora and fauna, water depth.
- Complex terrain and sensitive area resource assessment.
- Cold and icing climates resource assessment.
- Test site design conditions and methods to be adapted to mirror potential and new sites.
- Market surveys of developing country markets.
- Dedicated WT types for low wind speed inland locations, for high wind speed/high turbulence locations, and for cold climates and offshore locations.

Complex Terrain

There is an urgent need for more reliable methods for the prediction of wind conditions in complex terrain. At the moment, there is very limited support for R&D in this area. The wind energy community is collaborating with meteorological institutes and carrying out its own research. Also, the short-term prediction of the output of farms in complex terrain is limited because of a lack of knowledge and tools.

Icing Environments

The potential for WTs in icing environments needs further investigation. Particular issues include blade heating versus power performance and safety aspects of ice-throw from the blades.

Developing World Markets

In the developing world, priority should be given to market development, before dedicated R&D efforts can be fully utilised. Following identification of possible markets, market demand should be built and financiers reassured through large-scale demonstration programmes. In parallel, technology oriented R&D programmes should be initiated, and carried out by industry in cooperation with R&D institutes.

5.9 Offshore Wind

Offshore and onshore R&D should be integrated to a degree. Although the parameters involved in onshore and offshore R&D differ, the issues are essentially the same. For example, loading must be analysed for both offshore and onshore turbines and, although different data sets exist in each case, the software necessary to analyse them can be of similar type. Such integration would also help avoid potential conflicts of interest between industries in the coastal countries of northern Europe and southern Europe, the former typically having a larger offshore resource. In addition, it would reduce duplication in

R&D efforts. Furthermore, it should be borne in mind that although the offshore sector is growing fast, by 2020 it is estimated that three-quarters of installed capacity will still be onshore.

R&D Objectives

- Monitoring of environmental impacts of near and far offshore projects.
- Potential conflicts of interest: defence, fisheries, shipping, oil and gas exploration and pipelines, and sand mining, etc.
- Legal research into offshore ownership in coastal waters, Exclusive Economic Zones, etc.
- Higher tip speed designs, as noise issues are less significant offshore.
- Minimisation of O&M-related downtime. The distance offshore and the water depth at the site have significant impacts on O&M.
- Special designs of systems and components for erection, access and maintenance of offshore turbines.
- Design studies of systems rated above 5 MW for offshore, possibly including multi-rotor systems.
- Offshore meteorology – short and long-term forecasting; hardware for measurements.
- Development of alternative, and deep water, foundation structures.
- Combined wind and wave loading.

5.10 Multi-Megawatt Turbines

The most important arguments for the development of larger machines are: for the exploitation of offshore sites, where a higher wind resource exists (typically 40% more energy content in the wind compared to onshore); relatively lower foundation and grid costs; and reduced visual impact on the landscape per unit of installed power. Demand drives the trend towards larger machines while R&D is increasingly expensive and complex as turbines increase in size and use more advanced technology, while yet new models are released with increasing frequency.

R&D Objectives

- Fundamental WT design research (aerodynamics, aeroelasticity, structural design, loads and safety, control, etc.).
- Development of test facilities to follow turbine developments.
- Adequate testing and certification of new turbine technologies, for insurance and finance purposes, such as "0-series" turbines (turbines for areas with low wind resource).
- Modelling of O&M requirements for large turbines, before installation.
- Effective output forecasting methods for large turbines.
- Transport requirements for blades, e.g. built in segments to reduce transportation size.
- Partnership between fundamental and market driven research is essential in ensuring reliability.

5.11 Summary of R&D Objectives

The Wind Energy Network, comprising discussions participated in by a large cross section of the wind energy sector, puts forward the following initial R&D recommendations and conclusions. These will be refined and built on in the final report of this study, to be released in the summer of 2005.

Broad Requirements:

- Long term wind energy R&D programmes
  to increase economic and technical efficiency of the wind energy sector, and the European electricity sector as a whole.
- Fundamental long term R&D
  in such fields as aerodynamics & aeroelastics, structural dynamics & design, loads & safety, integration into the European electricity transmission and distribution system, and resource assessment, and forecasting techniques.
- European standards for use by developers, investors & insurance companies
  on risk, economic viability, performance, reliability, and O&M of wind farms.

- European certification and accreditation systems
  for components, turbines and projects. Includes testing of components and turbines.
- European codes of practice for access of wind power into transmission grids.
- Standard European planning procedures for site assessment
  taking into account wind regime, environmental and social impact, accessibility, etc.
- Full public participation in wind energy exploitation
  through exploration of local beneficial impacts.
- R&D into the efficiency and control of very large wind farms.
- R&D into the dynamics of very large wind turbines.
- Concept development of integral optimised concepts of large wind farms both on land and offshore.

Specific Tasks include:

- Development of tools to identify new sites
  such as offshore, remote and complex terrain.
- Remodelling of European-wide grid systems
  taking into account large-scale electricity production from wind, and the benefits of distributed generation.
- Databases of member states' rules and regulations
  including national policies on planning, permitting and environmental issues.
- Databases of environmental impact issues
  to include public opinion surveys, ecological impacts, etc.
- Evaluation of market stimulation programmes & policy instruments
- Evaluation of European harmonization requirements in general
  to prepare the sector for eventual inclusion in the Internal Electricity Market.
- Reduction in installation, generation and O&M costs
  to optimise the cost/value ratio, and facilitate development of megawatt and multi-megawatt machines.

Endnotes

[1] 35th IEA Topical Expert Meeting "Long Term R&D Needs 2000 – 2020" The Netherlands, March 2001.

[2] For more information, visit www.wind-energy-network.org

WIND ENERGY - THE FACTS

VOLUME 2

COSTS & PRICES

Acknowledgments

This volume was compiled by Poul Erik Morthorst, Senior Research Specialist at Risø National Laboratory, Denmark. Our thanks also to the national wind associations around Europe for their contributions of data, and to the other project partners for their inputs.

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1 INTRODUCTION

From a European, as well as a global perspective, wind power is undergoing rapid development. Within the past 10 years the global installed capacity of wind power has increased from approximately 2.5 GW in 1992 to a little below 40 GW at the end of 2003, with an annual growth rate of around 30%. However, only at few sites with high wind speeds can wind power compete economically with conventional power production at present.

This section focuses on the cost structures of a wind power plant, including the lifetime of the turbine and operation and maintenance costs. Finally, it analyses how the costs of wind power have developed in previous years and how they are expected to develop in the near future.

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 vast bulk of the market value of installed turbines.

2 COST AND INVESTMENT STRUCTURES

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 (O&M) costs.
- Electricity production/average wind speed.
- Turbine lifetime.
- Discount rate.

Of these, the most important parameters are the wind turbines' (WT) electricity production and their investment costs. As electricity production is highly dependent on wind conditions, choosing the right site is critical to achieving economic viability. The following sections outline the structure and development of capital costs and efficiency trends of land based WTs.

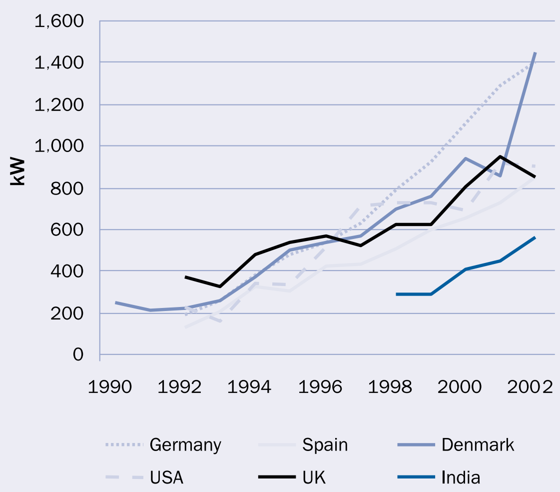
In general, three major trends have dominated the development of grid-connected WTs in recent years:

- The WTs have grown larger and taller – thus, the average size sold has increased substantially.
- The efficiency of WT production has increased steadily.
- In general, investment costs per kW have decreased.

Figure 2.1 shows the growth in average size of WTs sold each year in a number of the most important wind power countries. The annual average size has increased significantly within the last 10-15 years, from approximately 200 kW in 1990 to almost 1.5 MW in Germany and Denmark in 2002. But, as shown, there is quite a difference between the individual countries. In Spain, the US and the UK, the average size installed in 2002 was approximately 850-900 kW, significantly below the levels of Denmark and Germany of 1,450 kW and 1,400 kW respectively. The large increase in Denmark from 2001 to 2002 was mainly caused by the Horns Reef offshore wind farm which came onstream in 2002 equipped with 80 WTs of 2 MW each.

In 2002, the best-selling WTs had a rated capacity of 750-1,500 kW and a market share of more than 50%. But WTs with capacities of 1,500 kW and above had a share of 30% and have been increasing their market shares. By the end of 2002, WTs with a capacity of 2 MW and above were becoming increasingly important, even for on-land sitings.

Figure 2.1: Development of the Average Wind Turbine Size Sold in Different Countries



Source: BTM Consult

The wind regime at the chosen site, the hub height of the WTs and the efficiency of production mainly determine power production from the WTs. Thus, increasing the height of the WTs has, by itself, yielded a higher power production. Similarly, the methods for measuring and evaluating the wind speed at a given site have improved substantially in recent years, thus improving the siting of new WTs. In spite of this, the fast development of wind power capacity in countries such as Germany and Denmark implies that most of the good wind sites are, by now, taken. Therefore, any new on-land turbine capacity has to be erected at sites with a marginally lower average wind speed. It should be added, however, that the replacement of older and smaller WTs with new ones is getting increasingly important, especially in countries that have taken part in wind power development for a long time, as is the case for Germany and Denmark. In 2002, a successful re-powering scheme in Denmark had a substantial impact on market development.

The development of electricity production efficiency owing to better equipment design, measured as annual energy production per swept rotor area (kWh/m^2) at a specific reference site, has correspondingly improved significantly over the last few years. Taking into account all the three mentioned issues of improved equipment efficiency,

improved turbine siting and higher hub height, overall efficiency has increased by 2% to 3% annually over the last 15 years.

Capital costs of wind energy projects are dominated by the cost of the WT itself (ex works[1]). Table 2.1 shows the cost structure for a medium sized turbine (850 kW to 1,500 kW) sited on land and based on a limited data-selection from the UK, Spain, Germany and Denmark. The WTs share of total cost is typically a little less than 80%, but, as shown in Table 2.1, considerable variations do exist, ranging from 74% to 82%.

Table 2.1: Cost Structure for a Typical Medium Sized Wind Turbine (850 kW – 1500 kW)

	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

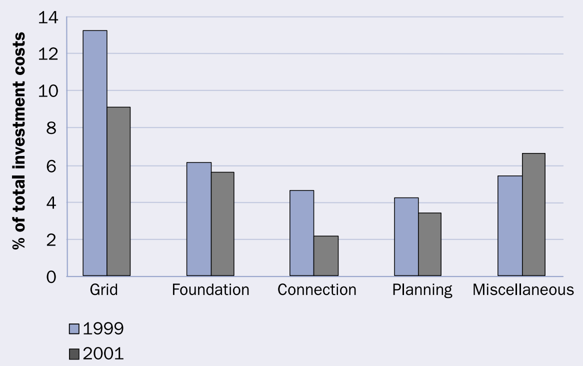
Based on data from Germany, Denmark, Spain and UK for 2001/02.

Of other cost components, dominant ones are, typically, grid-connection, electrical installation and foundation, but other auxiliary costs such as road construction could represent a substantial proportion of total costs. There is considerable variation in the total level of these auxiliary costs, ranging from approximately 24% of total turbine costs in Germany and the UK to less than 20% in Spain and Denmark. The costs depend not only on the country of installation, but also on the size of the turbine.

Typical ranges of these other cost components as a share of total additional costs are also shown in Figure 2.2. As seen, the single most important additional component is the cost of grid-connection which in some cases can account for almost half the auxiliary costs, followed, typically, by lower shares for foundation costs and the cost of the electrical installation. Thus, these three issues might add significant amounts to the total cost of the WT. Cost components such as consultancy and land rental normally account for only a minor share of additional costs.

In Germany, the development of these additional costs has been further investigated in a questionnaire carried out by Dewi (2002), looking at the actual costs for wind turbines installed in 1999 and 2001 (Figure 2.2). As shown, all additional cost components tend to decrease over time as a share of total WT costs, with only one exception. The increase in the share of miscellaneous costs is mostly on account of increasing prefeasibility costs. The level of auxiliary costs in Germany has, on average, decreased from approximately 31% of total investment costs in 1999 to approximately 28% in 2001.

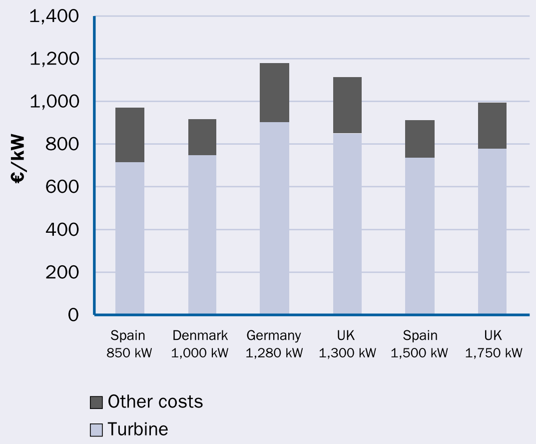
Figure 2.2: Development of Additional Costs (Grid-Connection, Foundation, etc.) as a Percentage of Total Investment Costs for German Turbines



Source: Dewi (2002).

The total cost per installed kW of wind power capacity differs significantly between countries, as exemplified in Figure 2.3. The cost per kW typically varies from approximately 900 €/kW to 1,150 €/kW. As shown in Figure 2.3, the investment costs per kW were found to be almost at the same level in Spain and Denmark, while the costs in the data-selection were approximately 10% to 30% higher in the UK and Germany. However, it should be noted that Figure 2.3 is based on limited data.

Figure 2.3: Total Investment Cost, Including Turbine, Foundation, Grid-Connection, etc., Shown for Different Turbine Sizes and Countries of Installation (€/kW)



Based on reported data from Germany[2], UK, Spain and Denmark.

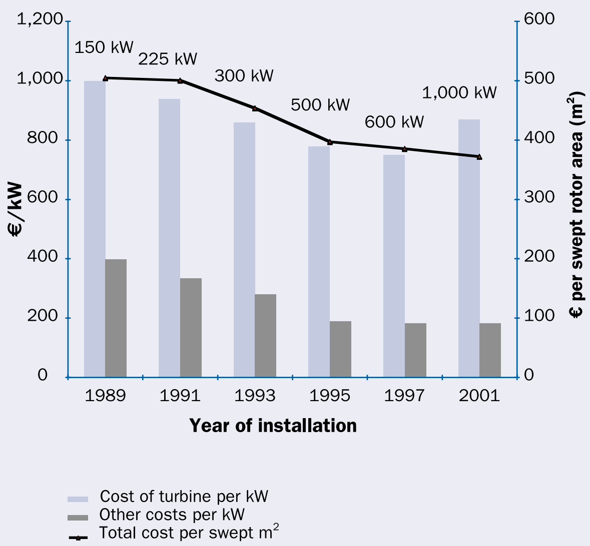
Figure 2.4 shows how investment costs have developed, exemplified by the case of Denmark for the period 1989 to 2001. The data reflect turbines installed in the particular year shown[3]. All costs at the right axis are calculated per swept rotor area, while those at the left axis are calculated per kW of rated capacity.

Swept rotor area is a good proxy for the turbines' power production and this measure is therefore a relevant index for cost development per kWh. As shown in the figure, there has been a substantial decline in costs per unit swept rotor area in the period under consideration and for all turbines. Thus, 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 (per kW), the same decline is found in the period 1989 to 1997. Surprisingly, however, investment costs per kW have increased from the 600 kW machine to the considerably larger 1,000 kW turbine. The reason is to do with the dimensioning of the turbine. With higher hub heights and larger rotor diameters, the WT is equipped with a relatively smaller generator although it produces more electricity. It is particularly important to be aware of this when analysing WTs constructed to be used in low and medium wind areas, where the rotor diameter is dimensioned to be considerably larger compared to the rated capacity.

Another reason for the increase in capacity costs is that, in 2001, the 1,000 kW machine was fairly new. It is usually the case that, due to economies of scale, a reduction in price is seen over time.

Figure 2.4: The Development of Investment Costs, Exemplified by the Case of Denmark for the Period 1989 to 2001



Right axis: Investment costs divided by swept rotor area (€/m² in constant 2001 €). Left axis: Wind turbine capital costs (ex works) and other costs per kW rated power (€/kW in constant 2001 €).

Also, the share of other costs as a percentage of total costs has decreased. In 1989, almost 29% of total investment costs were related to costs other than the turbine itself. By 1997, this share had declined to approximately 20%. The trend towards lower auxiliary costs continues for the last vintage of turbines shown (1,000 kW), where other costs amount to approximately 18% of the total.

3 OPERATION AND MAINTENANCE COSTS OF WIND POWER

O&M costs constitute a sizeable share of the total annual costs of a WT. For a new machine, O&M costs might easily have an average share over the lifetime of the turbine of approximately 20%-25% of total levellised cost per kWh produced – as long the WT is fairly new, the share might constitute 10%-15% increasing to at least 20%-35% by the end of its life. Thus, O&M costs are increasingly attracting the attention of manufacturers seeking to develop new designs requiring fewer regular service visits and less out-time.

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 WT's total lifespan. On the other hand, costs for repair and related spare parts are much more difficult to predict. Although all cost components tend to increase, costs for repair and spare parts are particularly influenced by turbine age, starting low and increasing over time.

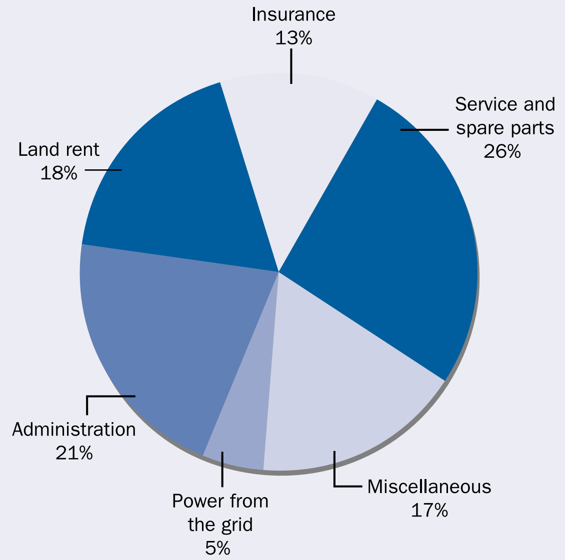
Due to the newness of the wind energy industry, only a limited number of WTs have existed for their expected lifespan of 20 years. Compared to the average size WTs commercially available nowadays, these older WTs are nearly all small and have, to a certain extent, been constructed using more conservative, less stringent design criteria than that used today. Some cost data can be gleaned from existing older WTs, but estimates of O&M costs should nevertheless be considered highly uncertain, especially around the end of a turbine's lifetime.

Based on experiences from Germany, Spain, the UK and Denmark, O&M costs are, in general, estimated to be at a level of approximately 1.2 to 1.5 c€/kWh of produced wind power seen over the total lifetime. Data from Spain indicate that a little less than 60% of this amount goes strictly to O&M and installation, with this proportion split into approximately half for spare parts and the rest equally distributed between labour costs and fungibles. The remaining 40% is almost equally split between insurance, rental of land[4] and overheads.

In Germany, a questionnaire by Dewi (2002) also looked into the development and distribution of O&M costs for German installations. For the first two years of its life, a WT is normally covered by the manufacturer's warranty. Thus, in the German study, O&M costs for the first two years were fairly low at 2%-3% of total investment costs, corresponding to approximately 0.3-0.4 c€/kWh. After six years, total O&M costs had increased to constitute a little less than 5% of total investment costs, which is equivalent to approximately 0.6-0.7 c€/kWh. These figures are in line with calculated O&M costs for newer Danish turbines (see below).

Figure 3.1 shows an average over the period 1997 - 2001 of how total O&M costs were split into six different categories based on the German data from Dewi. The cost of buying power from the grid and land rental (as in Spain) are included in the O&M cost calculation for Germany.

Figure 3.1: O&M Costs for German Turbines as an Average over the Period 1997-2001



Source: Dewi (2002).

Figure 3.2: O&M Costs Reported for Selected Sizes and Types of Wind Turbines

Source: Jensen *et al.* (2002).

A recent study in Denmark has analysed the development of O&M costs, insurance costs, etc., including the economic and technical lifetime of WTs. Based on a survey of national wind organisations and an existing database, time series for O&M cost components were established going back to the early 1980s. Relevant O&M costs were defined to include reinvestments – for example, replacement of blades or gears – if any. Due to the industry's evolution towards larger WTs, O&M cost data for old WTs exist only for relatively small units, while data for younger WTs relate primarily to larger units. In principle, the same sample should have been followed throughout successive years. However, due to the appearance of new WTs, the scrapping of older ones, and general uncertainty about the statistics, the sample is not constant over time, particularly for the larger WTs. Some of the key results are shown in Figure 3.2.

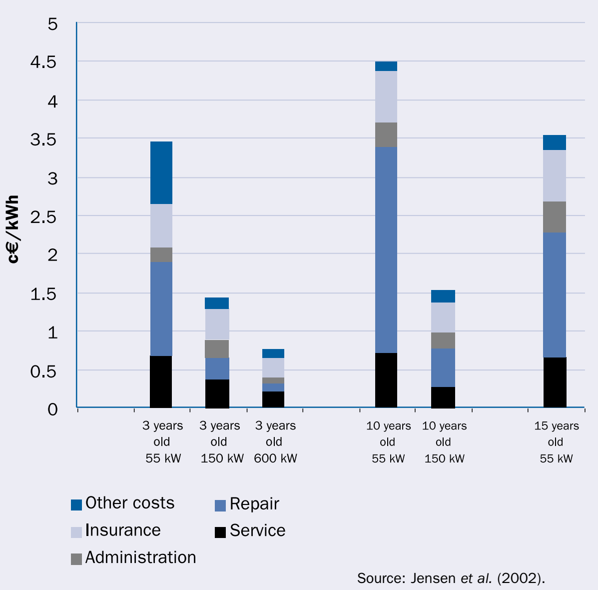
The figure shows the development of O&M costs for selected sizes and types of turbines since the beginning of the 1980s. The horizontal axis represents the age of the WT while the vertical axis is the total O&M costs stated in constant 1999 €. As seen, the 55 kW WTs now have a track record close to 20 years, implying that the first serial-produced machines are now reaching the end of their life. The picture for the 55 kW machine is patchy, showing rapidly increasing O&M costs right from the start, and reaching a fairly high but stable level of approximately 3-4 c€/kWh after five years.

Furthermore, the figure shows that O&M costs decrease for newer and larger WTs. The observed strong increase for the 150 kW WTs after 10 years represents only a very few machines; therefore, it is not known at present if this increase is representative of the 150 kW type or not. For turbines with a rated power of 500 kW and more, O&M costs seem to be under or close to 1 c€/kWh. What is also interesting is that the 225 kW machine over its first 11 years has O&M costs at around 1-1.3 c€/kWh, closely in line with estimated O&M costs in Germany, Spain, the UK and Denmark.

Thus, the development of O&M costs appears to be strongly correlated with turbine age. In the first few years, the manufacturer's warranty[5] implies a low level of O&M expenses for the owner. After the 10th year, however, larger repairs and reinvestments should be expected: from experience with the 55 kW machine, these are the dominant O&M costs during the last 10 years of the turbine's life.

Figure 3.3 shows the total O&M costs as found in the Danish study and details how these are distributed among the different O&M categories, according to the type, size and age of the turbine. Thus, for a three-year-old 600 kW machine, which was fairly well represented in the study[6], approximately 35% of total O&M costs are for insurance, 28% for regular service, 11% for administration, 12% for repair and spare parts, and 14% for other purposes. In general, the study found that expenses for insurance, regular service and administration were fairly stable over time, while, as mentioned above, costs for repair and spare parts fluctuated heavily. Finally, in most cases, other costs were of minor importance.

Figure 3.3: O&M Costs as Reported for Selected Types and Vintages of WTs



Source: Jensen *et al.* (2002).

Figure 3.3 clearly shows the trend towards lower O&M costs for new and larger machines. Thus, for a three-year-old turbine, O&M costs have decreased from approximately 3.5 c€/kWh for the old 55 kW machine to less than 1 c€/kWh for the newer 600 kW. The figures for the 150 kW WTs are almost at the same level as the O&M costs identified in the three countries mentioned above.

That O&M costs increase with turbine age is, again, fairly clear, although not to the same extent as shown in Figure 3.2.

With regard to the future development of O&M costs, care must be taken in interpreting the results of Figure 3.3. Firstly, as WTs exhibit economies of scale in terms of declining investment costs per kW with increasing turbine capacity, similar economies of scale may exist for O&M costs. This means that a decrease in O&M costs will, to a certain extent, be related to up-scaling of the WTs. Secondly, the newer, larger WTs are more optimised with regard to dimensioning criteria than the old ones, implying an expectation of lower lifetime O&M requirements than the older, smaller machines. This might, however, imply that newer WTs are not as robust as older ones and are less capable of dealing with unexpected events.

Taking this reasoning into account, the O&M cost percentage for a 10-15 year old 1,000 kW WT could be expected not to rise to the same level as seen today for a 55 kW WT of the same age. Most likely, the O&M costs for newer turbines will be significantly lower than those experienced to date for the 55 kW WTs. How much lower future O&M costs go will also depend on whether the existing trend of up-scaling continues.

4 THE COST OF ENERGY GENERATED BY WIND POWER

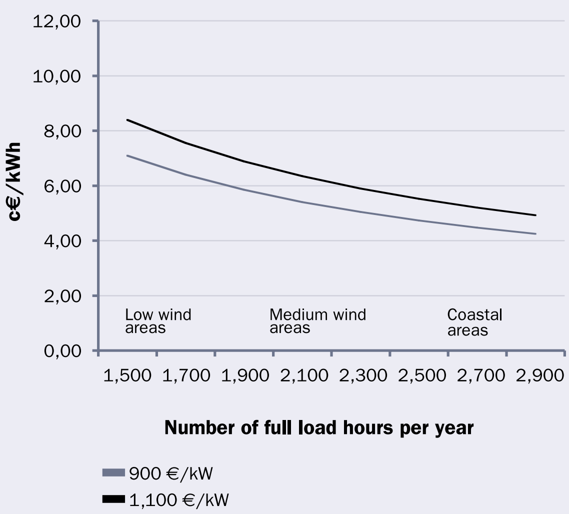
The total cost per produced kWh (unit cost) is traditionally calculated by discounting and levelising investment and O&M costs over the lifetime of the WT, divided by the annual electricity production[7]. The unit cost of generation is thus calculated as an average cost over the lifetime. In reality, 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 WT use.

The production of power is the single most important factor for calculating the cost per generated unit of power. 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-produced energy will be calculated based on a number of assumptions. Due to the importance of the power production, this parameter will be treated on a sensitivity basis. Other assumptions include the following:

- The calculations relate to a new land-based medium-sized WT of 850-1,500 kW, which could be erected today.
- Investment costs reflect the range given in section two, i.e. a cost per kW of 900 to 1,100 €/kW. These costs are based on data from Spain, UK, Germany and Denmark.
- O&M costs are assumed to be 1.2 c€/kWh as an average over the lifetime of the WT.
- The lifetime of the WT is 20 years, in accordance with most technical design criteria.
- The discount rate is assumed to range within an interval of 5% to 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. No taxes, depreciation, risk premia, etc. are taken into account. Everything is calculated at fixed 2001 prices.

The calculated costs per kWh wind power as a function of the wind regime at the chosen sites are shown in Figure 4.1 below[8]. As shown, the cost ranges from approximately 6-8 c€/kWh at sites with low average wind speeds to approximately 4-5 c€/kWh at good coastal positions[9]. 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 terrain in mid- and southern Europe in Germany, France, Spain, Holland, 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. Therefore, strong fluctuations in the wind regime are to be expected, even for neighbouring areas.

Figure 4.1: Calculated Costs per kWh Wind Power as a Function of the Wind Regime at the Chosen Site (Number of full Load Hours)

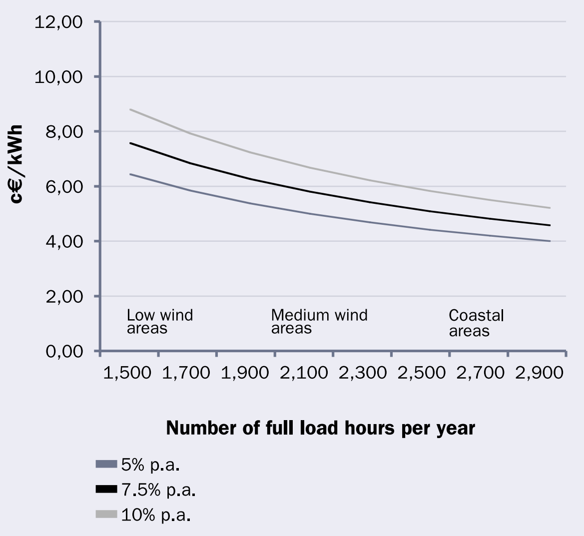


For assumptions: see above.

Approximately 75% of total power production costs for a WT are related to capital costs, i.e. costs for the WT itself, foundation, electrical equipment and grid-connection. Thus, WTs are a so-called capital-intensive technology compared with conventional fossil fuel-fired technologies such as a natural gas power plant, where 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 4.2, the costs per kWh wind power are shown as a function of the wind regime and the discount rate, where the latter varies between 5% and 10% a year.

As shown in Figure 4.2, costs range between approximately 5 and 6.5 c€/kWh at medium wind positions, indicating that a doubling of the interest rate induces an increase in production costs of 1.5 c€/kWh. In low wind areas, the costs are significantly higher, 6.5-9 c€/kWh, while production costs range between 4 and 5.5 c€/kWh in coastal areas.

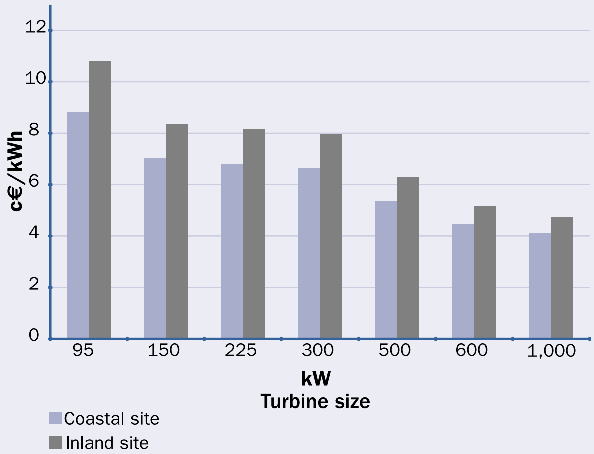
Figure 4.2: The Costs of Wind Power as a Function of Wind Speed (Number of Full Load Hours) and Discount Rate



5 DEVELOPMENT OF THE COST OF WIND POWER

The rapid European and global development of wind power capacity has had a strong influence on the cost development of wind power within the past 20 years. To illustrate the trend towards lower production costs of wind power, a historical case showing the production costs for different sizes and vintages of WTs has been constructed. Due to limited data, it has only been possible to construct this case for Denmark, though a similar trend was observed in Germany at a slightly slower pace.

Figure 5.1: Total Costs of Wind Power (c€/kWh, Constant 2001 Prices) by Turbine Size



For assumptions on wind speed, see endnote 10.

Figure 5.1 shows the calculated unit cost for different sizes of turbines based on the same assumptions as used in the previous section. Thus, a 20-year lifetime is assumed for all turbines in the analysis and an annual discount rate of 7.5% is used. All costs are converted into constant 2001 prices. Electricity production is estimated for two wind regimes, a coastal and an inland medium wind position, respectively. The starting point for the analysis is the 95 kW machine that was mainly installed in Denmark during the mid 1980s, followed by successively newer WTs (150 kW, 225 kW, etc.), ending with the most recent - the 1,000 kW turbine typically installed around year 2000. It should be noted that WT manufacturers, as a rule of thumb, expect the production cost of wind power to decline by 3%-5% for each new generation of WTs that they add to their product portfolio. Further cost reductions are therefore likely to have occurred with the longer production series of WTs over 1,000 kW. Note that the calculations are performed for the total lifetime (20 years) of the WTs, which means that calculations for the old WTs are based on track records of up to 15 years (average figures), while newer WTs might have a track record of only a few years. Thus, the newer the WT, the more uncertain the calculations.

In spite of this, Figure 5.1 clearly illustrates the economic consequences of the trend towards larger WTs and improved cost-effectiveness. For a coastal position, for example, the average cost has decreased from approximately 8.8 c€/kWh for the 95 kW WT (mainly installed in the mid-1980s) to approximately 4.1 c€/kWh for a fairly new 1,000 kW machine – an improvement of more than 50% over a 15 year period at constant 2001 prices.

6 FUTURE DEVELOPMENT OF THE COST OF WIND POWER

In this section, the future development of the economics of wind power is illustrated by the use of experience curve methodology. The experience curve approach was developed back in 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 (Johnson, 1984). Thus, if the cumulative sale of a product is doubled, the estimated learning rate gives you the achieved reduction in specific product costs.

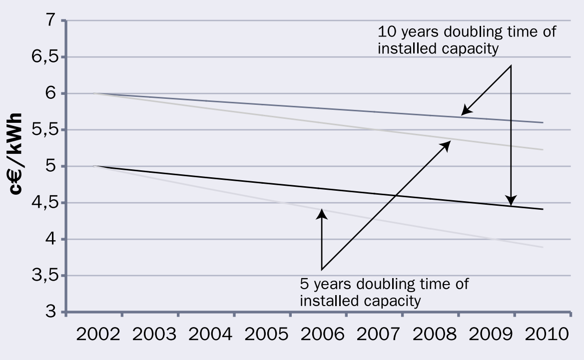
The experience curve is not a forecasting tool based on estimated relationships. It merely points out that if existing trends are to continue, then we might see the proposed development. It converts the effect of mass production into an effect on production costs, but other casual relationships are not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

For a number of projects, different experience curves have been estimated[10], but, unfortunately, most used different specifications, which means that they cannot be directly compared. To get the full value of the experiences gained, not only should the price-reduction of the WT (€/kW-specification) be taken into account, but the improvements in efficiency of the WTs production should be included too. The latter requires the use of an energy specification (€/kWh) which excludes many of the mentioned estimations (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 to 0.91, corresponding to learning rates of 0.17 to 0.09. That is, when total installed capacity of wind power is doubled, the costs per produced kWh for new turbines are reduced by between 9% and 17%. In this way, both the efficiency improvements and embodied and disembodied cost reductions are taken into account in the analysis.

Wind power capacity has developed very rapidly in recent years, on average approximately by 30% per year during the last 10 years. Thus, at present, total wind power capacity is doubled every three years. The EU has set a target of 40,000 MW of wind power by year 2010, compared to approximately 23,500 MW installed in the EU at the end of 2002. The European Wind Energy Association (EWEA) has recently published a target of 75,000 MW for Europe by 2010. The EU target implies an annual growth rate of approximately 7% (a doubling time of a little more than 10 years), while the EWEA target requires an annual growth rate of almost 16% (a doubling time of 4.8 years). In Figure 6.1 below are shown the consequences for wind power production costs according to the following assumptions:

- A learning rate between 9% and 17% is assumed, implying that each time the total installed capacity is doubled, then the costs per kWh wind power is reduced by 9%-17%.
- The growth rate of installed capacity is assumed to double cumulative installations every 5th, respectively every 10th year.
- The starting point for the development is the cost of wind power as observed today, i.e. in the range of 5 to 6 c€/kWh produced for an average medium sized turbine (850-1,500 kW) sited at a medium wind regime (average wind speed of 6.3 m/s at a hub height of 50 m).

Figure 6.1: Using Experience Curves to Illustrate the Future Development of Wind Turbine Economics until 2010



Costs illustrated for a turbine installed in a medium wind regime with a present day production cost of 5 to 6 c€/kWh.

The consequences of applying the above-mentioned results for wind power are illustrated in Figure 6.1. At present, the production costs for a medium sized WT

(850-1,500 kW) installed in an area with a medium wind speed is approximately 5-6 c€/kWh produced power. If a doubling time of total installed capacity of 10 years is assumed, the cost interval in 2010 would be approximately 4.4 to 5.6 c€/kWh. A doubling time of five years only would imply a cost interval in 2010 of 3.9 to 5.2 c€/kWh. If the WT is located in a coastal area with a higher wind speed (average wind speed of 6.9 m/s at a height of 50 m), the costs per kWh produced in 2010 could be as low as 3.1 to 4.4 c€/kWh in the case of a five-year doubling time of total installed capacity.

7 COSTS OF CONVENTIONAL POWER PRODUCTION

The cost of conventional electricity production is determined by three components:

- Fuel cost
- O&M costs
- Capital cost

When conventional power is substituted by wind power, the avoided cost depends on the degree to which wind power substitutes each of the three components. It is generally accepted that implementing wind power avoids the full fuel cost and a considerable portion of O&M costs of the displaced conventional power plant. The level of avoided capital costs depends on the extent to which wind power capacity can displace investments in new conventional power plants and is thus directly tied to the capacity credit of wind plant.

The capacity credit will depend on a number of different factors: among these is the level of penetration of wind power and how the wind capacity is integrated into the overall energy system and market. In general, for marginal levels of wind penetration, the capacity credit for WTs is close to the annual average capacity factor. Thus, 25% is considered to be a reasonable capacity credit for wind power when the volume of wind electricity is less than 10% of total electricity production[11]. This capacity credit declines as the proportion of wind power in the system increases; but even at high penetrations a sizeable capacity credit is still achievable if the management and future development of grid infrastructure are conducted with a view to the expected increase in distributed generation from wind power and other renewable energy sources.

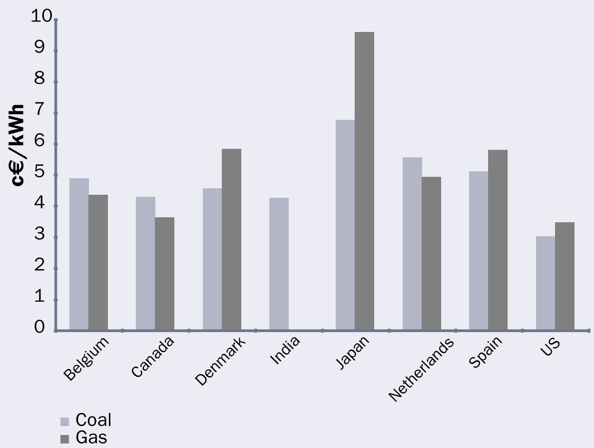
The capacity credit of wind power depends heavily upon the structure of power markets. Studies of the Nordic power market, NordPool, show that the cost of integrating intermittant wind power is, on average, approximately 0.3-0.4 c€/kWh wind power at the present level of wind power capacity (20% in Denmark). Under existing transmission and market conditions, and as in the case of capacity credit, these costs are supposed to increase with higher levels of wind power penetration.

To get a comparable picture, *"Projected Costs of Generating Electricity - Update 1998"* (OECD/IEA, 1998)[12] has projected the costs of electricity generation with state-of-the-art coal-fired and gas-fired base load power plants, given the following common assumptions:

- Plants are commercially available for commissioning by the year 2005
- Costs are levellised using a 5% real discount rate and a 40-year lifetime[13]
- 75% load factor
- Calculations are carried out in constant 1996 US$, converted to € 2001 prices

The OECD/IEA calculations were based on data made available by OECD member countries. Costs related to electricity production, pollution control and other environmental protection measures were included in the calculated generation costs, while general costs, such as central overheads, transmission, and distribution costs were excluded. Losses in transmission and distribution grids were also not taken into account. Fuel price developments were projected in accordance with national assumptions. Figure 7.1 shows the costs of conventional power as projected by OECD/IEA, updated to 2001 € prices.

Figure 7.1: Projected Costs of Conventional Power (2001 c€/kWh)



Source: OECD/IEA (1998), updated to 2001 € prices.

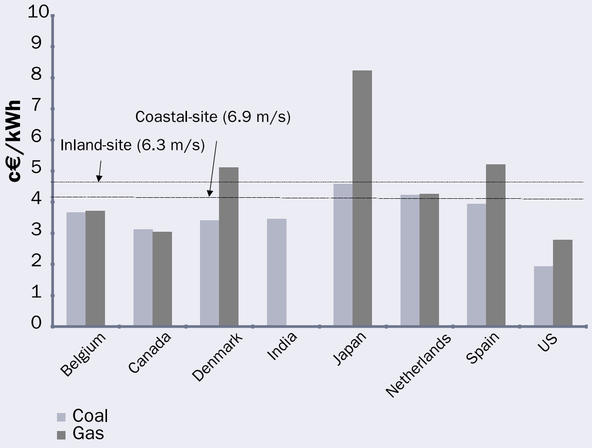
The figures are based on the above cost data from OECD/IEA (1998) for a selected number of countries and power technologies. The costs for the conventional technologies were originally stated in 1996 US$, but at the aggregate level converted to 2001 € prices. Thus, considerable uncertainty exists for the costs shown owing to changes in exchange rates, national differences in inflation rates and different national assumptions on fuel price development. Finally, although no major changes are expected, investment costs for conventional power plants may have changed quite substantially since 1998.

Figure 7.2 shows those costs of conventional power which are avoidable through wind electricity, assuming that all conventional fuel and O&M costs are avoided and that wind power is assigned a capacity credit of 25%. For example, in Spain, for each kWh of electricity generated by wind power which displaces a kWh of gas power, approximately 5.2 c€/kWh are saved in gas fuel, O&M costs and displaced capital costs. Therefore, if a wind turbine could be installed in Spain at an average cost below 5.2 c€/kWh, this would make wind power economically competitive in comparison with new gas-fired power plant in Spain. For comparative purposes, the estimated total costs (including capital costs and calculated using an annual discount rate of 5%) for a medium sized on-land turbine at average coastal and inland sites are also shown (4.2 and 4.8 c€ per kWh, respectively[14]). As shown in Figure 7.2, under the assumption of a 25% capacity credit for wind energy, a medium sized turbine is actually approaching competitiveness in terms of direct costs in a number of countries, compared to technologies based on coal and gas.

Of course, if a higher capacity credit for wind than 25% is assumed, this would raise the avoided costs of conventional technologies and thus improve wind's competitiveness. Similarly, if a lower capacity credit were assumed, this would make wind power less economically competitive.

Capital costs are more important for coal based power than for natural gas fired plants, and therefore assumptions about wind's capacity credit are particularly important regarding coal plants, as shown above. However, this importance may change in the future as electricity markets increasingly move away from centralised generation planning and towards increased competition. Much of wind energy's future competitiveness will depend on short-term wind predictability and on the specific conditions which develop for bidding into short-term forward and spot markets at the power exchange.

Figure 7.2: Projected Avoided Costs of Conventional Power Compared to Costs for Wind Electricity (2001 c€/kWh), Assuming 25% Capacity Credit for Wind Power



Source: OECD/IEA (1998), updated to 2001 € prices.

Finally, it should be stressed that the above-mentioned costs of conventional generation are based upon national assumptions on the development of fossil fuel prices which, of course, are subject to significant uncertainties. As discussed by Awerbuch (2003), these uncertainties relating to future fossil fuel prices imply a considerable risk for future generation costs of conventional plants, while the costs per kWh generated by wind power are almost constant over the lifetime of the turbine when first installed. Thus, although wind power today might be more expensive than conventional power technology per kWh, it may nevertheless take up a significant share in investors' power plant portfolios, taking on the role of hedging against unexpected rises in future prices of fossil fuels. Thus, the constancy of wind power costs justifies a relatively higher cost per kWh compared to the more risky future costs of conventional power.

8 EXTERNAL COSTS OF POWER PRODUCTION

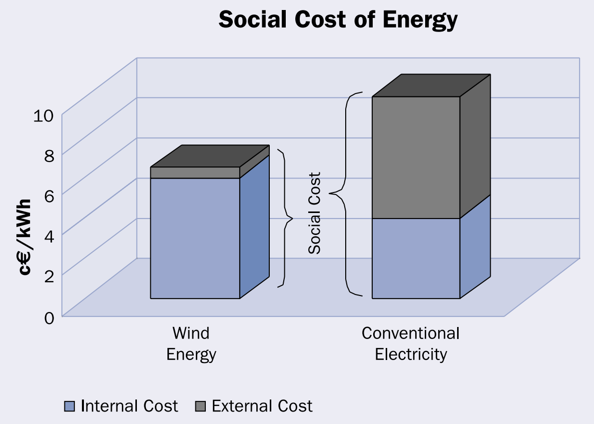
The competitiveness of wind power is dependent on the particular market conditions where wind developments are placed. Figure 7.2 shows that wind costs are marginally higher than conventional power technologies such as coal and natural gas. However, it is generally appreciated that wind energy and other renewable energy sources have environmental benefits when compared to conventional electricity generation. But are these benefits fully reflected in the market prices of electricity? And, on the other hand, is conventional power generation charged for the environmental damage caused by polluting emissions?

This section deals with these questions in order to estimate the hidden benefits/costs of the different electricity production activities not taken into consideration by the existing pricing system. To establish a fair comparison of the different electricity production activities, all internal and external costs to society need to be taken into account.

Hence, it is important to identify external effects of different energy systems and to monetise their costs, especially if these are of a similar order of magnitude as the internal costs of energy and if the external costs vary substantially between competing energy systems such as conventional electricity generation and wind energy. The question arises whether the inclusion of external costs – the externalities – in the pricing system (internalisation) could have an impact on the competitive situation of different electricity generating technologies. Results from different studies are shown in Figure 8.1. The external costs of conventional power systems make these technologies less competitive in comparison with wind energy as the externalities are included to take account of the social cost of energy production. The internal cost of wind energy is practically unchanged by including the externalities.

Volume 4 'Environment', presents a more detailed analysis of the external cost of energy as well as the latest results obtained for different generation technologies. In addition, an analysis focusing on the avoidable external costs of wind energy for European member states, along with an estimation of the total avoided external costs, are also introduced.

Figure 8.1: An Illustrative Example of the Social Cost of Energy



Endnotes

1. "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.
2. For Germany, an average figure for the installed capacity in 2001 is used.
3. All costs are converted to 2001 euros.
4. In Spain the rental of land is seen as an O&M cost.
5. In the Danish study, only the costs to be borne by the wind turbine owner are included, i.e. costs borne by the manufacturer in the warranty period and subsequently by the insurance company are not taken into account.
6. The number of observations was, in general, between 25 and 60.
7. The cost of wind energy should not be confused with the price of wind power. The latter relates to the amount per kWh the wind turbine owner receives for the power he/she sells.
8. In the figure, the number of full load hours is used to represent the wind regime. Full load hours are calculated as the turbine's average annual production divided by its rated power. The higher the number of full load hours, the higher the wind turbine's production at the chosen site.
9. In this context, a coastal position is defined as a site with an average wind speed of 6.9 m/s at a height of 50 m above the ground. Correspondingly, the medium and low wind sites have average wind speeds of 6.3 and 5.4 m/s at a height of 50 m.
10. See, for instance, Neij (1997), Neij (1999), Milborrow (2003) or Neij *et al.* (2003).
11. EPRI (1997) suggests that wind turbines located in highly windy areas could achieve capacity factors of 40%-45% by 2005.
12. This seems to be the most recent update of the projected costs of generating electricity available.
13. National assumptions on plant lifetime might be shorter, but calculations were adjusted to 40 years.
14. Average wind power production costs calculated using an annual 5% discount rate as shown in chapter 4.

WIND ENERGY - THE FACTS

VOLUME 3

INDUSTRY & EMPLOYMENT

Acknowledgments

The employment chapters of this volume were compiled by Henrik Jacobsen, Senior Researcher at Risø National Laboratory, Denmark. Our thanks also to the national wind associations around Europe for their contributions of data, and to the other project partners for their inputs.

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1 INDUSTRY STATUS

1.1 Introduction

Since the last *Wind Energy - The Facts* report published in 1999, the European wind energy industry has made significant progress. There are several ways of monitoring this progress, such as measuring electricity output in MW or kW hours. However, the usual method is to use a measurement of installed capacity, so this chapter demonstrates national markets and their growth in terms of MW capacity installed.

Wind experienced a surge of growth in California in the 1980s thanks to a combination of state and federal energy and investment tax credits[1]. From 1980 to 1995, around 1,700 MW of wind capacity was installed and, although there were some turbines of poorer quality, the boom period provided a major export market for European manufacturers, and did much to establish the credibility of the industry. Since then, Europe has turned the tables and consolidated its position as the global market leader. Within Europe, certain countries are particularly strong: the top five in terms of installed capacity being Germany, Spain, Denmark, The Netherlands and Italy.

1.1.1 NEW DEVELOPMENTS

There have been significant changes in the industry over the last five years, and it is still in a state of considerable flux. Some major structural changes are taking place within the sector as it matures; these are significant for any company wishing to participate in the wind industry over the long term.

The unit size, both of individual turbines and of wind farms has grown significantly. Five years ago, a wind farm of 20 MW would be considered large. Now, particularly as the North American market reopens, the Spanish market continues to grow, new markets open, and the offshore market takes off, very large wind farms are being introduced, in the scale of hundreds of MW.

The definition of a wind farm is somewhat vague, but if a wind farm is considered, somewhat artificially, as a single financing, then the year 2001 saw a major breakthrough, with a single financing in Spain of more than 1,000 MW (1 gigawatt, GW). With a more limited definition - that of a single location - then the King Mountain project in Texas is the largest single installation, at 278 MW. Continued activity in the US suggests that such large projects, although unlikely to become commonplace, will certainly occur more frequently.

Growth in wind farm size has, to a degree, followed growth in wind turbine (WT) size. These same large wind farms cannot, however, be installed in all markets, and space requirements in some hitherto very active European markets will ultimately limit growth onshore. This constraint has now been recognised by several northern European governments, and active plans for the development of offshore projects have begun. Indeed, the construction of Denmark's second large-scale offshore projects has been completed with a capacity of 160 MW.

1.1.2 MARKET CHANGES

Structural changes to the industry have taken place in recent years, and new companies have arrived. The increased size of wind farms, growth of business at approximately 30% per annum, improved technology and, in particular, improved turbine availability, have all allowed the wind energy business to be considered seriously by main players in the conventional power industry: Shell has formed a wind energy subsidiary, Shell Wind Energy; and the Enron subsidiary, Enron Wind Corporation, was purchased by General Electric to form GE Wind Energy.

SIIF, a French company 35% owned by Electricité de France, is emerging as a major player with global aspirations, recently purchasing the US operations and maintenance provider and developer enXco. Substantial construction by the Italian conglomerate EDENS, as well as ongoing activity by FPL and most of the Spanish utilities, all underline the nature of today's wind developers, as compared with those of the previous decade, which tended to be small and independent.

The last year has also seen the separation of Gamesa Eolica, the leading supplier in the Spanish market, from its Danish partner, Vestas. This step has produced a major new competitor worldwide. The Indian company,

Suzlon, has also emerged on the world market as a turbine supplier.

Over the past decade, the wind turbine manufacturing industry has become increasingly concentrated. This was emphasised by the announcement of a merger in December 2003 between the world's largest and third largest manufacturers Vestas Wind Systems and NEG Micon. If approved, they will have a combined global market share of approximately 35%.

1.2 Demand Drivers

1.2.1 MARKET TYPES

The market may be split into two separate segments, the "conscience" market and the "needs" market.

Conscience Market

In the conscience market, the driver for development of wind energy has hitherto been a desire to produce electricity by cleaner means. This has been supported by incentives, described in volume 5 chapter 1, and, hence, has been essentially a political market. There are signs, however, that as the cost of wind energy continues to fall there are some applications for which wind energy is competitive in its own right and the nature of these markets will therefore change.

Needs Market

For the needs market, motivations are somewhat different. Such markets are characterised by a growing, and unsatisfied, need for energy, and a limited amount of new generating capacity coming online. In these markets, wind energy is considered as one of several alternatives. Given the relative ease with which wind technology adapts to different countries and requirements, and the relatively short time between initiating construction and delivering power, it has become the most attractive alternative for some.

A good example of this latter category is wind power's initial development in India. The way in which the Indian market developed in the mid 1990s shows that there can be a danger in too rapid development of a new technology. Quality problems arose, both in initial manufacture, which were later revealed in severe storms in Gujarat and also, perhaps more severely, in inadequate preparation of projects. In particular, inadequate measurement was carried out of the wind resource on project sites. Whereas in industrialised countries it is normal to have several years' wind data before a project is built, in India there was, at best, only a few months' and, in some cases, no data at all. This is a dangerous position.

Another major flaw in the Indian framework of the 1990s, was the existence of a subsidy to wind turbine owners which was based on the rated capacity of the wind turbines rather than an incentive to optimise production of the renewable electricity. That proved problematic because a subsidy was given whether or not production was efficient. This incentive resulted in poor siting of wind turbines, and manufacturers followed customer demands to use very large generators, which improved project profitability but reduced production and also attracted manufacturers with highly dubious products, which gave the entire technology a bad name. India has since corrected the inherent flaws of its incentive scheme and the market has started to develop again.

With the experience of these mistakes, it is noticeable that the second round of incentives in the Indian market is rather different, and the market is presently being much more tightly controlled, both in terms of development qualifications and also in quality control of the turbines produced. As a result, wind energy in India now has a sustainable future. Other countries in this category presently considering serious development of wind energy include Brazil, Tunisia, China, Egypt, Morocco, the Philippines, Turkey and Vietnam.

The key difference between the two market types is that, for the conscience market, comparisons are always made between wind costs and, say, combined cycle gas costs whereas, for the needs market, the comparison may be the cost of having power rather than not having power. The conditions for commercial viability are, therefore, quite different.

1.2.2 POLITICAL RISK

There are many examples of political uncertainty in both the needs and the conscience markets: a few examples are given here.

The risks associated with establishing a wind farm in a developing country are similar to those encountered with any other form of development. There is political risk, technology risk and financial risk. There is also, in the case of wind energy, an additional risk that the technology will be copied and an indigenous product developed without a license agreement.

In both the conscience and the needs market there is political risk. The cost of wind energy has declined sharply over the last decade, but still requires some form of incentive to encourage its widespread development. This incentive is inevitably political in nature although it may be drafted in any number of different ways, from tax credits to premium prices, to tradable green certificates. If the political attitude changes in any one of the active countries, the market in that country can undergo radical alteration. This has, indeed, been seen on many occasions. For example, in Germany, there was some uncertainty in 1999 about the planning regime within which wind energy developments were built. Whilst that uncertainty was being clarified, the market declined, but it has since recovered and achieved three record years. When US President Carter left office in the early 1980s, the market stopped overnight. Early in 2003, the premium price in Spain fell, although this was coupled with an increase in pool price and hence the composite kWh (kilowatt hour) price was almost unchanged. Nevertheless, the risk of price change was accentuated.

In the case of the EU, underpinning individual domestic policies for renewable energy and environmental policy, there is strong support from both the European Commission and the Parliament. Targets for renewable energy have been set and enshrined in EU law. Hence, at a higher level of policy, significant support exists for ongoing development of renewables, including wind. Wind energy is particularly well received in this context as it has demonstrated an ability both to reduce its price significantly with increases in volume, and to create significant employment.

The wind power industry has experienced the risk of relying too heavily on one single market. In the middle of the 19980s, manufacturers were entirely relying on the Californian market. In the 1990s, they found themselves equally dependant on the Indian market for wind power technology. When those two markets collapsed due to political and economic turmoil, many manufacturers went bankrupt. Today, the global wind power market is more geographically spread. However, the three largest markets still accounts for app. 70% of the global market (2002).

1.3 The Onshore Market

1.3.1 MARKET STATUS (CUMULATIVE MARKET)

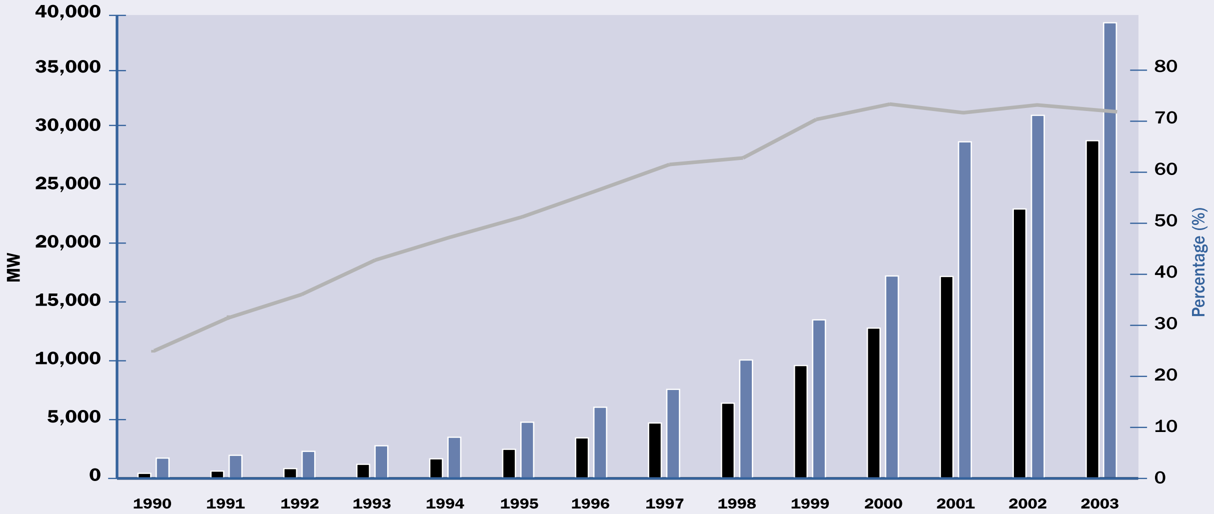
The progress of wind power around the world in recent years has been impressive. By the end of 2003 more than 39,400 MW of electricity-generating WTs were operating in 50 countries. Of these, more than 28,000 MW were installed in the EU, enough to meet 2.4% of EU-15 electricity demand.

Europe dominates the global wind market, with European manufacturers controlling 90% of the global market in 2002. The most successful markets for wind power in recent years have been Germany, Spain and Denmark. Outside the EU, India and the US are leading markets, but over 70% of the market remains in the EU. Between 1992 and 2002, cumulative installed capacity multiplied 27 times. 2002 itself was a record year for EU installations, with over 5,800 MW of new capacity.

Wind energy is now established across parts of western and southern Europe, and installations are beginning to take off in the new member states of central and eastern Europe, for example in Latvia and Poland. Figure 1.1 shows installed MW capacity in the EU-15, compared with that installed worldwide.

The curve demonstrates the percentage of global installed capacity installed in the EU-15: in 1990 this figure stood at 25%. Over the last five years, the European market has grown by an average 30% per annum and, by the end of 2002, EU-15 countries represented 74% of installed capacity worldwide.

Figure 1.1: EU-15 and Global Cumulative Installed Wind Capacities (MW)



	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
EU-15	439	629	844	1,211	1,683	2,497	3,476	4,753	6,453	9,678	12,887	17,315	23,098	28,440
WORLD	1,743	1,983	2,321	2,801	3,531	4,821	6,104	7,636	10,153	13,594	17,357	28,857	31,128	39,500
EU % of world	25	32	36	43	48	52	57	62	64	71	74	73	74	72

Table 1.1: EU-15 Cumulative Installed Capacities (MW) by Country

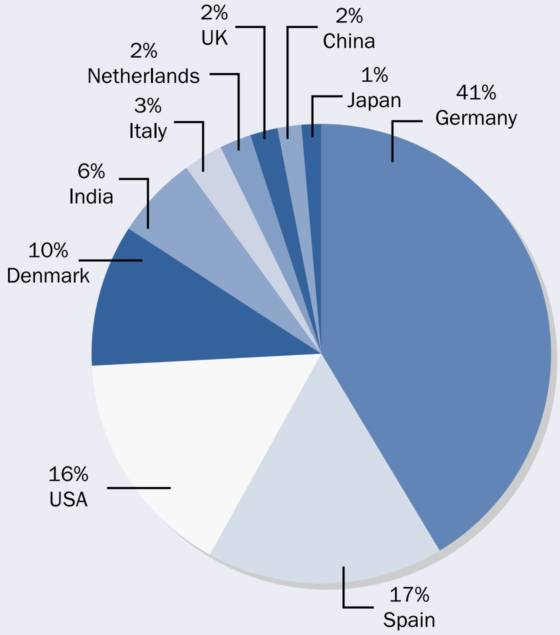
Country	1995	1996	1997	1998	1999	2000	2001	2002	2003
Austria	5	10	20	30	34	77	94	140	415
Belgium	4	4	4	6	6	13	31.6	35	68
Denmark	619	842	1,129	1,443	1,771	2,417	2,489	2,889	3,110
Finland	6	7	12	17	39	39	39	43	51
France	3	6	10	19	25	66	93	148	239
Germany	1,132	1,552	2,081	2,875	4,442	6,113	8,754	11,994	14,609
Greece	28	29	29	39	112	189	272	297	375
Ireland	7	11	53	73	74	118	124	137	186
Italy	32	70	103	180	277	427	682	788	904
Luxembourg	2	2	2	9	10	10	15	17	22
Netherlands	249	299	319	361	433	446	486	693	912
Portugal	8	19	38	60	61	100	131	195	299
Spain	133	249	512	834	1,812	2,235	3,337	4,825	6,202
Sweden	69	103	122	174	220	231	293	345	399
UK	200	273	319	333	362	406	474	552	649
EU-15 Total	**2,497**	**3,476**	**4,753**	**6,453**	**9,678**	**12,887**	**17,315**	**23,098**	**28,440**

Table 1.2: New Member State Cumulative Installed Capacity (MW)

	1995	1996	1997	1998	1999	2000	2001	2002[1]	2003[1]
Cyprus [2]	0	0	0	0	0	0	0	2	2
Czech Republic [3]	11	11	11	11	11	6	7	3	10
Estonia [4]	0	0	0	0	0	0	0	2	3
Hungary [5]	0	0	0	0	0	0	1	3	3
Latvia [6]	1	1	1	1	1	1	1	24	24
Lithuania	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0	0
Malta	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0	0
Poland [7]	1	1	2	2	3	4	22	27	57
Slovakia	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0	3
Slovenia	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0	0
EU New Members Total	13	13	14	10	17	18	33	61	102

[1] All data for 2002 - 2003 from EWEA
[2] Data for 1995 - 2001 from Cyprus Institute of Energy
[3] Data for 1995 - 2001 from Czech Society for Wind Energy
[4] Data for 1995 - 2001 from Latvian Wind Energy Association
[5] Data for 1995 - 2001 from Horvath Engineering, Hungary
[6] Data for 1995 - 2001 from Latvian Wind Energy Association
[7] Data for 1995 - 2001 from Vis Venti Association for Supporting Wind Energy, Poland

Figure 1.2: Top 10 Cumulative Global Market Shares in 2002 (MW)

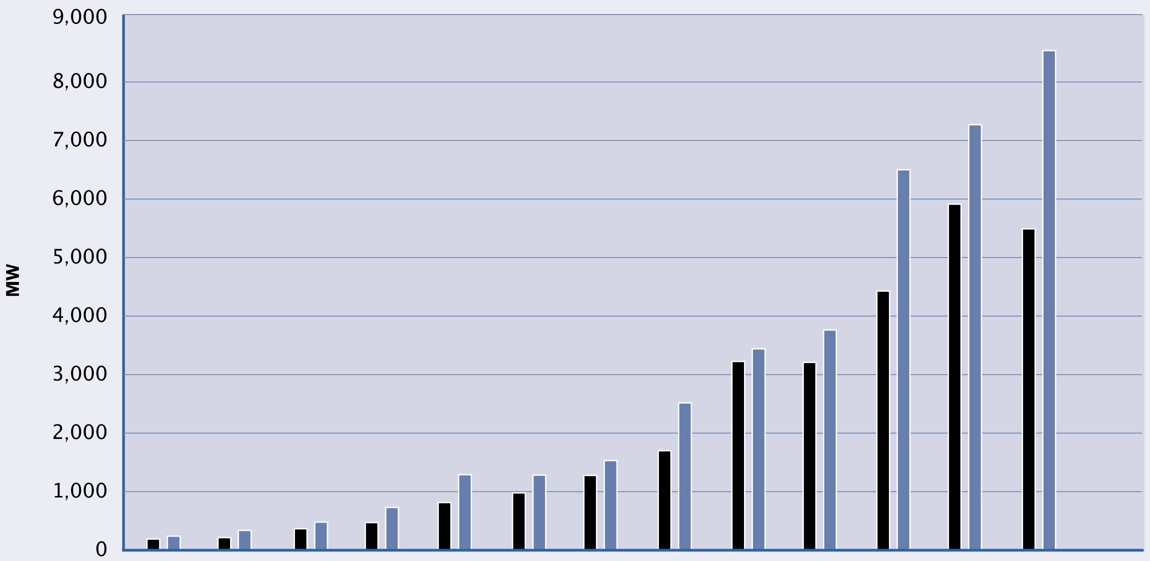


Country	Cumulative Installed Capacity End, 2002	% Share
Germany	12,001	41.4
Spain	4,830	16.7
USA	4,685	16.2
Denmark	2,880	9.9
India	1,702	5.9
Italy	785	2.7
Netherlands	688	2.4
UK	552	1.9
China	468	1.6
Japan	415	1.4
Total	**29,006**	**100.0**

1.3.2 MARKET GROWTH (ANNUAL MARKET)

Germany, Spain and Denmark accounted for almost 80% of the wind power capacity installed in Europe in 2003 (see Table 1.3). With 2,645 MW, Germany accounted for 49% of the installed capacity, reaching a total of 14,609 MW by the end of 2003, enough to meet 6% of national electricity needs from wind power. Spain followed with 1,377 MW, to achieve a total of 6,202 MW. Denmark installed 243 MW to reach 3,110 MW, and the industry association expects that wind will meet approximately 20% of the country's electricity needs in 2004.

Figure 1.3: EU-15 and Global Annually Installed Wind Capacity (MW)



	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
EU-15	190	215	367	472	814	979	1,700	1,700	3,225	3,209	4,428	5,913	5,411
WORLD	240	338	480	730	1,290	1,283	2,517	2,517	3,441	3,763	6,500	7,271	8,400

Table 1.3: EU-15 Annually Installed Capacity by Country

Country	1996	1997	1998	1999	2000	2001	2002	2003
Austria	5	10	10	4	43	17	46	276
Belgium	0	0	2	0	7	19	3	33
Denmark	223	287	314	328	646	72	506	243
Finland	1	5	5	22	0	0	4	8
France	3	4	9	6	41	27	55	9
Germany	420	529	794	1,567	1,671	2,641	3,247	2,645
Greece	1	0	10	73	77	83	25	78
Ireland	4	42	20	1	44	6	13	49
Italy	38	33	77	97	150	255	106	116
Luxembourg	0	0	7	1	0	5	2	5
Netherlands	50	20	42	72	13	40	222	226
Portugal	11	19	22	1	39	31	64	107
Spain	116	263	322	978	423	1,102	1,488	1,377
Sweden	34	19	52	46	11	62	52	54
UK	73	46	14	29	44	68	87	103
EU-15 Total	**979**	**1,277**	**1,700**	**3,225**	**3,209**	**4,428**	**5,913**	**5,411**

Table 1.4: New Member State Annually Installed Capacity (MW)

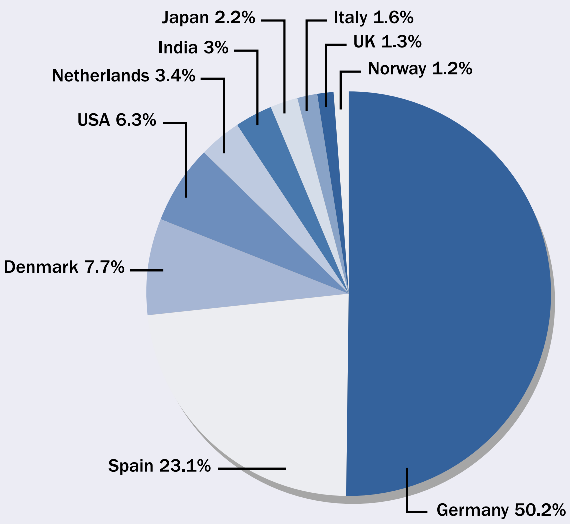
	1996	1997	1998	1999	2000	2001	2002	2003[1]
Cyprus [2]	0	0	0	0	0	0	0	0
Czech Republic [3]	0	0	0	0	-5	0	0	7
Estonia [4]	0	0	0	0	0	0	2	1
Hungary [5]	0	0	0	0	0	1	1	0
Latvia [6]	0	0	0	1	0	0	20	0
Lithuania	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0
Malta	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0
Poland [7]	0	1	0	1	1	18	5	30
Slovakia	n/a	n/a	n/a	n/a	n/a	n/a	n/a	3
Slovenia	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0
EU New Members Total	0	1	-4	7	1	15	29	41

[1] All data for 2003 from EWEA
[2] Data for 1995 - 2002 from Cyprus Institute of Energy
[3] Data for 1995 - 2002 from Czech Society for Wind Energy
[4] Data for 1995 - 2002 from Latvian Wind Energy Association
[5] Data for 1995 - 2002 from Horvath Engineering, Hungary
[6] Data for 1995 - 2002 from Latvian Wind Energy Association
[7] Data for 1995 - 2002 from Vis Venti Association for Supporting Wind Energy, Poland

Table 1.5: Offshore Installed Capacities

Location	Country	Installed Capacity (MW)	Year	Cumulative Installed Capacity (MW)
Vindeby	Denmark	5	1991	5
Lely	Ijsselmeer, The Netherlands	2	1994	7
Tunø Knob	Jutland, Denmark	5	1995	12
Dronton	IJsselmeer, The Netherlands	17	1997	29
Bockstigen-Valor	Gotland, Sweden	3	1998	32
Blyth	United Kingdom	4	2000	36
Middelgrunden	Copenhagen, Denmark	40	2000	76
Utgrunden	Sweden	10	2000	86
Yttre Strengrund	Sweden	10	2001	96
Samsø	Denmark	23	2003	119
North Hoyle	United Kingdom	60	2003	179
Horns Rev	Denmark	160	2003	339
Nysted	Denmark	158.4	2003	497.4
Arklow Bank	Ireland	25	2003	522.4

Figure 1.4: Top 10 Global Annual Market Shares in 2002 (installed MW per annum)



Country	Annual 2002	% Share 2002
Germany	3,247	50.2
Spain	1,493	23.1
Denmark	497	7.7
USA	410	6.3
Netherlands	217	3.4
India	195	3.0
Japan	140	2.2
Italy	103	1.6
UK	87	1.3
Norway	80	1.2

1.4 Offshore Market

To date, only Europe has installed wind capacity offshore, although projects are planned for the US. Fourteen projects are now operating in four EU countries with a total capacity of 522 MW.

Since the first offshore turbines were installed in 1991, development has been gradual. 2003 saw the world's first major offshore wind farm installed at Horns Rev off the Danish coast.

Figure 1.5 demonstrates the great leap made in 2003, chiefly thanks to the installation of the three Danish wind farms - Horns Rev, Nysted and Samsoe, while Table 1.6 below gives an impression of the potential for offshore wind farms in the EU up to 2006 - a little under 9 GW (9,000 MW). Worldwide, the database prepared by

Douglas-Westwood show the current planned offshore windfarms to total around 50 GW up to 2010. It should be noted that these figures are for identified projects alone and those currently under development - and the potential exists for much more.

As demonstrated by the existing level of its onshore installed capacity (57 MW) Poland is moving ahead with wind installations faster than the other new member states, and it is the only new member state to have an off-shore installation in the planning phase (see Table 1.6).

Figure 1.5: Annual and Cumulative Offshore Capacity, 1991 - 2003

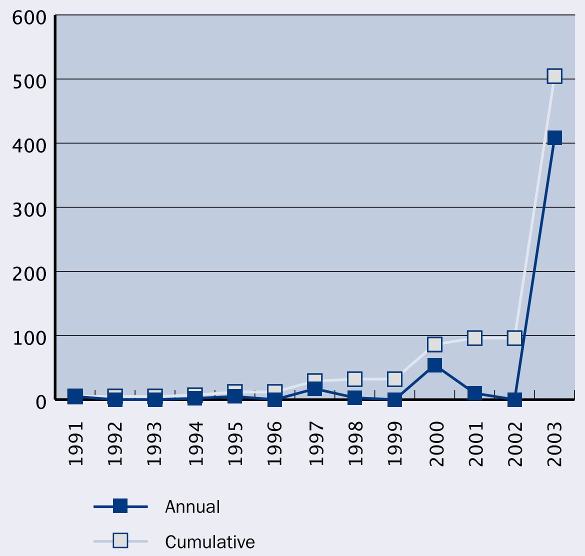


Table 1.6: EU-25 Planned Offshore Installations up to 2006

Country	Name/Location	Date	MW
Germany	Nördlicher Grund phase 1	2004	360.0
Belgium	Thornton Bank	2005	216.0
Finland	Kokkola	2005	207.0
Germany	Borkum Riffgrund phase 1	2005	231.0
Germany	Nordergründe	2005	266.0
Germany	Sky 2000	2005	150.0
Ireland	Arklow Bank phase 2	2005	216.0
Netherlands	Near Shore wind park	2005	99.0
Netherlands	Q7-WP	2005	120.0
Poland	Bialogora	2005	120.0
Sweden	Fladen	2005	140.0
UK	Barrow	2005	108.0
UK	Cromer	2005	108.0
UK	Gunfleet Sands	2005	108.0
UK	Lynn	2005	108.0
UK	Robin Rigg (Solway Firth)	2005	108.0
France	Ile de Groix	2006	100.0
Germany	Adlergrund phase 1	2006	320.0
Germany	Amrumbank West	2006	288.0
Germany	Arkona-Becken Südost phase 1	2006	195.0
Germany	Beltsee	2006	249.0
Germany	Borkum Riffgrund West phase 1	2006	280.0
Germany	Butendiek	2006	240.0
Germany	DanTysk phase 1	2006	400.0
Germany	He Dreiht	2006	535.5
Germany	Meerwind phase 1	2006	262.5
Germany	Nordsee Ost phase 1	2006	400.0
Germany	North Sea Windpower phase 1	2006	166.5
Germany	Riffgat	2006	198.0
Germany	Sandbank 24 phase 1	2006	360.0
Germany	Uthland	2006	400.0
Ireland	Arklow Bank phase 3	2006	263.0
UK	Shell Flat	2006	324.0
Other	**Less than 100 MW in size**	**-**	**1072.8**
Total	**-**	**-**	**8719.3**

Source: The World Offshore Wind Database, Douglas-Westwood (2003).

1.5 Domestic Market

Europe continues to play a dominant role, both in the development and manufacture of WTs and in the exploitation of its wind resource through the development of wind farms. The top three EU-15 markets - Germany, Spain and Denmark - as well as promising new member states markets are discussed below.

Germany

Germany continues to be the leader in terms of cumulative and annual MW installed. 2003 saw a notable drop in the annual MW installed from 3,247 to 2,645 in 2003, however that rate of decline is not forecast for the coming years (see Table 1.3). The wind sector is large, and the political commitment to wind energy remains strong - the revision of the EEG is likely to reflect that, albeit with some tougher conditions, for example for lower wind speed sites at inland sites. The decline of the onshore market will occur this decade, and an increase in offshore wind farms and the rise of a repowering market. This changing market will create ups and downs in the figures, but Germany remains the major wind market in Europe this decade.

The presence of a strong German industry is also important, as is the potential for repowering. Furthermore, Germany has significant offshore plans, the development of which may continue to buoy up its domestic market, even as the onshore market begins to decline over the next decade.

Spain

Spain has been the next most active market after Germany. Now, more than 4% of Spain's electricity is supplied by wind power. As is to be expected, the most energetic sites were largely used in the early days of development and, hence, those presently being developed do not have the same level of resource. Nevertheless, the cost of installation is reducing, and this has allowed the exploitation of less energetic sites to be undertaken with a similar return on capital. Informed commentators consider that it is unlikely that the Spanish government will wish to undermine the market for what is now a considerable Spanish industry by withdrawing the present beneficial tariff system. A notable achievement of the wind industry in Spain is the very high level of Spanish manufacturing content, which is now starting to export elsewhere. A notable event in 2001 was the separation of the market leader in Spain, Gamesa, from its previous joint venture partner, Vestas of Denmark. Gamesa Eolica is now competing on the international market.

Galicia, in the north west led the country in terms of installed capacity in 2002 - installations in this region alone amounted to 341.5 MW. Castilla La Mancha follows, while Aragón, Navarra and Castilla y León are also thriving. Spain's wind power boom has been spurred on by a thriving turbine manufacturing industry. Three of the country's manufacturers, Gamesa, Made and Ecotecnia are among the world's top 10, with Gamesa achieving fourth position in the global league table, according to the latest report from BTM Consult (2003).

The situation in Spain is rather different to that in Germany, since the winds are higher and there is more space available. Commentators expect to see the present level of the market sustained in Spain until it is limited by other concerns, possibly that of grid connection. This limitation is already seen in some large-scale projects currently being developed.

Denmark

Denmark continues to dominate the manufacturing side of the industry worldwide, and has also benefited from a buoyant home market. Denmark is a relatively small country with a high population density and already has a high level of penetration: 20% of Danish electricity consumption is covered by wind power. In 2003, some 243 MW were installed. A broad majority of the Danish Parliament has agreed on a long-term strategy for wind power - "Energy 21" from 1996. The goal is that by 2030, 40-50 percent of the Danish electricity consumption should be covered with power from wind turbines. Denmark is following a strategy on the one hand to expand wind power offshore, and on the other hand to replace some of the smaller, less productive turbines that were installed during the 1980's (machines up to 150 kW). Early Danish development was based on individual turbines sited near their owners and, hence, there were

many such turbines scattered across the Danish countryside. A repowering incentive is intended to tidy up this arrangement, and to use bigger turbines to replace a larger number of small ones. It has also allowed the better use of the more energetic sites which, again, were the first to be exploited. The Danish repowering programme has been running for a couple of years, and has been extremely successful not least due to good planning procedures. Three offshore projects have been constructed in 2003. The framework for the future Danish offshore tenders is expected to be published in the beginning of 2004.

Poland

Poland was the first eastern European country to make any real progress in the exploitation of its wind resource (see Table 1.2). The reasons for this pioneering step are three-fold. First, its immediate neighbour, Germany, has been the leading market for some years, and some components for the German and, indeed, the Danish industry are made in Poland. Second, the wind resource is very similar to that of its immediate neighbour, with developments along the North Sea expected. And third, the political and commercial position within Poland is generally favourable for external investors. It would probably be premature to suggest that the level of development could be comparable to that in northern Germany, but commentators expect to see Poland undertaking large developments, continuing to participate in the industry in terms of manufacture and, perhaps, taking a leading role in the development of the infrastructure for some offshore wind farms. The activity associated with the planned offshore wind farm will result in a closer connection with the industry as a whole. Several leading WT manufacturers are considering the possibility of establishing Polish factories. A law exists requiring utilities to connect wind farms to the grid, but there is not yet any well functioning tariff structure set for the purchase of electricity.

Other New Member States

There is no doubt that there will be activity in several new member states, including the Czech Republic, the Slovak Republic and several Baltic states, as well as accession countries such as Romania. Wind energy can be a key tool in the process of cleaning up new member states' electricity production systems which are, at present, heavily reliant on nuclear power and fossil fuels.

Wind energy associations have been established in six new member states: Estonia[2], the Czech Republic, Hungary, Latvia, Poland[3], and Slovakia[4]. The objective of these associations is to establish greater wind capacities in their respective countries.

1.6 Export Market

The export market is extensive and includes both countries falling into the conscience market and those constituting the needs market. The figures in Table 1.7 from BTM Consult are computed on the basis that an export market is one outside the manufacturer's base country. The Table shows the total number of MW by manufacturer exported and installed domestically, as well as the resulting export percentage of their sales. As the report from BTM points out, these figures do not express actual cross border sales as some manufacturers are producing outside their base country and within the "export" market, for example Vestas manufacturing in Italy and GE Wind in Germany (national base of the now defunct Enron Wind bought by General Electric).

The existing export market for the EU-25 as a whole includes Norway, which recently installed two 40 MW wind farms. Key non-European markets include the US, Canada, India, Japan, China and Australia. Other markets set to emerge in the future are discussed in volume 5 chapter 2.

Table 1.7: Export of Manufacturers Worldwide in 2002

Company	Country	Installed 2002 (MW)	Domestic 2002 (MW)	Export 2002 (MW)	Export Share (%)
Vestas	Denmark	1,605	266	1,338	83.4
NEG Micon	Denmark	1,033	166	867	83.9
GE Wind	US	638	62	576	90.4
Bonus	Denmark	509	74	435	85.5
Enercon	Germany	1,334	1,103	230	17.3
Nordex	Germany	504	284	220	43.7
Lagerwey	Netherlands	114	4	111	96.9
Mitsubishi	Japan	30	5	25	84
Gamesa	Spain	854	839	15	1.8
Made	Spain	247	234	13	5
Dewind	Germany	86	80	7	7.8
Repower	Germany	223	221	2	0.7
Ecotecnia	Spain	120	120	0	0
Suzlon	India	60	60	0	0
Fuhrlander	Germany	47	47	0	0

Source: BTM Consult (2003).

1.7 Industry Segments

1.7.1 MANUFACTURERS – MEGAWATT SCALE

Nine of the top 10 turbine manufacturing companies are European. Wind energy is an outstanding European success story, with European companies manufacturing more than 90% of the turbines sold worldwide in 2002. In terms of electricity generation, in 2003 WTs generated 2.4% of EU-15 electricity, in Denmark this figure is 20%, while in Germany it is 6%, and in Spain in 2002 the figure stood at 4%.

Table 1.8 shows the top 10 megawatt scale Turbine suppliers in 2002.

1.7.2 MANUFACTURERS – SMALL TURBINES

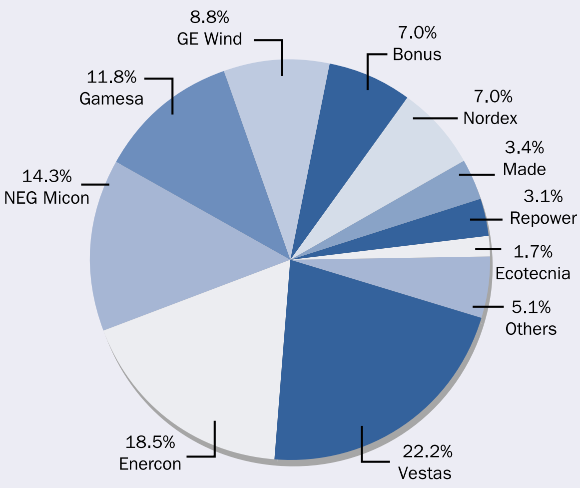
Smaller turbines may be installed in small wind farm configurations or as individual units. The vast majority of small WTs are less than 30 kW in capacity, with rotor diameters from 1 m up to around 15 m. Small turbines usually satisfy an individual power demand or property.

Table 1.8: Top 10 MW Scale WTG Suppliers 2002[5]

Company	Country	Accumulated MW 2001	Installed MW 2002	Share MW Installed 2002	Accumulated MW 2002	Share of Total MW Installed %
Vestas	Denmark	4,983	1,605	22.2%	6,588	20.6%
Enercon	Germany	3,206	1,334	18.5%	4,540	14.2%
NEG Micon	Denmark	4,510	1,033	14.3%	5,543	17.3%
Gamesa	Spain	2,125	854	11.8%	2,979	9.3%
GE Wind	USA	2,288	638	8.8%	2,925	9.1%
Bonus	Denmark	2,306	509	7.0%	2,815	8.8%
Nordex	Germany	1,473	504	7.0%	1,978	6.2%
Made	Spain	783	247	3.4%	1,030	3.2%
Repower	Germany	379	223	3.1%	602	1.9%
Ecotecnia	Spain	362	120	1.7%	482	1.5%
Others		3,677	371	5.1%	4,048	12.6%
Total		**26,092**	**7,436**	**103.00%**	**33,528**	**105.0%**

Source: BTM Consult (2003).

Figure 1.6: Top 10 MW Scale WTG Suppliers 2002



Source: BTM Consult (2003).

Included in this market sector are turbines that may be lowered in high winds, making them safe options for electricity generation in areas prone to storms. They may also be installed without the use of cranes - previously a limiting factor as many developing countries lack access to such hardware.

The small WT sector can be divided into five segments:

- Individual use
- Isolated communities and industries
- Connected to basic grids
- Connected to distribution grids
- Power source for water pumps

1.8 Wind Farm Developers

The Principal European Wind Farm Developers include:

Airtricity	Ireland
Elsam	Denmark
Energia Hidroelectrica de Navarra (EHN)	Spain
Italia Vento Power Corporation (IVPC)	Italy
National Wind Power	UK
Nuon Renewable Energy Projects	The Netherlands
P&T Technology	Germany
Renewable Energy Systems (RES)	UK
SIIF Energies	France
Windkraft Nord (WKN)	Germany

Airtricity is developing wind farms in the Republic of Ireland, Northern Ireland and Scotland. It is also developing the largest offshore wind farm in the world, off the Arklow coast in Ireland.

Elsam's offshore wind farm at Horns Rev comprises 80 wind turbines located 14-20 kilometres off the coast in the North Sea. It is the largest wind farm of its kind and produces enough electricity to supply 150,000 households, year-round.

At the end of 2002, Energia Hidroelectrica de Navarra (EHN) had installed a total of 1,380 MW. This represented approximately 30% of Spain's installed capacity. The group, at the time of writing, has plans for a further 1000 MW to be installed in the next few years. The wind energy production of the EHN group in 2003 was 1,376 GW hours, with a production share in Spain of 14%.

Italia Vento Power Corporation (IVPC) has 10 wind farms in the regions of Foggia and Benevento in Southern Italy, with an installed capacity of approximately 170 MW.

P&T Technology has primarily concentrated on securing wind farm locations under leasehold agreements. In addition, a range of wind farms has been constructed: since 2000, this amounts to approximately 210 MW.

Renewable Energy Systems (RES) has projects in the UK, Europe, North America, the Caribbean and Asia. At the end of 2003 RES had over 790 MW of wind energy capacity built and more than 6,000 MW under development.

SIIF Energies operates the largest wind farm in Portugal (Pinheiro and Cabril), is selecting potential sites in Europe (France, Italy, Spain) and Latin America (Mexico and Brazil), and has interests in the US and Scandinavia.

2 EMPLOYMENT IN THE WIND TURBINE SECTOR

Assumptions

1. The following chapters relate only to employment through manufacture, installation, operation and maintenance of wind turbines in EU countries. This excludes employment not associated with an input to the manufacture, installation and maintenance of turbines.

2. The total direct and indirect employment for the EU is calculated based on the installation of turbines in Europe. Employment in Europe and elsewhere associated with exports of turbines outside the EU is not included.

2.1 Direct and Indirect Employment Effects

The production structures of wind turbine (WT) manufacturers vary considerably. Some, for example, manufacture components, including blades, whereas others design and assemble components purchased from different sub-contractors. Because sub-contractors and component suppliers are a key link in the WT manufacturing process - from basic raw materials to the finished product - their inclusion in this analysis provides a more accurate assessment of the employment effects of the WT manufacturing sector in the EU as a whole. This measure is based on national account statistics (Eurostat, 2000) and input-output methodology.

Employment in WT manufacturing includes both direct as well as indirect employment.

2.2 Direct Employment in Wind Turbine Manufacturing

Within the EU, employment in manufacturing is concentrated in a few countries, with Germany, Denmark and Spain accounting for more than 90%. The WT manufacturing sector's share of total manufacturing employment is, on average, approximately 0.1% for the EU-15, but for countries with a large WT manufacturing sector, this share may be much higher. For example, in Denmark in 2002, the wind industry's share of total manufacturing employment was 1.2%, more than cement and steel production.

Figures for direct employment in Italy and the Netherlands have not been included in this analysis due to lack of data, although some WT manufacturing does take place in both these countries.

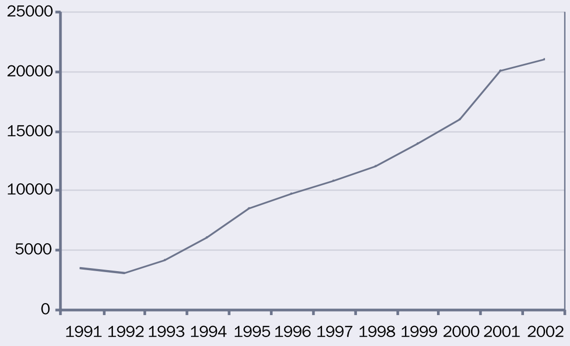
Employment throughout the manufacturing sector has been increasing considerably in the EU since the beginning of the 1990s, as exemplified by the Danish experience.

Table 2.1: Direct Employment in WT Manufacturing in Europe for 2002

Employment within EU	Turbine Manufacturing	Share
Total	30,946	100%
Austria	720	2.3%
Denmark	6,624	21.4%
UK	1,150	3.7%
France	756	2.4%
Germany	10,439	33.7%
Portugal	60	0.2%
Spain	11,197	36.2%

Source: EWEA (2003b)

Figure 2.1: Direct and Indirect Employment in Danish Turbine Manufacture



Source: Danish Wind Industry Association (2002).

Table 2.2: Direct Employment in WT Installation in Europe for 2002

Employment within EU	Turbine Installation
Austria	213
Denmark	1,500
UK	800
France	340
Germany	5,771
Greece	30
Portugal	100
Spain	4,500
Others	1,395
Total	14,649

Source: EWEA (2003b), own calculations.

The Danish Wind Industry Association estimates that direct and indirect employment in WT manufacturing in Denmark increased from around 2,900 in 1991 to 21,000 in 2002, a relative surge not experienced by any other manufacturing industry. It has brought WT manufacturing to the fore as an important sector for the Danish economy, and has contributed to reducing unemployment.

In recent years, the growth of employment in WT manufacturing in Germany and Spain has been higher than in Denmark with nearly a doubling in the numbers employed over the period 2000 to 2002.

2.3 Direct Employment in Wind Turbine Installation

WT installation itself offers significant employment opportunities, although there are differences in employment effect depending on the type of WT, the location and the country of installation. An estimate of the employment impact of WT installation is given in Table 2.2.

The employment effects of WT installation in other EU countries has been calculated, based on the average employment per MW installed. The variation in employment between the countries is shown in Figure 2.2, reflecting the same differences as those seen in the cost variation for installation included in the volume on costs and prices (Volume 2). As with costs, installation seems to require the highest employment figures in the UK.

The UK figures are considerably higher than earlier Danish studies suggest (Krohn, 1998 and Danish Wind Industry Association, 1995 and 1997). In these studies, the global employment figures for installation were found to be in the region of five individuals per MW in 1998. The largest part of installation activity is construction. For this activity, direct employment accounts for around two-thirds of the total employment related to the construction part of installation. The multiplier shows total employment in the EU associated with €1 million of output in the construction sector, including employment in all the sectors supplying inputs to the construction sector. Furthermore, the employment content will be reduced as a result of cost reductions achieved from 1998 to 2002. The employment factor used for countries not included in the Figure is three individuals per MW. This figure is within the range of the averages included in Figure 2.2.

Figure 2.2: Direct Employment Associated with WT Installation in Selected European Countries for 2002

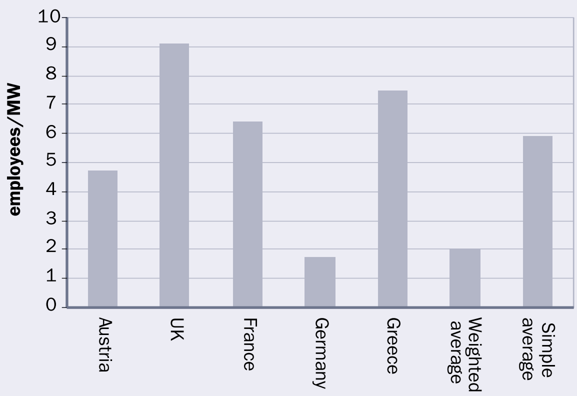


Table 2.3: Direct Employment in Maintenance in Europe for 2002

Employment within EU	Maintenance
Austria	60
Denmark	300
UK	50
France	44
Germany	1,010
Greece	90
Portugal	30
Spain	966
Others	218
Total	2,768

Source: EWEA (2003b), own calculations.

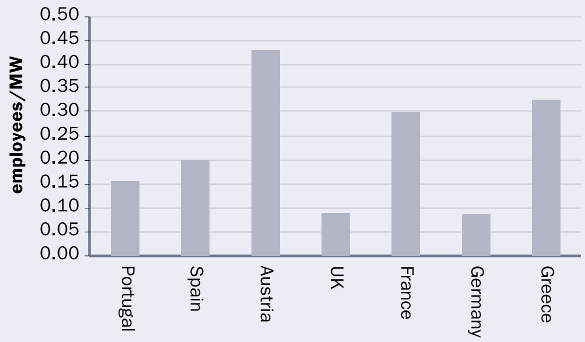
The high employment figure for WT installation in the UK can be partly attributed to the remote siting of wind parks that require quite extensive road construction and grid infrastructure investment.

2.4 Direct Employment in Maintenance Activities

Employment related to operation and maintenance (O&M) will increase considerably as installed capacity increases. However, present employment related to this activity is still small compared to that associated with manufacturing and installation.

The O&M employment calculation for the "other country" group is based on a conservative value of 0.1 person per MW of installed capacity in each of these countries (see Figure 2.3). The fluctuation in employment per MW capacity in Figure 2.3 is quite high. This could partly be caused by the difference in age of installed turbines or could be a function of wind turbine size and wind park grouping.

Figure 2.3: Employment in Maintenance of WTs in Selected European Countries for 2002



It seems from Figure 2.3 that maintenance is more employment-intensive in countries with the least installed capacity, namely Austria, France and Greece. It is noticeable that the UK has low maintenance employment figures compared to other countries, whereas its installation-related employment is the highest in the EU.

2.5 Indirect Employment in Manufacturing

Individual assessments of indirect employment in WT manufacturing have been made by the national associations in Denmark and Germany. For Germany, an indirect employment total of approximately 24,000 people for 2002 has been estimated and, for Denmark, 14,500.

Alternatively, the estimate of indirect employment content within different sectors is based on national account statistics from Eurostat's input-ouput tables (2002).

Input Structure for WT Manufacturing

Firstly, we have to establish the composition of intermediate inputs to the manufacture of WTs. The input structure varies a great deal both for individual manufacturers and for EU member states. The following is based on responses received from the national associations and earlier Danish data:

Table 2.4: Input Structure in the Danish WT Manufacturing Sector

Input structure	Denmark 1995 (%)
Generator	4
Gearbox	12
Rotor	18
Tower	18
Brakes	1.5
Electronic	4
Nacelle (remainder)	42.5
Total	**100**

The contributing sector of the 25 sector level data from the EU input-output table (see Appendix J) have been associated with the production inputs by judgement and based on Danish studies (Krohn, 1998; Danish Wind Industry Association, 1995 and 1997). Only limited data for the input structure of WT manufacturing in different EU countries are available.

Calculations of Indirect Employment in Manufacturing

All calculations in this section are based on installation of turbines in Europe and not the actual turnover figures which were not available. Estimated turnover is based on the investment cost for wind turbines given in Volume 2.

Calculated direct and indirect employment can be compared to direct employment figures reported by national associations. Reported direct employment is aggregated at European level and constitute 60% of the total direct and indirect employment totals found in Table 2.5. This is partly caused by omitting from the calculations the export element of turbine manufacturing activity in Europe.

For 2002, the figure for total European manufacturing and installation employment is closer to 12 individuals per MW installed. The global employment effect is somewhat higher than 12 per MW, because of imports of raw materials, etc. to Europe, which create employment abroad.

The calculations here might understate employment slightly because of the high import quota implicit in the employment multipliers for Europe.

2.6 Indirect Employment in WT Installation

Again, the direct employment reported by the national wind associations varies a great deal per MW installed capacity, and has, in a number of cases, been difficult to estimate. Therefore, a calculation based on the different elements of installation activities has been carried out in order to provide an alternative measure of employment. The different elements of installation activities have been estimated from national association data and other sources (Danish Wind Industry Association, 1997).

The question of divergence in installation cost composition between onshore and offshore wind turbines has not been addressed. If the cost composition is identical for the two locations, the different level of installation costs has no effect on employment per € million of installation costs.

Table 2.5: Calculation of Direct and Indirect Employment for WT Manufacturing

	Input Structure	Contributing Sector	Employment Multiplier 1995	Employment Multiplier 2002	Employment 2002
Generator	4%	Electrical goods	14.22	10.81	1,836
Gearbox	12%	Industrial machinery	13.6	10.33	5,268
Rotor	18%	Rubber and plastic products	14.27	10.84	8,292
Tower	18%	Metal products	19.84	15.08	11,528
Brakes	1.5%	Industrial machinery	13.6	10.33	659
Electronic	4%	Office and data processing machines	10.72	8.15	1,384
Nacelle (remainder)	42.5%	Industrial machinery	13.6	10.33	18,658
Total	**100%**				**47,625**

Source: Eurostat (2003).

In respect of the cost components, each one must be related to the national accounts sector that supplies the service. As construction is the major employment contributor during the installation phase, there will only be minor differences in the employment effect, even if the composition of cost differs between the countries. The aggregate employment effect is, however, also dependent on possible differences in the employment content for each € cost in the different countries. Labour productivity varies among EU member states, especially for non-traded goods such as construction activities and services. This aspect is not included in the calculations that use EU level statistics for labour content in construction.

Calculation of Indirect Employment in Wind Turbine Installation in Europe

1995 EU data for employment as part of the national accounts has been used with calculated multipliers as shown in Appendix J. The multipliers reflect the difference in indirect and direct employment for the various elements of WT installation. For example, construction of the foundations directly and indirectly employed 13.78 individuals per € million in 2002.

The basic assumption behind the calculation is that the composition of installation costs as an EU average did not change from 1995 to 2002. For the employment multiplier, an assumption of a 1.5% increase in labour productivity per year has been made. This implies that the employment multiplier per current cost unit (€) has decreased by around 4% per year.

2.7 Total Direct and Indirect Employment (Manufacturing, Installation and Maintenance in Europe)

The calculations in sections 2.2 - 2.6 provide an estimate for employment in the wind industry in Europe, including all activities such as sub-contractors, etc., associated with the installation activity in the EU.

The figures relating to maintenance employment have been adjusted to include indirect employment as it is estimated that only around 25% of maintenance costs are related to wages. If the manufacturing employment element relating to turbine export had been included, the total employment figures would have been somewhat higher.

Finally, it must be stressed that total employment relating to wind is considerably higher than the 72,000 given for Europe in Table 2.8, not only as a result of production and installation outside the European region, but also due to the indirect employment effects of imported inputs to European WT manufacturing.

Table 2.6 Installation Costs for Wind Turbines 2002

2002	Foundations	Infrastructure Roads, etc.	Electrical Installations, etc., Connections	Grid Reinforcement	Other Installation Costs	Total Installation Cost Excluding Turbine
France	34%	14%	42%	0%	9%	100%
Denmark (1995)	16%	5%	55%	16%	9%	100%
Spain	23%		54%		23%	100%
Portugal	22%	22%	22%	33%	0%	100%

Table 2.7 Calculation of Direct and Indirect Employment for Turbine Installation in Europe for 2002

	Average Share of Costs 2002 (Simple Average)	Contributing Sector Multiplier 1995	Employment Multiplier 2002	Employment 2002	Employment
Foundations	24%	Construction	18.14	13.78	4,706
Infrastructure Roads etc.	14%	Construction	18.14	13.78	2,665
Electrical Installations etc., Connections	40%	Construction/ Industrial machinery	15.87	12.06	6,790
Grid Reinforcement	16%	Construction	18.14	13.78	3,210
Other Installation Costs	6%	Other Market Services	57.61	43.78	3,780
Total	**100%**				**21,150**

Table 2.8: Total Direct and Indirect Employment Related to WT Manufacture in Europe for 1998-2002

	Employment in WT Manufacturing (for Home Market)	Employment in WT Installation	Employment in WT Maintenance	Total Employment
1998	16725	7400	950	25,075
2002	47625	21150	3500	72,275
Growth 1998-2002	185%	185%	268%	188%

Source: Own calculations based on installation of WTs in Europe and Eurostat (2000).

3 EMPLOYMENT PREDICTION AND METHODOLOGY

The history of employment relating to wind energy in the EU is very positive. Employment has been growing rapidly in recent years, and the sector has thus contributed to reducing unemployment in the region.

A broader understanding of employment in the wind energy sector is, however, not straightforward as there is great uncertainty about what this employment covers. Here, we have chosen to use a notion of direct and indirect employment and to separately examine the manufacture of turbines, their installation and employment arising from O&M. The use of different terms and the applied methodology is described in the section below.

The objective has been to examine the magnitude of employment in the sector directly producing WTs and employment associated with the production of inputs to turbine manufacturing. This is not a calculation of the employment created by WT manufacturing, as parts of the workforce in the WT sector today would certainly have been employed in other activities had the wind sector not existed. A similar approach would be to evaluate the net employment effect by deducting the employment associated with alternative electricity producing technologies from the employment associated with wind-based electricity production. This approach would result in a net employment lower than the gross employment associated with wind-based electricity production. The net effect is, however, assumed to be of a considerable size as the employment content is somewhat higher in WT manufacturing and installation.

Some might argue that the input-output approach does not address the wider employment effects of WTs. The argument is based on the fact that the income generated in the sector via wages paid and rents extracted will contribute to demand for other goods that, again, will generate employment. However, such arguments should lead to a consideration of how WT development is being financed. The funds used for WT investment might have been invested in other electricity producing equipment, or even in totally different sectors. These investments would have created jobs, as in the wind sector, and the net effect may have been higher or lower depending on the labour intensity of the activities in which the investment takes place.

One way of addressing these more complex economic linkages is to use macroeconomic general equilibrium models. However, these models very seldom include details of WT manufacturing.

Consequently, this work has focused on employment in activities directly producing WTs and those supporting and supplying to the wind sector. This is, therefore, not an attempt to address the employment created by the WT sector, or to give an overall figure for the *net employment* effect. Instead, this chapter tries to estimate the employment directly or indirectly associated with the WT manufacturing sector.

3.1 Direct and Indirect Employment

Direct employment relates to employment within WT manufacturing companies and sub-contractors whose main activity is supplying WT components etc., for example blade manufacturers. However, companies producing intermediates or components for the WT industry are deemed as providing indirect employment if this is only a minor part of their activities.

There is an important distinction between national and global employment patterns in WT manufacturing. Direct and indirect employment at national level does not include employment associated with imports. For small, open economies, this means that there will be a large difference between national and global employment content. For a larger country, or for the entire EU, the difference between national and global employment content will lessen as trade flows between countries are consolidated, with the effect being included in indirect employment at EU level. If direct and indirect employment effects for EU countries are amalgamated, this figure will be less than the direct and indirect employment effects calculated at the EU level.

3.2 Input-Output Methodology

The calculation of employment effects is based on input-output methodology used by economists. The basic idea

is to include the effects from suppliers of inputs (raw materials, etc.) to obtain a better measure of the total effect of the activity in question - in this case, WT manufacturing. Direct employment in manufacturing activities having WT-related products as their main output is seen as the first link in a chain of employment effects. Secondary links are employment associated with the production of components and raw materials used in the production of turbines. These secondary effects continue with employment used for extracting raw materials needed for products that are later used as WT components. The secondary effects diminish the further back in the production chain we go.

The employment used is the number of employees per output unit measured in € million.

Example:

- 1 MW installed capacity at a price of €1 million
- €0.75 million of wind turbine output in 2002 (the rest is installation costs, etc.):

Direct employment + indirect employment:
€0.75 million x 7.94 employees per € million

+ level 1 input: (input from sector "industrial machinery" x industrial machinery employment coefficient per € million output) + input from sector 2 x employment coefficient + input sector 3…

+ level 2 inputs: (input from sector 2 to sector "electric machinery" x employment coefficient in sector 2 per € million output in sector 2…

The calculation could continue indefinitely but, instead, we use the input-output methodology for calculating the inverse matrix and multiplying by the employment coefficients. The employment coefficient is the direct employment per output in the sector.

We have in this case calculated the direct and indirect employment effects from Eurostat's national account statistics for 1995. By using input-output methodology, we can calculate the necessary production increases in 20 sectors of the economy to produce an additional €1 million of output for each of the sectors. These production changes are then multiplied by the direct employment in each of the 20 sectors per € million of output.

To reach 2002 levels of employment multipliers, the calculated figures for 1995 must be projected forward. This can be done individually for the multipliers of all sectors, for example, by using trends in multipliers, or by assuming "productivity" increases. The latter approach was chosen here.

National Versus EU Employment

One important aspect is the distinction between national and global employment effects. If considered nationally, the employment effect would include the direct employment effect, but all the indirect effects would exclude the part of inputs that are being imported. Thus, the smaller the country, the larger the imported share of production inputs. In this way, the indirect employment effect is less for small, open economies. For larger countries or for a group of countries such as the EU, the indirect employment effect is larger as a much higher fraction of the inputs to the sector will originate within the EU. Then, if all the countries added the national (direct and indirect) employment effects, the sum of these would still be less than the direct and indirect effects for the entire EU, as this also includes employment effect of the intra regional trade flows.

Using Input-Output for Projections of Employment

The input-output methodology used for projections of employment allows the use of different assumptions on developments in productivity for different sectors, as well as possible shifts in the composition of inputs from other sectors in the manufacturing of WTs.

The productivity and composition changes are closely linked to assumptions that can be made about the overall cost reduction of WT manufacture. There must be consistency between the assumptions made on cost reductions and on reduction in employment per MW.

3.3 Projection/Prediction Parameters

In order to make consistent projections of employment, there are a number of parameters that have to be addressed. These include activity parameters as well as parameters of technological progress.

Turnover or Indicators for Output in MW

The total turnover for the WT manufacturing sector in the EU can be projected using a variety of methods. One method is to use the installation forecast for MW globally and then add the European market share of manufacturing (see below). Then, there needs to be a conversion from MW installation to turnover in € where 1 MW installed capacity might equal €1 million at today's prices, but the cost reductions should reduce this figure by at least 2% a year (according to experience curve and cumulated installation). These figures are in fixed price terms, which means that the cost of WTs decrease by 2% annually, compared to the price of other goods and services.

However, this also includes an assumption of an unchanged mix of WT categories between those with low investment cost relative to production and those with higher investment cost per MW, but higher production per installed MW. In some cases this can be observed as the larger machines have higher investment cost per MW, but lower investment cost per produced kWh.

Share of Production Taking Place in Europe

As the European market dominates both in terms of annual installed capacity, and in terms of manufacturing activity, the installation has been equal to European production and then some additional production for exports could be added. The share of worldwide production taking place in Europe will in the future be reduced and this development should be addressed by making explicit assumptions. Even though market shares are still high for the European producers, a larger fraction of manufacturing will take place locally at the markets where they are to be installed.

Labour Productivity

Apart from the cost reductions per MW, there will be increases in labour productivity. In the long term, a 2% annual increase in labour productivity (employment per output unit in fixed prices) is a reasonable assumption for the European economies. This also reduces the future employment effect per MW of installed wind capacity.

Input Composition in WT Manufacturing

Finally, the composition of inputs in WT manufacturing can be addressed. In many cases, there will not be the necessary amount of information to separately project this parameter. Thus, only overall cost reductions will be projected and equally distributed on all inputs. This implies a constant technical coefficient in the input-output system.

3.4 Sensitivity – Main Parameters

For all projections, there is a need to identify the most important parameters with respect to their possible variations and their impact on total employment in the sector in Europe.

Wind Turbine Market Growth and Regional Distribution

Future growth of the WT market is the main assumption for employment as it is clearly the driver for production. However, it is associated with some uncertainty since the market size in 15 years' time has a possible variation of a factor of 10.

Productivity/Cost Reductions

The sensitivity of employment projections to assumptions of cost reductions is less obvious than the sensitivity to market projection. In the longer term, assumptions about technological progress and cost reductions are, however, of a considerable accumulated size, and have a large impact on employment forecasts. With experience curves suggesting a 15% cost reduction per electricity output and

a 10% cost reduction for turbine costs for every doubling of installed capacity, these cost reductions must partly attribute to reductions in the use of labour input in the production of turbines. Moreover, the installation of turbines will become less labour intense due to productivity growth within all sectors of the economy.

The link between cost reductions and accumulated installation makes the cost reductions sensitive to wind market development, in addition to the uncertainty that relates to the experience curve itself. Cost reductions that reduce labour input in manufacturing are for installed MW and not relative to electricity production. Therefore, it is the 10% cost reduction mentioned above that is the relevant figure here. If market growth corresponds to a doubling of installed capacity in five years, then cost reductions per installed MW will decline by approximately 2% per year. This figure might just as well be 1% or 3% depending on market expansion and the "real" experience curve.

European Production Share

As wind energy develops and becomes more widespread, the European share of total installation will decline. Even though European producers will maintain a high market share, a larger part of their manufacturing activity will take place outside Europe. These foreseeable changes are very difficult to project, depending as they do on both market forces/demand and strategic developments/reorganisation of the WT manufacturing sector. The most likely development is that a larger proportion of European manufacturers' activities will take place outside Europe. The impact will be to reduce the growth of European employment within the WT manufacturing sector. European market share and location of production facilities is thus an important parameter for sensitivity analyses.

If long term projections are made, it is unclear how much European companies' manufacturing will take place in the country of installation.

4 SCENARIOS FOR EMPLOYMENT IN THE WIND TURBINE SECTOR

Based on scenarios for the future development of wind in Europe and globally, it is possible to identify corresponding employment scenarios.

4.1 Projection of Employment based on Wind Energy Installation in Europe and Globally

Based on assumptions for the parameters, etc. described in chapter 3 above, it is possible to develop a scenario for European employment in the wind sector. Here, a very simple scenario with the majority of composition parameters remaining unchanged will be presented.

Some basic assumptions are identical to those in *Wind Force 12* (EWEA, 2003c). The scenario projects European and global installation activity in 2020 as follows:

- Annual global installation will increase to approximately 150,000 MW in 2020, of which 15,000 will be in Europe.
- The European share of global WT manufacturing is assumed to decline to 25% by 2020.
- Turbine manufacturing input is assumed to have constant composition in Europe.
- Installation activity is assumed to have constant composition (no change from increased offshore expansion).
- Cost reduction is assumed at a rate of 2% annually.

An annual 2% growth in labour productivity is assumed for both manufacture and installation.

In this scenario, where a great deal of the employment increase will come from expansion of markets outside Europe, it will be mainly increases in manufacturing employment that are responsible for overall employment growth.

Manufacturing Employment

Global installation of 150,000 MW in 2020 and a European share of 25%, including those for the European market would require:

€1 million per MW in 2002 reduced by 1/1.02^18. This equals a total investment cost in 2020 of €26,256 million, of which 75% will consist of WTs produced in Europe (installation will not generate employment in Europe apart from that included below). WT manufacturing in Europe will be €19,692 million.

The employment multiplier for 2002 of 11.21 employees per € million of activity has to be reduced by the general productivity increase of 2% annually resulting in a multiplier for 2020 of 7.79 person per € million.

The resulting employment in WT manufacturing for the year 2020 will therefore be 7.79 x 19,692 = 153,400 employees.

Installation Employment

In 2020, 15,000 MW will be installed in Europe. Installation employment from 2002 has to be adjusted for the general increase in labour productivity and the reduced employment input that has contributed to lowering the total costs of installing WTs. This means that the cost reduction is assumed to be at a similar level for both manufacturing and installation.

Following on from this, the employment multiplier for installation in 2002 has to be adjusted. We assume that the composition between the components of installation activity is unchanged from Table 2.7, and that the employment multipliers for the contributing sectors all follow the same trend with a 2% annual reduction.

15,000 MW installed in Europe at a total cost of €1 million per MW in 2002 reduced by 1/1.02^18 equals a total investment cost in 2020 of €10,502 million.

Installation cost constitutes an unchanged share of 25% of this amount and the employment multiplier for installation is 14.89 in 2002 reduced with the annual productivity increase of 2% resulting in a multiplier for 2020 of 10.42 per € million of installation activity.

Direct and indirect employment in European WT installation for 2020 would therefore be 27,400.

Maintenance

By 2020, an accumulated 230,000 MW will have been installed in Europe. With the conservative value of 0.1 employees per MW in 2002, this would mean a considerable increase in employment for maintenance. The employment content also has to be adjusted for the general productivity increase of 2% annually. In maintenance, only the general productivity increase is assumed and there are no additional cost reductions.

With these assumptions, employment in O&M in Europe in 2020 would be 16,100.

Employment Scenario Results

For the scenario described above, employment in 2020 has increased considerably from that in 2002.

Total employment related to manufacturing, installation and O&M in Europe will be 196,900 in 2020 for this scenario, based on a considerable expansion of wind energy.

This is more than a doubling of today's employment in the European sector, but it is not the full employment story. However, it must be stressed that employment growth will be even higher in the regions outside Europe where installation growth is also highest. The employment effect in these countries will probably be even higher than in Europe due to lower productivity and wages.

European Scenario for Employment up to 2010

To illustrate the employment effects of wind turbine installation in Europe another scenario is included. Calculations are performed according to the above scenario (see Table 4.1). This scenario includes only employment effects in Europe from installation activity in Europe. The European WTs are thus assumed to be entirely manufactured in Europe. Furthermore the employment effect from export of European produced WTs is excluded.

Table 4.1 illustrates that even with moderate growth in WT installation, employment will be stable around the present level if export activity is not included. The reduction in employment associated with manufacture of WTs is balanced by the increase in employment associated with maintaining the already installed capacity.

Table 4.1: Direct and Indirect Employment Associated with European WT Installation

	2003	2004	2005	2006	2007	2008	2009	2010
Europe Cumulative Installed MW	29,116	35,216	41,516	47,966	54,566	61,316	68,216	75,216
Europe Annual Installation	5,900	6,100	6,300	6,450	6,600	6,750	6,900	7,000
Employment Manufacturing	45,300	45,017	44,687	43,975	43,250	42,515	41,772	40,732
Employment Installation	20,520	20,799	21,060	21,139	21,206	21,263	21,309	21,194
Employment Maintenance	2,854	3,385	3,912	4,431	4,942	5,445	5,939	6,420
Total	**68,674**	**69,201**	**69,659**	**69,545**	**69,398**	**69,223**	**69,020**	**68,346**

5 DEVELOPMENT & INNOVATION

Development and innovation have contributed to the fast progress of the WT manufacturing sector. One of the reasons for this is the ability of the sector to adapt technology from other sectors.

Technology transfer from the WT industry to other sectors has been more modest. One example, however, from Denmark, is the expansion of small-scale machine manufacturers to larger companies, based on their activities in the wind industry. These small companies, often characterised as “smiths”, have expanded their expertise with the technology developed for the wind sector. As these companies have often been located outside traditional business centres, this development has been seen as very positive trend to broader industrial development.

Along with the manufacturing of WTs, a range of specialised service suppliers for transport, installation, maintenance and insurance has developed.

One promising technology cross-over area is in aerodynamics where the use of new materials and the cost reductions associated with them has transferred from the aeronautic industry to WT blade manufacturers.

An EU-funded research project (Neij *et al.*, 2003) has analysed the possibility of using experience curve forecasts from the wind energy sector to predict possible developments within other renewable energy sectors. This is based on the idea that some of the technological innovations found for wind energy technology can be applied to other fields.

The turbines manufactured from the mid 1980s until the late 1990s were mainly constructed using standard components, the only major exception being the blades, which were designed and constructed for specific turbine use. But in the late 1990s the turbines had grown so large in size and were being manufactured in such large numbers, that special components started being designed and manufactured for turbine use only (see below).

Ball Bearings

As mentioned above, components such as ball bearings used for WTs were, until recently, mainly standard products. But with the development of 2-3 MW turbines it became necessary to produce special large ball bearings, designed to the specific requirements of WTs.

Another niche area in this industry is the bearings that support pitch-regulated blades. Because of the very small rotation angle of these WT components compared to their use in other kinds of machinery, the loads on these bearings are very high. To limit wear, specialised bearings are being developed that perform well within small rotation angles.

Blades

In turbine up-scaling, the weight of components such as blades, nacelles and towers is of the utmost importance. To keep loads down it is necessary to keep weight down. This is especially important for the blades; the longer the blades, the more the need for lightweight materials. Initially, blades were manufactured using glass fibre materials with weight reduced mainly through design improvements. But to manufacture blades longer than 40-50 m for 2-3 MW machines requires the use of reinforced composites. One of the most common new blade materials is glass fibre reinforced with carbon fibre, but hybrid versions using glass fibres and wood are also being used. Finally, a number of new technologies are being introduced to blade production.

Gearboxes

The gearboxes used in turbines were also, until recently, standard components. But the large numbers of turbines produced nowadays, and the need for lighter materials to reduce the weight of the nacelle and thus the loads on larger turbines have driven production of lighter and more compact gearboxes designed specifically for WTs.

Installations of Offshore Turbines

Installation of offshore turbines presents a fresh challenge and demands a new approach. Specially designed and constructed vessels have been developed that can carry two or more turbines from the nearest harbour to the offshore site and erect the turbine towers, nacelles and rotors. These vessels are continuously being improved to carry more turbine components, thus reducing the installation time.

These examples are all closely related to the WT sector itself; technology cross-over to other sectors should not be neglected, and deserves more research activity.

Endnotes

1 A form of financial support mechanisms instigated by some national governments to assist in the development of renewable energy technologies.

2 See www.tuuleenergia.ee (for further information).

3 See www.visventi.org.pl (for further information).

4 See www.save.apis.sk (for further information).

5 It should be noted that BTM Consult and EWEA figures of installed capacity vary slightly due to different methodologies in their compilation.

WIND ENERGY - THE FACTS

VOLUME 4

ENVIRONMENT

Acknowledgments

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1 INTRODUCTION TO VOLUME 4 - ENVIRONMENT

Sustainable development is an issue of prime importance both now and in the future. As defined by the Brundtland Commission in 1987, sustainable development is *"development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* (World Commission for Environment and Development, 1987).

Environmental pollution and emissions of CO_2 caused by the use of fossil fuels constitute a significant threat to sustainable development. A major contributor to these emissions is electricity generation based on fossil fuels. The Intergovernmental Panel on Climate Change (IPCC) predicted in its last report (IPCC, 2001) that human-induced greenhouse gas (GHG) emissions will lead to a substantial increase in GHG concentrations in the atmosphere causing increased radiative forcing, with CO_2 contributing about 50% to this anthropogenic greenhouse effect. Without drastic emission reductions of CO_2 and other GHGs a significant change in the world's climate is inevitable unless energy systems and sources are changed as soon as possible. In addition to the problem of climate change, emissions of SO_2, NO_x and other pollutants from energy conversion processes in conventional electricity generation cause substantial regional damage to human health and the environment.

As most renewable energy sources, such as wind power, emit neither GHGs nor other pollutants such as SO_2 or NO_x, they will be the basis of any long-term sustainable energy supply system (Fischedick *et al.*, 2000). The large-scale use of renewable energy sources is essential if the necessary reductions in CO_2 and other emissions from electricity generation are to be met and if sustainable development is to be achieved.

The following chapters provide a summary of our current understanding of the direct and indirect environmental impacts associated with wind energy, as well as its economic (external) costs and those associated with avoiding the environmental and health impacts of conventional electricity generation by substitution with wind energy. Public acceptance of wind energy is crucial for its successful introduction. Thus, a public acceptance analysis is included in this volume, showing the main elements affecting public acceptance along with the results of some recent surveys from a selected number of EU countries.

In the first part of this volume, the concept of the external cost of energy is introduced. As environmental and health costs caused by energy conversion processes are not taken into account in the calculations of the producer or consumer of energy, economists call these costs "externalities". Analysis of these externalities enables the environmental and health benefits of wind energy compared to fossil fuels to be expressed in economic terms.

Subsequently, the benefits of wind energy are discussed. In contrast to fossil fuel fired power plants, wind energy converters cause virtually no operational emissions. There may be minor losses of lubricants from the turbine gearbox but these do not normally find their way into the environment. Being a clean energy source is the main advantage of wind energy when compared to conventional electricity generation. Indirect emissions, which result from manufacturing, installation, maintenance and removal, do play a very small part in this equation. Nevertheless, these have been taken into account in our analysis.

By means of external cost analysis, it is possible to quantify the environmental and health costs of the different electricity generation technologies. To compare the external costs of wind energy and of the substituted conventional electricity generation, we need to analyse and calculate them. The net avoided external costs of wind power are the external monetary benefits of wind energy. Only if we combine these with a comparison of the internal costs of wind energy and conventional electricity generation substituted do we get a fair picture of the competitive situation of wind energy.

In chapter 1, a review of the external cost concept is given. In chapter 2.1 a short description of the background for the calculations of avoided emissions and avoided external costs from the use of wind energy in the EU and in new member states is presented. In chapter 2.2, a short overview of electricity generation structure in each country, as well as a very brief description of the national environ-

mental policy frameworks is given. In this chapter the total and specific emissions of CO_2, NO_x and SO_2 are given for each country.

Calculations of external costs of standard air pollutants are performed by the EcoSense model, which has been developed as part of a major European Commission research effort on the analysis of external energy costs. This model is briefly introduced in chapter 2.3, but a short description of the input data and modelling assumptions used are given here. Chapter 2.4 reports on the emissions and external costs which can be avoided by extending the use of wind energy in the EU and in the new member countries (Turkey, Romania and Bulgaria are also included). These are reported as total as well as specific values.

To facilitate a comparison of future and present calculations of emission and external cost reductions due to the use of wind energy, a standard methodology for calculating emission reductions has been designed. This is reported in chapter 3.

Based on the future diffusion of wind energy on the one hand and on improvements in conventional electricity-generating technologies on the other, mid- and long-term emission reductions are forecast in chapter 4.

Chapters 5 and 6 report the public debate on wind energy, as far as this has been subject to scientific research and as far as the results of this research are available. The debate considers such issues as visual intrusion, noise, and interference with birds, and their influence on public acceptance.

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1 EXTERNALITIES

1.1 Introduction to Externalities

The economics of wind energy show that the capital costs, O&M costs, taxes, insurance and other costs, along with the expected profit, comprise the price of a kWh of electricity. Depending on the market situation and, perhaps, additional promotional measures, wind energy may or may not be competitive. It is generally appreciated that although wind energy and other renewable energy sources have environmental benefits compared to conventional electricity generation, these benefits may not be fully reflected in electricity market prices. The question therefore is: "Do market prices for electricity give an appropriate representation of the full costs to society of producing electricity?"

The externalities of energy generation deal with these questions in order to estimate the hidden benefits/damages of electricity production not accounted for in the existing pricing system. The costs are "external" because they are paid for by third parties and by future generations. In order to establish a fair comparison of the different electricity production activities, all costs to society, both internal and external, need to be taken into account.

The following sections explain the basic concepts and describe present knowledge about the external costs of electricity generation. Chapter 2 will report on specific external costs, which can be avoided in the EU by the use of wind energy.

1.2 Definition and Classification

Looking at the foundations of externalities, the different definitions and interpretations are based upon the principles of welfare economics, which state that economic activities by any party or individual making use of scarce resources cannot be beneficial if they adversely affect the well-being of a third party or individual (Energy Information Administration, 1995).

From this, a generic definition of externalities is *"benefits and costs which arise when the social or economic activities of one group of people have an impact on another, and when the first group fails to fully account for their impacts"* (European Commission, 1994). Externalities are not included in the market pricing calculations and it can be concluded that private calculations of benefits or costs may differ substantially from society's valuation if substantial external costs occur.

Externalities can be classified according to their benefits or costs in two main categories: non-environmental and environmental externalities. Table 1.1 lists examples of these externalities of energy conversion (European Commission 1994; Centre for Energy, Policy and Technology, 2001):

Table 1.1: Classification of Externalities

Environmental and Human Health	Non–Environmental
• Human health (accidents, disease)	• Subsidies
• Occupational health (accidents, noise, physical stress)	• Research and development costs
• Amenity impacts (noise, visual impacts, odor)	• Employment
• Security and reliability of supply	• Effects on GDP
• Ecological impacts (acidification, eutrophication, soil quality)	
• Climate change (temperature rise, sea level rise, precipitation changes, storms)	

The environmental and human health externalities can additionally be classified as local, regional, or global, with the latter. referring to climate change caused by emissions of CO_2 or destruction of the ozone layer by emissions of CFCs or SF_6. Non-environmental externalities refer to hidden costs, such as those borne by tax-payers in the form of subsidies, research and development costs or benefits like employment opportunities, although for the latter it is debatable whether this constitutes an external benefit in the welfare economics sense.

1.3 Importance of Externalities

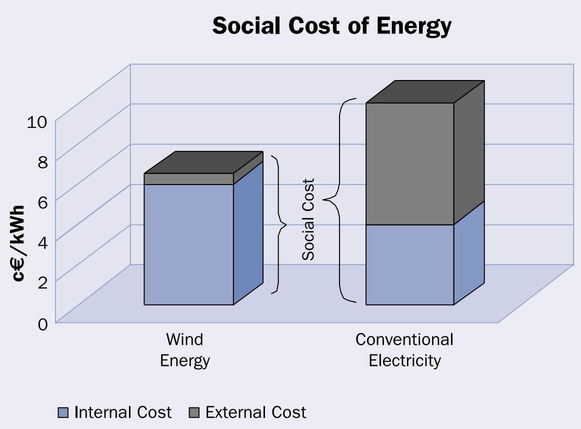
As markets neither include external effects nor their costs, it is important to identify external effects and to monetise the external costs of different energy systems if these are of a similar order of magnitude as the internal costs of energy, and if these external costs vary substantially between competing energy systems, like conventional electricity generation and wind energy.

As markets do not internalise external costs, internalisation has to be achieved by adequate policy measures like taxes or adjusted electricity rates. Before such measures can be taken, policy-makers need to be informed about the existence and the extent of external costs of different energy systems.

Analysing external costs is not an easy task. Science (to understand the nature of the impacts) and economics (to value the impacts) must work together to create analytical approaches and methodologies, producing results upon which policy-makers can base their decisions on appropriate measures and policies.

As much of the costing of non-market goods includes valuation procedures, for example by putting a value on a person becoming ill as a result of a nuclear accident or the cost of visual intrusion caused by a wind turbine (WT), or the cost of future damage caused by a tonne of CO_2, the externalities may pose uncertainties; include assumptions, risks and moral dilemmas. This sometimes makes it difficult to fully implement externalities by policy measures. Nevertheless, they offer a base for politicians to improve the allocation processes of the energy markets. Koomey and Krause (1997) in their introduction to environmental externality costs state that: *"... to not incorporate externalities in prices is to implicitly assign a value of zero, a number that is demonstrably wrong"*.

Figure 1.1: An Illustrative Example of the Social Cost of Energy



The question arises whether the internalisation of externalities in the pricing mechanism could impact on the competitive situation of different electricity-generating technologies, fuels or energy sources. As Figure 1.1 illustrates, a substantial difference in the external costs of two competing electricity generating technologies may result in a situation where the least-cost technology (where only internal costs are considered) may turn out to be the highest-cost solution to society, if all costs (internal and external) are taken into account.

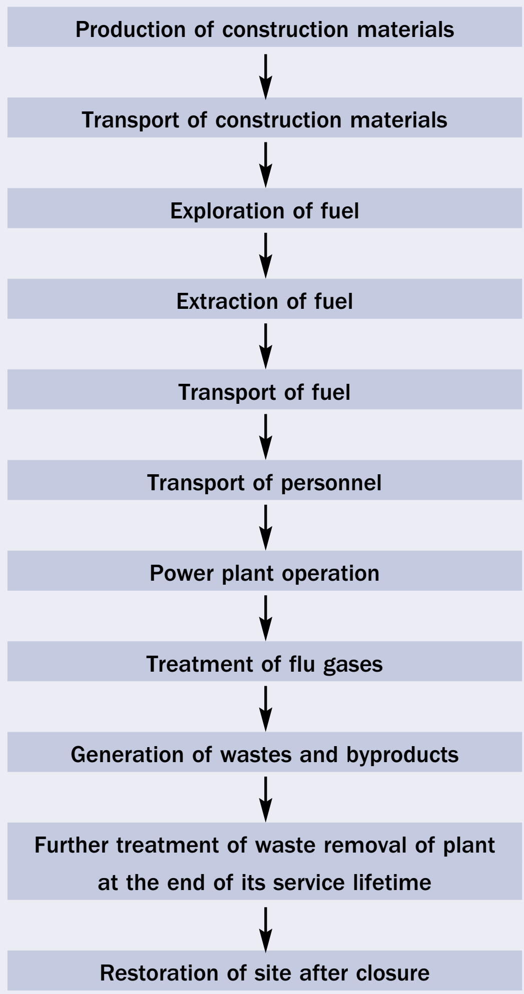
1.4 Externalities and Electricity Production

For the particular case of electricity production, the use of energy sources may *"cause damage to a wide range of receptors, including human health, natural ecosystems and the built environment, and they are referred to as external cost of energy"* (European Commission, 1994).

The externalities in the energy sector started to be quantified by pioneer studies in the late 1980s and beginning of the 1990s (Hohmeyer, 1988, Friedrich *et al*., 1989, Ottinger *et al*., 1990), which started the interest and gave a first insight into the importance of externalities for energy policy as a decision-making tool. The most outstanding project on determining the external cost of energy is the ExternE project, which developed a consistent methodology to assess the externalities of power generation in the EU. For that reason, a brief introduction of its methodology and an analysis of its results is provided in this chapter.

An important aspect in any analysis of the environmental externalities of electricity production is defining the activities that can have an impact. In that sense, the impacts of power production are not exclusively generated during the operation of the power plant, but also in the entire chain of activities needed for electricity production and distribution, such as fuel extraction, processing and transformation, construction and installation of the equipment, as well as waste disposal. These stages, which constitute the chain of electricity production and distribution, are known as the fuel cycle. Every technology (wind, hydro, coal, gas, etc) has its own very distinct fuel cycle. A generic fuel cycle can be seen in Figure 1.2.

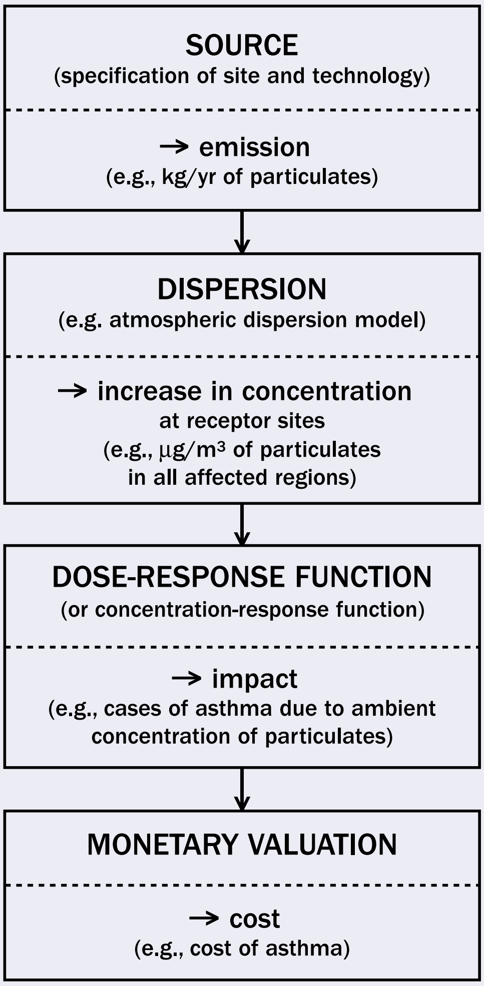
Figure 1.2: Generic Fuel Cycle



The impacts from any of the stages in the fuel cycle depend on the particular location of an activity. Impacts may vary greatly as a function of the sensitivity of the surrounding ecosystem, the population density, and economic and social aspects. In the case of renewable fuel cycles like wind, the major impacts of the fuel cycle arise from the activities required to produce and install a wind turbine and ancillary systems, while only minor externalities arise from wind turbine operation.

The ExternE methodology is a bottom-up approach, which first characterises the stages of the fuel cycle of the system in question (e.g. coal), defining the activities associated with the power technology. Subsequently, the fuel chain burdens are identified. Burdens refer to anything that is, or could be, capable of causing an impact of whatever type. After having identified the burdens, an identification of the potential impacts is achieved independent of their number, type or size. Every impact is then reported. This process just described for the fuel cycle is known as the Accounting Framework. For the final analysis, the most important impacts are selected and only their effects are calculated.

Figure 1.3: Impact Pathway Approach



Source: European Commission (1994).

Afterwards, the Impact Pathway approach developed by ExternE proceeds to establish the effects and spatial distribution of the burdens to see their final impact on health and the environment. Then, the economic valuation assigns the respective costs of the damages induced by a given activity.

The most important results of this study are found in its final phase in which the ExternE methodology was implemented in the EU in 1998 to take into account site-specific conditions, technologies, preferences, problems and policy issues. The aim was to create an EU-wide data set to assess the external cost. The results are shown in Table 1.2.

Table 1.2: External Cost Figures for Electricity Production in the EU for Existing Technologies (c€/kWh*)

Country	Coal&Lignite	Peat	Oil	Gas	Nuclear	Biomass	Hydro	PV	Wind
AT				1-3		2-3	0.1		
BE	4-15			1-2	0.5				
DE	3-6		5-8	1-2	0.2	3		0.6	0.05
DK	4-7			2-3		1			0.1
ES	5-8			1-2		3-5**			0.2
FI	2-4	2-5				1			
FR	7-10		8-11	2-4	0.3	1	1		
GR	5-8		3-5	1		0-0.8	1		0.25
IE	6-8	3-4							
IT			3-6	2-3			0.3		
NL	3-4			1-2	0.7	0.5			
NO				1-2		0.2	0.2		0-0.25
PT	4-7			1-2		1-2	0.03		
SE	2-4					0.3	0-0.7		
UK	4-7		3-5	1-2	0.25	1			0.15

* Subtotal of quantifiable externalities (such as global warming, public health, occupational health, material damage)
** biomass co-fired with lignites
Source: European Commission (1999), data updated in 2003.

Table 1.2 is a summary of the national reports with the final results. The values vary between countries since specific peculiarities from every country have an influence on the results due to a different range of technologies, fuels and pollution abatement options as well as locations. The fossil fuel cycles demonstrate the highest values (coal and lignite, peat, oil and gas), of which gas is the least damaging. Renewable energy and nuclear show the lowest externalities or damages.

In these results, the externalities for the nuclear cycle assume that waste and other hazardous impacts are well managed. As the results on nuclear power plants are based on calculations done for the ExternE project, and as the calculation of the underlying accident probabilities and source terms have never been made available for third party analysis, these figures are not as credible as the other estimates of external costs given in Table 1.2, where all assumptions underlying the calculations are revealed. What is more, the numbers seem to contradict the results of the German reactor safety study phase B which give rather more significant source terms and accident probabilities for severe core melt-down accidents with containment rupture (Gesellschaft für Reaktorsicherheit, 1989).

The ExternE results show that the damages vary substantially between countries. At present these external costs are hardly ever internalised, although the EU ordinance on subsidies for environmental measures (Official Journal of the European Communities, 2001) states that proven externalities may be compensated by public payments of up to 0.05 €/kWh without being considered as subsidies.

1.5 Impacts of Wind Energy and Other Technologies

The assessment of externalities is the result of the economic valuation of impacts on the environment and human health from all the activities required to produce a kWh of electricity. In order to provide an idea of the relevant impacts of wind energy and other technologies to assess the external cost, a broad description of the impacts of wind energy and other technologies is given.

Wind energy, a clean technology mainly due to the avoidance of air pollutant emissions, is not totally free of impacts on the environment and human health.

Wind energy has very few environmental impacts in its operation stage, although it may cause some impact in its direct vicinity in the form of aerodynamic noise. Furthermore, the visual impact of large WTs on the landscape may adversely affect some people. Visual intrusion of the turbines along with ancillary systems in the landscape and noise are considered as amenity impacts of the technology. Other impacts deal with indirect pollution from the production of components and construction of the turbine. A brief description of wind energy impacts follows:

- **Noise:** coming from WT operation, installation of the turbines at the wind farm site, turbine manufacturing processes, and transportation systems used in turbine delivery and maintenance. The dominant issue is aerodynamic noise from the turbines. However, modern WTs are seldomly heard at distances further than 300 m as background noise from wind in trees, for example, will be higher.

- **Visual intrusion of the turbines and associated equipment in the landscape:** the most difficult to quantify. Nevertheless, the total costs are generally overestimated, as the number of persons adversely affected is rather limited. In addition, since the beginning of the 1980s planners have become much more sophisticated. Today's wind power plants are erected in designated areas, thus further limiting the number of affected areas.

- **Indirect atmospheric emissions:** impacts of global warming and acid deposition due to emissions from materials processing and component manufacturing. Experience shows that these effects are in the range of less than 2% of the emissions avoided if fossil fuels are substituted. What is more, they decline as the share of clean renewable energy in the system increases.

- **Accidents:** affecting workers in manufacturing, construction and operation as well as accidents affecting the general public due to turbine operation and road travel by workers. So far, most accidents have affected workers installing and maintaining WTs.

- **Impact on birds:** collision in flight with turbines and behavioural disturbance from blade avoidance. Although numerous studies show that birds rarely collide with rotor blades this is an issue sometimes raised.

- **Impacts of construction on terrestrial ecosystems:** long-term loss of land where turbines are placed and impacts of erection activities together with electrical connections, buildings and access tracks. It has to be noted, however, that only the access roads and a very small area around the tower of a WT are lost for other uses. The Danish and German examples show that agriculture goes on in wind parks, which are often used for grazing cattle.

- **Electromagnetic interference:** the moving blades can affect radio waves and microwaves used for communication purposes although this has proven to be less of an issue.

These issues are explained in greater detail in the following chapters.

In order to also give an idea of the sources of externalities for other fuel cycles, Table 1.3 lists the priority impacts taken into account in the most important study available, the ExternE project. This list only includes those impacts which have been identified as having substantial importance. Other impacts such as land use by the installations, visual intrusion and interference of transmission lines on birds have not been included.

Table 1.3: Priority Impacts assessed in the ExternE Project

Fossil Fuel Technologies:
- Effects of atmospheric pollution on human health
- Accidents affecting workers and/or the public
- Effects of atmospheric pollution on:
  - materials
  - crops
  - forests
  - freshwater fisheries
  - unmanaged ecosystems
- Impacts of global warming
- Impacts of noise

Specific for some Activities in Fossil Fuel Technologies:
- Impacts of coal and lignite mining on ground and surface waters
- Impacts of coal mining on building and construction
- Resettlement necessary through lignite extraction
- Effects of accidental oil spills on marine life
- Effects of routine emissions from exploration, development and extraction from oil and gas wells

Nuclear Technologies:
- Radiological and non-radiological health impacts (routine and accidental releases to the environment)
- Occupational health Impacts (radiological and non-radiological exposures due to work accidents and radiation exposure)
- Impacts on the environment of increased levels of natural background radiation (major accident releases)

Renewable Technologies:

Wind
- Accidents affecting workers and/or the public
- Effects on visual amenity
- Effects of noise emissions on amenity
- Effects of atmospheric emissions (turbines' manufacturing, on site construction and servicing)

Hydro
- Occupational health effects
- Employment benefits and local economic effects
- Impacts of transmission lines on bird populations
- Damage to private goods (forestry, agriculture, water supply, ferry traffic)
- Damages to environmental goods and cultural objects

Source: European Commission (1999).

The nuclear fuel cycle in the ExternE project has eight stages covering electricity production from the mining of uranium oxide. The impacts deriving from this fuel cycle are caused by inhalation, external exposure and ingestion of agricultural products due to atmospheric emissions, liquid discharges and solid residues.

The hydro power fuel cycle differs greatly from the fossil fuel cycles. The particular impacts of this cycle are the intrusion of the infrastructure into the environment and the flooding of large areas in the case of large hydro dams.

1.6 Externalities of Wind Energy

Different studies and methodologies show that the externalities of wind energy are far smaller than the external costs of fossil fuel based electricity generation. The externality values shown in the final results of the national implementation of the ExternE project (see Table 1.2) range from 0.05 to 0.25 c€/kWh.

Looking at a conventional power production technology such as coal, the values observed are of the same order or double the magnitude of the internal electricity cost of these technologies. In general the lower and upper levels are between 2 and 15 c€/kWh.

With this information, it is possible to estimate the social cost of coal and wind power. Assuming that the cost of producing a kWh with coal is around 3 c€/kWh on average, internalisation of the coal externalities increase costs by between 5 and 18 c€/kWh resulting in rather high costs of electricity. Table 1.4 shows the social cost of coal and gas power systems for Spain, Denmark and Germany in which the external cost range given for coal is higher than the internal cost. For the case of gas the external cost is below the internal cost.

Based on the figures given in Volume 2, the cost of producing electricity with wind energy in coastal and inland sites can be derived. These costs were based on constant 2001 prices for Denmark. Taking the inland wind energy cost for machines of 600 and 1,000 kW along with the externality figures of Denmark from Table 1.2 the results are:

Table 1.5: Social Cost of Wind Energy

Costs	600 kW WT	1,000 kW WT
Cost of Wind c€/kWh	4.4	4.1
External Cost* c€/kWh	0.09 – 0.16	0.09 – 0.16
Social Cost	*4.49 – 4.56*	*4.19 – 4.26*

Note: *The external cost was not converted to € 2001 prices.

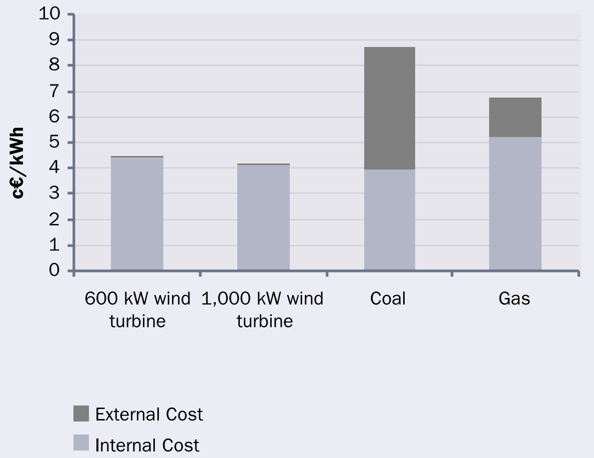
Table 1.4: Social Cost of Coal and Gas Powered Systems (Internal + External[a])

	Coal			Gas		
Costs	**Spain**	**Denmark**	**Germany[b]**	**Spain**	**Denmark**	**Germany[b]**
Internal cost[c] c€/kWh	3.93	3.41	3.14	5.2	5.23	2.85
External Cost c€/kWh	4.8 - 7.7	3.5 - 6.5	3.0 - 5.5	1.1 - 2.2	1.5 - 3.0	1.2 - 2.3
Total Cost	8.73 - 11.63	6.91 - 9.91	6.14 - 8.64	6.3 - 7.4	6.73 - 8.23	4.05 - 5.15

[a] The external cost was not converted to € 2001 prices.
[b] Germany coal and gas (combined cycle) cost is own calculation. Source: Hohmeyer *et al.* (2000).
[c] Projected avoided cost of conventional power assuming 25% capacity credit for wind power (see Volume 2).
Source: Coal prices from IEA/OECD updated to € 2001 prices.

The social costs are practically unchanged by the inclusion of the external cost of wind energy. Based on this total cost comparison, the cost of wind energy is very competitive to the cost of conventional power plants as shown in figure 1.1. The social cost of coal for Denmark as shown in Table 1.4 ranges from 6.9 to 9.9 c€/kWh. Figure 1.4 illustates the social cost estimated in the tables for coal, gas and wind in Denmark.

Figure 1.4: Social Cost of Coal, Gas and Wind in Denmark



As was mentioned before, a precise estimation of damages is not an easy task. In addition, the results of the national implementation phase of the ExternE project have to be used with care since social and environmental impacts are difficult to quantify and damages of the fuel cycles are not fully quantified. For the case of wind energy the external costs are strongly influenced by local factors. Thus, translating values to other locations is not recommended. However, the results do show the order of magnitude of the differences between clean energy technologies and conventional ways of producing electricity.

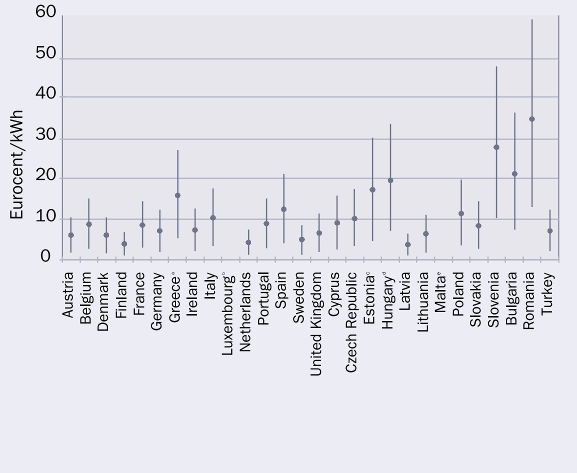
1.7 Benefits of Wind Energy

The benefits of wind energy are the avoided emissions and their impacts from fossil fuel electricity generation. The external costs avoidable through wind energy can be calculated as shown in chapter 2.

The evaluation includes damages from air pollutant emissions like SO_2 and NO_x as well as costs of the anthropogenic greenhouse effect resulting from CO_2 emissions. The analysis has been carried out based on a calculation with the EcoSense model (air pollutants) on the one hand and on the estimates of Azar and Sterner (1996) concerning the adverse effects of climate change on the other.

The calculations carried out for the EU-25, Turkey, Romania and Bulgaria take into account the replaceable energy mix of each country as well as the technological standards. The possible ranges of reductions in external costs due to the increased use of wind energy are shown in Figure 1.5.

Figure 1.5: Avoidable External Costs by the Use of Wind Energy in 2000 in c€/kWh, EU-25 and other European Countries

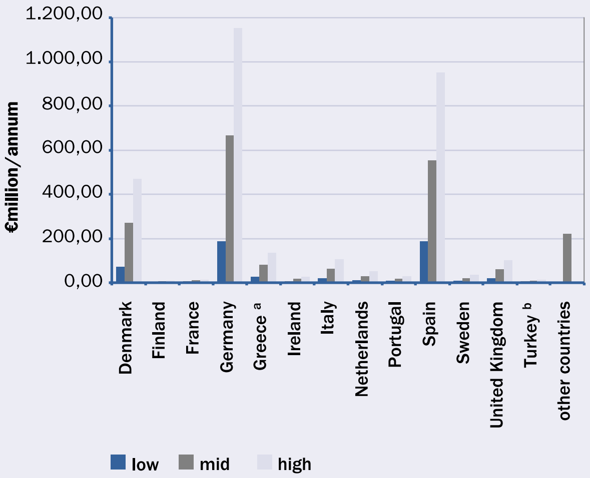


[a] source of CO_2 emission data: Ministry of Environment and Physical Planning: "National Programme for the Reduction of Greenhouse Gas Emissions", Athens 2002.
[b] no emission data available.
[c] all data are from 2002, source: EWEA (2003b).
[d] source of emission data: MVM, Hungary.
[e] no data available.
Source: Eurelectric (2002), own calculations.

Figure 1.5 gives an overview of the avoidable external costs by wind energy per kWh. It is observed that there is a noticeable difference between the countries covered by this study. Some new member states and accession countries, in particular, have very high emissions resulting in high external costs of electricity generation.

By combining the avoidable external costs with the amount of electricity produced by wind energy, the total amount of avoided external costs can be calculated. This is shown for the year 2000 in € millions for each country in Figure 1.6. Only three countries (Denmark, Germany and Spain) use substantial parts of their wind energy resource to reduce external costs. This reduction is more than €1 billion per year in the case of Germany.

Figure 1.6: Total Avoided External Costs by the Use of Wind Energy in 2000



[a] source of CO_2 emission data: Ministry of Environment and Physical Planning: "National Programme for the Reduction of Greenhouse Gas Emissions", Athens 2002.
[b] source of emission data: TEAS, Turkey.
Source: Eurelectric (2002), own calculations.

The ranges low, mid and high relate to the lower and upper bound and the central value of the specific externalities per kWh shown in the Figure above. The precise description of the calculations is given in chapter 2.

1.8 Present State of Knowledge

The current state of knowledge of external costs can be described as a process that was mainly initiated in the late 1980s, when the first studies were published attempting to quantify and compare the external costs of electricity generation. The studies released at that time started a public interest in externalities, as they showed for the first time that the differences in external costs are of the same order of magnitude as the direct internal costs of generating electricity. Since that time more research and different approaches, better scientific information and a constant improvement of the analytical methodologies used have driven an evolution of externalities research in Europe and the USA.

This development has resulted in a convergence of methodologies, at least for calculating the external costs of fossil fuel based electricity generation and wind energy. This has induced policy-makers to adopt some measures to attempt a first internalisation, as under the German Renewable Energy Law.

Despite the uncertainties and debates about externalities, it can be stated that with the exemption of nuclear power and long term impacts of GHGs on climate change, the results of the different research groups converge and can be used as a basis for developing policy measures aimed at a further internalisation of the different external costs of electricity generation.

Finally, it is worth drawing attention to issues that have not been mentioned in this chapter which may enhance the concept of external costs such as, for example, sustainability and security and reliability of supply.

With respect to sustainability, the neoclassical definition of externalities assumes that monetary valuation by manufactured and natural capital can be a substitute for environmental deterioration. This valuation is considered to be an indicator of weak sustainability (Rennings, 1996). In contrast, strong sustainability principles demand an economic system that does not exceed the capacity of the global ecological system and development that meets the needs of the present without compromising the ability of

future generations to meet their own needs (WCED, 1987). The neoclassical definition of externalities and sustainability principles should be linked to sustainable development issues (Weinreich, 2002).

The security and reliability of supply and its consequences for market risk is an aspect that can also enhance the concept of externalities of electricity generation. The inclusion or accounting of market risk due to supply disruption and, especially, fuel price volatility represents a security issue. This has an effect on the economics of fossil fuel which is not recognised in traditional analysis. Furthermore, renewable energies (e.g. wind and solar) are not subject to volatile fuel prices. The inclusion of volatility in the private costs equation could change the perception that renewables are high cost (Awerbuch, 2003). This topic needs further research.

2 ENVIRONMENTAL BENEFITS OF WIND ENERGY

2.1 Background

Emissions

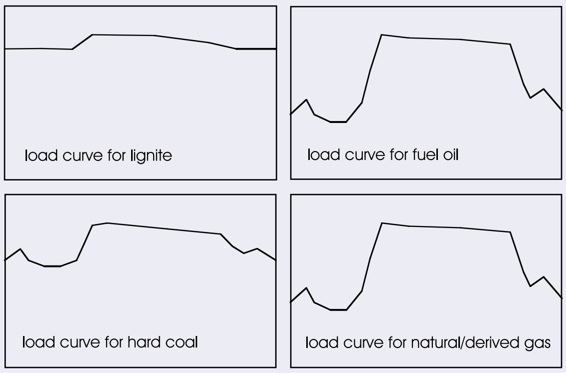
The most important emissions concerning electricity generation are CO_2, SO_2, NO_x and PM_{10} (particulate matter up to 10 micrometers in size). Emissions generally depend on the type of fuel used. CO_2 emissions are related to carbon content. There is no realistic opportunity of reducing carbon emissions by using filters or scrubbers, although techniques such as burning fossil fuel with pure oxygen and capturing and storing the exhaust gas may reduce the carbon content of emissions (IPCC, 2002). For SO_2, the quantity of emissions per kWh electricity generated depends on the sulphur content of the input fuel. Furthermore, SO_2 emissions can be reduced by filtering the exhaust gases and converting SO_2 to gypsum or elementary sulphur. In general, the sulphur content of lignite is rather high, fuel oil and hard coal have roughly a medium sulphur content and natural gas is nearly sulphur free. In contrast, NO_x emissions are practically unrelated to input fuel. As NO_x are formed from the nitrogen in air during combustion, their formation depends mainly upon the combustion temperature. Thus, NO_x emissions can be reduced by choosing a favourable (low) combustion temperature or by denitrifying the exhaust gases (by wet scrubbing).

Technology

Due to its intermittent nature, wind power can at present only replace specific segments of conventional electricity generation. And as it varies with available wind speed it cannot replace conventional base load power plants. As wind energy is a capital intensive technology, and because the fuel is free, it needs to be used as much as possible. Thus, it should be used to replace conventional power plants in the intermediate rather than peak load segment.

Keeping these facts in mind, we can define a reference system whereby wind farms may replace conventional power plants. Firstly, neither nuclear nor standard hydro power plants are replaceable by wind, as both almost exclusively operate in the base load segment. As pump storage (hydro) power plants are used to cover very short load peaks, they cannot be replaced by wind energy either, due to the latter's intermittent nature. This leaves electricity generation from the fossil fuels (assuming average generation structure): hard coal, lignite, fuel oil and gas. However, this assumption can lead to an overestimation of the share of the replaced electricity supplied by lignite, as this is predominantly used in the base load segment as well, and to an underestimation of substituted electricity from gas, which, due to the dynamic characteristics of gas fired power plants, lends itself perfectly to balance fluctuations in the supply of wind energy. As we know the current mode of operation of conventional power plants, the rules of their dispatch based on the so-called "merit order" and the dynamic behaviour of the different types of conventional power plants, we can safely assume a replacement of intermediate load by wind energy.

Figure 2.1: Load Curves for Lignite, Hard Coal, Fuel Oil and Gas



Source: based on VDEW (1998).

Apart from nuclear energy, all conventional fuel types are more or less used to generate intermediate load electricity. These are: hard coal, lignite, fuel oil, natural gas and derived gas. For our analysis, the contributions of the different energy sources to intermediate load electricity need to be specified. They probably differ substantially in different countries and there are virtually no national statistics available on their contributions. Therefore, data for the German situation supplied by Vereinigung Deutscher Elektrizitätswerke (VDEW, 2000) are used as the basis of our analysis. The load curves

for one typical load day (Figure 2.1) have been derived for each relevant type of fuel and will be taken as the basis for the calculation of shares of intermediate load.

The graphs show that the highest load variations during one day are displayed by fuel oil and gas. Hard coal shows some variation, while electricity production based on lignite is almost constant. Although, these load curves are based on the German electricity generation structure, power plants have common fuel-specific technical and economic characteristics. Therefore, load curves are assumed to have similar day-to-day variations in other countries.

Based on these considerations, Table 2.1 sets out assumptions for the intermediate load shares, with the percentage figures being based on the total volume of electricity produced for each fuel.

Table 2.1: Share of Intermediate Load

Fuel Type	Share of Intermediate Load
lignite	10 %
hard coal	30 %
mixed firing	50 %
fuel oil	100 %
natural/derived gas	100 %

2.2 Electricity Generation and Emissions in EU-25 and other European Countries

This section provides a short overview of the 28 countries covered by this study. The countries are divided into groups according to their geographical location.

The EU-15 countries can be sub-divided into three groups, shown in Table 2.2.

Table 2.2: EU-15 Countries

North	Central	South
Denmark	Austria	Greece
Finland	Belgium	Italy
Sweden	France	Portugal
	Germany	Spain
	Ireland	
	Luxembourg*	
	Netherlands	
	UK	

*data are not available for emissions in Luxembourg.

The 10 new member states, along with Turkey, Bulgaria and Romania can be divided into three similar groups (see Table 2.3).

Table 2.3: New EU Member States, Bulgaria, Romania and Turkey

North-east	East	South-east
Estonia	Czech Republic	Bulgaria
Latvia	Hungary	Malta*
Lithuania	Poland	Romania
	Slovakia	Slovenia
		Turkey
		Cyprus

*data are not available for electricity generation and emissions in Malta.

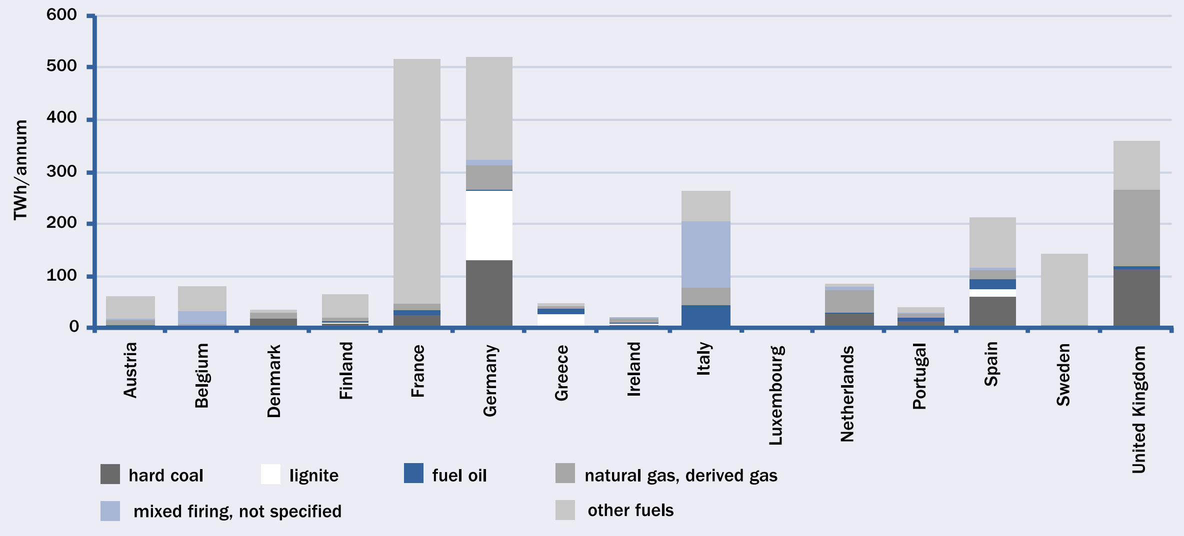
2.2.1 ELECTRICITY GENERATION SECTOR AND ENVIRONMENTAL POLICY FRAMEWORK

The countries covered by this study differ substantially in the volume and structure of their electricity generation. All data used have been taken from Eurelectric (2002). Therefore, the shares of input fuels for electricity generation vary strongly between different countries. The share of hydropower used is determined by the very different resources of the 28 countries, while the share of nuclear is a function of the nuclear energy policy of each country, varying from a very strong reliance on nuclear energy in the case of France to a policy of no nuclear energy in countries like Denmark and Austria. As has been explained above, intermittent renewable energy cannot at present replace nuclear or hydro power. Thus only fossil fuels are replaced by wind energy in this study. The structure of electricity generation by fossil fuel fired conventional thermal power plants is shown in Figures 2.2 and 2.3. Unfortunately, the only available comprehensive source of statistical data for the 28 countries studied (Eurelectric, 2002) does not allow a full disaggregation with respect to power plants suitable for more than one fuel ("mixed firing"). To permit a good comparison between electricity generation in all the countries, the same scale is used in the two figures.

As figure 2.2 shows, there are a few countries which use mainly hard coal and lignite for the fossil part of their electricity production. These are Germany, Greece, Spain, Denmark, Finland and Portugal. Other countries favour gas, for example the UK and the Netherlands.

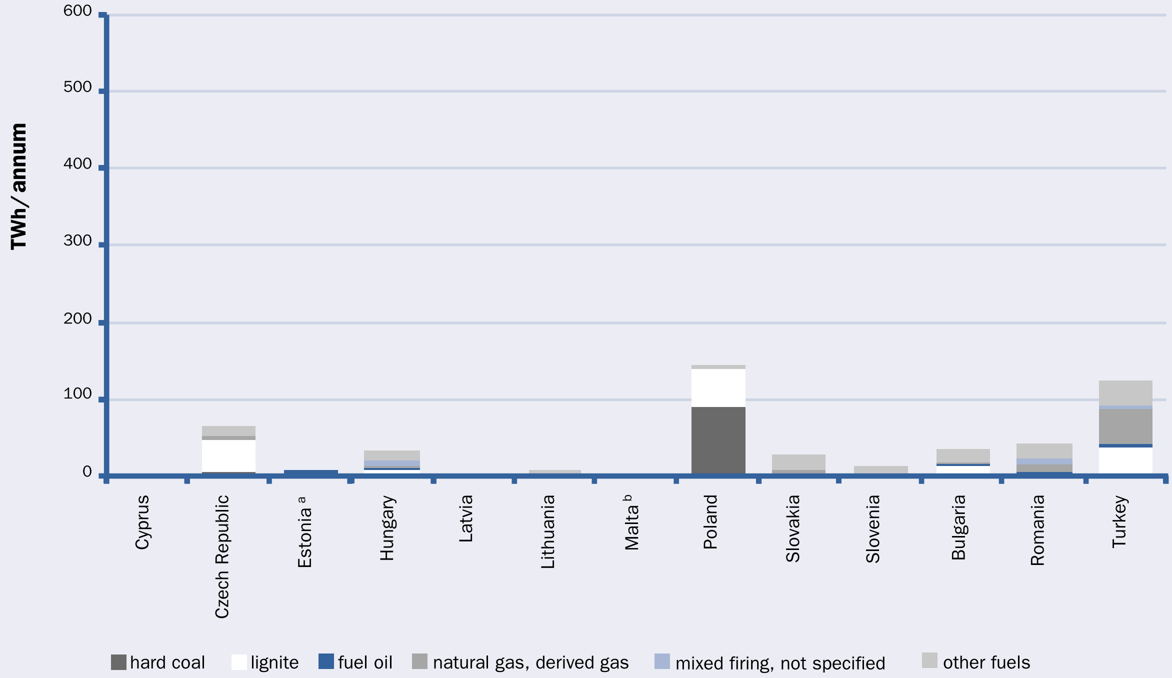
Some of the new member states and others mainly use hard coal and lignite for their fossil fuel based electricity generation. These are Poland, Slovenia, Czech Republic, Bulgaria, Slovakia and Hungary. Natural gas is favoured by Latvia, Turkey and Romania. The majority of these countries use a substantial share of nuclear energy for electricity generation.

Figure 2.2: Total Electricity Generation in EU-15 Countries in 2000



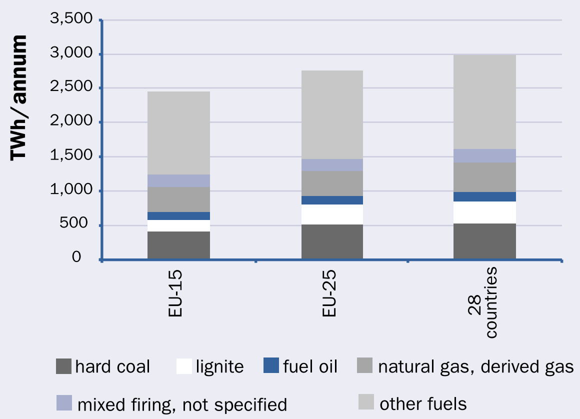
Source: Eurelectric (2002).

Figure 2.3: Total Electricity Generation in the 10 New Member States, Turkey, Bulgaria and Romania in 2000



[a] data are from 2002. Source: EWEA (2003b).
[b] no data available.
Source: Eurelectric (2002).

Figure 2.4: Total Electricity Generation in the EU-15, EU-25 and all 28 Countries in 2000

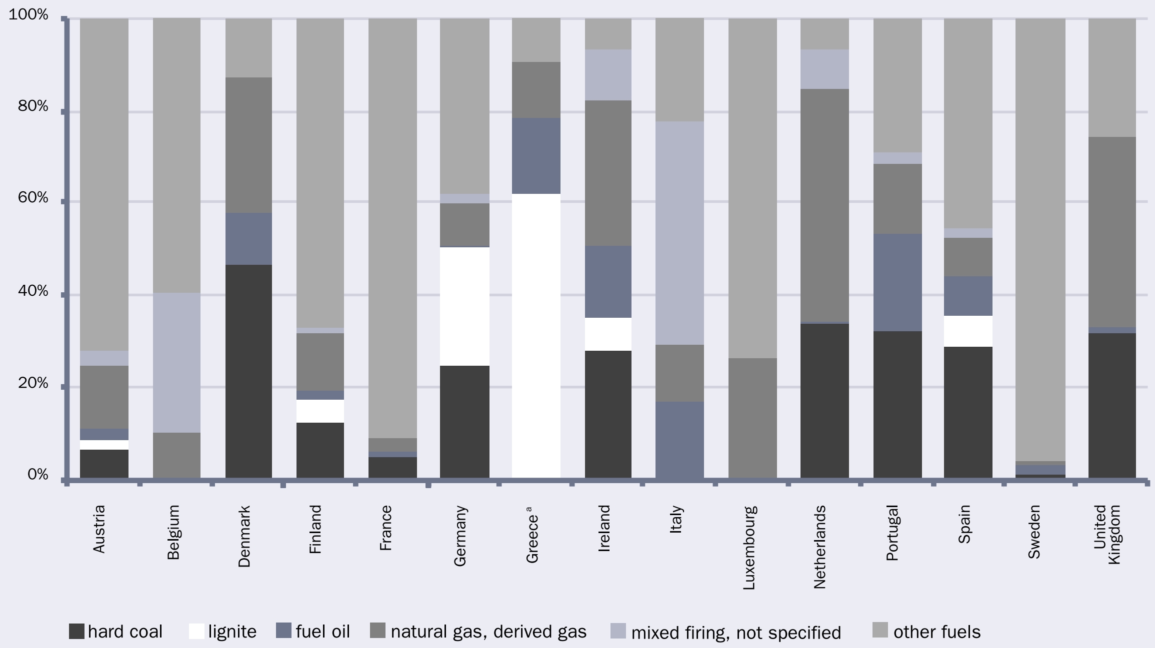


Source: Eurelectric (2002), own calculations. Data for Estonia are from 2002, source: EWEA (2003b). No data are available for Malta.

For a better orientation, the amounts of electricity generation in the EU-15, the EU-25 and in all 28 countries are shown in Figure 2.4. As this figure illustrates, the amount of electricity generation is very low in most of the countries outside the EU-15.

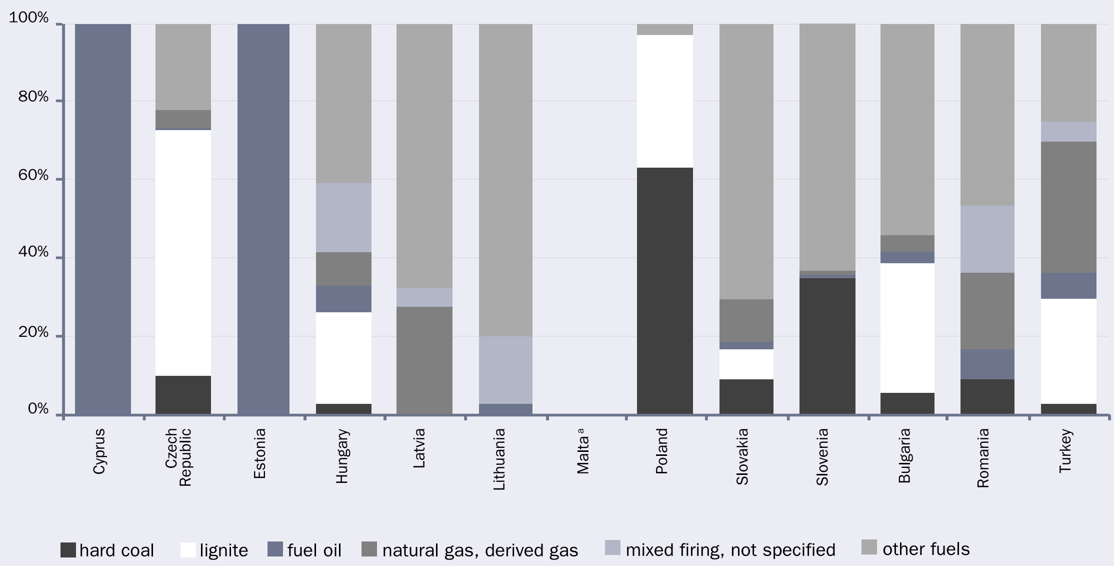
Figures 2.5 to 2.7 provide a detailed picture of the electricity generation fuel mix in the various countries.

Figure 2.5: Segmentation of Fuels for Electricity Generation in EU-15 Countries in 2000 (%)



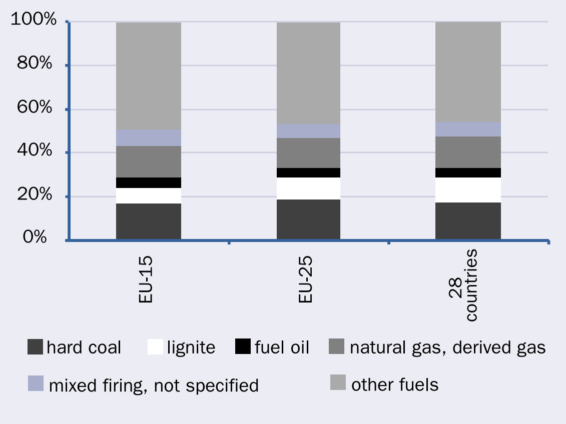
[a] data are from 2002, source: EWEA (2003b).
Source: Eurelectric (2002).

Figure 2.6: Segmentation of Fuels for Electricity Generation in the 10 New Member States, Turkey, Bulgaria and Romania in 2000 (%)



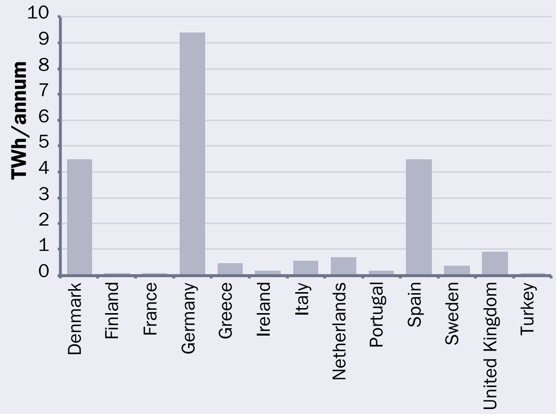
[a] no data available.
Source: Eurelectric (2002).

Figure 2.7: Segmentation of Fuels for Electricity Generation in the EU-15, EU-25 and all 28 Countries in 2000 (%)



Source: Eurelectric (2002), own calculations. Data for Estonia are from 2002, source: EWEA (2003b). No data are available for Malta.

Figure 2.8: Electricity Generation by Wind Energy in 2000 (TWh/a)



Source: Eurelectric (2002).

Electricity generation by renewable energies is widely spread around the European countries. The specific amount which is covered by renewable energies in each depends on geographical conditions and the country's policies on renewable energies. Therefore, the use of renewables differs widely between the 28 countries. Due to its relatively low internal costs, hydro power is used by most, with Austria and Latvia producing more than half their electricity from hydro power.

The use of wind energy differs very substantially across the 28 countries, with Germany, Denmark and Spain producing more than 4 TWh/annum (2000) and nine other EU-15 member states producing up to 1 TWh/annum. Of all the other countries, only Turkey was using any significant amount of wind energy in the year 2000. Countries generating electricity from wind energy (2000) are shown in Figure 2.8.

If wind energy production is looked at in terms of share of electricity produced, a somewhat different picture emerges, as only Denmark produced more than 10% of its electricity from wind in 2000 (12.8%), while Spain (2.1%), Germany (1.8%) and Greece (1.1%) were way behind. Nevertheless, the situation is changing dramatically; for example in Germany the installed capacity has more than doubled since the year 2000. For 2002, Germany produced 23.1 TWh which represents a share of 4.7% (Ender, 2003), Denmark's wind generation figures for 2002 showed production at 4.9 TWh representing a share of 14.8% (Danish Wind Industry Association, 2003) while Spain's production of 9.5 TWh for 2002 represents 4% (IDAE, 2003).

Here, it is very important to point out that the figures for electricity generation by wind energy have increased dramatically in recent years. In terms of installed wind capacity, Europe experienced a growth of 10,200 MW of total installed capacity from 2000 to 2002. This fact has an impact on the quantification of the benefits of wind energy. However, for the purposes of this study, the figures for electricity generation by wind energy were taken from the year 2000 (Eurelectric, 2002).

Although wind energy is only used in significant volumes in just four out of the 28 countries, the use of wind energy in the year 2000 has already resulted in significant emission reductions, which are discussed in chapter 2.4 below.

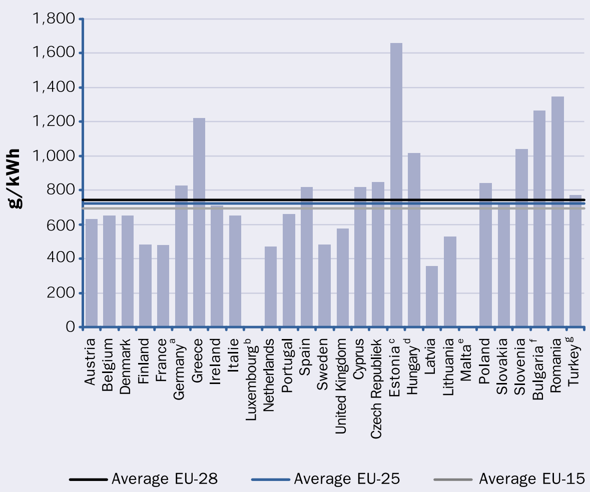
2.2.2 EMISSION DATA

To be able to analyse the possible environmental and health benefits of the use of wind energy we need to know the specific emissions of the electricity replaced by wind. These can be derived by dividing the absolute

emissions produced by a type of fuel in kilotons of CO_2/annum used for electricity generation in one country by the electricity produced from this fuel in kWh/annum. For clarity, the emissions statistics for each country are given on the CD attached to this report. Most of the data used for the calculations are from Eurelectric (2002). However, not all the necessary data were available from this source, so some calculations have been based on additional sources.

As explained in chapter 2.1, wind energy is capable of replacing intermediate load conventional power production. The emissions avoided by wind energy depend on three factors: the specific emissions from each type of generation facility; the fuel mix in each country; and the percentage of each fuel replaced by wind energy. A detailed calculation of avoidable specific emissions by wind energy in all the countries studied is shown in chapter 2.4.

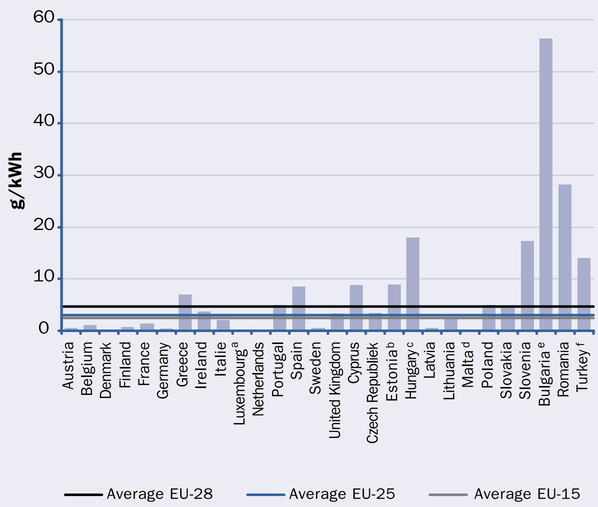
Figure 2.9: Specific Average CO_2 Emissions in g/kWh from Fossil Fuel Electricity Generation in 2000



[a] source of CO_2 emission data: Ministry of Environment and Physical Planning: "National Programme for the Reduction of Greenhouse Gas Emissions", Athens (2002).
[b] no emission data available.
[c] all data are from 2002, source: EWEA (2003b).
[d] source of emission data: MVM, Hungary.
[e] no data available.
[f] source of emission data: NEK, Bulgaria.
[g] source of emission data: TEAS, Turkey.
Source: Eurelectric (2002), own calculations.

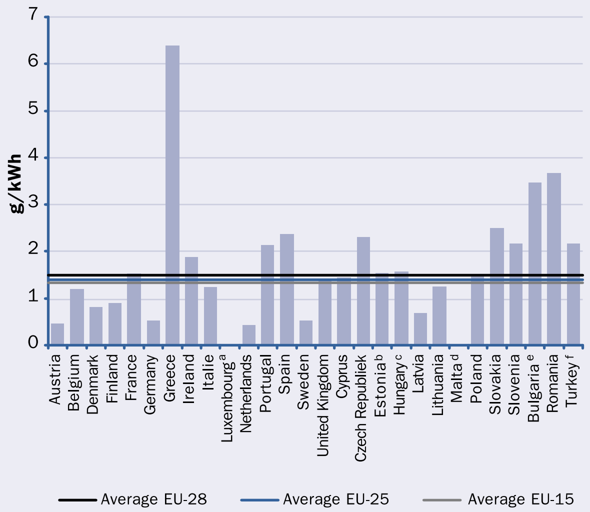
Average emissions per kWh were calculated to provide a starting point for examining the relationship between electricity production from fossil fuels and total emissions from the electricity sector in the different countries (see Figures 2.9 to 2.11). The results include all fossil fuel based electricity not just the intermediate load segment (see chapter 2.4).

Figure 2.10: Specific Average SO_2 Emissions in g/kWh from Fossil Fuel Electricity Generation in 2000



[a] no emission data available.
[b] all data are from 2002, source: EWEA (2003b).
[c] source of emission data: MVM, Hungary.
[d] no data available.
[e] source of emission data: NEK, Bulgaria.
[f] source of emission data: TEAS, Turkey.
Source: Eurelectric (2002), own calculations.

Figure 2.11: Specific Average NO_X Emissions in g/kWh from Fossil Fuel Electricity Generation in 2000



[a] no emission data available.
[b] all data are from 2002, source: EWEA (2003b).
[c] source of emission data: MVM, Hungary.
[d] no data available.
[e] source of emission data: NEK, Bulgaria.
[f] source of emission data: TEAS, Turkey.
Source: Eurelectric (2002), own calculations.

In summary, Figures 2.9 to 2.11 show that the southern European EU-15 countries (Greece and Spain), as well as all south-eastern countries (Bulgaria, Cyprus, Romania, Slovenia and Turkey), Hungary and Estonia have rather high emissions from electricity generation. Two of the centrally-located countries (Ireland and the UK), Italy and Portugal, Lithuania, and most of the eastern European new member countries (Czech Republic, Poland and Slovakia) show intermediate emission levels. Countries with rather low emissions are mostly northern or central countries - Denmark, Finland, Sweden, Austria, Belgium, France, Germany, the Netherlands, and Latvia.

Due to this distribution there is a significant increase of specific average emissions from electricity generation from northern to south-eastern Europe.

Figure 2.9 shows that the difference in specific CO_2 emissions is more than a factor of three between the various countries. This is related to differences in fuel mix as well as the fact that some countries have power plants with very low efficiencies.

The distribution of SO_2 emissions per kWh is very different, as shown in Figure 2.10. This is related to the very heterogeneous sulphur content of fuel and the use of desulphurisation in only the most advanced countries.

NO_X emissions differ between the countries according to the combustion process used, the combustion temperature, which is not optimal in all the countries, and the scrubbing technologies employed, as shown in Figure 2.11.

To determine avoidable emissions from the use of wind energy, specific emissions from electricity generation for the different fuels must be calculated. Specific emissions have been evaluated based on total emissions from electricity generation and the amounts of electricity generated in each country. For further information about this calculation see Appendix G.

2.3 The Calculation of External Costs with the EcoSense Model

In order to be able to calculate the external costs avoided by wind energy, it is necessary to model the pathway of emissions from conventional power plants to the different receptors, such as plants, animals and humans, which may be located thousands of kilometres away. As air pollutants can damage a number of different receptors, the task of analysing the impacts of any given emission is fairly complex. To allow such complex analysis, a tool has been developed during the last 10 years in a major co-ordinated EU research effort, the EcoSense model. This chapter explains the basics of the model, which is used in the calculations in chapter 2.4.

2.3.1 SOFTWARE DESCRIPTION

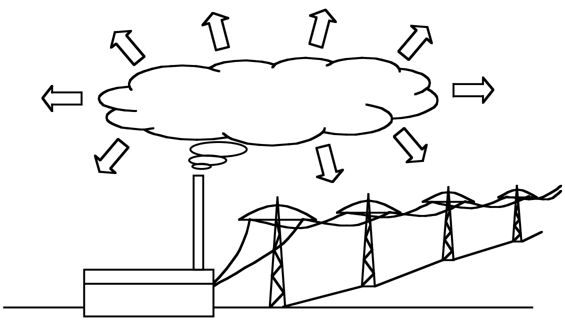
EcoSense is a computer model for assessing environmental impacts and the resulting external costs of electric power generation systems. The model is based on the Impact Pathway approach of the ExternE project and

provides the relevant data and models required for an integrated impact assessment related to airborne pollutants. (For extensive information on the model as well as the approach used, see European Commission, 1994)

EcoSense provides the windrose trajectory model (WTM) for modelling the atmospheric dispersion of emissions, including the formation of secondary air pollutants. For any given point source of emissions (e.g. a coal fired power plant) the resulting changes in the concentration and deposition of primary and secondary pollutants can be estimated on a Europe-wide scale with the help of this model. Developed in the UK by the Harwell Laboratory it covers a range of several thousand kilometres. The reference environment database, which is included in EcoSense, provides receptor-specific data as well as meteorological information based on the Eurogrid-co-ordinate system.

The Impact Pathway approach can be divided into four analytical steps:

- **Calculation of Emissions**



The first step is to calculate emissions of CO_2, SO_2 and NO_x per kWh from a specific power plant.

- **Dispersion Modelling**

Then air pollutant dispersion around the site of the specific plant is modelled. Based on meteorological data, changes in the concentration levels of the different pollutants can be calculated across Europe.

- **Impact Analysis**

Based on data for different receptors in the areas with significant concentration changes, the impacts of the additional emissions on these receptors can be calculated on the basis of so-called dose response functions. Important data on receptors included in the model database are, for example, and population density and land use patterns.

- **Monetisation of Costs**

The last step is to monetise the impacts per kWh caused by the specific power plant. In this stage, the calculated physical damage to a receptor is valued on a monetary scale based on the best available approaches for each type of damage.

2.3.2 INPUT DATA TO THE MODEL

As the EcoSense model requires a specified site as a starting point for its pollutant dispersion modelling we have chosen one typical electricity generation site for each country to assess the impacts and calculate the costs caused by emissions from fossil fuel fired power plants which may be replaced by wind energy.

The co-ordinates at each site are chosen in order to locate the reference plants centrally in the electricity generating activities of each country. Thus, it is assumed that the chosen site represents approximately the average location of electricity generating activities of each country has been chosen. For more information about the input data see Appendix H.

To control for effects caused by this assumption and to prevent extreme data results, a sensitivity analysis was carried out by shifting the geographical location of the plant. This analysis showed a relatively high sensitivity of external costs to the location of the electricity generation facilities. This is due to the very heterogeneous distribution of the different receptors in different parts of a country. For this reason, the specific external costs per kWh may differ by a factor of two. Unfortunately, the area covered by EcoSense is limited to 29° east, so substantial parts of eastern Europe are not included in the analysis and the impacts of eastward emissions due to the prevailing westwind drift are not fully accounted for. Thus, in countries located at the border of the area covered external costs may be substantially underestimated.

In order to run the model, the capacity of the power plant, its full load hours of operation and the volume stream of exhaust gas per hour are required. The assumptions made for the calculations are shown in Table 2.4 for the different fossil fuels.

Table 2.4: Technical Data of the Reference Facilities Assumed for the Calculation

Fuel Type	Capacity (MW)	Full Load Hours per Year	Volume Stream per Hour (m³)
Hard coal	400	5,000	1,500,000
Lignite	800	7,000	3,000,000
Fuel oil	200	2,000	750,000
Natural gas, derived gas	200	2,000	750,000
Mixed firing, not specified	400	5,000	1,500,000

For each country, calculations have been performed for a representative power plant location based on the specific national emission data for each fuel and each pollutant.

2.4 Benefits of Wind Energy - Results

2.4.1 AVOIDABLE EMISSIONS BY THE USE OF WIND ENERGY

As explained in chapter 2.1, electricity from wind energy can replace intermediate load from fossil fuel power plants. Avoidable emissions by wind energy can be calculated based on specific emissions derived in chapter 2.2. Due to the fact that there are no data available on specific emissions per fuel for most countries, specific emission data have been estimated by splitting up the total emissions from conventional thermal electricity generation based upon the shares of electricity generated by the different fossil fuels. Different power plants running on the same fuel are assumed to have the same specific emissions in any one country. Furthermore, it is assumed that the countries have attained the same relative emission abatement level for each fuel type. That is to say, for example, that one country would not rank high on SO_2 emissions from lignite but low on SO_2 emissions from oil. (The calculations are described in detail in Appendix G.)

The specific emissions per fuel and the share of intermediate load generated on the basis of each fuel are used to calculate the specific emissions which could have been avoided per kWh of wind energy in each country in 2000. Results are shown in Figures 2.12 to 2.14. Due to a lack of sufficient data there are no results for Luxembourg and Malta.

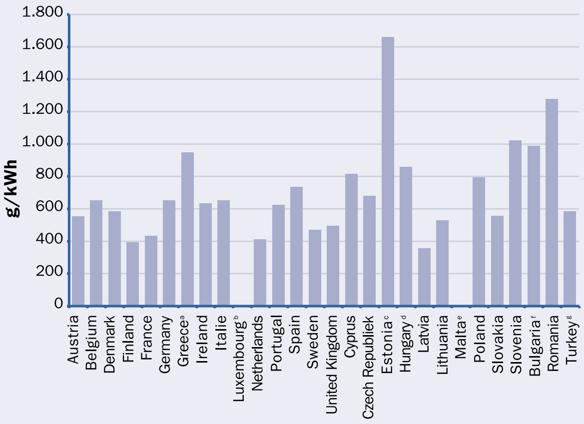
Due to the fact that wind energy replaces only part of the electricity produced by fossil fuels (intermediate load), specific avoidable emissions are different from average emissions from fossil fuel electricity generation. In most cases, avoidable emissions by wind energy are less than average emissions from fossil fuel electricity generation. This is justified by the fact that intermediate load electricity generation by fossil fuels is based on fuel with relatively low emissions (see chapter 2.1 for more information on this point).

As is to be expected, the specific emissions of intermediate fossil power which could be avoided by using wind energy, are higher in most new member states than in most of the EU-15. This is due to less efficient power plants and a lack of SO_2 and NO_x scrubbers. Consequently, new wind energy plants in the countries besides EU-15 countries could induce higher specific emissions. Nevertheless, this may not hold in the long run, as a convergence of technical standards is expected in the next 20 years.

Figure 2.8 reveals that some countries are already avoiding a sizeable amount of fossil fuel emissions through their use of wind energy. Due to the different specific emissions avoided per kWh in each country (Figures 2.12 to 2.14) the total emissions are not directly proportional to the wind energy produced. For Spain, in particular, total emission reductions for SO_2 and NO_x are comparatively high in relation to the electricity replaced. This is due to the high specific emissions of Spanish fossil fuel power plants.

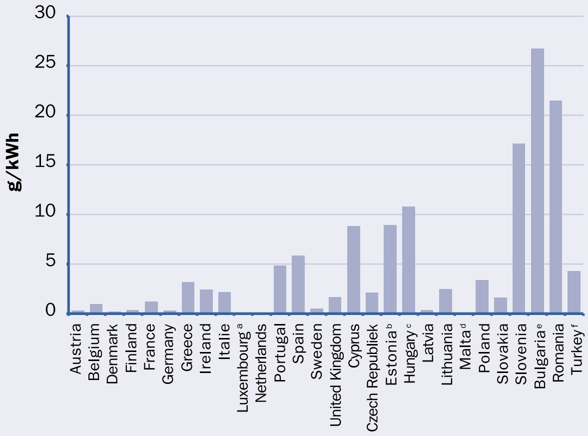
In 2000, approximately 15 Mt CO_2 were avoided by the use of wind energy as shown in Figures 2.15 to 2.17.

Figure 2.12: Specific Avoidable CO_2 Emissions in g/kWh by Wind Energy in 2000



[a] source of CO_2 emission data: Ministry of Environment and Physical Planning: "National Programme for the Reduction of Greenhouse Gas Emissions", Athens (2002).
[b] no emission data available.
[c] all data are from 2002, source: EWEA (2003b).
[d] source of emission data: MVM, Hungary.
[e] no data available.
[f] source of emission data: NEK, Bulgaria.
[g] source of emission data: TEAS, Turkey.
Source: Eurelectric (2002), own calculations.

Figure 2.13: Specific Avoidable SO_2 Emissions in g/kWh by Wind Energy in 2000



[a] no emission data available.
[b] all data are from 2002, source: EWEA (2003b).
[c] source of emission data: MVM, Hungary.
[d] no data available.
[e] source of emission data: NEK, Bulgaria.
[f] source of emission data: TEAS, Turkey.
Source: Eurelectric (2002), own calculations.

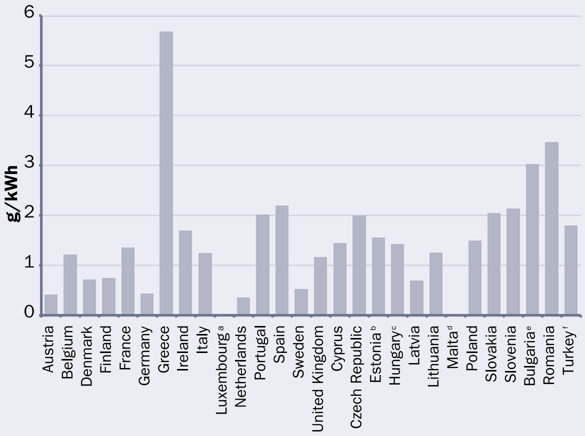
2.4.2 AVOIDABLE EXTERNAL COSTS BY THE USE OF WIND ENERGY

To calculate the external costs avoided by the use of wind energy, the external costs resulting from air pollutants such as SO_2 and NO_x (calculated by EcoSense) have to be added to the external costs of the anthropogenic greenhouse effect resulting from CO_2 emissions, which are not calculated by EcoSense.

As air pollutants can damage a large number of different receptors, calculations of external costs will generally include a large number of damages, which tend to be restricted to the most important impacts to allow a calculation of external costs with a limited resource input. At present, EcoSense includes the following receptors: humans (health), crops, materials (in buildings, etc.), forests and ecosystems, with monetary valuation only included for human health, crops and materials.

There are two approaches to evaluating effects on human health: value of statistical life (VSL); and years of life lost

Figure 2.14: Specific Avoidable NO_x Emissions in g/kWh by Wind Energy in 2000

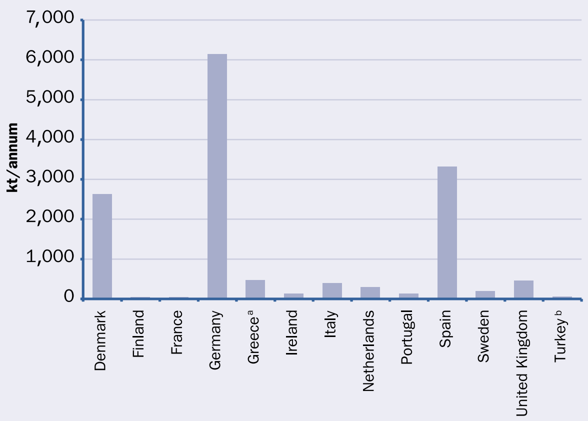


[a] no emission data available.
[b] all data are from 2002, source: EWEA (2003b).
[c] source of emission data: MVM, Hungary.
[d] no data available.
[e] source of emission data: NEK, Bulgaria.
[f] source of emission data: TEAS, Turkey.
Source: Eurelectric (2002), own calculations.

(YOLL). The VSL approach measures a society's willingness to pay to avoid additional deaths. This can be seen in spending on improved safety in the aircraft or car industry. In the EU and the US, figures of between US$/€1 million and US$/€10 million per life saved have been found in different studies. Earlier versions of the ExternE project adopted a figure of US$3 million per life saved for VSL calculations. In these calculations a person's age does not matter.

The YOLL approach takes age into account. In the case of chronic disease leading to death in a very old person, only the years of life lost due to the disease as compared to average life expectancy are taken into account. For each year of life lost approximately one-twentieth of the VSL value is used.

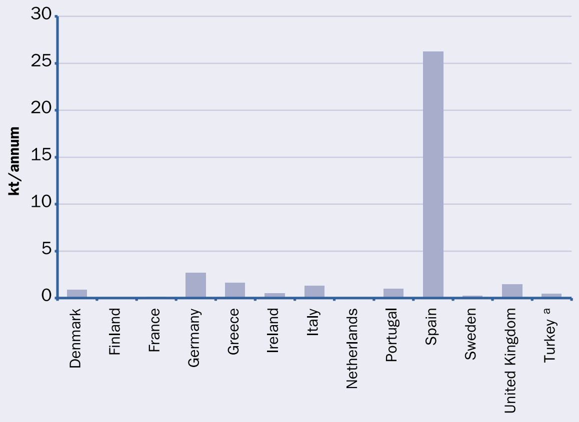
Figure 2.15: Total Avoided CO_2 Emissions in kt/annum by Wind Energy in 2000



[a] source of CO_2 emission data: Ministry of Environment and Physical Planning: "National Programme for the Reduction of Greenhouse Gas Emissions", Athens (2002).
[b] source of emission data: TEAS, Turkey.
Source: Eurelectric (2002), own calculations.

Using one or other approach may lead to substantially different results of monetised human health damages. Deciding which approach to use is a value judgement, based on society's underlying value system. Thus, calculations of the external costs of human health damages should always give both measures and leave it up to the reader or the policy-maker to decide which approach they think most appropriate.

Figure 2.16: Total Avoided SO_2 Emissions in kt/annum by Wind Energy in 2000



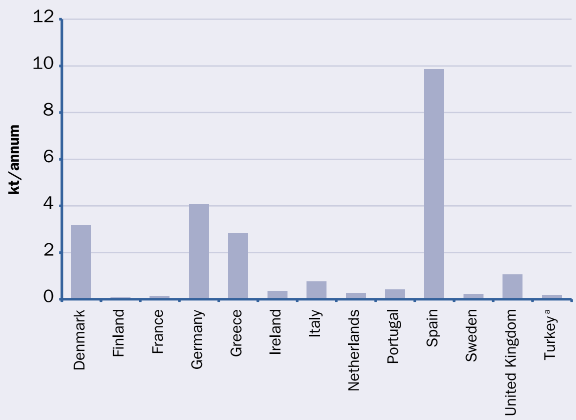
[a] source of emission data: TEAS, Turkey.
Source: Eurelectric (2002), own calculations.

Unfortunately, EcoSense does not provide a calculation based on the VSL approach. As pointed out above, VSL may lead to substantially higher external costs than the YOLL approach which is applied by the EcoSense model. Results of former ExternE studies estimate external costs based on both approaches. These resulted in VSL results approximately three times higher than those found with YOLL (Umweltbundesamt, 2002).

As the present version of EcoSense does not calculate VSL values, the EcoSense results on human health effects based on the YOLL approach have been scaled. This has been done with a factor of one for low damage cost estimates calculated for human health, a factor of two for medium cost estimates and a factor of three for high estimates.

As EcoSense does not calculate long-term damage from CO_2-induced climate change, the estimates of Azar and Sterner (1996) are used. As CO_2 remains in the atmosphere for about 100 years, most of the damage will occur in the distant future. If these damages apply to human health or irreversible environmental damages Rabel (1999) has strongly argued that no discounting should be applied, as the valuation of the damage increases with the discount rate. Based on a discount rate of 0%, dam-

Figure 2.17: Total Avoided NO_x Emissions in kt/annum by Wind Energy in 2000



[a] source of emission data: TEAS, Turkey.
Source: Eurelectric (2002), own calculations.

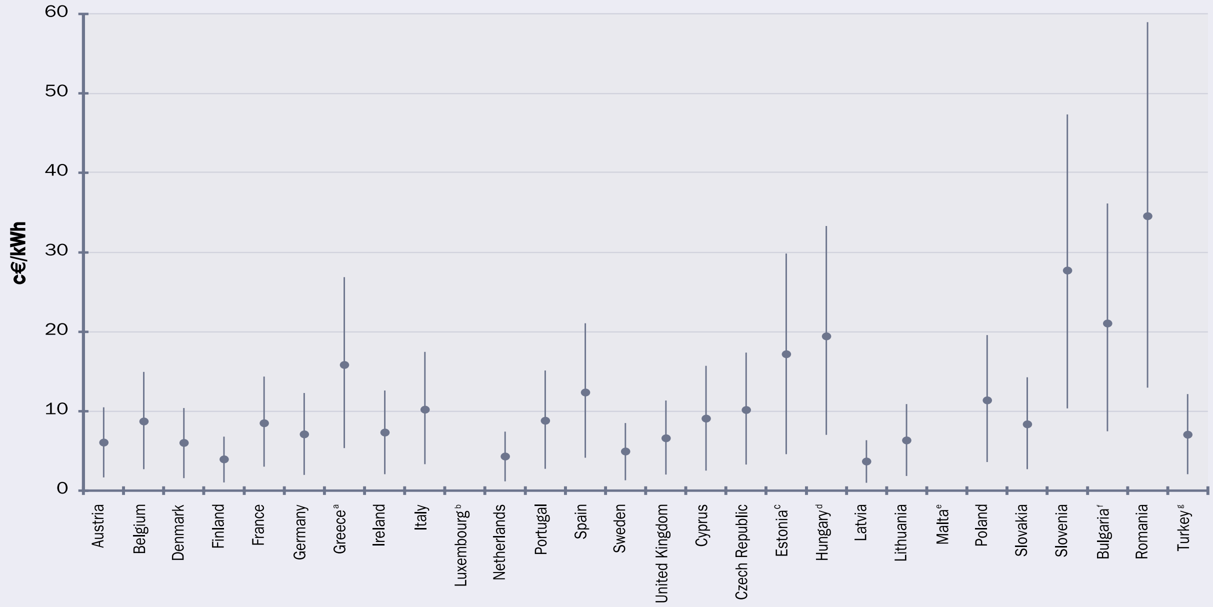
age costs of global warming are calculated by Azar and Sterner (1996) to be € (2000) 87.51 - 607.41/ton of carbon (see Appendix I). Recalculation in terms of CO_2 emissions leads to costs of € (2000) 23.87 - 165.69/ton of CO_2 (Umweltbundesamt, 2002). The remaining large range of the estimate is due to the time period taken into account for the analysed damages (300 or 1,000 years) and the way the question of damage in poor countries is dealt with.

Based on the EcoSense calculation, the avoidable external costs per kWh by wind energy have been evaluated. Results are shown in Figure 2.18.

The total avoided external costs in 2000 are shown in Figure 2.19.

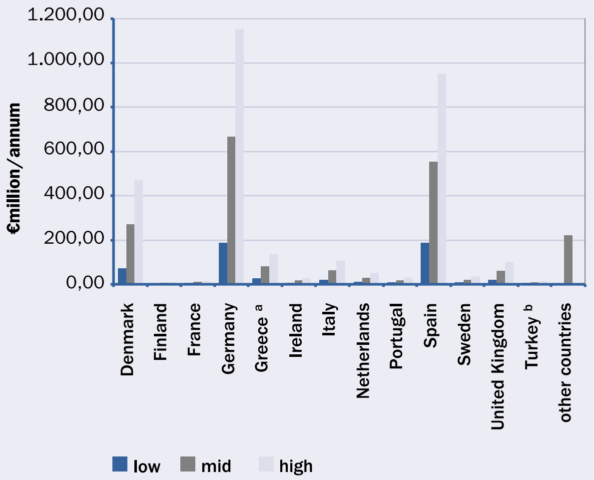
As can be seen in Figures 2.19 and 2.20, an amount of nearly €1.8 billion has been avoided by the use of wind energy electricity generation in 2000. Most of this applies to Germany (38%), Spain (31%) and Denmark (15%).

Figure 2.18: Avoidable External Costs in c€/kWh through the Use of Wind Energy in 2000, EU-25 and other European Countries



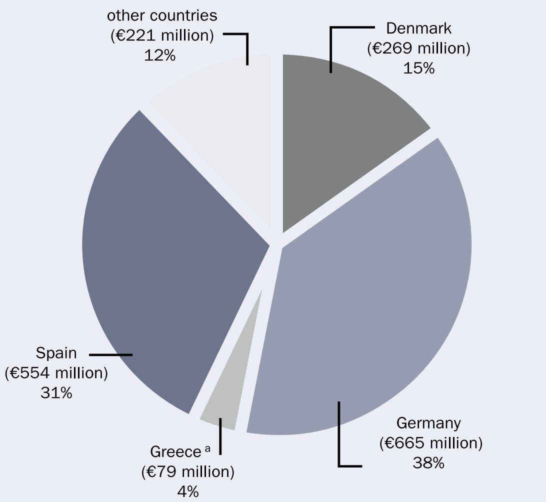
[a] source of CO_2 emission data: Ministry of Environment and Physical Planning: "National Programme for the Reduction of Greenhouse Gas Emissions", Athens (2002).
[b] no emission data available.
[c] all data are from 2002, source: EWEA (2003b)
[d] source of emission data: MVM, Hungary.
[e] no data available.
[f] source of emission data: NEK, Bulgaria.
[g] source of emission data: TEAS, Turkey.
Source: Eurelectric (2002), own calculations.

Figure 2.19: Total Avoided External Costs in €million/annum by the Use of Wind Energy in 2000



[a] source of CO_2 emission data: Ministry of Environment and Physical Planning: "National Programme for the Reduction of Greenhouse Gas Emissions", Athens (2002).
[b] source of emission data: TEAS, Turkey.
Source: Eurelectric (2002), own calculations.

Figure 2.20: Shares of Total Avoided External Costs by the use of Wind Energy in Europe 2000



[a] source of CO_2 emission data: Ministry of Environment and Physical Planning: "National Programme for the Reduction of Greenhouse Gas Emissions", Athens (2002).
Source: Eurelectric (2002), own calculations. Source of emission data for Turkey: TEAS, Turkey.

3 STANDARD METHODOLOGY FOR CALCULATION OF EMISSION REDUCTIONS

As shown above, the calculation of emission and external cost reductions achieved by the use of wind energy in the EU-15 and the 10 new member states along with Turkey, Bulgaria and Romania can be based either on the EcoSense model on the one hand or the regular reporting of electricity generation and emissions by Eurelectric (2002) on the other.

Forecasts of possible future emission reductions and reductions in resulting external costs can be carried out on this basis. Like the calculation of preceding emission reductions it can be divided into two parts: avoidable specific emissions (in mg/kWh) and avoidable total emissions (in kt/annum).

As the future emission reductions due to the use of wind energy cannot be calculated on the basis of present conventional electricity generating technologies and fuel mix, a forecast of future fuel mix and conventional technologies must be made.

Based on the specific avoidable emissions and the forecasted amount of electricity generated by wind energy, the total amount of avoidable emissions can be calculated.

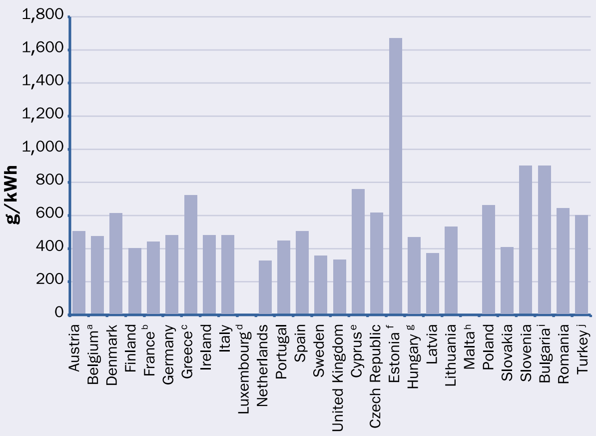
4 ANALYSIS OF EMISSION REDUCTIONS

The potential of future emission reductions has been carried out based on data for 2020. The year 2020 has been chosen as the last available year in Eurelectric forecasts. The options are combined with the volume of conventional electricity replaced by wind energy in Europe forecasted for the year 2020 by the EWEA (2003a).

4.1 Avoidable Specific Emissions through Wind Energy

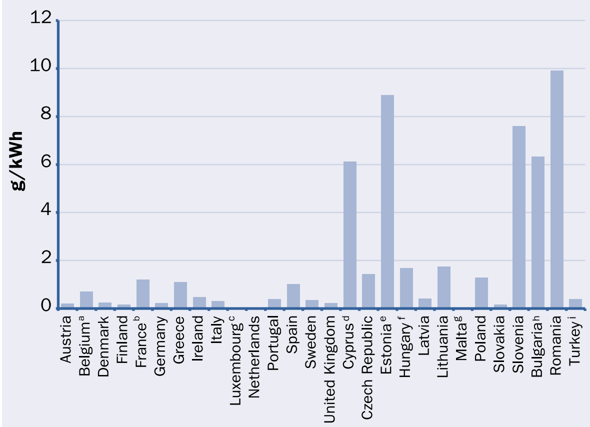
Future avoidable specific emissions through the use of wind energy are shown in Figures 4.1 to 4.3.

Figure 4.1: Specific Avoidable CO_2 Emissions in g/kWh by Wind Energy in 2020, EU-25 and other European Countries



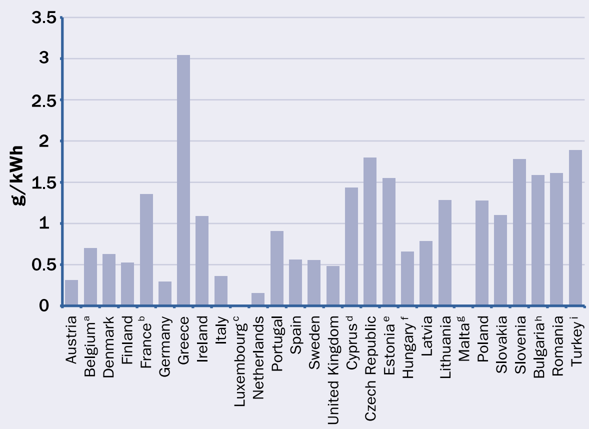
[a] all data are for 2010.
[b] all data are from 2000.
[c] source of CO_2 emission data: Ministry of Environment and Physical Planning: "National Programme for the Reduction of Greenhouse Gas Emissions", Athens (2002).
[d] no emission data available.
[e] all data are for 2010.
[f] all data are from 2002, source: EWEA (2003b).
[g] source of emission data: MVM, Hungary.
[h] no data available.
[i] source of emission data: NEK, Bulgaria.
[j] source of emission data: TEAS, Turkey.
Source: Eurelectric (2002), own calculations.

Figure 4.2: Specific Avoidable SO_2 Emissions in g/kWh by Wind Energy in 2020, EU-25 and other European Countries



[a] all data are for 2010.
[b] all data are from 2000.
[c] no emission data available.
[d] all data are for 2010.
[e] all data are from 2002, source: EWEA (2003b).
[f] source of emission data: MVM, Hungary.
[g] no data available.
[h] source of emission data: NEK, Bulgaria.
[i] source of emission data: TEAS, Turkey.
Source: Eurelectric (2002), own calculations.

Figure 4.3: Specific Avoidable NO_x Emissions in g/kWh by Wind Energy in 2020, EU-25 and other European Countries



[a] all data are for 2010.
[b] all data are from 2000.
[c] no emission data available.
[d] all data are for 2010.
[e] all data are from 2002, source: EWEA (2003b).
[f] source of emission data: MVM, Hungary.
[g] no data available.
[h] source of emission data: NEK, Bulgaria.
[i] source of emission data: TEAS, Turkey.
Source: Eurelectric (2002), own calculations.

The figures show that specific avoidable emissions are going to decrease from 2000 to 2020. This is due to two factors. Firstly, the fuel mix is going to change in coming decades in most of the countries covered by this study. In many cases, high emission fuels will partly be replaced by those with relatively low emissions. Accordingly, the share of fuel oil and, in particular, natural and derived gas will increase significantly. Parallel to this, the amounts of electricity generated by hard coal and lignite are going to decrease or stagnate. This will lead to a lower volume of specific avoidable emissions by wind energy in 2020 compared with 2000.

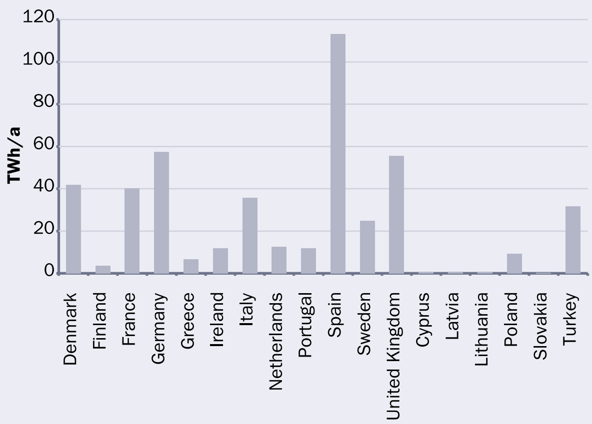
Secondly, there will be a significant improvement in the technology of fossil fuel based electricity generation. The east-European states, in particular, will up-grade their technology by fitting SO_2 scrubbers and improving combustion processes to reduce NO_x emissions.

4.2. Avoidable Total Emissions Through Wind Energy

Based on the expected amount of electricity generated by wind energy, avoidable total emissions have been calculated (see Figures 4.5 to 4.7).

Forecasts of electricity generation by wind energy are based on data from the EWEA (2003a) relating to total electricity generation and on data from Eurelectric (2002) concerning the distribution of generation between the countries.

Figure 4.4: Electricity Generation by Wind Energy in TWh/annum in 2020

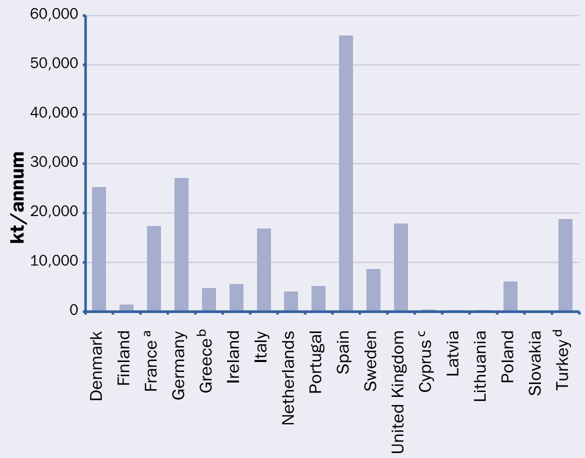


Source: EWEA (2003a), own calculations.

As shown in Figure 4.4, the amount of electricity generated by wind energy will increase strongly from 2000 to 2020. For 2020, a total of 425 TWh/annum is forecasted by the EWEA (2003a) for the EU-25 countries. For all 28, this would lead to a forecast of more than 450 TWh/annum in 2020, an increase of nearly 2,000% within 20 years.

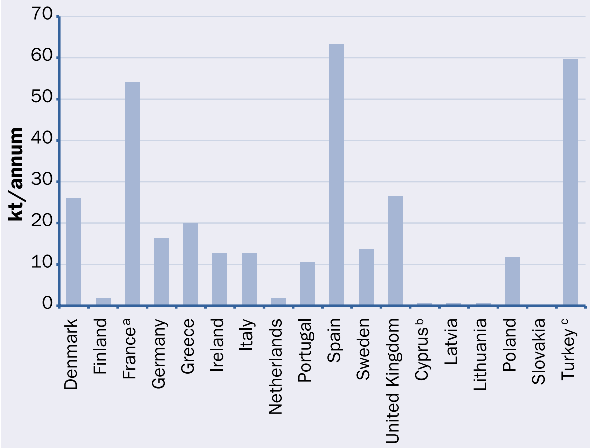
As shown in Figures 4.5 to 4.7, total avoidable emissions depend on the level of specific avoidable emissions in each country. Therefore, the total avoidable emissions are not only related to the amount of electricity generated by wind energy.

Figure 4.5: Total Avoidable CO_2 Emissions in kt/annum by Wind Energy in 2020, EU-25 and Turkey



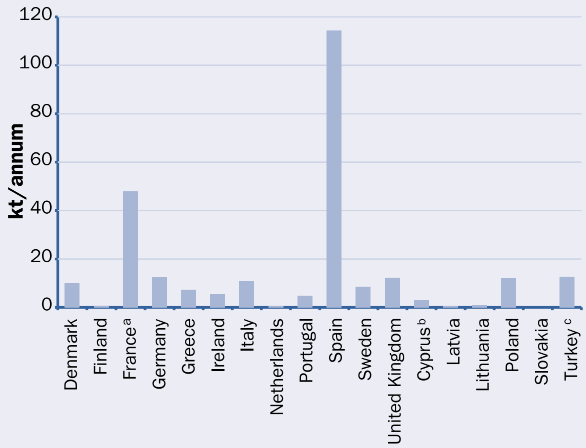
[a] all data are from 2000. Calculation of electricity generation by wind energy based on data for 2010 resp. 2020.
[b] source of CO_2 emission data: Ministry of Environment and Physical Planning: "National Programme for the Reduction of Greenhouse Gas Emissions", Athens (2002).
[c] all data are for 2010. Calculation of electricity generation by wind energy based on data for 2010 resp. 2020.
[d] source of emission data: TEAS, Turkey.
Source: Eurelectric (2002), EWEA (2003a), own calculations.

Figure 4.7: Total Avoidable NO_X Emissions in kt/annum by Wind Energy in 2020, EU-25 and Turkey



[a] all data are from 2000. Calculation of electricity generation by wind energy based on data for 2010 resp. 2020.
[b] all data are for 2010. Calculation of electricity generation by wind energy based on data for 2010 resp. 2020.
[c] source of emission data: TEAS, Turkey.
Source: Eurelectric (2002), EWEA (2003a), own calculations.

Figure 4.6: Total Avoidable SO_2 Emissions in kt/annum by Wind Energy in 2020, EU-25 and Turkey

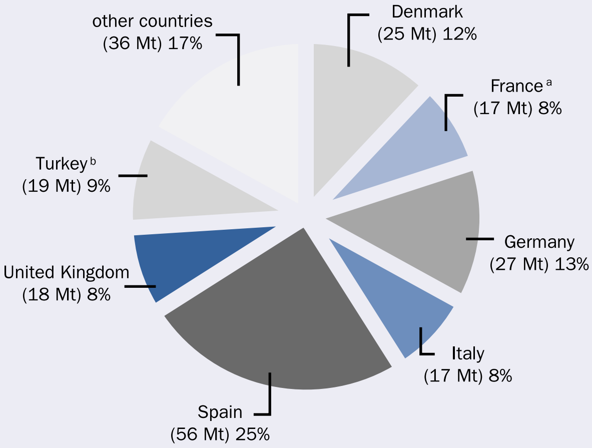


[a] all data are from 2000. Calculation of electricity generation by wind energy based on data for 2010 resp. 2020.
[b] all data are for 2010. Calculation of electricity generation by wind energy based on data for 2010 resp. 2020.
[c] source of emission data: TEAS, Turkey.
Source: Eurelectric (2002), EWEA (2003a), own calculations.

As can be seen in Figures 4.6 and 4.7, the potential for emission reductions is very high in Spain. This is again explained by SO_2 and NO_x emissions, which are forecast to still be relatively high in Spain in 2020 in comparison with other countries.

Figures 4.8 to 4.10 show the shares of total avoidable emissions in Europe in 2020. Again, avoidable emissions in Spain are a lot higher than in the UK, for example, even though wind energy generation in the UK will be at the same level as that in Spain. A comparison of the wind energy electricity generation capacity of Spain and Germany shows that Spain, according to Eurelectric estimates, will be producing twice the amount of wind generated electricity in 2020 than Germany. But the total avoidable SO_2 emissions in Spain will be 10 times higher than Germany's.

Figure 4.8: Avoidable CO_2 Emissions in Mt/annum Wind Energy in 2020

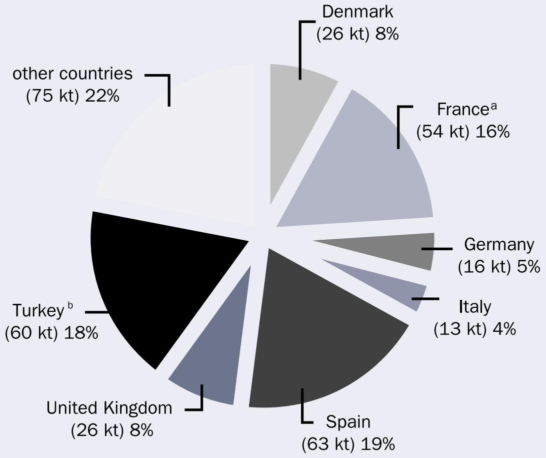


[a] all data are from 2000. Calculation of electricity generation by wind energy based on data for 2010 resp. 2020.

[b] source of emission data: TEAS, Turkey.

Source: Eurelectric (2002), EWEA (2003a), own calculations. Source of CO_2 emission data from Greece: Ministry of Environment and Physical Planning: "National Programme for the Reduction of Greenhouse Gas Emissions", Athens (2002). All data from Cyprus are for 2010. Calculation of electricity generation by wind energy for Cyprus based on data for 2010 resp. 2020.

Figure 4.10: Avoidable NO_X Emissions in kt/annum by Wind Energy in 2020

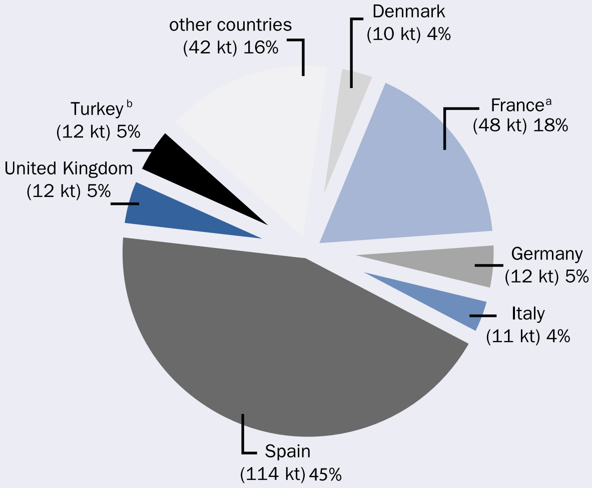


[a] all data are from 2000. Calculation of electricity generation by wind energy based on data for 2010 resp. 2020.

[b] source of emission data: TEAS, Turkey.

Source: Eurelectric (2002), EWEA (2003a), own calculations. All data from Cyprus are for 2010. Calculation of electricity generation by wind energy for Cyprus based on data for 2010 resp. 2020.

Figure 4.9: Avoidable SO_2 Emissions in kt/annum by Wind Energy in 2020



[a] all data are from 2000. Calculation of electricity generation by wind energy based on data for 2010 resp. 2020.

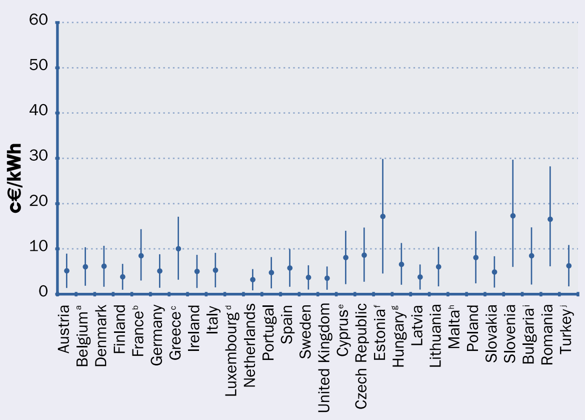
[b] source of emission data: TEAS, Turkey.

Source: Eurelectric (2002), EWEA (2003a), own calculations. All data from Cyprus are for 2010. Calculation of electricity generation by wind energy for Cyprus based on data for 2010 resp. 2020.

4.3 Avoidable External Costs Through Wind Energy

In line with the specific emissions, the avoidable specific external costs in c€/kWh decrease from 2000 to 2020, especially in south-eastern European states where avoidable costs are significantly less than in 2000 (see Figure 4.11).

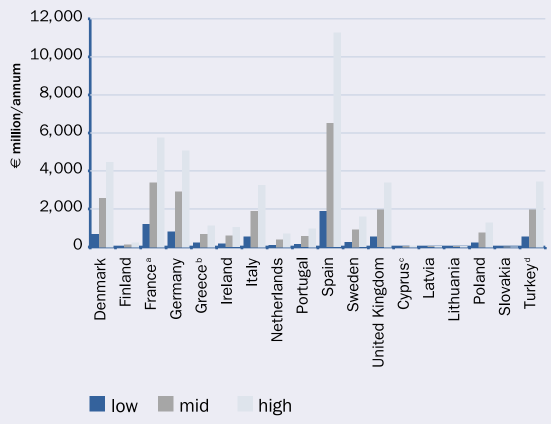
Figure 4.11: Avoidable External Costs in c€/kWh by the Use of Wind Energy in 2020, EU-25 and other European Countries



[a] all data are for 2010.
[b] all data are from 2000.
[c] source of CO_2 emission data: Ministry of Environment and Physical Planning: "National Programme for the Reduction of Greenhouse Gas Emissions", Athens (2002).
[d] no emission data available.
[e] all data are for 2010.
[f] all data are from 2002, source: EWEA (2003b).
[g] source of emission data: MVM, Hungary.
[h] no data available.
[i] source of emission data: NEK, Bulgaria.
[j] source of emission data: TEAS, Turkey.
Source: Eurelectric (2002), EWEA (2003a), own calculations.

Nevertheless, total annual avoidable external costs in 2020 are much higher than in 2000. They are expected to increase from €1.8 billion in 2000 to more than €25 billion a year in 2020 because of the expected increase in electricity generation by wind energy, from 22 TWh/a in 2000 to more than 450 TWh/a in 2020. While electricity generation by wind energy is expected to increase by nearly 2,000% from 2000 to 2020, avoidable external costs will increase by about 1,400%.

Figure 4.12: Total Avoidable External Costs in €Million/annum by the Use of Wind Energy in 2020, EU-25 and Turkey

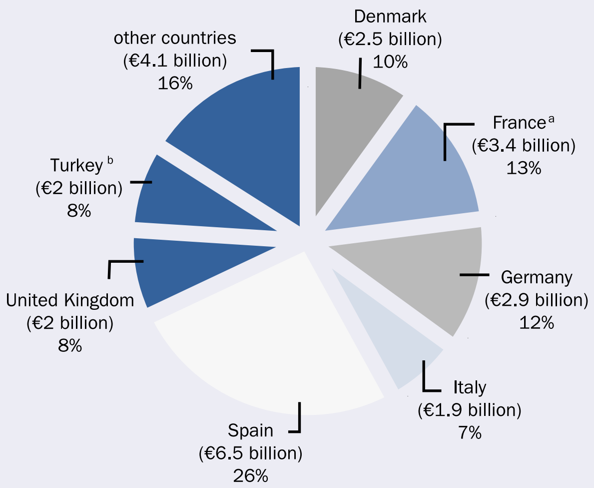


[a] all data are from 2000. Calculation of electricity generation by wind energy based on data for 2010 resp. 2020.
[b] source of CO_2 emission data: Ministry of Environment and Physical Planning: "National Programme for the Reduction of Greenhouse Gas Emissions", Athens (2002).
[c] all data are for 2010. Calculation of electricity generation by wind energy based on data for 2010 resp. 2020.
[d] source of emission data: TEAS, Turkey.
Source: Eurelectric (2002), EWEA (2003a), own calculations.

Total avoidable external costs in 2020 are shown in Figure 4.12. Spain will take over pole position from Germany in avoiding external costs by the use of wind energy.

Figures 4.12 and 4.13 show that many more countries will take part in avoiding external costs by the use of wind energy in 2020 than in 2000. Each of the seven countries shown in Figure 4.13 will avoid more external costs in 2020 by using wind energy than all the countries together in 2000 (each more than €1.8 billion a year); some of them are expected to avoid more than three times this amount (e.g. €6.5 billion in the case of Spain).

Figure 4.13: Shares of Total Avoidable External Costs by the Use of Wind Energy in Europe in 2020



[a] all data are from 2000. Calculation of electricity generation by wind energy based on data for 2010 resp. 2020.

[b] source of emission data: TEAS, Turkey.

Source: Eurelectric (2002), EWEA (2003a), own calculations. Source of CO_2 emission data for Greece: Ministry of Environment and Physical Planning: "National Programme for the Reduction of Greenhouse Gas Emissions", Athens (2002). All data for Cyprus are for 2010. Calculation of electricity generation by wind energy based on data for 2010 resp. 2020.

5 PUBLIC ACCEPTANCE ANALYSIS

Previous chapters have reported the environmental benefits of wind energy in the current European electricity supply system and shown its potential future benefits. How much of this potential can be achieved? What are the main obstacles to overcome, so that the sector continues to grow? These questions are being addressed through policy instruments, financial mechanisms, national renewable energy targets, R&D programmes, etc. Combined with increasing public awareness of climate change and sustainability, these are important drivers for a thriving renewable energy sector. But the most important issue is public acceptance, especially by local communities and individuals living at prospective wind farm sites. Whether an installation goes ahead or not often relies on them.

The purpose of this chapter is to give an overview of the environmental impacts and other factors affecting public acceptance of wind energy.

5.1 Environmental Impacts of Wind Energy

Although wind energy is a clean technology, it is not free of impacts on the environment. Wind energy has a number of special features, including:

- More than one wind turbine (WT) is needed for large-scale production.
- WTs are mainly located in remote and rural areas where the wind resource is present.
- The turbines may be visible from a great distance.
- The movement of the blades (flickering) may draw attention.

As well as these visual impacts, wind energy is associated with other environmental issues such as noise, land use and impacts during the construction phase. Some impacts, such as those on birds and flickering can be measured quantitatively; others, such as visual intrusion and noise require more subjective and qualitative criteria.

These impacts are considered in this section. In addition, an analysis of the primary energy consumption of a WT compared with a coal fired power plant is given.

5.1.1 VISUAL IMPACT

The siting of WTs affects the visual or aesthetic properties of the surroundings, especially in locations where people place a high value on the landscape. This is referred to as the 'visual impact' of wind energy. Visual impact has a direct effect on amenity, defined as resources available for people's convenience, enjoyment and comfort, in this case a landscape.

A landscape attracts different perceptions since aesthetic values such as beauty and diversity are subjective (Schwahn, 2002), while its value will also be influenced by use (e.g. national park, wildlife habitat, agricultural land).

Protected areas of national or regional importance are more sensitive to the visual impact of wind energy. In addition, wind energy may compete with other public uses such as recreation, agriculture, tourism, wildlife conservation, and others.

The perceptions of individuals in communities affected by wind energy will depend on their attitudes to scenery and natural beauty, the existing level of visual amenity and their general attitude to WTs (Manwell, 2002).

Modern turbines are becoming larger both in size and capacity, and hence more dominant in the landscape. At the same time, the spacing between turbines is increasing, thus lessening their density in a given area. The development of the technology is therefore changing the visual impact of wind farms from high density groupings with high rotational speeds to fewer, larger machines operating at lower rotational speeds.

Other visual impacts of WTs are lighting and, in the vicinity of airports for example, marking to reduce bird collisions. Ancillary facilities such as stores, substations, transmission lines and roads also impact on amenity.

In order to maintain public acceptance, wind farms need to be designed in such a way as to minimise these various aesthetic and amenity impacts (see Table 5.1).

Table 5.1: Aesthetic Guidelines for Wind Plants

Ensure visual uniformity (direction of rotation, type of turbine and tower, and height)
Avoid fencing
Minimise or eliminate roads
Bury intraproject power lines
Limit or remove ancillary structures from site
Remove inoperative turbines
Avoid steep slopes
Control erosion and promptly revegetate
Remove litter and scrap
Clean dirty turbines and towers

Source: Gipe (1995).

The use of a computer simulation to generate a virtual image of the proposed wind farm can help developers and planners assess its visual impact.

The visual impact of wind energy has a big influence on public perception and acceptance of the technology. Efforts to integrate WTs aesthetically into the landscape and the sharing of economic benefits with local communities may help to soften negative attitudes to wind energy. These aspects are discussed later in this section.

5.1.2 NOISE

Noise is defined as an unwanted sound. It can be measured quantitatively, and regulations exist to limit noise levels, but it also has a subjective element. Manwell (2002) classifies the effects of noise from wind energy into two main categories:

- Subjective effects including annoyance, nuisance, dissatisfaction.
- Interference with activities such as conversation.

Noise from WTs comes from the sound produced by the turning blades and from the gearbox, generator and hydraulic systems (although in modern WTs this mechanical noise has been reduced almost to zero). As with other impacts of wind energy, perception of the noise depends on local features (e.g. rural or urban area, topography), number and distance of residents from the WT site, and the type of community affected (residential, industrial, tourist). The interaction of these factors lessens or enhances the perception of sound from WTs.

Physically, sound is a pressure variation detected by the ear; It depends on the source and the medium through which it travels. The speed of sound is about 340 m/s in atmospheric air. It is important to make a distinction between sound power level and sound pressure level. The former is a property of the source of the sound whereas sound pressure level is a property of the sound at a given observer location. Noise is measured in decibels (dB) and the scale employed (dBA) is weighted to the range perceived by the human ear. Table 5.2 shows a comparison of different power and pressure levels of sound to indicate what can be considered a threshold of hearing or a pain threshold.

The most important factors affecting noise propagation are: type of noise source, distance from source, wind speed, temperature, humidity, precipitation and the presence of barriers and buildings. The factors with the most influence on noise propagation are the distance of the source from the observer and the type of source.

Table 5.2: Level of Sounds

Source	Distance from the Source (m)	Sound Level (dBA)	Environmental Noise*	Subjectivity/ Impression
Civil defence siren	140-130			Threshold of pain
Jet take-off	61	120		
		110	Rock concert	Very loud
Pile driver	15	100		
Ambulance siren	31	90	Boiler room	
Freight train	15	80		
Pneumatic drill	15	80	Printing press	Loud
Motorway traffic	31	70		Moderately loud
Vacuum cleaner	31	60	Data processing centre Department store/office	
Light traffic	31	50	Private business office	Quiet
WT > 1MW	200	49		
WT > 1MW	300	45		
Large transformer	61	40		
Soft whisper	2	30	Quiet bedroom	
	20		Recording studio	
	10			Threshold of hearing
	0			

WT data is an estimation for illustrative purposes (University of Flensburg).
* Environmental noise is shown as an equivalent noise source at the sound level given.
Source: National Wind Co-ordinating Committee (2002).

From the table, it can be seen that distance plays an important role in the perceived sound level. The noise from a WT can reach moderate sound pressure levels (< 50 dBA) when the distance from the turbine to the receptor is between 200 and 300 m. Typically, the sound power level of a modern WT is between 100 and 106 dBA depending on the type of turbine and the wind speed at which the sound is measured (typically 8 m/s).

The decibel scale must be carefully interpreted when evaluating the number of turbines to be placed and their effects. A WT with a capacity higher than 1 MW has a sound power level of 104 dBA for example. The installation of a second turbine with the same sound power level will cause an increase of only 3 dBA. Increasing the energy of a sound by 26% raises the noise power level 1 dBA. Tripling the energy of a sound yields an increase of 5 dBA. The dBA scale is a logarithmic scale. In other words, as the sound power is doubled (two turbines) the index increases by approximately 3 dBA. A sound level of 100 dBA thus contains twice the energy of a sound level of 97 dBA. The sound level decreases with greater distance from the source by approximately 6 dBA every time the distance is doubled (Gipe, 1995).

In summary, the total perceived noise is the relative sum of the ambient or background noise and the WT noise. The ambient noise can mask the turbine noise completely if the turbines are located in an industrial or urban area. Trees may also mask distant WT noise.

Another important factor is time. WT noise can be present for hours, days or for longer periods depending on the wind resource. An excellent wind resource location (e.g. load factors of 40%) can cause the turbines to operate for more than 3,000 hours a year. The frequency of the noise will also affect sound pressure levels.

Regulatory standards for determining acceptable sound pressure levels take this time component into account. The standards are as follows (Renewable Energy Research Laboratory, 2002):

- L_{10}, L_{50}, L_{90}: The A-weighted sound levels that are exceeded 10%, 50%, 90% of the time. For example 45 dBA L_{90} means that the sound level must not exceed the level indicated 90% of the time.
- L_{eq} (equivalent sound level): The average A-weighted sound pressure level which gives the same total energy as the varying sound level during the measurement period.
- L_{dn} (day night level): The average A-weighted sound pressure level during a 24-hour period, obtained after adding 10 dBA to levels measured in the night between 10 p.m. and 7 a.m.

Table 5.3 shows the noise limits of sound pressure levels in some European countries. State-of-the-art turbines with capacities higher than 1 MW generally have sound power levels of between 100 and 106 dBA. Thus, a modern turbine has to be placed at a distance of between 200 m and 300 m from the receptor to reach a sound pressure level of between 45 dBA and 50 dBA (see Table 5.2).

Table 5.3: Legal Noise Limits in dBA

	Commercial	Mixed	Residential	Rural
Germany				
Day	65	60	55	50
Night	50	45	40	35
Netherlands				
Day (L_{eq})		50	45	40
Night		40	35	30
Denmark (L_{eq})			40	45
UK				
High speed (L_{50})				45
Low Speed (L_{50})				40

Source: Gipe (1995).

A noise assessment aims to determine how the turbines affect the existing ambient background noise and also what is an acceptable level of noise from the turbines themselves. The assessment should be able to demonstrate compliance with national noise regulations.

5.1.3 LAND USE

Land use refers to any alteration of current and future uses that can be affected by the installation of WTs.

The wind project developer must contact regional, national and local agencies to check for any land use restrictions in order to seek permission for the development to go ahead. Equally important is the need to assess the views of the local population so that any concerns they may have on land use are investigated and resolved.

Given the diffuse characteristics of wind energy, it is necessary to locate several turbines together to achieve the same capacity as conventional fossil fuel power plants. Thus, wind energy installations require larger areas than conventional power plants. This is due to aspects such as turbine spacing, topography, location of power lines and other associated facilities, in conjunction with other issues such as protected areas, access roads, land use objectives of the community and incompatibility in land-use.

However, only 1% to 3% of the total area is occupied by the turbine (tower base area, the foundations are mostly underground). So up to 99% of the land on which the turbines are sited will still be available for other uses. In Europe, most wind energy sites are located in remote, rural areas where livestock grazing is a common practice (see Figure 5.1).

Figure 5.1: Wind Energy in Rural Areas

Source: University of Flensburg (Lehbek in Gelting. Schleswig-Holstein, Germany).

5.1.4 IMPACT ON BIRDS

The main impacts of WTs on birds are deaths caused by the birds colliding with power lines and blades, and disturbance to migration routes. The main causes are listed as follows (Manwell, 2002):

- Death or injury caused by rotating blades.
- Electrocution from transmission lines.
- Alteration of migration habits.
- Reduction of available habitat.
- Disturbance to breeding, nesting and foraging.

More sensitive areas are those on migration paths and with a high number of birds present. The impacts are variable depending on the species, season and site-specificity (BirdLife, 2002).

According to the latest report by BirdLife (2003), the main potential hazards to birds from WT sites are: disturbance leading to displacement or exclusion, including barriers to movement; collision mortality; and loss of, or damage to, habitats. These aspects are further explained as follows.

Disturbance

The BirdLife report cites several studies showing that within 600 m from WTs bird numbers are reduced. However, the report states that: "The scale of such habitat loss, together with the extent of availability and quality of other suitable habitats that can accommodate displaced birds, and the conservation status of those birds, will determine whether or not there is an adverse impact." (p.2)

Disturbance to bird populations may also result from increased human activities around the site, for maintenance purposes, etc., as well as WT noise and movement (BirdLife, 2003). In intensively farmed areas, however, the presence of WTs may have little effect on wild and farmland bird populations which will already be depleted due to intensive agricultural practices.

Collision Risk and Mortality

With respect to collision mortality, the two most critical examples are the Altamont Pass. California, USA and La Tarifa in Spain, both of which raised concerns over their impact on birds (National Wind Coordinating Committee, 2002). In the case of Altamont Pass, the issue arose in the late 1980s when the California Energy Commission recorded 99 dead birds in a four-year period from 1984 to 1988 which had been killed by the WT, transmission lines or other unknown cause (Gipe, 1995). The Altamont Pass wind park is characterised by a high density of turbines and the coexistence of turbines of diverse types and size. At Altamont Pass, the main losses were of raptors (birds of prey such as hawks and eagles) while at La Tarifa soaring birds (storks and vultures) were affected. Both areas have high concentrations of birds (BirdLife, 2003). These wind parks are examples of how poor siting and out-moded WTs and tower technology can adversely impact bird populations (Sagrillo, 2003). Subsequent experiences in Germany and Denmark show that such effects can largely be avoided by responsible planning practice.

In 2001, Western EcoSystems Technology Inc. was commissioned by the National Wind Coordinating Committee (NWCC) to study avian collisions with WTs and other structures. The study aimed "to provide a detailed summary of the mortality data collected at windplants and put avian collision mortality associated with windpower development into perspective with other significant sources of avian collision mortality across the United States".

The study estimated that in 2001 in the US, 33,000 birds were killed by the 15,000 turbines in operation, with the majority of these fatalities projected to occur in California where approximately 11,500 operational turbines exist. Most of the California turbines are older and smaller machines, with a capacity ranging between 100 to 250-kW (Western EcoSystems Technology Inc., 2001). The results indicate that each turbine in the US accounts for 2.19 avian deaths a year for all species combined and 0.033 raptor fatalities per turbine per year.

In Spain, a study carried out in the state of Navarra (EHN, 2003) on the impact of wind parks on bird life showed that 692 turbines located in 18 wind farms do not put any species at risk from death by collision. 88 deaths of medium and large birds were detected, which represents an annual mortality rate of 0.13 dead birds per turbine. In other words, it takes more than seven years for one turbine to kill one bird.

In a study for the Finnish Ministry of Environment, Koistinen (2002) showed that 10 birds were killed by 60 WTs in a one-year period.

The likelihood of bird collisions is determined by wind speed, nature and height of flight, species, age of bird and stage in its breeding cycle. Most studies have been carried out on smaller turbines (BirdLife, 2002); newer, larger turbines may have different effects. Low bird fatality rates do not mean that efforts to reduce the impact of WTs on bird populations are unnecessary; even a low collision rate in a sensitive area may be significant for some bird species.

Habitat Loss or Damage

Loss or damage to habitats is caused by turbine bases, substations, access roads and transmission line corridors. This is not believed to be a major concern to birds outside sensitive areas, such as designated sites of national and international importance (BirdLife, 2003).

Recommendations

Proper siting of turbines is important if adverse impacts on birds are to be avoided. The following criteria have been proposed (Manwell, 2002):

- Avoid migration corridors.
- Avoid siting in specific microhabitats.
- Use appropriate tower design (tubular towers or lattice towers.
- Route electrical lines underground.

These criteria could be incorporated into national or regional planning strategies. An EIA systematically examines the possible environmental consequences of implementing projects, programmes and policies (United Nations, 2002). EU Directive 85/337/EEC requires an assessment of the environmental effects of those public

and private projects which are likely to have significant effects on the environment. The Directive was amended in March 1997 by Directive 97/11/EC which included, in its Annex II, installations for the harnessing of wind power for energy production (wind farms). For wind energy developments every EU member state shall assess the project's environmental impacts on a case by case basis.

Impacts on Birds in Context

The impact of wind energy on birds must be placed in context (Youth, 2003). Virtually all threats to birds are human-related (99%), with habitat loss as a result of industrialisation, over-exploitation of natural resources, over-population (human), etc., being the biggest threat. Other threats include hunting, the pet trade, unsustainable fishing practices, oil spills, and oil and natural gas exploration, extraction and transportation. Chemical and pollution threats such as pesticides, lead from spent hunters' shot or sinkers left by anglers are also significant. Structures such as skyscrapers, communication towers and transmission lines kill migrating birds, while climate change poses a new threat to bird habitats.

With respect to wind park developments, location is a critical factor and there is a need for further research on the new, larger, generation of turbines.

In the US, the Western EcoSystems Technology Inc. (2001) study found a range of between 100 million to 1 billion bird fatalities due to collisions with artificial structures such as vehicles, buildings and windows, power lines and communication towers, in comparison to 33,000 fatalities attributed to WTs. The study reports that, "windplant-related avian collision fatalities probably represent from 0.01% to 0.02% (e.g. one out of every 5,000 to 10,000 avian fatalities) of the annual avian collision fatalities in the United States, while some may perceive this level of mortality as small, all efforts to reduce avian mortality are important".

In Finland, Koistinen (2002) reports 10 bird fatalities from turbines, and 820,000 birds killed annually from colliding with other structures such as buildings, electricity pylons and lines, telephone and television masts, lighthouses and floodlights.

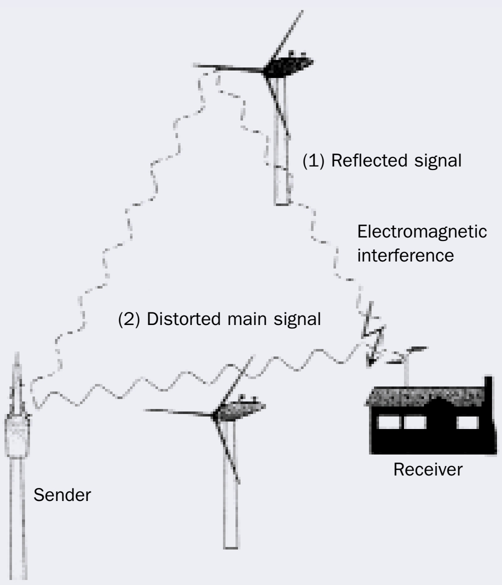
5.1.5 IMPACTS OF CONSTRUCTION ON TERRESTRIAL ECOSYSTEMS

These impacts consist of long-term loss of land from turbine installation and their associated electrical connections, buildings and access tracks. It has to be noted, however, that only the access roads and a very small area around the tower of a WT are lost. Danish and German research shows that agriculture may continue in rural wind parks, which are often used for grazing cattle.

5.1.6 ELECTROMAGNETIC INTERFERENCE (EMI)

WTs or generation equipment can interfere with communication systems that use electromagnetic waves (see Figure 5.2). This is caused mainly by the turbine blades, which sometimes scatter the signals as they rotate. The tower may also reflect signals, so interfering with the original signal arriving at the receiver (Manwell, 2002).

Figure 5.2: Electromagnetic Interference



Source: Manwell *et al*. (2002).

EMI mainly affects television reception, aircraft navigation and landing systems, as well as microwave links. Interference with television reception is the most common effect but it can be easily and cheaply corrected. Other mentioned impacts are unlikely to happen unless the turbines are placed in close proximity to the transmitter or receiver. EMI effects on FM radio, cellular phones and satellite services are very unlikely to occur.

EMI is a site-specific issue. It is recommended that an on-site assessment is performed to identify any effects on radio services in the area as well as the interference zones.

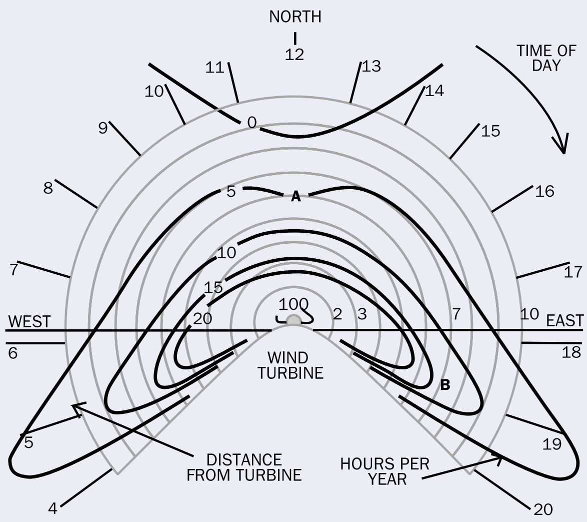
5.1.7 FLICKERING

The rotating turbine blades cast moving shadows which cause a flickering that can affect residents living nearby. Similarly, gloss surface blades flash when they rotate. This effect has been subject to analysis especially in northern Europe where this effect is considered, although it is not seen as an issue in the US (Gipe, 1995).

Figure 5.3 shows an example of the shadow flicker effect. The figure has been constructed for Denmark. The results would vary for different countries due to differences in cloud cover and latitude. There are two houses in the picture marked as A and B which are respectively six and seven hub heights away from the turbine in the centre. The diagram shows that house A will experience a shadow from the turbine for five hours per year. House B will experience a shadow for up to about 12 hours per year. Seasonal variation is also included in the calculation but is difficult to show without undue complication (European Commission, 1999).

In Germany, a court has ruled that the maximum allowable shadow flicker a year is 30 hours (Danish Wind Industry Association, 2003). Programmes exist that automatically shut the turbine down when conditions make flickering likely.

Figure 5.3: Shadow Calculation



5.1.8 CONSUMPTION OF ENERGY (ENERGY BALANCE)

In a conventional coal fired fossil power plant, the fuel cycle consists of exploring, mining, processing and transporting coal, as well as manufacturing and installing the equipment, the power plant operation and the disposal of waste. In the case of a renewable source like wind, the fuel cycle includes only the activities required to produce, install, maintain and decommission the turbine and its ancillary systems. The activities in the fuel cycle require an input of energy to make possible the production of energy from a wind turbine.

How long does a WT take to recover the energy spent in its fuel cycle, and how much energy does it produce? According to a study by the Danish Wind Industry Association (1997), modern WTs recover all energy inputs in three to four months (see Table 5.5) and will save between 63-78 times the energy input required to operate a coal fired plant over a 20 year period.

The study estimated the energy requirements of a typical Danish 600 kW WT during its 20-year lifetime (see Table 5.4).

Table 5.4: Energy Use During Life Cycle, 600 kW WT

Gross energy use	total (TJ)
Manufacture of turbine	1.9
Installation of turbine	0.495
O&M (20 years)	0.774
Total excluding scrapping	***3.169***
Scrapping, energy use	0.522
Scrapping, recovered energy	-0.733
Total including scrapping	***2.958***
Total incl. scrapping MWh	***821***

Source: Danish Wind Industry Association (1997).

The study then estimated how much energy usage (primary energy consumption) is required in a coal fired plant to produce the same amount of electricity as the turbine producers in one year.

Table 5.5 shows that to produce the same quantity of electricity per year, the WT requires far less energy input (821 MWh) than the coal-fired power plant. (3,202 MWh/2,598 MWh).

It should be noted that these are conservative estimates since the primary energy consumption does not include coal fired plant construction and operation or indirect energy use during the coal firing process. Furthermore, the comparison assumes a thermal efficiency of 45% which is well above the average figure for coal fired plant in the EU. In general, therefore, the WT energy recovery period will be even shorter (European Commission, 1999)

Delivery of the WT to a remote site makes very little difference to the above figures. For example, even if a 65 tonne turbine had to be shipped 10,000 nautical miles, this would only increase its net energy use by 1.5%.

R&D programmes continue to develop shorter WT energy recovery periods.

5.2 Environmental Impacts of Offshore Wind Energy

This section introduces the environmental impacts of offshore wind energy developments. It is based on a comprehensive study funded by the European Commission aimed

Table 5.5: Energy Recovery Time for a Wind Turbine

Wind Turbine Site Roughness Class (MWh/Year)	(A) Wind Turbine Electricity Production (MWh/Year)*	(B) Coal-Fired Plant Primary Energy Consumption* (MWh)	(C) Wind Turbine Energy Use (MWh)	(D) Wind Turbine Energy Recovery Period (year)	(E) Wind Turbine Energy Recovery Period (months) E = D x 12	(F) Wind Turbine Energy Saving Period** F = (B x 20)/C
Class 1	1,393	3,202	821	0.26	3.1	78
Class 2	1,130	2,598	821	0.32	3.8	63

* Input of energy required in a coal fired plant to produce 1,393 and 1,130 MWh/year of electricity considering only coal mining, transportation, energy content of coal and a plant efficiency of 45%.
** Wind energy saving over a 20 year period operation.

at gathering and distributing knowledge on all aspects of offshore wind energy, including: offshore technology; electrical integration; economics; environmental impacts; and political aspects (Garrad Hassan and Partners *et al*., 2001).

Questionnaires were sent to developers, utilities companies, consultants, research institutes and universities in different European countries in order to identify the relevant issues and collect information on factors such as public acceptance, environmental impacts, conflicts of interest and the political aspects of offshore wind development. With respect to environmental impacts, the survey found that birds, visual effects and impacts on recreation are the top European concerns.

Table 5.6: Ranking Environmental Impacts

Impacts	Indicator*
Birds	1.5
Visual effect	1.5
Recreational areas	1.8
Noise	2
Hydrography	2.1
Fish	2.2
Marine biology	2.3
Sea mammals	2.4
Sea currents	2.4
Marine archeology	2.4
Seabed	2.5
Water quality	2.5
Raw Materials	2.6

* 1 = high importance
2 = medium importance
3 = low importance
Source: Garrad Hassan and Partners *et al.* (2001).

Table 5.6 illustrates the average ranking of environmental impacts. The scale used is from 1 to 3, where 1 corresponds to an issue of high importance and 3 to one of low importance. The potential environmental impacts listed in Table 5.7 are the expected impacts identified by the study according to current knowledge. Further research is needed to improve understanding of these impacts, and identify others.

Table 5.7: Potential Negative Environmental Impacts

Birds:

- Collisions with turbines.
  - turbines acting as obstacles for migrating birds.
- Disturbance to feeding/breeding areas due to:
  - noise from turbines in operation and vessels during construction, maintenance and dismantling;
  - movements of blades or serious disruption to the food chain, e.g. due to new sediment structure or “unnatural” reef effect; and accidents.

Mammals:

- Loss of habitat due to:
  - noise;
  - movement of blades;
  - food chain changes;
  - electromagnetic fields and vibrations (affecting the animals’ sonar system); and
  - accidents.

Fish:

- Impacts on fish and fish larvae from sedimentation/turbidity, underwater noise, vibrations and electromagnetic fields.
- Effects from unnatural reefs.
- Accidents.

Benthic fauna and flora:

- Changes in sediment structure.
- Direct loss from foundation and cable footprints.
- Impact from foundations/hard substrates and electromagnetic fields.
- Disturbance/destruction of the seabed due to accidents with ships/aircrafts.

Coastline:

- Impact on coastline due to current/sediment changes caused by cables.
- Impact on coastline due to accidents.

Visual impact:

- Intrusive artificial obstacles in an otherwise pristine landscape.

Noise impact:

- Increased blade tip speed and the ability of sound to propagate more efficiently on sea surface may lead to noise impacts.
- Impact on birds, sea mammals and fish from underwater noise.

Source: European Commission (2002a).

In comparison with onshore wind energy development, the identification and understanding of offshore wind development impacts and their respective mitigation measures are still in their infancy. Easy assessment of potential impacts substantially facilitates development.

Table 5.8 lists some general recommendations for mitigating the expected impacts of large-scale offshore wind energy developments (Garrad Hassan and Partners *et al*., 2001).

Table 5.8 General Recommendations for Offshore Wind Energy Developments

Fish, birds and other groups.
- Identify and avoid sensitive areas.
- Avoid site works during sensitive time periods.

Birds:
- Design to accommodate migratory flight paths.

Sea mammals:
- Minimise noise levels during construction, operation and dismantling.

Fish:
- Minimise effects of structures and cabling on stocks.

Seabeds:
- Minimise sedimentation and turbidity.

Hydrographic, currents and water quality:
- Use appropriate foundation design.
- Avoid use of pollutants when protecting the foundation, tower and turbine from the marine environment.

Visual:
- Early assessment to take account of distance from shore, marking lights and nature of viewpoints.
- Well-balanced marking lights to take account of safety issues and visual impacts.

Noise:
- Ongoing public relations work to counter poor publicity.
- Maintain good standards of noise emissions despite increases in turbine size and tip speed.

Social conflicts:
- Promotion of openness and local involvement.

Risk management:
- Develop risk management methods and emergency procedures in order to reduce risks of ship collision and minimise consequences of collisions.

Source: European Commission (2002b)

5.3 Factors Affecting Public Acceptance of Wind Energy

The environmental impacts of wind energy are often seen as amenity issues which are mainly borne by local communities; but are they the only factors that need to be considered?

Society as a whole has a general understanding and awareness about the importance of environmentally friendly technologies, not only as a means of generating cleaner electricity but also to conserve natural resources and minimise waste. This recognition of renewable energy sources and other issues such as climate change, depletion of the ozone layer and the sustainable use of energy is often the result of government information programmes and campaigns, energy saving initiatives run by utility companies, media reports, etc.

Where such understanding and awareness is absent, getting the message across about environmentally friendly technologies, such as wind energy, is much more difficult. An informed society, on the other hand, will drive demand for environmental technology.

There is no guarantee that wind energy projects will be successfully implemented. The reasons lie in the distance between the costs (impacts borne by local communities) and benefits (for general society). This is the so-called NIMBY syndrome ("not in my back yard"), which is sometimes a response to unknown technology and impacts. The support of local communities is essential if a wind project is to go ahead. Support is more likely to be forthcoming where there has been a clear assessment of the impacts and the mitigation measures have been properly explained. Other factors are also relevant, however.

Local community participation is an essential element in project development in order to secure public acceptance. Such participation has the following advantages:

- Information is shared with the community and feedback becomes part of the planning process.
- Decision-making and control stays local.
- The permitting process is facilitated.

Local participation does not have to be limited merely to passing information between the parties but can also include economic involvement through:

- share ownership;
- cooperative association ownership;
- electricity bill discounts; or
- tax rebates.

Public involvement and investment has been a decisive factor in the successful expansion of wind energy in Denmark and Germany. The next chapter provides a summary of research aimed at exploring the public acceptance of wind energy in Europe, which builds on some of the ideas introduced here.

6 PUBLIC ACCEPTANCE IN THE EU

Some EU countries have carried out surveys on public acceptance of wind energy. Despite differences in methodology and focus, these surveys give an indication of the degree of acceptance of wind energy. This section summarises results from different studies. The findings of a pan-EU public opinion survey on energy-related issues are reported, followed by research from a number of EU member states on public acceptance of wind energy.

6.1 Attitudes of EU Citizens to Energy and Energy Technology Issues

The pan-EU survey "Energy, Issues, Options and Technologies" was commissioned by the European Directorate for Research. The aim of the survey was to gather information on the public view of energy-related issues, including scientific and technological aspects, and prospects for the future. Over 16,000 people were interviewed across the EU-15 during February and April in 2002. The survey did not focus on wind energy, but it does reveal general perceptions on issues such as climate change and renewable energy technologies, including wind energy.

The study analyses the perceptions of Europeans about energy sources. In general, the responses reflect the current situation for oil, coal and gas, but overestimate the use of both nuclear and renewable energy sources (see Figure 6.1).

Figure 6.1: Europeans' Perception of Energy Sources

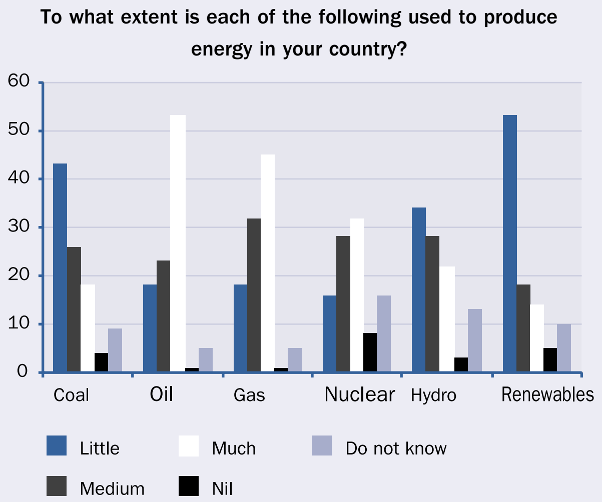


Table 6.1: Perception on Electricity Energy Sources

More than half of the electricity used in the EU comes from coal	
Yes, it is the case	21%
No, it is not the case	49%
Do not know	31%
More than one quarter of electricity produced in EU comes from nuclear power stations	
Yes, it is the case	55%
No, it is not the case	16%
Do not know	29%
More than a quarter of the electricity produced in EU coming from renewable energy sources, such as hydroelectric energy, wind or solar power	
Yes, it is the case	30%
No, it is not the case	43%
Do not know	27%

When asked about energy sources for the production of electricity (see table 6.1), there is an inaccurate perception regarding coal usage for electricity production in the EU. 49% of the respondents do not think that more than half of the electricity used in the EU comes from coal and 31% do not know. However 55% are correct in that more than one quarter of electricity produced in the EU comes from nuclear power stations; and 43% also rightly believe that it is incorrect that more than a quarter of the electricity produced in EU is generated from renewable energy sources.

One of the survey's main findings is that the public sees climate change as a serious issue (88% of respondents). Fossil fuels are recognised as one of the main causes of climate change (75%), along with transport emissions (74%).

With regard to energy dependency, 37% of respondents agree that this is an urgent issue and around a half think that more energy sources should be developed combined with greater encouragment for energy efficiency. A quarter want to see a reduction in imports of fossil fuels and uranium.

When asked about the future, environmental protection and low prices are the top priorities (72% and 62% respectively); 30% believe that ensuring uninterrupted energy supply should be a priority.

Europeans would like to know more about: how to save energy at home (53%); the use of renewable energy sources at home (42%); alternatives to petrol and diesel in vehicles (39%); nuclear safety and radioactive waste (36%); new energy options such as fuel cells (27%); EU activities in energy-related research and development (23%); and how to save energy at work (13%). The study concludes that *"energy, and in particular aspects of energy affecting them personally, is thus a subject on which Europeans appear to want to be better informed"*.

When asked about what will happen in 2050, 40% of respondents predict that the least expensive energy sources will be renewables like solar, wind and biomass, followed by hydroelectric power (24%) and natural gas (21%). Moreover, 27% consider that renewables will provide the greatest amount of useful energy and 67% think that renewable energy sources are the best environmental option. The report concludes that *"overall, the perceptions Europeans have of energy options in 20 and 50 years from now is clearly influenced by their own instinctive preferences for renewable energy sources"*. EU citizens expect that energy research will bring significant environmental benefits, more diverse energy sources (69%) and cleaner transport (51%). The following Figures illustrate these results.

Figure 6.2: Energy Resources Perception in 2050 – Least Expensive Source

In 2050, which energy resource will be least expensive?

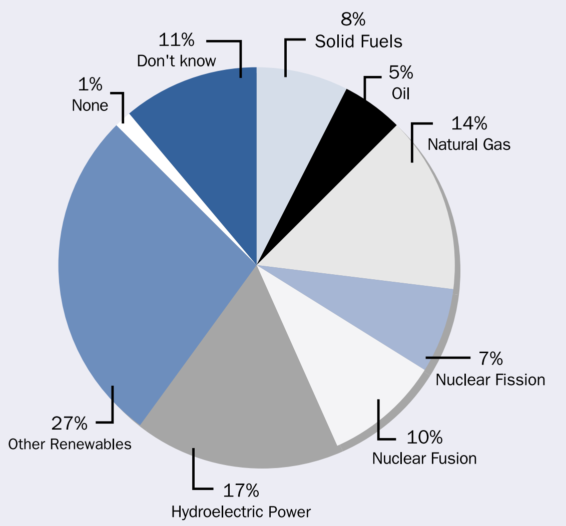


Figure 6.3: Energy Resources Perception in 2050 – Source with Greatest Amount of Useful Energy

In 2050, which energy resource will provide the greatest amount of useful energy?

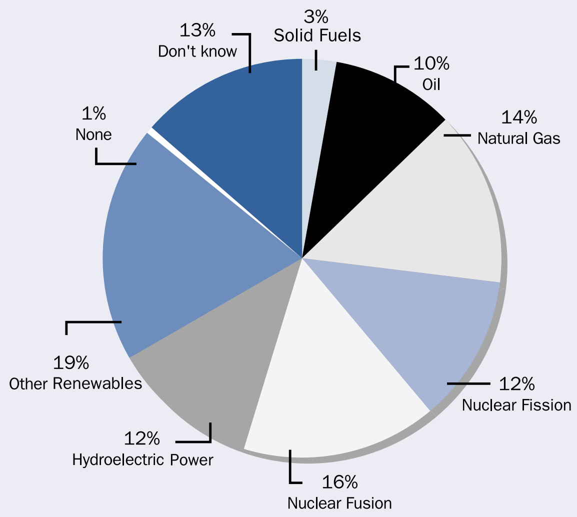


Figure 6.4: Energy Resources Perception in 2050
– Best Source for the Environment

In 2050, which energy resource will be the best for the environment?

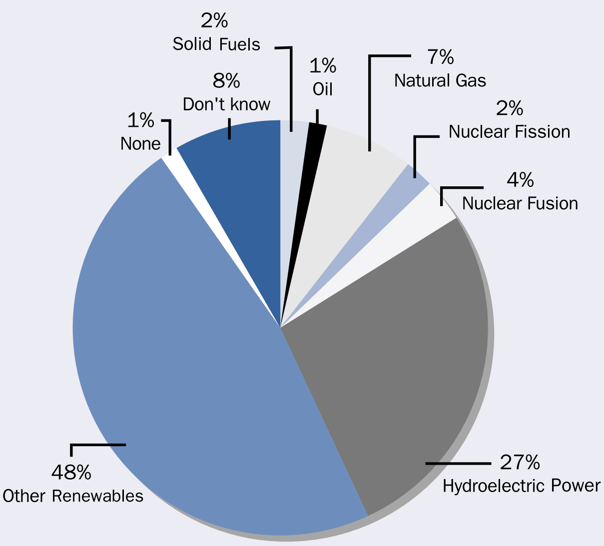
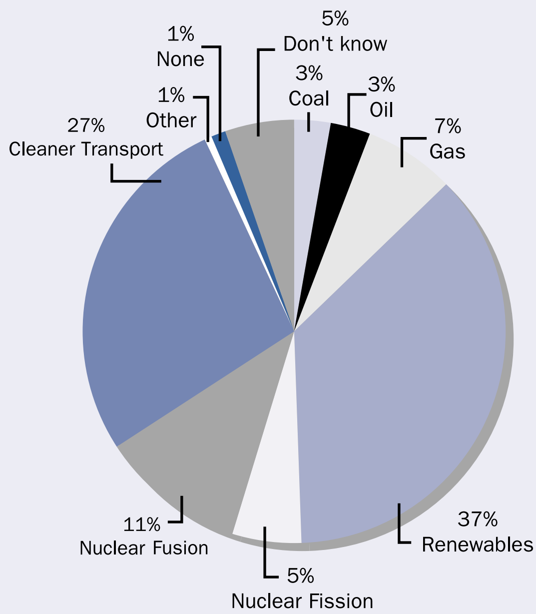


Figure 6.5: Energy Resources Perception in 2050
– More Research in the EU

In which areas should there be more energy-related research in the EU?



Finally, the survey found that attitudes vary according to country. For example, new energy sources and clean transport were chosen as priorities more often in Sweden, the Netherlands and Denmark.

6.2 Public Acceptance in Spain

Although there has been no national assessment of public acceptance of wind energy in Spain, regional information is available. The APPA (Spanish Renewable Energy Association) has provided valuable information on one of the most important developers, EHN, which is responsible for 30% of the wind capacity installed in Spain (36 wind parks as of December 2001). On behalf of the developer, CIES, a member of the Spanish Association of Opinion and Market Studies, carried out a survey on public acceptance of EHN's wind farms in different regions, with particular emphasis on the regions of Navarra (see Figure 6.6) and Castilla – La Mancha.

The development of wind parks has an important environmental component. Environmental impact assessments maximize the use of existing roads; and allocate existing and new infrastructure, and restoration of areas impacted during construction and installation. During the first five years of wind park operation, potential impacts – especially with regards to birds and other fauna - were evaluated. Great attention was paid to the integration of wind parks with the existing architecture, surroundings and the landscape. For example, substations were designed with the same facades as existing infrastructure.

Figure 6.6: Substation, Ibargoiti Wind Park in Navarra (22 MW)

Source: EHN (2001).

The development of wind parks in the states of Navarra and Castilla has generated 2,000 jobs. In 2001, 400 MW wind energy capacity was installed in the state of Navarra. CIES carried out 1,369 interviews in Navarra and found a very high acceptance for WTs (85%) (see Table 6.2). Even though the number of WTs increased dramatically over the period 1995 to 2001, the level of support has remained stable.

Table 6.2: Public Acceptance in Navarra

Year	1995	1996	1998	2001
Number of turbines*	6	40	217	600
Positive/very positive	85%	81%	81%	85%
Negative	1%	3%	3%	1%

* Mostly turbines of 660 kW capacity.
Source: EHN (2001).

A previous study carried out by CIES for EHN in 1998 on public perceptions in wind park areas in Navarra found:

El Perdón: 82% see the wind park as a step forwards whereas 2% think it is a step backwards. With regard to effects on the landscape, 41% say it makes no difference, 32% think it spoils the landscape, and 24% think it improves it.

Leitza-Beruete: 74% think the wind park is beneficial, 8% find it acceptable and 7% consider it damaging. With regard to effects on the landscape, 56% say it makes no difference while 36% think it does have an impact.

Guerinda: 76% see the wind park as beneficial and 4% consider it damaging. With regard to effects in the landscape, 56% say it makes no difference while 42% think it does have an effect.

Alaiz-Izco: 81% give positive support to wind parks whereas 6% are negative. With regard to effects on the landscape, 45% say it makes no difference, 29% think it spoils the landscape, and 19% think it improves it.

In Albacete province in the state of Castilla – La Mancha where 600 WTs are installed, a public acceptance assessment in 2001 found that 79% were positive about the WTs and 1% were negative.

In October 2002, a study carried out by CIES on behalf of Energías Eólicas Europeas (EEE) showed that 79% of respondents consider wind energy to be a benefit and 1% think it is damaging. The study also found that 62% think that wind parks make no difference to the landscape while 23% think they do have an effect.

The high acceptance of wind energy is due to environmental, energy-related and socio-economic reasons. Acceptability values higher than 70% were found in all areas surveyed, with 88% seeing wind as a clean energy source and 48% considering that it creates wealth and jobs. 69% of those surveyed thought that wind energy was the best energy source to produce electricity. This compares to 17% who support hydro, 2% thermal power and 1% nuclear.

A recent study carried out in Tarragona province (CERES, 2002) in the region of Cataluña also shows a majority favouring wind power (83%) over nuclear or fossil fuel technologies. Another interesting finding is the link between educational attainment and perceptions of wind energy. The higher the level of education, the greater the reluctance to accept certain aspects of wind energy such as visual intrusion. The Centre for Sociological Research, an autonomous state agency attached to the Office of the Presidency, carries out regular public opinion surveys. The last survey, in March 2003, showed that 65.4% backed further research on clean energy sources and 1.2% wanted to see more work on nuclear power.

6.3 Public Acceptance in the United Kingdom

The UK government aims to generate 20% of the UK's electricity from renewable energy sources by 2020, with the major focus on offshore wind energy. The latest poll to measure public support for this target shows that 74% support both the 20% goal and increasing the use of wind power.

Aggregating data from 42 surveys carried out between 1990 and 2002 shows, on average, that 77% of the public are in favour of wind energy with 9% against (British Wind Energy Association, 2003).

A summary of research on attitudes to wind power from 1990 to 1996 (Marie *et al*., 1996), concludes that an "overwhelming majority of residents in areas with a wind project are pro-wind, both in theory as a renewable energy source and in practice in their area, with an average of eight out of 10 supporting their local wind farm".

A survey of people living within 20 km of four wind farms in Scotland was carried out in 2000 for the Scottish Executive (System Three Social Research, 2000). The sample was divided into three zones of 5 km from the farm, 5-10 km and 10-20 km. The main results are as follows:

- 67% of respondents said there was something they liked about the wind park, this proportion increased to 73% for those living in the 5 km zone.
- With respect to visual impacts, 21% liked the look of the wind park whereas 10% thought it spoiled the view.
- Regarding future developments, there was a positive attitude towards wind parks; 14% of respondents would be concerned if extra turbines were added to the existing park.

A recent survey conducted for the Scottish Executive by MORI in 2003 (EWEA, 2003f) shows that people living close to Scotland's 10 largest wind parks strongly support wind energy, with 82% wanting an increase in electricity generated from wind, and more than 50% supporting an increase in the number of turbines at their local wind park. The MORI poll (see Table 6.3) covered 1,800 residents living within a 20 km radius of a wind park. Its main findings are:

- 20% of respondents think their local wind park has a broadly positive impact on the area while 7% felt that it has a negative impact. The majority are neutral.
- Before the construction of the wind park, 27% of respondents were concerned about landscape changes, 19% were concerned about traffic during construction and 15% about noise during construction. During the construction phase and afterwards, these figures fell to 12%, 6% and 4% respectively.
- 54% would support a 50% increase in the number of turbines at their local wind farm, 9% would not.
- With respect to other technologies, respondents want to see a decrease in nuclear, coal and oil power. Clean electricity production technologies are strongly supported with 69% in favour of wave energy and 82% in favour of wind energy.

Table 6.3: Results of MORI/Scottish Executive Poll

Question: What effect, if any, would you say the presence of the wind farm has had in your local area? Would you say it has had…

	%
A completely positive effect	7
A generally positive effect	13
Neither positive nor negative effect	51
A generally negative effect	5
A completely negative effect	2
Don't know/ No opinion	23

Question: Was the wind farm already here when you moved in, or has it been built since then?

	%
Wind farm already here	10
Built since moved in	77
Don't know	14

Question: I would like to know what you anticipated it might be like having a local wind farm (before it was built/ before you moved here), and then I will ask you about what it has actually been like.

Question: Which of the following problems, if any, did you think having a wind farm in the area might cause?

Question: And which, if any, have actually turned out to be problems caused by having a wind farm in the area?
Base: All who have lived in the area before the wind farm was built (1,547)

	Thought might be problems %	**Have been problems %**
Noise from the turbines	12	2
The look of the landscape being spoiled	27	12
Interference with TV and radio reception	6	1
Damaging effect on local business	3	1
Damage to plants or animals	12	3
Noise or disturbance during construction	15	4
Extra traffic during construction	19	6
A reduction in house prises	7	2
None of these	54	82

Question: To what extent would you support or oppose increasing the number of turbines at the wind farm by 50%? Would you…
(Base: All)

	%
Strongly support	26
Tend to support	28
Neither support nor oppose	25
Tend to oppose	5
Strongly oppose	4
Don't know	11

To what extend would you support or oppose increasing the number of turbines at the wind farm by 100%? Would you…
(Base: All)

	%
Strongly support	19
Tend to support	23
Neither support nor oppose	24
Tend to oppose	11
Strongly oppose	10
Don't know	14

Question: I am going to read out some different ways of generating electricity. For each one, I would like you to tell me whether you think the proportion of electricity generated in Scotland should increase, reduce or stay at about current levels over the next 15 years? First of all…
(Base: All)

	Increase	Keep same	Reduce	Don't know
	%	%	%	%
Coal fired power	9	24	60	6
Oil fired power	9	32	48	10
Nuclear power	7	17	68	9
Wind energy	82	11	2	6
Wave energy	69	11	3	17

Source: EWEA (2003f).

Two opinion polls have been carried out in Scotland to determine the effect, if any, of wind farms on tourism to the region. The first poll, of visitors to Argyll and Bute, revealed that wind parks "are not seen as having a detrimental effect... and would not deter tourists from visiting the area in the future" (MORI Scotland, 2002). The second concluded that the visual impacts of wind farms are a concern, especially in protected areas such as Areas of Outstanding Natural Beauty (NFO, 2002).

Table 6.4: Results of MORI Scottish Tourist and Visit Scotland Poll

Results of MORI Scottish Tourists Poll:

Question: What effect, if any, would you say the presence of wind farms has had on your impression of Argyll as a place to visit?

A completely negative effect	1%
A generally negative effect	7%
Equally positive and negative effect	43%
A generally positive effect	28%
A completely positive effect	15%
Don't know	6%

Question: Has the presence of wind farms in Argyll made you any more likely to visit the area in future, made it less likely, or has it made no difference?

Less likely	2%
No difference	91%
More likely	4%
Don't know	3%

Results of Visit Scotland Poll:

Views of development of wind farms as a means of generating power	(%)
Good idea - ecologically friendly	39
Good idea generally	17
Good idea - save digging fossil fuels	11
Good idea - need different sources of power	5
In favor of them	5
Necessary evil - better alternative to nuclear	4
Necessity but an eyesore	4
Against - can't generate enough power	2
Good idea - natural resource	1
If not too many - good idea	1
Other positive	1
Other negative	7
Don't know	5

Impact on further holidays in the Scottish countryside if the number of wind farms was to increase	(%)
Would make no difference	63
Steer clear of the area	15
Less likely to come back	10
Depends on the area	6
Minimal impact	2
Other	2
Don't know/not stated	5

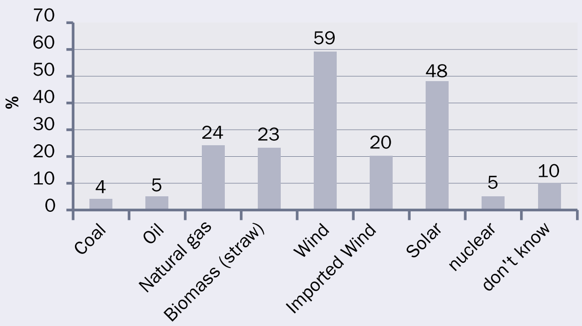
Source: EWEA (2003f).

6.4 Public Acceptance in Denmark

In Denmark, public opinion of wind energy over the last 10 years has been positive (Danmarks Vindmølleforening, 2002).

A survey (see Figure 6.7) carried out in 2002 shows that 59% would buy electricity from a renewable source, while 24% would not. Results from a study in 2001 illustrate that 86% of the population support wind energy with 68% wanting Denmark to install more WTs and 18% thinking that existing capacity is sufficient.

Figure 6.7: Energy Sources Preferences in Denmark



Source: Danmarks Vindmølleforening (2002).

A 1997 study carried out in the municipality of Sydthy, where 98% of electricity supplied to the 12,000 inhabitants is generated by wind, found that people with a high degree of knowledge about energy generation and renewable energy in particular tend to be more positive about wind power. In addition, 58% of householders in Sydthy have shares in their local wind park (Damborg, 1998).

In Denmark, 150,000 families are involved in wind energy projects due to the possibility of receiving financial benefits and/or a positive stance regarding the environmental benefits of wind energy (EMU and Hammarlund Consulting, 2003).

6.5 Public Acceptance in Germany

The northern state of Schleswig-Holstein in Germany had, as of December 2002, 1,800 MW of installed wind capacity, with a share of nearly 30% of the state's energy consumption (DEWI, 2003). An analysis of wind energy in Schleswig-Holstein was prepared for the state's Energy Ministry in 2002. Some issues of relevance to public acceptance are summarised here (Eggersglüß, 2002).

Germany's approach to wind energy has changed dramatically over the years. Initially, individuals who were interested in using wind energy, such as farmers, could install a WT on their own land. Then, the growing interest of non-local investors made it possible to develop wind parks on designated areas. In the meantime, many "citizen's wind parks" have emerged funded by companies who offer shares to local small-scale investors. These have proved very popular.

In general, the siting of a wind park is accepted by most people in a particular area when the following principles are followed:

- Sufficient distance from residential areas.
- Quiet turbines are chosen.
- The population is kept properly informed.
- There is some sort of financial benefit for the local community.
- The developer has its head-quarters and administration situated in the area.
- Land owners' views are sought when choosing a site.

Although wind energy is seen as a clean way of producing electricity and preserving natural resources, concerns have been raised about changes to the landscape, noise, flickering and effects on birds. Other worries include higher electricity prices and financial rewards for a few land owners and WT operators.

A study to assess the effects of onshore and offshore wind parks on tourism was undertaken by the Schleswig-Holstein tourist board (Günther, 2002). This concluded that the wind industry does not affect tourism in the region. Visitors are aware of the increasing number of turbines in the landscape, but they do not influence visitors' behaviour.

Research carried out by the EMNID Institute for the German science magazine *P.M.* in 2003 found that 66% of Germans are in favour of further construction of wind farms. The institute also conducted a survey in 2002 (see Table 6.5) showing that 88% supported the construction of more wind parks in Germany, with 86% agreeing that the share of wind power in the energy mix should increase (EWEA, 2003f).

Table 6.5: Results of EMNID Poll, 2002

Question: Which statements would convince you to support the erection of further wind turbines?

Wind turbines produce green electricity	89.2%
Wind power is a new technology that creates thousands of jobs	62.1%
Wind turbines are easy to control and secure	66.3%

Question: Gas, oil and coal are limited resources, whilst the use of wind power constitutes an alternative. Do you believe that the share of wind power in the energy mix is already sufficient?

Yes, it is sufficient	9.5%
No, it should be increased	86%
Don't know	4.5%

Question: Wind farms must fulfil certain criteria, such as there have to be minimum wind speeds, there has to be enough space between single wind turbines, additional standards in residential and nature conservation areas have to be met. Do you support the construction of further wind farms when those criteria are fulfilled?

Yes	88.3%
No	9.5%
Don't know	2.2%

Question: If we assume that offshore wind farms also have to meet strict standards, would you support their construction far away from the coast?

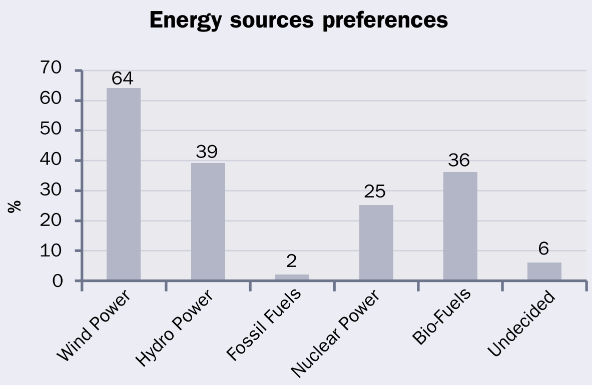
Yes	88.3%
No	9.5%
Don't know	2.2%

Source: EWEA (2003f).

6.6 Public Acceptance in Sweden

A recent survey in Sweden (see Figure 6.8) shows that wind power would be the preferred electricity production option, with 64% support (SIFO, 2002).

Figure 6.8: Energy Sources Preferences Sweden



Source: SIFO (2002).

Wind energy was the second choice for 25% of those respondents who placed nuclear power as a first option.

The SIFO survey also found that 73% of respondents thought that Sweden should increase its proportion of electricity generated from renewable sources.

With regard to tourism, a public acceptance study from 1988 to 2002 found that tourists have a negative attitude to onshore wind farms, especially in rural landscapes, but are more positive about offshore developments (EMU and Hammarlund Consulting, 2003). In some areas, opposition to onshore wind farms was mainly from tourists and non-permanent residents who place a greater value on landscape amenity than do permanent residents.

6.7 Public Acceptance in Austria

In July 2003, a national poll was conducted to determine the Austrian public's knowledge about renewable energy sources, their acceptance of renewables and their future

energy preferences. The Gallup Institute conducted the poll of 1,500 people for the Austrian Utilities Association Verband der Elektrizitätsunternehmen Österreichs (VEÖ). When asked about renewable energy, 45% of respondents knew what it was. Solar, hydro and wind were the most recognised renewable energy sources at 39%, 33% and 30% respectively.

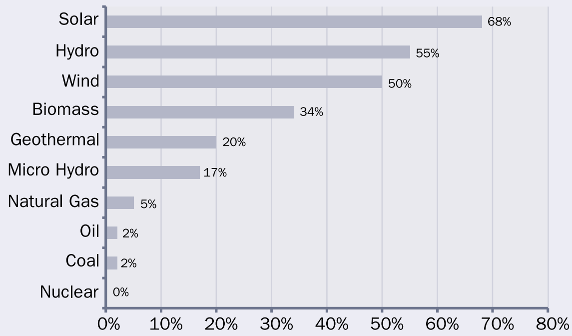
Hydro, solar, wind and micro hydro are the most popular energy sources when scored on a scale of 1 to 5 where 1 is very popular and 5 is very unpopular (see Table 6.6). With respect to future energy sources, 68% of respondents prefer solar, followed by hydro, wind and biomass. Fossil fuel has little support and nuclear none, as can be seen in Figure 6.9.

Table 6.6: Popularity Energy Sources

Source	Indicator*
Hydro	1.27
Solar	1.31
Wind	1.41
Micro Hydro	1.44
Geothermal	1.92
Biomass	1.97
Natural Gas	2.88
Oil	3.21
Coal	3.27
Nuclear	4.53

* 1 = very popular and 5 = very unpopular
Source: VEÖ (2003).

Figure 6.9: Future Preferred Energy Sources



Source: VEÖ (2003).

6.8 Public Acceptance in Belgium

A survey of residents living on the Belgian coast, a popular tourist area, was carried out in 2002 by the West Flemish Economic Study Office. It revealed that 78% of those surveyed have a positive or neutral attitude towards the construction of a wind farm 6 km offshore. However, the survey also found that 30% of the residents disapprove of wind farms in their surroundings. Table 6.7 summarises the attitudes of different groups of residents and tourists towards offshore wind parks in their immediate surroundings.

Table 6.7: Public Perception of Near Shore Wind Farms at 6 km from the Shore

Group	Very to Moderately Negative	Neutral to Very Positive
Residents	31.3%	66.5%
Second residence	10.2%	88.8%
Frequent tourists	18.7%	81.3%
Occasional tourists	19.5%	80.5%
Hotel, restaurant, pub with view of sea	6.8%	89.3%
Other	15.3%	84.7%
Total	20.7%	78.3%

Source: EWEA (2003f).

6.9 Conclusions

The countries mentioned here account for 88.8% of the total wind energy capacity in Europe (22,558 MW in 2002). Germany, Spain and Denmark accounted for 84.3% of that capacity in 2002 (EurObserv'ER, 2003).

The attitudes of EU citizens to renewable energies, and their awareness of climate change impacts, indicates that the environmental benefits of renewable energy sources, including wind, are understood. Fossil fuel and nuclear energy sources have less support, as shown by the data from Denmark, Sweden, Austria and Spain.

The surveys cited in this report point to very positive support for wind energy, with acceptance depending on perceptions of the technology and the way in which developers deal with local communities.

In Denmark and Germany, where many local citizens are financially involved and decisions are taken at the local level, there is a high public acceptance of wind energy. Efforts to minimise impacts and integrate wind parks into the landscape in an aesthetic way, combined with local participation, have yielded good results in Spain.

WIND ENERGY - THE FACTS

VOLUME 5

MARKET DEVELOPMENT

Acknowledgments

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1 MARKET INCENTIVES

1.1 Introduction

As mentioned in the section on externalities, the full costs to society of electricity production are not reflected in electricity prices. Those costs are paid by taxpayers and society as a whole in the form of increased health care and environmental costs such as climate change.

Wind energy is becoming increasingly competitive with conventional sources. However, it is likely that some form of incentive will be required for the foreseeable future, at least until environmental costs are fully internalised or increased economies of scale and technological development makes wind power fully competitive with conventional sources, such as coal and gas, without the need to consider externalities.

There are currently five main systems to support electricity from renewable energy sources in the EU member states: investment subsidies, fixed price systems, fixed premium systems, auctions, and certificates systems. The idea behind the mechanisms is to offset at least some of the competitive disadvantage for renewables as a consequence of electricity markets neglecting the environmental cost of production from conventional technologies. Low electricity prices are of little benefit if they lead to high costs to society as a whole through higher health care costs and environmental costs levied on current and future taxpayers and citizens.

If the environmental costs of power production were reflected in European power prices, wind power and many other renewable energy technologies would not need support, as pointed out in the European Commission's Green Paper on Security of Supply (European Commission, 2002a)

The Green Paper states that wind energy can fully compete with combined cycle gas if externalities are taken into account. Furthermore, both wind energy, biomass, small hydro, photovoltaics (PV) and geothermal are significantly cheaper for society than coal if externalities are included. Coal is almost twice as expensive as wind and biomass (1998 figures) according to the Green Paper.

The European Commission's ExternE project on external costs estimates that the cost of producing electricity from coal or oil in the EU would double and the cost of electricity production from gas would increase by 30% if external costs, in the form of damage to the environment and health, were taken into account (European Commission, 1999). Currently, average electricity production costs in the EU are 0.04 € per kWh. The study further estimates that the external costs amount to 1-2% of EU GDP or between €85 billion and €170 billion, not including the cost of climate change.

Table 1.1 summarises the incentives for wind power and other renewables available in the EU-15 as of 2003. The table only includes conditions for new installations. Other conditions may apply to existing renewable energy capacity.

Table 1.1: Support Mechanisms

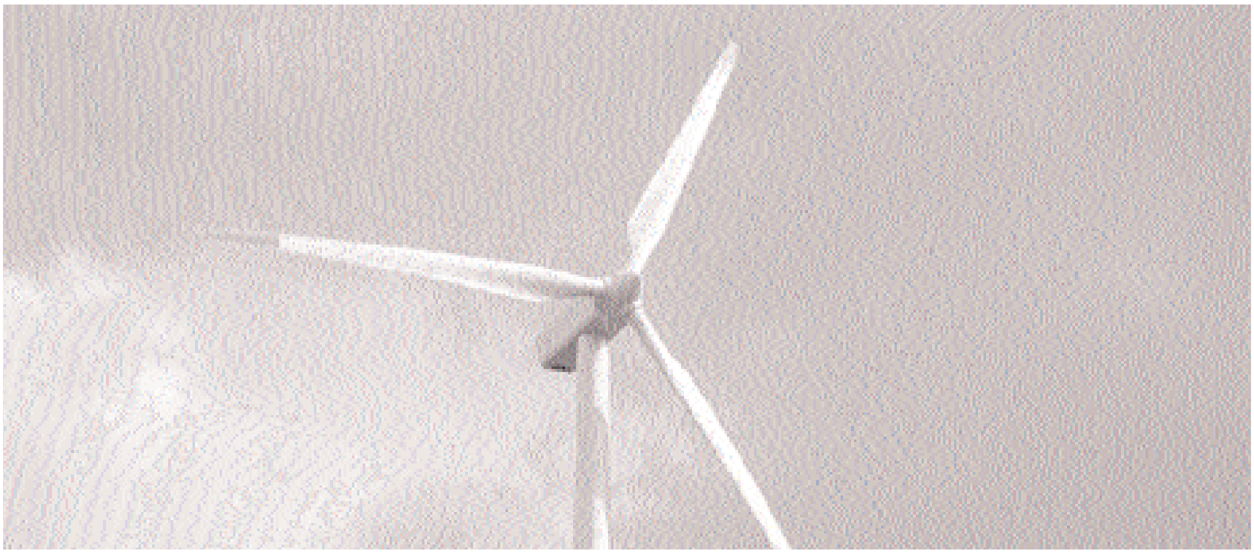
	Major Strategy	RES-E TECHNOLOGIES CONSIDERED Large Hydro	Small Hydro	'New' RES (Wind On- & Offshore, PV, Solar Thermal Electricity, Biomass, Biogas, Landfill Gas, Sewage Gas, Geothermal)	Municipal Solid Waste
Austria	FITs	No	Renewable Energy Act 2003. (Ökostromgesetz). FITs guaranteed for 13 years for plants which get all permissions between 1st of January 2003 and 31st of December 2004 and, hence, start operation by the end of 2006. Investment subsidies mainly on regional level.		No
Belgium	TGC + guaranteed electricity purchase	No	Federal: The Royal Decree of 10 July 2002 (operational from 1st of July 2003) sets minimum prices for RES-E. Except for offshore wind it will be implemented by the regional authorities: Wallonia: Quota obligation (based on TGCs) Wallonia: Quota obligation (based on TGCs) on electricity suppliers– increasing from 3% in 2003up to 12% in 2010. Flanders: Quota obligation (based on TGCs) on electricity suppliers– increasing from 3% (no MSW) in 2004 up to 6% in 2010. Brussels region: No support scheme yet implemented.		
Denmark	Partial Tax Exemption + tender	No	Act on Payment for Green Electricity (Act 478): Max combined price for wind power and partial tax exemption of 4.4 c€/kWh. Minimum price of 1.33 c€/kWh. Exemption of CO_2 tax (max 1.33 c€/kWh) depends on electricity market price. Plans for offshore wind tenders.		No
Finland	Tax Exemption	No	Tax refund 0.44 c€/kWh (plant <1MW)	Mix of tax refund and investment subsidies: From January 2003: Tax refund of 0.73 c€/kWh for wind and of 0.44 c€/kWh for other RES-E. Investment subsidies up to 40% for wind and up to 30% for other RES-E.	No
France	FITs	No	FITs for RES-E plant < 12 MW guaranteed for 15 years (20 years PV and hydro). Tenders for plant >12 MW. FITs in more detail[1]: biomass - 4.9 c€/kWh; biogas - 4.6 c€/kWh; geothermal - 7.62 c€/kWh; PV[2] - 15.25-30.50 c€/kWh; landfill gas - 4.50-5.72 c€/kWh; wind[3] - 3.05-8.38 c€/kWh; hydro[4] - 5.49-6.10 c€/kWh. Investment subsidies for PV, biomass and biogas (biomass and biogas PBEDL 2000 - 2006).		No
Germany	FITs	No	German Renewable Energy Act: FITs guaranteed for 20 years[5]. In more detail, FITs for new installations in 2003 are: hydro - 6.65- 7.67 c€/kWh; wind[6] - 6-8.9 c€/kWh; biomass - 5,8-10 c€/kWh; landfill gas, sewage gas and mine biogas - 6.65-7.67 c€/KWh; solar PV and solar thermal electricity - 45.7 c€/kWh; geothermal - 7.16-8.95 c€/kWh.		No
Greece	FITs + investment subsidies	No	FITs guaranteed for 10 years (at a level of 70-90% of the consumer electricity price)[7] and a mix of other instruments: a) Law 2601/98: Up to 40% investment subsidies combined with tax measures; b) CSF III: Up to 50% investment subsidies depending on RES type.		No
Ireland	Tender	No	Tendering scheme – currently AER VI with technology bands and price caps for small wind (<3 MW), large wind (>3 MW), small hydro (<5 MWp), biomass, biomass and biogas. In addition, tax relief for investments in RES-E.		No
Italy	TGC	Quota obligation (based on TGCs) on electricity suppliers: 2% target, increasing annually; TGC issued for all (new) RES-E (inc. large hydro and MSW) – with rolling redemption[8]; unclear penalty enforcement and market distortions[9]. Investment subsidies for PV (Italian Roof Top programme).			
Luxembourg	FITs	No	No	FITs[10] guaranteed for 10 years (PV 20 years) and investment subsidies for wind, PV, biomass and small hydro. FITs for wind, biomass and small hydro - 2.5 c€/kWh; for PV - 50 c€/kWh[11].	No
Portugal	FITs + investment subsidies	No	FITs (Decree law 339-C/2001 and Decree law 168/99) and about 40% investment subsidies small hydro and wave. FITs in 2003 - wind[12] - 4.3c€/kWh - 8.3c€/kWh; wave - 22.5c€/kWh; PV[13] - 22.4c€/kWh - 41c€/kWh; small hydro - 7.2c€/kWh.		
Spain	FITs	Depending on the plant size[14]	FITs (Royal Decree 2818/1998): RES-E producers have the right to opt for a fixed price or for a premium tariff[15]. Both are adjusted annually by the government according to the variation in the average electricity sale price. In more detail (only premium, valid for plant < 50 MW[16]): wind - 2.7 c€/kWh - PV[17] - 18-36 c€/kWh - small hydro - 2.9c€/kWh - biomass - 2.5 - 3.3 c€/kWh. Moreover, soft loans and tax incentives (according to "Plan de Fosento de las Energías Renovables") and investment subsidies on a regional level.		1.7 c€/kWh

FIT: Feed-in Tarifs
TGC: Tradable Green Certificates

RES-E TECHNOLOGIES CONSIDERED					
	Major Strategy	Large Hydro	Small Hydro	'New' RES (Wind On- & Offshore, PV, Solar Thermal Electricity, Biomass, Biogas, Landfill Gas, Sewage Gas, Geothermal)	Municipal Solid Waste
Sweden	TGC	No	Quota obligation (based on TGC) on consumers: Increasing from 7.4% in 2003 up to 16.9% in 2010. For Wind Investment subsidies of 15% and additional FITs ("Environmental Bonus"[18]) in size of 1.9 c€/kWh are available.		No
Netherlands	FITs + tax exemption		Mixed strategy: green pricing, tax exemptions and FITs. The tax exemption for green electricity amounts 2.9 c€/kWh and FITs range from 2.9 c€/kWh for mixed biomass and waste streams to 6.8 c€/kWh for wind, PV, tidal, wave and small hydro.		No
United Kingdom	TGC + investment subsidies	No	Quota obligation (based on TGCs) for all RES-E: Increasing from 3% in 2003 up to 10.4% by 2010 – penalty set at 3.51 £/kWh. Optional to the TGC-system, eligible RES-E are exempted from the Climate Change Levy certified by Levy Exemption Certificates (LECs), which cannot be separately traded from physical electricity. The current levy rate is 0.43 £/kWh. Investment grants in the frame of different programmes (e.g. Clear Skies Scheme, DTI's Offshore Wind Capital Grant Scheme, the Energy Crops Scheme, Major PV Demonstration Programme, and the Scottish Community Renewable Initiative).		No

1 Without efficiency premiums.
2 30.5 €/kWh for Corsica and Overseas Departments.
3 Stepped FIT: 8.38 c€/kWh for the first 5 years of operation and then between 3.05 and 8.38 c€/kWh depending on the quality of site.
4 Producers can choose between four different schemes. The figure shows the flat rate option. Within other schemes tariffs vary over time (peak/base etc.).
5 The law includes a dynamic reduction of the FITs (for some RES-E options): For biomass 1% per year, for PV 5% per year, for wind 1.5% per year.
6 Stepped FIT: 8.9 c€/kWh for the first 5 years of operation and then between 6 and 8.9 c€/kWh depending on the quality of site.
7 Depending on location (islands or mainland) and type of producer (independent power producers or utilities)
8 In general only plant put in operation after 1st of April 1999 is allowed to receive TGCs for their produced green electricity. Moreover, this allowance is limited to the first 8 years of operation (rolling redemption).
9 GRTN (Italian Transmission System Operator) influences strongly the certificates market selling its own certificates at a regulated price – namely at a price set by law as the average of the extra prices paid to acquire electricity from RES-E plant under the former FIT-programme (CIP6).
10 Only for plants up to 3 MW except up to 50 kW for PV systems.
11 For plants commissioned in 2004 the FIT will be in the range of 45 c€/kWh
12 Stepped FIT depending on the quality of the site.
13 Depending on the size: <5kW - 42 c€/kWh or >5kW - 22.4 c€/kWh
14 Hydropower plant with a size between 10 and 50 MW receive a premium depending on the farm size according to the formula: Premium (c€/kWh) = 2.9 * (50-'plant size in MW') / 40. For plants >50MW the premium tariff is set to 0.6 c€/kWh.
15 In case of a premium tariff, RES-E generators earn in addition to the (compared to fixed rate lower) premium tariff the revenues from the selling of their electricity on the power market.
16 For Small Hydro the plant size is limited to 10 MW.
17 Depending on the plant size: <5kW: 36c€/kWh or >5kW: 18c€/kWh
18 Decreasing gradually down to zero in 2007

Source: EWEA, Rexpansion Project, forthcoming.



1.2 Environmental Taxes

Energy taxes that reflect the actual environmental impacts of each technology constitute an effective means to internalise external costs. Taxes could make the full production costs of electricity generation transparent, level the playing field in the future internal electricity market and introduce fair competition between renewables and conventional power technologies. This is recognised by the European Commission. In a Communication to the Council, the European Parliament, the Economic and Social Committee and the Committee of the Regions in February 2001, the Commission states:

> *"Environmental taxes and charges can be an appropriate way of implementing the 'polluter pays' principle by including the environmental costs in the price of goods and services and by this means internalising external costs. The White Paper emphasised that the environmental benefits of renewable energy justify favourable financing conditions, e.g. through tax exemptions in products from RES."*

After six years of negotiations, an EU Directive[1] setting minimum tax rates for energy products came into force on 1st January 2004. As a result of numerous compromises between the member states, the level of the minimum energy tax rates is close to being the lowest common denominator for the Community and is considerably lower than originally proposed by the Commission in 1997, and by the Parliament in 1999. For electricity, the Directive introduces minimum taxes of 0.5 €/MWh for business and 1 €/MWh for non-business. Due to the low minimum tax levels, the many general exemptions and the lack of mandatory exemptions for renewables, the effect of the Directive on wind power will be insignificant in the short term. However, the importance of reaching a final agreement cannot be underestimated, as it emphasises the political will in the EU to contribute to the "polluter pays" principle set out in Article 174 of the Treaty establishing the European Community.

Electricity generators are not financially penalised for the pollution they cause and the associated costs that society has to bear. Environmental costs do not disappear from the face of the earth just because they do not appear on the electricity bill or because they are not included in electricity producers' costs of generating energy. They are being paid for by society as a whole through taxes on households and companies and through environmental degradation such as that caused by climate change.

Meaningful environmental taxes are an effective way to level the playing field in the electricity markets, but are difficult and time consuming to agree upon at EU level. The same is true for removal of state aid to conventional power production technologies. Efforts should be made to remove harmful subsidies to mature electricity technologies based on fossil fuel and nuclear, as suggested by an OECD study on improving the environment through reducing subsidies. The higher the subsidies to polluting technologies, the higher the costs to society of introducing clean technologies.

The OECD argues that *"support is seldom justified and generally deters international trade, and is often given to ailing industries"*. It further argues:

> *"This policy [state aid] is often both costly and ineffective in the long run. Technological change and the development of new product markets will generally lead to an even further loss in the competitiveness of the supported industry. As a result, larger amounts of support will be required in order to maintain the industry... . In many cases, support is used to prop up declining industries, merely postponing their certain demise at the expense of taxpayers and consumers."*

The OECD also argues *"that support may be justified if it lowers the long-term marginal costs to society as a whole. This may be the case with support to 'infant industries', such as producers of renewable energy."*

The problem with subsidies is that, once introduced, they are difficult to remove. The existence of environmentally damaging state aid to mature industries such as coal and nuclear will inevitably lead to higher environmental policy costs.

Removing state aid to fossil fuels, nuclear and other mature and environmentally damaging industries has many attractions. Not only would it contribute towards a more level playing field in the electricity markets and create less biased market conditions, it would also save large amounts of money currently spent on unproductive state aid schemes and, finally, make it considerably cheaper to develop the environmental technologies that are a precondition to securing the EU's indigenous supply of electricity. Removing environmentally harmful subsidies should ideally be supplemented by energy taxes. Taxation can be an effective tool in energy policy if it aims to internalise the costs to society of environmental degradation, and contribute to the polluter pays principle.

Tax Incentives

Several EU countries have introduced specific tax incentives for renewable energy. These are summarised in Table 1.2.

Table 1.2: Tax Incentives

Country	Tax Incentives
Austria	Private investors get tax credits for investments in using renewable energies (personal income tax). The amount is generally limited to 2.929€ per year.
Belgium	13.5–14% of RES-investments deductible from company profits, regressive depreciation of investments. Reduced VAT on building refurbishing if energy efficiency is included (6% instead 21%).
Denmark	The first 3,000 DKK of income from wind energy are tax free.
France	Deduction of 15% investment costs with a maximum of 3,000 € per person. Reduced VAT (5.5%) on renewable equipment (not applicable to installation costs).
Germany	Losses of investments can be deducted from the taxable income. This fact increases return on investments into wind projects.
Greece	Up to 75% of RES-investments can be deducted.
Ireland	Corporate Tax Incentive: Tax relief capped at 50% of all capital expenditure for certain RES-investments.
Portugal	Up to 30% of any type of investments on RES can be deducted with a maximum of 700€ per year. Reduced VAT (12%) on renewable equipment.
Spain	Corporation Tax: 10% (up to 20% in some autonomous regions) tax liability instead of 35% for investments in environment friendly fixed assets.
The Netherlands	EIA scheme: RES-investors (most renewable energy systems) are eligible to reduce their taxable profit with 55% of the invested sum. Lower interest rates from Green Funds: RES- investors (most renewable energy systems) can obtain lower interest rates (up to 1.5%) for their investments. Moreover dividends gained are free of income tax for private investors.

Source: EWEA (2003).

1.3 Payment Mechanisms – the "Second Best" Solution

With environmentally harmful subsidies still in place, and in the absence of environmental taxes that fully reflect the internal costs of energy production, a second best solution to create a level playing field in the electricity markets is for member states (and potentially the EU) to provide frameworks that create adequate incentives to increase renewable electricity's share of the electricity consumption.

Usually, the level of the incentive depends on the production cost of wind power compared to other technologies and the market prices for electricity. As a result of the gradual liberalisation of electricity markets, competition is increasing in the European electricity sector. There is some concern, however, that Europe is moving from a situation of national electricity monopolies to private monopolies or oligopolies, rather than perfect competition. Increased competition, in combination with the present over-capacity in European electricity generation, will probably in the short term make conditions more difficult for wind power and other renewables as wholesale electricity prices decrease. The price reduction will continue until generating companies close down the least competitive part of their generation capacity and electricity demand increases (the European Commission expects electricity consumption in the EU to grow by 1.3% annually up to 2030[2]).

Several mechanisms can be applied to promote the increased deployment of wind power. These can be grouped into three main categories:

- Voluntary systems where the market determines the price and the quantity of renewable energy (green marketing).

- Systems where the government dictates the electricity prices paid to the producer and lets the market determine the quantity (fixed prices).
- Systems where the government dictates the quantity of renewable electricity and leaves it to the market to determine the price (renewables quotas).

Fixed price systems and renewables quotas are both ways of creating a protected market, separate from the open electricity market where electricity from new renewable energy sources would have difficulties competing with existing, already depreciated nuclear and fossil based power plants. They are also ways of offsetting (fully or partly) the competitive disadvantage arising from markets' neglect of the environmental effects of conventional energy production.

It is sometimes argued that systems where the government fixes the quantity of renewable electricity demand (e.g. renewables quotas with green certificate trading) is more "market oriented" than systems where governments fix the price. However, a system where the government fixes quantity and leaves it to the market to determine the price is unlikely to be more "market oriented" than a system where the government fixes the prices and leaves it to the market to determine the quantity.

Few would argue that the oil cartel OPEC is a market oriented mechanism because the members have chosen to control the market through quantities rather than prices. The reason is that quantities are easier to administer. In the WTO, however, quantitative restrictions are generally banned while tariffs are accepted to some degree because quotas are regarded as more market distorting.

The main purpose of the wide range of available economic measures to support wind energy and other renewable energy technologies is to provide incentives for technological improvements and cost reductions of environmental technologies, in this case the production costs of wind turbines (WTs). The aim is to ensure the future availability of cheap, clean technologies as a competitive alternative to conventional power sources. It is less important whether markets are controlled through prices or through quantities. What matters is that control is achieved in a rational and effective manner.

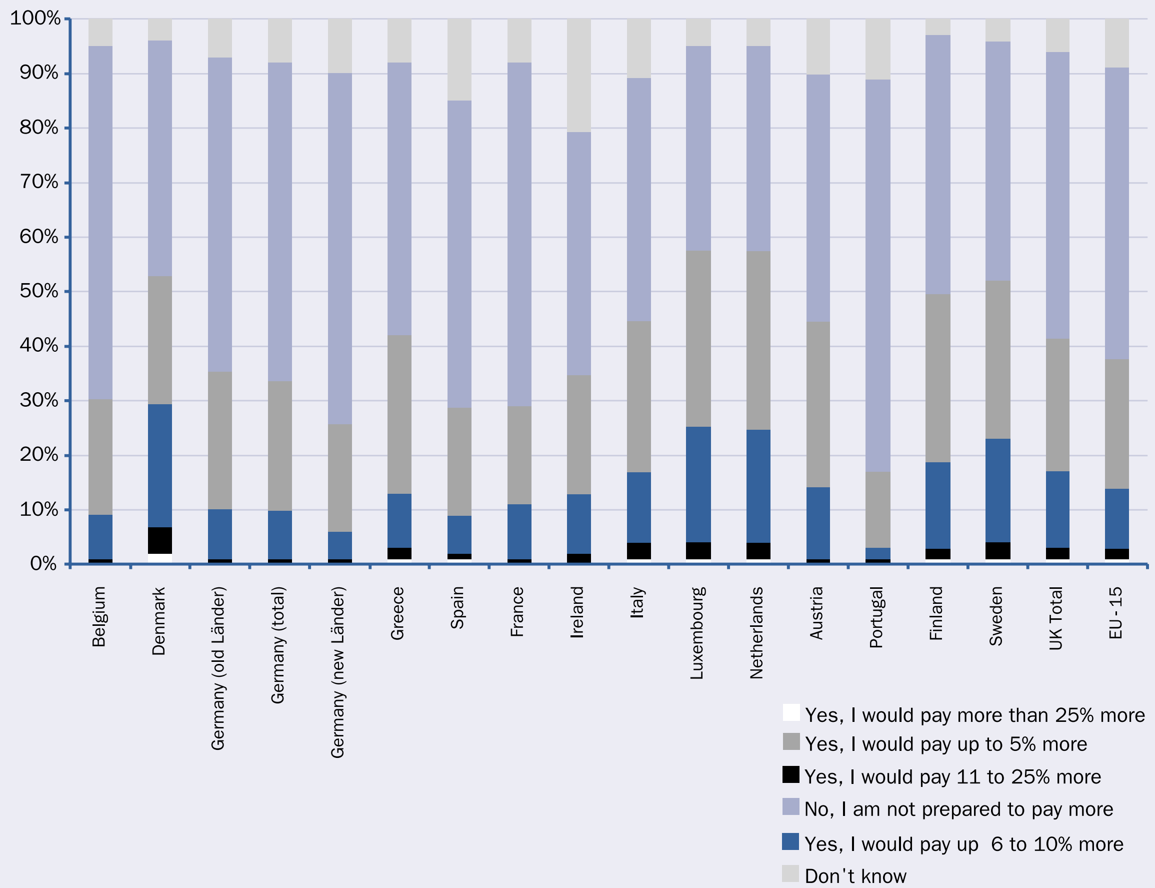
The main difference between quota-based systems and price-based systems is that the former introduces competition between the electricity producers (WT operators). Competition between WT manufacturers, which is crucial in order to bring down production costs, is present regardless of whether government dictates prices or quantities.

1.3.1 VOLUNTARY SYSTEMS AND GREEN MARKETING

In theory, voluntary demand could provide a market for wind power and other renewable energy technologies independently of government policy. However, experience with voluntary systems or "green marketing programmes" to date clearly suggests that voluntary green power schemes purely based on customers' willingness to pay extra for green electricity (ie. without additional measures), have had no noticeable impact on the deployment of wind energy and other renewable energy sources.

A survey by European Opinion Research Group from 2003 shows that some willingness exists among Europeans to pay more for energy produced from renewable energy sources (see Figure 1.1).

Figure 1.1: Results of the Survey Relating Willingness to Pay More for Energy Produced from Renewable Sources



Source: European Opinion Research Group (2003).

However, the number of customers signing up for green marketing programmes cannot be directly translated into support for renewables, as most products contain less than 100% renewables. In Pennsylvania, USA 60,000 out of 80,000 customers signed up for a "green" electricity product that had a renewable energy content of less than 1%.

Much research into voluntary green electricity systems has been conducted in the US where approximately 40% of households have access to a green power product. One study conducted by Lawrence Berkeley National Laboratory at the University of California shows that 0.6% of the residential customers with access to voluntary green electricity products are signed up (2000). In Denmark, only 0.5% of the customers of a Copenhagen-based supply company have decided to buy its green electricity product. For comparison, in a survey by Ramboll, a majority of 58% of Danes answered yes to the question: "Would you consider buying more environmentally friendly electricity, when it becomes possible?"

The Lawrence Berkeley study suggests that the collective impact of green marketing schemes on renewable electricity generation has been very modest. The study concludes that there is a considerable difference in consumers' stated attitudes toward environmental products and the actual demand for them[3].

Schemes referred to as "shareholder programmes", "contribution programmes", "ethical trusts", "green electricity tariffs" or "green electricity labels" are frequently referred to as voluntary schemes, because customers subscribe

to a service of their own free will. However, in most cases where voluntary schemes are perceived to be successful (in terms of subscriber numbers), the driving force behind the increase in these so-called "green" customers is the politically determined framework for investments in wind power and other renewables rather than high voluntary demand for clean power.

The Dutch "Voluntary" System

One example of this is the Netherlands. Following the opening of the Dutch retail market for electricity in July 2001, the number of renewable electricity customers increased from 250,000 to 1.4 million in January 2003. However, the main reason behind the rapid increase in customers signing up to green power schemes was not the population's willingness to buy green. Exemption from a 6 c€/kWh ecotax on electricity in combination with a production incentive (2 c€/kWh in 2002) was the main driver. By surrendering a guarantee of origin (not to be confused with tradable green certificates), supply companies could claim exemption from the ecotax. That made it possible for suppliers to sell green electricity as cheap or cheaper than conventional power.

The Dutch system had obvious flaws, mostly related to the possibility of importing green electricity from abroad. The high level of support for renewables in the Netherlands made it a highly attractive market for foreign renewable electricity producers, which led to high costs in the form of large avoided tax revenues. That would not be so serious a problem had the incentive increased the renewable electricity production abroad. But most imports came from existing plant, e.g. Danish wind power and Swedish hydropower that would have been produced and sold domestically in the absence of the export opportunity to the Netherlands.

In short, Dutch taxpayers were paying for renewable electricity production that would have been produced anyway and, thus, did not increase EU production of renewable electricity by one single kilowatt hour. Furthermore, it was unclear whether the Netherlands or the exporting country could claim the production towards meeting their renewables Directive targets.

Finally, the system was problematic for Dutch wind power developers as they had to compete with cheap production from existing, already depreciated renewables plant abroad, making them reluctant to build domestic capacity. As a consequence of these shortfalls, the Dutch Ministry of Economic Affairs has decided to change the framework.

"Green" Marketing in Denmark

An important issue relating to green marketing is that it can be difficult for the consumer to make informed choices between different suppliers. Determining whether a product is "green" and how to define "green" requires time and effort for electricity customers, suppliers and regulators.

A Danish electricity supplier was marketing a green electricity product, Naturstrom (Natural Power). In 2002 the Danish Energy Regulatory Authority (Energitilsynet) notified the company that it was not allowed to charge its customers a premium price for Naturstrom since the company could not prove that the product had any effect on the environment. Ironically, for the Danish Energy Regulatory Authority it was not a problem that the company actually sold the product (that is up to the ombudsman). The only problem was that it charged a premium price for it. In 2003, the company decided to pay back the surcharges it had collected from its "green" customers.

The case illustrates the challenge facing the electricity consumer who wants to make an informed choice. In the Naturstrom case, Danish customers were paying surcharges for renewable electricity that would have been produced regardless of the green marketing programme. No additional green electricity was produced. Furthermore, Danish customers were paying extra for green electricity that Swedish taxpayers had already paid for once through investment subsidies and feed-in tariffs to wind power.

That the transparency of the green electricity product market leaves much to be desired is underlined by the fact that Naturstrom was endorsed by the Danish Society for the Conservation of Nature and certified by the Swedish Society for Nature Conservation which claims to have "the

world's toughest environmental label". However, for renewable electricity supplies it is not a requirement to obtain the Swedish label that more renewable electricity production takes place, says the organisation.

Obviously, not all green marketing schemes are flawed. Following a decision by the Irish government to open the electricity market to suppliers of green power, Irish company Airtricity started supplying green electricity, predominantly from wind. The company builds, owns and operates its own wind farms and sells the electricity output directly to end customers. Due to Ireland's enormously rich wind resource, it is possible for the company to deliver electricity to its customers below or at the same price as the national electricity monopoly ESB. 26,000 Irish businesses have signed up to Airtricity. According to the company, the production from its wind farms saved the release of 502,968 tonnes of CO_2 into the atmosphere in 2003, equivalent to taking 119,754 cars off the road for a year.

1.3.2 FIXED PRICE SYSTEMS

Figure 1.2 shows the level of feed-in tariffs for onshore wind energy in the EU-15 as of mid 2003.

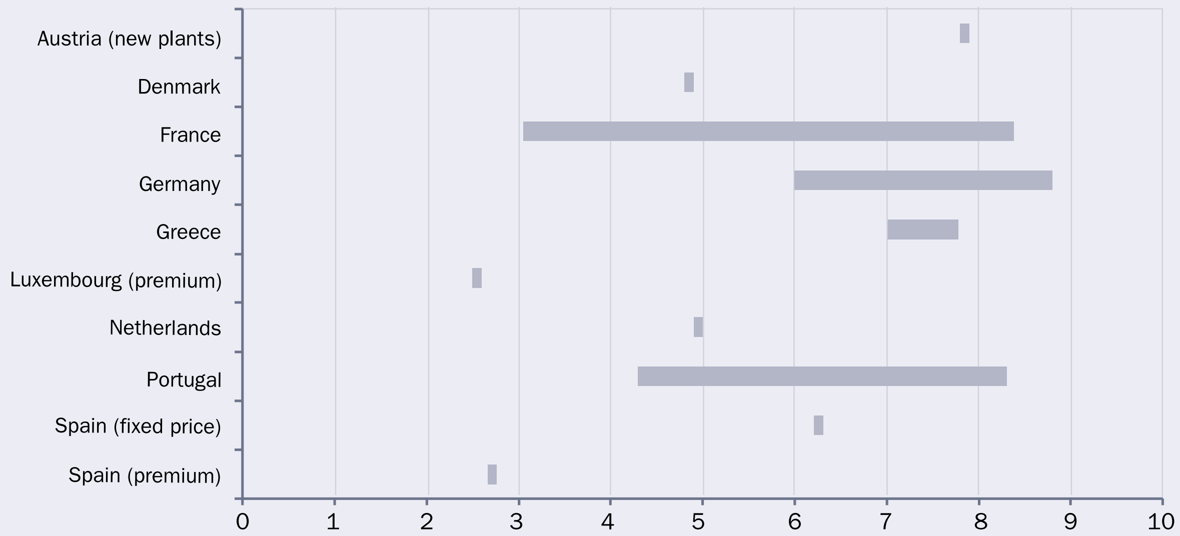
In France, Germany, Greece and Portugal, the tariff is related to the siting of the turbine. In high wind areas, the tariff is lower than in low wind areas. This is to avoid concentrating the development of wind energy in very windy areas of a country. In Spain, WT operators can choose between a fixed tariff per kWh or a premium above a fluctuating electricity price.

1.3.3 INVESTMENT SUBSIDIES

In the early days of wind power development, investment subsidies were often used as an incentive to investors, normally given on the basis of the rated power (in kW) of the generator. It is generally acknowledged that systems that relate the amount of support to the size of the WT rather than the production of the electricity are not ideal because they lead to less efficient turbines. The incentive should be related to efficiency of electricity production rather than to completing the construction phase of a project.

In the 1990s, India gave a subsidy to WT owners based on the rated capacity of the turbines. This proved problematic because the subsidy was given whether or not production was efficient. The scheme resulted in poor sit-

Figure 1.2: Feed in Tariffs for Onshore Wind Plants (c€/kWh)



ing of WTs, and manufacturers followed customer demands to use very large generators, which improved project profitability but reduced production and also attracted highly dubious products. India has since corrected the inherent flaws of its incentive scheme and the market has started to develop properly.

For wind energy, the global trend is to reject investment subsidies as the only means of encouraging investments, because it is considered economically inefficient as illustrated by India's experience.

However, investment subsidies can be effective if combined with other incentives, as is seen in the UK. In order to take account of the higher cost of offshore wind power compared to onshore, the UK government offers investment grants to offshore projects to complement the Renewables Obligation (RO), a renewables quota system. In the absence of such investment grants either onshore development only would be possible or it would be necessary to create two separate RO markets – one for onshore and one for offshore, assuming that both are priorities for the government.

1.3.4 FIXED FEED-IN TARIFFS

Mechanisms based on fixed feed-in tariffs (FITs) have been widely adopted throughout Europe. Operators of wind farms are paid a fixed price for every kWh of electricity they feed into the grid. The cost of the system - defined by the difference between the level of the tariff and the market price of electricity - is borne by the taxpayers or the electricity consumers.

The structure of the mechanism makes it impossible to predict the level of support per kWh. If the level of the tariff remains constant, the level of support will change as a result of changing electricity prices. The level of support per kWh could become negative if electricity prices were to rise above the level of the tariff. Such a situation has occurred in Scandinavia recently. In 2002/2003, electricity prices on the Nordic power exchange Nord-Pool has periodically increased dramatically as a result of low levels of water (low electricity supply) in the Norwegian and Swedish hydropower reservoirs combined with increasing power demand. At times, this has led to the somewhat paradoxical situation that owners of coal power plants receive higher prices for the electricity they supply than owners of WTs.

In Germany, as a rule of thumb, the additional cost of the FIT adds approximately 1 € to the average household electricity bill per month but, as indicated above, the level is difficult to establish when power prices fluctuate. Large German electricity users receive a discount on the tariff contribution.

FIT systems have been highly effective at attracting wind power investments in Denmark, Spain and Germany. Other countries with FITs in place are Austria, France, Greece, Luxembourg, the Netherlands and Portugal.

The main determinant of whether a FIT model is successful at attracting investments is the level of the tariff. Of course, the payment mechanism has to be supplemented by adequate grid connection conditions and a well functioning planning framework. Good planning and grid connection frameworks are a precondition for any mechanism to be successful.

The relatively high level of the FITs in Denmark, Spain and Germany is the reason for their success. In contrast, Belgium, Norway and Sweden have all been running FIT systems that did not contribute much to wind power or other renewable energy development. Profitability, rather than the system itself, is what determines success, together with effective planning and grid connection regulation.

The main benefit of a FIT is that it is simple and often encourages better planning. A FIT is not associated with a formal power purchase agreement (PPA) and has no definite term of existence. In principle, therefore, the level of the tariff can be changed at any time or removed by repealing the law. The main disadvantage of a FIT is the political risk inherent in the system.

The political risk of the FIT in Spain, seen from an investor's point of view, is perceived to be somewhat lowered, since the government has established some degree

of assurance that changes in the tariffs will not bankrupt existing projects built under previous conditions. However, the risk of political change is not eliminated in Spain, and investors can only guess how long the tariff will continue and at what level. Investors therefore have to include a risk premium when planning the financial soundness of projects.

Germany has been able to reduce much of the political risk by guaranteeing payments for 14 to 20 years. If the tariff is believed to be reduced it will have a negative effect on the market for new wind power capacity in Germany, as was seen in 2003. But those who have already invested will not be affected – that is unless the government decides otherwise. Some political risk is therefore still inherent in the German system as investors generally consider it less risky to enter into long-term PPAs enforceable under civil law rather than rely on the good will of a government or parliament.

Greece is a good example that a sufficiently high FIT does not guarantee development of wind energy. The FIT of 90% of the consumer price or approximately 5.75 c€/kWh (around 7 c€/kWh if there is no grid access) is supplemented by up to 40% capital grants. That level would be sufficient to develop wind energy taking into account Greece's wind resources. However, wind power development was not taking off in Greece. The main barrier was in the planning system rather than the level of the tariff.

France is faced with a similar problem to Greece. The financial incentives in the form of FITS for projects smaller than 12 MW and auctions for larger projects seem adequate, but little wind development is taking place. The main problem in the past has been grid and, especially, planning barriers. However, the French government seems determined to overcome these following a national energy debate in 2003.

The political risk of FITs is usually understood as the risk that a government will progressively lower the tariff to reflect the fact that wind power becomes cheaper as the technology develops. But there is also the potential risk that a government will take no action when a FIT is no longer sufficient to attract investments under the overall economic climate.

Fixed payments for wind power supplied to the grid in Denmark and Germany, combined with technology improvements, falling interest rates and low inflation have undoubtedly added to the profitability of investing in wind turbines (WT) over the past decade. On the other hand, higher profitability has been somewhat offset by the increasing use of sites with lower wind speeds.

But what if interest rates had gone up instead of down? Under a fixed price system, turbine owners would not receive any compensation for the higher cost of finance - and the outcome would have been lower profitability - unless the fixed price had been adjusted upwards. WTs are capital-intensive investments with low operating costs, so the cost of finance can have profound impact on project profitability. Had inflation added further to the decline in profits, a situation could occur where technology improvements and economies of scale in WT manufacturing would not be sufficient to offset the higher costs of finance and lower inflation-adjusted income.

Such a situation has not occurred, so there is no evidence of politicians' willingness to increase tariffs to reflect higher wind power production costs. However, it is probably fair to assume that it would be more difficult to convince governments to raise the tariffs – at least in established markets – than to lower them. That test of political will has yet to be seen. The main point is that a fixed price system is rather rigid when it comes to adjusting tariffs – whether up or down – to reflect changes in the production costs of wind power. It should be mentioned that inflation risk can be avoided by including an automatic inflation adjustment to the mechanism, as is done in the US production tax credit (see section 1.3.6).

1.3.5 FIXED PREMIUM SYSTEMS

A "fixed premium" or "environmental bonus" mechanism is another variant of the fixed price system. Rather than fixing the price, the government fixes a premium to be added

to the electricity price. The cost per kWh of the system is, contrary to the fixed FIT, predictable, although the total costs to society depends on the level of development.
From the perspective of a WT owner, the total price received per kWh (electricity price plus the premium) is less predictable than under a FIT because it depends on a changing electricity price.

In theory, a mechanism that is based on a fixed premium/environmental bonus that reflects the external costs of conventional power generation could establish fair trade, fair competition and level the playing field in the internal electricity market between renewable energy sources and conventional power sources. Together with taxing conventional power sources in accordance with their environmental impact (see volume 4), fixed premium systems are, theoretically, the most effective way of internalising external costs.

From a market development perspective, the advantage of a price premium is that it allows renewables to penetrate the market very quickly if their costs drop below the electricity price plus premium. If the premium is set at the "right" level (theoretically at a level equal to the external costs of conventional power), it allows renewables to compete with conventional sources, without the need for politicians to set quotas.

In practice, however, basing the mechanism on the environmental benefits of renewables is challenging. Very ambitious American and European studies (such as the European Commission's ExternE project) on the external costs of power generation have illustrated that establishing the exact costs is very complex. How do we account for lost homes on Pacific islands if the icecap melts, or put a price on deteriorating health? In reality, fixed premiums for wind power and other renewable energy technologies, such as the Spanish model, are based on estimated production costs and comparisons with the electricity price rather than the environmental benefits of renewable energy.

1.3.6 TAX CREDITS

A tax credit is another variant of the fixed price system. Whether an incentive is given in the form of a tax credit or a cash payment does not make a big difference from a socio-economic or investor perspective. Politically, however, it can make a difference whether an incentive is paid by the electricity consumer or by the taxpayer.

The largest wind power market to make use of a tax credit is the US. Canada is also considering introducing a tax driven system. The US market is driven by the federal production tax credit (PTC), which is worth approximately 1.8 c/kWh. It is adjusted annually to take inflation into account.

In recent years, there have been three separate phases of the PTC. The first phase ended on 30th June 1999 and was not renewed until 1st January 2000. The second PTC expired on 31st December 2001. Again, there was a gap before its extension was announced in March 2002, with the third PTC continuing until December 2003. As at December 2003, the tax credit has not been extended, as it is included in a controversial energy Bill on which Congress has not yet reached.

As a result of the relatively short lifetime of each individual PTC, the market has been very volatile and characterised by "boom and bust" cycles. Activity usually picks up dramatically prior to the end of a PTC. There was an enormous amount of activity in late 1998 and early 1999, almost no activity in 2000, and a great deal of activity again in 2001. Activity was picking up again prior to the December 2003 deadline. For both investors and manufacturers, these boom-bust cycles are highly problematic because it makes planning very difficult. Most European WT manufacturers have plans to start up local production in the US, but are reluctant to execute them until long-term stability is secured.

1.4 Fixed Quantity Systems

In fixed quantity or "renewable quota" systems ("renewable portfolio standards" in the US), the government sets a quota for the level of renewable energy that should be produced. It is then up to market forces to determine the price. Two types of renewable quota systems have been employed in national wind power markets: "tendering systems" and "green certificate systems".

1.4.1 TENDERING SYSTEMS

Tendering systems or competitive bidding has been or is being used to promote wind power in Ireland, France (for wind farms larger than 12 MW) and the UK. Scotland and Northern Ireland have also made use of the mechanism. Developers of wind farm projects are invited to bid for a limited wind energy capacity in a given period. The companies that bid to supply electricity at the lowest cost win the contracts. Usually, 15-year PPAs are entered into. The difference in price between these contracts and the price of conventional power represents the additional costs of producing green electricity.

One of the major drawbacks of the tenders made so far is that they have encouraged gaming of the system. Wind energy is a technology that gets cheaper with time. Therefore, a contract holder will wait as long as possible before building a project. Partly because of this inherent flaw, the UK's non-fossil fuel obligation (NFFO) tender system did not result in many projects being built. Another flaw of the NFFO model was that it did not penalise developers if they failed to install the capacity for which they had secured a power purchase contract. In principle, anyone was free to make an unrealistic low and unprofitable bid, win the contract and not develop the project. The ineffectiveness of the UK NFFO system led the government to abandon the model and introduce a new system based on tradable green certificates (see below).

The NFFO was heavily criticised for its failure to deliver, and the UK experience has discredited tendering systems substantially. Although the NFFO had obvious flaws, as described above, that does not mean that tendering systems cannot function. They need to be better designed. The problem with falling production costs over time could have been overcome by introducing deadlines. Furthermore, the model should be combined with a performance bond and meaningful penalties for failing to meet the contract. Finally, poor planning procedures in the UK must also take their share of the blame for the disappointing performance of the NFFO.

If designed correctly, tendering systems can work. One of the main attractions of the model is that the 15-year power purchasing contracts that bidders compete for are enforced under civil law. From an investor risk perspective, a long contract is very attractive since it minimises risk. A second attraction of a well-designed tendering system is that the government (as well as electricity users and taxpayers) does not have to make best guesses about the cost of producing wind power. Through the bidding process, the market sends a clear signal to the government about the cost of wind power production. The political risk of tendering systems is therefore lower than that of fixed price systems. However, investors are faced with another risk element under tendering. All developers that enter a bid risk losing the planning costs if the bid is not accepted or if planning permission is not given on the location in question.

Following the NFFO experience, most countries have disregarded tendering procedures. At present, only Ireland continues its competitive bidding procedure through the AER (see table 1.3), although it is considering changing its system. The overall objective of the AER is to secure 500 MW of new renewable energy capacity in the period 2000 to 2005. The winners of the tender are awarded PPAs for 15 years.

Table 1.3: Status of AER Contracts

AER No.	Launched	Technology	Supported Capacity Amount (MW)	Cap Price/KWH
AER I	1994			
		Wind	73,1	IR £0,04
		Hydro	4,3	IR £0,04
		Biomass	11,8	IR £0,04
		CHP	22,6	IR £0,04
AER II	1995			
		Biomass/waste	30	IR £0.036
AER III	1997			
		Wind	137,3	≤IR£0,039
		Hydro	4,4	≤IR£0,039
		Biomass/waste	17	≤IR£0,039
AER IV	1997			
		CHP	49,6	≤IR£0,03
AER V	2001	Large scale		
		wind (>3MW)	318,3 MW	c€ ≤4,812
		Small scale		
		wind (<3MW)	35,795	c€ ≤5,297
		Biomass	8 MW	c€ ≤5,916
		Hydro	0,949	c€ ≤6,475
AER VI	2003			
		Large scale		
		Wind (<3MW)	259,82	c€ ≤ 5,216
		Small scale		
		wind >	19,6	c€ ≤5,742
		Offshore Wind	50	c€ ≤8,4
		Hydro	5,483	≤
		Landfill gas	1,309	c€ ≤7
		Biomass		
		(anaerobic		
		digestion)	2,022	c€ ≤6,412
		Biomass CHP	26,83	c€ ≤ 7,018

Source: Ener-lure Project Phase III (2002), Sustainable Energy Ireland (2003).

Denmark is planning to introduce a tendering procedure for its future offshore wind power development. The country, which gets some 20% of its electricity from wind power in 2004, is following a strategy that future development of wind power should be offshore combined with repowering of onshore wind energy. The tender conditions were expected to be published in December 2003 but had not been published at the time of writing. However, at a meeting arranged by the Danish Wind Turbine Owners' Association on 27th November 2003, a leading civil servant from the Danish Energy Authority revealed a few details of the forthcoming tender. The information currently available indicates that the competitive bidding will be combined with a price cap of 4.8 c€/kWh. Both the Danish Wind Industry Association, which represents Danish WT manufacturers, and the Danish Wind Turbine Owners' Association have already expressed some concerns about the price cap.

The main criticism is that the cap will make the tender meaningless as bids will not be made. Potential developers are asked to take the risk of low electricity prices on the power exchange, but will not get any benefit if electricity prices increase above the cap. The Danish organisations suggest that the tender is conducted as an auction over the lowest "environmental bonus", defined as the premium above the market price that is required to build the power plants. The cap should be removed in order to create competition and attract a sufficient number of bids. Only then will the price signal about the cost of offshore wind power be effective and able to secure the lowest cost to the consumers. Furthermore, the organisations argue, it is neither market compatible nor in accordance with the polluter pays principle that wind power developers, as the only electricity producers in Denmark, are asked to bear the downside risk of low market prices and at the same time face income restrictions if market prices go up. Although the final proposal had not been published at the time of writing, the debate is already taking place and is illuminating some of the issues that are relevant to the design of tendering mechanisms.

If designed correctly, tendering systems could probably function adequately, as have offshore oil and gas leases. However, it still remains to be proved that the system can be effectively applied to wind power investments.

The sunk planning cost risk described above will also have an effect on the ownership structure of the wind energy market. As projects increase in size the sector is witnessing a shift in ownership away from individuals

towards larger developers. The popular element of the early days of wind power cooperatives and individual ownership will probably vanish unless new collective risk-sharing project development institutions are developed. Another effect of the tendering system would be to concentrate development in the windiest areas. That is desirable from an economic efficiency perspective, but may have implications for planning and public opinion.

Finally, the model is probably better suited to large offshore wind farms than onshore projects. But the planning issues must be dealt with, deadlines must be in place and there should be meaningful penalties for not building. Imposing price caps appears incompatible with the basic idea of tenders – to get the market to provide price signals for the production of wind power.

1.4.2 TRADABLE GREEN CERTIFICATE SYSTEMS

Tradable green certificate (TGC) systems are similar to tendering. The main difference is that the price for the power and certificate is settled daily on the electricity market and there is a separate market for tradable certificates (tendering systems are typically based on 15-20 year PPAs). With daily setting of prices, the TGC model is more risky for the investor unless an effective market for long-term certificates contracts (probably in the form of financial futures or options) is developed.

If a TGC market works effectively, the price of a certificate will reflect the difference between the market price of electricity and the generation costs of new renewable generating capacity. The value of a certificate thus represents the additional cost of producing renewable electricity compared to conventional sources. That value will only by coincidence be equal to the environmental benefits of wind power and other renewables.

In theory (we have not yet seen a well functioning TGC market for wind power), the mechanism should work as follows: the government sets a specific and gradually increasing quantity – or minimum limit – for the amount of renewable electricity in the supply portfolio. An obligation is placed on either the electricity suppliers or end users of the electricity (it is of little importance who has the obligation). The generators (producers), wholesalers, retailers or consumers (depending who is obliged in the electricity supply chain) are obliged to supply/consume a certain percentage of electricity from renewable energy sources. At the settlement date, they have to submit the required number of certificates to demonstrate compliance. Obligated parties obtain certificates in three ways:

- they can own and operate renewable energy plant;
- they can purchase certificates from another renewable energy generator; or
- they can purchase certificates from a generator or broker by purchasing certificates that have been traded independently of the power itself.

The (gradually increasing) obligation creates a demand for TGCs. It is left to the market to deliver the supply of and establish a price for certificates. TGCs are issued to producers of renewable electricity in proportion to the volume of green electricity they generate. A TGC serves as evidence that a specific amount of green power has been produced and fed into the grid. If demand for certificates exceeds supply - the amount of renewable electricity produced is lower than the government quota - then the price of certificates will rise. It will continue to do so until the price satisfies investors' requirements for return, whereas new capacity will be installed to meet the quota.

Currently, the introduction of tradable renewable certificate systems has been proposed or is being implemented in Denmark, UK, Belgium Sweden and Italy (see Table 1.4).

Table 1.4: Overview of Various Certificates Models

	Denmark	UK	Belgium (Flanders)	Belgium (Wallonia)	Italy	Sweden
Period	start 2002	start 2002	start 2002	start 2002	start 2002	start 2003
Obligation	20% by end 2003 (proposal abandoned)	3% in 2002; 4.3% in 2003; 10.4 % in 2010; 15% in 2015	1.2% (2003), 2% (2004) increasing up to 6% in 2010	3% in 2003 increasing up to 12% in 2010 From September 2010 onward, the quota will be multiplied by a factor of 1.01	2% in 2002 and will be increased annually by 0.35% between 2004 and 2008	7.4% in 2003, 16.9% in 2010
Obligation on	end user	supplier	supplier	supplier	producers and importers	end user
Technology bands (baskets) within overall quota	no	no	no	no	no	no
Involved technologies	small hydro, wind, bio-mass, solar, geothermal energy, no waste	small hydro, wind, biomass, solar, geothermal energy, no waste	all renewables, no solid municipal waste	all renewables and high quality CHP	all renewables (incl. large hydro), facilities not older than eight years	small hydro (<1.5 MW), large hydro (only in some cases), wind, biomass, geothermal, wave energy
International trade allowed	no	no	no	no	yes, but only in exchange for physical electricity	no
Price restrictions (min/max price)	min= € 0.014/kWh max= € 0.037/kWh	not planned, max price according to penalty	max price according to penalty, min at federal level. From 1.7.03 onward the grid operator has the obligation to buy TGCs issued anywhere in Belgium for the minimum prices per TGC of: € 90 (offshore wind); € 50 (onshore wind) € 50 (hydro); € 150 (solar); € 20 biomass	max price defined by penalty. Min - producers of RES-E may exchange their TGC for a subsidy at a fixed price of € 65. At federal level, from 1.7.03 onward the grid operator has the obligation to buy TGCs issued anywhere in Belgium for the minimum prices per TGC of: € 50 (onshore wind); € 50 (hydro); € 150(solar); € 20 biomass	n.a.	min prices in the introductory phase: in 2003 € 6 in 2004 € 5.5 in 2005 € 4.4 in 2006 € 3.3 in 2007 € 2.2 in 2008 € 0. max price according to penalty
Penalty	€ 0.037/kWh	The buy- out price is £30.51/kWh (for 2003/2004) (~€ 45/kWh)	€ 75 per certificate (1,000 kWh) in 2003, € 100 in 2004 and € 125 in 2005	from 1.4.03 onward: € 100 per TGC (1,000 kWh)	n.a.	150% of the market price, but with a maximum of a SEK 175 for certificates that should have been surrendered during 2004, and SEK 240 for 2005
Trading scheme	n.a.	stock exchange	stock exchange	open trading and direct support	free or in the power pool	open

Comments: **Denmark**: the proposed TGC was abandoned. **UK**: recent developments have shown that the certificate price is higher than the buy-out price. This development is due to a shortage of certificates due to limited RES-E construction and the fact that the buy-out revenues for non-compliances are recycled to the suppliers in proportion to the certificates they have used for complying with the obligation. **Belgium**: the green certificate system is run by regional regulators. Only certificates for offshore wind energy (non-existent as yet, but expected) will be issued by the federal government. **Italy**: GRTN (Italian Transmission System Operator) strongly influences the certificates' market by selling its own certificates from old CIP6 plants at a regulated price, namely that set by law as the average of the extra prices paid to acquire electricity in the CIP6 programme that year. The Italian system has little to do with TGC systems because both the price and the quantity of certificates issued are fixed.

The Dutch system (see section 1.3.1) is also sometimes erroneously promoted as a TGC system, due to some confusion about the difference between TGCs and guaranties of origin (GoO). A GoO can be compared to content descriptions in the supermarket. They are not tradable in themselves unless the products are homogenous in nature and a financial market is established. The existence of GoOs in the Netherlands does not therefore make it a TGC system.

Complex Design

The TGC mechanism is more complex in nature than other payment mechanisms. WT operators will have to be active in two interrelated financial markets: one for TGCs and one for power. One of the problems is that there seems to be an asymmetry between the demand and the supply side in the markets. WT owners would prefer to have as long a contract as possible to minimise risk, while the electricity companies on the demand side seem to prefer short contracts. It is essential that the certificate market is able to attract financial arbitragers and speculators that can allocate risk.

Ideally, there should be no floor or cap on the price of certificates. However, there will need to be a penalty for not complying. As with any other penalty, this should be set at a level so high that it will never be enforced. A high penalty is one reason for the success of the US SO_2 trading market. If the penalty is set too low (too close to the expected market price of the certificates) it will act as a price controlling factor, which will distort the market.

In the ideal market, the price of the certificate and the expected price of electricity will always add up to what economists refer to as the “marginal cost” of producing wind power; that is, the costs of adding one more unit - a WT - to the generating base. In reality, any change in costs associated with wind power production will be compensated for by an equal change in the combined income from selling the electricity and its accompanying certificate. If, for example, interest rates rise, so will the combined payment. If sites with poorer wind resource are used the combined payment will also rise. And if technology improves it will fall.

In theory, under a Renewables Portfolio Standard (RPS) all changes - or rather, all expected changes - in the cost determinants of wind power investment will be immediately reflected in the combined price of electricity and the price of renewable energy certificates. Likewise, a fall in electricity prices will be accompanied by an equal rise in the price of the certificate.

As with tendering mechanisms, the rationale behind the TGC system is to reduce the costs of expanding renewable capacity by introducing competition between producers of renewable energy. Price competition will be transferred further down the system and renewable energy producers will seek to bargain with turbine manufacturers and land owners for lower prices to a larger extent than under the fixed price system.

The role of the TGC market, as any other market, is to establish a price according to the laws of supply and demand. But determining a price is problematic when supply and demand are fixed in the short term (the problem of vertical demand and supply curves). A price cannot be determined if a situation where demand equals supply is an exception. The effect will be that the price will tend to be banging either against the price cap created by the penalty or the price floor (if there is one), rather than floating in the mid-range.

In other words, if there is one certificate more in circulation than is needed to comply with the obligation, nobody will want to buy it and it has no value. This is a problem arising from fixed demand and fixed short-term supply - it causes the price to become very volatile, fluctuating between zero or infinity (or zero and the level of the fine for not complying with the obligation).

In order to eliminate price fluctuations caused by the fixed demand and to secure flexibility in payment, a system of “banking” must be available. Certificates will be issued at the time of production of renewable energy and will be destroyed, in accordance with the requirements of the obligation, on delivery to an independent authority. But there will most likely be an imbalance between actual production of wind kilowatt hours and the quota obligation for any given period. The market must be structured to cope

with the imbalance. A banking system could be a solution. Such a system gives consumers the option of buying future production - and WT owners the option of selling future production by trading borrowed certificates. This stabilises fluctuating prices by creating a basis for long-term certificate purchase contracts. The system thus allows participants in the market the option of hoarding certificates in the expectation of future price changes, and WT owners the option of borrowing certificates in case their turbines do not produce enough electricity to meet their long-term delivery contracts.

Because of the expected imbalances between actual production and the renewables quota, and the problems of volatile certificate prices, consumers or electricity suppliers (who bear the weight of the obligation to buy renewables) must be able to hand in contracts on future delivery by sending a larger number of certificates to destruction. This can be viewed as the "interest" on a certificate. With no interest element, the obligation will be met at the latest possible juncture, causing disturbance in the market.

For owners of WTs (and their sources of finance) it is of paramount importance that any payment system allows a fair amount of certainty to be attached to cash flow projections. In support systems based on fixed price this tends to be less of a problem. But when selling power and certificates on spot markets with fluctuating prices it could become a problem. It increases the risk and thereby the cost of producing wind power.

Financial long-term contracts could limit this problem through the establishment of a futures or options market. By selling electricity and certificates on long-term futures or options contracts, the risk (and the price) can be reduced. Futures and options contracts make it possible to sell or buy certificates for delivery some time in the future at a price that is agreed upon today. Such a market would need an institution to facilitate trade and guarantee delivery if a WT owner is unable to deliver.

Another aspect to consider is whether all renewables technologies defined in the EU Directive on promotion of electricity from renewable energy sources should be included in a single "umbrella certificate" or whether a certificate for each technology is the answer. One certificate, however, only ensures development of the cheapest renewable technology, while several certificates will result in a market with dangerously low liquidity, at least in the beginning of development.

One way to deal with the problem is to accept, say, that PV is 10 times more expensive than wind power and issue 10 times the number of PV certificates. But such a solution brings us back to the fixed price problem - there is no easy way of estimating the true production costs of the various technologies, which makes it difficult to determine the proportional relationship between the costs of wind and solar. What if the cost of solar drops 10% from its current level, and the certificate proportion is not changed politically to reflect the drop? Investment in solar would soar and nobody would invest in other renewables options, even though they may be several times cheaper in real terms - hardly a cost effective way of meeting renewable energy targets. Offshore wind, being more expensive than the onshore variety, gives rise to the same problem; a way needs to be found of stimulating its development if politically desirable.

Furthermore, issuing certificates in proportion to estimated production costs requires constant evaluation of the costs of technologies as well as political intervention in the form of changed certificate proportions. The political risk in such a market would be substantial. One certificate for all technologies would also make it impossible to determine the price of pollution abatement in relation to the individual technology and determine when a technology will no longer need support: an "umbrella certificate" will still have a positive value when the least costly technology becomes competitive. The risk is that support will be given to technologies that no longer need it.

On the other hand, the liquidity problem of having several certificates cannot be ignored. Low liquidity is a problem for efficiency in any market. There are compromise solutions, however. Certificates could be issued to different technologies in exactly the same proportions, with the less competitive technologies receiving separate subsidies. Or instead of granting direct capital investment subsidies, auctions could be held for subsidised contracts, to

encourage competitive bids and provide an incentive to reduce costs, much along the lines of the UK NFFO.

Voluntary Demand and TGCs

In the meantime, there is "green marketing" (see section 1.3.1) to consider. There is potential for the introduction of a green pricing market where like-minded citizens and companies can opt to pay a premium to receive their electricity from a renewable source.

Consumers who want to buy renewable energy in excess of the obligation must have the opportunity of doing so without being cheated. So far there is no European structure in place to allow for this.

Discussions to date among electricity sellers have centred on offsetting electricity bought by consumers in excess of the obligation against the quota requirement. Should this be allowed, consumers would be fools to buy excess certificates. Such purchases would not lead to more renewable energy being produced and these green consumers would be paying for those who declined to meet their obligation. A clean environment is considered a public good. If a neighbour buys it, they cannot prevent you from benefiting from their purchase for free.

Legislation is necessary if the market is to work properly. Just as it is on stock and bond markets. Legislation and rules create a framework within which the market can work. Once the framework has been established, intervention from law-makers should be kept at an absolute minimum. Otherwise prices on the market will reflect expectations of political action rather than fundamental economic relationships.

Economic theory, however, does not reflect the real world. When politicians get into the game of creating free markets, so do numerous opposing views and compromises. WT owners want one thing, electricity companies another and consumers (voters) a third. Senseless compromises can very well create disturbances to the market mechanism and, in the worst case, render it useless.

The UK Renewables Obligation

The most ambitious attempt to promote green electricity through tradable green certificates is the UK's RO. This came into force in April 2002, replacing the much maligned NFFO tendering procedure. Suppliers have to demonstrate compliance with the RO through the presentation of renewables obligations certificates (ROCs) which are issued in proportion to green electricity production. Each ROC represents 1 MWh of renewable electricity from eligible generators. Ofgem, the regulator, is responsible for the administration of the RO and for the compliance. For the period of 2003/2004 suppliers have to meet 3.4% of total electricity consumption through renewables. The obligation runs yearly, rising to 10.4% in 2010 and to 15% in 2015. It is due to finish in 2027. To meet the RO suppliers have three options:

- purchase ROCs through the supply of renewable energy purchased from eligible generators;
- buy ROCs from other suppliers or from the NFPA which periodically auctions the ROCs it has acquired under the existing NFFO contracts; or
- pay the penalty or buy-out price set by Ofgem for not meeting the quota.

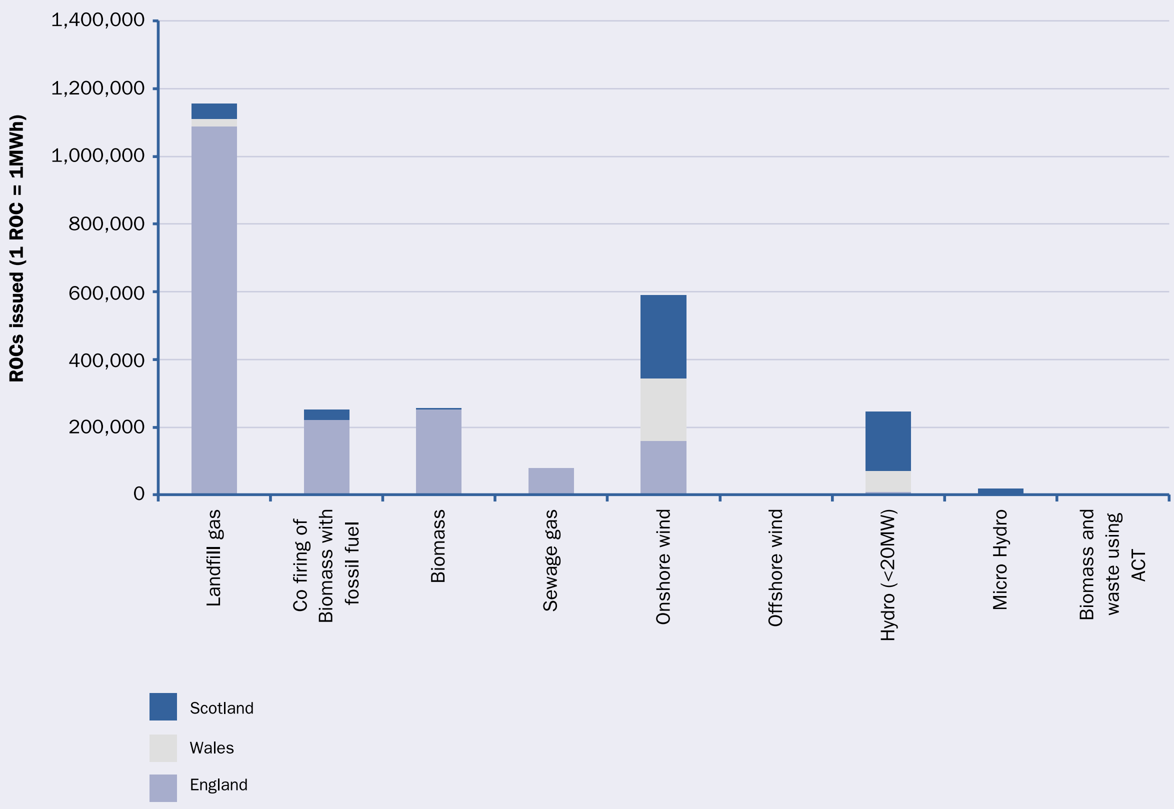
The buy-out price is currently set at £30.51 per MWh. All payments proceeding from the buy-out price made by suppliers for each MWh of shortfall between the amount of their obligation and the number of ROCs presented are placed in a central fund. This money is redistributed to suppliers which have met the obligation in proportion to the number of ROCs presented. Therefore, the real costs for a supplier who is not complying with the obligation is higher than the buy-out price. That explains why ROCs are trading at higher prices than the penalty. ROCs are traded at approximately £40 to £50 while the buy-out price is £30. Figures released by Ofgem in 2003 show that electricity companies missed the target for renewable electricity by 40% in the first year of the RO. 5.5 TWh of renewable electricity was produced, while the obligation was around 9 TWh. The RO does not differentiate between different renewable technologies so only the cheapest technologies will be developed unless additional measures

are introduced or other markets are developed. For offshore wind power, the government supplements the RO with capital grants to reflect the fact that offshore wind power is currently more expensive than onshore.

The UK ROC system is providing valuable experiences with the complicated task of developing TGC systems. So far, the mechanism has not proved effective in adding renewable capacity and the cost of the system (on a cost per kWh basis) is high. However, it is still early days in the ROC market and the UK government seems determined to make the necessary adjustments and prove sceptics wrong.

Figure 1.3 shows the number of ROCs issued in the UK between October 2002 and February 2003 by technology and country.

Figure 1.3: ROCs Issued Between October 2002 and February 2003 by Technology and Country in the UK



Source: Ofgem Newsletter (2003).

1.5 Renewables in the New Member States

From 1 May 2004, 10 new EU member states will have to comply with the EU renewables Directive. Electricity from renewable energy sources met 5.6% of the new member states' electricity supply in 2000. To meet the indicative targets, that share will need to rise to 11% by 2010 (see Table 1.5).

Some of the new member states already have payment mechanisms in place. Hungary, Latvia and Estonia have introduced renewable tariffs. But development of wind power faces bigger barriers than simply the payment mechanism. There is a need to develop more accurate resource assessments, wind maps, reliable grid reinforcements and grid connection frameworks. In many countries, distribution and transmission grids are not robust enough to support large penetration of wind power. In Poland, up to 1,000 MW of wind power is planned in the north of the country on the Baltic coast. Infrastructure reinforcements will be needed to transport the electricity generated to the main population areas further south. Both the Polish and Czech Republic governments are currently in the process of debating new frameworks for investing in wind power and other renewables. Fixed FITs are currently in place in both countries, but it is difficult to obtain long-term PPAs.

Appendix K provides an overview of wind power development in various new member states.

1.6 The EU Legal and Political Framework

The Treaty establishing the European Community calls for: a *"balanced and sustainable development of economic activities"* and *"a high level of protection and improvement of the quality of the environment"* (Article 2); *"the integration of environmental protection requirements in the implementation of Community policies with a view to promote sustainable development"* (Article 6); and bases its Community policy on the environment on the principles that preventive action should be taken: *"that environmental damage should, as a priority, be rectified at source and that the polluter should pay"* (Article 174).

Table 1.5: Renewables in the New Member States

	1999/2000			2010		
	Renewable Gross Consumption (TWh)	Total Gross Consumption (TWh)	Proportion Renewable Electricity (%)	Renewable Gross Consumption (TWh)	Total Gross Consumption (TWh)	Proportion Renewable Electricity (%)
Cyprus	0.00	3.00	0.05	0.26	4.27	6
Czech Republic	2.34	61.70	3.8	5.66	70.7	8
Estonia	0.01	6.75	0.2	0.37	7.3	5.1
Hungary	0.22	28.30	0.7	1.71	47.4	3.6
Latvia	2.76	6.50	42.4	4.09	8.3	49.3
Lithuania	0.33	9.95	3.3	0.80	11.4	7
Malta	0.00	1.80	0	0.10	2	5
Poland	2.35	140.00	1.6	10.50	140	7.5
Slovak Republic	5.09	28.30	17.9	9.24	29.8	31
Slovenia	3.66	12.20	29.9	4.91	14.6	33.6
Total EU 10	16.8	298.5	5.6	37.62	335.77	**11.21**
Total EU 15	338.41	2435.00	13.9	646.6	3000.26	**21.6**
Total EU 25	355.2	2733.5	13.03	684.22	3336.03	**20.5**

Source: Directorate-General for Transport and Energy (2003).

The Lisbon strategy aims to make the European economy "*the most competitive and dynamic knowledge-based economy in the world, capable of sustainable economic growth with more and better jobs and greater social cohesion*".

According to the Commission's Green Paper on security of energy supply, in two decades Europe will be importing 70% of its energy (up from 50% today) unless it changes direction. Wind power can plug the gap in the European energy supply and, at the same time, contribute greatly to the goals set out at Lisbon: economic growth, high quality jobs, technology development, global competitiveness, and European industrial and research leadership. Furthermore, wind power and other renewable energy technologies will have a large impact in meeting the EU's Kyoto commitments and contributing to sustainable development. The Green Paper recognises that:

> *"Renewable sources of energy have a considerable potential for increasing security of supply in Europe. Developing their use, however, will depend on extremely substantial political and economic efforts... In the medium term, renewables are the only source of energy in which the European Union has a certain amount of room for manoeuvre aimed at increasing supply in the current circumstances. We cannot afford to neglect this form of energy."*

> *"Effectively, the only way of influencing [European energy] supply is to make serious efforts with renewable sources."*

1.6.1 THE ELECTRICITY DIRECTIVE

In December 1996, joint rules for an internal electricity market in the EU were adopted. The overall goal is to increase the economic efficiency of the electricity supply in the EU by introducing competition. EU countries are therefore in the process of gradually liberalising their electricity markets and full liberalisation should be achieved by 2007. So far, renewables have avoided being included in the liberalisation process because their contribution to total electricity supply is small and therefore causes little distortions.

But as the contribution of renewable energy sources to the EU supply mix grows, so too will the distorting effects of the many different payment mechanisms currently in place in the EU. That is not compatible with free trade, according to the European Commission, and they could eventually be subject to internal market conditions.

On 26th June 2003 the European Parliament and the Council adopted a new Directive concerning common rules for the internal market in electricity. The new Directive seeks to achieve the complete opening of the EU electricity market by July 2007. It aims to reduce the risk of market dominance and predatory behaviour and ensure non-discriminatory transmission and distribution tariffs and network access. Furthermore, it establishes provisions for the unbundling of transmission and distribution operators and establishes labelling requirements for electricity suppliers regarding CO_2 emissions and radioactive waste from electricity production as well as the contribution of each energy source in the supplier's fuel mix.

The EU recognises that wind power and other renewables remain at a competitive disadvantage to fossil and nuclear sources. The support and payment mechanisms currently in place in the member states can be regarded as a substitute for a pollution tax on energy. Renewable electricity technologies do not benefit from decades of financial support and would be required to compete with existing nuclear and fossil fuel power stations producing at marginal costs, because interest and depreciation of power plants have already been paid for by electricity consumers and taxpayers. The medium term solution could be to create an internal market for renewables and the European Commission may, if it deems necessary, propose a harmonised framework for renewable electricity in 2005.

1.6.2 THE RENEWABLES DIRECTIVE

Directive 2001/77/EC on the promotion of electricity from renewable energy sources aims to double the amount of electricity produced by renewable energy by 2010. Indicative targets for shares of electricity have been set for each member state (see Appendix M). The

Commission is assessing member states' progress towards meeting the targets. The Directive States:

(1)" The potential for the exploitation of renewable energy sources is underused in the Community at present. The Community recognises the need to promote renewable energy sources as a priority measure given that their exploitation contributes to environmental protection and sustainable development. In addition this can also create local employment, have a positive impact on social cohesion, contribute to security of supply and make it possible to reach Kyoto targets more quickly. It is therefore necessary to ensure that this potential is better exploited within the framework of the internal electricity market."

(2)" The promotion of electricity produced from renewable energy sources is a high Community priority as outlined in the White Paper in renewable energy sources for reasons of security and diversification of energy supply, of environmental protection and economic cohesion."

Article 9 stipulates that member states shall bring into force the laws, regulations and administrative provisions necessary to comply with the Directive not later than October 2003.

The purpose of the Directive is:

"To promote an increase in the contribution of renewable energy sources to electricity production in the internal market for electricity and to create a basis for a future Community framework thereof." (Article 1).

The Directive recognises that:

"It is too early to decide on a Community-wide framework regarding support schemes, in view of the limited experience with national schemes and the current relatively low share of price supported electricity produced from renewable energy sources in the Community."

However, the Directive states that mechanisms should eventually be adapted to include renewable energy sources in the internal electricity market:

"It is, however, necessary to adapt, after a sufficient transitional period, support schemes to the developing internal electricity market."

Furthermore, it is emphasised that the intention is to use market forces to make renewable energy sources competitive.

"It is important to utilise the strength of the market forces and the internal market and make electricity produced from renewable energy sources competitive and attractive to European citizens."

The Directive on electricity from renewable energy provides the wind power and other renewables industries with crucial assurance that the EU is determined to further progress the development and integration of renewable energy technologies. It sends a powerful signal to the industry of long-term political commitment at European level which, in return, should reduce investment risks and thereby the cost to society of developing and integrating renewable energy sources.

The liberalisation process will not create a perfect market or a level playing field overnight and the RES-E Directive ensures that short-term distortions of the European electricity markets do not undermine the possibility of developing those renewable energy technologies that will facilitate a future European energy supply that is cheap, clean and independent of fluctuating oil and gas prices.

For many years, the European Wind Energy Association (EWEA) has called for a level playing field in the electricity sector, including the internalisation of external costs in electricity prices and the removal of state subsidies to conventional energy sources. The Commission has actively pursued the same agenda, e.g. by proposing common energy taxes and reductions in the level of state aid to conventional energy technologies. However, these have still to materialise. In the meantime, the renewables Directive serves as a good substitute. It will allow the industry to develop the renewable energy technologies that will secure the availability of cheap, clean energy and a future European indigenous energy supply.

No later than October 2005 the Commission shall present (Article 4):

A well-documented report on experience gained with the application and coexistence of the different [payment] mechanisms. The report shall assess the success, including cost-effectiveness, of the support systems referred to in paragraph 1 in promoting the consumption of electricity produced from renewable energy sources in conformity with the national indicative targets referred to in Article 3(2). This report shall, if necessary, be accompanied by a proposal for a Community framework with regard to support schemes for electricity produced from renewable energy sources.

Any proposal for a framework should:

(a) contribute to the achievement of the national indicative targets;

(b) be compatible with the principles of the internal electricity market;

(c) take into account the characteristics of different sources of renewable energy, together with the different technologies, and geographical differences;

(d) promote the use of renewable energy sources in an effective way, be simple and, at the same time, as efficient as possible, particularly in terms of cost; and

(e) include sufficient transitional periods for national support systems of at least seven years and maintain investor confidence."

Presidency Conclusions - Brussels, 20 and 21 March 2003

At its meeting in March 2003, the Council urged member states to accelerate progress towards meeting the indicative renewable electricity targets (section 1). *Ensuring delivery on the environmental dimension of sustainable development,* subsection *Reversing unsustainable trends:*

"53. Economic and social development will not be sustainable in the long run without taking action to curb environmental pressures and preserve natural resources within the framework of the comprehensive sustainable development strategy launched at Göteborg. This must include action aimed at decoupling environmental degradation and resource use from economic growth. Despite some progress, the worrying trends observed when the Strategy was launched have not been reversed, and a new impetus must therefore be given."

"54. Against this background, the European Council:
- invites Member States to accelerate progress towards meeting the Kyoto Protocol targets, including the reduction of greenhouse gas emissions, the increase in the share of renewable energy, setting an EU-wide indicative target for renewable energy of 12% of primary energy needs and of 22% of electricity needs by 2010 and encouraging national targets; increased energy efficiency, inviting the Environment Council to examine setting indicative targets in a cost-efficient manner and with minimum distortionary effects; and achieving a final agreement on the emissions trading Directive;"

1.7 Concluding Remarks

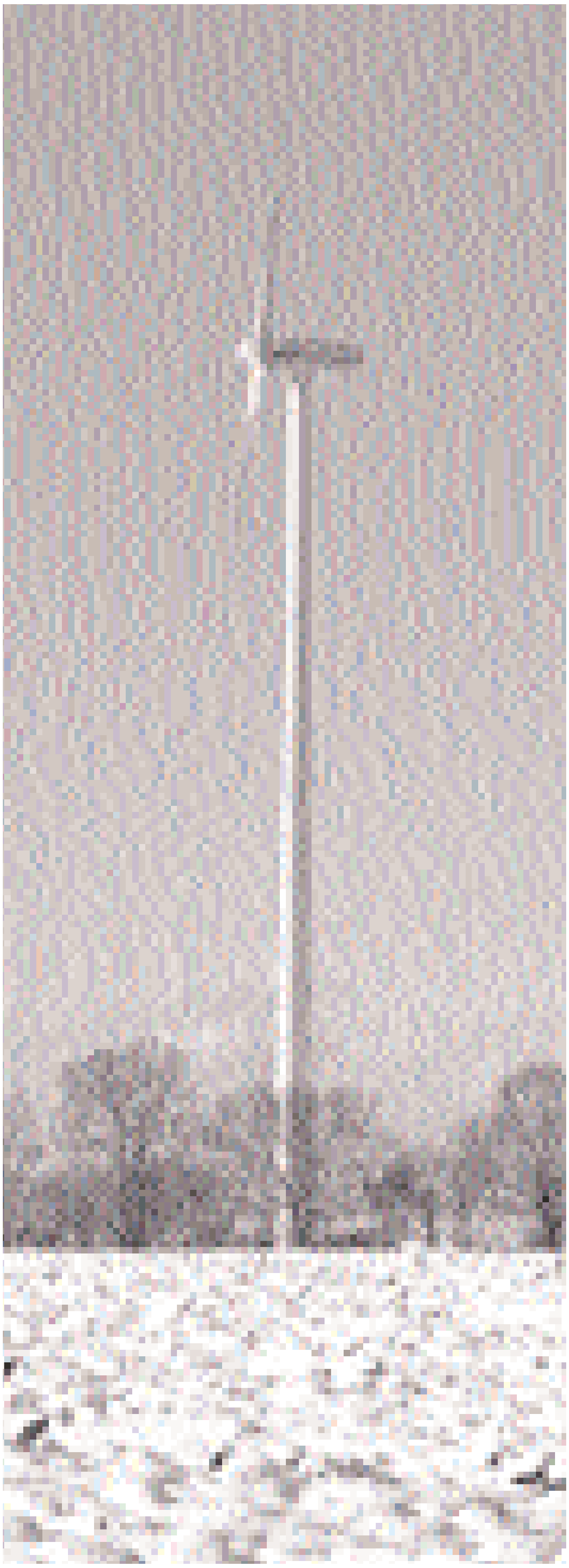
The analysis in this section has focused specifically on national mechanisms. National experiences are obviously useful when analysing the effectiveness of various mechanisms, but the analysis cannot be directly translated into a Community-wide system. Introducing cross-border trade in the economic analysis of payment mechanisms raises a myriad of additional questions related to the functioning of the support mechanisms. It is beyond the scope of this report to analyse the effects of international trade on renewable energy sources. The two year RE-Xpansion project funded by the European Commission is currently looking into the European-wide dimension of payment mechanisms.

One issue is crucial, however, regardless of which mechanism is considered at a EU-wide level. A precondition for a well-functioning internal market in renewable energy is that rules and regulations relating to WT investments are harmonised. It therefore makes sense to continue the practice followed by the Community ever since the signing of the Single European Act in 1986. Without harmonisation of rules and regulations, e.g. in relation to grid access

conditions, tax treatment, safety standards, etc., the market will be distorted.

It is clear from the industry's experience of various mechanisms that, although the price paid for electricity is vital, of equal importance, particularly if project finance is needed, is consistency of the market, the creditworthiness of the offtaker and hence the ability to make a long-term plan. Finally, planning procedures and fair grid access at reasonable cost is of equal importance to the development of wind power and other renewable energy technologies.

Successful countries are characterised by substantial inward investment by suppliers who see a future market in that country, and who see the benefits of local supply. The most successful in this respect have been Spain, Denmark and Germany, which now have not only a substantial installed wind capacity, but also a substantial wind energy industry.



2 FUTURE MARKETS

2.1 Introduction

This chapter presents two market scenarios; a conventional and an advanced scenario to the years 2007 and 2012. The advanced scenario is, taken from *Wind Force 12* - a scenario for a greatly increased market due to higher political and policy support than is envisaged today. For the status of European Markets see volume 3, chapter 1.

Future market assessments are essentially scenarios that are shaped by the assumptions and data used, by historical trends and their extrapolation, and by individual perspectives, all interacting with a wide range of external factors. The assumptions behind any future estimates of what is a rapidly evolving and changing market are key to determining the status and scope of that prediction.

Specific factors that define future wind market prospects include:

- Future demand for electricity generating capacity.
- Future power plant decommissioning.
- Government political priorities and policies on energy, electricity, environment and climate change.
- Continuous and increasing acknowledgement of the environmental benefits of renewable energy production as well as the external costs to society of conventional energy production.
- Prospects for emerging new markets to follow the current "big three" (Germany, Spain, Denmark).
- The economics of wind power itself and its competitiveness with other electricity generating technologies.
- Prospects for the large amount of wind power capacity currently awaiting final completion and construction.
- Evolving status of the leading commercial wind actors, the industry structure, and new entrants and stakeholders.
- Effectiveness and improvements of wind power technology through R&D and scale.
- Detailed understanding of wind resources and their exploitation.

Some of the trends and data on the industry's development are described earlier in this report. The nature of the major commercial players is changing, and it is predicted that the trend towards larger companies will continue.
Some commentators predict the market will continue to grow, with more established conventional energy companies joining the sector in larger numbers, as wind power emerges as a major energy source, not just an environmental "add-on".

2.2 Conventional Scenario

Specific market assessments for the short to medium term future wind energy markets are made by a number of players within the sector: wind companies and developers; consultancies; members of the financial services community, and by external institutions such as the IEA and the EU. Market analyses that are not published are undertaken by a number of consultancies, investors and institutions. This assessment by EWEA for the conventional scenario utilises inputs from Garrad Hassan and compares them to other leading market opinions of DEWI and BTM Consult.

The conventional scenario takes the following core assumptions which, to some degree, could be classified as a "favourable business-as-usual scenario". In this, EWEA estimates that the current strong development of the wind power market to date will continue as long as commitment to the sector by a number of governments continues to strengthen, and that such support is converted into actual deployment. But there is no potent policy intervention on the scale of that envisaged in the advanced scenario in Wind Force 12, which assumes, for example, that the Production Tax Credit in the USA (a tax incentive for investing in renewables) will be renewed. A market assessment of around five years is generally regarded as being a more accurate forecast. Beyond that, the predictive ability is greatly reduced because the defining factors are difficult to foresee with any real accuracy.

What is apparent is that future markets are going to be rather different from historical ones. The annual level of growth of approximately 35% observed over the last four to five years can only be sustained for a limited period, as such a growth level is only possible from a low starting point. Eventually, two obstacles will appear: an inability to produce additional manufacturing resource at the required rate; and the inroads which such rapid development make on the general level of demand for new generating capacity, conventional or renewable.

2.2.1 CONVENTIONAL SCENARIO RESULTS

Table 2.1: Market Projection by Region - Annually Installed MW

	2002	2003	2004	2005	2006	2007
Europe	5,983	6,050	6,300	6,550	6,750	7,000
(Of which EU-15)	(5,871)	(5,900)	(6,100)	(6,300)	(6,450)	(6,600)
North America	450	1,600	1,200	1,500	2,000	2,000
Central & South America	10	100	200	300	500	600
Asia	411	600	700	800	850	850
Africa	11	25	50	100	150	150
Australia & New Zealand	119	150	250	250	300	300
Others	17	75	100	100	100	100
Total	**7,001**	**8,600**	**8,800**	**9,600**	**10,650**	**11,000**

Table 2.2: Market Projection by Region - Cumulative Installed MW

	2002	2003	2004	2005	2006	2007
Europe	23,291	29,341	35,641	42,191	48,941	55,941
(Of which EU-15)	(23,056)	(28,956)	(35,056)	(41,356)	(47,806)	(54,406)
North America	4,923	6,523	7,723	9,223	11,223	13,223
Central & South America	144	244	444	744	1,244	1,844
Asia	2,610	3,210	3,910	4,710	5,560	6,410
Africa	148	173	223	323	473	623
Australia & New Zealand	225	375	625	875	1,175	1,475
Others	59	134	234	334	434	534
Total	**31,400**	**40,000**	**48,800**	**58,400**	**69,050**	**80,050**

Table 2.3: Market Projection for the World - Cumulative Installed MW[1]

	2008	2009	2010	2011	2012
World	**92,000**	**105,800**	**121,670**	**139,920**	**160,900**

[1] Assuming 15% average annual growth in cumulative capacity between 2007 and 2012.

The average annual growth rate in cumulative capacity between 2002 and 2007 is 20.6%.

The European data corresponds to those outlined in the targets in Chapter 3. Europe continues to dominate, with increased interest in France and the UK predicted, together with a gentle decline in German onshore activity followed by an uptake of the offshore segment. Spanish activity remains dominant but fairly flat. In Europe, the leading markets will remain Germany and Spain, although important markets in France, the UK, the Netherlands, Italy and Sweden will emerge.

The market forecast indicates a slight slowing down of the onshore European market, but an increase in activity in countries which have not played a major role to date. There will be a time gap before the offshore market takes off to replace it. In the meantime, there will be significant

growth in the US. New markets are starting to develop in Australia, Japan and South America. There is relatively little installed capacity in these countries and, hence, the potential for future growth is large.

Other countries that are considering serious investment include Canada, Brazil, Tunisia, China, Egypt, Morocco, the Philippines, Turkey and Vietnam.

2.3 Other Forecasts

BTM Consult in its World Market Update of 2002, forecasts a global market of **83,000 MW** by the end of **2007**, and **177,000 MW** by the end of **2012**.

DEWI's WindEnergy-Studie 2002, an annual survey of several hundred wind companies, estimates that the market will be **80,000 MW** installed worldwide by the end of **2007**, and **120,000 MW** by the end of **2010**.

Hamburgische Landesbank's study in July 2002, *Wind Power: Evaluating International Markets for Wind Power and Wind Power Generator Manufacturers*, estimates **80,800 MW** installed worldwide by the end of **2006** and **144,000 MW** by the end of **2011**.

Dresdner Kleinwert Wasserstein's 2001 report Power Generation to the 21st Century predicted the global market by the end of **2006** to be **67,000 MW**.

The EU and other international institutions have also made future market assessments (see box).

Europe in 2010	
European Commission	
White Paper (1997)	40,000 MW
EU *Energy Outlook for 2020* (1999)	22,600 MW
EU *Energy Trends to 2030* (2003)	69,900 MW
World in 2010	
IEA World *Energy Outlook reference scenario* (2002)	55,000 MW
IEA forecast (2003) *Renewables for Power Generation, Status and Prospects*	120,000 MW

2.4 Wind Force 12 – The Advanced Scenario

EWEA has published advanced scenarios for the wind power sector since 1999 - *Wind Force 12* (May 2003) is in its fourth edition. It is the main long-term scenario analysis for the wind power sector worldwide and can be accessed in full at www.ewea.org.

2.4.1 METHODOLOGY

The aim of the Wind Force 12 study is to assess the technical, economic and resource implications for a penetration of wind power into the global electricity system equal to 12% of total future demand in 2020. The intention has been to work out whether a 12% penetration is possible within that timescale in terms of technical feasibility, industrial ability and resource availability.

The methodology used explores the following questions:

- Are the world's wind resources large enough and appropriately distributed geographically to achieve a level of 12% penetration?
- What level of electricity output will be required and can this be accommodated in the existing grid system?
- Is wind power technology sufficiently developed to meet this challenge? What is its technical and cost profile?
- With the current status of the wind power industry, is it feasible to satisfy a substantially enlarged demand and what growth rates will be required?

The first *Wind Force* study was carried out by BTM Consult for the Danish Forum for Energy and Development (FED) in 1998. This served as the model for a more detailed analysis released in 1999 by FED, Greenpeace and EWEA, entitled *Wind Force 10*. An update, *Wind Force 12*, was published in 2003 by EWEA and Greenpeace.

The 1998 study examined the potential for 10% wind penetration by working with two different scenarios for world electricity demand. In the more detailed *Wind Force 10* report (1999) only one parameter of future electricity demand was used - the IEA's 1998 "World Energy Outlook", a projection which assumes "business as usual" and in which electricity consumption is predicted to double by 2020.

2.4.2 REGIONAL UPDATE OF WIND FORCE 12 ADVANCED SCENARIO

Table 2.4 provides an update from the *Wind Force 12* scenario, split into regions. In this assessment, a breakdown by region for the years 2007 and 2012 has been carried out - taking into account the initial status (2002 figures). It shows that a few regions, namely Europe and the US, are on track to achieving their potential, while others have not yet left the starting blocks. To calculate the cumulative figures for each continent, a certain average annual growth rate of annual installation is chosen and later turned into a growth rate for cumulative installation. Typically, this results in a high value for new and emerging regions and a more modest value for regions already on track, i.e. OECD Europe.

Table 2.5: Summary of Conventional and Advanced Market Scenarios (Cumulative Installed MW)

Year	2007	2012
ADVANCED scenario - Europe	59,000	112,000
Average annual growth rate	20%	14%
ADVANCED scenario - world	106,000	311,000
Average annual growth rate	27%	24%
CONVENTIONAL scenario - Europe	55,941	-
CONVENTIONAL scenario - world	80,050	160,900
Average annual growth rate	20.6%	15%

The average annual growth rates are for the periods 2003 - 2007, and 2008 - 2012.

Table 2.4: Wind Force 12 Scenario Update - Breakdown by Region in 2007 and 2012

Region	2002[1] Installed Capacity	Average Growth of Cumulative Installation 2003 - 07	New Annual Capacity In 2007	Cumulative Capacity in 2007	Average Growth of Cumulative Installation 2008-12	New Annual Capacity 2012	Cumulative Capacity in 2012	Distribution of the Total World's Wind Power Capacity By 2012
	MW	%	MW/yr	MW	%	MW/yr	MW	%
OECD Europe	23,832*	20%	7,900	59,000	14%	10,750	112,000	36.0 %
US & Canada	4,944	29%	5,200	17,500	30%	14,090	65,000	20.9 %
Latin America	143	74%	1,420	2,300	51%	4,560	18,000	5.8 %
OECD Pacific	730	45%	1,615	4,700	24%	4,630	13,500	4.3 %
East Asia	0	-	410	1,200	38%	2,225	6,000	1.9 %
South Asia	1,714	39%	1,470	9,000	23%	4,560	25,000	8.0 %
China	473	76%	2,270	8,000	37%	7,600	38,000	12.2 %
Middle East	32	90%	270	800	30%	960	3,000	1.0 %
Transition Economies	22	257%	1,185	2,500	59%	6,490	25,500	8.2 %
Africa	148	47%	305	1,000	38%	1,315	5,000	1.6 %
Total World Capacity WF12 Scenario (figures rounded)	32,038	27%	22,000	106,000	24%	57,000	311,000	100 %

* Source: EWEA (2003c).
[1] 2002 Figures sourced from BTM Consult (2003).

2.5 Overview of Non European Markets

2.5.1 NORTH AMERICA

Canada

Late 2001 and early 2002 saw a major change in the Canadian market. Hitherto, apart from one isolated development of a 100 MW project in Quebec, the Canadian market has been dormant. The Canadian Wind Energy Association has announced a very ambitious plan to achieve 10 GW of installed wind power capacity by the year 2010. Commentators consider that this is highly unlikely under the current legal framework, yet a concrete proposal for a tax credit, rather similar in nature to that in the US, has resulted in a high level of interest in several states. It has also reawakened interest in the wind energy business by many Canadian utilities.

Space is clearly not a limitation in the Canadian market, but the availability of grid connection for large-scale projects is likely to pose challenges. Wind maps have been produced, or are under production, for several of the Canadian provinces, and the authorities in Newfoundland, Saskatchewan, British Columbia and Quebec have expressed interest during the 2003. Little development took place in Canada during 2002, but there are signs that activity will accelerate. Expressions of interest have been sent to NRCan for 1,220 MW for commissioning in 2003; 1,500 MW for 2004; and 600 MW for 2005. A substantial failure rate and delay must be expected, but these are nevertheless sizeable numbers.

2.5.2 CENTRAL AND SOUTH AMERICA

Argentina

Argentina has long been considered a promising market for wind energy, since it has a prodigious resource in terms of both wind speed and space. Particular interest is often expressed in the large, open expanses of Patagonia. Several European companies have articulated detailed plans to exploit this resource, and some modest level of installation has taken place. However, the recent economic difficulties in Argentina suggest that any short to medium term large-scale exploitation is unlikely. Market commentators do not, therefore, see a lot of commercial activity in Argentina in the near future. In the longer term, Argentina does seem to be a good candidate for substantial investment, however.

Mexico

Mexico has continued to surprise the wind energy industry by its lack of development. A large-scale wind energy resource investigation has been conducted, and there is a need for new generating capacity. There have been several calls for tender for significant development, but none have yet been realised. No new capacity was installed in Mexico in 2002. However, 2003 has seen a significant change in mood, and it is expected that there will be Mexican development in the short term, and future development will be significant thereafter. Mexico has some areas of wind energy resource which are exceptional, and these are likely to be the first to be exploited. It now seems that there is interest of sufficient substance and local influence to allow developments to take place.

Brazil

In 2001, Brazil suffered a severe water shortage and, since its electricity industry is dominated by hydroelectric power, this translated directly into a shortage of electricity. As a result, a Ministry of Crisis was created; part of its responsibilities was to investigate new methods of procuring additional electrical capacity on a short time-scale. A new law to encourage renewable energy, and wind power in particular, was enacted: the Pro Eolica Law called for the immediate construction of 1,050 MW of wind energy in Brazil. Substantial interest was shown, with some 3,000 MW proposed. Ironically, since the level of interest was more substantial than the Brazilian government had been expecting, and consequently there was no mechanism in place to differentiate between the different proposals, the over-subscription resulted in delay. At the same time, the level of hydro resources returned to a more normal level. Neither of these events bodes well for the immediate development of large-scale wind energy in Brazil.

The financial arrangements for payment under the Pro Eolica Law are not yet clear, and it is possible that some new bidding mechanism or other form of competition may be invoked in order to determine where the contracts will be placed. The Brazilian electricity industry has recently been privatised, and many of the large ex-utilities have been purchased by European companies. As a result, it is possible, even in the absence of a resolution of the Pro Eolica difficulties discussed above, that some private, but nevertheless large, wind farm developments will proceed. This is possible by virtue of the use of direct Purchasing Power Agreements (PPAs) between wind farm developers and utilities who have some common ownership. Very recent changes again appear to suggest that large-scale development may be about to start. It is necessary, however, to view these possibilities with a cynical eye since there have been many false starts for wind energy in Brazil.

Costa Rica

Costa Rica already has a high level of wind power penetration into its relatively limited electrical grid. Nevertheless, the Costa Rican state utility has further plans for additional implementation of wind energy projects. Continued growth is expected in wind energy installation in this country.

Panama

Panama has recently completed the development of a wind resource map and, whilst specific plans to develop projects are not yet available, it seems reasonable to assume that some level of modest development will take place in the future.

Chile, Columbia, Peru, Venezuela

These countries have all expressed interest in wind energy projects, and plans and proposals in various forms have been discussed. To date, there has been little activity, but it is expected that, as developments take place in the countries surrounding them in the region, some modest activities will appear.

Development of a 24 MW wind farm by the Colombian utility EPM was planned for 2003.

2.5.3 AUSTRALIA AND NEW ZEALAND

Australia

The recent review of Mandatory Renewable Energy Target (MRET) which places a legal obligation on wholesale purchasers of electricity to contribute towards the generation of an additional 9,500 GWh of renewable electricity annually by 2010 has caused some uncertainty but also a sudden and quite substantial increase in activity in Australia. To date, the level of installation is modest, but the planned activity is significant – of several thousand MW. At the time of writing, the obligation was set at 2% of 1999's total electricity production to come from renewables or specified waste-product energy sources by 2010. Australia's electricity consumption has risen quite substantially during the last few years and, hence, this level now equates more closely to 0.5% of total electricity production. The current target is estimated to result in the construction of 900 MW by 2010.

A MRET review report was released in January 2004 and will pass through the political process during 2004. Currently, the dominant players are the incumbent generators, but many private developers are also present in the market, and it is particularly interesting to note that some European developers who are expecting a downturn in the onshore German market, have chosen to make investments.

The biggest hindrance to development in Australia is the lack of substantial grid connections. The electricity grid follows the centre of populations along the coastal areas of the South East, with separate grids in the different states. Western Australia and the Northern Territory are completely disconnected from the south. There is no clear mechanism for resolving this issue at present.

Local benefits, in terms of indigenous manufacturing, are going to be a key consideration, and several states are in the late stages of negotiation with wind turbine manufacturers. In order to gain a permit for the construction of

a wind farm in Australia, it will be necessary to demonstrate local benefit. “Local”, meaning the state rather than the country.

Some commentators see Australia as “the new Spain”. One market commentator considers that the Australian market is going to be substantial within the next few years. It has wind, it has space, it has an excellent industrial infrastructure and a clear code of business ethics. It does, however, require some amendments to its electricity and renewable energy legislation.

New Zealand

There has been little activity in New Zealand in recent years. Nevertheless, there are some projects at the planning stage, and there is significant resource assessment activity in progress. The early promise of New Zealand as a new market, indicated by the construction of the 40 MW Tararua project, has not been realised, due largely to the continued weakening of the New Zealand dollar, the further reorganisation of the electricity industry, and a continued drop in the electricity price. The New Zealand market is expected to continue to be flat for some years.

2.5.4 ASIA

India

In the mid- to late-1990s there was a great deal of activity in India, driven by a combination of energy shortages and tax credits. Unfortunately, the market mechanisms gave particular benefit to the installation of wind farms, rather than to their efficient operation. The result was a series of irresponsible developments, with poor engineering and inadequate resource assessments in advance of construction. That spate of activity was followed by several years of minimal activity as a result of the general economic crisis in Asia but, recently, the Indian market has restarted in a much more controlled fashion. Market commentators expect this approach to continue and, hence, growth in the Indian market to continue at this level. It is considered beneficial to analyse the way in which the Indian market has changed and to consider the new mechanisms which have been put in place. It may be sensible for other countries which suffer from power shortages and financially weak utilities to use India as a model e.g. some of the micro-financing models in place could serve as good inspiration for developing countries.

A notable characteristic of the previous Indian development was the fact that, by the end of the Indian “wind rush” in the late 1990s, some 70% of the turbines installed were manufactured in India. This high level of indigenisation is an important characteristic of the wind industry as a whole, and should be given due weight when considering new export markets. Most of the turbines manufactured in this way were made under licence from European or American vendors. A significant result of this approach has been the emergence of Suzlon Energy as a manufacturer in its own right. Suzlon purchased the German company Sudwind, and is now developing its own turbine technology and has a research centre in Germany and a blade factory in the Netherlands. It is presently operating its prototype 1 MW turbine in California and is developing a 2 MW successor. Suzlon turbines are now being offered for sale outside India and Suzlon itself is operating as a developer in other countries. This step is significant, not only for India, but for the industry as a whole: a continuation of the relatively modest growth over the last two years with a slight increase over time is likely.

Japan

Historically, the Japanese market has not been active, despite the fact that Japan boasts not only a major manufacturer in the form of MHI, but also several of the leading wind farm developers - Tomen Power Corporation (Eurus), Marubeni and Nichimen. This imbalance has been redressed in the last two years as a result of some attractive incentives, both in terms of kWh price and capital grants. The Purchasing Power Agreements (PPAs) have a long-term lifespan of 17 years which creates investor confidence. The wind speeds are relatively low, and the cost of construction in Japan seems high by world standards. Therefore, some caution must be exercised in considering tariffs in a more general context. Japan is relatively densely populated in areas where construction is feasible. It is considered that some of the Japanese terrain will complicate large-scale developments. It is, therefore, noted that

the Japanese are also considering the possibility of offshore development, but there are some limitations because of water depth and the occurence of typhoons. Commentators expect the level of installation in Japan to increase from that experienced over the last few years, but not to rise dramatically due to space limitations and a reluctance on the part of the Japanese utilities to accept wind energy projects under current conditions.

China

The development of the Chinese market has been somewhat disappointing. Several years ago there was a lot of activity aimed at developing both a domestic Chinese manufacturing industry, and various aid-assisted projects which were intended to lead to a substantial uptake of wind energy in various of the Chinese states. Many of the aid-assisted projects now appear to have foundered and, hence, the rate of uptake expected is rather slower than was previously anticipated. The construction of conventional power stations in China, using predominantly brown coal, has slowed slightly. This is also likely to have the effect of reducing the uptake of wind. It is considered that the level of introduction of wind energy in China will depend very strongly on the level of licence agreements or indigenous manufacture which can be achieved. Several Chinese companies are developing indigenous technology, to date with limited success.

2.5.5 AFRICA

North Africa

All of the countries along the southern coast of the Mediterranean, with the exception of Algeria, are expressing a keen interest in wind energy. Plans have developed in Morocco, Tunisia, Libya and Egypt. There has been much discussion in Morocco over the last two to three years of developments of the order of 100 MW. The tendering process has been very protracted, however, and is still not resolved. It is, nevertheless, acknowledged that there is a very substantial resource available, with exceptional wind speeds at some sites. However, the incumbent utility's lack of willingness to develop these projects is a major cause for delay.

In Tunisia, matters are progressing slowly but steadily and, although there is little activity to date, it is likely that the future will see significant installation in Tunisia within the next two years. The geographical proximity of Italy may, in itself, have an effect, and the presence of the Vestas manufacturing plant in Taranto will be useful.

Libya has recently called for assessments to be made of its wind resource and for the establishment of a technology centre for the development of wind energy. No concrete plans are known to date but it is thought that some will appear in a foreseeable future. The political situation, however, makes Libya a difficult market, at least in the short to medium term.

Egypt has benefited for a long period from various overseas aid-related projects from different European countries and, hence, does have a base of installed capacity. Together with the World Bank, these aid agencies are continuing to show an interest in Egypt. The wind resource along the Nile is substantial and is now reasonably well documented, but there is still no sign of any real commercial development of this market.

Mild growth is expected in this block of countries over the next five years.

The Rest of Africa

The vast majority of the African continent does not have sufficient wind to merit any serious investigation for large-scale installations. The situation may be rather different for local, small-scale generation. There should, nevertheless, be a promising market in South Africa, since it is well away from the equatorial belt, where winds are limited. Interest has been shown in South Africa but, until the South African utility, ESKOM, becomes convinced of wind power's efficacy, and a political decision is taken to develop it, it seems unlikely that there will be substantial development there. Wind maps have been produced and detailed discussions have taken place, but there is still little real sign of activity at a larger scale. Notwithstanding the comments made above, recent expressions of interest have been shown from Kenya and, perhaps in the longer term, this country may see some modest developments.

2.5.6 THE EAST

Turkey

Turkey is considered to be a very substantial long-term market. It has a major shortage of energy, substantial space, a reasonably good electrical infrastructure and a very good wind resource. Turkish industrial companies with substantial financial muscle have invested in a large-scale resource assessment, and some 2,000 MW of potential development exists. A major hurdle has been the country risk, in particular political and currency instability. During 2001, this resulted in the virtual cessation of Turkish wind development activities. However, new legislation is being considered and, it is expected that projects will eventually be completed and, hence, a market is anticipated, although not for several years.

The Middle East

Syria, Jordan and Iran have all shown interest in wind energy. The promise of some of the early development, particularly in Iran, has not been followed through with further projects and, given the political situation in these countries, a substantial long-term market is not envisaged at present.

The Far East

Interest in wind energy is beginning to emerge in Malaysia, Indonesia, the Philippines, Vietnam and South Korea. There are some concrete projects being planned in all these countries, with some modest activity expected. Many of these countries suffer from a combination of relatively low mean wind speeds and very high extreme wind speeds which, therefore, require a major capital investment for a relatively limited return in energy. Consequently, these countries are not expected to have a substantial market in the near future, although Korea, for example, has repeatedly expressed an interest in establishing an indigenous industry and this appears to be under way.

3 NEW TARGETS

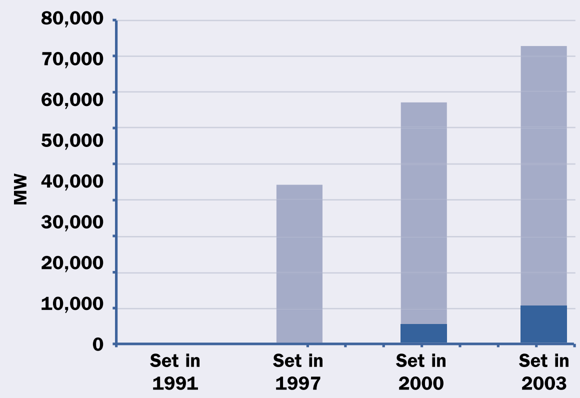
3.1 EWEA Targets - Onshore and Offshore

EWEA targets for wind energy installed capacity in the EU-15 are as follows:

- In 2010 - 65,000 MW onshore, and 10,000 MW offshore: 75,000 MW in total
- In 2020 - 110,000 MW onshore, and 70,000 MW offshore: 180,000 MW in total

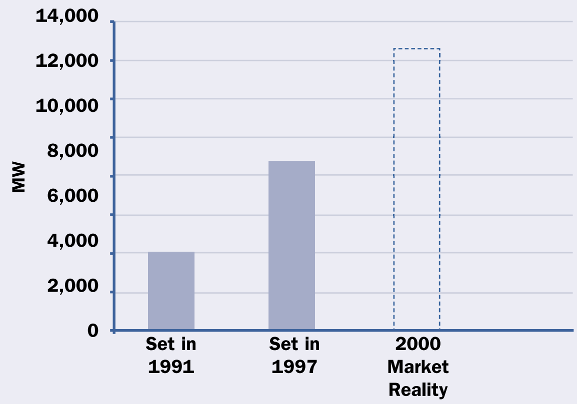
In 1997, EWEA adopted the target set out in the European Commission's White Paper on Renewable Sources of Energy of 40,000 MW by 2010 (Figure 3.2). Three years later, EWEA revised its target to 60,000 MW by 2010 including 5,000 MW offshore; and 150,000 MW by 2020 including 50,000 MW offshore (see figures 3.2 and 3.3). These figures were then revised to the above in 2003.

Figure 3.2: EWEA Targets for 2010 (MW Installed in EU)



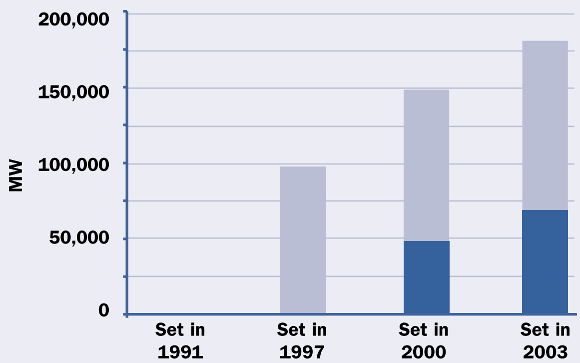
MW Onshore	-	40,000	55,000	65,000
MW Offshore	-	-	5,000	10,000

Figure 3.1: EWEA Targets for 2000 (MW Installed in EU)



MW Onshore	4,000	8,000	12,887	-
MW Offshore	-	-	-	-

Figure 3.3: EWEA Targets for 2020 (MW Installed in EU)



MW Onshore	-	100,000	100,000	110,000
MW Offshore	-	-	50,000	70,000

In 2003, EWEA published *Wind Force 12*, which demonstrates that wind power is capable of supplying 12% of the world's electricity within two decades, even if the overall electricity demand increases by two-thirds in that period, given increased political will. The study is not a long-term forecast or a prediction, but rather a feasibility study for future scenarios taking into account the physical limitations for large-scale development of wind power. It assesses and compares actual industrial growth patterns seen in the wind power sector so far with hydro and nuclear power development.

In this 12% global scenario, Europe (defined more broadly as OECD Europe, under IEA classifications) will install 100 GW by 2010 and 230 GW by 2020, producing 564 TWh/year and saving 338 million tonnes of CO_2 emissions per year. Equally important, it is envisaged that around 1,000 GW of wind power will be installed in non-European countries during the same period.

BTM Consult (2003) in its recent *World Market Update 2002* predicts that the cumulative capacity in Europe will reach 58 GW by the end of 2007 and 108 GW by 2012.

3.1.1 EUROPEAN COMMISSION - HISTORICAL TARGETS

In 1997, the European Commission's White Paper on Renewable Sources of Energy set the goal of doubling the share of renewable energy in the EU from 6% to 12% by 2010. One of the White Paper targets was to increase EU renewable electricity production from 337 TWh in 1995 to 675 TWh in 2010. Within this target, the goal for wind power was for 40,000 MW (40 GW) of installed capacity in 2010, which could produce 80 TWh of electricity.

The subsequent Directive (2001/77/EC) on the promotion of electricity from renewable energy sources sets national indicative targets for the contribution of electricity from renewable energy sources as a percentage of gross electricity consumption. The overall Community goal is to increase renewables' share of electricity from 14% in 1997 to 22% in 2010.

3.1.2 EUROPEAN COMMISSION – NEW TARGETS

The European Commission has dramatically increased its projections for wind power installed by 2010. In its recently published report *European Energy and Transport*, the Commission stretched its previous forecast by more than 200%.

Its earlier prediction (based on the energy model PRIMES) for installed wind power capacity in the EU-15 was 22.6 GW by 2010, a level already reached in 2002. The Commission now predicts a total of 69.9 GW of wind power capacity to be installed in the EU by 2010. Thus, the new Commission estimate is more in line with the EWEA target of 75 GW by 2010.

However, the Commission's energy model is exceptionally pessimistic regarding the long-term forecast for wind power beyond 2010. For the two decades from 2010 to 2030 PRIMES predicts a combined net increase in capacity that will be less than the net increase in the current decade (see Table 3.1).

Table 3.1: Primes - Installed Generation Capacity by Plant Type in EU (GW)

	1995	2000	2010	2020	2030
Nuclear	126.2	131	121.9	100.1	105
Large Hydro	85.1	87.7	88.9	88.9	89.2
Small Hydro	2	2.1	8.1	12.2	14.5
Wind	2.5	12.8	69.9	94.8	120.2
Other RES	0	0.2	0.5	0.6	14
Thermal Plant	322.9	344.8	399.5	516.1	608.1
Total	539	579	689	813	951

One of the shortcomings of the model is that it does not consider technological change. The new Commission estimates for wind power in 2010 have been dramatically revised to better reflect current reality and future industry projections. However, the projections for the period 2010 to 2030 remain unrealistically low. As wind power becomes cheaper, electricity demand is likely to increase by some 1.5% per year in the coming decades, and many conventional power plants will be decommissioned in the

coming 25 years. Furthermore, wind power will become increasingly competitive.

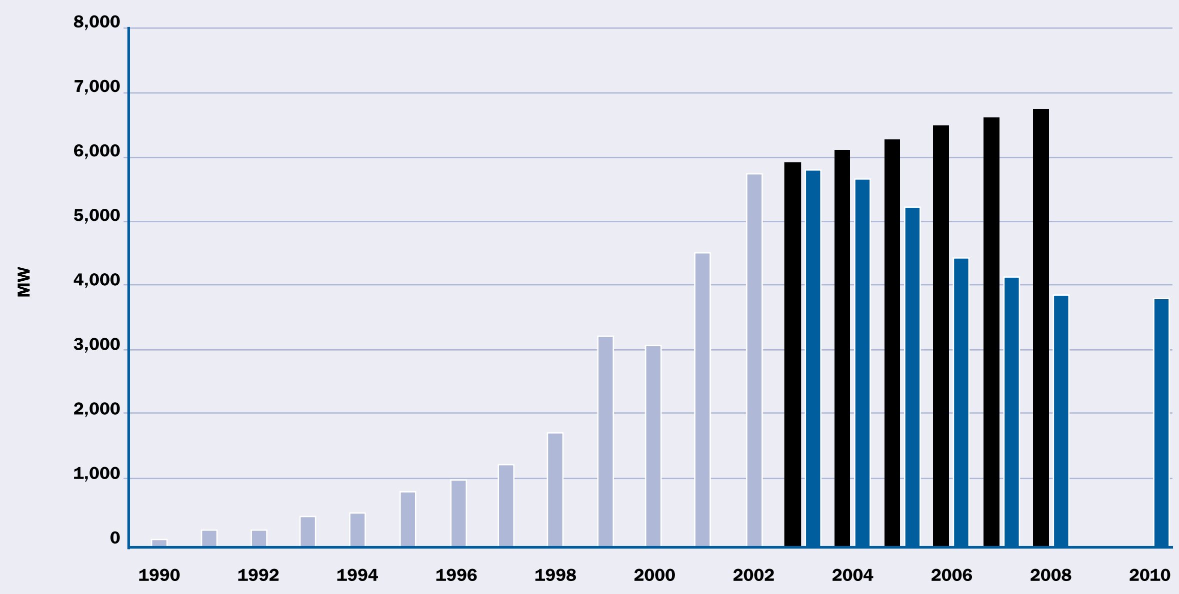
3.2 Increasing Wind Power Targets for Europe

Figures 3.4 and 3.5 detail the new industry targets which show that wind installation will continue to increase, but at a lower rate. The high growth of the last few years has been based mainly on the German and Spanish markets. Market forecasts for coming years indicate that annual installations will stabilise in Spain and will decrease in Germany. A 3.5% increase in annual installations is assumed for the year 2003, decreasing gradually to 1.4% in 2010. This corresponds to a 25.7% increase in total installed capacity in 2003 gradually decreasing to 10.3% in the year 2010.

In order to estimate the electricity production from wind power, and the corresponding CO_2 emission reductions, during the period 2001 - 2010, a yearly projection development has been performed. The average capacity factor (see glossary) of WTs is assumed to increase from 0.25 in 2001 to 0.28 in 2010. Over the past two decades, capacity factors have improved as a result of both better initial design and better siting.

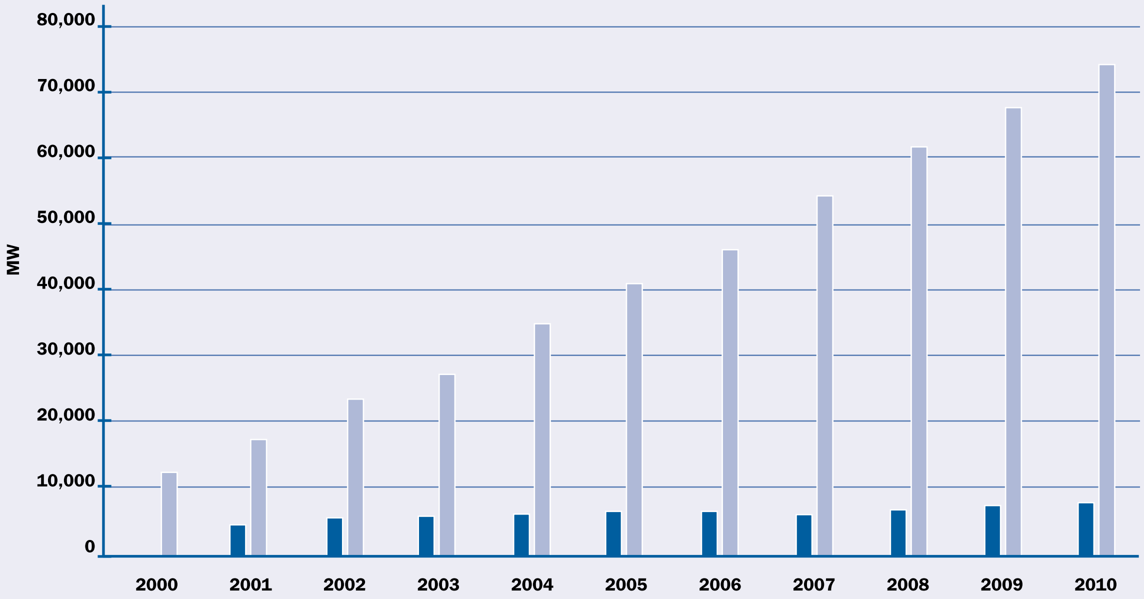
The major contributions to improved capacity factors have been the increased hub height above ground level of the larger turbines and technological improvements from R&D activities. It is worth noting that, for a technology that utilises a free resource, a high capacity factor is not a goal in itself. Improving the capacity factor of WTs presents no technical problems, but it does affect grid integration, modelling and generation costs.

Figure 3.4: Projections of Annual Installations (2003 – 2010) in the EU-15



New Capacity - target 75 GW													5,900	6,100	6,300	6,450	6,600	6,750	6,900	7,000
New Capacity - target 60 GW													5,744	5,650	5,200	4,550	4,150	3,900	3,900	3,850
Actual Market	190	215	367	472	814	979	1,277	1,700	3,225	3,209	4,428	5,871								

Figure 3.5: Wind Power Target Projections up to 2010 (MW) in the EU-15



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
New Capacity (MW)		4,500	5,700	5,900	6,100	6,300	6,450	6,600	6,750	6,900	7,000
Cumultative Capacity	12,800	17,300	23,000	28,900	35,000	41,300	47,750	54,350	61,100	68,000	75,000
Annual Growth of New Capacity			26.7%	3.5%	3.4%	3.3%	2.4%	2.3%	2.3%	2.2%	1.4%
Annual Growth of Cumulative Capacity		35.2%	32.9%	25.7%	21.1%	18%	15.6%	13.8%	12.4%	11.3%	10.3%

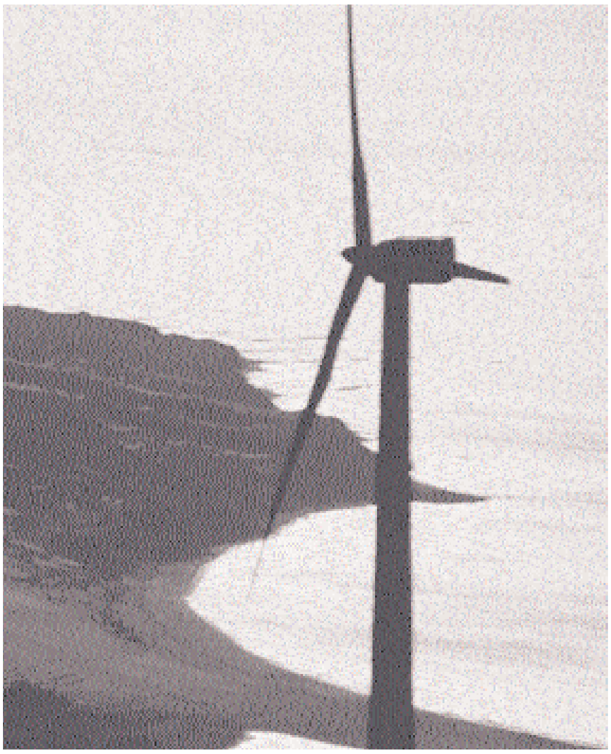
3.3 Targets for the EU-15 in 2010

Table 3.2: Installed Wind Power Capacities by Member State (MW)

	1996	1997	1998	1999	2000	2001	2002	2010
Austria	10	20	30	34	77	94	140	500
Belgium	4	4	6	6	13	31	35	250
Denmark	842	1,129	1,443	1,771	2,417	2,489	2,889	5,000
Finland	7	12	17	39	39	39	43	500
France	6	10	19	25	66	78	148	6,000
Germany	1,552	2,081	2,875	4,442	6,113	8,754	11,994	28,000
Greece	29	29	39	112	189	272	297	2,000
Ireland	11	53	73	74	118	125	137	1,500
Italy	70	103	180	277	427	697	788	3,700
Luxembourg	2	2	9	10	10	15	17	50
Netherlands	299	319	361	433	446	493	693	2,500
Portugal	19	38	60	61	100	125	195	1,500
Spain	249	512	834	1,812	2,235	3,337	4,825	15,000
Sweden	103	122	174	220	231	290	345	2,500
United Kingdom	273	319	333	362	406	474	552	6,000
European Union	**3,476**	**4,753**	**6,453**	**9,688**	**12,886**	**17,313**	**23,098**	**75,000**

Given the current distribution of wind power in EU-15 countries, historical rates of growth, the wind potential of each country, and the current status of the wind-related policies and targets of each, a possible distribution of the total installed capacity for each member state in 2010 is shown in Table 3.2.

In this table, the projected capacities in 2010 are shown, together with the installed capacities of the last seven years for each EU member state. Over the period 2001 - 2010, Germany, Spain, France and the UK comprise 74% of the expected total capacity installed. The increase for a certain number of countries, like the Netherlands, Denmark and the UK is based on the foreseen rapid development of offshore wind during the second half of the decade. Some, like the UK, France, Ireland and Greece have the potential to increase their projected installed capacity substantially if the framework conditions become more favourable for renewables and if several existing barriers are removed.



3.3.1 HOW MUCH ELECTRICITY WILL THIS PROVIDE?

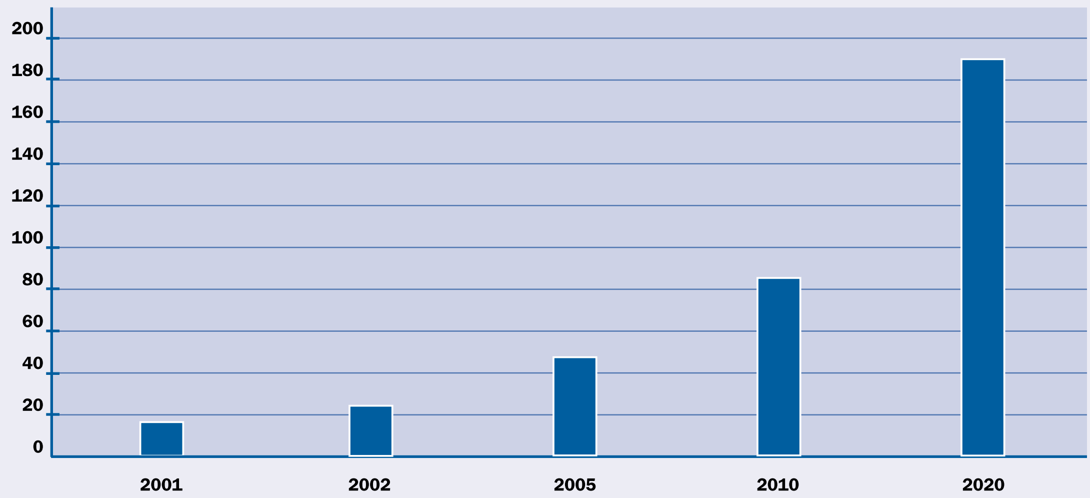
The electricity output from the EWEA targets can be expressed in terms of the equivalent amount of household electricity consumed by the average individual or household in Europe, as in Table 3.3. The calculations are based on data and forecasts from Eurostat and Eurelectric, and the European Commission's *Energy Outlook to 2020* report. These forecasts assume that whilst population and number of households will increase by only a small amount, average household electricity consumption will increase by 16% by 2010 and by 30% by 2020.

The number of people per household will decline by 2020. Therefore, the total amount of households or individuals whose average electricity use is provided by the wind power targets will become progressively less as some of the additional wind power targets output is used for the additional consumption patterns. In 2020, for example, wind power will generate 425 TWh; this is 50% of the forecast EU household electricity consumption in 2020, but 66% of that consumed in 2001.

Table 3.3: Household Electricity Consumption and Supply Forecast

Country	Unit	2001	2005	2010	2020
Austria	TWh	15.00	16.10	17.50	18.70
Belgium	TWh	17.10	18.10	19.50	21.90
Denmark	TWh	9.60	9.50	9.90	10.40
Finland	TWh	19.40	21.50	22.50	23.70
France	TWh	129.74	143.42	157.10	178.20
Germany	TWh	131.00	132.00	132.00	132.00
Greece	TWh	14.50	17.10	20.80	28.40
Ireland	TWh	7.40	8.40	10.00	12.60
Italy	TWh	61.60	65.80	74.20	87.70
Luxembourg	TWh	0.80	0.80	0.90	1.00
Netherlands	TWh	22.90	25.30	28.90	34.50
Portugal	TWh	10.60	11.70	13.60	16.90
Spain	TWh	50.60	60.10	72.60	94.90
Sweden	TWh	43.10	42.40	43.70	44.20
United Kingdom	TWh	115.30	122.50	127.20	136.80
Total EU-15 Consumption	TWh	648	694	750	841
Total EU-15 Consumption	Million KWh	648,640	694,720	750,400	841,900
Total EU-15 Population	Million	378	381	384	386
Average Household Size		2.50	2.50	2.50	2.30
EU-15 Number of Households	Million	151	152	153	167
Average Household Electricity Consumption	KWh	4,284	4,558	4,885	5,016
Average household Electricity Consumption per person	KWh	1,713	1,823	1,954	2,181
Wind Power Production	TWh	32.40	86.50	167.40	425.00
Households Supplied by Wind Power	Million	7.56	18.98	34.27	84.72
People Supplied by Wind Power	Million	18.91	47.44	85.66	194.86
Households/People Supplied by Wind Power	%	5.00	12.45	22.31	50.48

Figure 3.6: Equivalent Electricity Needs Met by Wind Power 2001 - 2020 (Million People)



	2001	2002	2005	2010	2020
European People (millions)	18.91	25.72	47.44	85.66	194.86
Wind Power Production (Twh)	32.4	44.8	86.5	167.4	425

3.3.2 WHAT PROPORTION OF TOTAL EU ELECTRICITY FROM WIND?

According to the IEA's *World Energy Investment Outlook 2002*, consumption of electricity is expected to increase by 1.6% per year over the period 2001 - 2020 (International Energy Agency, 2003). With this assumption, total electricity demand in the EU will increase from 2,572 TWh in 2000 to 3,064 TWh in 2010 and to 3,511 TWh in 2020.

The total share of the EU's electricity consumption that is generated by wind power will be 5.5% in 2010 and 12.1% in 2020.

The IEA study estimates that the installed power capacity requirements are expected to increase by some 210 GW during this period and, additionally, that approximately 235 GW of new capacity will be required to replace decommissioned plants. Thus, the EU is projected to build approximately 445 GW of new plants over the 2001 - 2020 period. Wind power can cover a substantial part of this new capacity. As mentioned above, the contribution of wind power is underestimated in the IEA scenario. If we assume that the wind industry targets will be met, wind will then substitute other conventional energies foreseen in the IEA scenario. Assuming that wind power is substituting intermediate loads covered by fossil fuels (gas, oil and coal) with the average efficiency foreseen by the IEA study, the total installed generation capacity of 445 GW will be increased by 63.7 GW in the period 2001 - 2020 due to the lower capacity factor of wind.

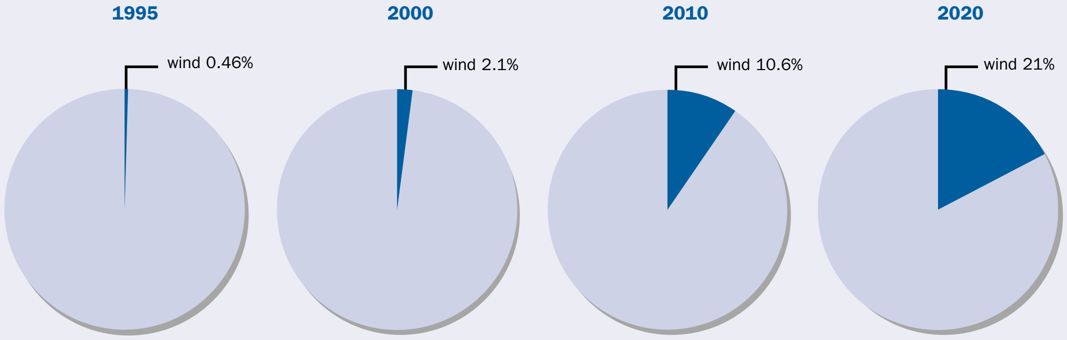
In 2000, wind power represented 2.1% of the total EU generating capacity. This share will increase to 10.6% in 2010 and 21% in 2020.

3.3.3 WHAT SHARE WILL WIND HAVE OF TOTAL NEW CAPACITY INSTALLED?

The leading role that wind power will play in the power generating system of the EU in the coming two decades is even more evident when considering its share of new generating capacity expected to be installed in Europe in the first two decades of this century.

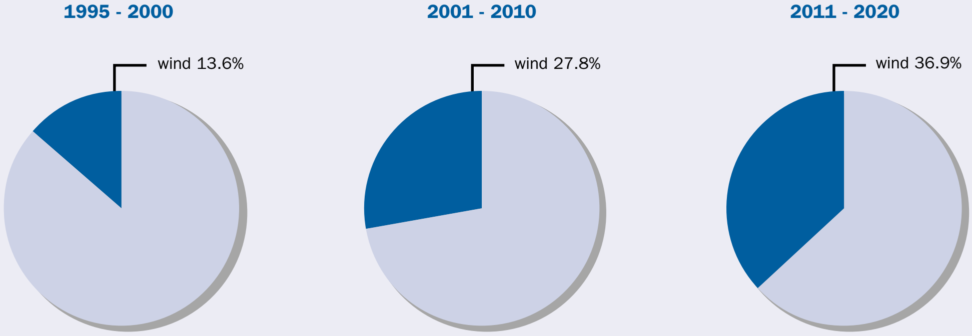
In the period 1995 - 2000, wind power accounted for 23.4% of net increase in generating capacity across the EU. During the period 2001 - 2010, wind power will account for 50% of net increase installed generating capacity and 70.3% for the period 2011 - 2020 (Figure 3.8).

Figure 3.7: Contribution of Wind Power (GW) to EU Electricity Generation Capacity 1995 – 2020 (%)



	1995	2000	2010	2020
Total Generation Capacity (GW)	538.8	580.7	706	855.4
Total Wind Generation Capacity (GW)	2.5	12.3	75	180
Share of Wind (%)	0.46%	2.1%	10.6%	21%

Figure 3.8: Contribution of Wind Power to New EU Generation Capacity (GW)



	1995 - 2000	2001 - 2010	2011 - 2020
Additional Generation Capacity (GW)	41.9	125.3	149.4
New Wind Capacity (GW)	9.8	62.7	105
Share of Wind (%)	23.4%	50%	70.3%
Capacity Retirement (GW)	30	100	135
Total New Capacity Construction (GW)	71.9	225.3	284
Share of Wind (%)	13.6%	27.8%	36.9%

Of total new construction of electricity generating capacity, including capacity replacement of decommissioned plants, wind power will represent 27.8% during the period 2001 - 2010 and 36.9% for the period 2011 - 2020.

3.4 International Energy Agency Scenarios

The IEA estimations in the "reference scenario" presented in the recent *World Energy Investment Outlook 2003* report, are very conservative and do not reflect current trends in the market: 33 GW in 2010, 57 GW in 2020 and 71 GW in 2030. Given the current rate of installation in the EU (almost 6 GW in 2002) and the actual growth rates during the previous years, the IEA's reference scenario estimations would mean a complete reversal of this trend in the next few years resulting in continuously decreasing rates of installation. Even the predictions in the "alternative policy scenario" are very conservative (see below).

In *World Energy Investment Outlook 2003* the IEA visualises an increase in electricity demand of around 50% up to 2030. This would require an additional 650 GW of capacity, and the replacement of about 330 GW of existing capacity. The agency projects that more than half of the new capacity installation will take the form of gas fired plant, and 20% in the form of renewable energy technologies, excluding hydro, with the emphasis on wind and biomass. Renewables, according to the reference scenario of the study, will capture approximately one-third of investment in new power plants in OECD countries.

Table 3.4: Reference Scenario for EU-15

Generating Capacity (GW)	2000	2010	2020	2030
Coal	146	134	122	136
Oil	78	77	55	33
Gas	98	176	310	372
Hydrogen fuel cell	0	0	1	30
Nuclear	124	118	88	76
Hydro	118	124	129	134
Other RES (inc. wind)	19	50	87	120
Total	584	679	792	901

Source: IEA (2003).

3.4.1 OECD ALTERNATIVE POLICY SCENARIO

It is important to point out that the alternative IEA scenario includes increased policy support for renewables. The need for such is voiced in the EWEA feasibility study Wind Force 12, which states that the wind industry is sufficiently advanced to be able to supply 12% of the world's electricity by 2020, but increased political will and policy support will be required if it is to do so.

While the reference scenario only includes policies already in place by mid 2002, the IEA's alternative policy scenario visualises electricity consumption and use under the influence of more aggressive policy measures, principally aimed at CO_2 abatement through increased use of renewables, among other measures. Under the alternative policy scenario, emissions of CO_2 would fall to 2000 levels by 2030.

The policy measures in the alternative scenario directly related to renewables include the EU's renewable energy Directive, the renewable portfolio standard in the US and Canada, and renewable energy targets in Japan, Australia and New Zealand. Under the influence of these supportive measures, renewable energy technologies feature much more prominently.

The policies under consideration in the alternative scenario are projected to achieve a 25% share across the OECD of renewable generation by 2030 compared to 17% under the reference scenario above.

The support mechanisms in use in this scenario do not constitute an exhaustive list of the measures available to policy-makers: for more information, please consult chapter 1 in this volume, on policy support mechanisms.

Endnotes

[1] Directive 2003/96/EC of 27 October 2003.

[2] Source: European Commission, European Energy & Transport Trends to 2030.

[3] Wiser, Bolinger and Holt, Customer Choice and Green Power Marketing: A Critical Review and Analysis of Experience to Date (University of California: Lawrence Berkeley National Laboratory).

WIND ENERGY - THE FACTS

APPENDICES

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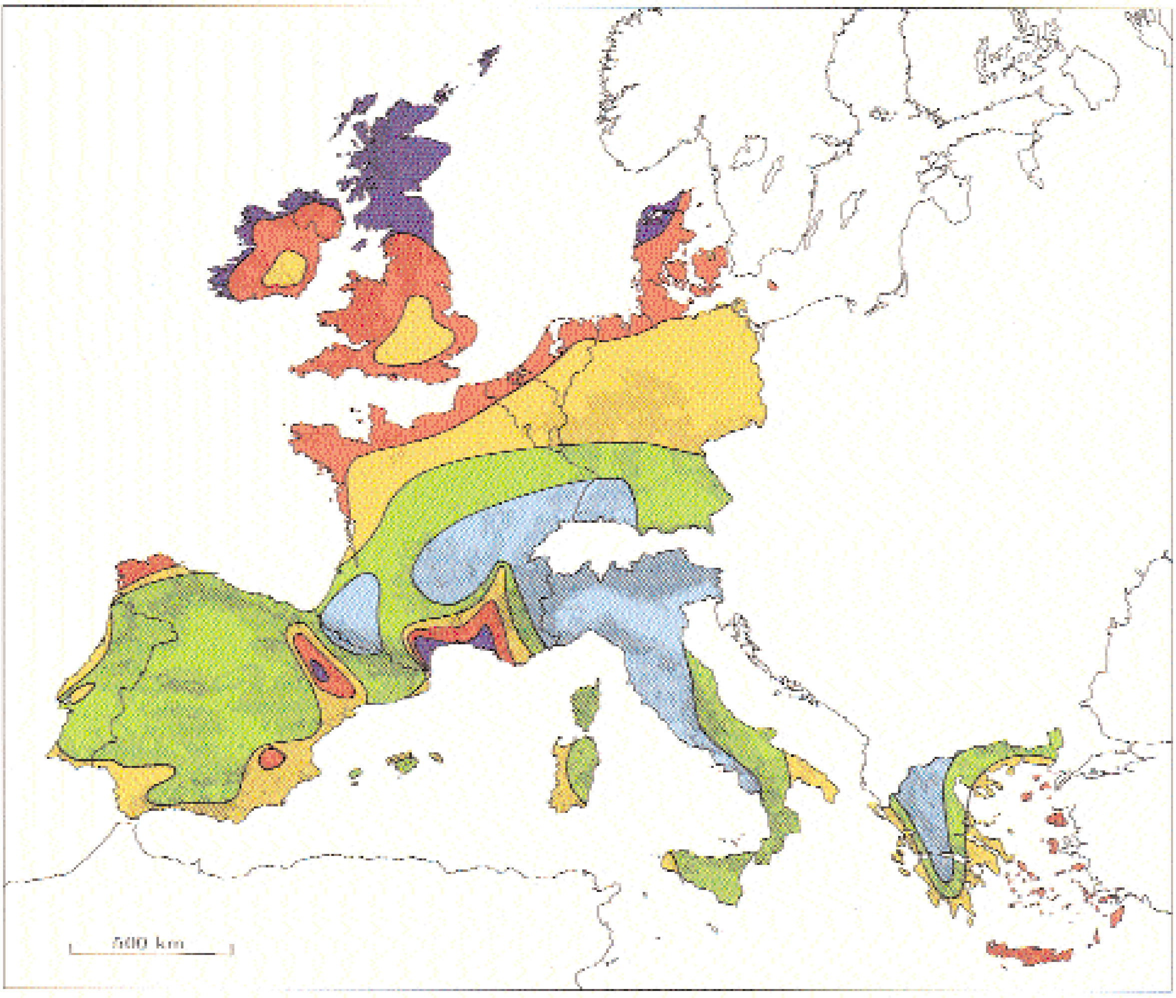
APPENDIX A: ONSHORE WIND MAPS

Figure A.1: European Wind Atlas, Onshore (EU-12). Source: Risø National Laboratory.



Wind resources at 50 metres above ground level for five different topographic conditions										
	Sheltered terrain		Open plain		At a sea coast		Open sea		Hills and ridges	
	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}
	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0- 8.5	400- 700
	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

Figure A.2: Denmark Wind Atlas. Source: Risø (1999).

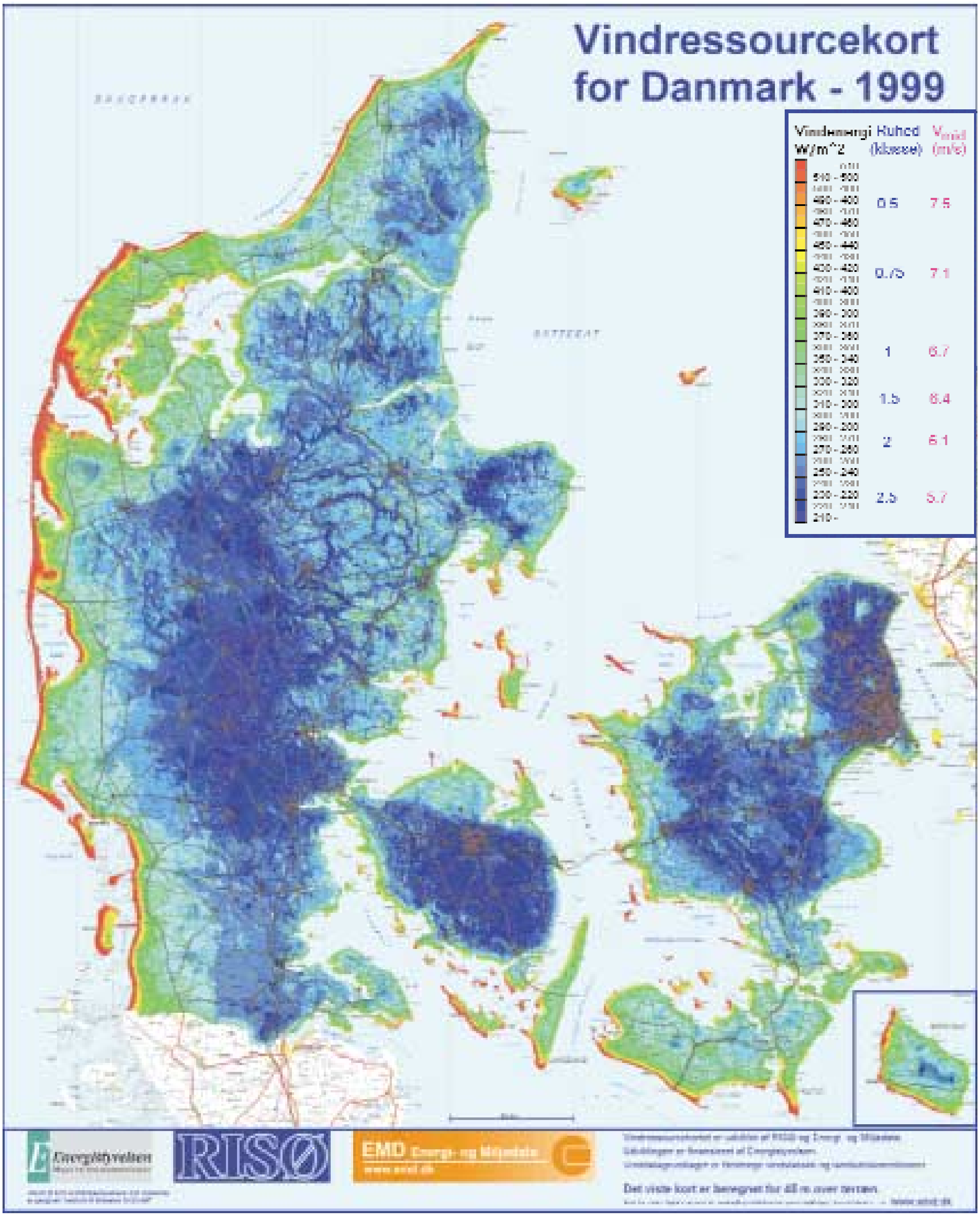


Figure A.3: German Wind Atlas. Source: Deutscher Wetterdienst.

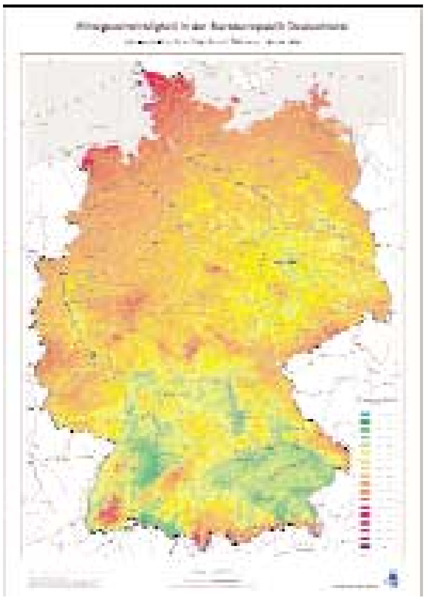
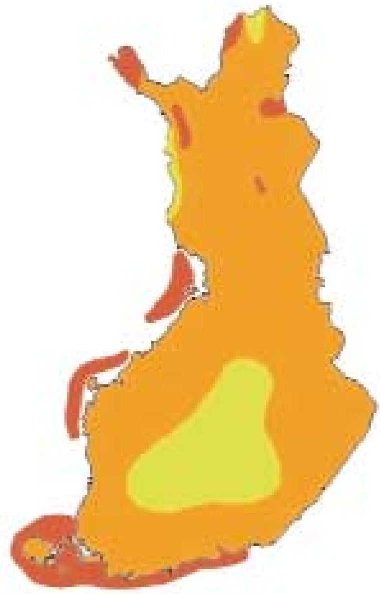


Figure A.4: Finland Wind Atlas. Source: FMI/Energy Group (1991).



Sheltered Terrain m/s	Sheltered Terrain W/m²	Open Plain m/s	Open Plain W/m²	At a Sea Coast m/s	At a Sea Coast W/m²	Open Sea m/s	Open Sea W/m²	Hills and Ridges m/s	Hills and Ridges W/m²
> 6.0	> 250	> 7.5	> 500	> 6.0	> 700	> 9.0	> 800	> 11,5	> 1800
5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0-8.5	400-700
< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

Wind resources at 50 meters above ground level for five different topographic conditions

Figure A.5: Greece Wind Atlas. Source: CRES (2001).

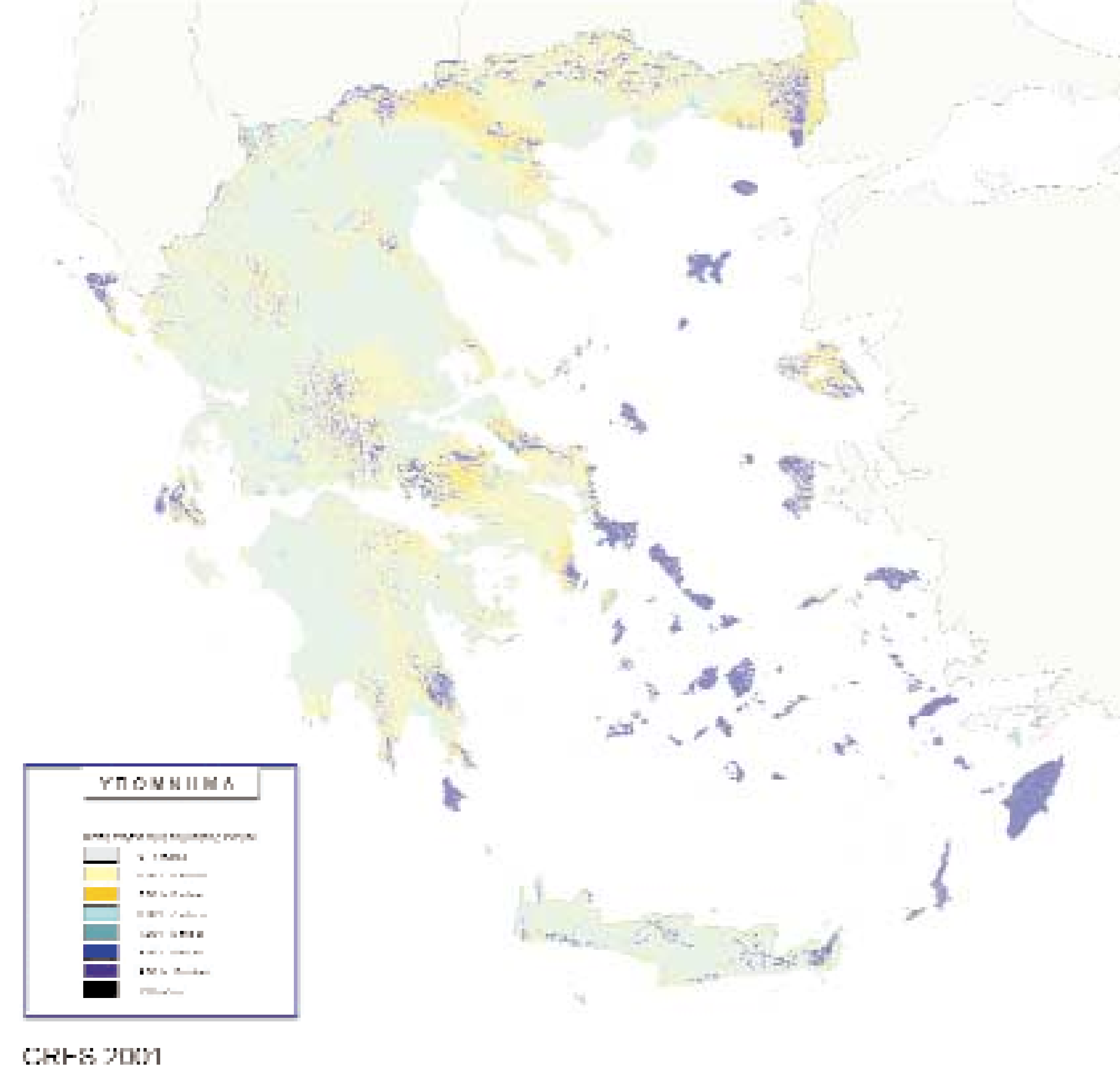


Figure A.6: Ireland Wind Atlas. Source: True Wind Solutions (2003).

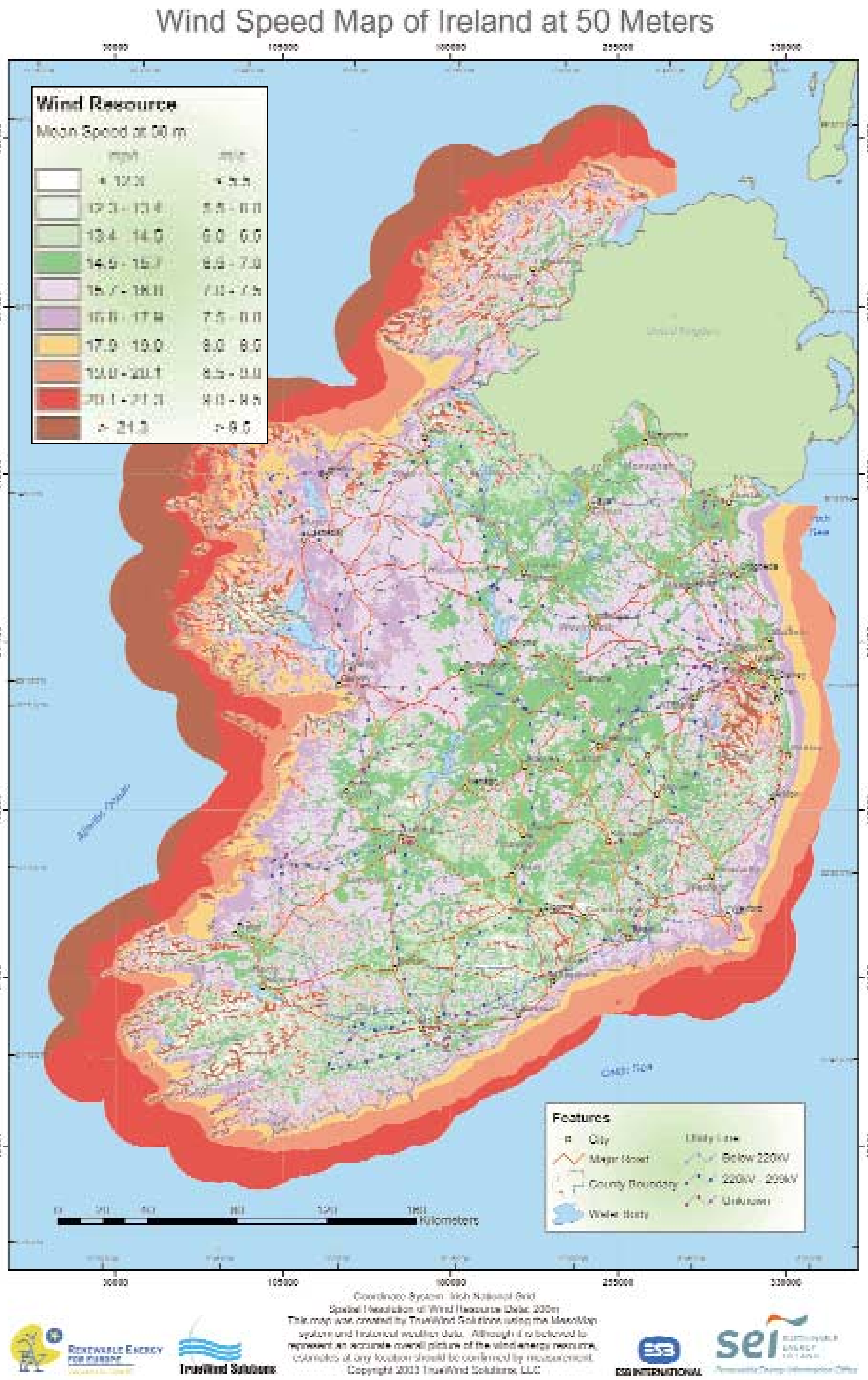


Figure A.7: Sweden Wind Atlas. Source: SMHI, *Vindatlas för Sverige* (1992).

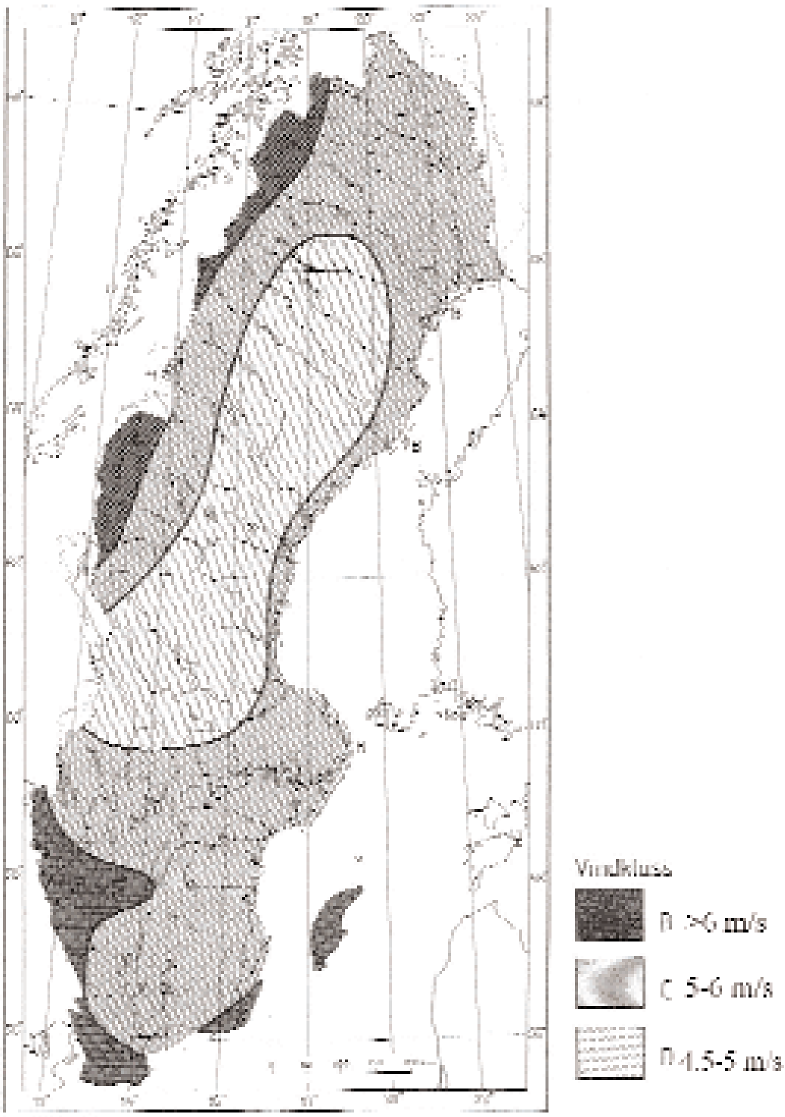


Figure A.8: UK Wind Atlas. Source: Burch & Ravenscroft (1992).

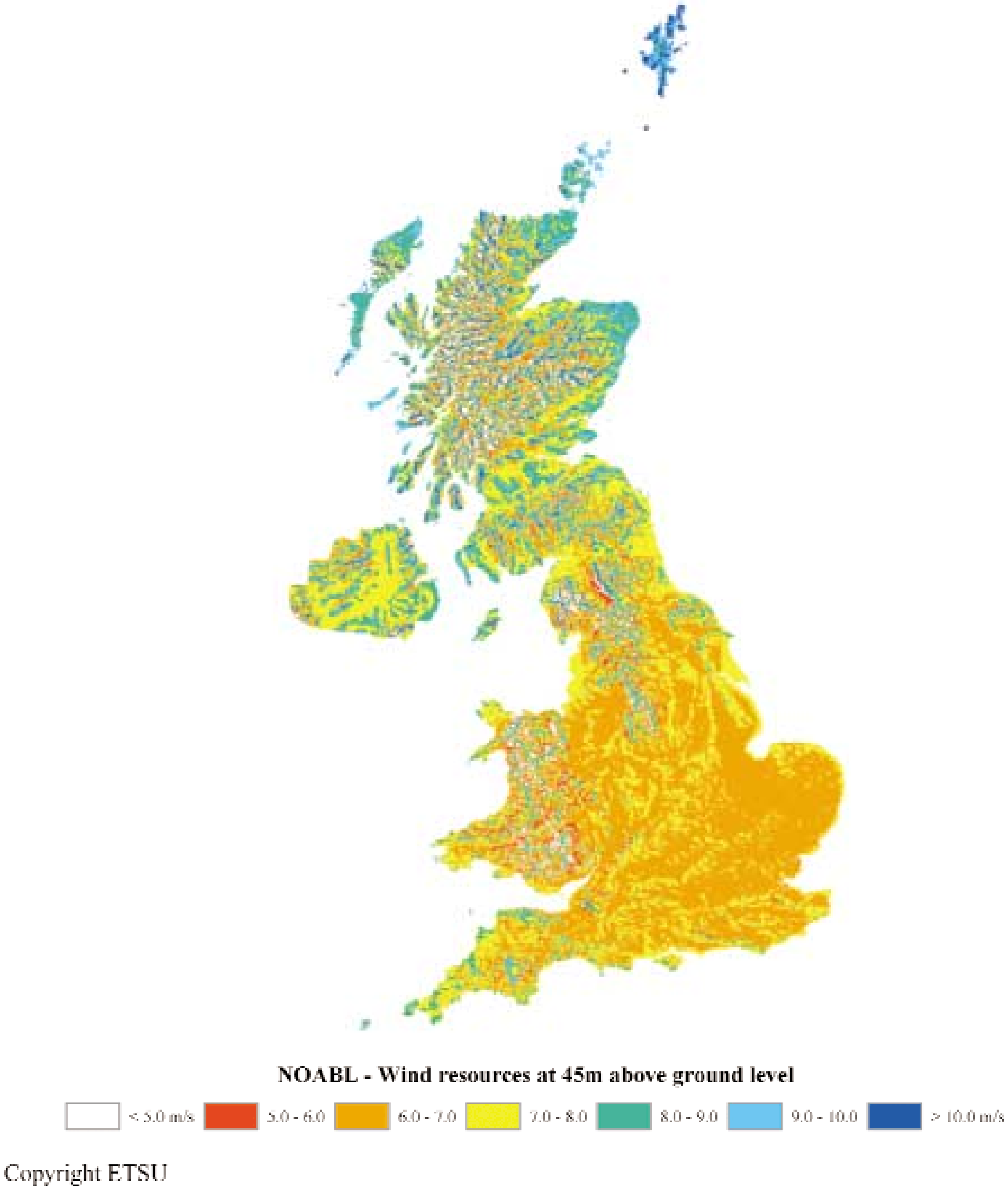


Figure A.9: Central European Wind Atlas. Source: Dobesch & Kury (1997).

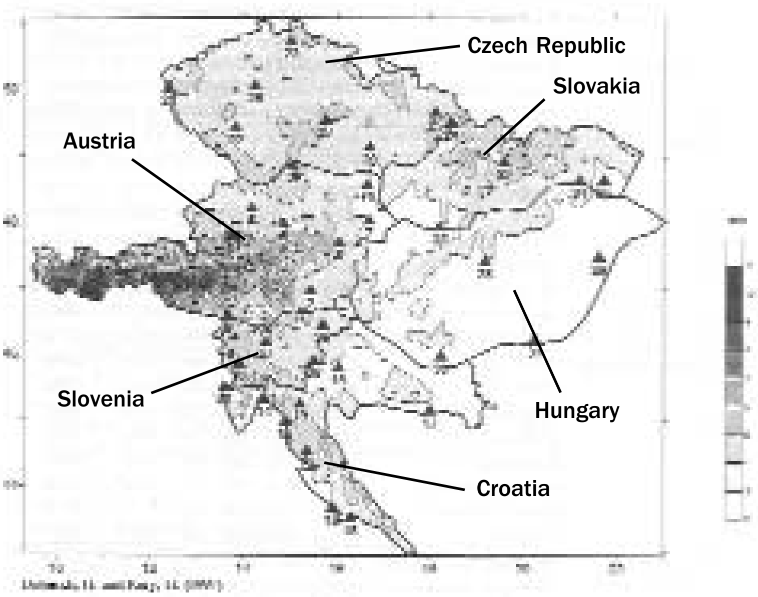
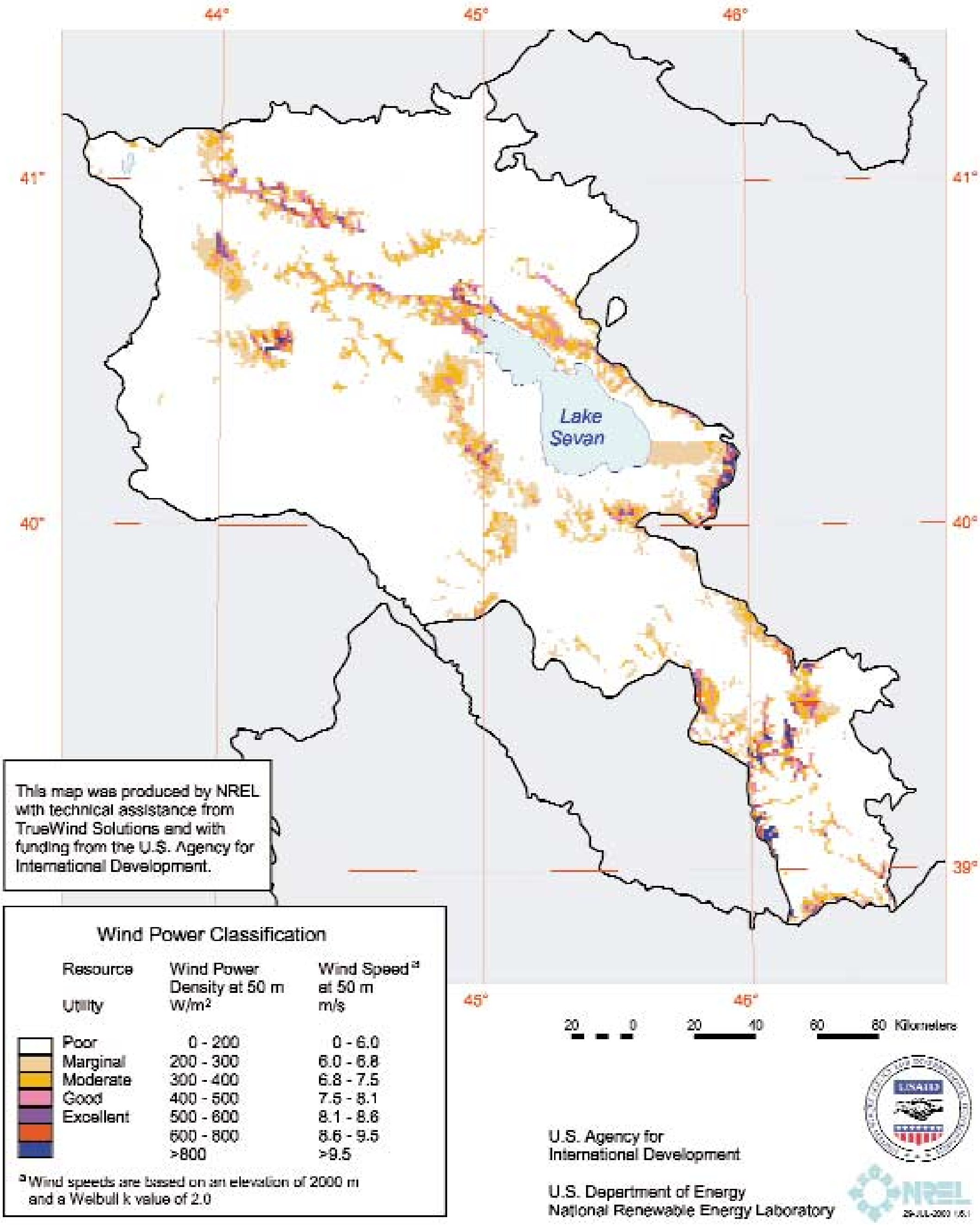
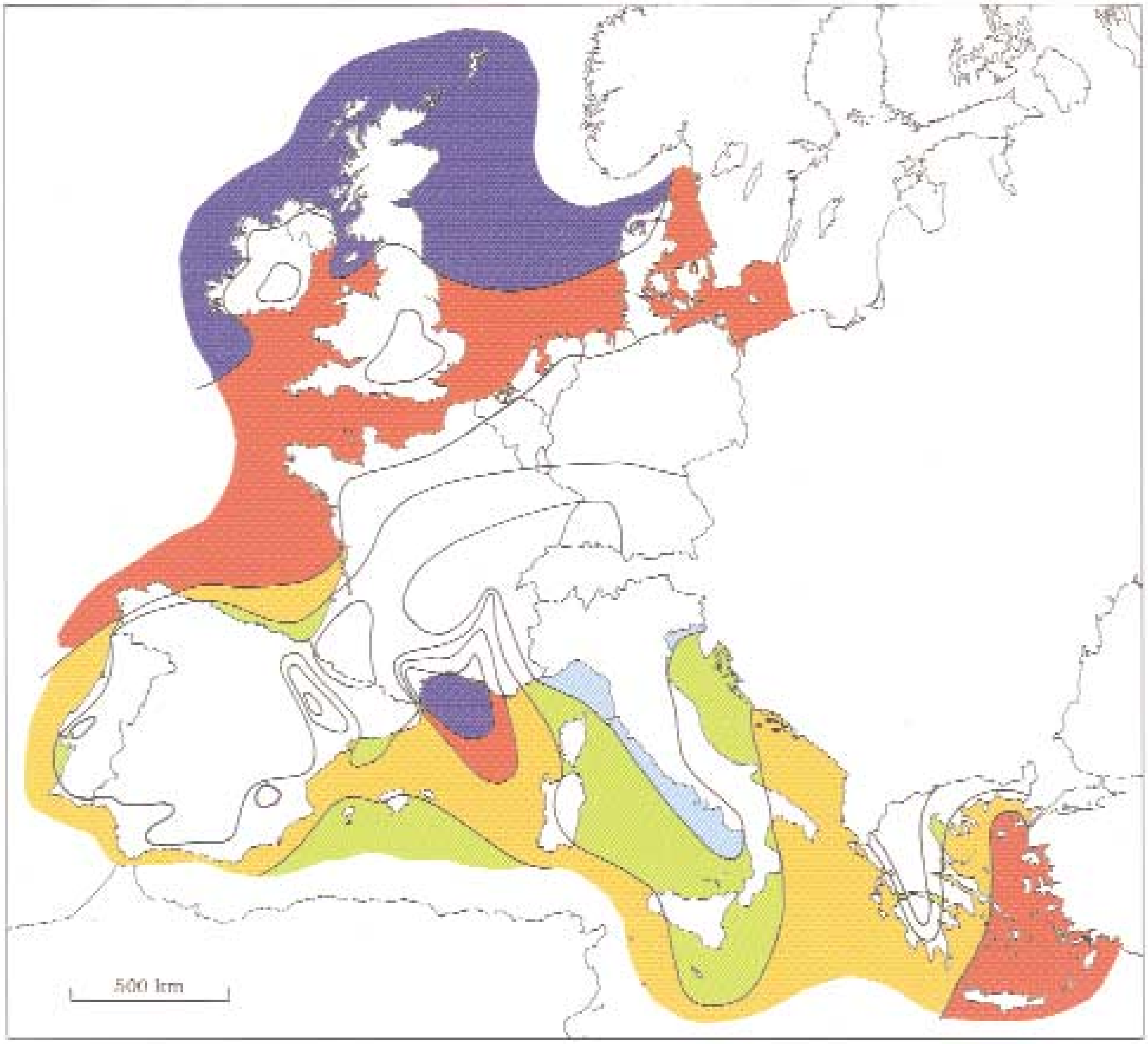


Figure A.10: Armenia Wind Atlas. Source: Elliott *et al.*, NREL (2003).



APPENDIX B: OFFSHORE WIND MAPS

Figure B.1: European Wind Atlas, Offshore. Source: Risø National Laboratory.



Wind resources over open sea (more than 10 km offshore) for five standard heights										
	10 m		25 m		50 m		100 m		200 m	
	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}
	> 8.0	> 600	> 8.5	> 700	> 9.0	> 800	> 10.0	> 1100	> 11.0	> 1500
	7.0-8.0	350-600	7.5-8.5	450-700	8.0-9.0	600-800	8.5-10.0	650-1100	9.5-11.0	900-1500
	6.0-7.0	250-300	6.5-7.5	300-450	7.0-8.0	400-600	7.5- 8.5	450- 650	8.0- 9.5	600- 900
	4.5-6.0	100-250	5.0-6.5	150-300	5.5-7.0	200-400	6.0- 7.5	250- 450	6.5- 8.0	300- 600
	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 6.0	< 250	< 6.5	< 300

OFFSHORE WIND MAPS MODELLED IN "STUDY OF OFFSHORE WIND ENERGY IN THE EU" (GARRAD HASSAN *ET AL.*, 1995)

Figure B.2: Denmark - Germany

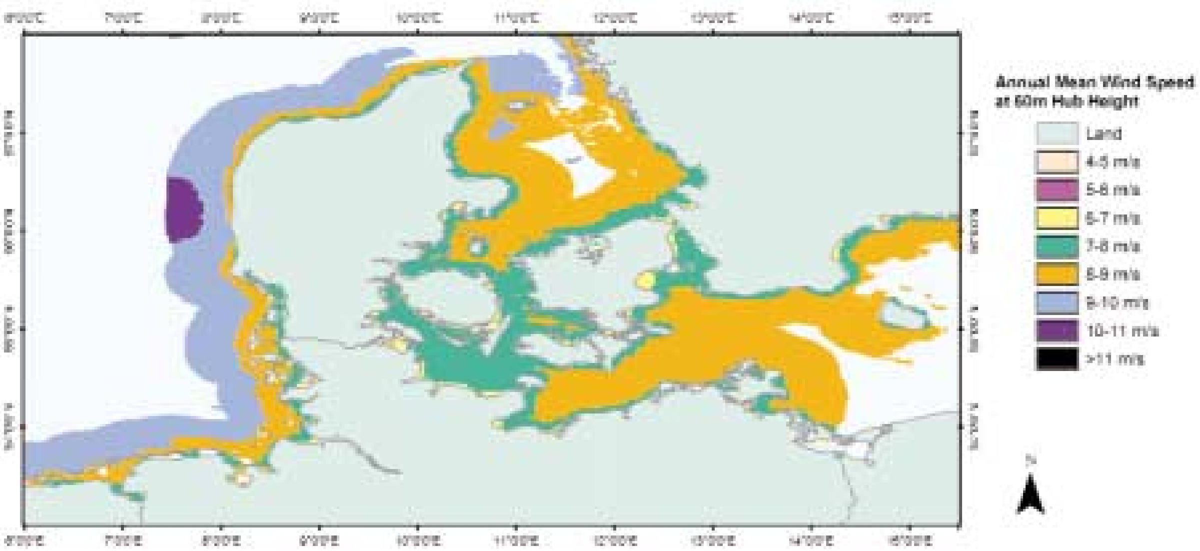


Figure B.3: France - Atlantic

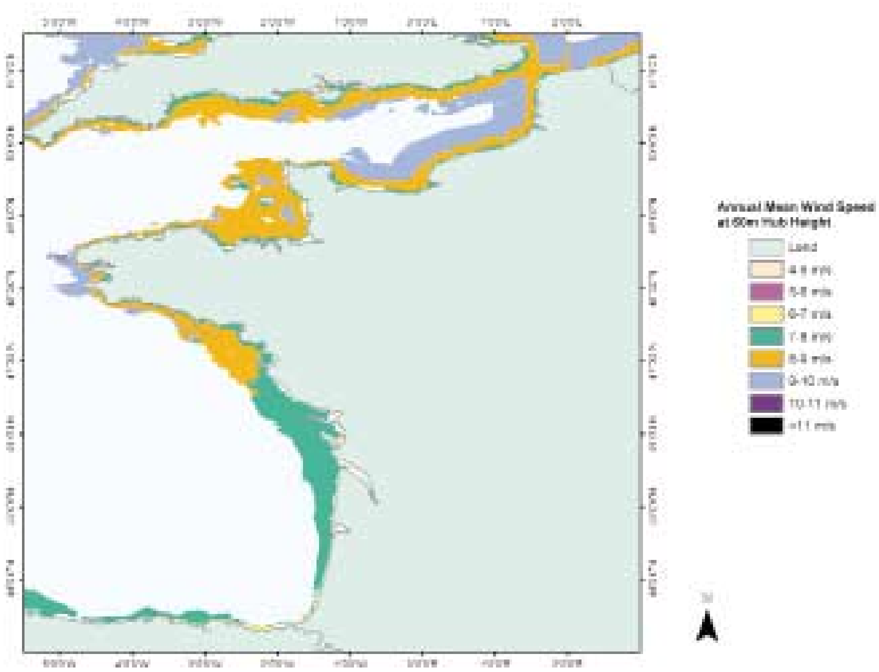


Figure B.4: France - Mediterranean

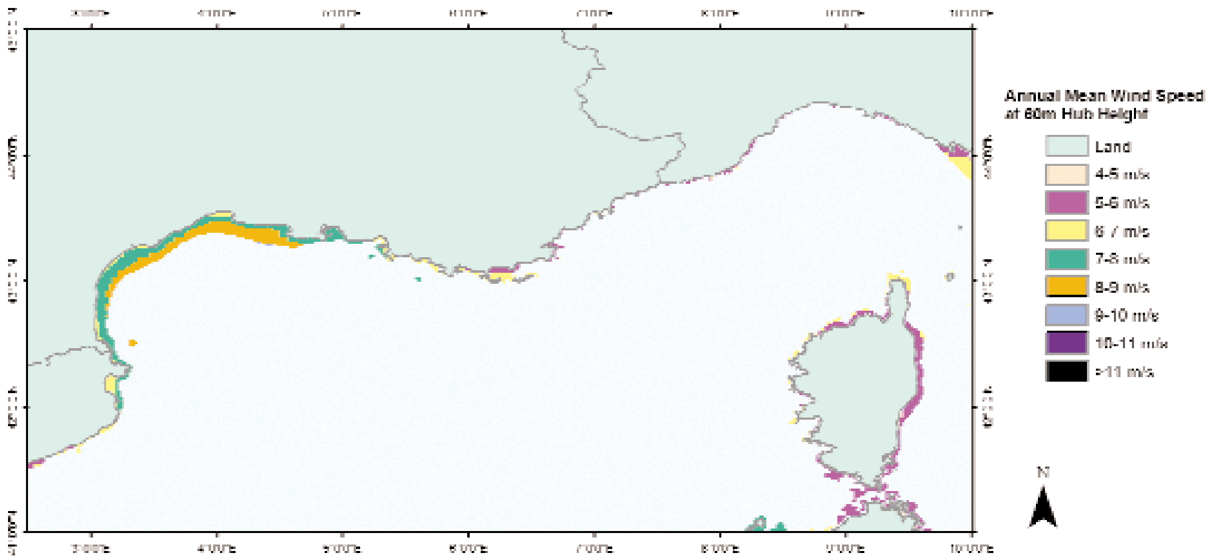


Figure B.5: Great Britain - North

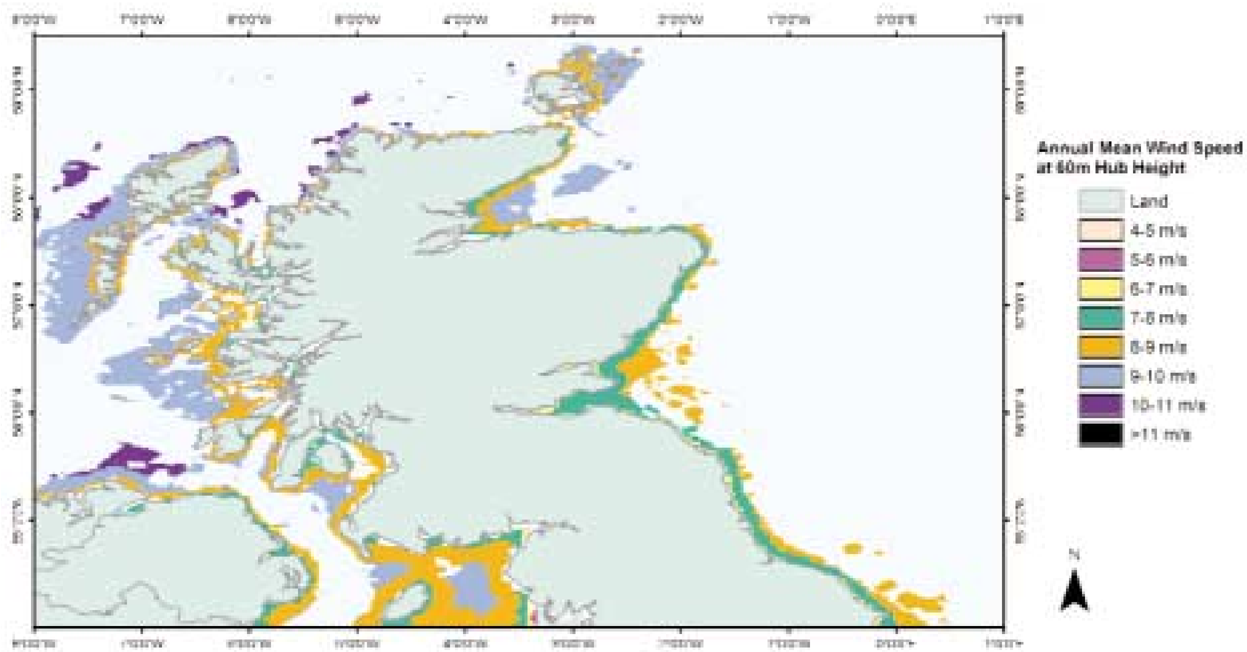


Figure B.6: Great Britain - South

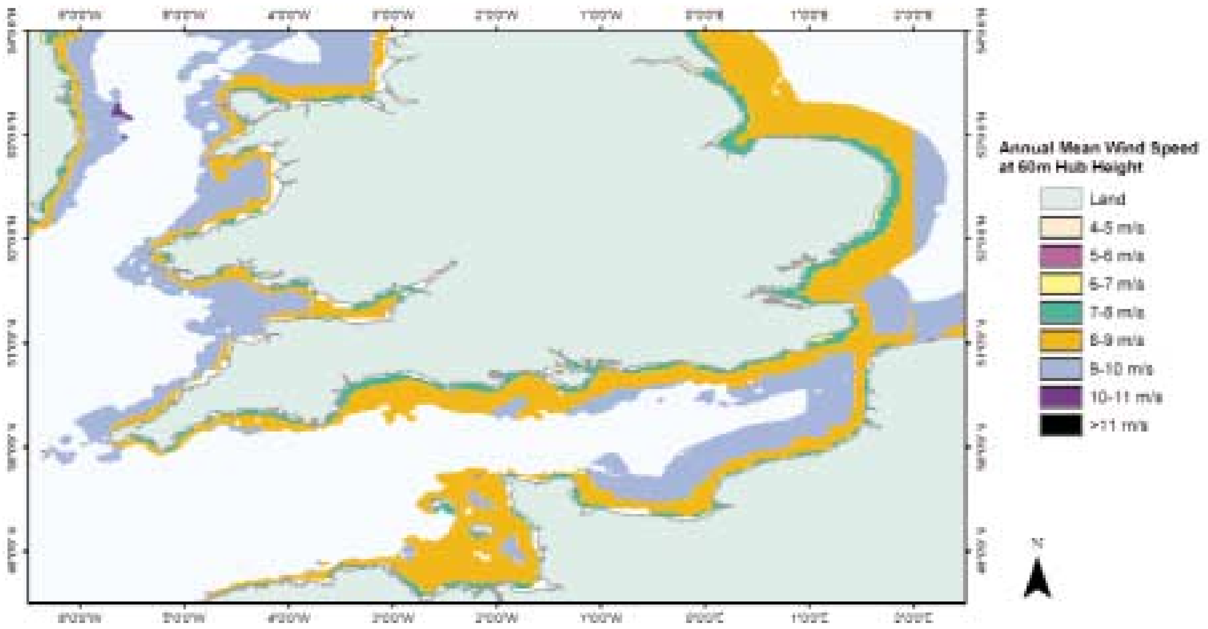


Figure B.7: Greece

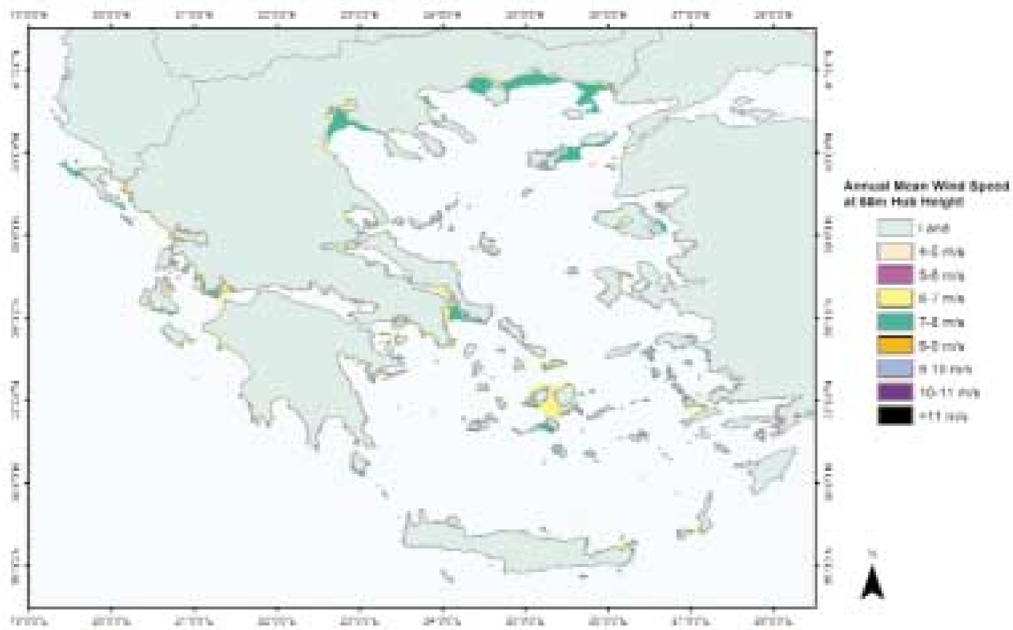


Figure B.8: Ireland

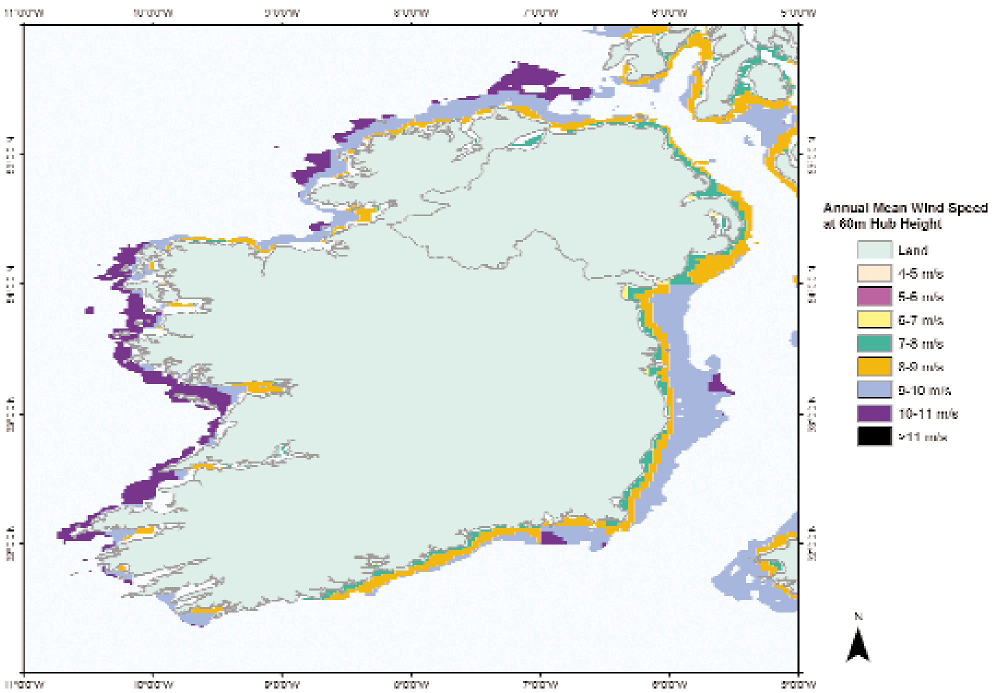


Figure B.9: Italy

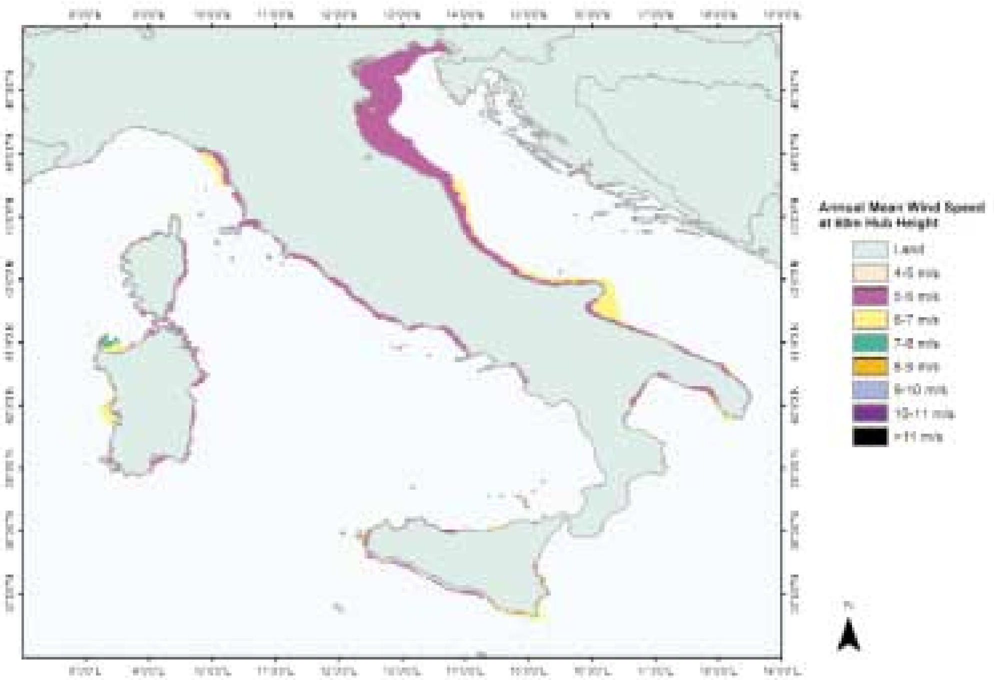


Figure B.10: Netherlands - Belgium

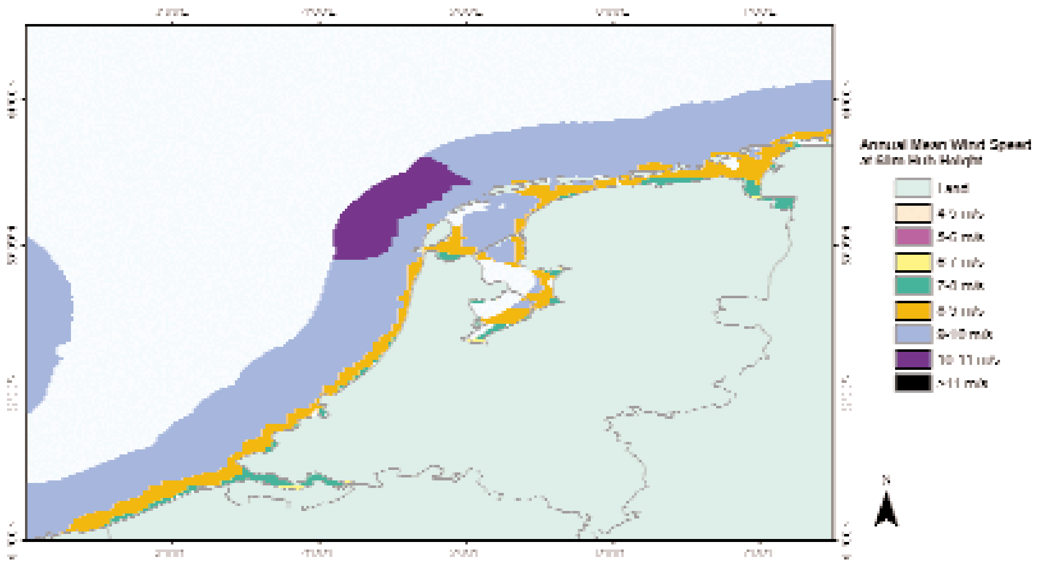
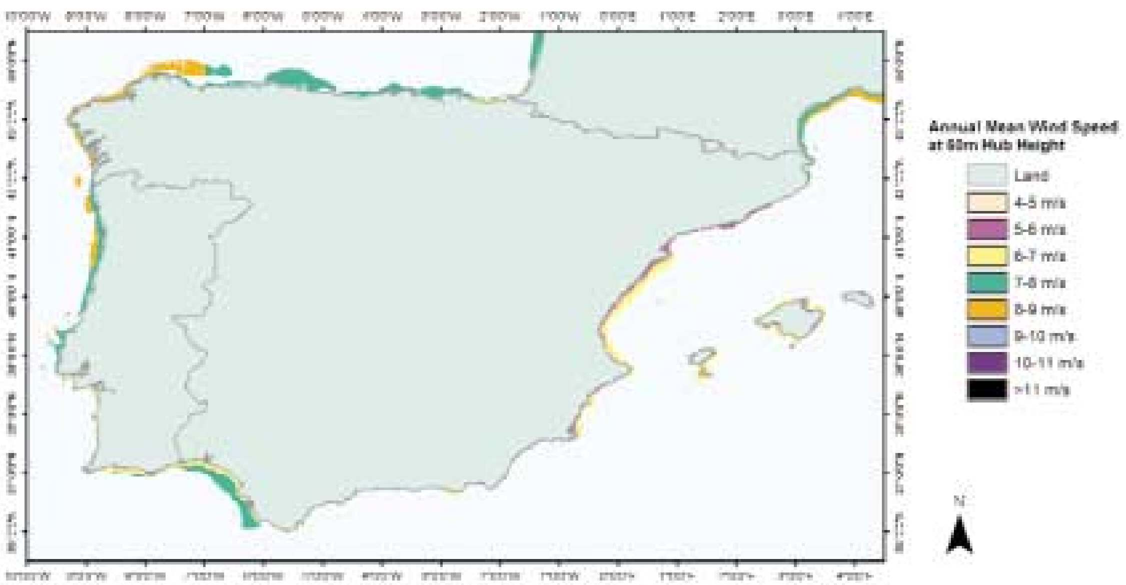


Figure B.11: Spain - Portugal



APPENDIX C: WORKED EXAMPLE FOR CUILLIAGH MOUNTAIN WIND FARM, IRELAND

C.1 Introduction

The main text has provided a general discussion of the assessment of the wind resource and energy production. This Appendix is included in order to provide a "worked example". It demonstrates all the different aspects of the process outlined in the main text. The project considered is the Cuilliagh Mountain wind farm in Ireland, which consists of 18 Vestas V47 WTs and was constructed in 2000. The following specific analyses are presented:

1 The results of the pre-construction projection of the expected energy production of the wind farm, including uncertainty analysis.
2 The review of the actual production of the wind farm over a 17-month period.
3 The results of a "wind in–energy out" validation test of the predictive methodologies employed in 1) above.

Airtricity, a leading international wind farm developer, owns the Cuilliagh Mountain Wind Farm and thanks are to be extended to Airtricity for allowing their proprietary data to be used for this example case.

C.2 Description of the Site and Monitoring Equipment

The site lies in central County Donegal approximately 14 km southwest of Letterkenny. The wind farm site lies on Cuilliagh Mountain with maximum elevation of approximately 360 m.

The site at Cuilliagh Mountain has had one 30 m and two 10 m temporary meteorological masts installed in the period since mid-1997. The 10 m data are not considered further within this report.

The wind data from the 30 m site mast have been recorded using NRG sensors with a Maximum 40 anemometer and wind vane at 10 m and 30 m. A NRG 9210 logger was programmed to record hourly mean wind speed, wind speed standard deviation, three-second gust and direction.

C.3 Malin Head Meteorological Station

The assessment of the wind climate at the site uses data recorded at a nearby meteorological station, Malin Head, which is situated on the coast approximately 65 km north-northeast of the Cuilliagh site. From discussions with Met Éireann (the Irish Meteorological Service) staff and consideration of other meteorological stations in the region, it was concluded that Malin Head was the most appropriate reference meteorological station for this analysis. Data from 1979 to 2000 have been used in the analysis reported here. Discussions with Met Éireann staff indicate that there has been no change during this period which will have a significant effect on the consistency of the measurements. This is important since the analysis method used here relies on long-term consistency of the measurements at the meteorological station.

C.4 Wind Data

The data sets from Malin Head and the Cuilliagh site, as used in the analyses described in the following sections, are summarised in Table C.1:

Table C.1: Data available from Cuilliagh and from Malin Head

Cuilliagh Mountain Mast 05 NRG (206940, 402500)	Hourly mean wind speed, standard deviation, gust and direction at 30 m	05 July 1997 - 24 Jan 1999
	Hourly mean wind speed, standard deviation, and direction at 10 m	
Malin Head Meteorological Station NRG (241950, 458550)	Hourly record of 10-minute mean wind speed and direction (time series data).	05 July 1997 - 24 January 1999
	Hourly record of 10-minute mean wind speed and direction (frequency table).	1979 - 1998

C.5 Description of the Proposed Wind Farm

The wind turbine model selected for the Cuilliagh Mountain Wind Farm was the Vestas V47 660 kW model with a hub height of 45 m. The basic parameters of the turbine are presented in Table C.2 below.

Table C.2: Main Parameters of the Vestas V47 660 kW Wind Turbine

Diameter	47.0	m
Hub height	45	m
Rotor speed	28.5	rpm
No. of blades	3	
Nominal rated power	660	kW

The power curve used in the analysis has been supplied for an air density of 1.225 kg/m³ and is presented in Table C.3.

Table C.3: Performance Data for the Vestas V47 660 kW Wind Turbine

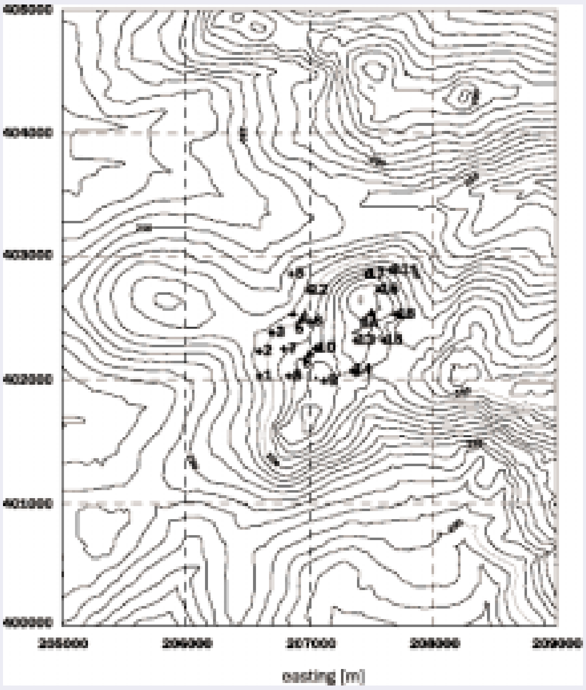
Wind Speed [m/s at hub height]	V47 Power Output [kW]
4	2.9
5	43.8
6	96.7
7	166
8	252
9	350
10	450
11	538
12	600
13	635
14	651
15	657
16	659
17	660
18	660
19	660
20	660
21	660
22	660
23	660
24	660
25	660

From data recorded at local meteorological stations and with standard lapse rate assumptions, the Cuilliagh Mountain site is predicted to have an air density of 1.205 kg/m³. Since the predicted mean air density at the site differs from the air density for which the power curves were supplied, a small air density adjustment following the IEC 61400-12: 1998 standard was made to the power curves used in the analysis.

The power curve for the Vestas V47 660 kW turbine has been compared to a reference curve from an independent test of the performance of the turbine. It was found that the reference curve out-performed the supplied curve by 2% for the wind regime at the Cuilliagh site. This result indicates that the supplied curve is broadly in line with the performance that might be expected.

The Cuilliagh Mountain Wind Farm has a total nameplate capacity of just under 12 MW. It is located approximately 1.5 km south of the Cark wind farm. The effect of these turbines on the predicted energy production of the Cuilliagh development was estimated.

Figure C.1: Layout of the Cuilliagh Mountain Wind Farm



C.6 Results of the Analysis

The analysis to determine the wind regime and expected energy production of the proposed Cuilliagh Mountain wind farm involved several steps:

- The directional correlations between wind speeds recorded at Cuilliagh Mast 05 at 30 m and at Malin Head were established.
- The correlation relationships were applied to historical wind data recorded at Malin Head to produce a description of the long-term wind regime at Cuilliagh mast 05.
- Wind flow modelling was carried out to determine the hub height wind speed variations over the site relative to the 30 m anemometry mast.
- The energy production of the wind farm was calculated, taking account of array losses and topographic effects.
- The seasonal variation in the energy production of the wind farm was calculated.
- Sources of uncertainty in the wind speed and energy production estimates were identified and quantified.

C.7 Correlation of Wind Regime at Cuilliagh Mountain and Malin Head

The measured wind direction at Cuilliagh Mast 05 at 30 m is compared to the concurrent wind direction measured at Malin Head in Figure C.2. The directions recorded between the two locations show some scatter but are generally well correlated for the most frequent sectors.

The monitored wind speeds at 30 m height in each of 12 30˚ direction sectors are compared to the concurrent wind speed at Malin Head in Figure C.3. The quality of the correlation is considered to be reasonable for all direction sectors. The wind speed ratios for each direction sector are presented in Table C.4.

Table C.4: Wind Speed Ratios between Cuilliagh Mast 05 at 30 m and Malin Head

Direction Sector	Number of Hours Analysed	Wind Speed Ratio
345-15	278	0.701
15-45	194	0.767
45-75	229	0.800
75-105	461	0.718
105-135	795	0.957
135-165	1098	0.976
165-195	1622	0.879
195-225	1208	0.897
225-255	1210	0.894
255-285	1230	0.868
285-315	708	0.834
315-345	421	0.819
All	9454	0.861

Figure C.2: Correlation of Wind Direction at Malin Head and at Cuilliagh Mast 05 at 10 m

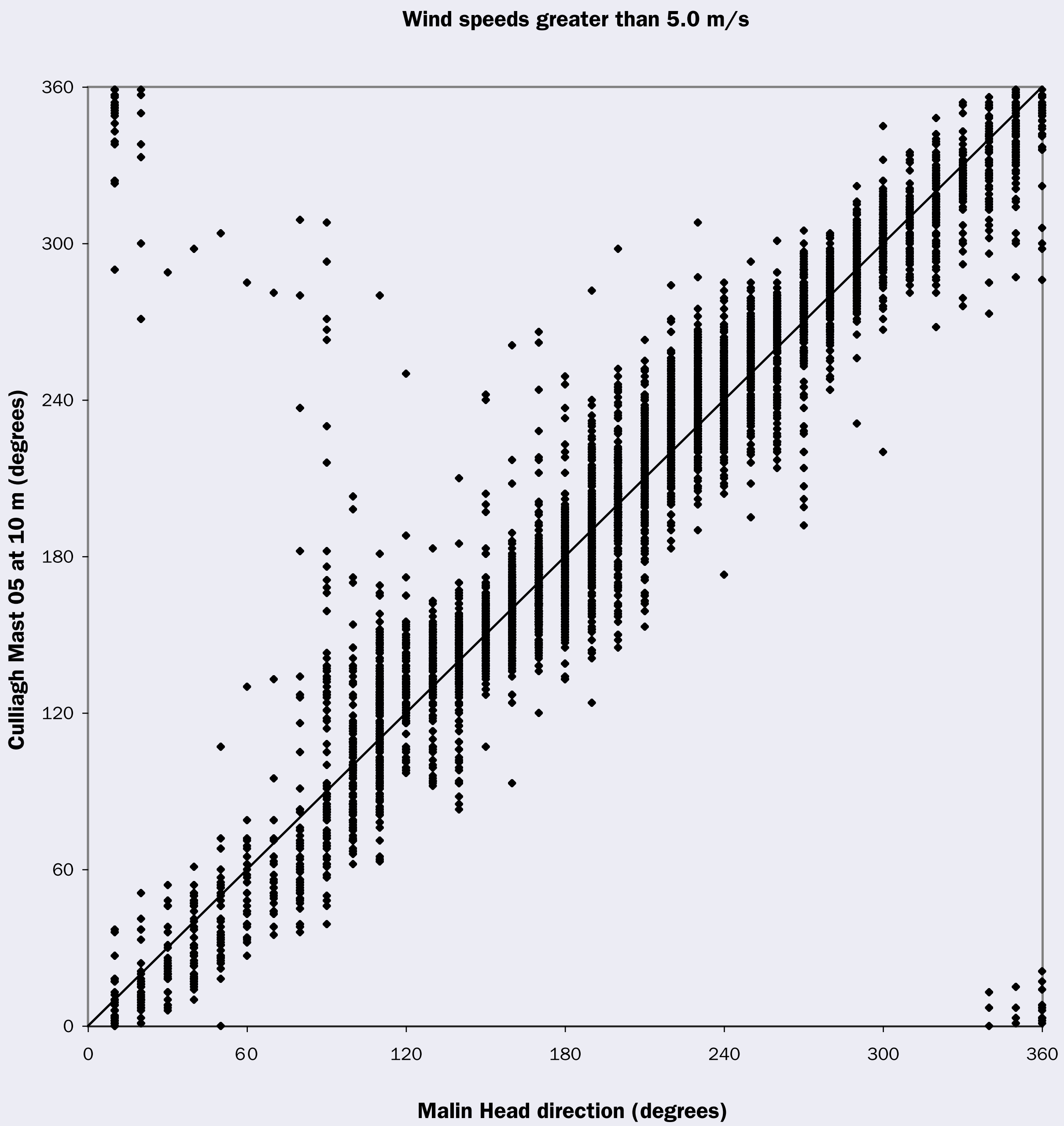


Figure C.3a: Correlation of Wind Speed at Malin Head and at Cuilliagh Mast 05 at 30 m – Continued

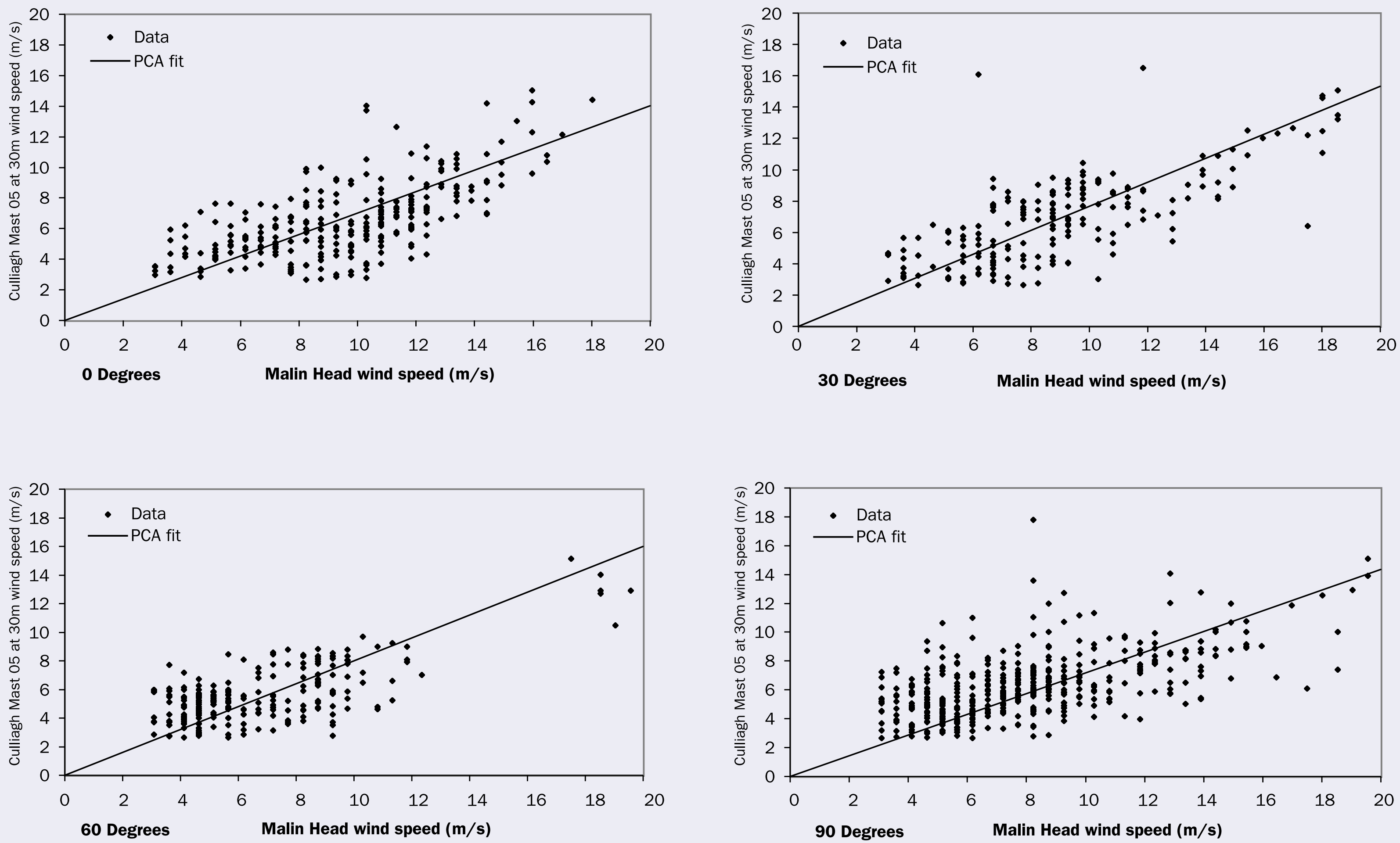


Figure C.3b: Correlation of Wind Speed at Malin Head and at Cuilliagh Mast 05 at 30 m – Continued

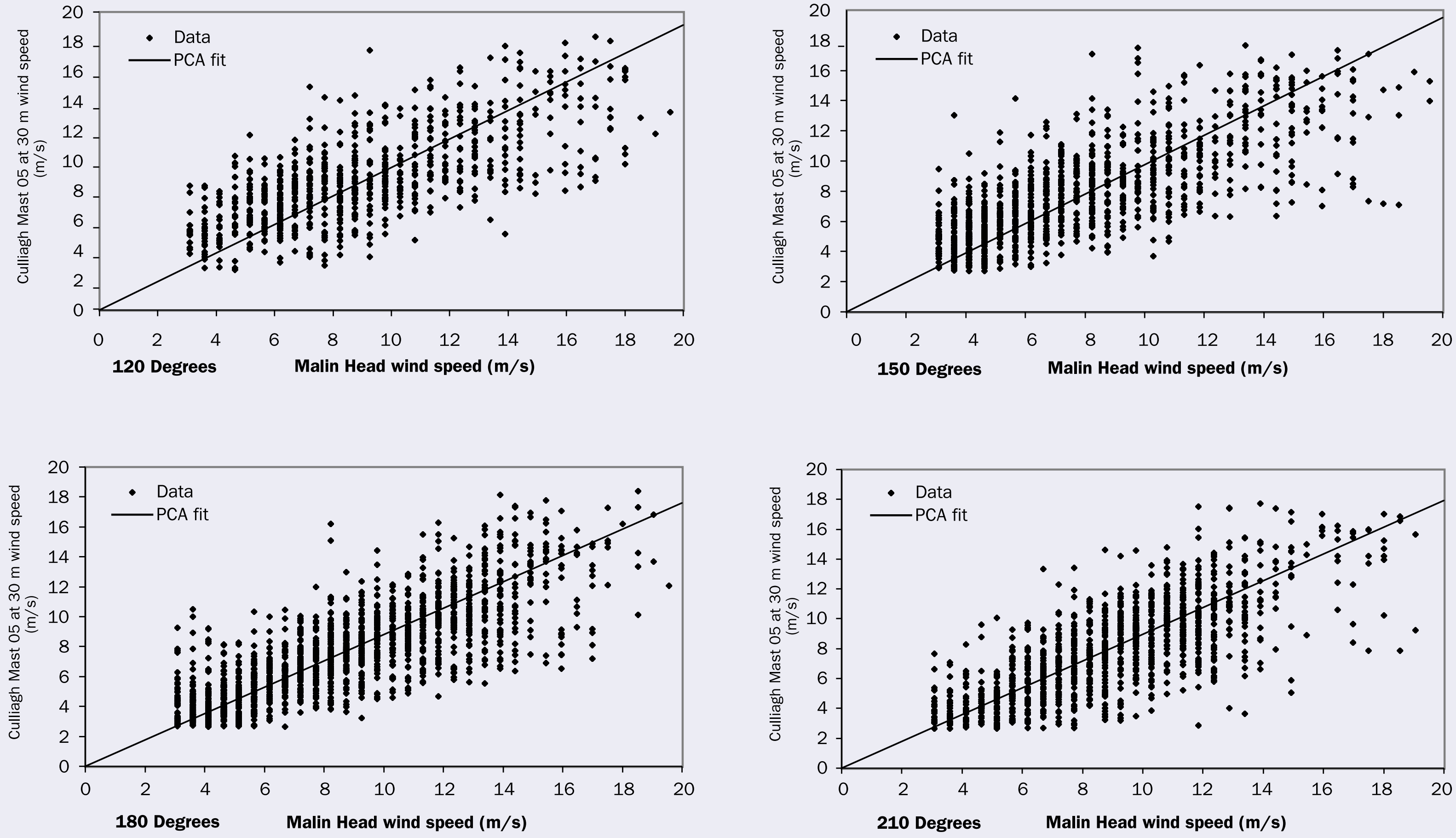
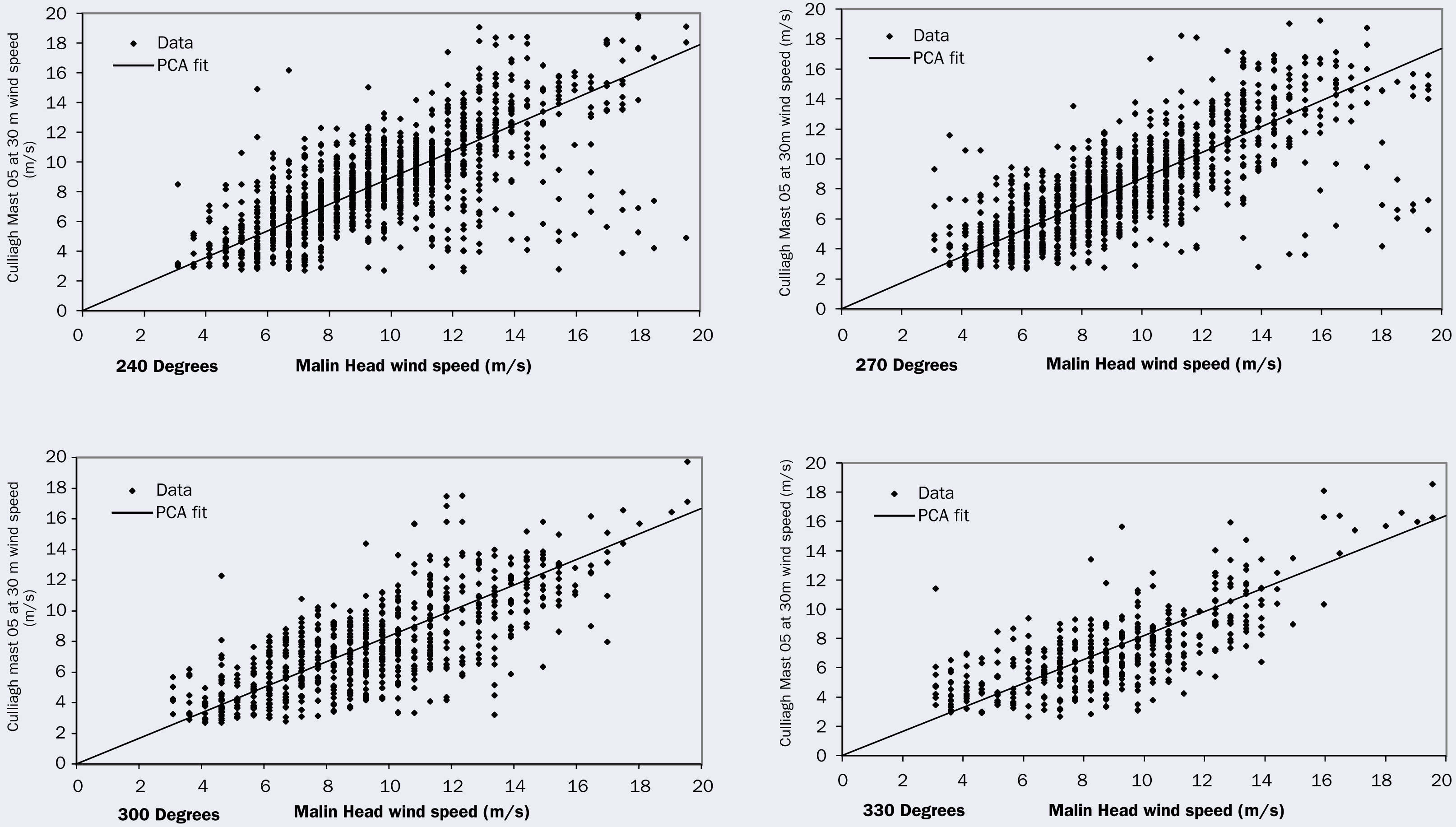


Figure C.3c: Correlation of Wind Speed at Malin Head and at Cuilliagh Mast 05 at 30 m – Concluded

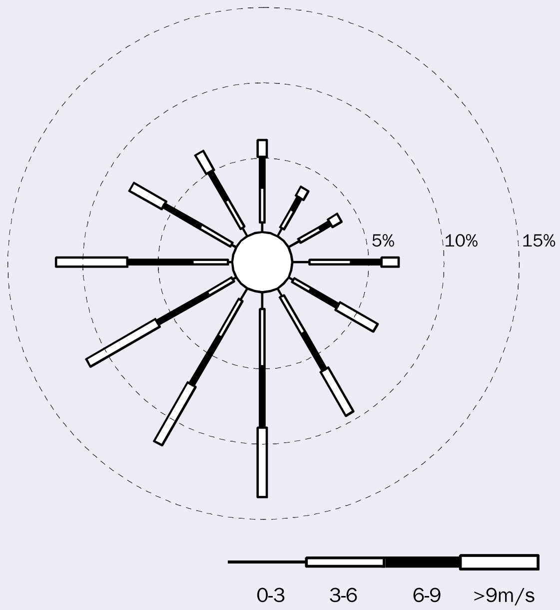


C.8 Long-term Mean Wind Speed at Cuilliagh Mountain

The wind speed ratios listed in Table C.4 were used to factor the long-term wind speeds at Malin Head for the period 1979 to 1998. By this method, the long-term mean wind speed at Cuilliagh Mast 05 at 30 m was calculated to be 7.2 m/s.

The corresponding joint wind speed and direction frequency distribution for Cuilliagh Mast 05 over the historical period 1979 to 1998 is presented in Figure C.4 in the form of a wind rose.

Figure C.4: Annual Wind Rose for Cuilliagh Mast 05 at 30 m.



C.9 Site Wind Speed Variations at Cuilliagh Mountain

The variation in wind speed over the Cuilliagh Mountain site has been predicted using the WAsP computational flow model. WAsP was used to model the wind flow over the site, being initiated from the long-term wind speed and direction frequency distribution derived for Mast 05 at 30 m.

Table C.5 shows the predicted long-term mean wind speed at each wind turbine location at hub height. The average long-term mean wind speed at a hub height of 45 m for the whole wind farm was found to be 8.1 m/s.

Table C.5: Mean Wind Speed and Projected Energy Output of Individual Wind Turbines

Turbine Number	Mean Hub Height Wind Speed[1] [m/s]	Energy Output[2] [GWh/Annum]
1	7.7	2.2
2	7.8	2.1
3	7.8	2.1
4	7.6	1.9
5	7.4	2.0
6	7.8	2.0
7	8.0	2.1
8	8.1	2.3
9	8.4	2.5
10	8.0	2.2
11	8.2	2.3
12	7.6	2.0
13	8.6	2.4
14	8.2	2.3
15	8.2	2.3
16	8.8	2.5
17	8.5	2.4
18	8.3	2.3
Overall	8.1	

[1] Wind speed at location of turbines at 45 m height, not including wake effects.
[2] Individual turbine output includes topographic and array effects only.

C.10 Projected Energy Production

The predicted energy production for the wind farm is detailed in Table C.6 below. The energy capture of individual turbines is given in Table C.5.

Table C.6: Predicted Energy Production of Cuilliagh Mountain Wind Farm

Ideal energy production	40.2	GWh/annum
Topographic effect	*107.0 %*	*Calculated*
Array effect	*92.7 %*	*Calculated*
Electrical transmission efficiency	*97.0 %*	*Estimate*
Availability	*97.0 %*	*Estimate*
Icing and Blade fouling	*99.0 %*	*Estimate*
High wind hysteresis	*99.6 %*	*Estimate*
Substation maintenance	*100.0 %*	*Not considered*
Utility downtime	*100.0 %*	*Not considered*
Power curve adjustment	*100.0 %*	*Not considered*
Columnar control losses	*100.0 %*	*Not considered*
Wake effect of existing wind farms	*99.8 %*	*Estimate*
Net energy production	36.9	GWh/annum

The energy production predictions include calculation of the array and topographic effects, an estimate of availability and electrical loss and factors to account for WT icing, high wind hysteresis and the wake effect of existing turbines. Other potential sources of energy loss are also listed. It is recommended that the client carefully consider these issues since at the time of this energy assessment there was insufficient information to estimate the effect on the predicted energy production.

C.11 Seasonal Variations

The monthly energy production of the wind farm is presented in Table C.7. There is a large seasonal variation of the predicted long-term monthly energy production, with winter and summer months producing approximately 140% and 60%, respectively of the long-term mean monthly energy production.

Table C.7: Monthly Variation of the Projected Energy Output[1] of the Wind Farm

January	4.27
February	3.87
March	3.84
April	2.53
May	2.16
June	1.86
July	2.05
August	2.21
September	2.85
October	3.60
November	3.67
December	3.99

[1] Energy output includes all losses.

C.12 Uncertainty Analysis

The main sources of deviation from the central estimate have been quantified and are shown in Tables C.8a and C.8b which consider future periods of 10 years and one year respectively.

Table C.8a: Uncertainty in Projected Energy Output[1] of the Proposed Wind Farm – 10 Year Future Period

Source of Uncertainty	Wind Speed [%]	Wind Speed [m/s]	Energy Output[1] [%]	Energy Output[1] GWh/Annum
Anemometer accuracy	2.0	0.14		
Correlation accuracy		0.19		
Period representative of long-term	1.3	0.10		
Total wind		**0.26**		**2.22**
Wake and topographic calculation	-	-	3.0	1.11
Wind variability (10 years)	1.9	0.14		1.19
Overall (10 years)				**2.75**

[1] Sensitivity of net production to wind speed is calculated to be 8.68 GWh/annum/(m/s)

Table C.8b: Uncertainty in Projected Energy Output[1] of the Proposed Wind Farm – One Year Future Period

Source of Uncertainty	Wind Speed [%]	[m/s]	Energy Output[1] [%]	Wh/ Annum
Anemometer accuracy	2.0	0.14		
Correlation accuracy		0.19		
Period representative of long-term	1.3	0.10		
Total wind		**0.26**		**2.22**
Wake and topographic calculation	-	-	3.0	1.11
Wind variability (1 year)	6.0	0.43		3.75
Overall (1 year)				**4.49**

[1] Sensitivity of net production to wind speed is calculated to be 8.68 GWh/annum/(m/s)

The figures in these tables, when added as independent errors, give the following uncertainties in net energy production of 4.5 GWh/annum for a future one year period and 2.7 GWh/annum for a future 10 year period. The detailed derivation of the above uncertainties is presented below:

There are four main categories of uncertainty associated with the site wind speed prediction at Cuilliagh Mountain:

1 There is an uncertainty associated with the measurement accuracy of the site anemometers. The instruments used on this site have not been individually calibrated to MEASNET standards and a consensus calibration has been applied. Batch calibration of NRG Maximum 40 anemometers have shown them to conform to the consensus calibration to within 1.5%. Therefore, a figure of 2% is assumed here so as to account for other second order effects such as overspeeding, degradation, air density variations and sensor mounting. No allowance has been made for uncertainty in the Malin Head anemometer as consistency and not absolute accuracy is important.

2 An error analysis was carried out on the correlation for each direction sector and from this the standard error for the long-term mean wind speed was determined. This was carried out for the correlation between Malin Head and Cuilliagh Mountain.

3 There is an uncertainty associated with the assumption made here that the historical period at the meteorological site is representative of the climate over longer periods. A study of historical wind records from a number of reference stations indicates an average variability of 6% in the annual mean wind speed. This figure is used to define the uncertainty in assuming the long-term mean wind speed over a 20-year period.

4 For a finite number of future years, the mean wind speed may differ from the long-term mean due to the natural variability of a random process. Account is taken of the future variability of wind speed in the energy confidence analysis but not the wind speed confidence analysis.

It is assumed that the time series of wind speed is random with no systematic trends. Care was taken to ensure that consistency of the Malin Head measurement system and exposure has been maintained over the historical period and no allowance is made for uncertainties arising due to changes in either.

Uncertainties type 1, 2 and 3 from above are added as independent errors on a root-sum-square basis to give the total uncertainty in the site wind speed prediction for the historical period considered.

There are four categories of uncertainty in the energy output projection:

1 Long-term mean wind speed dependent uncertainty is derived from the total wind speed uncertainty (types 1, 2 and 3 above) using a factor for the sensitivity of the annual energy output to changes in annual mean wind speed. This sensitivity is derived by a perturbation analysis about the central estimate.

2 Wake and topographic modelling uncertainties. Validation tests of the methods used here, based on full-scale wind farm measurements made at small wind farms have shown that the methods are accurate to 2% in most cases. For this development, an uncertainty in the wake and topographic modelling of 3% is assumed.

3 Future wind speed-dependent uncertainties described in 4 above have been derived using the factor for the sensitivity of the annual energy output to changes in annual mean wind speed.

4 Turbine uncertainties are generally the subject of contract between the developer and turbine supplier and therefore no allowance has been made for them in this work.

Again, those uncertainties which are considered are added as independent errors on a root-sum-square basis to give the total uncertainty in the projected energy output.

C.13 Summary of the Results of the Analysis

Wind data were recorded at the Cuilliagh Mountain site for a period of 18 months. Analysis of this data, in combination with concurrent data and historical wind data recorded at Malin Head Meteorological Station, results in the following conclusions with regard to the wind regime at the Cuilliagh Mountain site:

1 The long-term mean wind speed is estimated to be 7.2 m/s at a height of 30 m above ground level.

2 The standard error associated with the predicted long-term mean wind speed at 30 m is 0.26 m/s. If a normal distribution is assumed, the confidence limits for the prediction are as given in Table C.9:

Table C.9: Confidence Limits – Wind Speed

Probability of Exceedence [%]	Long-term Mean Wind Speed at 30 m [m/s]
90	6.9
75	7.0
50	7.2

Site wind flow and array loss calculations have been carried out, from which the following conclusions are drawn:

3 The long-term mean wind speed averaged over all turbine locations at 45 m is estimated to be 8.1 m/s.

4 The projected net energy capture of the proposed Cuilliagh Mountain wind farm is predicted to be 36.9 GWh/annum.

These predictions of net energy include topographic effects, array losses, availability, electrical transmission losses, air density adjustments and factors to account for turbine icing, high wind hysteresis and the wake effect of existing turbines. Other potential sources of energy loss are listed section C.9.

The net energy predictions presented above represent the long-term mean, 50% exceedence levels, for the annual energy production of the wind farm. These values are the best estimate of the long-term mean value to be expected from the project. There is therefore a 50% chance that, even when taken over very long periods, mean energy production will be less than the value given in the table. Estimates of long-term mean values with different levels of exceedence are set out below.

5 The standard error associated with the prediction of energy capture has been calculated and the confidence limits for the prediction are given in Table C.10.

Table C.10 Confidence Limits - Energy

Probability of Exceedence [%]	Net Energy Output [GWh/Annum] 1 Year Average	Net Energy Output [GWh/Annum] 10 Year Average
90	31.1	33.4
75	33.9	35.1
50	36.9	36.9
75	39.9	38.7
90	42.7	40.4

C.14 Actual Production of the Wind Farm

Commissioning of the Cuilliagh Mountain wind farm took place in late 2000; by November 2000 the wind farm was in full commercial operation. A review of its performance was undertaken early in 2002.

Table C.11: Expected and Actual Production of Cuilliagh Mountain Wind Farm

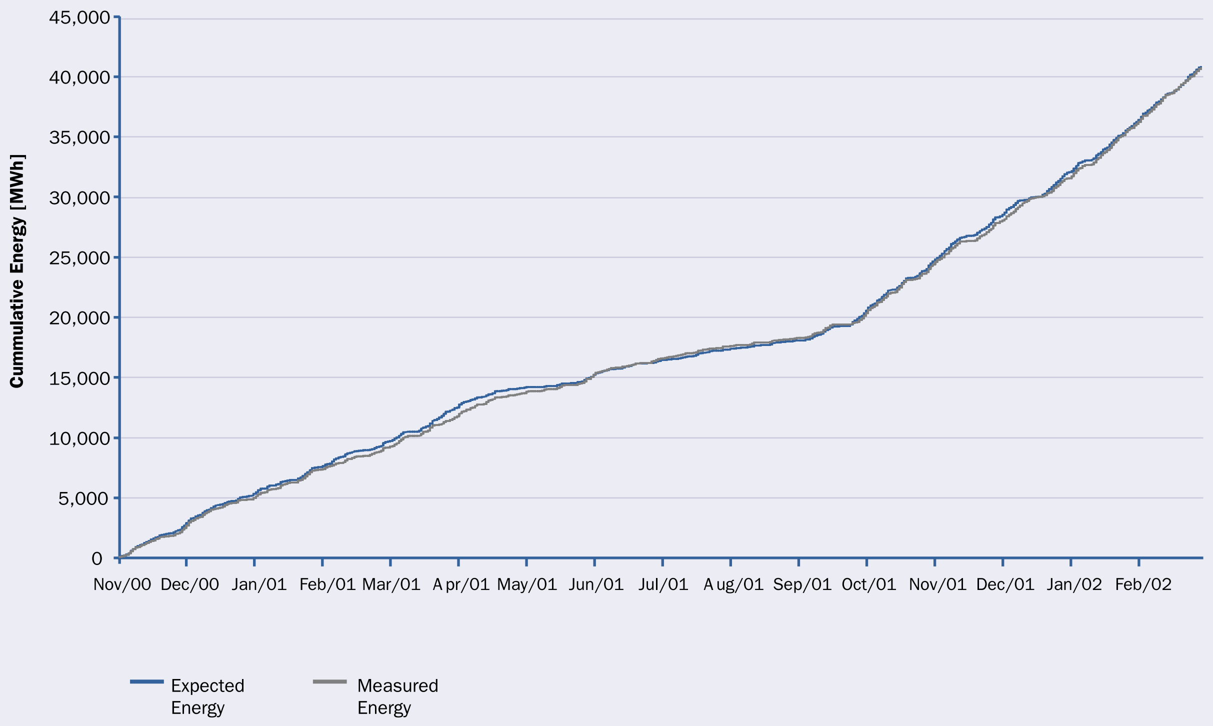
Month	Year	Expected Production (GWh)	Actual Production (GWh)
Nov	2000	3.670	3.703
Dec	2000	3.990	3.530
Jan	2001	4.270	3.546
Feb	2001	3.870	2.876
Mar	2001	3.840	3.410
Apr	2001	2.530	2.850
May	2001	2.160	1.699
Jun	2001	1.860	2.608
Jul	2001	2.050	1.813
Aug	2001	2.210	1.538
Sep	2001	2.850	2.941
Oct	2001	3.600	4.369
Nov	2001	3.670	3.645
Dec	2001	3.990	3.679
Jan	2002	4.270	4.801
Feb	2002	3.870	4.604
Mar	2002	3.840	4.037
	Total	**56.540**	**55.649**

Table C.11 presents the expected long-term monthly energy production of the wind farm, along with the actual energy production over the period November 2000 to March 2002. It can be seen that individual months can deviate substantially from long-term expectations; for example February 2001 experienced production which was only 74% of the long-term expectations for this month while in June 2001 140% of the long-term expectations for energy production in this month was produced. Over the 17-month period for which data are available the actual production of the wind farm was 1.6% below long-term expectations. This figure is well within the 75% and 90% exceedence levels for the prediction presented above. A detailed assessment of the availability of the wind farm over the above operational period has not been undertaken, but it is understood that high availability levels have been achieved.

The data recorded at Malin Head indicates that the windiness of the period from November 2000 to March 2002 was some 4.9% down on long-term expectations, making suitable assumptions about the seasonal variation of wind speed. This implies that over the longer term it is likely that the energy production of the wind farm will, in fact, exceed the central estimate value of 36.9 GWh/annum and may settle at a level which is close to the 25% exceedence level presented above. A more detailed assessment which includes issues such as wind direction, air density and availability would be required to provide a revised central estimate of wind farm production.

A separate validation of the accuracy of the modelling techniques employed to predict the long-term energy production of the Cuilliagh Mountain Wind Farm was undertaken. A comparison was made between the expected energy production of the wind farm, based on the actual mean wind speed recorded at Malin Head Meteorological Station and the actual wind farm energy production. This was undertaken on an hourly basis. Thus, the accuracy of the correlation relationships between Malin Head and the site, and of the site flow model and turbine wake models was assessed using a “wind in–energy out” test. Suitable adjustments were made to reflect the actual air density at the site. The comparison was undertaken for the operational period described above and data were only compared where all turbines were available and when wind farm SCADA data and data from Malin Head Meteorological Station were also available. Using these criteria, a comparison was made over a total of approximately 8,300 hours. The results of the comparison of the expected and actual energy production of the wind farm are presented in Figure C.5 as a cumulative plot. Over the full period considered, the actual production was 99.7% of that expected, which provides confidence in the accuracy of the methods employed. It is noted that for individual months and for individual turbines larger discrepancies between the expected and actual energy production is observed.

Figure C.5: Cumulative Plot Showing Measured Energy against Concurrent Expected Energy for the Operating Period



C.15 Concluding Remarks

This Appendix has shown that the techniques outlined in the main text can be used to predict the behaviour of a wind farm with a good level of agreement. It has also demonstrated that the methods can be used to determine both mean values and associated uncertainties. It is hoped that it has proved a useful illustration of the techniques which are presently used by the industry.

APPENDIX D: DETAILED DESCRIPTION OF CORRELATION TECHNIQUES

Over the past decade, there has been an ongoing industry debate over which correlation methodologies provide the best prediction of the long-term mean wind speed at a site. All correlation methods have common features in that they (i) establish a relationship between the concurrent data recorded at the site and reference station, and (ii) apply the relationship to the historic data recorded at the reference station to predict the long-term wind regime at the site. Such methodologies are commonly called measure correlate predict (MCP) analyses. Variables in such correlation analyses mooted over the past decade include those defined in Tables D.1 and D.2 below.

Table D.1: Prediction Methodologies Based on 10-minute or Hourly Data

Technique	Option 1	Option 2	Others …
Directional bin size	30°	Other	
Regression analysis technique	Principal component analysis	Least squares fit	
Fitting method	One parameter fit	Two parameter fit	Non-linear
Low wind speed cut off	Exclude lowest wind speed data	Include lowest wind speed data	

Table D.2: Prediction Methodologies Based on Longer Term Data

Technique	Option 1	Option 2	Others …
Averaging period	Monthly	Daily	
Fitting method	One parameter fit	Two parameter fit	Non-linear
Threshold for data coverage	Varies		

The above tables present a bewildering array of options. While the technical merit of some methods over others can be argued, experience has shown that where the wind regimes at the site and reference meteorological station are well correlated, the results obtained tend to be relatively insensitive to the specific correlation methodology adopted. For cases where the correlation between the site and reference station is less good, then significant divergence is sometimes seen between the results obtained with different methods. In such circumstances, careful checks are required to ensure that the correlation is sufficiently good to justify the use of the reference meteorological station. Due consideration also needs to be given to the interpretation of the uncertainty associated with a specific correlation methodology.

The methods based on 10-minute data or hourly data typically use the long-term wind rose recorded at the reference meteorological station. Those based on daily or monthly correlations are dependent on the site wind rose. In practice, it is often observed that where hourly or 10-minute correlations between a site and reference station are poor, a reasonable correlation is observed over longer data collection periods, such as monthly.

Detailed Description of a MCP Analysis

A detailed description of the steps within a MCP analysis is described below, based on hourly data from the site and reference station. As indicated in the previous section, different approaches may be used. In the following discussion, the proposed wind farm site is referred to as the "target site" and the meteorological station is referred to as the "reference site".

The first stage is to measure, over a period of about a year, concurrent wind data from both the target site and the nearby reference site for which well-established long-term wind records are available. The short-term measured wind data are then used to establish the correlation between the winds at the two locations. Finally, the correlation is used to adjust the long-term historical data recorded at the reference site to calculate the long-term mean wind speed at the target site.

The concurrent data are correlated by comparing wind speeds at the two locations for each of 12 30° direction sectors, based on the wind direction recorded at the reference site. This correlation involves two steps:

- Wind directions recorded at the two locations are compared to determine whether there are any local features influencing the directional results. Only those records with speeds in excess of, say, 5 m/s at both locations are used.

- Wind speed ratios are determined for each of the direction sectors using a “principal component analysis”.

In order to minimise the influence of localised winds on the wind speed ratio, the data are screened to reject records where the speed recorded at the reference site falls below 3 m/s (or a slightly different level) at the target site. The average wind speed ratio is used to adjust the 3 m/s wind speed level for the reference site to obtain the different level for the target site, so ensuring an unbiased exclusion of data. The wind speed at which this level is set is a balance between excluding low winds from the analysis and still having sufficient data to carry out the analysis. The level used only excludes wind speeds below the cut-in wind speed of a WT, which do not contribute to the energy production.

The result of the analysis described above is a table of wind speed ratios, each corresponding to one of 12 direction sectors. These ratios are used to factor the wind data measured at the reference site over the historical reference period, to obtain the long-term mean wind speed at the target site. This estimate therefore includes the following influences:

- “Speed-up” between the target site and the reference site on a directional basis. This can be a very important characteristic; sometimes speed-ups differ by a factor of as much as 2.
- The wind patterns at the reference site have been translated through the correlation process so that the long-term pattern at the target site has also been established.

APPENDIX E: CONNECTION CONSIDERATIONS

E.1 Timing Constraints

In many cases, the time to construct the network connection and any additional network reinforcement can be longer than the time it takes to design, finance and build the wind farm itself. This is a new situation which applies to all embedded generation and also to some new forms of large-scale generation. For traditional conventional generation projects, the network connection is not on the "critical path".

Timing issues are particularly significant on the transmission system, as it can take several years to obtain permission and construct new or reinforced transmission lines.

E.2 Network "Strength"

An important consideration is the strength of the network at the proposed point of connection, varying from "strong" to "weak". Embedded generation and large consumers, where either output or demand can change significantly over a short time-frame, can cause relatively large changes in the network voltage on a weak electrical system. A strong network, on the other hand, will be relatively unaffected by changes in generation and demand.

A weak electrical system will have a low "fault level" or "short circuit level", which is usually measured in MVA. The strength of a point on the network is determined by impedance between that point and the main generators on the system. Put another way, a weak point on the electrical system is one which is further away from large amounts of generation than a strong point on the system. The strength of a network also determines the current that will flow in the event of a fault.

Wind farms in windy rural areas often find that the network is weak, primarily because these are often sparsely populated areas of low demand, with long distances from the main users and generators. Although on its own the strength of a network does not indicate the maximum wind capacity that can be connected, it is a good indicator of the kind of issues that might emerge. If a study shows that the strength of a chosen network is not sufficiently high to enable the addition of new wind generation capacity, then the options are to connect to another stronger network (which may be further away), or to reinforce the network.

E.3 Voltage Range

For distribution networks, the rise in voltage adjacent to the wind farm is often the limiting factor for wind farm size. The power and reactive power produced or consumed by the wind farm causes the voltage levels within the network to change. The exact effect is complex and depends on other power and reactive power flows, as well as the voltage control equipment which already exists in the network. If the voltage level at a customer is estimated to go outside the statutory limits, then something must be done. For example:

- improve voltage control equipment;
- install power factor correction equipment;;
- control the reactive power output of the wind farm;
- limit the wind farm size; or
- reinforce the network.

Sometimes, the point on the network which is most affected by such changes is the wind farm itself. In this case, it is possible to agree a connection where the voltage range is expected to be greater than the statutory range. However, the voltage range at the WT terminals must still be within the acceptable range specified by the turbine supplier.

If this issue cannot be addressed through the above means then it may be necessary to curtail the output of the wind farm when voltage levels may go outside the acceptable range. It may be worth accepting this occasional loss of production for rare combinations of circumstances. Equally, it may be possible to adopt a different turbine choice that will be better equipped for dealing with the characteristics of the network.

E.4 Thermal Rating Limits

Thermal ratings of cables, overhead lines and transformers may also be limiting factors. In this case, network rein-

forcement is often the only solution. It may be possible to negotiate some automatic or manual means to reduce wind farm output when thermal limits are approached. This may only occur rarely, e.g. when one line of two is out of service, and the loss of production may therefore be acceptable.

E.5 Fault Current Ratings

The calculated "fault current levels" (the current that flows in the event of defined faults) on a system may be close to the ratings of the switchgear which will have to interrupt that fault current. This is particularly true in urban and on higher voltage networks. New generation on the system may therefore force replacement of the switchgear with new equipment with a higher rating, which can be expensive.

The fault current issue may also be more significant at transmission level, as the high cost of uprated switchgear means that transmission networks are often already operated close to switchgear ratings.

E.6 Power Quality Issues

Power quality does not often limit wind farm size, but it is of concern to network operators and must always be considered. Network operators need to provide a certain quality of power to their customers. WTs can affect networks such that power quality seen by other customers is affected. Therefore, network operators demand that these effects are quantified and, if necessary, limited. There are four main issues:

- Voltage step changes.
- Flicker.
- Harmonic distortion.
- Voltage imbalance.

IEC 61400-21 is an international standard which provides means to calculate, from measurements, parameters that characterise the power quality of a WT design. WT manufacturers can get their machine tested by a third party and produce test certificates in a similar way to a power curve or noise emission characteristic.

The standard also provides formulae by which the characteristic parameters of a WT can be used in conjunction with project dependent parameters, in order to estimate what the power quality effects of a proposed wind farm will be. The results can be compared with the network operator's requirements to decide if the wind farm will be acceptable.

E.6.1 VOLTAGE STEP CHANGE

Currents flowing in the electricity network affect the voltage seen by other customers. A sudden increase or decrease in current will cause a step change in voltage which may be perceptible to other customers. Such changes may also occur too rapidly for the voltage control systems operated by the network operator (principally adjustment of the ratio of main transformers), causing the voltage at some point in the network to go outside the statutory limits. Typically, the maximum voltage step is limited to between 2% and 5%.

Voltage step changes can be caused by WTs starting up, particularly fixed speed wind turbines with induction generators. It is especially an issue for fixed speed stall-regulated wind turbines because they have no control over the rate at which the rotor accelerates during start-up, and have to energise the generator just as its rotational speed matches synchronous speed. There is often some speed mismatch at this point and so there is an "inrush current" to accelerate or decelerate the rotor to match synchronous speed, as well as the normal inrush current to magnetise the generator.

The same effect occurs when fixed speed WTs with two speeds (two generators) change from one speed to the other. A similar effect is seen when the WT stops, especially when shutting down from full power due to the upper wind speed limit being exceeded.

Pitch-regulated WTs can control rotor speed during start-up, so this effect is reduced. The effect is even less for variable speed turbines. Fixed speed machines often use "soft start" power electronic devices to reduce the voltage step change to insignificant levels.

As it is accepted that WTs in a wind farm will not start simultaneously, this is only a problem for single turbines or small clusters, perhaps two or three, on weak networks.

E.6.2 VOLTAGE FLICKER

Flicker is a concern for many system operators. In reality, it is rarely a real problem, although it must always be checked. As a general rule, if the effect of a wind farm in terms of voltage rise and other basic technical issues is satisfactory, then flicker is probably satisfactory too.

Flicker is caused by small voltage changes occurring rapidly and sequentially, which causes lighting to flicker and hence customer annoyance. Flicker therefore tends to be more of an issue with one or a few WTs on lower voltage distribution networks with low fault levels. For large wind farms, the smoothing effect of the power fluctuations from large numbers of turbines means that the flicker effect is greatly reduced.

The most important flicker-producing events are turbine starts and stops, and switching between generators (for two-speed WTs). Fortunately, switching operations can be limited in frequency of occurrence through appropriate programming of the turbine controller. Again, flicker is not normally a problem for variable speed turbines.

E.6.3 HARMONIC DISTORTION

Variable speed WTs have power electronic converters which can emit currents at frequencies above the fundamental frequency (50 or 60 Hz). These harmonic currents can cause annoyance to customers and can even damage equipment. This is only an issue for variable speed wind turbines. There is a tendency for the more modern WTs to use power electronic converters and so harmonics do need to be addressed. Harmonic emissions are, however, well understood by WT manufacturers. Generally, they are also quite low and rarely considered an issue in practice.

To keep harmonic emissions within the required levels, WTs often use frequency converters with "pulse width modulation" (PWM). These produce very low levels of harmonics at frequencies (approximately 2 kHz) above the range usually of concern to network operators.

In summary, harmonic emissions should not be a problem unless there are specific features of the network in question.

E.6.4 VOLTAGE IMBALANCE

Network operators try to keep the currents in all three phases of the network similar so that the voltages are also similar. Unbalanced currents can cause the voltages to differ, which can damage customer equipment.

Voltage imbalance is often included within power quality by network operators. However, for WTs it is a different kind of issue and is not therefore dealt with by the IEC 61400-21 standard.

As three-phase rotating machines, WTs make no real contribution to system voltage imbalance. In fact, as induction machines they tend to reduce the imbalance. The downside of this is that large "negative phase sequence" currents can flow within the generator and cause excessive heating.

Network operators often do not know the existing levels of voltage imbalance at a specific point on their system. It can be measured but, as it is a function of load currents, it varies during the day, week and, possibly, over the year. Network operators may say they aim to keep it below agreed limits, but it could, in practice, be significantly higher at some locations. If this problem is identified, network operators will attempt to cure it by re-allocating single-phase customers across the three phases. This can take some time and may not be a complete solution. A complete solution may require network reinforcement which implies cost and delay.

In some rural networks these risks may justify making measurements of voltage imbalance before choosing a point of connection.

Voltage imbalance is usually only an issue on weak lower-voltage networks.

E.7 Typical Upper Limits

Table E.1 lists some "rule of thumb" limits for the amount of embedded generation that may be connected within a network. (Note that in many systems, 100 kV or above would be considered as part of the transmission system.)

These figures are upper limits. In any one case, there could be many factors which would limit the maximum capacity below these levels.

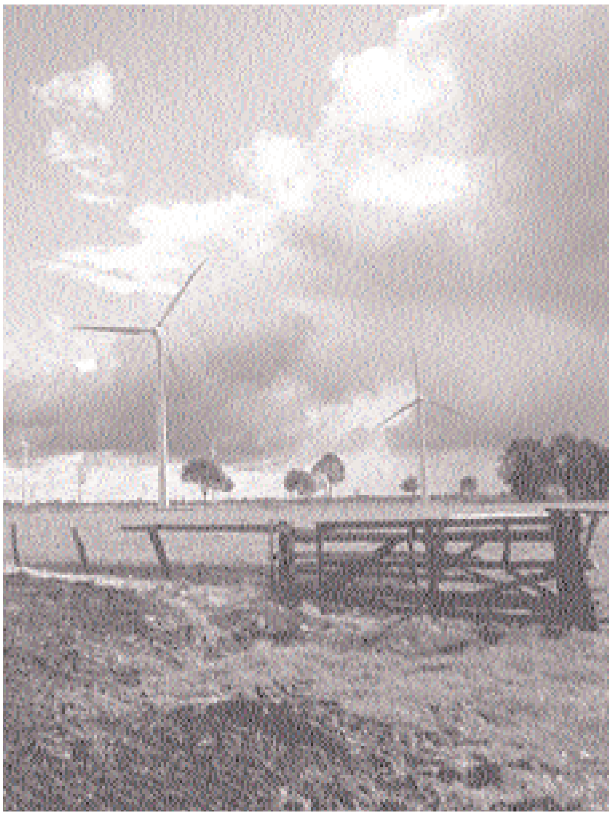
Table E.1: Rule of Thumb Limits for Embedded Capacity

Connection Point	Typical Maximum Generation Capacity Which May be Connected
Low voltage	A few kW of embedded generation capacity
Lower levels of the distribution system (typically 10 or 11 kV)	Up to 2 MW, or possibly more than 2 MW close to the transformer feeding the network
Upper levels of the distribution system (20 – 35 kV): existing overhead line or cable	Can take 10 to 15 MW
Upper levels of the distribution system (20 – 35 kV): existing busbar in a substation	Is likely to accept up to the rating of the transformers, which could be 60 MW or more.
'Subtransmission' system (70 – 150 kV): existing overhead line or cable	A typical limit is 100 MW
'Subtransmission' system (70 – 150 kV): existing busbar in a substation	A typical limit would be several hundred MW
Transmission systems	Generalisations not possible

E.8 Connections for Offshore Wind Farms

Offshore wind farms must connect to land-based networks in the same manner as for onshore wind farms. They are therefore subject to the same network considerations. However, as economic reasons favour most offshore wind developments to be large in comparison to onshore developments, it is more common for an offshore wind farm to connect directly into a transmission system rather than a distribution system. Issues such as power quality are therefore unlikely to be important.

It should be noted that, although offshore developments must connect to land-based networks, there may be cases where a utility will extend its own system out to an offshore development, rather than the wind farm constructing a line to an existing utility network. As with all wind farm developments, the location of the connection into the utility system is likely to bear heavily on the costs of the development and so will be subject to case-by-case discussions between the parties involved on how these costs are to be met.



APPENDIX F: POSSIBLE GRID CODE REQUIREMENTS

Grid code documents set the requirements for users of the transmission or distribution system. These have evolved to suit conventional generation, and substantial modifications are required to apply them to new forms of generation, particularly wind. Such modifications have been produced, or are in the process of being developed, in many European countries. The following sections summarise common grid code requirements for wind, drawn from published or draft documents.

F.1 Power Cap

A power cap is an adjustable maximum limit on the output of a wind farm. It is relatively easy to implement and is a function that is, or will shortly be, available from most of the major WT manufacturers. The power cap allows the system operator to limit the maximum output of wind farms in its area for short periods. This is particularly useful for critical periods such as:

- times of very low demand;
- times of great volatility in demand; and
- times when great volatility in the output of the wind generation is expected, for example, due to the passage of a storm.

Clearly, it is economically advantageous to use all other available options before applying a power cap, as this wastes "free" energy and increases emissions from conventional forms of generation.

F.2 Ramp Rate

A ramp rate is a limit on the maximum rate of change of the output from a wind farm. A positive ramp rate is easy to implement using WT and wind farm SCADA systems. Rates of around 10% of wind farm capacity per minute have been specified by network operators.

A negative ramp rate is much harder to achieve. A crude partial solution is to limit the rate at which turbines can shut down. To fully meet the intention of this requirement, forecasting of wind farm output is necessary so that if a sudden drop in output is foreseen, output can be reduced in advance in order to keep the ramp rate at less than the set limit.

As for the power cap function, ramp rate limits will waste free energy and should only be used when essential.

F.3 Voltage and Frequency Operating Range

Historically, when a disturbance was seen on the system (manifested as voltage or frequency going out of the acceptable range), wind farms were required to disconnect as soon as possible. However, when wind capacity penetration is high enough for the system not to be able to withstand this sudden loss of generation, this principle has to be changed. Instead, the wind generation must continue to operate over a wider range of voltage and frequency. This is perfectly feasible for most WTs, although not all existing designs will be able to meet the new criteria.

F.4 Frequency Regulation

Conventional generation provides frequency regulation by automatically changing the output of a few of the major generators in response to changes in system frequency which, in turn, are due to changes in customer demand. This is relatively easy to do.

Pitch-regulated WTs can also provide adjustment of output power in response to changes in system frequency but only by "spilling" available wind. This is, therefore, an expensive way to provide this function.

Stall-regulated turbines will have much greater difficulty in providing a similar effect.

An alternative solution is to set up a market for frequency regulation to which generators can bid. Those generators (such as major conventional plant) which can provide this service at relatively low cost will therefore be chosen to do so. Generation which finds this difficult (such as wind) will not need to do so.

F.5 Reserve

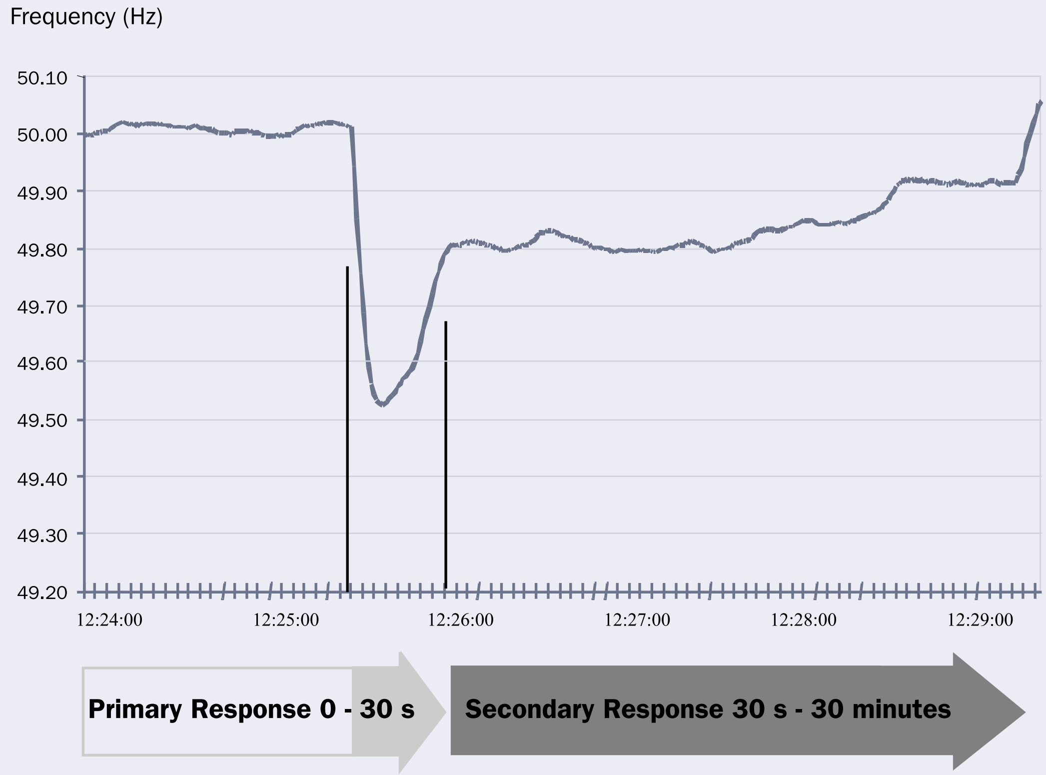
Reserve is required by system operators in order to cope with the sudden loss of a major generator either due to a failure of that generator or to a failure of the transmission system connected to that generator. Reserve is conventionally provided by the stored energy within conventional generation including that stored within the steam systems of thermal plant. For the first few seconds after the loss of a major generator, the system frequency will drop and energy is rapidly extracted from all the remaining generators by opening their steam governors (or equivalent) in response to the drop in frequency. This process takes only a few seconds; then, increased fuel flow into the conventional generators acts to restore system frequency. If necessary, other generators may be started up on timescales of minutes.

Figure F.1 demonstrates such a drop in frequency, and the rapid increase in production from the remaining generation within a 30-second timeframe.

Wind generation cannot provide a contribution to reserve requirements except at high cost, i.e. by always operating at a point below the power that could be produced in the given wind conditions. Wind is, therefore, a very expensive way of meeting reserve requirements and, as for frequency regulation, there is an argument that a market for reserve may be more appropriate than enforcement of reserve requirements on generators.

There is a possible argument that variable speed WTs may be able to contribute to reserve requirements for the first few seconds by extracting energy from the spinning inertia. Although in principle simple to achieve, in practice the implementation and the requirement to be able to demonstrate this capability to system operators mean that, in all likelihood, WT manufacturers will not develop this facility unless a market or some other reward for providing this benefit exists.

Figure F.1: System Reserve



F.6 Reactive Power and Voltage Control

Conventional generation can be controlled to produce or consume reactive power almost at will and at little cost. This feature is used to control voltages at points on the system. If conventional generation is displaced, wind must fulfil the same function. This is not currently possible with most WTs, but some manufacturers offer such a facility and more are expected to follow. The costs for this function are expected to be minor for variable speed WTs and more expensive for fixed speed turbines.

It is not clear whether electricity systems actually require the large reactive power production or consumption ability of synchronous generators (power factor 0.85 or less). Therefore, it is not clear if this wide range should be required of wind generation.

F.7 Transient Stability ("Fault Ride-through")

Wind farms can no longer expect to be disconnected in the event of system transient disturbances. As wind penetration increases, it is increasingly important that wind generation continues to operate during transient system disturbances. It is usually necessary to demonstrate that this is possible to the network operator before any such event occurs. For conventional power generation this is done using simulation models. Such models are being developed for WTs, but there is considerable difficulty in understanding, developing and validating these models. This is currently a research area.

APPENDIX G: CALCULATION OF SPECIFIC EMISSIONS OF STANDARD AIR POLLUTANTS FROM FOSSIL FUEL ELECTRICITY GENERATION (METHODOLOGY)

All calculations are based on the only available data, that for electricity generation per fuel (TWh/a) and for total emissions from electricity generation (kt/a). The latter are divided according to the shares of electricity generated from the different fossil fuels. It is assumed that different types of power plants have different specific emissions. Calculations are made assuming three different reference emission level scenarios (best case - very good scrubbers; intermediate case - good scrubbers; worst case - no scrubbers at all and worst fuel quality), shown in Table G.1.

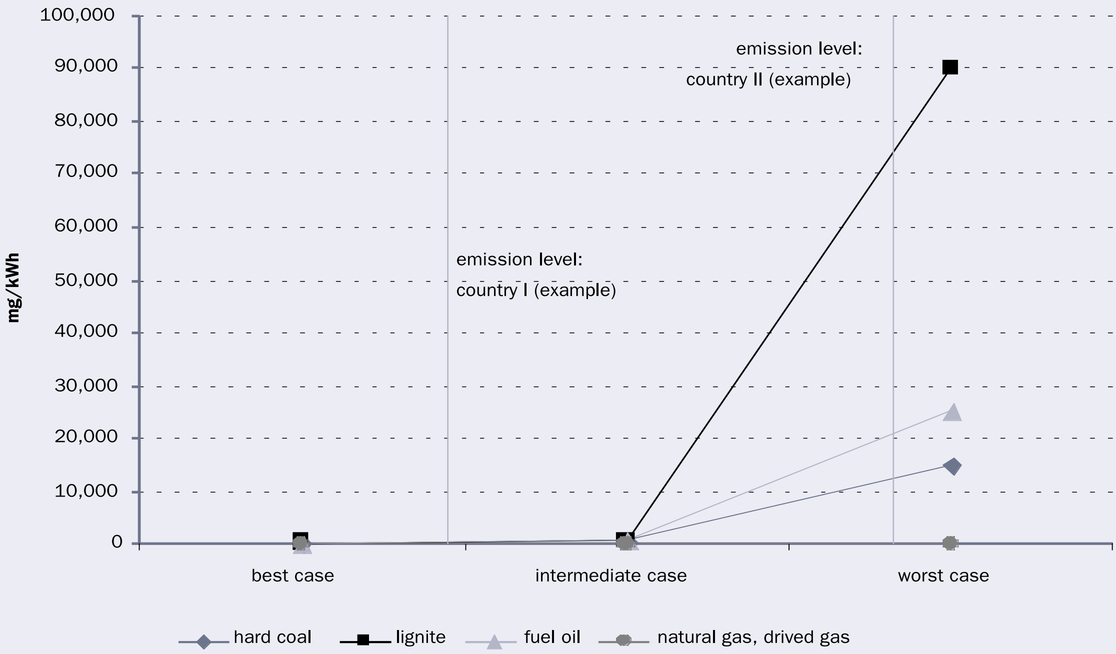
Table G.1: Assumed Emission Levels of Power Plants

Fuel Type	Best Case	Intermediate Case	Worst Case
		SO_2 (mg/kWh)	
hard coal	350	700	15000
lignite	350	700	90000
fuel oil	350	700	25000
natural gas, derived gas	0	0	100
mixed firing, not specified		Average emissions	
		NO_X (mg/kWh)	
hard coal	350	700	3000
lignite	350	700	3000
fuel oil	350	700	3000
natural gas, derived gas	150	300	1500
mixed firing, not specified		Average emissions	

It is assumed that the specific emissions for all types of power plants and fuels are at the same technical level for each country. The graphs in Figure G.2 show a fixed relationship between emissions and different fuels.

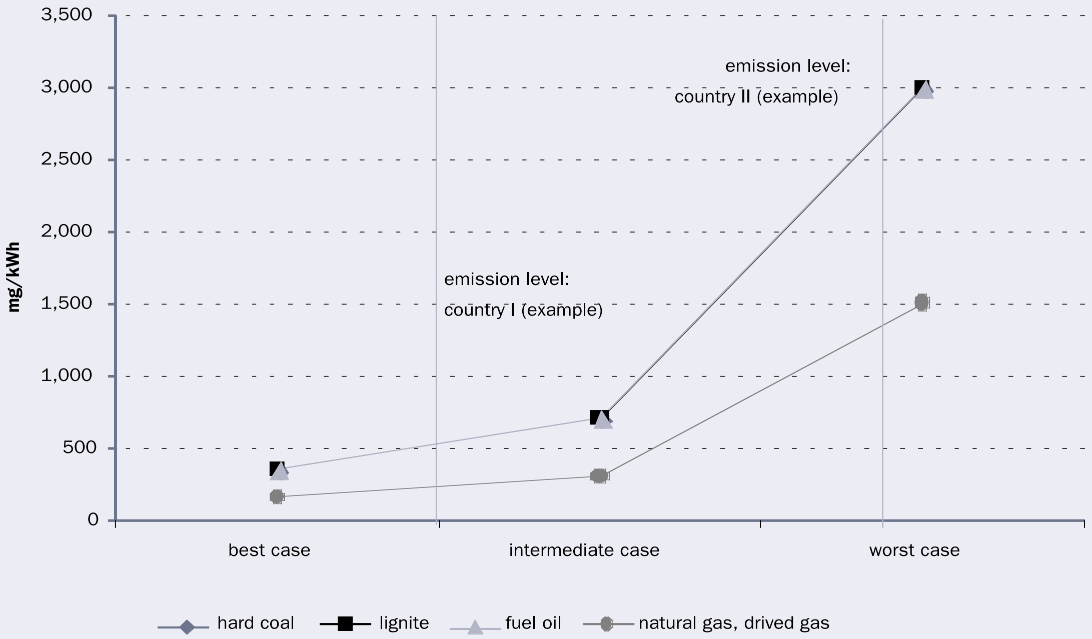
The mathematical model used for the calculation of specific SO_2 emissions, the inputs to the EcoSense model, plus the software and all other relevant calculations are documented on the CD attached to this report.

Figure G.1: Fixed Relations of Emission Levels of SO_2 for Different Fuels in a Country



Source: own calculations.

Figure G.2: Fixed Relations of Emission Levels of NO_X for Different Fuels in a Country



Source: own calculations.

APPENDIX H: ASSUMPTIONS FOR THE CALCULATIONS OF EXTERNAL COSTS WITH ECOSENSE

Calculations of Specific External Costs Assume the Following Geographical Locations of the Power Plants in each Country

	Country	Northern Latitude	Eastern Longitude
AT	Austria	48	16
BE	Belgium	51	4
DK	Denmark	56	12
FI	Finland	60	24
FR	France	49	2
DE	Germany	51	7
GR	Greece	40	22
IE	Ireland	53	-9
IT	Italy	45	9
LU	Luxembourg	50	6
NL	Netherlands	52	5
PT	Portugal	39	-9
ES	Spain	43	-6
SE	Sweden	56	14
GB	UK	53	-1
CY	Cyprus	35.25	29*
CZ	Czech Republic	50	13
EE	Estonia	59	27
HU	Hungary	48	20
LV	Latvia	57	24
LT	Lithuania	55	25
MT	Malta	36	14
PL	Poland	50	19
SK	Slovakia	49	22
SI	Slovenia	46	15
BG	Bulgaria	42	26
RO	Romania	45	25
TR	Turkey	40	29*
included area	from	35.25	-10
	to	73.86	29

* In the case of Turkey and Cyprus, the generation facilities are assumed to be at the eastern border of the area covered by the model because of the limited area covered by EcoSense.

APPENDIX I: MARGINAL COST OF CO_2 EMISSIONS

The values of the marginal cost of CO_2 in the following Table are in US$/tonne of carbon (1996 dollars). The lower value in each box corresponds to a time horizon of 300 years, the upper value to 1,000 years. In the first row, the distribution of income is not taken into account. In the second row, this aspect is included on the assumption that it remains constant over time (Azar and Sterner, 1996, p. 181).

	The Pure Rate of Time Preference			
	0 %/year	0.1%/year	1%/year	3%/year
The marginal cost of CO_2 emissions, MC1	85-200	75-140	32-33	13-13
The marginal cost of CO_2 emissions, MC2	260-590	230-410	95-98	39-39

APPENDIX J: CALCULATED EMPLOYMENT IN EU LEVEL SECTORS

	Employment per Final Demand Unit (mio ECU) 1995 EU	Direct	Indirect	Total EU
1	Agriculture, forestry and fishery products	31.66	5.78	37.44
2	Fuel and power products	3.29	19.49	22.79
3	Ferrous and non-ferrous ores and metals	4.93	8.51	13.44
4	Non-metallic mineral products	10.13	4.73	14.86
5	Chemical products	6.12	13.83	19.95
6	**Metal products except machinery**	**13.11**	**6.73**	**19.84**
7	**Agricultural and industrial machinery**	**9.75**	**3.85**	**13.60**
8	**Office and data processing machines**	**9.87**	**0.85**	**10.72**
9	**Electrical goods**	**9.56**	**4.66**	**14.22**
10	Transport equipment	7.25	2.90	10.14
11	Food, beverages, tobacco	6.37	10.69	17.05
12	Textiles and clothing, leather and footwear	17.89	1.89	19.78
13	Paper and printing products	10.67	8.58	19.25
14	**Rubber and plastic products**	**9.11**	**5.16**	**14.27**
15	Other manufacturing products	15.12	1.91	17.03
16	**Building and construction**	**13.33**	**4.81**	**18.14**
17	Recovery, repair services, wholesale, retail	20.62	19.19	39.81
18	Lodging and catering services	19.04	2.37	21.41
19	Inland transport services	14.89	6.84	21.73
20	Maritime and air transport services	6.58	1.25	7.83
21	Auxiliary transport services	6.89	5.11	12.01
22	Communication services	13.60	4.52	18.12
23	Services of credit and insurance institutions	12.02	19.34	31.36
24	**Other market services**	**12.89**	**44.72**	**57.61**
25	Non-market services	21.30	3.33	24.62
	Simple Average	12.24	8.44	20.68

APPENDIX K: *EASTERN PROMISE*, WIND DIRECTIONS, EWEA, MARCH 2003

New EU member states and other Central and Eastern European countries

BULGARIA

Population: 8.3 million
Capital: Sofia
Generation capacity: Fossil fuels (54%), nuclear (31%), hydro (15%)
Although a countrywide wind atlas has identified areas with average wind speeds in excess of 9m/s, there are no turbines operating yet and no mechanism in place to encourage them. Nonetheless, a project with 19 Nordex 1.3 MW turbines has been proposed by a private developer at Peak Murgash, north of Sofia, where wind speeds are said to average 10 m/s. Construction is scheduled for 2005.

A study by the National Institute of Meteorology in Sofia has estimated the total wind power potential in Bulgaria at 2,200 to 3,400 MW. The most promising sites are on the Black Sea coast, in the central mountain range and in the Rhodop Mountains in the southwest. Meanwhile, four out of six reactors at the Kozloduy nuclear plant are scheduled to close as part of the conditions for Bulgaria's membership of the EU, expected to take place in 2007.

CZECH REPUBLIC

Population: 10.3 million
Capital: Prague
Generation capacity: Coal (54%), nuclear (32%), hydro (14%)
Wind power in the Czech Republic was given a boost at the end of 2001 with the introduction of a new feed-in tariff set at 9.5 c€/kWh. This is the minimum amount to be paid to wind producers by the distribution companies, who have an obligation to accept new supply. A number of areas around the country have wind speeds in the range of 8-9 m/s, so the prospects are good. The Czech Wind Power Association puts the total potential at 600-700 MW, half of which could be installed over the next five years if long-term contracts were available.

Operating wind capacity at the end of 2002 was 7 MW, mainly consisting of small turbines erected during the 1990s. But one development of 14 larger turbines is expected to start construction this spring, with more to follow. German developer UTEC-Thomsen, active across a number of East European states, has plans for up to 250 MW.

HUNGARY

Population: 10 million
Capital: Budapest
Generation capacity: Fossil fuels (77%), nuclear (22%), hydro (0.6%)
Although average wind speeds are relatively low, Hungary has the potential to join the wind power leaders among the new East European accession states, especially with successful implementation of government support programmes aimed at reducing CO_2 levels. One projection from the Horvath Engineering consultancy is that 800 MW could be installed over the next 10 years.

Hungary's electricity supply presently comes from a mixture of nuclear and fossil fuel plants, increasingly using natural gas. Under a new law, however, every licensed electricity company has to accept renewable power generation, as long as it complies with certain technical requirements. The price paid is guaranteed within a range varying from 6.5 c€/kWh up to 9.5 c€/kWh, depending on the time of day the power is delivered.

The Hungarian government has also pledged to meet 6% of the country's electricity needs from renewables by 2010, double the present 3%. However, the powerful Ministry of Economic Affairs, sees the main renewables contribution coming from biomass, geothermal and solar PV, and is rather less than enthusiastic about wind.

Supply competition: Steady privatisation has moved through Hungary's electricity sector, with a 2001 Electricity Act introduced specifically to bring the country into line with EU Directives on third party access, subsidy elimination and segmenting the electricity market into generation, distribution and power trading companies. Supply competition is also being introduced in a rolling programme. A handful of WTs have gone up so far, all individual Nordex and Enercon machines. Three Enercon E-40

600 kW turbines have been developed with backing from E.ON Hungaria, a major power supplier and developer. The most prominent developer active in Hungary is German company UTEC-Thomsen, which is progressing plans for a number of large wind farms using a mixture of Nordex and NEG Micon turbines. The first of these, 40 x 1.5 MW turbines near Tesz, should start building during 2003. Leading manufacturers Bonus, Vestas and GE Wind have also all shown interest in the market potential.

Consultant Dr Gabor Horvath says that the most important technical criteria for wind farms in Hungary are a minimum average wind speed of 5-6 m/s at a height of 40-50 m, a nearby grid connection, accessibility to a main road for heavy vehicle traffic and a satisfactory environmental impact assessment. Wind resource and environmental assessments are being carried out at sites with the potential for several hundred MW of capacity, he adds.

ESTONIA

Population: 1.4 million
Capital: Tallinn
Generation capacity: Oil shale (94%), gas (6%)
The coastal regions of Estonia have a good potential for wind energy, and a number of national policy decisions have already been taken to encourage its exploitation. Following a 1998 long-term development plan for the energy sector, which envisaged a strategic increase in the contribution from both wind and hydro power, an energy law passed the same year placed an obligation on the national distribution company to purchase renewable energy. Most recently, new legislation will link the tariff for renewable power to the price for output from the large oil shale power stations at Narva on the Russian border, which generates most of the country's electricity. Renewables, including wind, will receive 1.8 times the Narva price, at present 2.8 c€/kWh, bringing the wind price up to 5.1 c€/kWh.

Payments under the new law, expected to start operating from this summer, would last for two years, but with a cut-off date at the end of 2015. This is not a strong enough incentive, according to the Estonian Wind Power Association (EWPA), which has been calling for the tariff price to be raised to 6.2 c€/kWh, a level at which (combined with other incentives) developers would be prepared to invest. Working together with environmental organisations and the Ministry of the Environment, the EWPA would also like to see the price unbundled from the Narva plant and for contracts under the purchase obligation to last at least 10 years.

Weak grid: Estonia has the potential for at least 560 MW of wind capacity, generating roughly 1.28 TWh, according to the EWPA. But that would require major improvements to the relatively weak grid in many parts of the country. The best sites are to be found round the long Baltic coastline and on the large islands of Hiiumaa and Saaremaa. In the short term, the EWPA expects about 100 MW to be built. Only one wind farm is already operating – a 1.8 MW development with three Enercon E-40 turbines commissioned last October at Virtsu on the Baltic coast with German government assistance. This was inaugurated by the Estonian President, Arnold Rüütel. But many more are in the pipeline, the first of which should be a project with up to eight Nordex 2.5 MW turbines on the Paldiski peninsula, just along the coast from the capital Tallinn. German project developer Ostwind is involved in a joint venture with an Estonian partner at Tamba, on the Baltic coast near the town of Pärnu. Good wind conditions and a satisfactory grid connection have already been established, ready for the installation of four Südwind 1.5 MW turbines. Ostwind is looking for a total of 20-30 MW in Estonia, but "this requires partners willing to share the risk," says the company's Christoph Markl-Meider. "This is linked to the political and legal conditions, which do not yet comply with EU structures, but which are a prerequisite for successful development in the long run." German developer UTEC-Thomsen also has plans for 150 MW of capacity, using NEG Micon or Vestas turbines.

Tax concessions: Apart from the payment tariff still pending in the current legislation, wind developers can benefit from tax concessions under Estonian law. No VAT is payable on wind or hydro power until summer 2004, when a rate of between 5% and 10% will be introduced. Although import duty is payable on equipment such as turbines brought in from overseas, this is recoverable in full at the end of the financial year. Tax on business turnover

of 18% is also recoverable if it is used for reinvestment in the business itself.

The EWPA adds that a soft loan may be available through the government agency KIK's environmental arm (www.kik.es) and equity involvement through the Baltcap fund (www.baltcap.com).

LATVIA

Population: 2.4 million
Capital: Riga
Generation capacity: Hydro (74%), fossil fuel (26%)
Latvia has 23.8 MW of installed wind capacity. Most of this is accounted for by the 19.8 MW Veja wind farm at Liepaja on the Baltic coast, with 33 Enercon E-40 turbines installed in April 2002. An indication of the problems encountered by such projects in a country with relatively poor infrastructure is that the crane used to install these turbines had to be imported from Finland. The Veja wind park was commissioned under a now abandoned system based on a payment of twice the household tariff. The government has since passed a new law providing a guaranteed tariff for the first eight years of a turbine's operation. This is set lower, at twice the average electricity selling price, about 5 c€/kWh. After eight years, however, the price falls to the average selling price, which is currently just 2.5 c€/kWh. A further drawback is that the system is based on competitive tenders for a fixed amount of capacity. A wind atlas of the country shows that there are several areas with wind speeds in excess of 6m/s at a height of 30 m. The best sites are located along the Baltic coast and around the Gulf of Riga. According to a study by the European Bank of Reconstruction and Development (EBRD), there is potential for 550 MW of wind capacity.

LITHUANIA

Population: 3.7 million
Capital: Vilnius
Electricity production: Nuclear (73%), fossil-fuelled CHP (21%), hydro (6%)
Lithuania could successfully accommodate 500 MW of wind capacity, according to a study carried out for the EBRD. This would be an important shift from the Baltic state's current dependence on the Ignalina nuclear plant for 73% of its power. However, phased closure of Ignalina, starting with one unit in 2005, is a condition of accession to the EU. According to the country's National Solar Programme, which runs until 2005, the aim is to introduce a range of renewable technologies, including solar PV, geothermal, wind and small hydro, but with the emphasis on biomass. The programme also calls for a lessening in the influence of state energy monopolies and the establishment of a guaranteed purchase price for renewable electricity.

The only WTs installed so far in Lithuania have been in the 60 kW range, mostly designed and built locally during the 1990s. Subsequent technical problems with these machines are explained by a mixture of lack of expertise and the need for more thorough resource assessment.

A 4 MW demonstration wind farm is planned at Butinge on the Baltic coast, but has yet to secure financing. Meanwhile, the Lithuanian government now says it wants to replace Ignalina with a new nuclear plant, a decision which, apart from the safety implications, would commit the country to a major capital outlay. It is still unclear how much of the promised EU compensation payment for the closure of Ignalina will go on decommissioning costs, and how much to support alternatives like wind.

POLAND

Population: 38.6 million
Capital: Warsaw
Generation capacity: Fossil fuels (94%), hydro (6%)
Poland encourages renewables through a quota system under which power utilities are expected to source an increasing proportion of their supply from renewables. This is supposed to rise from 2.4% in 2001 to 7.5% in 2010. The system does not contain any real penalty for failure to comply, however, and potential investors are now waiting for a new energy law, scheduled to come into force July 2003, to strengthen the purchase obligation. Wind power producers are currently obtaining a price of about 6-6.5 c€/kWh for their output from the distribution companies, although the power regulatory body URE has been reluctant to accept any "green premium" element in payments.

A demand by the national grid operator that generators provide details of their output 48 hours in advance has also disadvantaged wind producers. Although low interest loans and financial support are available from the EcoFund and National Fund for Environment Protection, the biggest problem for investors is the lack of long-term PPAs lasting at least 10 years. The country presently has 52 MW of modern WTs, all installed in the last three years. The largest developments, both with 2 MW Vestas machines, are 18 MW at Cisowo near Darlowo, developed by Energia-Eco, and 30 MW at Zagorze near Wolin on the Baltic coast, developed by EPA and commissioned at the beginning of this year. The best sites are in the southern mountainous region and close to the Baltic.

New developments: The Zagorze wind farm, Poland's largest to date, is located in an ideal site close to the Zalew Szczecinski seawater lake. Construction work was overseen by Wolin North Spolka, a subsidiary of the Danish utility Elsam, which owns the project. Polish companies were involved in supplying the towers, foundations and electrical connections. Annual output is expected to be between 63 and 70 million kWh. Many more projects are in the pipeline, a number involving developers from across the German border. UTEC-Thomsen, for example, says it wants to build up to 650 MW of capacity, using a mixture of Vestas and NEG Micon turbines, over the period up to 2007. German utility MVV, working with turbine supplier DeWind, is looking to install 10 wind parks, each with 50 MW capacity, along the Baltic coast. Dutch utility NUON has plans for 60 MW near Wolin, using the Kyoto Joint Implementation mechanism. The biggest Polish development company is EPA from Szczecin, which has been involved in all the recent projects.

Vis Venti, the Polish wind energy lobbying group, expects 50 MW to be installed during 2003 and 100 MW during 2004. Up to 1,600 MW could be built over the next five years, it anticipates. There are also major plans to develop Poland's offshore potential.

ROMANIA

Population: 22 million
Capital: Bucharest
Electricity production: Fossil fuels (62%), hydro (28%), nuclear (10%)
Although Romania has eagerly signed up to the principal international agreements on environmental protection and climate change mitigation, including the Kyoto Protocol, any follow-up measures, such as a clear environmentally based energy policy, have been hesitant and slow. Nuclear power is still viewed favourably by the government, whilst large hydro projects are seen as satisfying the need for renewable energy.

A broadly based national wind map was drawn up in the 1990s showing that the most favourable areas are along the Black Sea coast, with average wind speeds up to 7.1 m/s, and in the mountains at above 1,500 m. The same study assessed the overall potential at 2,000 MW, half of that offshore in the Black Sea itself. Work has also been carried out under the EU's OPET programme to map the wind potential along the Black Sea coast more closely. Only a few demonstration turbines currently operate in Romania, however, mainly because of the lack of any regulatory framework or incentives to encourage new renewables.

The most ambitious plan for a larger scale project has been a 24.5 MW wind farm proposed along two dikes totalling 14 km in length at the port of Constanta on the Black Sea. Despite these reservations, a recent assessment by the EBRD placed Romania as the "top candidate for wind energy development" among East European states. The assessment concluded: "Well documented resources, a broad range of applications, from small autonomous units for rural areas to large offshore potential, and the government's will to comply with EU regulations, all indicate fertile ground worth tilling."

RUSSIA

Population: 147 million
Capital: Moscow
Electricity production: Fossil fuels (66%), hydro (19%), nuclear (15%)
Less than 10 MW of wind capacity is currently operating in Russia, but an enormous potential is waiting to be tapped. One estimate is that the technically exploitable

wind resource in just the European part of the country, where most of the population lives, amounts to 2,308 TWh/year. This is as much as the whole of the EU's electricity consumption in 1995. The main problem is that some of the windiest sites, for instance in the north of the country, are both distant from population centres and often not easily accessible by the grid.

Most of the WTs erected over the past 10 years have been small, locally produced models. But the first substantial wind farm went up during 2002 at Kulikovo in the Kaliningrad region as a result of a cooperation agreement between the Russian Ministry of Energy and the Danish government. This 4.5 MW project consists of 20 Vestas V27 225 kW turbines originally installed in Denmark, and relocated to Kaliningrad by Danish company SEAS Energy Service following a repowering project. In the Arctic region, Russian company VetroEnergo has already installed an initial turbine near the port of Murmansk, and now has plans for a 3-5 MW wind park at Teriberka, 100 km east of Murmansk. A study of the Kola Peninsula, including Murmansk, shows that the region has the potential for up to 800 MW of wind capacity.

Two years ago, the Russian government approved a national energy plan which included installation of up to 232 MW in 28 regions. This was estimated to cost 10.6 billion roubles, 7% of which would come from the government, the rest from local budgets and private sources. The same plan envisaged domestic manufacture of turbines, with an investment of 1.3 billion roubles, 17% from the government. Specific future plans include the country's first offshore wind farm - a 50 MW development with 25 x 2 MW turbines set close to the Baltic coast near the town of Baltiysk. A €1 million feasibility study is due to be carried out by SEAS, and the project would be implemented by a joint Russian-Danish company. Like other East European countries, Russia is going through a process of electricity market liberalisation, with a timescale running through to 2009. This includes breaking up large state companies into competing units, establishing separate generation and distribution entities, and creating a wholesale market which, among other things, will need to see electricity prices rise in order to reflect the real cost of delivering power. This should help the economics of wind.

SLOVAKIA

Population: 5.4 million
Capital: Bratislava
Generation capacity: Nuclear (36%), fossil fuels (33%), hydro (31%),
There are no large-scale WTs operating yet in Slovakia, although a 2.4 MW project (4 x 600 kW) is being planned at Malé Kaparty, north of Bratislava, part funded under the EU's PHARE programme. A mixture of government inaction and low electricity prices hampers further progress. Under proposed legislation, however, there would be a duty on power companies to "purchase and transmit" electricity from renewable sources for "economically acceptable prices". A report to the EBRD has pointed out that increasing the renewables contribution would not only improve the environment, but would also create up to 5,000 jobs. German developer UTEC-Thomsen has plans for 35 MW of capacity, to be built during 2004-5 using a mixture of Vestas and NEG Micon turbines.

SLOVENIA

Population: 2 million
Capital: Ljubljana
Electricity production: Fossil fuels (43%), hydro (31%), nuclear (26%)
Assessing Slovenia's wind power potential is limited by a shortage of suitable meteorological data, although wind speeds are generally low (under 5m/s on average). The government provides only fiscal incentives for investment in renewables. Its favoured option is expansion of the current hydro capacity - by upgrading existing plant and building new ones.

UKRAINE

Population: 49 million
Capital: Kiev
Electricity production: Fossil fuels (48%), nuclear (45%), hydro (7%)
Although nearly all small turbines by European standards, Ukraine now has 44 MW of wind capacity. How fast this expands, however, may depend on establishing closer ties with the mainstream European industry.

The most important initiative has been the Complex Wind Farms Construction Programme, introduced by the government in 1996. This set a target for 1,990 MW of capacity to be installed by 2010. By 2030 it is projected that 20%-30% of the country's electricity production could be satisfied by wind power, saving the annual equivalent of 18 million tonnes of oil. Financial support for the programme comes through an additional payment for the output from officially accepted projects. This currently increases the tariff to between 3 and 3.5 $c/kWh. However, during 2003 it is planned to introduce a new variable tariff based on a turbine's productivity, with a lower rate for the most productive.

Guaranteed payback: For potential overseas investors, the uncertainty of return on their investment is the main stumbling block to involvement in the Ukrainian wind market. A number of companies have expressed interest over the past decade, including Enercon, Nordex and the US developer SeaWest, but the absence of a fixed tariff over a guaranteed period has eventually proved the major obstacle. The government is now working out a new appendix to the law on electricity supply which would stipulate a tariff guaranteeing a payback period of seven years. Quite apart from these fundamental economic questions, a number of technical issues must be addressed if wind power is to progress in Ukraine. Most important of these is the effective identification and selection of suitable sites, especially in a country with relatively low average wind speeds. The most promising areas are in the Crimean peninsula, along the coastline and shallow shores of the Azov and Black Seas, and in the Carpathian Mountains. Effective use of site selection programs still depends on reliable long-term data covering wind speed and direction. This is not generally available in Ukraine. Although the Inter-branch Scientific and Technical Centre has developed an original technique of numerically designing meteorological parameters where no wind data is available, which has proved its effectiveness in practice, this offers only a partial solution. Until historic wind monitoring data is available for at least a year at a given site there will be no guarantee against the sort of mistakes which have already been made at some operating wind farms.

New partnerships: Most turbines currently operating in Ukraine are USW 56-100s with a capacity of 107.5 kW. These are based on a design by the American company US Windpower, which successfully installed many thousands of similar machines in California during the 1980s and early 1990s. Altogether, over 490 of these turbines had been produced by autumn 2002 employing a cluster of Ukrainian factories, and they are still being installed.

If Ukraine is to seriously expand its wind capacity, however, it will almost certainly have to develop partnerships with established European manufacturers. This is already beginning to happen. German manufacturer Fuhrländer says it is working on a licensing agreement to produce its FL1000 1 MW turbine, but is still investigating suitable partners to produce the towers, nacelles and rotor blades, and to carry out a qualified service. Two Turbowinds 600 kW machines are also expected to be erected at existing wind farms during the first half of 2003. The Ukrainian government's main demand is that 100% of the components are manufactured inside the country, allowing former military production plants, for example, to be transformed into wind power factories. The plus side of this is that a Ukrainian produced 600 kW machine could cost as little as US$380,000, compared to more than US$650,000 if it was imported. The minus side is that some plants are just not capable of coping with more complicated production processes.

APPENDIX L: EWEA MEMBERS

Full details of the EWEA membership can be found at www.ewea.org

3E	Belgium
A2SEA A/S	Denmark
ABB Motors OY	Finland
ABB TRANSMIT OY	Finland
ACB Engineering	France
ADEME	France
AEDIE (Associacion para la investigation y Diagnosis de la Energia)	Spain
Airtricity	Ireland
ANZ Investment Bank	United Kingdom
APER	Italy
APPA	Spain
APREN Energias Renováveis	Portugal
ARMINES - Ecole des Mines de Paris	France
Australian Wind Energy Association	Australia
Austrian Wind Energy Association	Austria
Ballast Nedam Offshore Energy	The Netherlands
Baltimore Technologies	Spain
Barclays Bank	N. Ireland
Bayerische Hypo und Vereinsbank	Germany
Black Emerald	USA
Bonus Energy A/S	Denmark
British Wind Energy Association	UK
Brown Rudnick	United Kingdom
Bulgarian Wind Energy Association	Bulgaria
Bundesverband Windenergie (BWE)	Germany
Casco A/S	Denmark
Catamount Energy	USA
CDE	France
CENER, Centro Nacional de Energías Renovables	Spain
Ciemat	Spain
Circe Foundation	Spain
Clipper Windpower Inc	USA
CORUS BI-STEEL	UK
C-Power	Belgium
Czech Society for Wind Energy	Czech Republic
Danish Turbine Owners Association	Denmark
Danish Wind Industry Association	Denmark
De Brandt N.V.	Belgium
Densit A/S	Denmark
Det Norske Veritas	Denmark
Deutsche Structured Finance GmbH	Germany

DeWind GmbH	Germany
DHD France	France
DUWIND	The Netherlands
ECN Solar and Wind Energy	The Netherlands
Eco Wind Power Ltd	Ireland
Ecofys BV	The Netherlands
Ecotecnia SCCL	Spain
Electricité de France	France
EMD (Energi og Miljodata)	Denmark
Endesa Cogeneration and Renewables (ECYR)	Spain
Enercon GmbH	Germany
Energia Hidroelectrica de Navarra (EHN)	Spain
Enis Renewable Energy Systems LLC	USA
Envimac Technology and Consultants Corporation	Taiwan
Eole RES	France
EPA	Poland
ERGA	Italy
Ernst & Young	UK
Escuela Universitaria Politecnica (University L.P.G.C.)	Spain
Espace Eolien Developpement	France
Estonian Wind Power Association	Estonia
Eurowind AB	Sweden
Feria de Zaragoza	Spain
FINE - Faroe Island New Energy	Faroe Islands
Finnish Wind Power Association	Finland
FME-Groep Windenergie	The Netherlands
FOI - Aeronautics FFA	Sweden
Fördergesellschaft Windenergie e.V (FGW)	Germany
Forgital S.p.a.	Italy
France Energie Eolienne	France
Frisa Forjados SA de CV	Mexico
Gamesa Energia S.A.	Spain
Garrad Hassan and Partners Ltd	UK
GE Wind Energy GmbH	Germany
Germanischer Lloyd WindEnergie GmbH	Germany
Gothaer Allgemeine Versicherung AG	Germany
Hamburg Messe	Germany
Hammonds	UK
Hansen Transmissions Int. NV	Belgium
Hellenic Aeolian Parks	Greece
Hellenic Association of Wind Energy Investors	Greece
Hellenic Wind Energy Association	Greece
Hempel Paints	Denmark
Hrvoje Pozar Energy Institute	Croatia
Hungarian Wind Energy Association	Hungary

Hungarian Wind Energy Scientific Association	Hungary
Hydratight Sweeney Ltd	United Kingdom
IED Innovation Energie Développement	France
Indian Wind Energy Association	India
INEGI	Portugal
Institutt for energiteknikk	Norway
Irish Wind Energy Association	Ireland
IRO Offshore Wind Energy Group	The Netherlands
ISES Italia	Italy
ISET	Germany
Israeli Ministry of National Infrastructures	Israel
IVPC Srl	Italy
Japan Wind Energy Association	Japan
Japan Wind Power Association	Japan
KBC Finance Ireland	Ireland
KK Electronic A/S	Denmark
Korean Wind Energy Research Group	Korea
La Compagnie du Vent	France
La Française d'Eoliennes	France
Latvian Wind Energy Association	Latvia
LM Glasfiber A/S	Denmark
Madesta Trade Ltd	Ukraine
Mammoet Van Oord BV	The Netherlands
Messe Husum	Germany
Metso Drives OY	Finland
Moteurs Leory-Somer	France
National Technical University Athens	Greece
NEG Micon A/S	Denmark
Netherlands Wind Energy Association (NEWIN)	The Netherlands
New Zealand Wind Energy Association	New Zealand
Nigerian Wind Energy Association	Nigeria
Nippon Chemi-Con Corp.	Germany
NMH Search	UK
Nordex Energy GmbH	Germany
Norwegian University of Science and Technology (NTNU)	Norway
NRG Systems Inc	USA
Nuon Renewable Energy Projects	The Netherlands
Observ'ER	France
Orix Corporate Finance Ltd	United Kingdom
Orrick, Herrington & Sutcliffe	United Kingdom
Owens Corning Composites	Belgium
P&T Technology AG	Germany
Pauwels International NV	Belgium
PB Power	UK
Plataforma Empresarial Eolica	Spain

Polski Rejestr Statkow SA	Poland
Power@Sea NV	Belgium
Pricewaterhouse Coopers LLP	UK
Promau	Italy
QinetiQ	United Kingdom
Ramboll	Denmark
REM Chemicals, Inc.	USA
Renewable Energy Systems Ltd	UK
RISOE National Laboratory	Denmark
Romanian Wind Energy Association	Romania
Russian Association WindPower Industry (RAWI)	Russia
Saint-Gobain Advanced Ceramics	USA
Scanvib	Denmark
SER (Syndicat des Energies Renouvelables)	France
Shell WindEnergy BV	The Netherlands
SIIF ENERGIES	France
Slovak Association for Wind Energy	Slovakia
South African Wind Energy Association	South Africa
Ssesco, Inc	USA
Suisse-Eole	Switzerland
Swedish Wind Energy Technology Group - SWIND	Sweden
TBS Shipping Services Europe GmbH	Germany
Technical University of Denmark	Denmark
Tech-Wise A/S	Denmark
Tripod Consult APS	Denmark
TTZ - Bremerhaven	Germany
Turkish Wind Energy Association	Turkey
Ukranian Wind Energy Association (UANE)	Ukraine
United Utilities Green Energy Ltd	United Kingdom
Urenco Power Technologies	UK
VDMA	Germany
Vergnet	France
Verlinde SA	France
Vestas Wind Systems A/S	Denmark
Vindkraftforeningen i Finland	Finland
Vindkraftsleverantörerna i Sverige	Sweden
Vis Venti	Poland
Volker Stevin Marine Contracting	The Netherlands
WindLab Systems	Australia
Windpro	UK
WINDTEST Kaiser-Wilhelm-Kooj GmbH	Germany
WIP	Germany
Wirtshaftsverband Windkraftwerke e.V.	Germany
WKN WINDKRAFT NORD	Germany

APPENDIX M: DIRECTIVE 2001/77/EC

27.10.2001 EN Official Journal of the European Communities L 283/33

DIRECTIVE 2001/77/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL

of 27 September 2001

on the promotion of electricity produced from renewable energy sources in the internal electricity market

THE EUROPEAN PARLIAMENT AND THE COUNCIL OF THE EUROPEAN UNION,

Having regard to the Treaty establishing the European Community, and in particular Article 175(1) thereof,

Having regard to the proposal from the Commission [1],

Having regard to the opinion of the Economic and Social Committee [2],

Having regard to the opinion of the Committee of the Regions [3],

Acting in accordance with the procedure laid down in Article 251 of the Treaty [4],

Whereas:

(1) The potential for the exploitation of renewable energy sources is underused in the Community at present. The Community recognises the need to promote renewable energy sources as a priority measure given that their exploitation contributes to environmental protection and sustainable development. In addition this can also create local employment, have a positive impact on social cohesion, contribute to security of supply and make it possible to meet Kyoto targets more quickly. It is therefore necessary to ensure that this potential is better exploited within the framework of the internal electricity market.

(2) The promotion of electricity produced from renewable energy sources is a high Community priority as outlined in the White Paper on Renewable Energy Sources (hereinafter referred to as 'the White Paper') for reasons of security and diversification of energy supply, of environmental protection and of social and economic cohesion. That was endorsed by the Council in its resolution of 8 June 1998 on renewable sources of energy [5], and by the European Parliament in its resolution on the White Paper. [6]

(3) The increased use of electricity produced from renewable energy sources constitutes an important part of the package of measures needed to comply with the Kyoto Protocol to the United Nations Framework Convention on Climate Change, and of any policy package to meet further commitments.

(4) The Council in its conclusions of 11 May 1999 and the European Parliament in its resolution of 17 June 1998 on electricity from renewable energy sources [7] have invited the Commission to submit a concrete proposal for a Community framework on access for electricity produced from renewable energy sources to the internal market. Furthermore, the European Parliament in its resolution of 30 March 2000 on electricity from renewable energy sources and the internal electricity market [8] underlined that binding and ambitious renewable energy targets at the national level are essential for obtaining results and achieving the Community targets.

(5) To ensure increased market penetration of electricity produced from renewable energy sources in the medium term, all Member States should be required to set national indicative targets for the consumption of electricity produced from renewable sources.

(6) These national indicative targets should be consistent with any national commitment made as part of the climate change commitments accepted by the Community under the Kyoto Protocol.

(7) The Commission should assess to what extent Member States have made progress towards achieving their national indicative targets, and to what extent the national indicative targets are consistent with the global indicative target of 12 % of gross domestic energy consumption by 2010, considering that the White Paper's indicative target of 12 % for the Community as a whole by 2010 provides useful guidance for increased efforts at Community level as well as in Member States, bearing in mind the need to reflect differing national circumstances. If necessary for the achievement of the targets, the Commission should submit proposals to the European Parliament and the Council which may include mandatory targets.

(8) Where they use waste as an energy source, Member States must comply with current Community legislation on waste management. The application of this Directive is without prejudice to the definitions set out in Annex 2a and 2b to Council Directive 75/442/EEC of 15 July 1975 on waste [9]. Support for renewable energy sources should be consistent with other Community objectives, in particular respect for the waste treatment hierarchy.

(1) OJ C 311 E, 31.10.2000, p. 320 and OJ C 154 E, 29.5.2001, p. 89.
(2) OJ C 367, 20.12.2000, p. 5.
(3) OJ C 22, 24.1.2001, p. 27.
(4) Opinion of the European Parliament of 16 November 2000 (OJ C 223, 8.8.2001, p. 294), Council Common Position of 23 March 2001 (OJ C 142, 15.5.2001, p. 5) and Decision of the European Parliament of 4 July 2001 (not yet published in the Official Journal). Council Decision of 7 September 2001.
(5) OJ C 198, 24.6.1998, p. 1.
(6) OJ C 210, 6.7.1998, p. 215.
(7) OJ C 210, 6.7.1998, p. 143.
(8) OJ C 378, 29.12.2000, p. 89.
(9) OJ L 194, 25.7.1975, p. 39. Directive as last amended by Commission Decision 96/350/EC (OJ L 135, 6.6.1996, p. 32).

Therefore, the incineration of non-separated municipal waste should not be promoted under a future support system for renewable energy sources, if such promotion were to undermine the hierarchy.

(9) The definition of biomass used in this Directive does not prejudge the use of a different definition in national legislation, for purposes other than those set out in this Directive.

(10) This Directive does not require Member States to recognise the purchase of a guarantee of origin from other Member States or the corresponding purchase of electricity as a contribution to the fulfilment of a national quota obligation. However, to facilitate trade in electricity produced from renewable energy sources and to increase transparency for the consumer's choice between electricity produced from non-renewable and electricity produced from renewable energy sources, the guarantee of origin of such electricity is necessary. Schemes for the guarantee of origin do not by themselves imply a right to benefit from national support mechanisms established in different Member States. It is important that all forms of electricity produced from renewable energy sources are covered by such guarantees of origin.

(11) It is important to distinguish guarantees of origin clearly from exchangeable green certificates.

(12) The need for public support in favour of renewable energy sources is recognised in the Community guidelines for State aid for environmental protection ([1]), which, amongst other options, take account of the need to internalise external costs of electricity generation. However, the rules of the Treaty, and in particular Articles 87 and 88 thereof, will continue to apply to such public support.

(13) A legislative framework for the market in renewable energy sources needs to be established.

(14) Member States operate different mechanisms of support for renewable energy sources at the national level, including green certificates, investment aid, tax exemptions or reductions, tax refunds and direct price support schemes. One important means to achieve the aim of this Directive is to guarantee the proper functioning of these mechanisms, until a Community framework is put into operation, in order to maintain investor confidence.

(15) It is too early to decide on a Community-wide framework regarding support schemes, in view of the limited experience with national schemes and the current relatively low share of price supported electricity produced from renewable energy sources in the Community.

(16) It is, however necessary to adapt, after a sufficient transitional period, support schemes to the developing internal electricity market. It is therefore appropriate that the Commission monitor the situation and present a report on experience gained with the application of national schemes. If necessary, the Commission should, in the light of the conclusions of this report, make a proposal for a Community framework with regard to support schemes for electricity produced from renewable energy sources. That proposal should contribute to the achievement of the national indicative targets, be compatible with the principles of the internal electricity market and take into account the characteristics of the different sources of renewable energy, together with the different technologies and geographical differences. It should also promote the use of renewable energy sources in an effective way, and be simple and at the same time as efficient as possible, particularly in terms of cost, and include sufficient transitional periods of at least seven years, maintain investors' confidence and avoid stranded costs. This framework would enable electricity from renewable energy sources to compete with electricity produced from non-renewable energy sources and limit the cost to the consumer, while, in the medium term, reduce the need for public support.

(17) Increased market penetration of electricity produced from renewable energy sources will allow for economies of scale, thereby reducing costs.

(18) It is important to utilise the strength of the market forces and the internal market and make electricity produced from renewable energy sources competitive and attractive to European citizens.

(19) When favouring the development of a market for renewable energy sources, it is necessary to take into account the positive impact on regional and local development opportunities, export prospects, social cohesion and employment opportunities, especially as concerns small and medium-sized undertakings as well as independent power producers.

(20) The specific structure of the renewable energy sources sector should be taken into account, especially when reviewing the administrative procedures for obtaining permission to construct plants producing electricity from renewable energy sources.

(21) In certain circumstances it is not possible to ensure fully transmission and distribution of electricity produced from renewable energy sources without affecting the reliability and safety of the grid system and guarantees in this context may therefore include financial compensation.

(22) The costs of connecting new producers of electricity from renewable energy sources should be objective, transparent and non-discriminatory and due account should be taken of the benefit embedded generators bring to the grid.

([1]) OJ C 37, 3.2.2001, p. 3.

(23) Since the general objectives of the proposed action cannot be sufficiently achieved by the Member States and can therefore, by reason of the scale or effects of the action, be better achieved at Community level, the Community may adopt measures, in accordance with the principle of subsidiarity as set out in Article 5 of the Treaty. Their detailed implementation should, however, be left to the Member States, thus allowing each Member State to choose the regime which corresponds best to its particular situation. In accordance with the principle of proportionality, as set out in that Article, this Directive does not go beyond what is necessary in order to achieve those objectives,

HAVE ADOPTED THIS DIRECTIVE:

Article 1

Purpose

The purpose of this Directive is to promote an increase in the contribution of renewable energy sources to electricity production in the internal market for electricity and to create a basis for a future Community framework thereof.

Article 2

Definitions

For the purposes of this Directive, the following definitions shall apply:

(a) '*renewable energy sources*' shall mean renewable non-fossil energy sources (wind, solar, geothermal, wave, tidal, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases);

(b) '*biomass*' shall mean the biodegradable fraction of products, waste and residues from agriculture (including vegetal and animal substances), forestry and related industries, as well as the biodegradable fraction of industrial and municipal waste;

(c) '*electricity produced from renewable energy sources*' shall mean electricity produced by plants using only renewable energy sources, as well as the proportion of electricity produced from renewable energy sources in hybrid plants also using conventional energy sources and including renewable electricity used for filling storage systems, and excluding electricity produced as a result of storage systems;

(d) '*consumption of electricity*' shall mean national electricity production, including autoproduction, plus imports, minus exports (gross national electricity consumption).

In addition, the definitions in Directive 96/92/EC of the European Parliament and of the Council of 19 December 1996 concerning common rules for the internal market of electricity [1] shall apply.

[1] OJ L 27, 30.1.1997, p. 20.

Article 3

National indicative targets

1. Member States shall take appropriate steps to encourage greater consumption of electricity produced from renewable energy sources in conformity with the national indicative targets referred to in paragraph 2. These steps must be in proportion to the objective to be attained.

2. Not later than 27 October 2002 and every five years thereafter, Member States shall adopt and publish a report setting national indicative targets for future consumption of electricity produced from renewable energy sources in terms of a percentage of electricity consumption for the next 10 years. The report shall also outline the measures taken or planned, at national level, to achieve these national indicative targets. To set these targets until the year 2010, the Member States shall:

— take account of the reference values in the Annex,

— ensure that the targets are compatible with any national commitments accepted in the context of the climate change commitments accepted by the Community pursuant to the Kyoto Protocol to the United Nations Framework Convention on Climate Change.

3. Member States shall publish, for the first time not later than 27 October 2003 and thereafter every two years, a report which includes an analysis of success in meeting the national indicative targets taking account, in particular, of climatic factors likely to affect the achievement of those targets and which indicates to what extent the measures taken are consistent with the national climate change commitment.

4. On the basis of the Member States' reports referred to in paragraphs 2 and 3, the Commission shall assess to what extent:

— Member States have made progress towards achieving their national indicative targets,

— the national indicative targets are consistent with the global indicative target of 12 % of gross national energy consumption by 2010 and in particular with the 22,1 % indicative share of electricity produced from renewable energy sources in total Community electricity consumption by 2010.

The Commission shall publish its conclusions in a report, for the first time not later than 27 October 2004 and thereafter every two years. This report shall be accompanied, as appropriate, by proposals to the European Parliament and to the Council.

If the report referred to in the second subparagraph concludes that the national indicative targets are likely to be inconsistent, for reasons that are unjustified and/or do not relate to new scientific evidence, with the global indicative target, these proposals shall address national targets, including possible mandatory targets, in the appropriate form.

Article 4

Support schemes

1. Without prejudice to Articles 87 and 88 of the Treaty, the Commission shall evaluate the application of mechanisms used in Member States according to which a producer of electricity, on the basis of regulations issued by the public authorities, receives direct or indirect support, and which could have the effect of restricting trade, on the basis that these contribute to the objectives set out in Articles 6 and 174 of the Treaty.

2. The Commission shall, not later than 27 October 2005, present a well-documented report on experience gained with the application and coexistence of the different mechanisms referred to in paragraph 1. The report shall assess the success, including cost-effectiveness, of the support systems referred to in paragraph 1 in promoting the consumption of electricity produced from renewable energy sources in conformity with the national indicative targets referred to in Article 3(2). This report shall, if necessary, be accompanied by a proposal for a Community framework with regard to support schemes for electricity produced from renewable energy sources.

Any proposal for a framework should:

(a) contribute to the achievement of the national indicative targets;

(b) be compatible with the principles of the internal electricity market;

(c) take into account the characteristics of different sources of renewable energy, together with the different technologies, and geographical differences;

(d) promote the use of renewable energy sources in an effective way, and be simple and, at the same time, as efficient as possible, particularly in terms of cost;

(e) include sufficient transitional periods for national support systems of at least seven years and maintain investor confidence.

Article 5

Guarantee of origin of electricity produced from renewable energy sources

1. Member States shall, not later than 27 October 2003, ensure that the origin of electricity produced from renewable energy sources can be guaranteed as such within the meaning of this Directive according to objective, transparent and non-discriminatory criteria laid down by each Member State. They shall ensure that a guarantee of origin is issued to this effect in response to a request.

2. Member States may designate one or more competent bodies, independent of generation and distribution activities, to supervise the issue of such guarantees of origin.

3. A guarantee of origin shall:

— specify the energy source from which the electricity was produced, specifying the dates and places of production, and in the case of hydroelectric installations, indicate the capacity;

— serve to enable producers of electricity from renewable energy sources to demonstrate that the electricity they sell is produced from renewable energy sources within the meaning of this Directive.

4. Such guarantees of origin, issued according to paragraph 2, should be mutually recognised by the Member States, exclusively as proof of the elements referred to in paragraph 3. Any refusal to recognise a guarantee of origin as such proof, in particular for reasons relating to the prevention of fraud, must be based on objective, transparent and non-discriminatory criteria. In the event of refusal to recognise a guarantee of origin, the Commission may compel the refusing party to recognise it, particularly with regard to objective, transparent and non-discriminatory criteria on which such recognition is based.

5. Member States or the competent bodies shall put in place appropriate mechanisms to ensure that guarantees of origin are both accurate and reliable and they shall outline in the report referred to in Article 3(3) the measures taken to ensure the reliability of the guarantee system.

6. After having consulted the Member States, the Commission shall, in the report referred to in Article 8, consider the form and methods that Member States could follow in order to guarantee the origin of electricity produced from renewable energy sources. If necessary, the Commission shall propose to the European Parliament and the Council the adoption of common rules in this respect.

Article 6

Administrative procedures

1. Member States or the competent bodies appointed by the Member States shall evaluate the existing legislative and regulatory framework with regard to authorisation procedures or the other procedures laid down in Article 4 of Directive 96/92/EC, which are applicable to production plants for electricity produced from renewable energy sources, with a view to:

— reducing the regulatory and non-regulatory barriers to the increase in electricity production from renewable energy sources,

— streamlining and expediting procedures at the appropriate administrative level, and

— ensuring that the rules are objective, transparent and non-discriminatory, and take fully into account the particularities of the various renewable energy source technologies.

2. Member States shall publish, not later than 27 October 2003, a report on the evaluation referred to in paragraph 1, indicating, where appropriate, the actions taken. The purpose of this report is to provide, where this is appropriate in the context of national legislation, an indication of the stage reached specifically in:

— coordination between the different administrative bodies as regards deadlines, reception and treatment of applications for authorisations,

— drawing up possible guidelines for the activities referred to in paragraph 1, and the feasibility of a fast-track planning procedure for producers of electricity from renewable energy sources, and

— the designation of authorities to act as mediators in disputes between authorities responsible for issuing authorisations and applicants for authorisations.

3. The Commission shall, in the report referred to in Article 8 and on the basis of the Member States' reports referred to in paragraph 2 of this Article, assess best practices with a view to achieving the objectives referred to in paragraph 1.

Article 7

Grid system issues

1. Without prejudice to the maintenance of the reliability and safety of the grid, Member States shall take the necessary measures to ensure that transmission system operators and distribution system operators in their territory guarantee the transmission and distribution of electricity produced from renewable energy sources. They may also provide for priority access to the grid system of electricity produced from renewable energy sources. When dispatching generating installations, transmission system operators shall give priority to generating installations using renewable energy sources insofar as the operation of the national electricity system permits.

2. Member States shall put into place a legal framework or require transmission system operators and distribution system operators to set up and publish their standard rules relating to the bearing of costs of technical adaptations, such as grid connections and grid reinforcements, which are necessary in order to integrate new producers feeding electricity produced from renewable energy sources into the interconnected grid.

These rules shall be based on objective, transparent and non-discriminatory criteria taking particular account of all the costs and benefits associated with the connection of these producers to the grid. The rules may provide for different types of connection.

3. Where appropriate, Member States may require transmission system operators and distribution system operators to bear, in full or in part, the costs referred to in paragraph 2.

4. Transmission system operators and distribution system operators shall be required to provide any new producer wishing to be connected with a comprehensive and detailed estimate of the costs associated with the connection. Member States may allow producers of electricity from renewable energy sources wishing to be connected to the grid to issue a call for tender for the connection work.

5. Member States shall put into place a legal framework or require transmission system operators and distribution system operators to set up and publish their standard rules relating to the sharing of costs of system installations, such as grid connections and reinforcements, between all producers benefiting from them.

The sharing shall be enforced by a mechanism based on objective, transparent and non-discriminatory criteria taking into account the benefits which initially and subsequently connected producers as well as transmission system operators and distribution system operators derive from the connections.

6. Member States shall ensure that the charging of transmission and distribution fees does not discriminate against electricity from renewable energy sources, including in particular electricity from renewable energy sources produced in peripheral regions, such as island regions and regions of low population density.

Where appropriate, Member States shall put in place a legal framework or require transmission system operators and distribution system operators to ensure that fees charged for the transmission and distribution of electricity from plants using renewable energy sources reflect realisable cost benefits resulting from the plant's connection to the network. Such cost benefits could arise from the direct use of the low-voltage grid.

7. Member States shall, in the report referred to in Article 6(2), also consider the measures to be taken to facilitate access to the grid system of electricity produced from renewable energy sources. That report shall examine, *inter alia*, the feasibility of introducing two-way metering.

Article 8

Summary report

On the basis of the reports by Member States pursuant to Article 3(3) and Article 6(2), the Commission shall present to the European Parliament and the Council, no later than 31 December 2005 and thereafter every five years, a summary report on the implementation of this Directive.

This report shall:

— consider the progress made in reflecting the external costs of electricity produced from non-renewable energy sources and the impact of public support granted to electricity production,

— take into account the possibility for Member States to meet the national indicative targets established in Article 3(2), the global indicative target referred to in Article 3(4) and the existence of discrimination between different energy sources.

If appropriate, the Commission shall submit with the report further proposals to the European Parliament and the Council.

Article 9

Transposition

Member States shall bring into force the laws, regulations and administrative provisions necessary to comply with this Directive not later than 27 October 2003. They shall forthwith inform the Commission thereof.

When Member States adopt these measures, they shall contain a reference to this Directive or shall be accompanied by such a reference on the occasion of their official publication. The methods of making such reference shall be laid down by the Member States.

Article 10

Entry into force

This Directive shall enter into force on the day of its publication in the *Official Journal of the European Communities.*

Article 11

Addressees

This Directive is addressed to the Member States.

Done at Brussels, 27 September 2001.

For the European Parliament
The President
N. FONTAINE

For the Council
The President
C. PICQUÉ

ANNEX

Reference values for Member States' national indicative targets for the contribution of electricity produced from renewable energy sources to gross electricity consumption by 2010 (*)

This Annex gives reference values for the fixing of national indicative targets for electricity produced from renewable energy sources ('RES-E'), as referred to in Article 3(2):

	RES-E TWh 1997 (**)	RES-E % 1997 (***)	RES-E % 2010 (***)
Belgium	0,86	1,1	6,0
Denmark	3,21	8,7	29,0
Germany	24,91	4,5	12,5
Greece	3,94	8,6	20,1
Spain	37,15	19,9	29,4
France	66,00	15,0	21,0
Ireland	0,84	3,6	13,2
Italy	46,46	16,0	25,0 (1)
Luxembourg	0,14	2,1	5,7 (2)
Netherlands	3,45	3,5	9,0
Austria	39,05	70,0	78,1 (3)
Portugal	14,30	38,5	39,0 (4)
Finland	19,03	24,7	31,5 (5)
Sweden	72,03	49,1	60,0 (6)
United Kingdom	7,04	1,7	10,0
Community	338,41	13,9 %	22 % (****)

(*) In taking into account the reference values set out in this Annex, Member States make the necessary assumption that the State aid guidelines for environmental protection allow for the existence of national support schemes for the promotion of electricity produced from renewable energy sources.

(**) Data refer to the national production of RES-E in 1997.

(***) The percentage contributions of RES-E in 1997 and 2010 are based on the national production of RES-E divided by the gross national electricity consumption. In the case of internal trade of RES-E (with recognised certification or origin registered) the calculation of these percentages will influence 2010 figures by Member State but not the Community total.

(****) Rounded figure resulting from the reference values above.

(1) *Italy* states that 22 % would be a realistic figure, on the assumption that in 2010 gross national electricity consumption will be 340 TWh. When taking into account the reference values set out in this Annex, Italy has assumed that gross national electricity production from renewable energy sources will attain up to 76 TWh in 2010. This figure includes the contribution of the non-biodegradable fraction of municipal and industrial waste used in compliance with Community legislation on waste management.
In this respect, the capability to reach the indicative target as referred to in this Annex, is contingent, *inter alia*, upon the effective level of the national demand for electric energy in 2010.

(2) Taking into account the indicative reference values set out in this Annex, *Luxembourg* takes the view that the objective set for 2010 can be achieved only if:
— total electricity consumption in 2010 does not exceed that of 1997,
— wind-generated electricity can be multiplied by a factor of 15,

— biogas-generated electricity can be multiplied by a factor of 208,
— electricity produced from the only municipal waste incinerator in Luxembourg, which in 1997 accounted for half the electricity produced from renewable energy sources, can be taken into account in its entirety,
— photovoltaically generated electricity can be raised to 80 GWh, and

in so far as the above points can be achieved from the technical standpoint in the time allowed.

In the absence of natural resources, an additional increase in electricity generated by hydroelectric power stations is ruled out.

(3) *Austria* states that 78,1 % would be a realistic figure, on the assumption that in 2010 gross national electricity consumption will be 56,1 TWh. Due to the fact that the production of electricity from renewable sources is highly dependent on hydropower and therefore on the annual rainfall, the figures for 1997 and 2010 should be calculated on a long-range model based on hydrologic and climatic conditions.

(4) *Portugal*, when taking into account the reference values, set out in this Annex, states that to maintain the 1997 share of electricity produced from renewable sources as an indicative target for 2010 it was assumed that:

— it will be possible to continue the national electricity plan building new hydro capacity higher than 10 MW,
— other renewable capacity, only possible with financial state aid, will increase at an annual rate eight times higher than has occurred recently.

These assumptions imply that new capacity for producing electricity from renewable sources, excluding large hydro, will increase at a rate twice as high as the rate of increase of gross national electricity consumption.

(5) In the *Finnish* action plan for renewable energy sources, objectives are set for the volume of renewable energy sources used in 2010. These objectives have been set on the basis of extensive background studies. The action plan was approved within the Government in October 1999.

According to the Finnish action plan, the share of electricity produced from renewable energy sources by 2010 would be 31 %. This indicative target is very ambitious and its realisation would require extensive promotion measures in Finland.

(6) When taking into account the reference values set out in this Annex, *Sweden* notes that the possibility of reaching the target is highly dependent upon climatic factors heavily affecting the level of hydropower production, in particular variations in pluviometry, timing of rainfall during the year and inflow. The electricity produced from hydropower can vary substantially. During extremely dry years production may amount to 51 TWh, whereas in wet years it could amount to 78 TWh. The figure for 1997 should thus be calculated with a long-range model based on scientific facts on hydrology and climatic change.

It is a generally applied method in countries with important shares of hydropower production to use water inflow statistics covering a time span of 30 to 60 years. Thus, according to the Swedish methodology and based on conditions during the period 1950-1999, correcting for differences in total hydropower production capacity and inflow over the years, average hydropower production amounts to 64 TWh which corresponds to a figure for 1997 of 46 %, and in this context Sweden considers 52 % to be a more realistic figure for 2010.

Furthermore, the ability of Sweden to achieve the target is limited by the fact that the remaining unexploited rivers are protected by law. Moreover, the ability of Sweden to reach the target is heavily contingent upon:

— the expansion of combined heat and power (CHP) depending on population density, demand for heat and technology development, in particular for black liquor gasification, and
— authorisation for wind power plants in accordance with national laws, public acceptance, technology development and expansion of grids.

GLOSSARY

A

Active Stall Another term for pitch-to-stall WT power control (see Pitch Regulation).

Air Density The power output of a WT at a given wind speed increases with increasing air density, ie. the mass of the air per cubic metre of space at the WT location.

Anemometer An instrument for measuring wind speed. Ultrasonic, laser, hot wire and cup varieties are available: cup anemometers (consisting of a number of cups attached to an axle) are almost invariably used throughout the wind industry. Good quality anemometers are vital for accurate wind resource assessment.

Angle of Attack The angle between the oncoming wind and the blade chord.

Aspect Ratio The ratio of the characteristic chord of the blade to its length.

Auxiliary Costs Costs other than those of the turbine itself, ie. foundation, grid-connection, electrical installation, road construction, consultancy, financial charges, etc.

Availability The availability of a WT describes the amount of the time that it is actually functional, not out of order or being serviced. Clearly, the higher the availability the better.

B

Betz Limit The theoretical limiting efficiency of a WT (typically about 59%).

Blade The blades of a WT are the wing-like structures attached to the hub. A blade is very similar in look and function to an aeroplane wing - air flow past the blade generates aerodynamic lift which, in the case of a WT, causes the rotor to spin and makes power generation possible. Most modern electricity-generating WTs have three blades (the so-called "Danish concept"). However, many two-bladed examples also exist, and even one-bladed designs have been known. Rotors for water pumping and battery charging may have many more blades to allow them to function in low winds.

Blade Element-Momentum Theory (BEM) An aerodynamic theory linking the drag and lift forces experienced by each section of a WT blade to the change in momentum of air passing through the rotor disc.

Blade Passing Frequency The frequency at which the blades of a WT pass the tower. For a three-bladed WT, this will be three times the rotational frequency.

Boundary Layer The layer of the atmosphere in which interaction with the Earth's surface influences air flow patterns. The thickness of the boundary layer varies between about 100 m on clear nights with low wind speeds to 2 km on fine summer's days.

C

Carbon Dioxide (CO_2) CO_2 is "a naturally occurring gas, and also a by-product of burning fossil fuels and biomass, as well as land-use changes and other industrial processes. It is the principal anthropogenic greenhouse gas that affects the Earth's radiative balance" (IPCC, 2001; p.70).

Capacity Credit A WT can only produce when the wind blows and, therefore, it is not directly comparable to a conventional power plant. The capacity credit is the percentage of conventional capacity that a given turbine can replace. A typical value of the capacity credit is 25% (see Capacity Factor), ie. 100 MW of wind power is assumed to replace 25 MW of conventional fossil fuelled capacity.

Capacity Factor The amount of energy a WT actually produces in a year, divided by the amount of energy if could theoretically produce if it were to run at its rated power 24 hours a day, 365 days a year. The capacity factor is expressed as a percentage; for a typical WT installation it is around 25%-30% (although it can get up to 50%).

Capital Costs The total investment cost of the turbine, including auxiliary costs.

CENELEC The European Committee for Electrotechnical Standardisation, a non-profit technical organisation composed of the National Electrotechnical Committees of 23 European countries. CENELEC's mission is to prepare voluntary electrotechnical standards to help develop the Single European Market/European Economic Area for electrical and electronic goods and services, so removing barriers to trade, creating new markets and cutting compliance costs.

Certification Authority An organisation which checks the designs of WT manufacturers and issues an independent assessment, often called a certificate. The most prominent are Det Norsk Veritas and Germanischer Lloyd.

Climate Change Defined as "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability

observed over comparable time periods" (IPCC, 2001; p. 71).

Control Strategy Modern WTs feature computer control (the controller) whereby the computer will execute a given control strategy, telling the WT how to behave under different conditions. Examples of components of a control strategy would be the cut-in and cut-out wind speeds, when the WT should cut out in low, falling wind speeds and when it should cut back in at high, falling wind speeds when it has already cut out (see Hysteresis). Depending on the type of WT (fixed/variable speed, pitch/stall-regulated), there will be other more complicated logic in the control strategy.

Controller The computer equipment that monitors the turbine and controls its operation.

Coriolis Force A virtual force experienced by a body relative to a rotating body as it moves outward from the centre of rotation. For example, the Coriolis force causes air flowing southwards in the northern hemisphere to veer westwards relative to the rotating globe below; hence it has a huge influence on the behaviour of the atmosphere. It is a consequence of the principle of conservation of angular momentum (but should be distinguished from gyroscopic effects).

Coriolis Parameter A parameter describing the strength of the Coriolis force at any point on the globe, featuring in the log law.

Costs of Generated Wind Power See Levillised Costs.

Cut-In and Cut-Out Wind Speeds A WT is usually programmed only to start operating above a particular wind speed (the cut-in wind speed) and to stop operating when the wind speed exceeds another particular wind speed (the cut-out- wind speed). There is very little energy available below the cut-in wind speed, making operation of the WT unviable or impossible. Above the cut-out wind speed (typically 25 m/s) the loads on the WT could cause damage if it did not shut down. Though such high-speed winds are clearly very energetic, they are experienced so rarely at most locations that very little energy is wasted by cutting out at these speeds.

D

Data Logger The electronic equipment used to record the output of anemometers, wind vanes and other instruments (eg. air temperature and pressure gauges) at a monitoring station. Some data loggers store data on site, others are able to relay it to distant computer systems.

Dinotail An "add-on" device sometimes attached to a stall-regulated turbine blade which enhances the lift on a section. It extends backwards from the trailing edge and looks rather like a dinosaur tail.

Direct-Drive A new generation of WTs has recently emerged where the rotor is connected directly on a single shaft to a special high-torque, low speed generator without the use of a gear box. Such WTs are generally variable speed and feature power electronic converters to convert the frequency of the generated power to the grid frequency. Direct-drive WTs offer higher efficiency and lower noise levels due to the absence of a gear box, but the complex generator and power electronics may make them more expensive.

Direct Employment Direct employment is the total number of people (skilled, unskilled and self-employed) employed in companies belonging to a specific sector, ie. WT manufacturing.

Discount Rate The interest rate used to calculate the present-day cost of turbine installations.

Diurnal A term describing a daily frequency, ie. a period of 24 hours. Some weather effects occur on a diurnal basis, associated with the daily heating and cooling of the Earth's surface.

Doubly Fed Induction Generator (DFIG) The DFIG provides the operational advantages of an induction and a synchronous machine. It offers variable speed operation and the advantage of reactive power control. This is achieved by injecting appropriate currents into the rotor circuit of a wound rotor induction generator. Control of the frequency of the injected currents provides variable speed control of the machine, whereas manipulation of the magnitude and phase of the rotor currents provide power factor control.

Dynamic Stall As WT blades rotate, they experience constantly changing angles of attack due to wind shear and yaw. Under these conditions, a phenomenon known as dynamic stall (as opposed to static stall) occurs. The angle of attack will increase beyond the point at which the blade would normally have stalled in a quasi-static situation in a wind tunnel, but the delayed stall is very sudden and hard when it occurs at some large angle of attack, causing large loads in the blades and significant fatigue.

E

Edgewise Used to define the direction in an axis set in the rotating blade. Edgewise motion is motion in the plane of rotation and is perpendicular to flatwise motion.

Efficiency In general of any component, this describes the amount of energy coming out of the component as a percentage of the energy put into it. For a WT, it describes the amount of active electrical power generated as a percentage of the wind power incident on the rotor area (see also Betz Limit).

Emissions Defined by the UN (2002) as "the discharge of pollutants into the atmosphere from stationary sources such as smokestacks, other vents, surface areas of commercial or industrial facilities and mobile sources, for example, motor vehicles, locomotives and aircraft". With respect to climate change, emissions refer to "the release of greenhouse gases into the atmosphere over a specified area and period of time" (IPCC, 2001; p. 72).

Energy Pay-Back Period The amount of time it takes for a WT to generate as much energy is required to make the WT in the first place, install it, maintain it throughout its lifetime and, finally, scrap it(typically two to three months at a site with reasonable wind exposure).

Experience Curve The curve relates the cumulative quantitative development of a product with the development of the specific costs. Thus, the more that is produced of a product, the more efficient the production process and the cheaper it becomes.

External Costs Those costs incurred in activities which may "cause damage to a wide range of receptors, including human health, natural ecosystems and the built environment" (European Community, 1994), and yet are not reflected in the price paid by consumers.

F

Fatigue The phenomenon by which a repeated loading and unloading of a structure causes its various components to gradually weaken and eventually fail. Owing to the highly repetitive nature of WT operation, fatigue is a serious issue.

Feather Blade feathering is possible on WTs with adjustable pitch. The blades are rotated so the chord is pointing upwind which, when the blade is in motion, gives a negative angle of attack which will rapidly slow the rotor to a standstill. This effect can be used to assist WT cut-out in very high winds and as an emergency brake. In very high winds, if the WT can be parked with the blades feathered, this will reduce the loads on the whole WT.

Fixed Speed A fixed speed WT will, once started, always rotate at the same speed, regardless of the wind speed. As power must be injected at a constant frequency onto the grid, operating at a fixed speed simplifies the generator and power electronic requirements for the WT considerably, making it cheaper. However, as the WT will only be able to operate at maximum efficiency at one particular wind speed, fixed speed WTs are around 10% less efficient than variable ones. A compromise is to use a WT that can operate at two different fixed speeds.

Flatwise Used to define the direction in an axis set in the rotating blade. Flatwise motion is motion perpendicular to both the plane of rotation and to edgewise motion.

Forced Yaw See Motor Yaw.

Free Stream Used to describe wind conditions at a location in the absence of the WT.

Free Yaw Rotating WT rotors will tend to align themselves to face the oncoming wind (even upwind rotors will do this). A WT which allows this natural tendency to align the rotor is known as a free yaw WT. This mode of operation is not popular in large WTs due to the possibility of damage from gyroscopic forces. Also, rotors will not recover from positions of large yaw misalignment, for example after periods of calm or sudden large changes in wind direction.

Friction Velocity A parameter featuring in the log law.

Fuel Cycle The impacts of power production are not exclusively generated during the operation of the power plant, but also in the entire chain of activities needed for the electricity production and distribution, such as fuel extraction, processing and transformation, construction and installation of the equipment as well as the disposal of waste. These stages, which constitute the chain of electricity production and distribution, are known as the fuel cycle.

Full Load Hours The turbine's average annual production divided by its rated power. The higher the number of full load hours, the higher the turbine's production at the chosen site.

G

Gearbox The gearbox in a WT is used to convert the low speed, high torque rotation of the rotor to a high speed, low torque rotation suitable for driving the generator to produce alternating current at the correct grid frequency. Not all modern WTs have gearboxes (see Direct Drive).

Generator (Synchronous, Induction) The generator is the piece of electrical machinery that actually converts the rotating motion of the rotor into alternating current electrical power. Most fixed (or partially variable) speed WTs have induction generators, whereas variable speed WTs have synchronous generators. The principle components of a generator are the rotor and the stator.

Geostrophic Wind Winds higher in the atmosphere driven purely by temperature and pressure differences within the atmosphere, and unaffected by the surface of the Earth.

Glass-Reinforced Plastic (GRP) The material from which most WT blades are made. GRP consists of a web of glass fibres set into solid plastic (polyester is often used).

Greenhouse Gas "Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the earth's surface, the atmosphere, and clouds. Entirely human made greenhouse gases in the atmosphere such as halocarbons and other chlorine- and bromine-containing substances are dealt under the Montreal Protocol. Beside carbon dioxide, nitrous oxide and methane, the Kyoto protocol deals with the greenhouse gases sulphur hexafluoride, hydrofluorocarbons, and perfluorocarbons" (IPCC, 2001; p. 74).

Grid-Connected A WT is said to be grid-connected when its output is channelled directly into a national electric grid or the like (see also Stand-Alone).

Grid Reinforcement A weak grid can be reinforced by uprating its connection to the rest of the grid. The cost of doing this may fall to the wind farm developer.

Gurney Flaps Aerodynamic devices which are used to enhance lift on a stall-regulated blade.

Gyroscopic Effects A rotating WT rotor will experience gyroscopic forces if direction of the axis of rotation is shifted (stemming from the principle of conservation of angular momentum). If the rotor is allowed to yaw in an uncontrolled manner, these forces can cause large loads in the WT, potentially causing failures.

H

Harmonic Ideally, the alternating electrical signal output by any device onto the electrical grid should be perfectly sinusoidal in form. A regular, non-sinusoidal signal can be made up of sinusoidal components at integer multiples of the so-called base frequency. These higher frequency components are known as harmonics, and whilst they make music sound nice, they cause problems in electrical networks (see Power Quality). The sinusoidal output from a power electronic converter (PEC) is digitally synthesised and hence is not a perfect sinusoid. Older PECs would inject significant harmonics on to the electrical grid; more modern ones do not.

High-Speed Shaft In WTs featuring gearboxes, the high-speed shaft is the shaft connecting the gearbox to the generator. This shaft also features lower torques.

High Voltage Direct Current (HVDC) It is proposed that in linking offshore wind farms to land by buried cable, HVDC links will be used instead of alternating current power transmission.

Hill Effect Wind speeds up as it passes over the top of hills, making hilltops good sites for WTs. Note, however, that in extreme cases negative wind shear may occur (ie. the wind closer to the ground on the hilltop is faster than that higher up) and complex hilly terrain may cause additional turbulence and flow separation.

Horizontal Axis Wind Turbine (HAWT) A generic description of the propeller-type WTs seen throughout the world (see also Vertical Axis Wind Turbine).

Hub The hub of a WT is the rotating component to which the blades are fixed.

Hub Height The height of the rotor axis above the ground.

Hysteresis In general, this term describes a process that does not proceed in the same way when run in different directions; a simple example would be that you do not get the same amount of energy out of an elastic band when you allow it to relax as when you stretch it (some energy goes to heat the elastic band). Hysteresis is often used in wind energy to describe the way in which, whilst a WT may cut out when the wind speed reaches 25m/s, it will not cut back in again until the wind speed drops below (for example) 23m/s. There is also a hysteresis loop involved in blade behaviour in dynamic situations (see Dynamic Stall).

I

Impact Pathway Approach The impact pathway approach developed by ExternE establishes the effects and spatial distribution of the burdens from the fuel cycle to find out their final impact on health and the environment. Subsequently, the economic valuation assigns the respective costs of the damages induced by a given activity.

Indirect Employment Refers to those employed in sectors and activities supplying intermediate products/components to, for example, WT manufacturers. Indirect employment includes employment throughout the production chain.

Induced Velocity The change in the velocity of the wind caused by the presence of a WT blade.

Input-Output The national accounts of a country's or region's economic transactions keep track of all the inputs and outputs between economic sectors.

Insulated Gate Bipolar Transistor (IGBT) The IGBT has the output switching and conduction characteristics of a bipolar transistor but is voltage-controlled like a MOSFET. IGBTs are used in power switching applications where high current handling and ease of control are desired.

Intermedial Load Intermedial load refers to those electricity generation technologies contributing to satisfy the demand in a range between base load and peak load of the electricity system. A generating unit that normally operates at a constant output (amount of electricity delivered) for several hours, eg. during a year, take all or part of the base load of a system. In contrast, a peak load unit is only used to reach specific peak periods of a few hours when the demand is high.

International Standards Organisation (ISO) ISO is a federation of national standards bodies from around 150 different countries. Established in 1947, it is non-governmental organisation with a mission broadly to promote the development of standardisation with the objective of facilitating international trade. ISO standards are prefixed with ISO (eg. ISO 9000).

Inverter A power electronic device used to convert direct current to alternating current. An inverter will often form part of the power electronics used with variable speed WTs, along with a rectifier.

Investment Cost of Turbine The cost of the turbine itself, including transport from the factory to the place where the turbine is erected.

Islanding The phenomenon by which a piece of the electrical network which has become disconnected from the rest of the network (for instance due to a lightning strike on an overhead pylon) continues to function, as the power sources on that section of the grid (for example a wind farm) continue to supply the loads. Islanding is a serious problem that can result in danger to personnel and damage to equipment; a number of safeguards are used to try to prevent it.

L

Laminar Laminar air flow is where layers of air moving at different speeds slide smoothly across one another without mixing, for example around the leading edge of an unstalled WT blade.

Leading Edge The blunter edge of a WT blade; this edge is the one that moves forwards through the oncoming wind.

Learning Rate A learning curve parameter. The learning rate is estimated on available data for WTs; it tells you the achieved reduction in specific product costs. Thus, if the learning rate is 15%, then costs are assumed to be reduced by this percentage when total installations of WTs are doubled.

Levellised Costs The present-day average cost per kWh produced by the turbine over its entire lifetime, including all costs (investments, reinvestments and operation and maintenance costs). The levellised costs are calculated using the discount rate and the turbine lifetime.

Lift Defined as the force experienced by a body in an airflow perpendicular to the direction of the airflow.

Log Law The log law is a parameterised mathematical equation used to describe the increase in wind speed with height above ground in the surface layer (see also Wind Shear). The equation includes the surface roughness of the ground and the Coriolis parameter.

Logger See DataLlogger.

Low Speed Shaft This connects the rotor to the gearbox in WTs featuring gearboxes. It is a high-torque shaft.

M

Measure, Correlate and Predict (MCP) To produce a confident prediction of how much energy a proposed wind

farm will produce, many years of wind data from the site would be necessary. As there is usually only a year or maybe two of data from the site available, the MCP process is adopted instead. The data measured at the site itself is correlated with data for the same period of time from a nearby meteorological station, and this correlation is then applied to the remainder of the data from the station to produce a synthetic long-term set of wind data for the wind farm site. This long-term data is then taken to be indicative of the likely future wind climate at the site and used to predict the future energy output of the wind farm.

Meteorological Mast The tall, thin, guyed pole upon which instruments such as anemometers and wind vanes are mounted when conducting wind resource measurements.

Meteorological Station A long-term installation for measurement of various properties of the atmosphere, wind speed, direction, air temperature and pressure, precipitation, insolation. etc. It is often possible to buy many decades worth of hourly data from these installations, and this can be used in combination with considerably shorter periods of more detailed 10-minute measurements made at the proposed site of a new wind farm to produce good estimates of how much energy a new wind farm could produce in the long term. This is done by the measure, correlate predict process.

Monopile A means of securing offshore WTs by boring a deep hole in the seabed and hammering a large pile into the hole, to which the WT is attached.

Motor Yaw The opposite of free yaw. In a motor yaw, WT electrical motors are used to precisely control the orientation of the nacelle and rotor and to prevent free yawing motion. The WT control system will decide in which direction to point the nacelle based on wind direction data averaged over a few minutes. Also known as forced yaw.

Multiplier/Multiplicator An employment multiplicator, for example, measures the direct and indirect employment effect of producing €1 million worth of output from the WT manufacturing sector. Basically, this assumes that it is valid to multiply total WT manufacturing in euros with a factor giving the necessary employment to produce this output. Series of multipliers for historic national account statistics exist.

N

Nacelle The nacelle of a WT is the enclosed volume mounted on top of the tower, containing the gearbox, generator and yaw drive, among other things.

Nitrogen Oxide (NO_X) According to the United Nations (2002), NO_X is a "product of combustion from transportation and stationary sources. It is a major contributor to acid depositions and the formation of ground-level ozone in the troposphere. It is formed by combustion under high pressure and high temperature in an internal combustion engine. It changes into nitrogen dioxide in the ambient air and contributes to photochemical smog".

O

Offshore Wind speeds are typically higher and turbulence lower offshore. Combined with reduced visual impact to sensitive landscapes this has meant that interest in building offshore wind farms has increased in recent years.

Operation and Maintenance Costs (O&M) The cost of repairs to, and servicing of, WTs throughout their lives.

Overspeed Protection Devices fitted to the WT to prevent the rotor from accelerating to dangerous speeds should a failure (generator, gearbox) occur in the WT. Such devices include tip brakes and shaft brakes.

P

Park Effect The effect whereby WTs positioned together in large wind parks each produce less energy than they would if in the same position on their own, due to the wind shadows of the other WTs in the park.

Pitch To control the power output and to assist in starting and stopping, the blades of some WTs can be rotated about their longitudinal axes by hydraulic activators. This motion of the blade is known as pitching. The angle that the blade chord makes with the rotor disc is the pitch.

Pitch Regulation Once the rated wind speed has been reached, a WT will be unable to make use of all of the wind energy incident on the rotor plane and must shed some. A pitch-regulated WT will do this either by pitching the blades to reduce the angle of attack and thus the torque and power captured (in pitch-to-feather machines) or by pitching the blades to increase the angle of attack

to cause sections of the blade to stall (in pitch-to-stall-machines).

Pole Switching A means by which a generator can be made to operate at two different rotational frequencies.

Pollutant Defined as a "substance that is present in concentrations that may harm organisms (humans, plants and animals) or exceed an environmental quality standard. The term is frequently used synonymously with contaminant" (United Nations, 2002).

Power Curve A plot of power output vs. wind speed, characteristic of a particular WT model and configuration.

Power Electronic Converter (PEC) A PEC is necessary on fully variable-speed machines in order to convert the frequency of the generated power from whatever it is being generated at to the grid frequency. This is achieved by first rectifying then inverting the signal to the required frequency. Older PECs generate problematic levels of harmonics, newer ones less so.

Power Law An approximation used as an alternative to the log law for approximating the wind speed at a particular height in the surface layer.

Power Quality Utilities are committed to supplying electricity within narrow bands of frequencies and voltages and with defined low levels of harmonics to consumers: this is described as the power quality. They are thus concerned that any generating device attached to their networks should inject power of sufficiently high quality. Variable speed and stall-regulated machines will smooth over the effects of wind gusts, but the presence of power electronic converters may increase the injection of harmonics onto the network.

Prevailing Wind Direction The direction from which the wind comes for the largest proportion of the time.

Pressure Face The side of a WT blade upon which the air flow around the blade causes a pressure rise.

Principal Component Analysis A particular way of fitting a curve through a set of data points which minimises the fitting error.

Productivity Productivity is used here as employees per output unit in fixed prices. The 2% increase in productivity used as a basic assumption implies that 2% less people are needed to produce the same output every year. If additional cost reductions of turbines are assumed, this must partly be attributed to additional productivity increases further reducing the need for employees.

Profile (Blade) The blade profile describes the shape you would see if you were to take a slice through the blade. It has a profound effect on the behaviour of the blade. There are a large number of standard profiles in use, described by names such as "NACA4412" which indicate the shape family and proportions of the blade.

Progress Ratio This ratio is related to the learning rate so that if the learning rate is 15%, then the progress ratio is 85% (progress ratio is 100% minus learning rate).

R

Rated Capacity Refers to the nameplate capacity that shows how much the turbine can produce when running at full load.

Rated Power The maximum power output possible from the WT. This is dictated by the generator size and loads that the WT can bear. Choice of rated power for a site is a balance dictated by the amount of energy available in the wind at different wind speeds and the cost of increasingly large and powerful WTs.

Rated Wind Speed The minimum wind speed at which a WT will generate its rated power.

Reactive Power If the voltage and current signals in an electrical network are not in phase, the out-of-phase component gives rise to reactive power flow. Reactive power cannot be used, but still causes losses in an electrical network, hence its flows should be minimised. Induction generators consume reactive power, and the network operator may wish to be compensated for the losses this causes. Synchronous generators can be made to consume or produce reactive power as desired, which may be of use to the network operator.

Rectifier A power electronic device used to convert alternating current into direct current. A rectifier will often form part of the power electronics used with variable speed WTs, along with an inverter.

Re-Energisation When a body of air has decelerated and is moving slowly (for example in a WT wake or towards the trailing edge of a blade), turbulent mixing with neighbouring fast-moving airflows can re-energise the body of air, reaccelerating it.

Reference Site A chosen location with known wind conditions. The reference site is used to compare efficiency and power production of different turbines.

Reinvestments When a larger and more costly part of the turbine has to be replaced, eg. a gearbox or a blade.

Root The root of the blade is the section nearest the hub. Rotor The rotor is the combination of the hub and blades. This term is also used to describe the rotating part of an electrical generator. The design of a generator rotor depends on the type of generator in question.

Rotor Area See Swept Area.

Rotor Disc The rotor disc is the imaginary circular surface swept out by the rotor blades as they rotate.

Roughness Class A classification system for the roughness of different surfaces. Examples include: landscape with many trees and buildings (class 3-4); sea surface (class 0); concrete runway (class 0.5). Tables of roughness classes for different surfaces are available.

Roughness Length The distance above ground level at which the wind speed should theoretically be zero, due to the roughness of the surface at that point.

S

Scale Parameter A parameter describing the height of a Weibull distribution.

Sea Breeze In the first half of the day as the land heats up, wind will tend to blow off the sea onto the land as heated air above the land rises (a weaker land breeze also occurs in the evening).

Separation An airflow is said to become separated from the object around which it is moving when the flow ceases to follow the contours of the body but instead features turbulent mixing and flow reversal close to the surface.

Shadow Flicker If a WT comes between an observer and the sun, the observer will experience a flickering as the light passes between the rotating blades of the WT; this can be very distracting. Wind farms should be planned to avoid causing shadow flicker at nearby residences, and wind farm design software can assist in doing this.

Shaft Brake A braking mechanism to stop the rotation of the WT by arresting the motion of one of the shafts in the WT. As the high speed shaft has much lower torque, a lighter and cheaper brake can be used if it is positioned on this shaft. However, should the gearbox fail, the high-speed shaft brake will be unable to stop the WT rotor.

Shape Parameter A parameter describing the variation of a Weibull distribution about the mean.

Shear Air in contact with the ground is not moving: air at high altitudes is moving at high speeds. The gradual increase of wind speed with increasing altitude is knows as wind shear, and is particularly relevant over the area of a typical WT blade.

Slip In induction generators, the slip is the difference in angular velocity between the rotor and the rotating magnetic field, expressed as a fraction of the angular velocity of the rotating magnetic field.

Soft-Start If an induction generator is started by connecting it directly to the grid, it will initially draw a large current as the generator is magnetised; this large current could cause voltage drops in the local network. To avoid this, a soft-start unit regulates the amount of current drawn by the generator, allowing it to magnetise more slowly and preventing voltage dips on the network.

Soft Tower A soft tower has a natural frequency lower than the blade passing frequency but greater than the rotational frequency of the WT.

Soft-Soft Tower A soft-soft tower has a natural frequency lower than the rotational frequency of the rotor.

Solidity The frontal area of the blades on a WT divided by the total swept area, expressed as a percentage.

Squirrel Cage A description of the rotor of an induction generator.

Stability The stability of the boundary layer above the Earth's surface can be described as stable, neutral and unstable. Stable conditions, when the surface of the Earth is cooling, are characterised by little vertical mixing of the air.. Unstable conditions occur when the Earth's surface is heated and more vertical mixing occurs. Neutral conditions lie somewhere in between. We are largely concerned with conditions of neutral stability in wind energy.

Stall Above a particular angle of attack, the air flow around the suction face of a blade will become separated. Once this happens, the drag on the blade will increase dramatically and the lift will fall. The stalled section of blade ceases to function as an efficient aerofoil.

Stall Delay It is observed that sections of rotating WT blade close to the hub stall at higher angles of attack than would normally be expected. The reason for this is uncertain.

Stall Regulation The blades on a stall-regulated- WT cannot be pitched. To achieve control of power captured above rated wind speed, the blades are carefully designed

so that they progressively stall starting at the blade root and moving out towards the tip as the wind speed increases further. Stall-regulated WTs will respond much more quickly to gusts than pitch-regulated WTs (where mechanic pitch adjustments take finite amounts of time to effect), improving the power quality output by the WT above rated wind speed.

Stall Strip A stall strip is a device attached near the maximum thickness of the chord of a stall-regulated blade which is intended to promote stall.

Stand-Alone This refers to a WT operating without being attached to the electricity grid, for example in charging batteries or running in parallel with a diesel generator.

Stator The non-rotating part of an electrical generator, consisting of many windings of electrical cable.

Stiff Tower A stiff tower has a first natural frequency higher than the blade passing frequency.

Stream Tube An imaginary tube extending upstream and downstream of the WT, containing all the air that interacts with the rotor. The diameter of the stream tube is initially constant far upstream of the rotor, expands as air approaches the rotor disc and slows, then continues to expand for a short distance after the rotor disc as the air flow slows.

Suction Face The side of a WT blade upon which the air flow around the blade causes a pressure drop.

Sulphur Dioxide (SO_2) According to the United Nations (2002), SO_2 is a "heavy, pungent, colourless gas formed primarily by the combustion of fossil fuels. It is harmful to human beings and vegetation, and contributes to the acidity in precipitation".

Surface Layer The first 100 m or so of the atmosphere, in which most wind energy activity takes place.

Surface Roughness See Roughness Class.

Surface Winds The winds occurring near the surface of the Earth (in the first kilometre or so), heavily influenced by the properties of the Earth's surface and obstacles in the region (see also Geostrophic Winds).

Swept Area The area swept out by the blades as the rotor rotates - the area of the rotor disc - is also known as the rotor area. Often used as a proxy for a turbine's power production.

Switched Reluctance Generator (SRG) A SRG differs from conventional machines in that it does not have any windings or permanent magnets on the rotor. The stator typically consists of slots containing a series of coil windings, the energisation of which is electronically switched to generate a moving field. The reluctivity of the rotor results in a torque which tends to move the rotor in line with the energising coils, minimising the flux path. For an SRG, mechanical energy is converted to electrical energy by the proper synchronisation of stator phase currents with rotor position. By appropriate control of stator switching it is possible to achieve variable speed operation for the generator.

Synchronisation When using synchronous generators, it is vital that the alternating current produced is in phase with the alternating current on the network to which it is connected; the process of achieving this (part of the WT start-up programme) is known as synchronisation.

Synoptic Describes variation in the typical frequency of arrival of different weather systems, generally with a period of around four days.

T

Teeter The blades on two-bladed wind WTs are usually, in fact, one single piece stretching the whole diameter of the rotor disc. To reduce stresses on the WT as a whole when the blades pass the tower, this single piece is allowed to pivot at the centre; this is known as a teetered rotor.

Tilt The tilt angle is the angle between the horizontal and the rotor axis.

Tip The tip of the blade is the end furthest from the hub.

Tip Brake These are fitted to some WTs to avoid runaway situations when other braking mechanisms have failed. The tips of the blades are separate from the rest of the blade, and mounted on spring-loaded, threaded rods. As the rotor accelerates, centrifugal forces cause the tips to pull away from the body of the blade, and the thread on the rods causes the tip's sections to rotate, spoiling the aerodynamics of the blade and regulating the speed of the rotor, preventing overspeed.

Tip Loss Tip loss describes the loss in performance of a blade due to the fact that it is finite in extent and hence some air flow goes round the tip rather than over the chord. It is borrowed from the propeller industry.

Tip Noise The noise made by the WT blades tips moving through the air. This increases with increasing speed, so WTs near centres of population are often run more slowly

than say offshore WTs, especially at night when there is less background noise and people are sleeping. In general, tip noise is only audible at low wind speeds when there is little other wind noise around.

Tip Speed Ratio (λ) The ratio of the speed at which the blade tips are moving to the speed of the oncoming wind. A WT will typically reach peak efficiency at a particular value of λ, regardless of wind speed (see variable speed) and this is often denoted λ_{max}.

Torque The "turning force" applied to an object. Measured in Newton metres, this is calculated as the distance from the axis of rotation at which a force is applied to a rotating object, multiplied by the magnitude of that force.

Tower (Lattice, Tubular, Guyed Pole) The tower is the column supporting the nacelle and rotor above the ground. Towers are typically lattice (like an electricity pylon, consisting of a network of thin struts) or tubular (a single tubular column). For small WTs, the tower can also be a guyed pole.

Tower Shadow As wind flows around a WT tower, regions of lower wind velocity are created just upstream and downstream of the tower, particular in the case of tubular towers. As the blades pass through the tower shadow, they experience a periodic dip in loading which causes fatigue damage to blades and can excite harmonics (resonance) in the blade.

Tower Strike Occurs when extreme atmospheric conditions cause a blade to strike the tower as it passes

Trailing Edge The sharper edge of a WT blade, to the rear of the blade as it rotates.

Transformer A piece of electrical equipment used to step up or down the voltage of an electrical signal. Most WTs will have a dedicated transformer to step up their voltage output to grid voltage.

Troposphere The first 11km of the atmosphere, in which weather occurs.

Turbine Lifetime The expected total lifetime of the turbine, normally 20 years.

Turbulence The stochastic (random) motion of air characteristic of all natural winds. Though wind can be said to have an underlying steady direction and speed, on a small scale different parcels of air will move in random directions at random speeds. There is energy in turbulence that can be captured, but it also causes damage to WTs after long periods of exposure due to the constantly varying random loads a WT experiences.

Turbulence Intensity A measure of the strength of the turbulence of the wind compared to its underlying average speed. Defined as the standard deviation of the wind speed variations about the mean wind speed divided by the mean wind speed, using 10 minute or 1 hour averaging periods.

Twist The tips of a WT blade move through the air faster than the roots in the direction of rotation, but the oncoming wind speed is similar at all points along the blade. Hence, to achieve the optimal angle of attack along its length, a WT blade is twisted so that the pitch of the blade reduces from the root to the tip.

U

Upwind A WT which operates with the rotor upwind of the tower is said to be an upwind WT. Most modern WTs are upwind.

V

Value of Statistical Life (VSL) VSL is an approach that measures a society's willingness to pay to avoid additional cases of death. This can be seen in spending for improved safety in the aircraft or car industry. In the EU and the US, values of between one and 10 million US$ or € per life saved have been found in different studies. Earlier versions of the ExternE project adopted a figure of US$3 million per life saved for VSL calculations. In these calculations the age of a person saved does not matter.

Variable Speed The rotor on a variable speed WT will rotate at a speed calculated to make it as efficient as possible at the prevailing wind speed (i.e. at λ_{max} – see Tip Speed Ratio). Variable speed WTs will produce less tip noise at low wind speeds as they will be rotating more slowly, and can be up to 10% more efficient than fixed speed WTs. However, they are more complex than fixed speed WTs and require power electronic converters (PECs) to convert their output to grid frequency. A variety of partially-variable speed WTs are available, bringing most of the efficiency gains with only some added complexity and no PEC.

Velocity Deficit The amount by which the wind speed is reduced in the wake of a WT, as compared to the free stream.

Vertical Axis Wind Turbine (VAWT) An alternative design of wind turbine where the rotor rotates about a vertical axis, rather than a horizontal one. It proved difficult to scale these designs up effectively, so modern VAWTs are of limited size; also, VAWTs are less efficient than HAWTs. As the concept of yaw is irrelevant to VAWTs; they can however be rather simpler than HAWTs.

Vortex Generator Vortex generators are small mechanical devices which are attached to the suction surface of the stall-regulated blade which generate local vortices. These vortices re-energise the boundary layer and hence prevent stall. When viewed from above they are often V-shaped with the sharp end of the V pointing towards the leading edge.

W

Wake As wind passes through the rotor disc, it is slowed as energy is extracted from it, and vorticity is introduced into the air by the blades. This stream of slowed air can extend up to 10 rotor diameters behind the WT and is known as the wake. WTs placed in the wake of others will experience lower wind speeds and increased turbulence, reducing power output and increasing wear and tear.

Weak Grid An area of the electrical grid where the voltage and power quality is likely to be significantly influenced by the presence of large loads or power supplies, such as a wind farm. It may be necessary to perform grid reinforcement if a wind farm is to be connected to the grid where it is currently weak.

Weibull Distribution A probability distribution specific to a given location describing the probabilities that the wind will blow with particular strengths.

Wind Atlas An atlas mapping the wind resource across an area, for example The European Wind Atlas.

Wind Resource A reference to the quantity of energy potentially available from the wind in a particular place (as in “The wind resource of the British Isles could supply all our electricity several times over”).

Wind Rose A circular diagram giving a visual summary of the relative amounts of wind available in each of a number of direction sectors (often 12) at a given location, and the speed content of that wind.

Wind Vane An instrument for measuring the direction in which the wind is blowing, usually consisting of a vane mounted on the end of a rod, free to rotate in the horizontal plane about a pivot.

Y

Yaw Angle As the direction of the wind is constantly changing, it is normally the case that the wind does not strike the rotor disc at right angles. The angle between the rotor disc and the incident wind is known as the yaw angle (often denoted by Greek letter γ).

Yaw Control Another means of WT power control (alongside pitch- and stall-regulation), primarily used in very small WTs. The WT is deliberately misaligned from the prevailing wind direction, reducing the area of the rotor disc seen by the oncoming wind and thus the power output of the WT.

Yaw Drive This controls the direction in which the nacelle (and hence rotor) of the WT is pointing. Electrical motors are used to ensure that the WT is facing the prevailing wind direction at all times.

Yaw Error The amount by which the WT rotor is misaligned from the prevailing wind direction.

Years of Life Lost (YOLL) The YOLL approach takes into account that due to different causes people of very different age groups may be at risk. In the case of a chronic disease leading to the death of very old people, only the years of life lost due to the disease as compared to the average life expectancy are taken into account. For each year of life lost approximately 1/20st of the value of statistical life is used.

Z

Zone of Visual Influence (ZVI) In planning a new wind farm, it is important to consider the effect it will have on the local landscape. Wind farm software will analyse topographical maps of the area surrounding a planned wind farm and highlight the areas from which the new wind farm will be visible - known as the ZVI.

Technical Units

kW	kilowatt	1,000 Watts
MW	megawatt	1,000,000 Watts (1,000 kW)
GW	gigawatt	1,000,000,000 Watts (1,000 MW)
kWh	kilowatt hour	1,000 Watt hours
MWh	megawatt hour	1,000 kilowatt hours
GWh	gigawatt hour	1,000 megawatt hours

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