WIND ENERGY - THE FACTS

VOLUME 1

TECHNOLOGY

Acknowledgments

This volume was compiled by Paul Gardner, Andrew Garrad, Peter Jamieson, Helen Snodin and Andrew Tindal of Garrad Hassan and Partners, United Kingdom. Special thanks also to Airtricity for their permission to case study Cuilliagh Wind Farm. Our thanks also to the national wind associations around Europe for their contributions of data, and to the other project partners for their inputs.

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.

VOLUME 1 - TECHNOLOGY: TABLE OF CONTENTS

INTRODUCTION TO VOLUME 1 3

CHAPTER 1 TURBINE TECHNOLOGY 7

1.1 Evolution of Commercial Wind Technology 7

1.1.1 Achievements 7
1.1.2 The Challenge 8
1.1.3 A Unique Technology 8
1.1.4 Run up to Commercial Technology 9
1.1.5 Design Styles 10
1.1.6 Design Drivers for Modern Technology 13
1.1.7 Growth of Wind Turbine Size 14
1.1.8 Architecture of a Modern Wind Turbine 16
1.1.9 Erection of Large Wind Turbines 17

1.2 Technology Trends 19

1.2.1 Larger Diameters 19
1.2.2 Tip Speed - Offshore and Land Based Designs 20
1.2.3 Pitch versus Stall 21
1.2.4 Speed Variation 21
1.2.5 Hub Height 22
1.2.6 Rotor Mass 22

1.3 Recent Developments 23

1.3.1 Direct Drive Generators 23
1.3.2 Hybrid – Single Stage of Gears and Multi-Pole Generator 25
1.3.3 Rotor Blade Developments 26
1.3.4 Single Bearing Arrangement 28
1.3.5 Offshore Technology 28

1.4 Technology Status 32

1.4.1 Overall Design Trends 32
1.4.2 Size Limitations 33
1.4.3 The Success of Wind Technology 36

1.5 Concluding Remarks and Future R&D 37

CHAPTER 2 WIND RESOURCE ESTIMATION 38

2.1 Introduction 38

2.2 Regional Wind Resources 38

2.3 Wind Atlases 39

2.3.1 Onshore 39
2.3.2 Offshore 41

2.4 Energy Estimates 41

2.4.1 Onshore 41
2.4.2 Offshore 44
2.4.3 Updating Resource Potential 44
2.4.4 Concluding Remarks 45

2.5 Local Wind Resource Assessment and Energy Analysis 45
2.5.1 Introduction 45
2.5.2 The Importance of the Wind Resource 47
2.5.3 Best Practice for Accurate Wind Speed Measurements 47
2.5.4 The Annual Variability of Wind Speed 49
2.5.5 Analytical Methods for the Prediction of the Long Term Wind Regime at a Site 53
2.5.6 The Prediction of the Energy Production of a Wind Farm 55
2.5.7 Definition of Uncertainty in Predicted Energy Production 57

2.6 Offshore Wind Farm Design and Resource Estimation 58
2.6.1 Fundamentals 58
2.6.2 Measurement Offshore 59
2.6.3 Wind Analysis Offshore 59
2.6.4 Energy Prediction 59
2.6.5 Other Effects to Consider Offshore 59

2.7 Forecasting 60
2.7.1 Overview of the Method 61
2.7.2 Improvement over Persistence 62
2.7.3 Power Output 62
2.7.4 Portfolio Effects 63
2.7.5 Conclusions 63

2.8 Future Developments 63

CHAPTER 3 WIND FARM DESIGN 65

3.1 Introduction 65

3.2 Preliminary Layout Design 65

3.3 Detailed Layout Design 65

3.4 The Infrastructure 66
3.4.1. Civil Works 66
3.4.2. Electrical Works 67
3.4.3. SCADA and Instruments 67

3.5 Construction 67

3.6 Costs 68

3.7 Commissioning and Operation 68

3.8 Concluding Remarks 69

CHAPTER 4 TRANSMISSION AND DISTRIBUTION NETWORKS 70

4.1 Introduction 70

4.2 Setting the Scene 70
4.2.1 Large Interconnected Networks 70
4.2.2 Small Isolated Networks 71

4.3 Electricity Networks 72

4.4 Considerations for Wind Energy 74

4.4.1 Connections 74
4.4.2 Operation 75
4.4.3 Strategic Planning Considerations 77

4.5 Issues for High Wind Penetration in Europe 80

4.6 Concluding Remarks 82

CHAPTER 5 RESEARCH AND DEVELOPMENT 84

5.1 Wind Industry Research and Development Overview 84

5.2 Socio-Economic, Policy and Market Issues 85

5.2.1 Transparency 85
5.2.2 Increasing the Value of Wind Power 86
5.2.3 Education and Human Resources Development 86

5.3 Environmental and Social Impacts 86

5.4 Turbine and Component Design Issues 87

5.5 Testing, Standardisation, Certification and Safety 88

5.6 Grid Integration, Energy Systems, and Resource Prediction 88

5.7 Operation and Maintenance 89

5.8 Location of Wind Farms 90

5.9 Offshore Wind 90

5.10 Multi-Megawatt Turbines 91

5.11 Summary of R&D Objectives 91

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 improvements 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

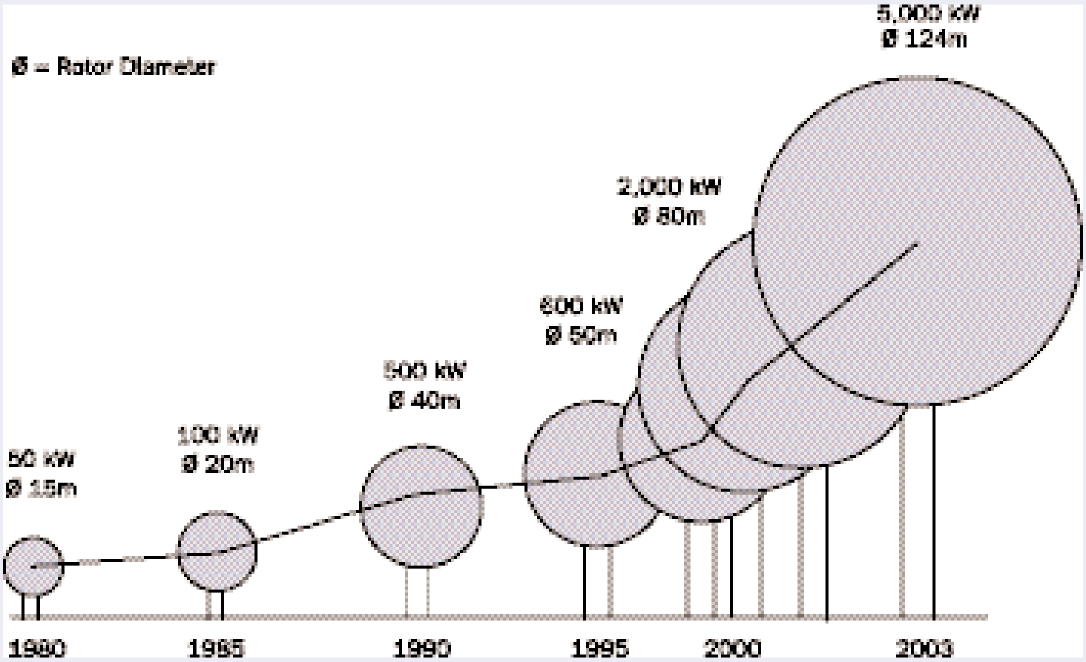
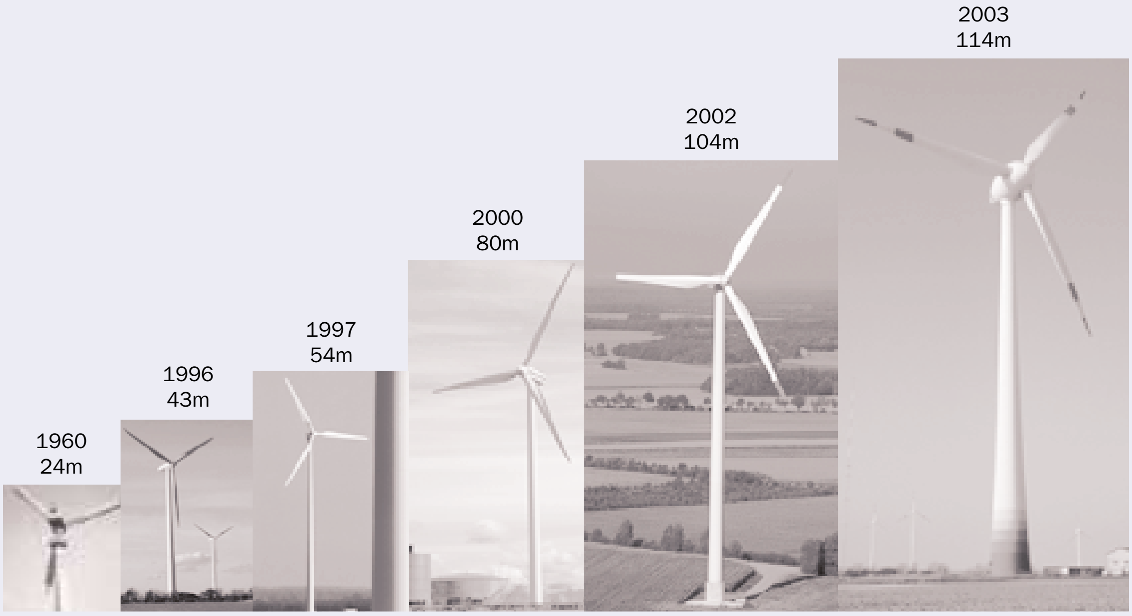


Figure 1.7: Growth in Size of Commercial Wind Turbine Designs



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

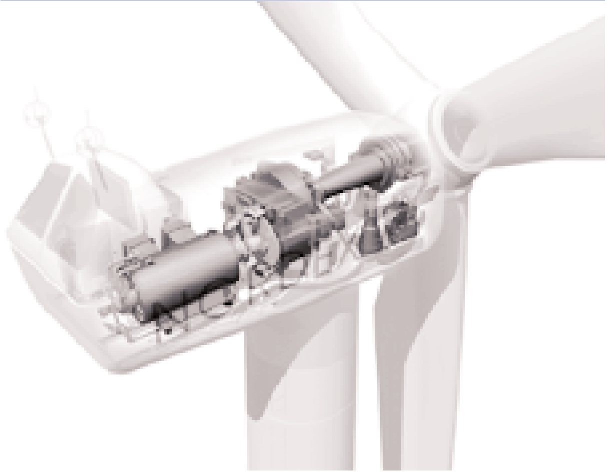
1.1.8 ARCHITECTURE OF A MODERN WIND TURBINE

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

Preparation of foundation | Tower Assembly | Hub Lift

Rotor Lift | Rotor Lift

Nacelle Lift | Hub Lift | Rotor Assembly

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.

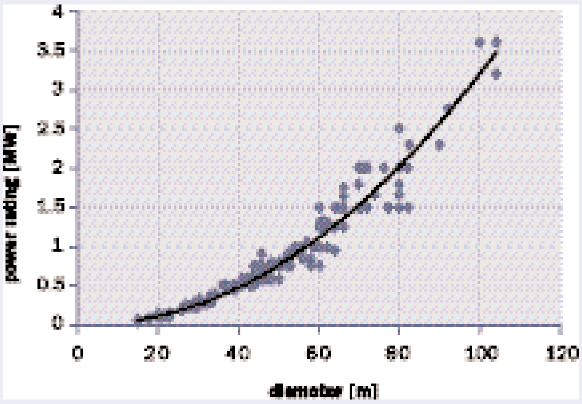
Considering the range of wind turbine sizes, the increase in diameter to rating ratio of the latest turbines has been a consistent trend. In the early 1990s, rated power typically varied as diameter, $D^{2.4}$. This parameter is important because as the turbine increases in diameter it also increases 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**

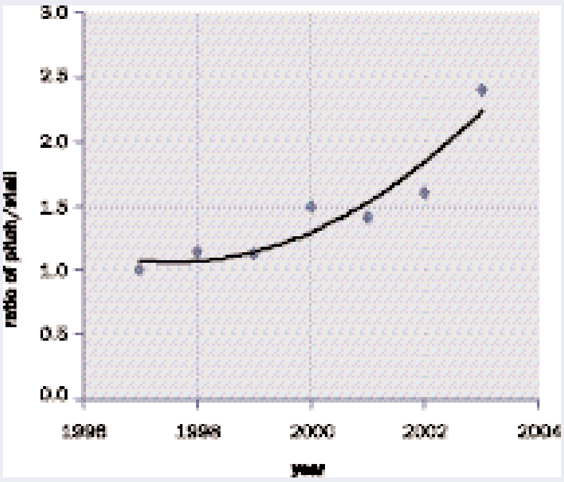
Tip speed trends of some larger scale designs are summarised in Table 1.3. The largest turbines (2 MW rating or more, highlighted) usually target the offshore market. Comparing the tip speed of the offshore design of each manufactures with the average tip speed of the designs targeted at land based applications, 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.

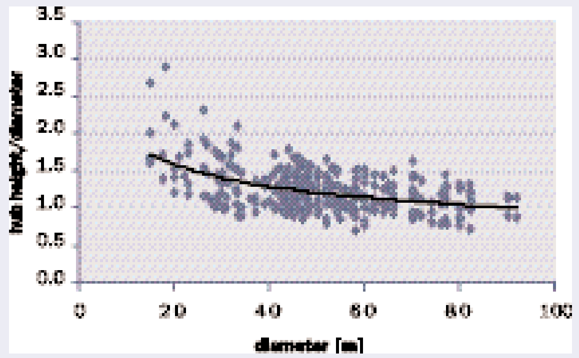
Other novel generator configurations have been proposed for WT applications, including the switched reluctance (SR) (also known as variable reluctance) machine. All rely on full-size power converters, and are therefore also at a disadvantage relative to the DFIG. The DFIG configuration used at present 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, $H=3.8786D^{-0.3}$



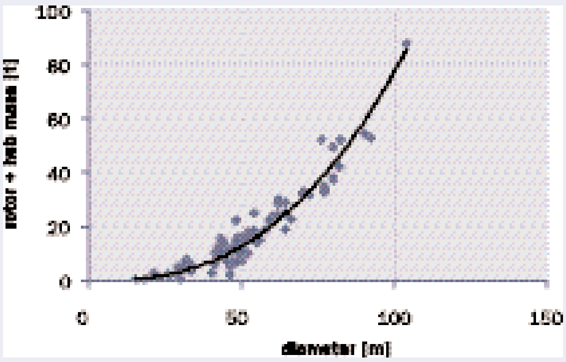
1.2.6 ROTOR MASS

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

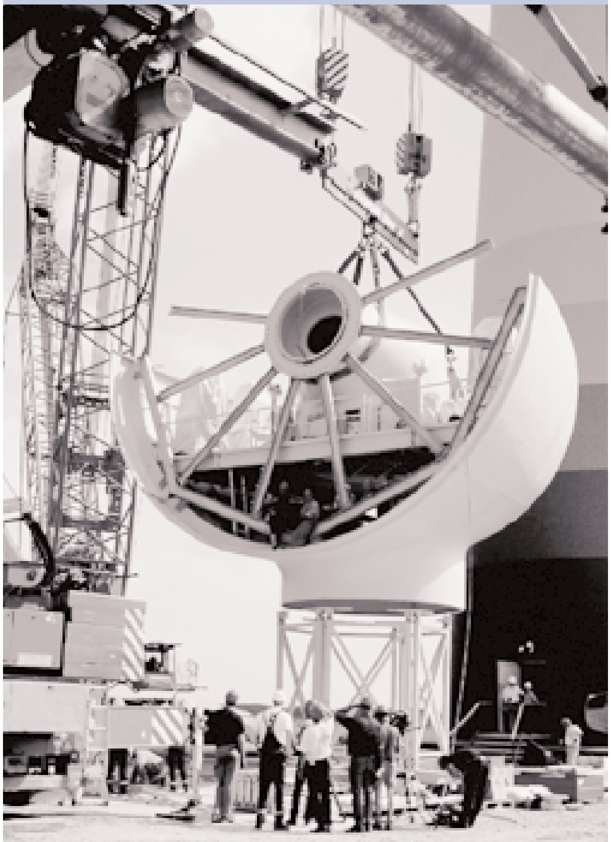
Direct drive transmission systems for WTs, avoiding the gearbox as a cost and maintenance item, are of increasing interest. Historically, gearboxes have presented challenges; hence their removal through the direct drive concept may seem desirable. It is, however, possible that mechanical difficulties 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 protection 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

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

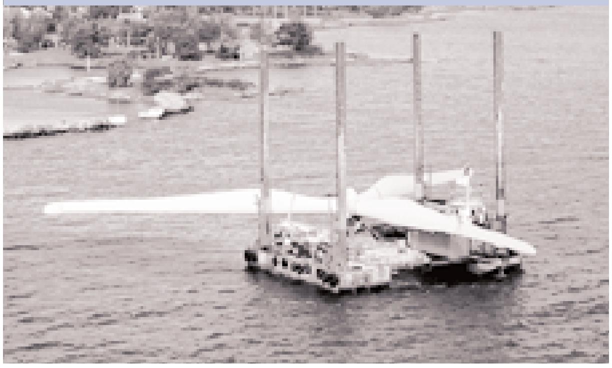
Location	Capacity (MW)	Turbines	Year of installation
Vindeby, Denmark	5	11 Bonus 450kW	1991
Lely, The Netherlands	2	4 NedWind 500kW	1994
Tunø Knob, Denmark	5	10 Vestas V39 500 kW	1995
Dronton, The Netherlands	17	28 Nordtank 600kW	1997
Bockstigen-Valor, Sweden	3	5 Wind World 500kW	1998
Blyth, UK	4	2 Vestas 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

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

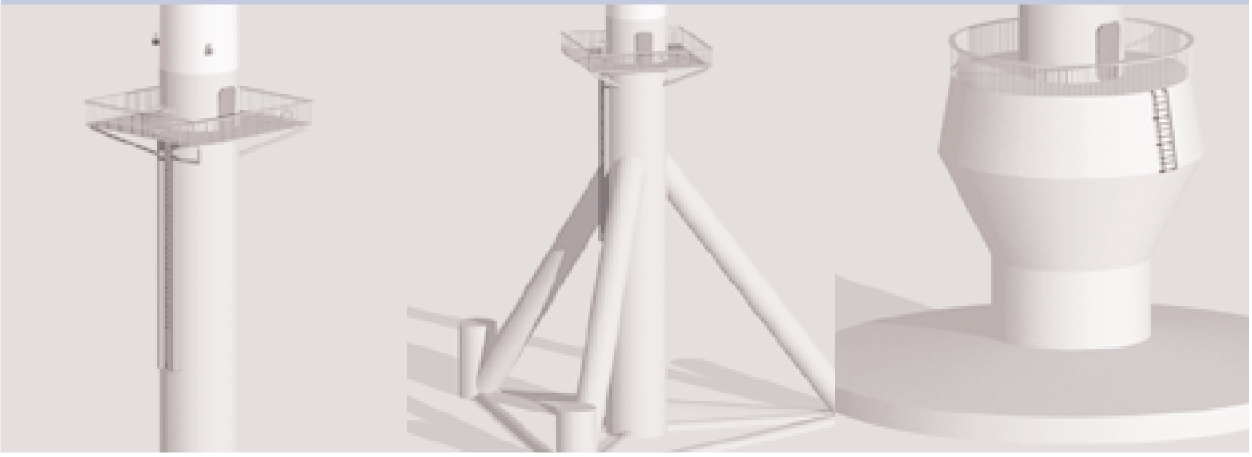
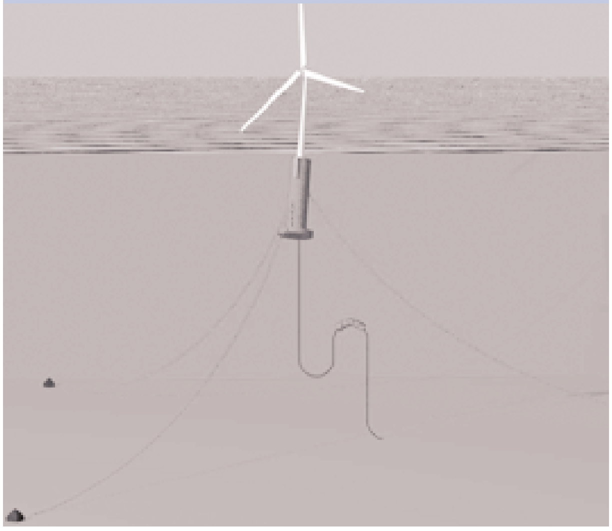


Figure 1.28: Floating Support



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

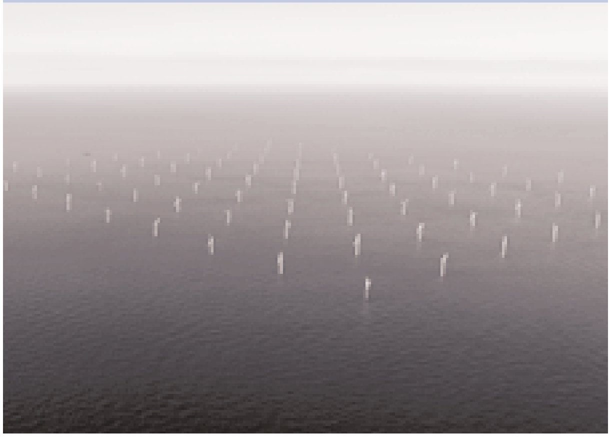


Figure 1.29 shows the development at Horns Rev, Denmark.

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?

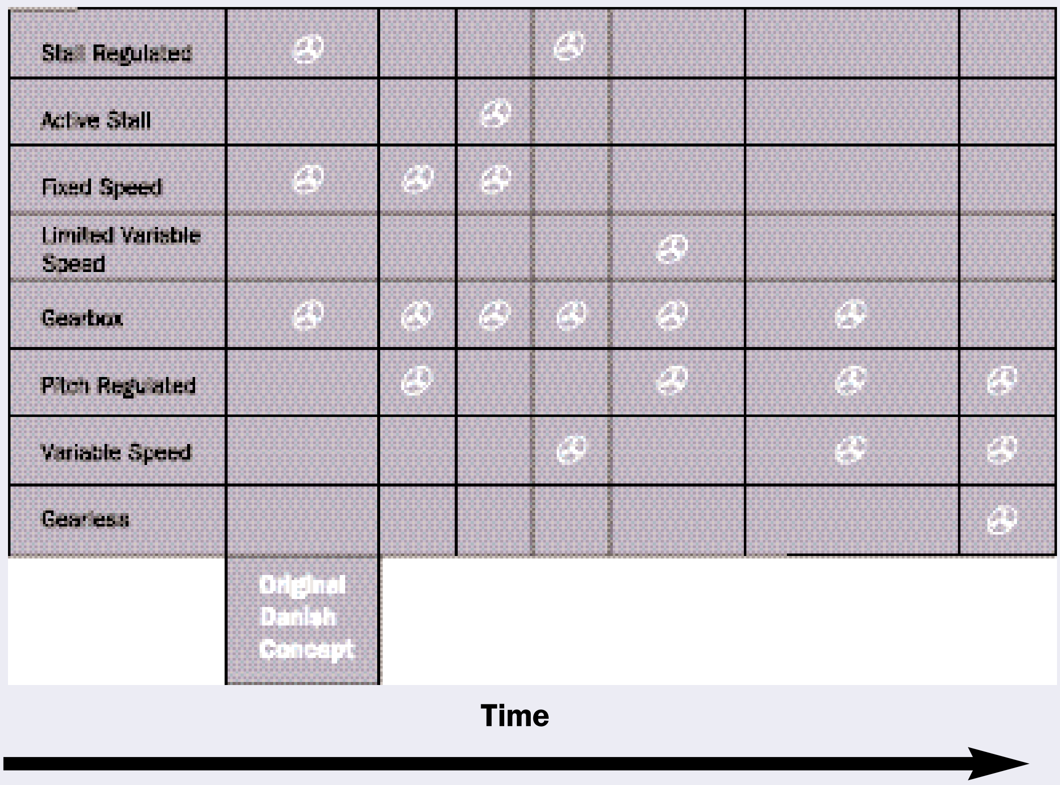
Although there has always been a wide variety of designs on the margins of commercial technology, in the early days the Danish, three-bladed, single fixed speed, stall regulated turbine dominated the market at rated power levels of generally less than 200 kW. Blades were almost invariably manufactured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

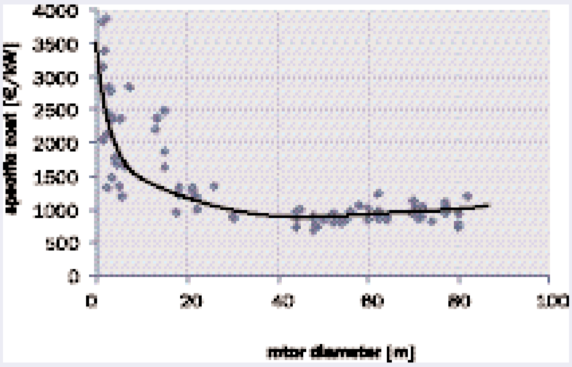
Since the initial commercialisation of wind energy in the early 1980s, there have, of course, been huge cost reductions and this is a direct consequence of the dramatic growth in the market.

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 published 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

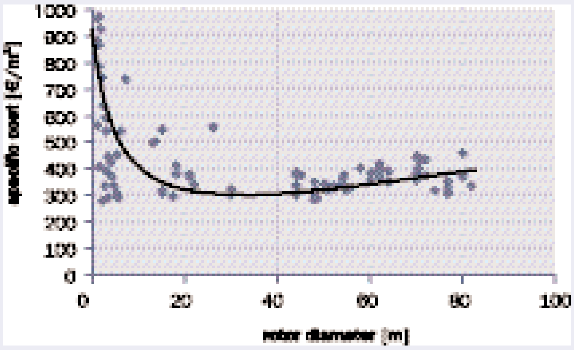


At larger sizes these factors diminish and costs reduce. However, the cost (net manufacturing cost of turbine ex-works) rises gradually for rotor diameters in excess of about 50 m. Taking account of land utilisation, infrastructure costs and maintenance costs, there is, however, still a net cost benefit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

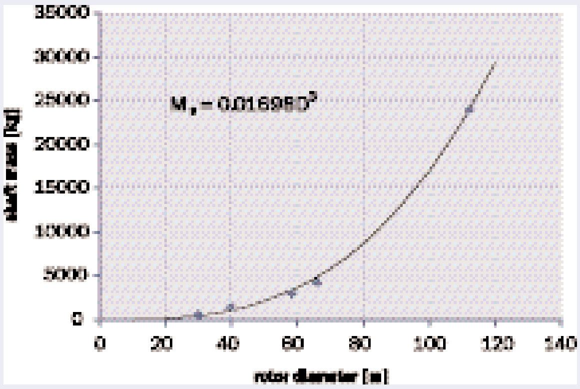
Figure 1.32: Price Trends of Large Wind Turbines



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

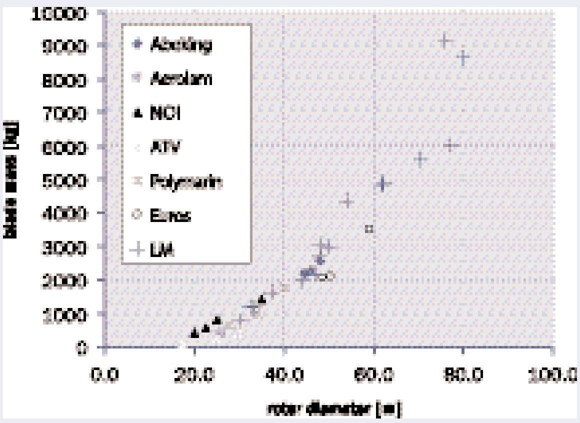


Table 1.6: Blade Mass versus Diameter Trend Line Exponents

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

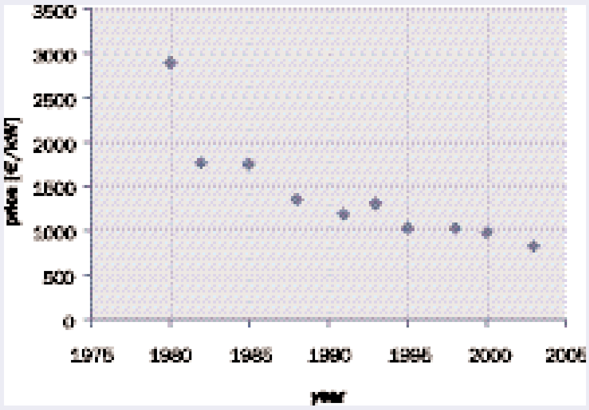


Figure 1.36: Typical Availability for a Large Wind Farm Since Erection

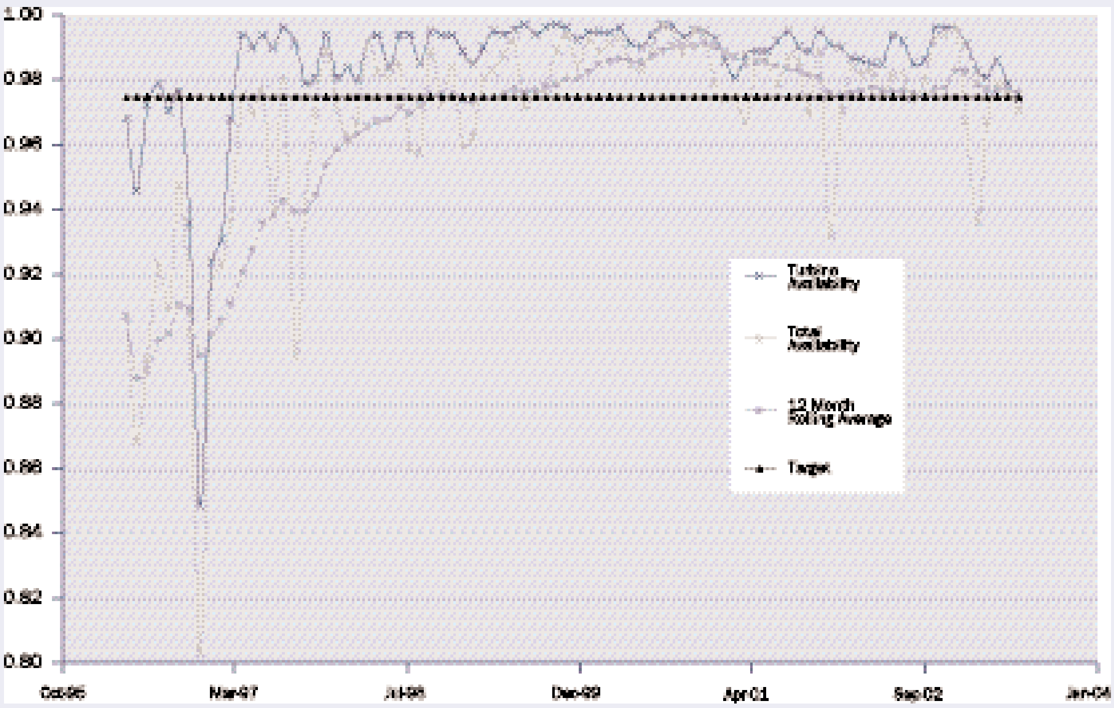


Figure 1.36 shows a time history of availability from a large European wind farm. It demonstrates that the availability in mature operation is in excess of 98%. It also shows the way in which the availability climbs as the turbines "run in". This project was built and commissioned in three phases. These 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.

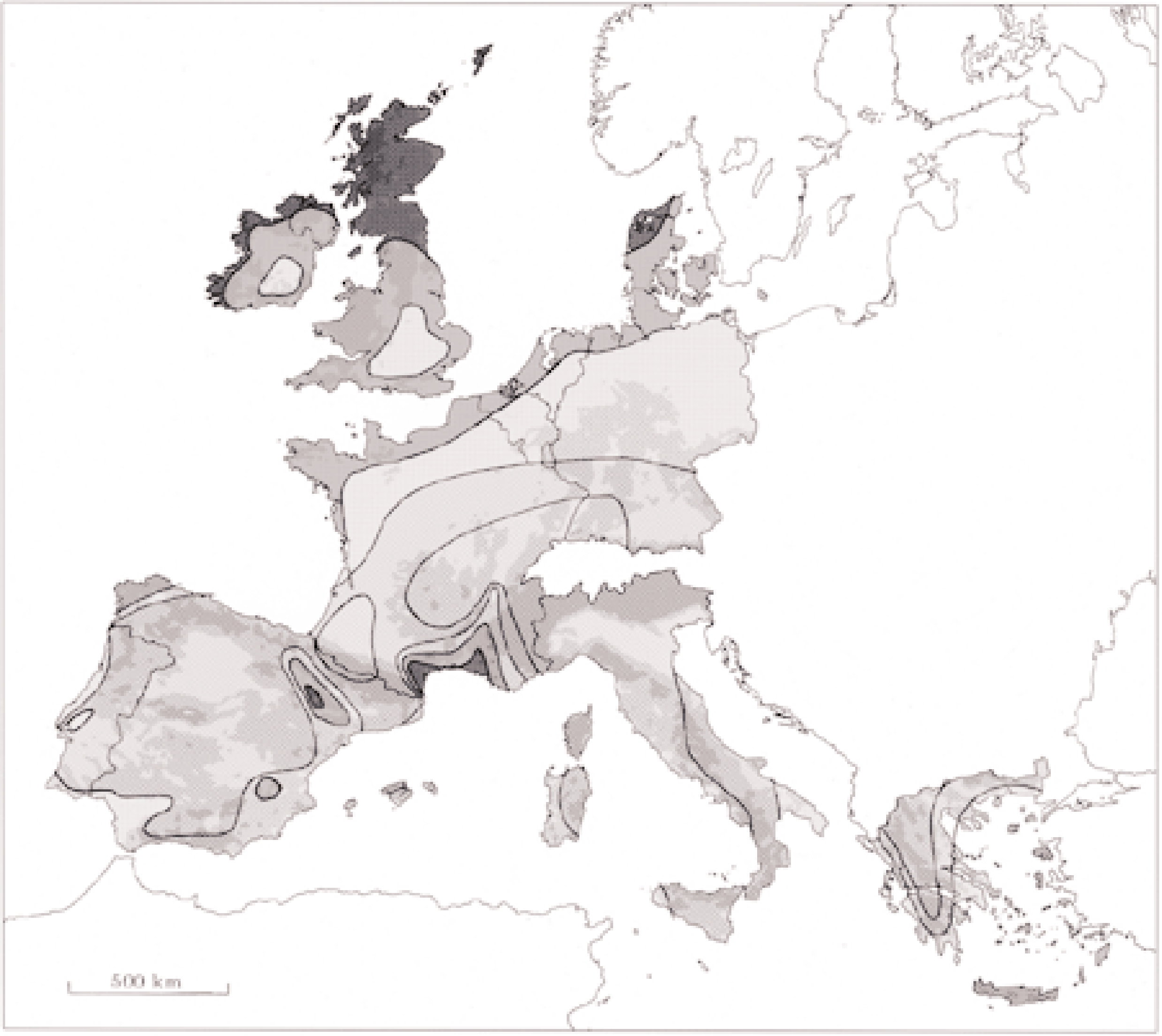
The wind speed above which commercial exploitation can take place varies according to the specific market conditions. While countries such as the UK and Ireland clearly have exceptional potential, every European country has an exploitable wind resource.

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.

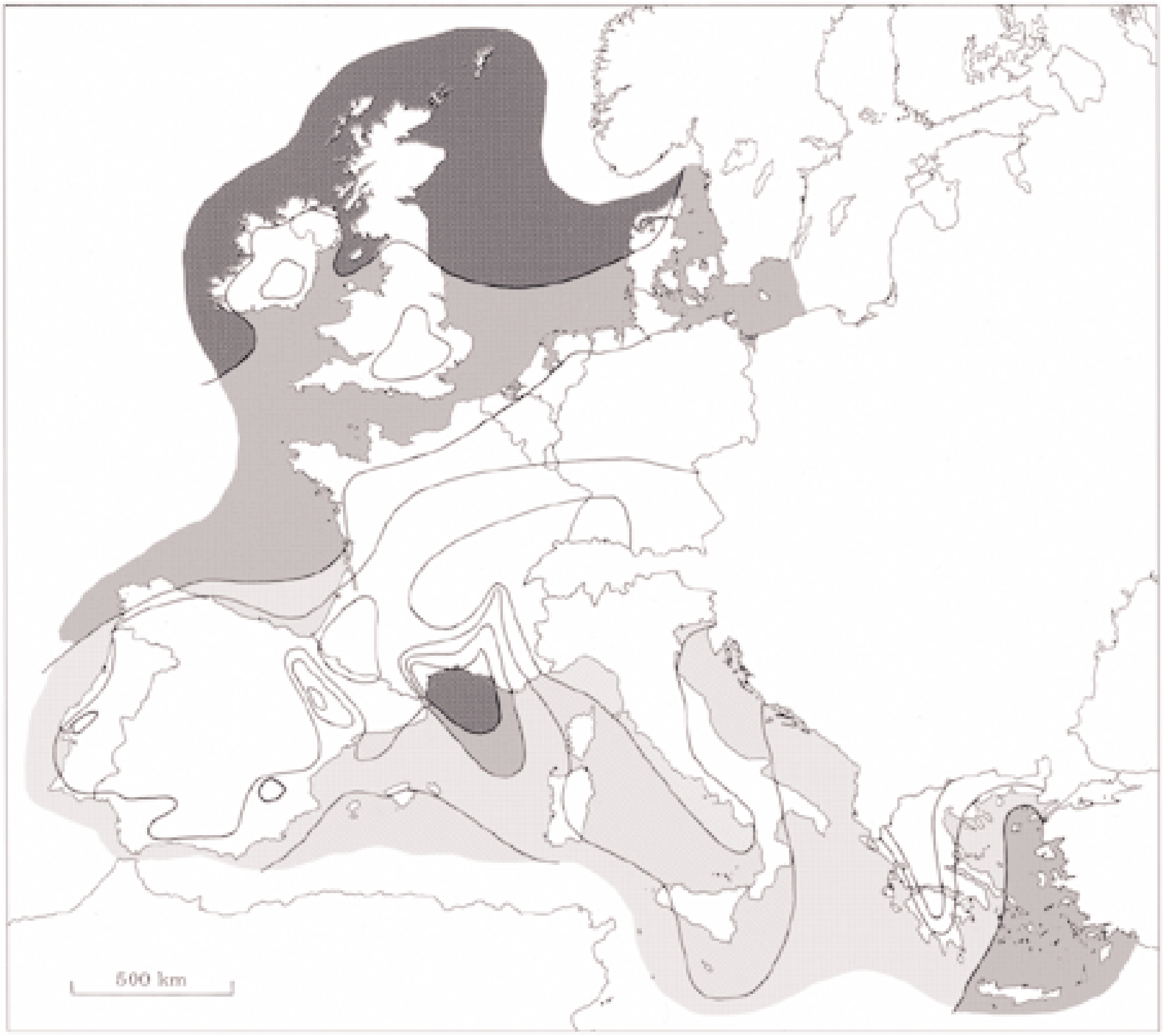
2.4 Energy Estimates

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/km². 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

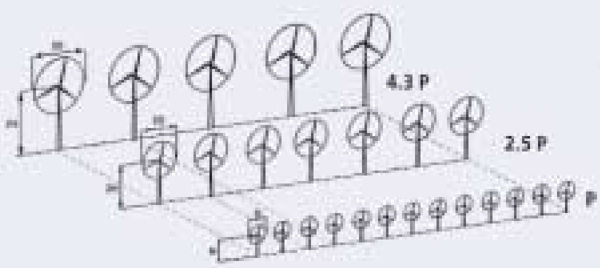
Country	Yr 2002 Consumption (TWh)	GH-GL Study (TWh/y)	CA-OWEE Survey (TWh/y)
Belgium	78.0	24	4
Denmark	37.2	550	26
Finland	71.9		20
France	533.3	477	44
Germany	543.5	238	45
Greece	48.9	92	5
Ireland	22.9	184	11
Italy	270.3	154	10
The Netherlands	92.4	137	33
Portugal	44.1	48	2 - 3
Spain	216.3	140	7
Sweden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

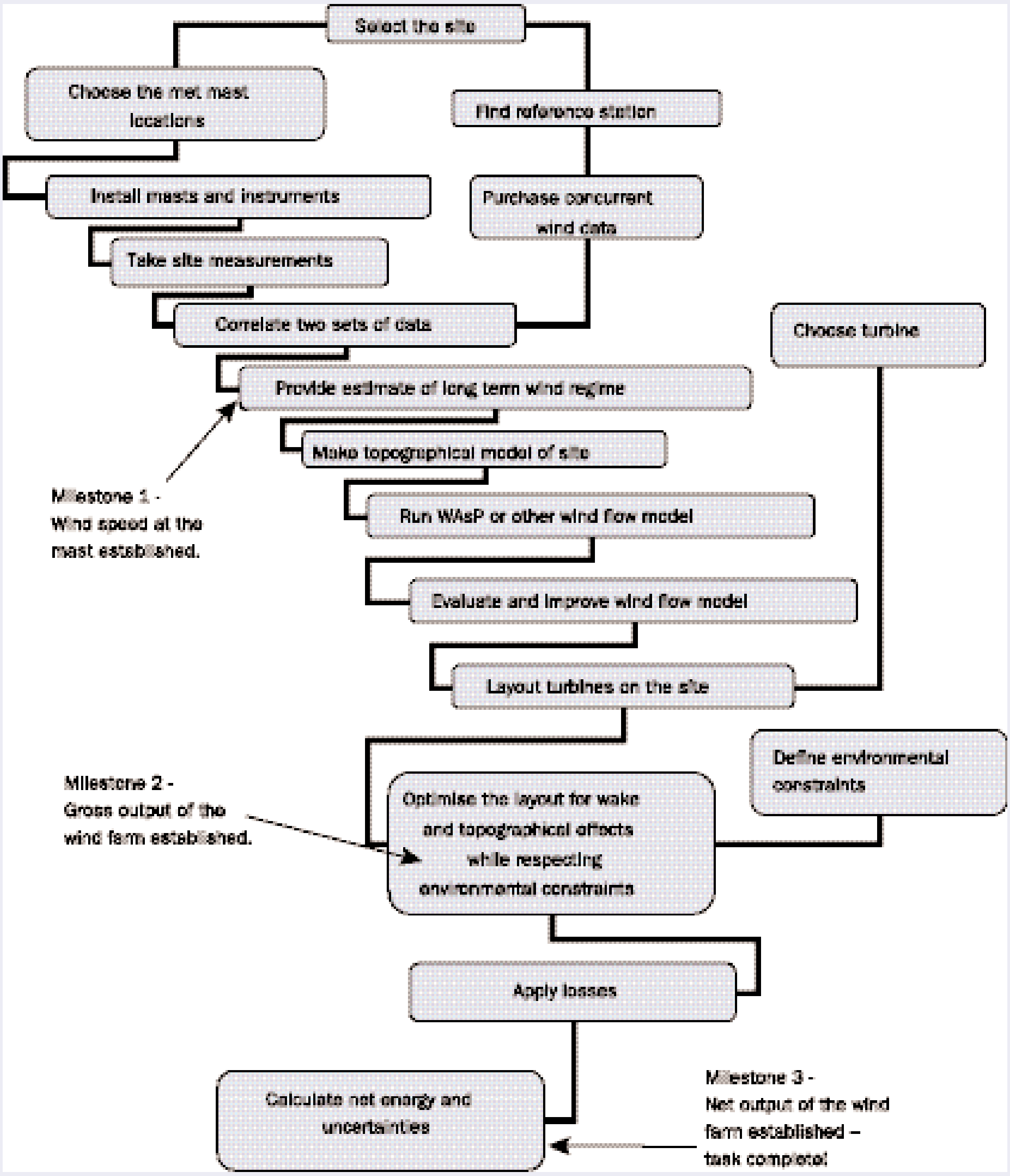
2.5.1 INTRODUCTION

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

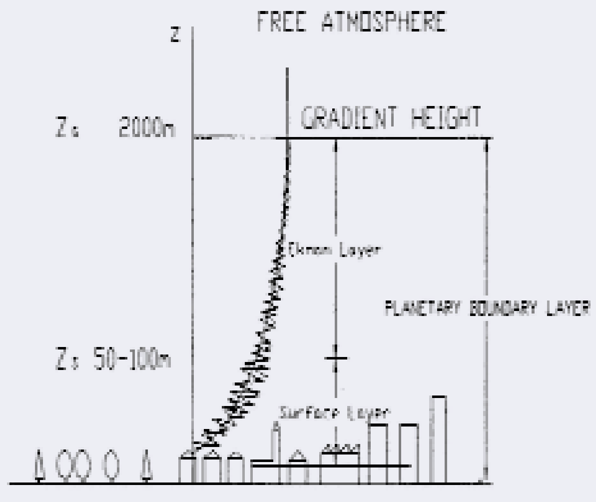
[1] Assumes typical turbine performance, air density of 1.225 kg/m^3, total losses of 12 % and Raleigh wind speed distribution.

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

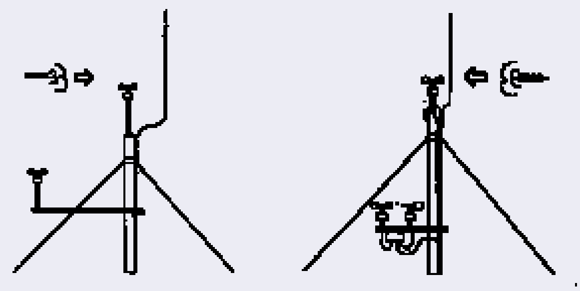
In recent years, it has become increasingly common to download data via modem. This approach has made managing large quantities of data from masts on a range of prospective sites significantly more efficient than manual downloading. It also has the potential to improve data coverage rates.

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



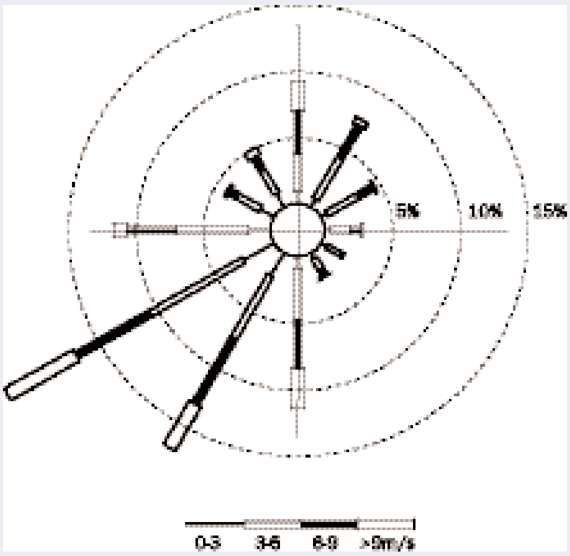
If the guidance presented above is followed, a high quality set of wind data should become available, in time, from a prospective site. The absolute minimum requirement is one year to ensure that any seasonal variation is properly captured. In addition to specifying and installing appropriate equipment, 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



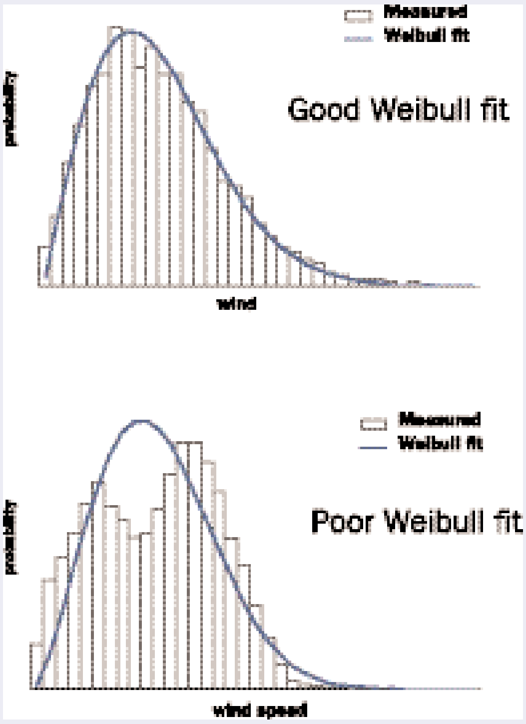
The description above has concentrated on the wind speed and wind rose. The other important parameter which determines the output of a wind farm is the wind speed distribution. This distribution describes the amount of time on a particular site that the wind speed is between different levels. This characteristic 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

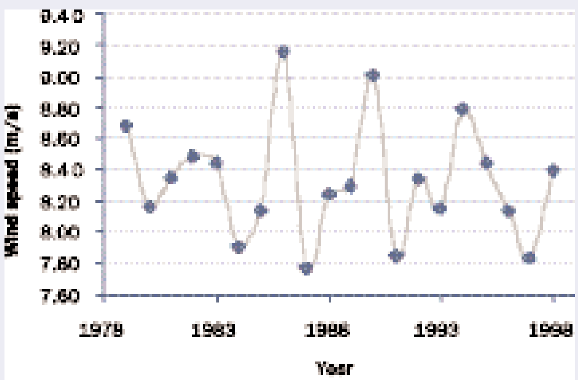


Table 2.7: Wind Speeds and Energy Production for the Average, Lowest and Highest Wind Speed Year in the Period 1979 to 1998 Based on a Nominal 10 MW Wind Farm at Malin Head

	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

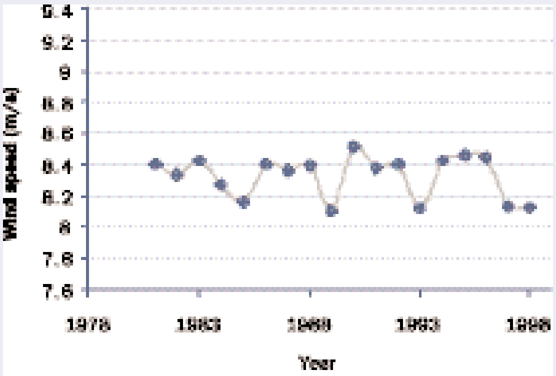


Table 2.7 shows that, had wind speed measurements been made on the site for just one year, and this one year had been assumed to be representative of the long term, then the predicted long-term wind speed at the site could have been in error by 10%. It is often the case that little on-site data is available 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).

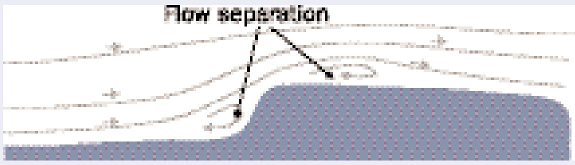
Within WFDTs, site wind flow calculations are commonly undertaken using the WAsP model (Troen and Petersen, 1989) which has been widely used within the industry over the past decade. Other commercial models which are physically similar to WAsP are also sometimes used. This area of the wind farm energy 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.

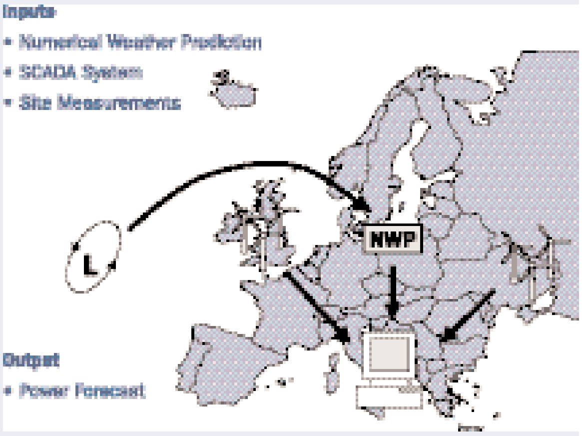
The numerical weather predictions (NWP) models run by national institutes are typically of continental, if not global, scale. Consequently, their resolutions tend to be too coarse for wind energy needs. For example, the model run by the UK Meteorological Office for north-west Europe has a minimum horizontal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

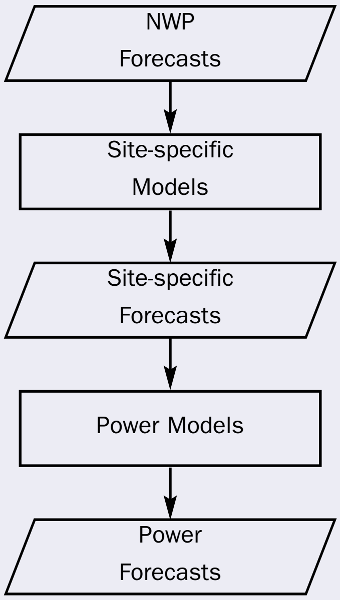
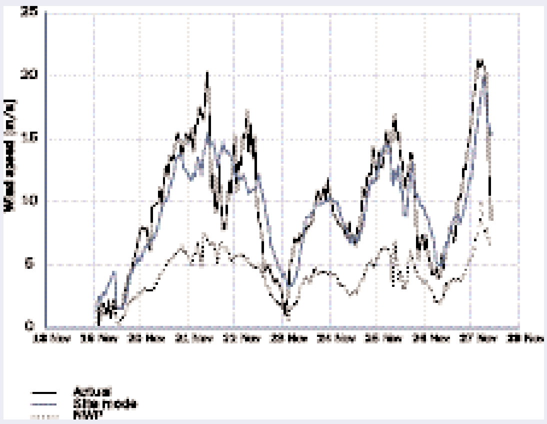


Figure 2.14: Example Time Series of Wind Speed Forecast, T+12h



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.

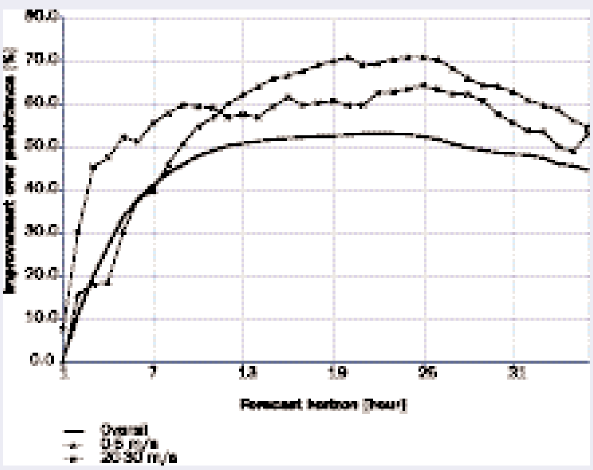
2.7.2 IMPROVEMENT OVER PERSISTENCE

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

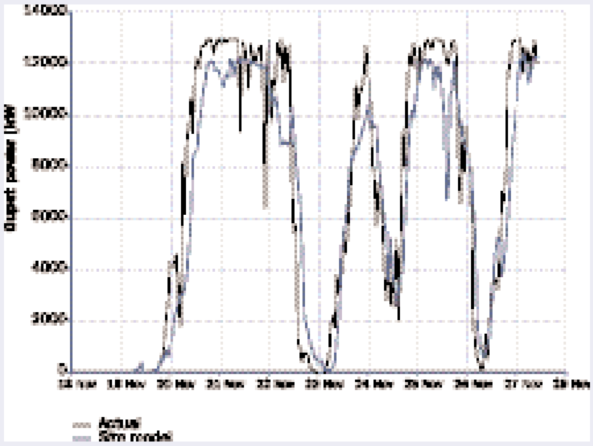


2.7.3 POWER OUTPUT

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.

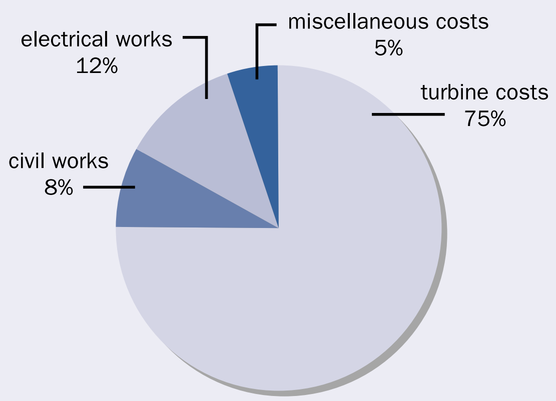
In conclusion, the design of a wind farm is a compromise between high energy, easy access, easy permitting and commercial viability.

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

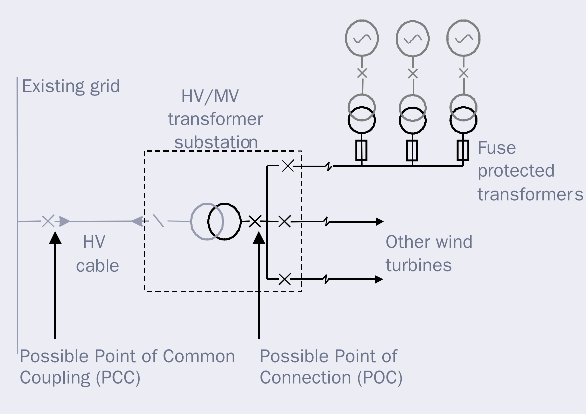
The foundations must be adequate to support the turbine under extreme loads. Normally, the design load condition for the foundations is the extreme, once-in-50-year wind speed. In Europe, this wind speed is characterised by a three-second gust which would probably lie between 45 and 70 m/s. At the lower 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 varia-

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

tions 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.

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 purchase 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 world-wide 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, subsuppliers 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.

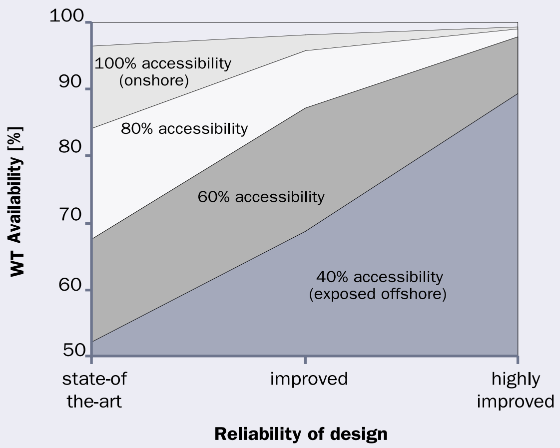
An increase in predictability of wind farm output will reduce requirements for spinning reserve. Improved levels of grid interconnection among European countries will also reduce the need for spinning reserve, as intermittency becomes less of an issue with increased geographical spread. Analysis of spinning 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