European Commission
Directorate-General for Energy

WIND ENERGY - THE FACTS

Volume 1

TECHNOLOGY

EXECUTIVE SUMMARY

Introduction

The technology volume reviews:

- the wind resource which is the basis of all wind energy developments
- state of the art of European technology
- research and development requirements

Resource

In 1995, electricity production in the EU amounted to 2384 TWh. The estimated annual wind potential is 588 TWh (land based resource) which is adequate for a 20% penetration of supply. This excludes the annual offshore resource estimated to be in excess of 2500 TWh.

Status of the technology

A major achievement of the EU wind industry is that about 10 megawatt scale wind turbines are now commercially available. Cost trends show these latest megawatt machines as competitive although it is now pressing to address the limits of up-scaling and the need for new concepts for large offshore units. Gradual innovation has led to the emergence of variable speed and direct drive designs to complement the established Danish stall regulated concept with geared drive train.

Increased wind turbine reliability and the in-roads made into markets world wide mean the future for the technology is bright. The real benefits of the substantial investment made by the European Commission and the EU member states into research to improve the understanding of wind turbine behaviour, through careful modelling and measurement, is just starting to bear fruit. It must be carefully sustained and is set to play a major role in future technology development.

Status of European research and development

Extensive measurement and model validation activities have been made possible through funding provided by national and international research programmes such as the EU JOULE programme. Design tool development is ongoing in areas of wind field representation, rotor aerodynamics, computational fluid dynamics, aeroelasticity, aerofoil design, and aeroacoustics. There is also considerable potential for further development of wind farm design tools and hardware systems for wind farm management. Key research areas include, lightweight/flexible designs, rotor systems development, aerofoil design, blade materials development, direct drive systems, optimum unit sizing, grid integration, hostile sites, hybrid systems and multi-megawatt design. Harmonised international design standards are being achieved and are crucial to the continuing success of wind technology.

The next great leap for the wind energy industry will be in the area of offshore development. The potential for this technology is vast and it requires, and deserves sustained and substantial research and development support.

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1 INTRODUCTION

This volume summarises:

- the wind resource which is the basis of all wind energy developments
- state of the art of European technology
- research and development requirements

A Technical Appendix is provided giving a detailed background of the evolution of the technology. This comprises a historical perspective, the present technology, wind farming issues and regulatory matters.

This structure is intended to allow the reader to assess the future requirements of the technology without, necessarily, having to appreciate the historical perspective and the more detailed technical aspects of the industry.

2 RESOURCE

"Exploitation will not be limited by resource!"

In order to put wind energy technology in its proper context it is important to have at least an approximate estimate of wind energy's strategic potential. An approximate estimate of the resource is adequate because the potential, at least in its simplest form, is vast.

Most attempts at estimating this potential use the same basic steps:

1. Define the climatic and physical characteristics - average wind speed and areas where turbines can be placed
2. Estimate the space available for development from the results of (1)
3. Using current technology estimate the energy yield which can be derived.

Step (2) has a major influence on the final result and is very difficult to perform accurately. This point is well illustrated in the table below where the results of two studies are compared.

van Wijk and Coelingh [1] used a systematic, and rather more conservative, approach than Grubb and Meyer [2]. They considered that any land which had a mean wind speed greater than 5.1 m/s was potentially exploitable and they further assumed that only 4% of that land could be used as a result of practical and social constraints. A recent study undertaken in Germany, by the Bundesministerium fur Wirtschaft, has further underlined the importance of the assumptions used in such calculations. It has shown that if land with mean wind speeds of between 4 and 5 m/s is included then the technical potential in Germany alone increases to over 90 TWh/annum. None of these studies include the offshore potential which was estimated by Matthies and Garrad [3] to be in excess of 2 500 TWh/annum, in European waters alone.

Region	Grubb and Meyer [1] (TWh/annum)	Wijk and Coelingh [2] (TWh/annum)
Africa	10 600	-
Australia	3 000	1 638
North America	14 000	3 762
Latin America	5 400	-
Western Europe	480	520
Eastern Europe and CIS	10 600	-
Rest of Asia	4 900	-
Total OECD		6351
Approximate world total	50 000	20 000
World consumption of electricity in 1994	12 500 TWh/annum	
OECD consumption	6 351 TWh/annum	

Table 2.1 Regional wind energy potential and world-wide electricity consumption

It is instructive to follow Wijk and Coelingh's analysis further since they provide a detailed description of the resource in Europe. This is illustrated in the table overleaf which shows not only the technical potential but also the electricity consumption of each country. In this table the offshore potential already identified in Sweden and Denmark is also included. If it is further assumed that any national grid system could accommodate a 20% penetration of wind energy then a realistic potential can be calculated which is shown in the last column. Applying this limitation ignores the potential for exporting wind generated electricity which will be an important commodity in the future.

Country	**1995 Electricity production (TWh/annum)**	**Technical wind potential Wijk and Coelingh (TWh/annum)**	**Realistic potential = lesser of 20% consumption and technical potential (TWh/annum)**
Austria	60	3	3
Belgium	82	5	5
Denmark	31	27	6.2
Finland	66	7	7
France	491	85	85
Germany	534	24	24
UK	379	114	75.8
Greece	41	44	8.2
Ireland	17	44	3.4
Italy	207	69	41.4
Luxembourg	1	0	0
The Netherlands	89	7	7
Portugal	32	15	6.4
Spain	178	86	35.6
Sweden	176	58	35.2
Total EU	**2384**	**588**	**343.2**

Table 2.2 The European wind energy potential and electricity consumption

The message from this brief introduction to the wind energy potential is very clear - its exploitation will not be limited by the resource.

3 STATUS OF WIND TECHNOLOGY - SUMMARY

"... the future for the technology is bright!"

European wind technology is a great success story. In a matter of a decade and a half it has evolved from an industry making small, simple and sometimes unreliable machines into a technology which can compete with the well established conventional forms of power generation. It has volume production of medium size machines in the 600 kW range and some 10 designs in the megawatt range with commercial prospects. The increase in available rated capacity (by about a factor of 3 from 500 or 600 kW to 1.5 MW) is striking and has been a very rapid development since 1990. The arrival of the largest units is timely as the industry prepares for major offshore developments. This evolution is shown schematically in Figure 3.1.

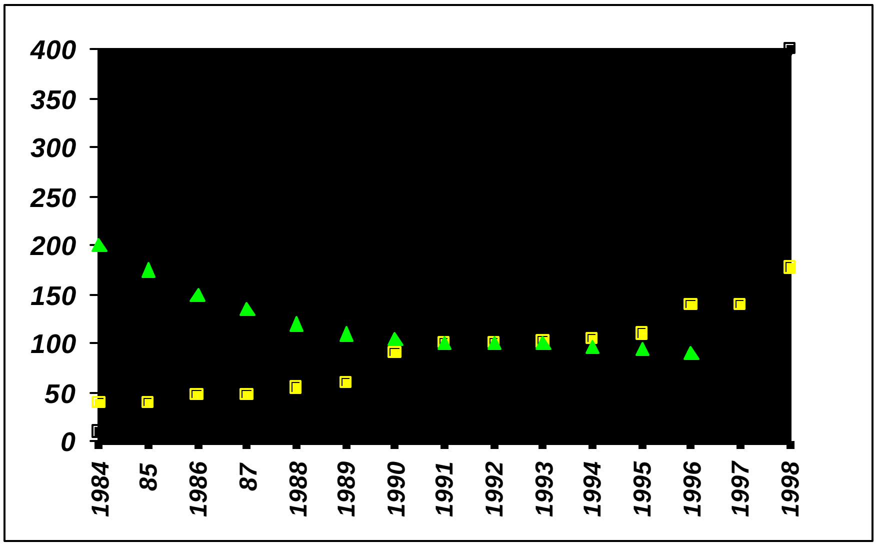

Figure 3.1 The development of commercial machines (1992 = 100% for all parameters)

To provide confidence to investors continued effort is required on standards and certification. This important area of work has been responsible for a steady improvement of both design and manufacturing quality and has helped the industry move from its early pioneering stage to a competitive industry which can compete on a world wide market. Continued efforts on this front are vital.

Design consolidation has taken place with three bladed designs predominating to an even greater extent than previously. There is increasing use of variable speed systems. A major recent innovation has been the introduction of direct drive generator technology.

Widespread exploitation of wind energy potential will require properly optimised machines for different types of site:

- high and low wind speed
- onshore and offshore
- remote and grid connected
- large and small applications

Cost trends show the latest megawatt machines as competitive although it is now pressing to address the limits of up-scaling and the need for new concepts for large offshore units. Major offshore developments are certain in the early part of the next century. This will be the next major step for the technology and will result in a dramatic increase in potential in particular in the northern European waters.

Careful consideration of the interaction between wind turbines and the grid is now, and will continue to be, an important area of both technical design and political action. This matter will come to the fore over the next decade as the substantial goals established for the industry are realised. It will require a radical re-think of the way grid management is organised on a Europe wide basis.

The increasing reliability of wind turbines and growing penetration of world wide markets mean the future for the technology is bright. The real benefits of the substantial investment made by the European Commission and the EU member states into research to improve the understanding of wind turbine behaviour, through careful modelling and measurement, is just starting to bear fruit. It must be carefully sustained and is set to play a major role in future technology development.

4 STATUS OF EUROPEAN WIND ENERGY R&D

"The next great leap for the wind energy industry will be in offshore development."

In this section the status of the different areas of technology are assessed and research and development requirements are identified.

4.1 Future design needs

4.1.1 Design tools

Over the last twenty years research workers have played a vital role in the development of mathematical models which can represent the behaviour of wind turbines. This work has involved extensive measurement and model validation activities and has been made possible through funding provided by national and international research programmes such as the EU JOULE programme.

As confidence in the mathematical models developed by research organisations has grown, there has been increasing interest from wind turbine manufacturers wishing to make use of such models as the basis of their design calculations, replacing the simplistic design approaches of the early days of the industry. It is therefore a challenge to the research community that they should now develop software tools which offer reliable models of wind turbine behaviour but also provide the quality, robustness and ease of use required by the designers. This process is well underway and there are already a number of computer programs which originate from European research and consultancy organisations and are now being used by manufacturers for design and certification of wind turbines.

There are several aspects of the methods currently used for the design calculation of wind turbine performance and loading which require further research and development effort:

Wind field representation

Further research is required to investigate suitable models of the wind characteristics experienced by wind turbines operating in the following situations:

- in wake flow within wind farms,
- on complex terrain sites,
- in different conditions of atmospheric stability .

An area of great importance and significant uncertainty is that of the modelling of extreme wind conditions. Current design standards are based on rather arbitrary deterministic descriptions of extreme wind events and there is an urgent need for the validation of this approach or its replacement with alternative, probabilistic methods.

Rotor aerodynamics

Although there has been extensive research in this area, the general understanding of the development of aerodynamic stall on a rotating wind turbine remains poor and the modelling of stall is considered to be the most significant inadequacy of current design calculation methods. The present uncertainty results in poor confidence in the design calculations of performance and loading for stall regulated wind turbines.

The development of models of steady and dynamic stall, reliable across a range of aerofoil sections and rotor configurations, requires the continuation of the major experimental and theoretical research programmes already underway in this area.

Computational fluid dynamics

Computational fluid dynamics tools are being developed in a wide range of engineering disciplines. Wind energy is only one area in which they can be used. There are still important aspects of wind energy technology which are not properly understood - the local flow over the blades and the flow of wind over complex terrain. Both will profit greatly from the application of CFD tools. Better understanding of wind flow and local air flow will yield major improvements in the confidence with which the technology can be applied and significant cost reductions will result.

Aeroelasticity

The current generation of wind turbine research codes and design tools has received very little validation against measurements from flexible machines. Further research effort will be required in this context leading to design tools which can be used to undertake reliable calculations of the coupled modal properties, aeroelastic stability and loading of wind turbines with flexible components exhibiting large deflections.

It is anticipated that with the continuation of relevant research programmes and the increasing power of computers, the sophistication and reliability of the design calculations undertaken by wind turbine manufacturers will continue to improve. This trend can only help to reduce unnecessary design conservatism and lead towards lower costs for wind generated electricity.

4.1.2 General R&D

In addition to the areas of research identified above, other areas requiring further research effort include:

- aerofoil design
- aeroacoustics
- verification and enhancement of design standards
- reliability analysis
- improvement of reliability of materials data
- design methods and assumptions for offshore wind turbines

Aerofoil development continues to be of importance, not because it is possible to get much more energy from wind turbine rotors but because tailoring of stall, management of loads and the structural implication of aerofoil size and shape can all contribute to more cost effective rotor blades and wind turbine systems.

There is also considerable potential for further development of wind farm design tools and hardware systems for wind farm management.

4.2 Wind turbine concept development

4.2.1 Lightweight/flexible designs

There is clear requirement for larger generating units, especially for offshore sites, where there may be greater freedom from some environmental constraints. High speed lightweight turbines may be considered. As has been discussed, the exploitation of structural flexibility to achieve weight and cost reduction is still more limited than may have been supposed. The development of composite hinges and other essentially “smart materials” developments may find increasing application in wind turbine systems. Optical fibres are already being evaluated for monitoring fatigue of blade structures.

4.2.2 High/low wind speed designs

The best wind resource in Europe, in the UK generally and in Scotland in particular, has been the latest to be exploited. This implies that feedback from the operation of European wind turbines on high wind speed sites has been quite limited and validation of designs for such sites is ongoing.

The general approach to high wind speed sites has been to offer a lower diameter in relation to power rating and conversely in low wind speed sites to offer increased rotor diameter. This is often done in a non-optimum but very expedient way using "hub extenders" - tubes inserted between the hub flange and blade root which increase overall rotor diameter. Tower height is also often increased on low wind speed sites.

It is, however, an oversimplification of the issue of coping with varying site conditions to consider it purely as a diameter/power rating adaptation. The differences in total design and cost implications of machines for high as opposed to low wind speed sites is substantial for genuinely optimised designs. As order books grow, more differentiated high wind speed and low wind speed designs may emerge.

4.3 Rotor systems development

4.3.1 Aerofoil design

Development of improved aerofoil sections for wind turbines has been ongoing. Low lift aerofoils with reduced roughness sensitivity and to shed maximum loads have been the focus of US developments [4]. In Sweden and the UK [5] high lift aerofoils have been designed which are suited to variable speed operation. LM Glasfiber have conducted many experiments with new aerofoils and also with new tip shapes designed to minimise tip sound.

Over recent years there has also been a move towards using higher camber NACA sections in an attempt to reduce rotor solidity. This, however, appears to have been accompanied by an increase in the likelihood of stall induced vibrations. The prevailing tendency among blade manufacturers is to use NACA 63 sections which may have in-house modifications in order to ease manufacture etc.

There is still considerable potential for rotor design optimisation and system load reduction (though not for much energy gain) through new aerofoil developments. Such developments will be very gradual. There are considerable overheads in changing blade tooling, some risk of unsatisfactory performance and time required for testing to develop confidence in new rotor designs.

4.3.2 Blade materials

The historical development of blade materials from metals to composites (natural and man-made) are discussed in Appendix Section 4.5. Much development of existing composite material components is ongoing in respect of suitability for manufacturing methods. There is interest in resin transfer moulding, in pre-pregs (cloths pre-impregnated with resin - as used by Vestas in both the spar and shell structures of their blades), different weaves of glass cloth that alter the structural characteristics and also the required resin content etc. In wood epoxy

manufacture the range of usable woods is being further explored and there is ongoing demand for materials testing in support of materials innovation for cost reduction.
Interest in the use of materials which can be re-cycled is developing as is the use of natural fibres. The application of these techniques is particularly relevant to an environmentally friendly technology such as wind energy.

4.3.3 Control mechanisms (beyond stall/pitch)

There have been many experiments to improve stall regulation. Vortex generators are widely used by blade manufacturers and there is interest in using air jet vortex generators [6] as an active method of boundary layer control.

Research has suggested that partial span systems of pitch control provide a more responsive and better quality of power control than full span pitching and also may be more economic. Concern about sound emission has probably deterred many manufacturers from pursuing such systems. Smart materials [7] are available, relatively expensive at present, that may slowly find application in wind turbine rotors allowing the development of intelligent blades.

4.4 Direct drive designs

The advantage of direct-drive concepts is the omission of the gearbox, by utilising a generator that can operate at the rotational speed of the rotor. This has benefits in two separate areas:

- for small and very small turbines, where rotor rotational speed is relatively high anyway, with the aims of saving cost and achieving very low maintenance,
- for very large turbines, where rotational speeds are low and torques very high, principally to achieve cost reduction through a simplified integrated design.

4.4.1 Micro-turbines (< 3 kW)

These turbines are in the range 0 to 3 kW approximately, and are characterised by the almost exclusive use of direct drive permanent magnet generators (PMG) for battery charging. The market is for remote telecommunications, electric fences, domestic systems, nomadic peoples, leisure craft and caravans. Almost 90% of micro-turbines use PMG technology.

4.4.2 Small wind turbines (< 30 kW)

The benefits of direct drive are the expected low maintenance and high reliability. Capital cost and efficiency are less important. Wind turbines with direct drive generators of 2 to 10 kW rating have been developed by Bergey, Westwind, Proven and LMW. All use permanent magnet generators. There are of course several non-direct-drive wind turbines in this size range.

Several manufacturers have direct drive turbines in the design or prototype stages at ratings up to 50 kW. All use PMGs except for the Atlantic Orient Corporation (AOC) 20 kW design which uses a switched-reluctance generator.

AOC generators are current being laboratory tested. The switched reluctance generator is the simplest generator of all with only laminated iron on the rotor.

4.4.3 Large wind turbines

The perceived benefits of direct drive systems for large wind turbines are:

- lower cost than a gearbox system;
- reduced tower-head mass and nacelle length;
- efficiency savings of several percent.

It is as yet unclear if these benefits are being realised in present designs, but it is quite clear that the new technology is already on a par with conventional solutions.

Direct drive machines always take advantage of the opportunity for variable-speed operation allowed by the AC/DC/AC converter. Most direct drive systems would be difficult to implement in fixed-speed operation as they lack the compliance of induction machines. Turbines with direct drive systems range from 200 kW to 1.5 MW (production and prototype machines). Both permanent-magnet and wound-rotor designs are used. Current direct drive designs include;

- Enercon E30 (200 kW), E40 (500 kW) and E66 (1.5 MW): synchronous generator, wound rotor, concept proven through extensive operating experience.
- Lagerwey LW45/750 (750 kW) at prototype stage, synchronous generator, wound rotor.
- Genesys 600, Tacke TW1500: proposed machines, permanent magnet excitation rather than a wound rotor, and reduced generator diameter.
- Aeolus III (3 MW): proposed development of existing AEOLUS II wind turbine, not yet built, using permanent magnets.
- PMG designs (prototypes tested up to 120 kW): ferrite magnets, elegant modular design.

While it would appear optimistic to expect large mass or cost savings in large wind turbines purely by the introduction of a direct drive system, it is likely that in a fully integrated design (with common bearings for the generator rotor and wind turbine rotor) the simplification of design, provision of wide range variable speed and elimination of gearbox maintenance will all favour the continuing development of direct drive systems.

4.5 Multi-megawatt design

Although the wind industry has demonstrated the technical and commercial feasibility of units of about 1.5 MW, and larger wind turbines have been built, the present generation of megawatt machines may well be close to the economic limit of up-scaling. In some land based applications and in the offshore application especially, yet larger generating units are desirable.

Multi-rotor systems with a number of rotors on a single support structure are a possible route to units of 5 to 10 MW capacity for good economics with minimum innovation and development costs. Such systems have been under consideration for a long time and a few (very old) and a recent design of Lagerwey have been built. Recent research in the UK [8] and studies in the Netherlands [9], [10] over a number of years confirm interest in this concept.

It is apparent that there is considerable overlap in the issues of larger turbine design and design for offshore which is now discussed.

4.6 Offshore design

The next great leap for the wind energy industry will be in the area of offshore development. The potential for this technology is vast and it requires, and deserves sustained and substantial research and development support.

4.6.1 System concepts

Most European turbines operate with a blade tip speed less than 65 m/s principally in order to contain sound emission within acceptable limits. It has been recognised that if offshore wind turbines are remote from the coast and can be allowed increased sound emission, then there is considerable scope for reduction of the weight and cost of the turbines themselves. A tip speed of 100 m/s may be acceptable for offshore wind turbines.

As with sound, if there is some relaxation in concern about the near field visual effect for offshore wind farms, there is added potential for cost reduction in support structures and greater tolerance of more unusual design configurations that may have economic merit.

Thus the general view is that, if higher tip speeds can be exploited, the cost of the wind turbine component of the offshore system can be significantly reduced compared to land based designs. Obviously this is very desirable to help offset the increased costs of foundations and electrical transmission associated with offshore projects.

A key objective for the design of cost effective offshore wind turbines will be that inspection and maintenance requirements are reduced to a minimum. Design for high reliability will be an important priority with an emphasis on minimising long term operation and maintenance costs, possibly at the expense of a somewhat higher wind turbine capital cost.

4.6.2 Optimum unit sizes

The largest offshore wind farm in the world is the 17 MW Dronten wind farm (based on 600 kW units). This farm is, however, only offshore in the sense that it has its foundations in the water of an inland sea. According to various studies, larger machines of several MW need to be used to reduce generation costs.
Total array costs decrease by a factor of more than 2.5 for support structures for machines with rotor diameters in the range 50m to 100m [11]. The costs of electrical power collection and

transmission are also significantly reduced. Offshore wind turbines will have minimum tower heights determined by extreme wave and tidal statistics. Having fewer maintenance points and fewer interconnection between turbines per wind farm of given capacity will favour large wind turbines. The requirement for larger units of generating capacity is clear and possible technology for this was discussed in Section 4.4 Appendix.

4.6.3 Design tools for offshore wind turbines

There are at present very few design tools available which are capable of dealing with the combined wind and wave loading experienced by offshore wind turbines [12], [13]. There is an increasingly urgent need to validate analytical methods capable of the prediction of the loading and dynamic behaviour of offshore wind turbines. With the growing interest in offshore wind power over the last decade, there is a need to provide the manufacturing industry with design tools which can deal reliably with the complexity of combined wind and wave loading. As prototype offshore wind turbines are installed it is important therefore that detailed measurement programmes are undertaken to provide the data necessary for such validation work.

4.6.4 The future deep water offshore resource

There have been a number of studies throughout Europe to investigate the feasibility of floating wind farms installed in deep water. Various concepts for floating systems have been considered. The FLOAT [14] study undertaken in the UK investigated the outline design and costing of an offshore wind farm with floating turbines for water depths up to 100 m. According to this study, however, the cost of the floating platform, the cost of moorings and of transmission to land would seem to clearly indicate that floating wind turbine systems would only be exploited (if at all) in a second generation of projects after systems on sea bed foundations are generally established.

4.7 Grid integration

In order to meet the EWEA and, indeed, the EC targets which have been established for wind energy in the EU large scale penetration of the European grids will be required. To date this problem has been addressed in only a very superficial way. Research is required to determine an economic means of exporting electricity from the remote, wind rich areas of Europe to the more central areas of high load. National and Europe wide system studies are required as well as continued work to provide a better understanding of the interaction of wind turbines and the electrical system.

4.8 Hostile sites

In this context "hostile" is used to describe sites with environmental characteristics outside the normal, conditions which are presently being commercially exploited. There is little experience to date of low temperature, high turbulence or very high wind speed sites. Such sites often exhibit both extreme loading conditions and high energy yield and hence an improved ability to exploit them will provide significant benefits.

4.9 Hybrid systems

There has been relatively little attention to date to the integration of wind energy with other renewables. Such applications will be at a smaller scale than most of the other areas identified in this report when taken individually but when considered in total their contribution is substantial. There is enormous scope for application of hybrid systems: wind-photo-voltaic, wind-biomass, wind-diesel and desalination. This market is vast and largely untapped. It also offers a means of bringing energy to some of the most deprived areas of the world in an environmentally friendly fashion.

4.10 Standards and certification

The development of a harmonised set of internationally recognised standards and certification procedures has proved to be of vital importance for the building of confidence in wind energy. This point is particularly germane to the establishment of good relations with the financial sector. The process is now firmly under way but requires continuous improvement and refinement to keep pace with new developments in the technology. Continued research and development on this front is therefore required.

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