LONG-TERM RESEARCH AND DEVELOPMENT NEEDS FOR WIND ENERGY

FOR THE TIME FRAME 2000 to 2020

Ad Hoc Group Report to the Executive Committee

Of the

International Energy Agency Implementing Agreement for Co-operation in the Research and Development of Wind Turbine Systems

Approved by the IEA R&D Wind Executive Committee, October 2, 2001

The Implementing Agreement

This report on long-term R&D needs for wind energy was produced by the Implementing Agreement for Co-operation in the Research and Development of Wind Turbine Systems (IEA R&D Wind), which forms part of a programme of international energy technology collaboration which is undertaken under the auspices of the International Energy Agency (IEA).

The IEA is the energy forum for 25 industrialised countries established in 1974. Its mission, as adopted by Energy Ministers of IEA countries in their Shared Goals in 1993, is to create conditions in which the energy sectors of their economies can make the fullest possible contribution to sustainable economic development and the well-being of their people and of the environment. Research, development, and market deployment of new and improved energy technologies and international co-operation, including industry participation and co-operation with non-Member countries, are an essential part of the shared goals.

The IEA R&D Wind Implementing Agreement, begun in 1977, has provided a flexible framework for cost-effective joint research projects and information exchange on wind energy for the past 25 years. Member countries in 2001 were Australia, Austria, Canada, Denmark, European Commission, Finland, Germany, Greece, Italy, Japan, Mexico, the Netherlands, New Zealand, Norway, Spain, Sweden, the United Kingdom, and the United States.

The basis for the IEA R&D Wind collaboration is the national wind energy programs of the Member countries. By participating in IEA R&D Wind, Members exchange information on the planning and execution of national large-scale wind system projects and undertake collaborative R&D projects approved as annexes to the original Implementing Agreement. The activities of national programs and of the collaborative R&D projects, called Tasks, are reported each year in a 200-page Annual Report that is provided to Members for their distribution. Overall control of information exchange and the R&D Tasks performed under Annexes is vested in the Executive Committee (ExCo). The ExCo consists of a Member and an Alternate Member from each Member country that has signed the Implementing Agreement.

Collaborative Research

Each Task is managed by an Operating Agent, usually one of the contracting parties to the IEA R&D Wind agreement. Participants in a Task sign an Annex proposal agreeing to contribute funds to support the work of the Operating Agent and, often, to perform specific tasks in their own laboratories. The technical results of Tasks are shared among participating countries. Each participant receives results from the effort of five to ten participating research organizations—a very good return on investment. In 2001, Members of the IEA R&D Wind Agreement were working on five Tasks. Several additional Tasks are being planned as new areas for cooperative research are identified.

Task XI - Base Technology Information Exchange

Operating Agent: Swedish Defence Research Agency (FOI). Participants conduct Topical Expert Meetings and Joint Actions in specific research areas designated by the IEA R&D Wind ExCo. Participants also prepare documents in the series "Recommended practices for wind turbine testing and evaluation" by assembling an Experts Group for each topic needing recommended practices. For the latest meetings scheduled, visit http://www.vindenergi.foi.se/IEA_Annex_XI/TEM.html.

Task XVI - Wind Turbine Round Robin Test Program

Operating Agent: National Renewable Energy Laboratory - NREL, United States.

Task XVII - Database on Wind Characteristics

Operating Agent: RISØ National Laboratory, Denmark.

Task XVIII - Enhanced Field Rotor Aerodynamics Database

Operating Agent: Netherlands Energy Research Foundation, ECN, the Netherlands.

Task XIX - Wind Energy in Cold Climates

Operating Agent: Technical Research Centre of Finland.

Summary

The dawn of research and development (R&D) for using wind energy to generate electricity was technologically driven. Later, when the technology became more mature, other topics emerged such as those related to noise from wind energy systems, integration of wind generators into utility systems, public attitudes toward wind development, and the impact of wind developments on the environment. The benefits of past R&D in the wind energy sector have been clearly demonstrated by the increasing sizes of turbines and the lower prices per installed production capacity of electricity. Production costs of wind turbines have been reduced by a factor of four from 1981 to1998. Today, wind energy is cost competitive with other forms of electrical generation at locations with a good wind resource. The cost of energy from wind power at such favourable sites can be as low as 0.047 U.S. dollars per kilowatt hour (USD/kWh). The cost of wind energy in 2020 has been projected to be 0.025 USD/kWh. This projection is based on an installed capacity of 80 gigawatts(GW) in 2010 and 1,200 GW by 2020 [1].

Thanks in large part to successful R&D, the wind energy market is in a state of rapid development. The market for wind turbine generators is growing faster than the personal computer industry and almost as quickly as the cellular phone market. In the last three years, a number of growth studies have been presented about wind energy. In a study called Wind Force 10, a scenario has been presented for production of nearly 3,000 terawatt hours (TWh) of electricity from wind by 2020 [1]. This corresponds to around 11% of the expected world consumption of electricity in that year. Under this scenario, the annual investment requirements for achieving this goal would be 3 billion USD in 1999 and 78 billion by 2020. This level of development would increase employment in the wind industry and supplying sector from 82,000 people in 2005 to 180,000 in 2020. The environmental benefit from this scenario would be an annual reduction of CO_2 emissions by 2020 of 1,780 million tonnes.

Research and development has been an essential activity in achieving the cost and performance improvements in wind generation to date. During the last five years, company R&D has put emphasis on developing larger and more effective wind turbine systems utilising knowledge developed from national and international generic R&D programs. Continued R&D is essential to provide the necessary reductions in cost and uncertainty to realise the anticipated level of deployment. Continued R&D will support revolutionary new designs as well as incremental improvements. Researchers will improve understanding of how extreme wind situations, aerodynamics, and electrical generation affect wind turbine design. The challenge is to try to find those evolutionary steps that can be taken to further improve wind turbine technology. For example, in large-scale integration of wind turbines into the electric generation grid, incorporating wind forecasting results and information on grid interaction with other energy sources may eliminate uncertainties that would otherwise inhibit the development of the technology in the deregulated electricity markets.

Arguments for continuing support for long-term research were touched upon at an IEA R&D Wind Topical Expert Meeting in April 2001. One of the conclusions in the resulting report was:

> *"There is a consensus on the view that there still is a need for generic long-term research. The main goal for research is to support the implementation of national/international visions for wind energy in the near and far future. It was the opinion that it is possible to reach this goal for the near future with available knowledge and technology. However, large-scale implementation of wind energy requires a continued cost reduction and an improved acceptability and reliability. In order to achieve a 10 to 20% part of the worldwide energy consumption provided by wind, major steps have to be taken. The technology of turbines, of wind power stations, of grid connection and grid control, the social acceptability and the economy of wind power in a liberalized market, all have to be improved in order to provide a reliable and sustainable contribution to the energy supply. It is for this objective that there is a need for long term R&D. Besides that, there is also a need for a short- to mid-term research that mainly is in the interest of utilities/manufacturing industries and to some extent to society." [2].*

For the mid-term time frame, R&D areas of major importance for the future deployment of wind energy are forecasting techniques, grid integration, public attitudes, and visual impact. R&D to develop forecasting techniques will increase the value of wind energy by allowing electricity production to be forecast from 6 to 48 hours in advance. R&D to facilitate integration of wind generation into the electrical grid and R&D on demand-side management will be essential when large quantities of electricity from wind will need to be transported through a grid. R&D to provide information on public attitudes and visual impact of wind developments will be necessary to incorporate such concerns into the deployment process for new locations for wind energy (especially offshore).

For the long-term time frame, it is of vital importance to perform the R&D necessary to take large and unconventional steps in order to make the wind turbine and its infrastructure interact in close co-operation. Adding intelligence to the complete wind system and allowing it to interact with other energy sources will be essential in areas of large-scale deployment. R&D to improve electrical storage techniques for different time scales (minutes to months) will increase value at penetration levels above 15% to 20%.

There is a need for continued long-term research supported by society in addition to internal product development and research, which is carried out within the industry. These are the R&D priorities this paper recommends in the mid-term and long-term time frame.

1. Introduction

During the first 25 years of modern wind energy deployment, national R&D programs have played an important role in promoting development of wind turbines towards more cost effectiveness and reliability. The technology has been deployed by accompanying demonstration programs in co-operation with industry. Commercial turbine sizes have increased from some hundreds of kilowatts to 2 MW during this period. The interaction between industry and national R&D programs has been important for the development of effective turbines.

1.1 History of R&D

In the middle of 1970, the oil crisis prompted investigations of energy sources that were not based on fossil fuels. At that time, wind energy was considered to be one such energy source that had the possibility to reduce dependency on fossil fuels. The propeller-type, horizontal axis wind turbine was identified as the most promising system for converting the kinetic energy of the wind to electricity.

The efforts to develop effective wind turbines were carried out by two kinds of groups. The first one within governmental programs focused on big, multi-megawatt wind turbines that would be operated by utilities. The second group consisted of activists and entrepreneurs building small turbines, starting at 20 kW. Both groups discovered that designing wind turbines was far more complicated and costly than was expected in the beginning.

The design knowledge base was rudimentary or outdated, and the need for R&D was identified at an early stage. As a result, national R&D programs were initiated in many countries. The early studies conducted in these programs pointed out that existing knowledge in meteorology, electrical machinery, and aeronautical fields could be applied in wind engineering. The wind energy research organisations were, to a large extent, coupled to meteorological and aeronautical research institutes and universities. As time and knowledge developed, the research topics were directed more towards specific questions relevant for wind technology, such as wind modelling, resource assessment, aerodynamics, and structural dynamics. In order to demonstrate the application of the technology, a number of megawatt-size demonstration programs were realised in the beginning of the 1980s. The main objectives were to improve technology and system integration in order to demonstrate feasibility.
Commercial turbines appeared on the market around 1980 and coincided with the boom in market demand for small turbines (50 – 200 kW) in Denmark and California. In spite of the good market conditions, many companies went bankrupt due to technical problems and poor understanding of loads interacting with the wind turbine. The demonstration programs of megawatt-class machines in the United States, Germany, Denmark, and Sweden had problems mainly related to fatigue. These prototype turbines provided useful information of system behaviour that has been applied in later years.

Later in the 1980s, wind turbines became larger (250 – 300 kW). Market demand increased mainly due to subsidies and tax credits. However, an expected lifetime of 20 years was difficult to achieve due to reliability and system integration problems. The technology could not compete economically without support.

In the beginning of the 1990s, wind turbines became larger and were installed in small groups called wind farms. Increasing national R&D programs were promoting the trend towards larger turbines with a standard size around 500 kW. This period's engineering challenges were related to the bigger turbine size and the conditions turbines experienced in wind farms. Problems related to fatigue were reduced due to better understanding of the interaction between loads and structures. The market was turbulent – new companies appeared, smaller companies were purchased, new collaborations were formed.

During the rest of the 1990s, turbine sizes increased. At good wind sites, wind turbines started to become competitive with new traditional fossil fuel and nuclear generation. The number of turbines in each wind farm grew. As a result, the penetration of wind-produced electricity on the grid was high in some areas. This resulted in a need to develop knowledge of power quality and interaction with weak grids. In addition, there was the need to find new locations offshore and in complex

Source	Location	Cumulative installed [GW]	
		Year 2010	Year 2020
European Union White Paper, 1997 [6]	Europe	40	
EWEA, revised goals, 2000 [7]	Europe	60	150
IEA World Energy Outlook, 2000 [8]	Europe	34	67
BTM World Market Update, 2000 [5]	Europe	145	
Wind Force 10, Scenario, 1999 [1]	Europe	181	1,200

Table 1: Projections of installed cumulative capacity, year 2010 and 2020, in gigawatts

terrain where the wind resource was good. Around the world, new developments in standardisation and design codes were supporting market development and international trading.

In 1995, the need for continuing R&D was discussed at a Topical Expert Meeting sponsored by the R&D Wind Implementing Agreement of IEA. Some of the conclusions at that meeting were:

> *"... we have now reached a stage where the industry should be able to foot a larger share of the R&D bill. Also the fact that the industry has moved from the precompetitive phase into the competitive stage indicates that most of the product and component development should take place within the companies.*
>
> *However, there was consensus on the view that there is still a need for basic, generic research to be carried out outside the companies and wholly or partly funded by public money, and that this need will continue as long as there is wind energy develoment." [3]*

The conclusions at the 1995 meeting are still valid today. During the last five years, company R&D efforts have put emphasis on developing larger and more effective wind turbine systems utilising knowledge developed from national and international generic R&D programs.

1.2 Present and future markets

The Kyoto protocol has called for a decrease in the emission of CO_2 gases. Using wind energy to generate electricity can play a major part in achieving this target. At good wind sites, wind energy is already competitive with new traditional fossil fuel and nuclear generation. During the past five years, wind energy installed capacity has grown at around 30%/yr. At the beginning of 2001, generating capacity of 18.4 GW was installed worldwide (Figure 1). Production during 2000 was 37 TWh.

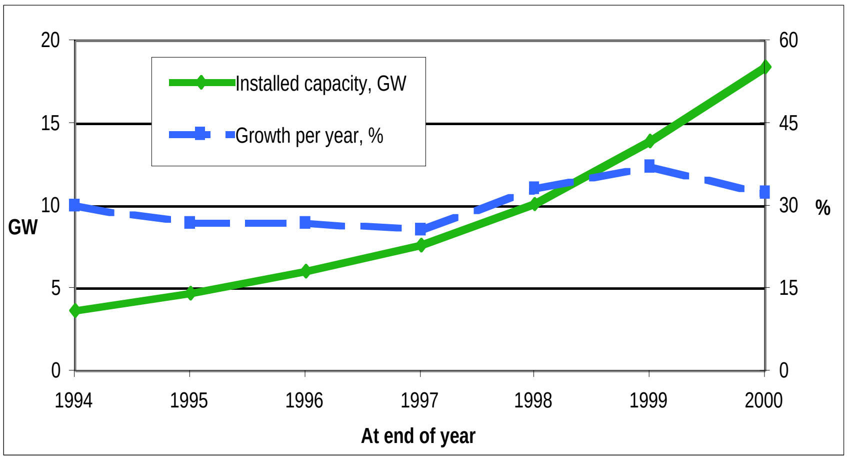

Figure 1: Installed cumulative capacity and growth rates per year [4, 5]

Predictions of global wind energy growth are published by many different organisations. In 1991, the European Union made a prognosis for the end of year 2001 of 4 GW. This was a great underestimate compared to the situation at the end of 1999, when 13.5 GW was already installed. Many other previous studies have shown such underestimations of the growth of wind energy capacity.
In the last three years, a number of growth studies have been presented (Table 1). Four of these are discussed in this paper.

The Wind Force 10 scenario for 2020 corresponds to a production of almost 3,000 TWh which is around 11% of the expected world consumption of electricity in that year. The annual investment requirements for achieving this goal, under this scenario, will be 3 billion USD in 1999, reaching a peak of 78 billion in 2020. This will increase employment in the wind industry and supplying sector from 82,000 people in 2005 to 180,000 in 2020. The environmental benefit from this scenario will be an annual reduction of CO_2 emissions by 2020 of 1.8 million tonnes.

The large spread in predictions for the future (Figure 2) probably result from the fact that wind energy is a relatively young technology. Compare, for example, trying to predict the future of the automobile in 1910 or of the Internet in 1990.

Another way to evaluate the current growth compared to other businesses is found in the Worldwatch Institute book *Vital Signs 2000* [9]. The authors make the following observations.

- The wind turbine industry is now growing faster than the personal computer industry, and almost as quickly as the cellular phone market.
- As of early 2000, eight countries—all in Western Europe—had raised taxes on environmentally harmful activities and used the revenue to pay for cuts in taxes on income.

For the future, Worldwatch stated the following:

> *"If wind energy achieves its goal of supplying 10% of the world's electricity in 2020, this may only be part of the story. By 2020, wind-derived hydrogen could be fuelling many of the world's cars, factories and even jet airlines."*

1.3 Cost reductions

Today's wind turbines are similar in layout and design to the ones produced 10 to 15 years ago. But a number of steps have been taken in order to improve

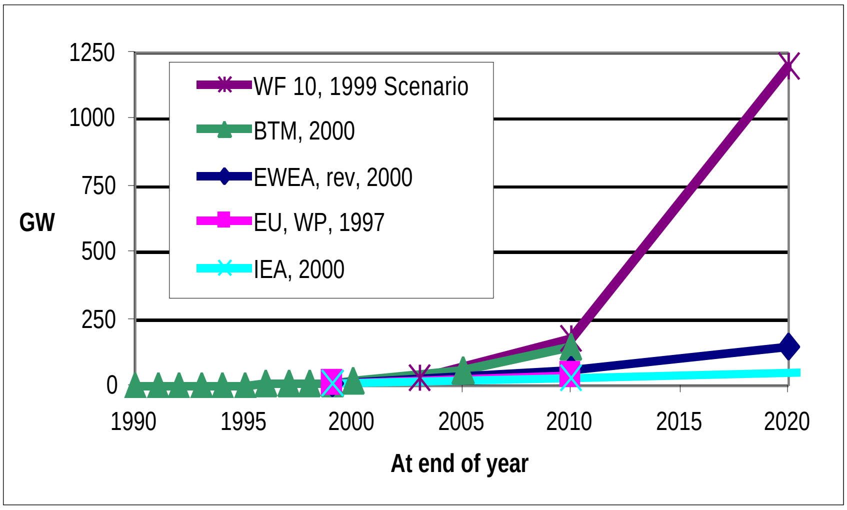

Figure 2: Actual (to end of 2000) and predictions of installed capacity, in gigawatts

the efficiency and to reduce cost. Examples are:

- Larger size
- More efficient use of materials
- Directly driven generators
- Improved system integration
- Flexible structures
- Control advancements

The cost of electricity produced from wind energy has decreased dramatically. Data from wind farms in California show a reduction from 0.45 USD/kWh in the early 1980s to less than 0.10 USD/kWh in the early 1990s [4]. Similar experiences have been reported from Denmark, where the cost has been reduced by a factor of almost four from 1981 to 1998 (1.2 to 0.3 DKK/kW). National research and demonstration programs combined with commercial programs have played an important role in supporting these improvements. Accepted values for the cost level of wind energy in 1999 follow.

Total investment cost:
1,000 USD/kW
Unit price, electricity:
0.047 USD/kWh

Recent studies by BTM in 1998 and 1999 apply learning-curve theory and assumptions and combine historical figures to project future cost reductions. (Figures 3 and 4) [4]. However, the results of the projections must be treated with caution, since they are based on a number of different assumptions and do not account for large technological steps.
The same study estimates sources of future cost reduction on wind power until 2004 (Table 2).

The most important contributor to cost reduction is assumed to be the economy of scale, which stands for half of the relative cost reduction. Contributions from improvements in design and performance are assumed to be 40%. This figure will be dependent on how successfully future R&D can be utilised in new machines.

2. Why continue long-term R&D?

In the first years of R&D (beginning of the 1980s), research institutes and universities produced more knowledge than the industry could handle. Research was mainly aimed at applying existing knowledge to the field of wind energy.

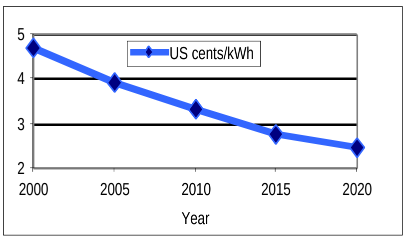

Figure 3: BTM Projected cost of energy [4]

Now, market-driven upscaling and offshore applications produce more uncertainties than the researchers can solve with current knowledge. Future research has to address the specific problems related to this engineering technology.
Examples are electricity generation, grid interaction, aerodynamics, and structural dynamics, where specific questions of three-dimensional (3D) flow and large rotating structures have to be addressed.

The argument for supporting long-term research in the future was touched upon at an IEA R&D Wind Topical Expert Meeting in April 2001. One of the conclusions was:

"There is a consensus on the view that there still is a need for generic long-term research. The main goal for research is to support the implementation of national/international visions for wind energy in the near and far future. It was the opinion that it is possible to reach this goal for the near future with available knowledge and technology. However, large-scale implementation of wind energy requires a conti-ued cost reduction and an improved acceptability and reliability.

In order to achieve a 10 to 20% part of the worldwide energy consumption provided by wind, major steps have to be taken. The technology of turbines, of wind power stations, of grid connection and grid control, the social acceptability and the economy of wind power in a liberalized market, all have to be improved in order to provide a reliable and sustainable contribution to the energy supply. It is for this objective that there is a need for long-term R&D. Besides that, there is also a need for a short-to mid-term research that mainly is in the interest of utilities/manufacturing industries and to some extent to society." [2].

In the text below, the following four categorisations are used as reasons for continuing R&D work:

- Increase value and reduce uncertainties
- Continue cost reductions
- Enable large-scale use
- Minimize environmental impacts

In addition, human resource development plays an important part in all the topics above and must also be one of the objectives for supporting R&D work. Skilled people in different disciplines and at varying education levels will play an essential role in the steady growth of the industry and deployment of this energy source.

Source of Cost Reductions	Relative Share (%)
Design improvements — weight reduction of wind turbine generators	35
Improved performance — improvement of conversion efficiency (aerodynamic and electric)	5
Economy of scale/manufacturing optimisation	50
Other contributions: foundations/grid connection/operating & maintenance cost	10

Table 2: Sources of future cost reduction on wind power from 1999-2004 [4]

2.1 Increase value and reduce uncertainties

2.1.1 Forecasting power performance

The value of wind energy will be increased if reliable predictions of power output can be made on different time scales, such as 6 to 48 hours in advance. This requires model development and strategies for online introduction of data from meteorological offices as well as actual production figures from wind turbines in large areas. The present models have an uncertainty of 15% to 20%; an improvement will yield 5% to 10%.

2.1.2 Engineering integrity, improvement and validation of standards

The market-driven upscaling and offshore applications require better understanding of extreme environmental conditions, safety, power performance, and noise.

The development of international standards will be essential for the successful deployment of wind energy in different countries. This work will help remove trade barriers and facilitate free trade. R&D activities in many fields of wind engineering will support background basics for standardisation work.

2.1.3 Storage techniques

Effective storing of electricity could enhance the value and reduce the uncertainty of wind-generated electricity through the levelling out of delivered power. This consideration is especially important when penetration levels rise above 15% to 20%. There is a need for different storage techniques at different time scales (Table 3).

2.2 Continue cost reductions

2.2.1 Improved site assessment and identifying new locations, especially offshore

Sites with high winds are crucial for economic utilisation of wind energy. The fact that energy production is related to mean wind speed to the power of 3 is not sufficiently recognised. This means that a 10% increase in wind speed will result in 33% more energy gained. Improved site assessment and siting will require better models and input from measurements.

Better measures to predict extreme wind, wave and ice situations at different types of locations and in wind farms will eventually result in lighter and more reliable machines. This will make it possible to design site-specific systems that eventually will produce cheaper and more reliable turbines.

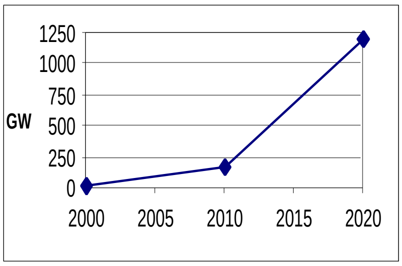

Figure 4: Cost reductions are based on total installed capacities, in gigawatts

2.2.2 Better models for aerodynamics and aeroelasticity

Improved methods for predicting 3D aerodynamic behaviour and aeroelastic stability are essential for calculation of loads on turbines. With the increasing size of turbines, new stability problems can occur. Solving the aeroelastic problems is a prerequisite for reliable upscaling. Incorporation of such models in aeroelastic models of the whole wind turbine is essential for optimised turbines that eventually will have lower weight and thus price.

2.2.3 New intelligent structures/materials and recycling

Wind turbines operating in the wake of another turbine will be exposed to excessive loads due to deficits in wind speed behind the upstream turbine. Reduction of loads through improved design and adding intelligence to single wind turbines in a wind farm will make it possible to optimise the use of land. Intelligent materials utilising adaptive control and interacting with the structure can be used to reduce strains and/or to control aerodynamic forces.

Development of new materials that can be part of a natural recycling process will increase the value and decrease environ-

Time scale	Function	Technology
Minutes	Fault protection	SMES, capacitors
Hours	Backup, smoothing, prediction	Batteries, flywheels, hydrogen
Days	Smoothing, prediction	Regenerative fuel cells, pumped hydro
Weeks	Smoothing, prediction	Regenerative fuel cells, pumped hydro
Months	Smoothing, prediction	Hydro storage, hydrogen storage (e.g., CH_4 creation from coal)

Table 3: Storage techniques for different time scales

mental impact of wind turbines. For example, new ways to decommission glass fibre blades must be developed.

2.2.4 More efficient generators, converters

Finding viable concepts and improving the design of direct-driven generators has great potential to make more efficient and lighter machines. Present generator technology results in large and very heavy machines.

It is also important to find combined solutions for generation and transmission of electricity, from low-voltage alternating current (AC) to high-voltage direct current (DC), while also achieving adaptable power factor (cos phi), and high power quality (low harmonic content and flicker frequency). By adding power plant characteristics to individual wind turbines, it may be possible to reduce the cost for transmission lines. Spinning reserve may also be utilised.

2.2.5 New concepts and specific challenges

Specific challenges include fly-by-wire concepts, adding intelligence to the turbine, and incorporating aspects of reliability and maintainability. Condition monitoring of components such as blade bearings and generators could reduce operations and maintenance costs. This is especially interesting at remote locations on land and offshore.

New concepts could include such things as highly flexible downwind machines and diffuser-augmented turbines.

2.2.6 Stand-alone and hybrid systems

Stand-alone turbines will be built in vast numbers, but the installed total capacity may not be large. However, the value of electricity from these machines can be of great importance, such as in remote locations where grid connection is not feasible.

System integration of wind generators with other power sources such as photovoltaic solar cells (PV) or diesel generating systems is essential in small grids where high reliability is required.

In the mid-term and long-term time frames, research will be needed on the interaction of wind turbine generators with the transmission and distribution grid. Photo: Sven-Erik Thor

2.3 Enable large-scale use

Projections of installed capacity indicate that deployment figures will increase dramatically during the next 20 years. The contribution of wind generation will be substantial on a local and/or national level. This will put special demands on the transmission grid and its interaction with the wind turbine generation units.

2.3.1 Electric load flow control and adaptive loads

Development of tools for modelling and controlling energy supply to the electric grid will be essential to large-scale deployment of wind energy, especially in areas where the share of wind energy is high. Combined technologies for generation and transport of large amounts of electricity will incorporate innovations in automatic load flow controls, adaptive loads and demand side management. Extensive use of high-capacity power electronic devices in national networks for high-voltage DC (HVDC) links will also be required.

There will be a need to study concepts for storage and AC/DC concepts in co-operation with other energy sources.

2.3.2 Better power quality

The ability to correct grid deficiencies, especially in weak grids, must be improved. Examples are voltage drops and flicker. Grid stability will also be a main concern.

2.4 Minimize environmental impacts

Finding suitable places where there is also general acceptance for implementation of wind turbines has become more and more complicated. Conflicting goals for use of the landscape by different interest groups is becoming more pronounced.

2.4.1 Compatible use of land and aesthetic integration

The environmental advantages of wind energy, such as reduced emissions of CO_2 and other greenhouse gases must be conveyed to the public. Public attitudes towards wind energy, as well as the influence from visual impact and interacting use of the landscape by different interest groups, have to be incorporated in the process of deployment.

2.4.2 Noise studies

Understanding of noise generation and transportation over large distances is essential. Challenges offshore are related to the acoustically hard water surface. Initial estimations that wind turbines may emit more noise offshore without disturbing onshore dwellings must be studied. Better knowledge and methods for design and prediction of noise must be validated to actual experiences.

2.4.3 Flora and fauna

Interaction between wind turbines and wildlife must be incorporated in the deployment process. This requires better understanding of background data and the behaviour of different species. This holds for both onshore and offshore application.

3. Conclusions and recommendations

Wind energy is not just a short-term solution to the energy needs of the world. On the contrary, wind energy is an integral and growing part of the energy supply system that will meet energy needs in an environmentally friendly way for the long term. To assure wind energy's contribution, short-, medium-, and long-term technology R&D are needed. Such R&D will increase benefits to society by making best use of its resources. R&D will accelerate the development of this cost-effective technology and promote system integration for various applications. In addition, R&D on the implementation of large-scale wind energy will help balance society's interests by promoting the design and control of energy systems appropriate to the energy market.

In the near-term and mid-term time frames, research will be needed to help find compatible land uses. Photo: Gunnar Britse

The main challenges for R&D efforts are to reduce technical uncertainties related to energy production, durability, and acceptability for future wind energy projects all over the world. R&D should continue development towards reliable and cost-optimised technology with improved power plant characteristics (power regulations, shared responsibility for power system stability, etc.). R&D should develop wind turbine technology for future applications such as large, highly reliable machines for offshore applications in shallow or deep waters; silent, "invisible" machines for distributed installations on land; or simple, easily maintained hybrid systems for smaller, isolated communities. R&D should develop technology that facilitates the integration of this variable energy source into energy systems such as HVDC transmission lines, energy storage technologies, and compensation units (voltage, frequency, power factor, phase imbalance, etc). And finally, R&D should develop methods to forecast electricity production from wind energy systems and to control wind power plants for optimal production and distribution of electricity.

In the mid-term time frame, research to help minimize environmental impacts of wind turbines will be needed.

Photo: Gunnar Britse

Similarly, there are challenges related to implementation uncertainties that can be addressed through R&D. Improved information can facilitate physical planning to optimise land use and minimise negative effects to people and nature. Improved understanding will help develop suitable markets (green certificates, fixed prices or others). R&D results can also help the integration of wind energy systems with distributed generation, which accommodates the varying production from most renewable energy sources through load control, energy storage, or international energy trading and transmission.

The overall aim of future research is to support development of cost-effective wind turbine systems that can be connected to an optimised and efficient grid or be used as non-grid-connected turbines. Future R&D will support incremental improvements in, for example, understanding extreme wind situations and reducing system weight. But, the challenge is to try to find those revolutionary steps that can be taken to further improve wind turbine technology. For example, in large-scale integration of wind generation into the electric grid, incorporating wind forecasting and coordinating grid interaction with other energy sources could speed deployment of wind energy.

In addition to challenges associated with the integration of the technology to produce electricity, wind energy could be used to produce other energy carriers, such as hydrogen. Wind energy technology has traditionally been used in producing electricity and will continue to do so in the future. But innovative concepts in hybrid systems and storage techniques may benefit other sectors of the economy—e.g., in transportation both on land and in the air.

For planning purposes, the time frame for research results to be obtained is divided into three different periods:

1. Short-term, 0–5 years—system development, human resource development, etc.
2. Mid-term, 5–10 years—mix of 1 and 3
3. Long-term, 10–20 years—increasing the value of wind, supporting strategic goals, etc.

In Table 4, the focus is on the last two time frames.

In the mid-term and long-term time frames, research will be needed to develop storage for electricity and to forecast when electricity will be generated. Photo: Gunnar Britse

3.1 Mid-term time frame

The research areas of major importance in the mid-term time frame for the future deployment of wind energy are forecasting techniques, grid integration, public attitudes, and visual impact.
Forecasting techniques will increase the value of wind energy by the fact that production can be forecast, for example 6 to 48 hours in advance. Integration of wind generation into the electrical grid and demand-side management will be essential when large quantities of electricity from wind will be transported in a grid. This is so because most existing grids are not suited for such large. quantities of power. Finding new locations for wind energy will require that public attitudes and visual impact are incorporated in the deployment process.

3.2 Long-term time frame

For the long-term time frame, it is of vital importance to conduct research that leads to large and unconventional steps in order to make the wind turbine and its infrastructure interact in close co-operation. Research that results in adding intelligence to the complete wind system, interacting with other energy sources, will be essential in areas of large deployment. In addition, developing storage techniques for different time scales (minutes to months) can increase value at penetration levels above 15% to 20%.

Research Area	Focus On	Time Frame/ Priority		Present Activity in IEA R&D Wind
		Mid-term	Long-term	
Increase value and reduce uncertainties				
Forecasting power performance	Increase value of electricity	++		Topical Expert Meeting 2000
Reduce uncertainties related to engineering integrity, improvement and validation of standards	Supply background material	++		Topical Expert Meeting 2001
Storage techniques	Storage for different time scales		++	
Continue cost reductions				
Improved site assessment and new locations, especially offshore	Extreme wind and wave situations, forecasting techniques	++		Annex XVII Wind Characteristics
Better models for aerodynamics/aeroelasticity	3D effects, aeroelastic stability	++	++	Annex XI Joint Action on Aero
New intelligent structures/materials and recycling	Extremes, adaptive intelligent structures, recycling		++	Topical Expert Meeting 2002
More efficient generators, converters	Combined solutions for generation and transmission	++	+	Topical Expert Meeting 2001
New concepts and specific challenges	Intelligent solutions for load reduction		+	
Stand alone and hybrid systems	Improved system performance	++		
Enable large-scale use				
Electric load flow control and adaptive loads	Improve models, load flow control, power electronics		++	
Better power quality	Power electronics	++		Recommended Practice
Minimize environmental impacts				
Compatible use of land and aesthetic integration	Information and interaction	++		Topical Expert Meeting 2002
Noise studies	Offshore issues	++		Topical Expert Meeting 2000
Flora and fauna	Background data	++		

++ Denotes high priority + Denotes priority

Table 4: Research priorities in the mid- and long-term time frames

4. References

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This document presents recommendations of the Implementing Agreement for Co-operation in the Research and Development of Wind Turbine Systems (R&D Wind) that operates under the auspices of the International Energy Agency (IEA). Work to develop this document began when IEA's Renewable Energy Working Party (REWP) asked the Executive Committees of Implementing Agreements dealing with renewable energy to contribute to a workshop on long-term research needs and to identify R&D issues that cut across implementing agreements.

The members of IEA R&D Wind then proceeded to develop a guideline for the long-term research needed to advance wind energy technology. A first step was to hold a meeting of experts on the subject of long-term R&D needs. Topical Expert Meetings are convened on important research topics several times per year under Annex XI to IEA R&D Wind, Base Technology Information Exchange. After the Experts Meeting, an ad hoc group wrote the first draft of this document, which was then reviewed by all members of IEA R&D Wind. This final version incorporates their valuable comments and has been approved by the Executive Committee of the IEA R&D Wind Implementing Agreement.

The next challenge is to design and carry out research and development projects to address the specific topics outlined in this document. The members of the IEA R&D Wind Implementing Agreement will use this document to identify areas for co-operation to mutual advantage. In addition, it is hoped that other research organizations will find this document useful in setting their own research agendas to advance wind energy technology.

For more information on the work of IEA R&D Wind or an electronic version of this document, visit the following Web sites: www.afm.dtu.dk/wind/iea/
www.iea.org

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