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Discussion

Current Direction of Danish Wind Energy Research—The Researchers Point of View

Flemming Rasmussen and Peter Hauge Madsen
Risoe National Laboratory, P.O. Box 49,
DK-4000 Roskilde, Denmark

Introduction

With an installed wind turbine capacity that, in a normal wind year, will supply 20% of the national electricity demand and a wind turbine industry that supplies 40–50% of the world market and employs a total workforce of 20,000, the wind energy sector in Denmark is of national importance and stirs strong international interest. The development of the Danish wind energy sector has been supported and promoted by 25 years of continuously focused publicly funded research and development; an effort that has seen profound changes during the last couple of years. The paper reviews the background and discusses the current direction of the Danish wind energy research.

The Energy Scene

Wind power has maintained its status as the World's fastest growing energy source during recent years. Installed capacity has, over the last 5 years, grown at an annual rate of nearly 30%. By the beginning of 2004, global wind power installations had reached a level of 40,000 MW, of which 8,300 MW alone was added during 2003. Europe accounts for 74% of this capacity, although almost 50 countries now contribute to the global total. It is estimated that nearly 100,000 people world-wide are employed by the industry.

The possibilities for wind energy should be seen in the following context:

The ability to maintain the energy supply is important for the stability of the modern society. The importance of easy access to the exploitation of hydrocarbons for the evolution of human culture can hardly be overestimated (see, for example, Hall et al. [1]) and the world has become heavily dependent on enormous flows of cheap oil. There are considerable political and social uncertainties that could result in less oil being available than existing models predict. At the same time, the limited oil reserves will show an effect at some point of time in the foreseeable future, creating a high risk of volatile energy prices and unreliable energy supply.

In this context, wind power could be seen as having a role for establishing economic stability of society. The reliability of wind power on a short-term basis is not high, but the energy supply and cost of energy from wind on an annual or longer basis is highly predictable. In this perspective wind power should be seen as providing the base load. This point of view is also realistic for the power system. Consider, e.g., a wind power plant and a hydro power station, possibly including also high efficiency pumped storage. In such an integrated power system the best use of the wind power plant is to deliver the base load. This perception could be extended to systems with fossil fuel power plants, in which the fossil power plant should be used only when power from storage is needed to cover the difference between the demand and the wind power plant production. This means that wind power has first priority or is base load, and the concept of saving an ever increasing amount of fossil fuels with the continuous development of the power system is introduced.

In this perception the possibilities for wind energy are enormous; they are emphasized further if the predictability of the wind energy supply is taken into account in the financial analysis of energy investments (see Awebuch [2]), thus advancing the competitiveness of wind power. According to Wind Force 12 [3], based on realistic assumptions of a continuation of the last 10 years growth until 2020, the wind power market will by then be 151,000 MW annually, representing an annual investment of 75 billion euros. In this scenario wind power will produce 12% of the World's electricity consumption by 2020, by which time the consumption is assumed to be doubled compared to the present days total consumption of 15,000 TWh/year. The technological vision is to reduce the cost per produced kWh of wind power by 40% compared with 2002.

It has been estimated in Wind Force 12 that the world's exploitable wind resources on land are 53,000 TWh annually. In order to get an impression of the area needed to produce the World's present total electricity consumption of 15,000 TWh/year, this could be done (in a fictitious scenario) in The Great Plains in the United States in a square of the order of 1000 km by 1000 km in which 98% of the land is still available for agricultural use.

The total installed wind power capacity in Denmark by the end of 2003 was 3115 MW, which is nearly double what was anticipated for 2005 in ''Energy 21,'' the official Danish energy plan from 1996. Of this capacity, 2708 MW is installed onshore and 420 MW offshore. The offshore installations constitute more than 80% of the total installed offshore capacity in the world. Nearly 20% of the total electricity consumption (35.2 TWh in 2003) is generated from wind power in a year with normal wind conditions. In spite of the growing total capacity, the number of wind turbines is decreasing due to a re-powering scheme. The average size of the new installed wind turbines has grown gradually, from 750 kW in 1999; to 889 kW in 2000 and 2001; to 1.36 MW in 2002 and to 2 MW in 2003.

The societal effect of the wind turbine industry has become very important with a total turn over for 2002 of more than 21 billion DKK, and 21,000 people employed. Danish wind turbine industry maintained a world wide market share of 40–50% in 2002 and 2003.

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In 2003, offshore installations accounted for 196 MW, whereas onshore capacity only increased by 29 MW. The offshore wind farms illustrate the global trend that wind energy is evolving into large power plants in a market dominated by professional power sector corporations rather than by individual investors.

A possible constraint to the future deployment of wind energy into the Danish energy system is maintaining the power balance or dealing with the electricity surplus. Due to the high share (approximately 50%) of electricity from combined heat and power (CHP) and the high share (approximately 20%) from renewable electricity (mainly wind power), a substantial part of the Danish electricity production is directly dependent on weather conditions (outdoor temperature and wind speed). This limits the system's ability to adapt to quickly changing electricity prices on the market but also demonstrates the role of wind energy (and CHP) to provide base load, while the traditional power plants provide ''storage'' capabilities and satisfy the peak load demand. Power balance and system stability, however, are facilitated by Denmark being connected to the hydro plants in Norway and Sweden and connected to the German electrical grid.

Wind power's unique position to exploit the 12% world power penetration possibility has been achieved as a result of 25 years of development of the wind energy industry, the technological level and the research capacity. However, the growth opportunity contains a number of challenges with respect to creation of an efficient innovative research environment and requires action in terms of reducing the technical uncertainties associated with the further up-scaling and optimization of large wind turbines. Assuming that the present rate of development will continue, 10 MW turbines can be expected by the year 2010. Analyses show that this size is still below ''the physical limit,'' at least by a factor 2–4. In total, wind power has the potential, through a united effort, to become the cheapest, environmentally best and most accessible low-risk ''base-load'' provider in the power system.

Policy Developments (Danish Policy)

In the 1980s and the 1990s, Denmark implemented vigorous energy policies with broad political support involving a broad range of actors: energy companies, industry, municipalities, research institutions, nongovernmental organizations (NGOs) and consumers. Both demand-pull policy instruments (financial and other incentives) and technology-push policy instruments (research, development and demonstration or R, D & D programs and certification schemes) have been used as tools in the strategies.

Danish wind energy research has, since the beginning, been planned and conducted in close dialogue and cooperation between the public authorities, the research community and the industry. Another important part in this dialogue has been the consumers or wind turbine owners, which used to be private persons represented by the organization of wind turbine owners, but now is mainly utilities or large energy companies. This is considered one of the reasons for the success of the Danish wind power industry. In addition, however, continuous political support of, e.g., wind energy research is considered more important than the actual size of the public funding. The Danish public funding has been, on average, around 4% of the world's total funding of wind energy R & D; during the 1990's it was between 5 and 10%, however.

The technology-push instruments have been reduced in conjunction with the development of a liberalized market for electricity, including wind energy. The new government changed its focus for support of R, D & D in 2002. Funds for the Energy Technology Program were reduced, and the special Development Program for Renewable Energy Sources was stopped in 2002. Likewise, the plans for further three offshore wind farms were cancelled.

In place of these programs the government introduced a new overall strategy for renewable energy research, which will be implemented over the coming years.

The Danish government's policy today is to strengthen the use of market-based instruments in the energy sector. In its 2002 strategy for liberalization of the energy markets, the government emphasized the need to increase competition in the energy sector and to encourage cost efficiency in renewable energy plants. In its 2003 climate strategy, the government again emphasized cost efficiency and prioritized the most cost-efficient instruments for carbon dioxide reduction. The instruments planned to support wind energy are: (1) providing economic incentive to gradually change to market prices with the ''electricity plus environmental bonus,'' (2) strengthening fundamental research, and (3) offering tenders for offshore wind.

Policy goals have always been driving forces for the wind power development in Denmark. Energy, climate, research, and industry policy goals have been the basis for the wind energy deployment and thus the public research. The present energy policy builds on a *vision about well functioning energy markets supported by a legal, policy and administrative framework that will ensure high consumer and environmental protection, efficient energy consumption, moderate development in energy cost and a high degree of security of supply in both the short and long term*. However, the objective is, above all, to ensure that electricity is produced and sold under market conditions—without support. Security of supply has become higher priority the last few years.

For Denmark, special attention is given to the wind industry due to its export and employment importance. The industry is considered a knowledge-based industry with potential to contribute to the political goals of economic growth and further development of welfare in Denmark. It is, in general, the policy of the government to promote the development of promising new energy solutions and corresponding strong research environments. Reviews under the Ministry of Economy and Industry have identified wind energy as one of the most important industrial clusters in Denmark and extended exploitation of wind energy as one of the most promising and strategically important technologies for Danish industry.

On 29 March 2004 the Minister for Economic and Business Affairs in Denmark entered into an agreement with six of the coalition parties for the construction of new offshore wind farms and the replacement of wind turbines in unfavorable locations with new wind turbines in other places. This agreement also calls for increased research and development and demonstration of advanced energy technologies.

The Danish Energy Authority (DEA), under the Ministry of Economic and Business Affairs, is responsible for the administration of the strategic research program known as the Energy Research Program (EFP), and is assisted by the Advisory Council for Energy Research (REFU). EFP is intended to contribute to establishing the technological foundations required for the practical implementation of Danish energy policy and focuses on applied research to be carried out in collaboration between public research institutions and private businesses. The EFP has been of particular importance to the role of research in the development of the Danish wind turbine industry. For 25 years EFP has continuously funded wind energy R & D activities in Denmark with wind energy technology as a specific target area. These activities have ranged from establishment of fundamental expertise within topics such as aerodynamics, aero-elasticity and wind power meteorology to certification and standardization and very applied research for specific development and demonstration work. The primary instrument has been financial support to specific R & D projects, but a 5-year program comprising basic research like the development of CFD dedicated to wind turbine applications has also been supported.

Since the change of government in late 2001, the program has been in a transition phase, and the budget for the EFP in 2002 and 2003 has been 40 million DKK, which is only one-third that of previous years. The targeted areas have been renewable technologies such as biomass, wind energy, PV, fuel cells and storage.

However, for 2004 and forward the budget has been increased to 72 million DKK, and a new strategy for energy research is under development. The declared goal is a research program that focuses on the development of a sustainable energy system, rather than the development of specific technologies. While the various technologies must compete for research funding, the Danish Energy Authority, together with the administrators of the PSO-funds, are in the process of developing research strategies for selected technologies, including wind, to be used in the appraisal of proposals. The wind energy strategy priority areas are strongly influenced by the research strategy developed by the Danish research Consortium for Wind Energy (discussed later) but includes also environmental aspects and recycling, IEA cooperation and studies.

The Public Service Obligation (PSO) research program for environmentally friendly energy technologies is administered by the transmission system operators Eltra and Elkraft System. The PSO offers financial support for research, development and demonstration of such technologies as wind, where the research focus is on integration of wind power and exploitation of measurements and experiences from ongoing offshore wind farm projects. Wind energy R & D is only a minor part of this program, and wind proposals must compete with proposals on other technologies and applications.

According to an agreement reached in 2002 between the government and the opposition, an amount of 125 million DKK (35 million DKK in 2003 and 45 million DKK in 2004 and 2005) has been devoted to strategic renewable energy research projects. The Ministry of Science has asked the newly formed Council for Strategic Research to administer the funds. The program funds long-term research on an international scientific level based on original research ideas, and includes research on all renewable energy technologies, addressing technical, health, societal, economic and political aspects. In addition, the national research councils may provide additional funds for energy research.

The available funds dedicated for energy technologies research, including wind energy, are shown below (figures in million DKK).

	2003	2004	2005
Energy Research Program (EFP)	40,7	71,8	71,8
PSO-electricity production	100	100	130
Renewable energy R & D–Danish Ministry of Science	35	45	45
Total	175,7	216,8	246,8

All in all, the recent development in the Danish energy research is positive. However, it seems clear that the public research programs no longer will take the responsibility for a coherent and continuous long-term development of wind energy technology and its application.

Focus and Organization of Danish Wind Energy Research

In order to address this trend, enhancing the technical competencies in the wind energy research community and exploiting the cooperation and synergy between research and education, Risø, together with the Technical University of Denmark (TUD) in Lyngby, Aalborg University (AAU), and the Danish Hydraulic Institute (DHI) in May 2002 formed the Danish Research Consortium for Wind Energy. Together, these institutions provide more than 90% of the active wind energy researchers outside the industry. This relationship builds on existing close co-operation with TUD on aero-elastic design and with AAU on electrical design. The cross-disciplinary consortium is intended to improve the network and coordination between research, education, and industry. The research is planned and implemented around the following themes: (1) climatic conditions; (2) wind turbine design; (3) electrical systems; (4) control and integration; and (5) society, market, and energy systems.

The consortium was formed through a five-step process. First, a strategic analysis of the pros and cons of a consortium was carried out in consultation with the industry by the parties together with a consultant. Second, an inventory of technical competencies and ongoing wind energy research among the parties was compiled. Third, the framework for a joint research plan was developed. Fourth, a formal agreement on cooperation between the parties was drawn up and signed. Fifth, a Governing Board or Steering Committee comprising the management from the four institutions, the wind energy industry and the power companies was formed to oversee the operation of the consortium, approve plans and results and provide advice on consortium activities.

In addition to common research planning and project implementation between the consortium partners, the aim is to accelerate, by pooling resources, the education of engineering candidates and PhD's. The PhD program was initially stimulated by a grant from the Council of Researchers Education to a national research school, the Danish Academy in Wind Energy, with the purpose of strengthening the education of doctoral candidates and attracting visiting students, researchers, and professors.

During its second year the Research Consortium initiated the development of a common strategy for wind energy research in order to focus the effort and facilitate the joint annual planning of research, education and communication activities.

This common strategy is based on a vision for the wind power plants of the future; a vision in which wind power is far from a temporary solution. Instead, by the year 2020, the vision calls for wind power to supply 10% of the electricity demand world-wide and represent an advanced energy technology for sustainable development. The wind industry is widely respected and integrated into the industrial complex and of great societal importance. The industry is based on an established research and education system in analogy to ''Aeronautical Engineering,'' which, to some extent, contains similar research disciplines.

The technological vision of the wind turbine of the future is of a highly advanced, multi-controllable, flexible and adaptive concept, characterized by its high content of advanced knowledge. The wind turbines are adapted to nature and the environment in shape and function and appear in a sustainable life cycle. The wind turbine blades, in particular, are constructed of bio-based or recyclable materials utilized to the limit and integrate multi-functional properties for adjustment of shape and function. The turbine is ''intelligent'' and optimizes operation and production for local conditions and application, using computer controls or neural networks. The size and technology is optimal for local conditions and application, with highly reliable and very large (20–40 MW) wind turbines for wind farms for offshore and remote areas and medium sized machines with minimal environmental impact for distributed installations on land.

Wind turbines are seen as integrated elements in a power system designed for a predominant supply from wind and other renewable energy sources. The turbines are interconnected to a grid with both decentralized and centralized control of, e.g., rotation speed and power output to adjust for wind, grid or market conditions and to function as power plants with power plant characteristics (voltage and frequency regulation, shared responsibility for power system stability, etc.). Technologies such as HVDC transmission system, energy storage technologies, compensations units (voltage, frequency, power factor, phase imbalance, etc.) and production forecasting and control of the wind power plants are developed that facilitate the integration of variable energy sources into the energy system.

The strategy assumes that within a time frame of 10–15 years the wind turbine technology diversifies into three development lines:

- Multi-MW ($>$5 MW) wind turbines for large wind power plants offshore or in remote areas,
- Medium sized ($>$1 MW) for grid integration onshore, single turbines or wind farms,
- Smaller turbines ($>$50 kW) for stand-alone, hybrid systems, and for electrification in developing countries.

The challenges associated with realizing this vision in the shorter term, 3–7 years, are a) further cost reductions, b) development of technology, reliability and implementation and operational methods for wind turbines offshore, c) integration of wind energy in the electrical system with a large amount of renewable energy, and d) development of markets and pricing for wind produced electricity.

In the long term, 5–15 years, the challenges are similar; however, the possibilities in relation to installation, application and market are global rather than Danish, the penetration by wind energy is bigger and there is more focus on system integration. Furthermore, revolutionary as well as evolutionary technology development is a possibility.

Hence, the long term challenges can be summarized as: a) reduction of uncertainties in natural conditions, b) optimization of construction and design methods, c) improvement in reliability and reduction of O&M costs, d) development of new wind turbine concepts, e) development of power plant characteristics, control, transmission and storage technologies, f) integration of wind power into an energy system with distributed production, hydrogen as energy carrier, fresh water production, and g) development of structures and procedures for the international energy markets.

From these identified challenges, research priorities in the short and the long term are proposed. In the short term, the objectives of the research are to contribute to a further cost reduction, contribute to application of wind turbines offshore and contribute to efficient integration into the electricity system. The priority research topics are:

- Cost reduction: Develop evolutionary design methods (including aeroelastic stability and control), improve estimate of loads and safety margins (using probabilistic design), develop new materials and develop improved components.
- Offshore turbines: Develop improved integrated dynamics design models (Aero-hydro-elasticity), develop approaches and methods for assessment of loads and safety, develop improved monitoring and service strategies and develop improved foundation and support structure designs.
- Wind power integration: Develop improved methods for prediction of wind energy production, control and transmission of power from large wind farms, develop improved models and methods for the interaction with other power plants and electricity markets and for monitoring and assessing the economy of wind energy.
- Reduced environmental impact: Develop new approaches and methods for reduction and assessment of noise and the influence of off shore turbines on the environment, develop methods for recycling of components and turbines.

In the long term, the wind turbine technology is expected to diverge into the three development lines, and the research priorities are:

- Establishment of knowledge and competences within wind energy technologic and scientific key areas at high level to ensure models, methods and development tools will be available for the industry. The priorities include: boundary layer meteorology, aerodynamics / aeroelasticity / CFD, dynamics, materials, loads and safety.
- Cost reduction of 50% for wind energy production. Priorities include evolution of the existing technology and development of new wind turbine concepts.
- Improvements in the technical preconditions for a cost effective Global exploitation. Priorities include expert systems for prediction of complete site conditions without previous measurements or collection of local information.
- Removal of limits for wind energy penetration. Priorities include integration with micro-CHP, storage technologies and stand-alone and hybrid systems.
- Development of new technologies and science for application in the wind energy sector.

While up-scaling of a few concepts has been a very efficient way to make wind energy cost effective so far, it is anticipated that in the future the competition will be based more on the technical knowledge and competences embedded in the product and on the technological differences. Knowledge and competences applied in the continuous development of wind turbine design will be crucial for the future development of the technology. Thus a very important precondition for the efficiency of the proposed strategy is to ensure the interaction between the society, expressed by the political / administrative system, which sets the priorities and finances research and education; the research system, which develops new knowledge and new technological foundations; and the industry, which exploits knowledge and develops competitive products. This interaction is often described as triple-helix. The research in such a system will be focused on a desired development and application, and the funding will be dependent upon acceptance of the direction and, in the long term, the efficiency of the research.

As earlier described, realization of the wind energy potential demands a knowledge-based effort covering the range from basic research to industrial product development. For the triple-helix model to be efficient, it is important that strategic research funds are available to connect the basic general research to the application.

The dependency of the strategic wind energy research on the industry and on the acceptance by the society of the research direction and impact (expressed by quality, relevance and impact) means that, for the interaction to be efficient, consideration of integration of the research results and ensuring the impact of these results must be an important part of the wind energy research strategy. The traditional instruments of publication and education are relatively indirect and must be supplemented by other means in order to secure innovation, dedicated embedment and impact in the short term. The most efficient instruments identified for accomplishing this, beyond publication and education, are: a) research cooperation with the industry, b) consulting service regarding cutting edge problems on a commercial basis, c) consultancy for the authorities, d) testing, e) standardisation, f) patenting, and g) developing software and design tools.

The responsibility, the strategy and the approach taken by the research consortium have been well received by the industry, the authorities and by the public research program administrators. During the first half of 2004, the consortium has received Danish grants for long-term research on aerodynamics, acoustics and resource assessment and grants for shorter-term research within the priority areas of cost reduction, offshore wind turbines and wind power integration. The consortium has been involved in all new EFP grants, in more than half of the PSO grants for wind energy research and in all of the wind energy grants from the Renewable energy R & D program of the Danish Ministry of Science.

Discussion and Conclusions

The successful development of wind power in Denmark during the last 25 years is due to a unique collaboration between research and industry and continuous support from the political/administrative system. The wind energy research is multidisciplinary and characterized by continuity, incrementalism and strong coupling to the industry. The research has been very focused, and the level and originality has developed, in conjunction with the industry, in the direction of advanced technology. The research areas within wind energy are comparable to aeronautics. In several areas the scientific level is now on par with the field of aeronautical engineering, and the possibilities to achieve significant derived effects in other fields by a general increase in the wind turbine technology level correspond to the same recognized effect for aeronautics.

The developments in the industry, the markets, the political priorities and the research-based knowledge community give rise to a re-evaluation of possibilities, visions, opportunities and objectives for the future development of wind power. Public policies concerning development and exploitation of wind energy, among this research and development, is presently undergoing substantial changes. The different sectors (the industry, the political/administrative system and the research system) are making strategic considerations in order to optimally use the resources available to promote a desirable development towards growth, wealth and environment.

However, the wind energy community also faces the serious problem that, from some political points of view, the industrial development has moved so far that it is perceived to have reached the point of ‘‘diminishing return,’’ referring to the considered return of invested public research funds. In other words, the wind industry is considered to have come close to a mature condition, or at least developed to a point where it can finance its own research. This has, to some extent, been the situation in the European Commission within the last few years, where wind energy has had no or a very low priority so far in the present 6th Framework Research Program, in particular with respect to long term research.

The strategic changes in Denmark in 2002, where the funding for the renewable energy demonstration program was completely removed and the strategic Energy Research Program was cut to 1/3 of its previous level, could be seen as being in line with this perception. However, at the same time some additional funding dedicated to renewable energy research was included in the basic and general energy research funds. The move of the research funds from demonstration toward more fundamental and long-term energy research could strengthen the area. However, the trend places the responsibility for the continuation of the wind energy technology research and development on the research community and the industry with a diminishing role of the third party of the triple-helix, the political/administrative system. Hence, the research community must now take responsibility for the focus, the quality and the effect of the basic wind energy research, and the industry must take responsibility for the continued technology development and fund the applied research/development contribution from the research community, while the research-industrial complex together must be responsible for continued development of the sector in the triple-helix context, the role previously dominated by the political/administrative system. The Danish wind energy research sector welcomes the challenge.

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