Energy Policy 36 (2008) 4397–4400

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Wind power as a clean-energy contributor ☆

Peter Tavner *

School of Engineering, Durham University, South Road, Durham DH1 3LE, UK

ARTICLE INFO

Available online 15 October 2008

Keywords:
Wind power
Wind turbine
Wind farm

ABSTRACT

Modern and sophisticated wind generators rated at up to 5 MW are in use on- and offshore in many European and other countries. They are made by a large and financially strong industry. In 2006, there were 1672 wind turbines in use in the UK, making up 2.5% of UK's electricity-generating capacity but producing under 1% of its electricity. The UK uses only about 1% of its wind power potential. Making use of more wind will involve developing new materials, new techniques and new mathematical modelling methods. The machines will need to be more reliable and robust, and will require a more flexible electricity system to feed into. In the longer term, there may be bigger machines of up to 10 MW, perhaps used in tandem with advanced electricity-storage technology. The growth of a European rather than UK power grid may allow renewables, including wind, to play a larger role.

© 2008 Queen's Printer and Controller of HMSO. Published by Elsevier Ltd. All rights reserved.

1. Background

Wind was rediscovered as a practicable power source in the 20th century. Europe played a critical role, particularly Denmark, Spain and Germany, in the development of modern wind turbine technology, because of an established technology base, local meteorological conditions, green politics and government investment. The wind turbines developed are complex, self-contained and, more recently, are generally variable-speed, power-generation products.

The application of wind to the generation of electrical power grew during the second half of the 20th century and oil price rises in the 1970s promoted intense interest in its value as a fuel-free, renewable energy source. Wind power was extensively but rather unsuccessfully exploited in USA in the 1980s, using small turbines rated at about 100–150 kW. The growth of the modern wind industry can be traced from these events and has resulted in 1–5 MW turbine products, with sophisticated aerodynamics and variable speed controls, being deployed onshore and offshore in a number of countries. The wind turbine and its conversion equipment are a complex product but are adaptable to mass production, leading to improvements in quality, reliability and cost-effectiveness. The wind turbine manufacturing industry has matured and has been rationalised into a few, large, financially strong, international players.

The UK has made important contributions to the research and development of wind power in innovative turbine design, blade aerodynamics, material development, turbine control, onshore and offshore installation technologies, and turbine operation. Most of this work was funded by the Government and some by private industry. The UK has a number of small but no large wind turbine manufacturers and a number of important international wind farm constructors and developers.

In 2006, onshore wind turbine products could be considered a mature technology and the UK has played a significant part in its development. However, the variable nature of the wind resource, the extreme conditions that wind turbines must survive and the highly competitive nature of the energy market mean that there are still significant scientific challenges to integrate these products into a large, secure, long-term, cost-effective, renewable source in a range of power systems. To some extent, this will mirror the way that constant-speed, steam-turbine technology developed from its birth in 1900 to worldwide pre-eminence in electric power generation by the 1950s.

In 2006, in the UK, there were 1672 wind turbines rated at 1742 MW installed onshore and offshore, operating in a total installed generating capacity of 82,000 MW. Therefore wind represents 2.5% of the installed capacity (British Wind Energy Association, 2006).

In 2005, the generation of electricity from wind power in the UK was 2.9 TW h (terawatt hours) in a total UK electrical consumption of 398 TW h. Therefore wind generated 0.73% of the electrical energy consumed (Department of Trade and Industry, 2006). The capacity factor for a wind turbine is defined as

$$\left[\frac{\text{average power produced by a turbine in a year}}{\text{turbine power rating}}\right]$$

☆ While the Government Office for Science commissioned this review, the views are those of the author(s), are independent of Government, and do not constitute Government policy.

* Tel.: +44 191 334 2460; fax: +44 191 334 2408.
E-mail addresses: Peter.Tavner@durham.ac.uk, christine.mcdougall@dius.gsi.gov.uk (P. Tavner).

0301-4215/$ - see front matter © 2008 Queen's Printer and Controller of HMSO. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.enpol.2008.09.033

Table 1
Contributions of wind power to electric power generation in Europe EU15, 2002 (extracted from European Wind Energy Association, 2005b)

	Electricity consumption (TW h)	Generated from wind (TW h)	Generated from wind (%)	Fraction of potential harnessed (%)
Austria	60.15	0.24	0.40	8.0
Denmark	81.73	5.28	6.00	18.0
France	431.86	0.20	0.04	0.2
Germany	531.78	18.49	3.47	77.0
Spain	221.42	11.95	5.00	14.0
UK	349.20	1.45	0.40	1.0
Total	1676.14	37.61	2.24	6.6

For wind turbines in the UK, the capacity factor range is 15–51% (British Wind Energy Association, 2006) in comparison to mean figures for Germany and Denmark of 11% and 15%, respectively. The reason for the difference is the higher average wind speeds in the UK, particularly offshore.

The contribution of renewable sources to the UK electricity production is planned to be 10% by 2010. Because of the UK's potential resource, wind power is seen as the largest viable contributor to meeting this target.

Table 1 (European Wind Energy Association, 2005b) summarises the European wind resources in 2002 in an analysis made in 2005. This shows that the UK at that time was harnessing only 1% of its wind energy potential, whereas the pioneers, Germany and Denmark, were harnessing 77% and 18%, respectively. The 'fraction of wind potential harnessed' is an approximate indicator only and figures more recent than 2002 show that the fraction of wind potential harnessed by the UK has increased significantly. But there is clearly substantial potential for growth in the UK, and some growth can be seen in the figures given above for 2005.

A possible penetration of 20% by wind power into the electricity system has been suggested (European Wind Energy Association, 2005a, b; United Kingdom Energy Research Centre, 2006) but this limit could be exceeded if measures are taken to balance the wind supply. The Danish system operator has looked at the implications of operating with a penetration of up to 70%.

2. Current science 2008

The background provided above shows that modern, large, wind turbine products have been established and standards developed (Ackermann, 2005; Burton et al., 2000; International Electrotechnical Commission, 2001; Ofgem, 2003). Though the science associated with their universal applicability in the power system is underway, it is not yet universally applied (European Wind Energy Association, 2005b; United Kingdom Energy Research Centre, 2006; Ofgem, 2003).

The following issues, associated with the growth and development of wind power as a long-term, cost-effective, renewable source, need attention:

- Lowering the capital cost of wind turbines and their installation.
- Improving the survivability of large wind turbines over time and in inclement conditions.
- Improving the technical and economic means for the more effective penetration of variable and intermittent wind power into existing and future electrical systems, including the consideration of small-scale wind installations.

These issues reduce to the following basic scientific/technical/economic choices:

- Large-scale wind vs small-scale wind.
  - Large scale, where resources are concentrated in large farms of huge turbines injecting power into the electrical transmission system, for sale in a highly regulated market at prices above but close to the wholesale price of electricity. Easier to plan strategically but harder to implement technically.
  - Small-scale wind turbines, or domestic microgeneration, injecting power into the distribution system, displacing domestic electricity purchased at the retail price. Wind microgeneration will access individual consumers and their disposable income. If flexible regulations are established, this market could grow more freely and there could be a potential to earn higher margins. Easier to implement technically but more difficult to predict a successful economic outcome.
- Large-scale wind onshore vs offshore.
  - Wind farms of onshore turbines, which raise visual impact issues and planning problems but are technically and financially tractable under present economic conditions.
  - Wind farms of offshore turbines, which can be larger and located in areas of higher wind resource, with higher capacity factors, but are exposed to more onerous aerodynamic, hydrodynamic, ambient and connection conditions, consequently incurring greater technical and financial risk. The UK's exploitation of North Sea oil and gas resources gives it unparalleled experience in solving such problems.
- Penetration and survivability of wind power as a major resource.
  - What are the economic and technical limits to the absorption of intermittent wind-generated energy in the electrical power system?
  - How can the reliability and longevity of wind-power and electrical-infrastructure technologies be improved to enable wind-generated energy to be absorbed more effectively?

The current key scientific challenges to resolve these issues and choices are summarised below; a representative rather than exhaustive reference list of current work is also provided:

- Aeroelastic analysis of turbine structures of increasing size and flexibility, resolving the compromises between the aerodynamic, hydrodynamic and structural loadings placed on large turbine structures possibly mounted in the sea (Causon et al., 2001; Coleman et al., 2003; Engelen et al., 2003; Leithead and Dominguez, 2004; Paynter and Dutton, 2003; Pesmajoglou and Graham, 2000; Qian et al., 2003; Sumer et al., 2001).
- Developing and modelling the new materials required to meet these compromises for larger turbines in an offshore environment (Cotton et al., 2001; Smith et al., 2001; Thanomsilp and Hogg, 2003; Tzetzis et al., 2003).
- Developing new techniques for the mounting and installation of wind turbines, including in the domestic environment.
- Control strategies for the wind turbine to ensure maximum energy extraction (Anderson and Campbell, 1992; Carlin et al., 2003; van der Hooft et al., 2003).
- Integration strategies to allow wind-generated energy to flow smoothly, predictably and reliably into the energy infrastructure (Dale et al., 2003; Johnson and Tleis, 2005; Mott MacDonald, 2003; Strbac and Black, 2004; Wu et al., 2004).

- Performance of arrays of wind turbines, particularly in the offshore environment (Barthelmie et al., 2003, 2004; Crespo et al., 1999; Hendriks and Zaaijer, 2004; Kühn et al., 1997; Taylor, 1990, 1994; Vermeer et al., 2003).
- Novel turbine and conversion technologies to improve the penetration of wind, both for large-scale but also, more pressingly, for small-scale wind (Department of Trade and Industry, 2005; Ingram et al., 2003; Mott MacDonald, 2004).
- Work to monitor and improve the reliability and survivability of the wind energy infrastructure (Braam et al., 2003; Jeffries et al., 1998; Tavner et al., 2006; University of Kassel, 2005).
- Transformation of electric distribution systems from passive entities to actively managed, flexible networks (Johnson and Tleis, 2005; Wu et al., 2004).

The key scientific advances required to meet these challenges are:

- Mathematical modelling of complete turbine structures, including the simplification necessary to extract robust design rules: *achievable*.
- Control modelling of turbine, generator and conversion systems to allow the injection of energy into the electricity system for a particular turbine design to be simulated under all conditions of the wind and the electrical system: *achievable*.
- The necessary simplification of the above models to allow integrated modelling of wind farm and grid systems under a variety of wind and grid conditions so that the detailed effects of wind energy penetration can be simulated and predicted: *achievable within a certain margin of error*.
- Economic modelling of these systems so that the influence of market, weather, technical and operational conditions can be predicted and improved: *achievable within a greater margin of error*.
- Reliability modelling of future designs of wind-power infrastructures and the condition monitoring of wind turbines and farms: *achievable*.
- International understanding of the technical and market performance of wind resources so that lessons learned are effectively communicated throughout the industry: *achievable*.

3. Future science 2006–2050

The key science factors for the future of wind power are:

- The impact of larger designs of wind turbines above those now in view, for example, from 7 to 10 MW, on the penetration of wind power.
- The greater interconnection of the UK electricity system with other energy grids and the European system as a means to expand the penetration of renewable sources into the system, including the contribution of wind.
  - The UK currently has one high-voltage direct-current (HVDC) link to Europe and another to Ireland. An increase in interconnection would mitigate the intermittent effects of wind and other renewable sources. HVDC could also be used to collect energy from huge wind farms further offshore, but in both cases the investments are long term and will require careful justification.
  - It is likely that the increase of interconnection and the injection of more renewable sources will require more concerted action in Europe to develop a more robust universal mode of operation and grid code, which mitigates intermittency but promotes the network.
  - Wind is a naturally distributed energy resource and this means that it has considerable potential in providing a highly redundant, secure source. This will be aided in the future by extended networks and economically viable bulk-energy storage, but that will demand turbine infrastructures of high reliability, availability and long life. It is likely that developments in this area will be achieved for wind turbines through mass-production techniques. Such future developments could give wind power, as a fuel-free source, a very high return on capital invested.
- Impact of fuel cells, nuclear fission or fusion on the survivability of wind power.
  - The availability of new energy sources will affect the applicability of wind as these are likely to be used in tandem with wind and other renewable sources in hybrid technical and economic arrangements. The development of harmonious and robust hybrid solutions will be an important part of future wind power research.
- Impact of storage technologies on the survivability of wind power.
  - Bulk-energy storage technology will improve the ability of power systems to absorb the output of large- and small-scale wind because it will eliminate the deleterious effects of variability.
- Impact of climate change on the survivability of wind power.
  - The reliability of wind and power system infrastructures during a period of climate change will have a profound effect on the practicability and cost-effectiveness of a large penetration of wind power into energy supply.
- Long-term survivability of wind as a significant energy contributor in the UK and elsewhere.

4. Conclusions

Wind has strong potential as a fuel-free renewable source of energy, which can contribute at least 20% and possibly a much higher proportion of the UK's electricity needs. Wind turbine technology is now mature but the focus of scientific attention needs to shift towards massive production from large- and small-scale sources and the integration of these sources into the domestic, national and international energy networks. This will require technical and economic modelling of the wind turbine products and the networks they feed.

References

Ackermann, T. (Ed.), 2005. Wind Power in Power Systems. Wiley, Chichester.

Anderson, C.G., Campbell, T.J., 1992. 'Front-end' aerodynamic control of horizontal axis wind turbines. Final Report. Contract E/5A/CON/6037/2259. US Department of Energy.

Barthelmie, R., Larsen, G., Pryor, L., Jorgensen, H., Berstrom, H., Magnusson, M., Schlez, W., Rados, K., Lange, B., Volund, P., Neckelmann, S., Mogensen, S., Schepers, G., Hegberg, T., Folkerts, L., 2003. Efficient development of offshore windfarms (ENDOW). EC Final Report ERK6-1999-00001, Risoe-R-1407(EN).

Barthelmie, R., Larsen, G., Pryor, L., Jorgensen, H., Berstrom, H., Schlez, W., Rados, K., Lange, B., Volund, P., Neckelmann, S., Mogensen, S., Schepers, G., Hegberg, T., Folkerts, L., Magnusson, M., 2004. ENDOW efficient development of offshore wind farms: modelling wake and boundary layer interactions. Wind Energy 7, 225–245.

Braam, H., Rademakers, L.W.M.M., Verbruggen, T.W., 2003. CONMOW: condition monitoring for offshore wind farms. Wind Energy Report ECN-RX-03-036. Energy Research Centre, Netherlands.

British Wind Energy Association, 2006. UK Wind Energy Database: 〈http://www.bwea.com/ukwed/index.asp〉 (accessed 26 May 2008).

Burton, T., Sharpe, D., Jenkins, N., Bossanyi, E., 2000. Wind Energy Handbook. Wiley, Chichester.

Carlin, P.M., Laxson, A.S., Muljadi, E.B., 2003. The history and state of the art of variable-speed wind turbine technology. Wind Energy 6, 129–159.

Causon, D.M., Mingham, C.G., Ingram, D.M., 2001. A Cartesian cut cell method for shallow water flows with moving boundaries. Advances in Water Resources 24, 899–911.

Coleman, S.E., Lauchlan, C.S., Melville, B.W., 2003. Clear-water scour development at bridge abutments. Journal of Hydraulic Research 41, 521–531.

Cotton, I., Jenkins, N., Pandiaraj, K., 2001. Lightning protection for wind turbine blades and bearings. Wind Energy 4, 23–37.

Crespo, A., Hernandez, J., Frandsen, S., 1999. Survey of modelling methods for wind turbine wakes and wind farms. Wind Energy 2, 1–24.

Dale, L., Milborrow, D., Slark, R., Strbac, G., 2003. A shift to wind is not unfeasible. Power 109, 17–25.

Department of Trade and Industry, 2005. Micro-Generation Strategy and Low-Carbon Buildings Programme. Consultation Document. Department of Trade and Industry, London.

Department of Trade and Industry, 2006. Digest of United Kingdom Energy Statistics (DUKES). Department of Trade and Industry UK Energy Statistics.

Engelen, T., Schaak, P., Lindenburg, C., 2003. Control for damping of the fatigue relevant deformation modes of offshore wind turbines. Technical Report ECN-RX-03-037, Energy Research Centre, Netherlands.

European Wind Energy Association, 2005a. Large-Scale Integration of Wind Energy in the European Power Supply: Analysis, Issues and Recommendations. European Wind Energy Association, Brussels.

European Wind Energy Association, 2005b. Wind Energy: The Facts. An Analysis of Wind Energy in the EU-25, Vol. 1. European Wind Energy Association, Brussels.

Hendriks, H.B., Zaaijer, M., 2004. Executive Summary of the Public Research Activities, Dutch Offshore Wind Energy Converter (DOWEC). Petten, NL. Energy Research Centre, Netherlands.

Ingram, S., Probert, S., Jackson, K., 2003. The impact of small-scale embedded generation on the operating parameters of distribution networks. PB Power Report: K/EL/00303/04/01.

International Electrotechnical Commission, 2001. Wind turbine generator systems: full-scale structural testing of rotor blades for wind turbine generators. 61400-23. International Electrotechnical Commission, Geneva.

Jeffries, W.Q., Chambers, J.A., Infield, D.G., 1998. Experience with bicoherence of electrical power for condition monitoring of wind turbine blades. IEE Proceedings—Vision, Image and Signal Processing 145 (3), 141–148.

Johnson, A., Tleis, N., 2005. The development of grid code requirements for new and renewable forms of generation in Great Britain. Wind Engineering Journal 20, 3.

Kühn, M., Cockerill, T.T., Harland, H., Harrison, R., Schöntag, C., van Bussel, G.J.W., Vugts, J.H., 1997. Methods assisting the design of offshore wind energy conversion systems. Contract JOR3-CT95-0087. Opti-OWECS Final Report, European Joule III Programme.

Leithead, W.E., Dominguez, S., 2004. Cancellation of the tower modes for the alleviation of fatigue loads. Report prepared for Vestas, University of Strathclyde.

Mott MacDonald, 2003. Capacity Mapping and Market Scenarios for 2010 and 2020. Renewables Network Impact Study. Carbon Trust and Department of Trade and Industry, London.

Mott MacDonald, 2004. System Integration of Additional Micro-Generation. Department of Trade and Industry, London.

Ofgem, 2003. Recommendations for the connection of small-scale embedded generators (up to 16 A per phase) in parallel with public low-voltage distribution networks. Engineering Recommendation G83/1, September. Ofgem, London.

Paynter, R.J.H., Dutton, A.G., 2003. The use of a second harmonic correlation to detect damage in composite structures using thermoelastic stress measurements. Strain 39, 73–78.

Pesmajoglou, S., Graham, J.M.R., 2000. Prediction of aerodynamic forces on horizontal axis wind turbines in free yaw and turbulence. Journal of Wind Engineering and Industrial Aerodynamics 86.

Qian, L., Causon, D.M., Ingram, D.M., Mingham, C.G., 2003. Cartesian cut cell two-fluid solver for hydraulic flow problems. Journal of Hydraulic Engineering 129 (9), 688–696.

Smith, F.C., Winkler, H., Hogg, P.J., 2001. Durability of non-crimp fabric composites in aqueous environments. Plastics Rubber and Composites 30 (5), 233–242.

Strbac, G., Black, M., 2004. Value of storage in managing intermittency. Report to the Department of Trade and Industry, London.

Sumer, B.M., Whitehouse, R.J.S., Tørum, A., 2001. Scour around coastal structures: a summary of recent research. Coastal Engineering 44, 153–190.

Tavner, P.J., Xiang, J., Spinato, F., 2006. Reliability analysis for wind turbines. Wind Energy 10.

Taylor, G.J., 1990. Wake measurements on the Nibe wind-turbines in Denmark. CEC Contract EN3W.0039, UK National Power Report ESTB/L/0158/R90.

Taylor, G.J., 1994. Full-scale measurements in wind-turbine arrays. CEC Contract JOUR-0064, National Power Report JEB 3490/001.

Thanomsilp, C., Hogg, P.J., 2003. Penetration impact resistance of hybrid composites based on commingled yarn fabrics. Composites Science and Technology 63, 467–482.

Tzetzis, D., Hogg, P.J., Jogia, M., 2003. Double cantilever beam model testing for vacuum infused repairs of GFRP. Journal Adhesion Science and Technology 17 (3), 309–328.

United Kingdom Energy Research Centre, 2006. The costs and impacts of intermittency: an assessment of the evidence on the costs and impacts of intermittent generation on the British electricity network, March. United Kingdom Energy Research Centre, London.

University of Kassel, 2005. Wind Energy Report. Germany 2004, Annual Evaluation of Wissenschaftliches Messung Evaluierungsprogramm (WMEP) zum Breitenstest, 250 MW Wind Project. ISET, Kassel, Germany.

van der Hooft, E., Schaak, P., van Engelen, T., 2003. Wind turbine control algorithms. Technical Report ECN-C-03-111, Energy Research Centre, Netherlands.

Vermeer, L.J., Sørenson, J.N., Crespo, A., 2003. Wind turbine wake aerodynamics. Progress in Aerospace Sciences 39, 467–510.

Wu, X., Jenkins, N., Strbac, G., Watson, J., Mitchell, C., 2004. Integrating renewables and CHP into the UK electricity system. Technical Report 13, Tyndall Centre.