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Grand Challenges in Wind Energy Research

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This is a brief summary of the author's views on the important future directions of wind energy research. It is impossible for a single researcher to provide a comprehensive review of a multi-dimensional subject but the recent publication of excellent and extensive multi-authored reviews, in 2019 (Veers et al., 2019) and 2016 (Van Kuik et al., 2016), is taken as justification for a more personal account. The author, moreover, is an engineer and will not cover issues associated with the societal context of wind energy. These range from the many aspects of noise which will be briefly mentioned here, to the intrusion of large wind turbines on isolated rural life (Aeon).

One of the most important conferences in wind energy is the "Torque" series. Torque 2020 was to be held at the Technical University of Delft at the end of May but was eventually run electronically in October. It had seven themes which are listed below in decreasing order of the number of abstracts accepted for oral or poster presentation:

Turbine technology: 156
Control and Monitoring: 108
Wind and Wind Farms: 99
Systems Design and Multi-scale Modelling: 49
Measurement and Testing: 47
Future Wind: 36
Small Wind and Developing Countries: 20

The total of 515 abstracts was substantially more than presented at the previous Torque 2018 conference which testifies to the vitality of wind energy research (IOPscience). The relative number of abstracts gives a measure of the areas that dominate current research. Any extrapolation is error prone, but it is tempting also to use these numbers as a guide to the future directions of wind energy research. **Turbine technology** covers the development of even larger turbines, which is driven by the huge and expanding offshore market and the intrinsic complexity of turbines with blades over 100 m in length. The design of modern turbines is multidimensional: aerodynamics, structure, dynamics, control, and operation must be considered concurrently. Hydrodynamics, wave action, and foundation issues need to be added to this list for offshore turbines. A simple and very effective graphical demonstration of what multidimensionality means for modern blade design compared to that of the 1980s is shown as figure 2 of (Veers et al., 2019). Multidimensionality requires complex and sophisticated **Systems design and multiscale modelling** from the microscales that determine material properties and fatigue behaviour to those of the earth's atmosphere and oceans that are responsible for the wind resource. It is often said that wind energy is a mature technology. Large wind turbines have evolved over many generations from the Burgess Shale stage of unusual and sometimes surreal designs and concepts (Burgess Shale). They now have a standard life form of three upwind blades rotating on a horizontal axis mounted on a monopole tower, where the major design decision is often whether to use a direct drive or induction generator. Nevertheless, the concurrency and interdisciplinarity are huge challenges and will continue to be so as size increases even further (Bak et al., 2013).

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Control and monitoring is important for at least two reasons: first to maximize power output at wind speeds typically below 12 m/s, and then to switch rapidly to protecting the turbine at higher speeds by limiting the power. The first task, called "maximum power point tracking" (MPPT), is currently done without measuring the wind speed although researchers are studying lidars and other sensors for this task (Wright et al., 2019) and commercial implementation may follow; to the casual reader, the fact that wind speed is not accurately measured by a wind turbine must seem somewhat strange. The active research in MPPT is matched by work on the methodology to safely limit power partly through pitch adjustment of the blades to change their angles of attack. This can cause high transient loads partly because the associated unsteady aerodynamics is not well understood. Improved load mitigation is needed to extend the fatigue life of turbines and reduce their extreme loads as well as address the wind farm issues described below. "Smart" blades using devices such as vortex generators and trailing edge flaps may be needed, (Van Kuik et al., 2016).

The first part of **Wind and Wind Farms** concerns the basis of the industry and the challenges of assessing the wind resource. Our knowledge of the atmospheric boundary layer at heights relevant to very large turbines, is poor, as emphasized in (Veers et al., 2019). Large numbers of turbines in a wind farm require detailed analysis of the flow (Porté-Agel et al., 2020). One important reason is that upwind turbines reduce the kinetic energy available to the downwind ones and thereby lower their power production while increasing the fluctuating loads and reducing their fatigue life. This interference can extend from one wind farm to another many kilometres away, especially for offshore installations (Nygaard et al., 2020). One of the biggest uses of computer resources in wind energy research is the simulation of interference and associated loads and the development of improved control strategies to mitigate them. Wind farm owners are also finding unexpected maintenance problems particularly with the blades and the drivetrain. For example, the Wind Energy Institute of Canada installed five 2 MW wind turbines on its littoral wind farm in 2013. The monthly capacity factor–the ratio of average power output to the rated value–can exceed a staggering 0.70 in winter compared to typical wind farm values of 0.30–0.40. There is, however, a price to pay: after 3 years the blades of one turbine had to be lowered for repair because of serious leading-edge damage caused by impinging rain droplets. The subject of leading-edge erosion combines aerodynamics, materials, meteorology, condition monitoring, and remaining useful life (RUL) assessment and knowledge gains are needed in all these sub-topics (Bech et al., 2018). Wind energy has a life cycle cost of around 7 g CO_2eq per kWh, see Table 9 of (Mendecka and Lombardi, 2019). When a wind farm reaches its operational life of around 20 years, many of the turbine components can be recycled. The exception is the blades which currently are, and for the foreseeable future will be made from petroleum-based resin and artificial composite reinforcements. Dead blades end up in landfill which is not a good outcome for a "renewable" technology (Bloomerg). More research is desperately needed into alternative bioresins and thermoplastics (Murray et al., 2017) which can be reused, along with natural reinforcements, such as bamboo and sisal. Other innovations include segmented blades to reduce costs and difficulties in transport (Peeters et al., 2017), and individual control of blade pitch (Jones et al., 2018).

The efforts of pioneers like Jamieson (Jamieson, 2011) often bear first fruit in **Future and small wind** and take us back to the Burgess Shale. How can we extract useful energy from the strong winds that blow regularly at altitudes of several kilometres? There is a range of fascinating technologies proposed for this, as well as companies building prototypes, e.g., (Roberts, 2018) and the other chapters of the book. Even basic issues, such as what is the maximum achievable power output, have not been fully resolved and the opportunities for research are legion (De Lellis et al., 2018). Small turbines have been around for a long time; up to the 1970s all wind turbines were small. Subsequently, they have suffered commercially because of the cheapness and reliability of photovoltaics but still have an important niche. Two examples follow of innovation because this is often easier at small scale. The first is alternate blade materials. To the author's knowledge, the only wind turbine blade made from reusable thermoplastics is 9 m long, (Murray et al., 2017). The second is diffuser-augmented wind turbines (DAWTs). Surrounding the turbine rotor by a diffuser is a seemingly simple modification which induces more airflow through the blades, and hence produces more power, but the optimum design is not known (Bontempo and Manna, 2020). Small DAWTs are now commercially available (Evans et al., 2020).

One major topic to be added to the list above covers the context of wind energy. By this is meant issues like wind turbine noise (Zhu et al., 2018), large scale resource assessment both in the atmospheric boundary layer and beyond (Bechtle et al., 2019), wind power forecasting (Qian et al., 2019), and integration into the electricity grid (Zhang et al., 2016). The intermittency of wind energy can be a major issue as the penetration of wind increases in many electricity grids; some have more than half their generation capacity in wind turbines and this fraction is likely to rise further. One way to achieve high penetration and grid stability is to have accurate forecasts for wind power over a range of times depending on the need. Forecast accuracy is slowly increasing, as is the accuracy of weather forecasting, but more needs to be done. Three other areas of context are noted as examples. First is the issue of "automatic generator control" (AGC) by which the system operator intervenes to alter wind farm power output for fine balancing of grid electricity production and consumption. Wind turbines and photovoltaics are the only generation technologies that can respond to AGC signals on very short time scales (Rebello et al., 2020). Second, wind-generated electricity is distributed by transmission lines whose capacity, called the "ampacity," is determined largely by the convective cooling by the wind, so that often the ampacity correlates strongly with wind power production. This correlation is starting to be exploited in grids around the world (Karimi et al., 2018). Electricity grids are evolving rapidly and there are many ways apart from AGC in which wind turbines and other intermittent renewable energy technologies, such as PV, will be important (Kroposki et al., 2017). Third, increasing numbers of increasingly large turbines will produce huge amounts of data for condition monitoring and RUL assessment. This "digitalization" can be implemented as a "digital twin" – a very detailed computer model of a turbine which can assess, for example, the RUL of critical components (Sivalingam et al., 2018).

Large wind turbines and wind farms will continue to grow, along with their contribution to world energy production, (Veers et al., 2019). This and the other applications mentioned above will drive the needs and opportunities for research. When the author started his academic career in 1981 there was only a small wind industry building small turbines, very little research and development and very few jobs in the industry. Nearly all the developments described above have happened since then. Progress has been and will continue to be remarkable. FER intends to make a significant contribution to the growth in wind energy research.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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Burgess Shale. The Burgess Shale in the Yoho National Park, British Columbia (https://www.burgess-shale.bc.ca/) yields fossils from the “Cambrian explosion” of life forms (https://en.wikipedia.org/wiki/Cambrian) such as the Opabinia regalis “a primitive anthropod with five eyes and a long ‘nozzle’ with claws” (https://burgess-shale.rom.on.ca/en/fossil-gallery/view-species.php?id=93&ref=i&). Regrettably, these wonderful and varied life forms are, like many wind turbine concepts, no longer with us (Accessed October 7, 2020).

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