Overcoming the Challenges of Offshore Wind Energy Through Research and Education

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Abstract

Wind energy installations in the United States have grown from 1,800 MW in 1990 to over 35,000MW by the end of 2009. Furthermore, a number of innovative offshore wind designs will be constructed in the near future. This growth is guided by a need for further technological development and research in critical areas such as grid penetration, reliability, cost, and performance. Since offshore wind turbines operate under harsh environmental conditions, research is ongoing to develop new materials capable of abating wear, corrosion, bio-fouling under extreme loading conditions. Gearboxes, electrical machines and power electronics have been used in wind turbines. Due to lack of reliability in offshore turbines, interdisciplinary research involving key manufacturers of wind turbines is being conducted on failure analyses of the gear box, the generator and the electrical system. However, despite these advances, a long-term perspective to develop offshore wind energy beyond the state of the art is imperative. This is driven by knowledge gaps in areas such as materials and structures, electrical conversion, electromechanical conversion, design methods, and soil-structure interaction. Moreover, challenging aspects of offshore wind energy such as predicting hydrodynamic effects for offshore wind turbines more efficiently is important. Thus the present study attempts to proclaim that there is a strong need for research in offshore wind energy. The project plan is to present the research challenges to be overcome for future development of offshore wind energy, discuss current research approach and propose pioneering research that if implemented would accelerate the development of offshore wind energy development. One of the key findings of this paper is that through research and development the fundamental design of wind turbine could be modified to mitigate the harsh environmental concerns of offshore wind turbines. Offshore wind power stations have to accomplish the L^3 conditions: low cost, long-lasting and low service requirement. The objective of this paper is to achieve these through research and this research work should provide educational values to researchers as well.

Introduction

Modern wind energy evolved 40 years ago as a result of global oil crisis. In many European countries, the perception was that it would not be difficult to build large wind turbines given the knowledge accumulated in aerospace and construction industries. In the 1980s wind turbines in the range of 1 to 5 MW were built and tested by Boeing, General Electric, Fokker, Hamilton Standard and others. All these machines failed miserably because the designs were based on the best conceptual designs for rotating machinery like helicopters incorporating advanced pitch control, flexible and hinged blades and variable speed. The aerospace approach failed due to acute underestimation of wind turbine specific technology and its design drivers. Denmark spurred the development of small turbine by promoting joint venture between individuals and small companies. This approach started with the development of 10 kW turbines leading to large wind turbines of today. The transition from onshore to offshore wind energy was also beset with similar fate. The oil and gas community severely underestimated specific offshore knowledge and had to learn by trial and error that onshore turbines are not capable of surviving at sea. In several European countries, offshore wind power supplies a substantial amount of the electricity consumption making the interaction between wind power, the grid and power stations challenging. Offshore wind power is a technology and application by its own as it builds on different fields such as offshore oil and gas, meteorology, aerospace and power systems. These integrated fields of technology pose research and application challenges as well [1].

Challenges Faced by the Offshore Wind Energy System

Prospective sustainable energy systems greatly rely on both onshore and offshore wind energy. Designing and developing this innovative part of the power supply system poses technical, economical, material and environmental challenges.

Technical challenges of Offshore Wind Energy System

Though a considerable amount of experience has been transferred from the oil and gas industry, it is being realized that conditions for offshore wind are remarkably different. Support structures in the offshore wind systems are smaller and the overall conditions are more dynamic with great consequences for the design process. For example, whereas the frequency domain analysis is useful and quite accurate for the design of offshore platforms, the same analysis cannot be applied directly to offshore turbines. This could be attributed to the nonlinearities in the rotor system and bottom fixed-fixed soil model or floating turbine mooring system [1]. It is difficult to predict hydrodynamic effects relevant to offshore wind turbines efficiently because hydrodynamic phenomena are quite complex and diverse due to difficulties of free surface flow and turbulence. Pile sizing and simulation models for soil-structure interaction are currently based on the p-y method which assumes soil may be treated as non-linear Winkler springs. Research into the current standards shows that the method underestimates pile displacement in sandy soil, and overestimates soil resistance for large lateral forces [2]. Similar studies conducted on clayey soil shows that the method underestimates the ultimate soil resistance and over estimates pile lateral displacement [3]. This is critical, because degradation of soil stiffness due to dynamic and cyclic loading may lead to permanent displacement of the turbine which may compromise its performance since pile head rotational tolerance is limited to 0.5 degree [4].

Scour phenomenon or erosion around the piles poses a challenge to soil model. Scour occurs during extreme events such as storms and since there are no adequate stochastic models to predict scour and its development, its solution remains elusive. Gearbox, generator and electrical system are relevant drivers of the wind turbine system. Their reliability and availability are at all-time low. The main causes of failure are not known and neither are the means these could be avoided. Offshore wind turbines operate under harsh environmental conditions and retaining long-term overall quality and protective material coatings due to wear and bio-fouling is a continuous problem. Rotor blades are made of fiber-reinforced plastics which experience highcycle fatigue loads. There are no dedicated models for predicting the fatigue life and knowledge about structural health monitoring is very limited [1]. Structural health monitoring has been used to predict the relationship between the damage state and the remaining life of a component. This explicit relation does not exist for rotor blades yet. Joining components for wind turbine structures is also a challenge due to the large sizes of the components. Large size leads to multi-axial loading conditions and may lead to increases in actual tolerances. Furthermore, there are technical and meteorological challenges associated with installing turbines in deep water. The meteorological ocean conditions that could pose challenges during construction include wind speeds, wave heights and currents.

Economic Challenges

The cost of energy generated by offshore wind depends on two factors: the capital cost of the wind farm, and the operation and maintenance costs. Capital cost of the wind farm consists of two main components: the first component is the installed hardware, which includes support structure, electrical infrastructure, turbines and towers, and the second component is the substation station and scour protection costs and installation cost of the offshore wind farm.

Installed hardware costs -

Support structure costs – A major limitation with the support structure is often not technical but economical in nature. For example, though it might be feasible technically to design and install larger diameter monopile or deep water jackets, the cost may be too prohibitive compared to other foundation types. Offshore wind foundation costs account for about 24 percent of the total costs of the wind farm investments.

Electrical infrastructure costs – Since offshore wind farms are located on the sea, a distance-based cost estimate for transmission infrastructure to connect the site to an existing electrical infrastructure such as a substation must be included in the estimate. In addition, the grids have to be reinforced on both the transmission and distribution levels. This could be as high as 15 percent of the total cost.

Turbine and tower costs – Studies conducted by the National Renewable Laboratory (NREL) show that turbine and tower makeup 33 percent of offshore project cost [7].

Substation station – Substations connect the offshore wind farm to the onshore power grid. Consists of platforms, high voltage switch gears, high voltage cables and transformers and other electrical equipment. The platform, cables, equipment, installation, and erection could cost as much as 15 percent of the total costs [6].

Scour protection – Due to the effect of a pile foundation on local flow pattern and velocities, a significant amount of soil around a pile can be removed leading to stability problems and decrease in natural frequency of the pile. Protection consists of rock and geotextile placement and could account for about 6 percent of the total cost.

Installation costs – Installation of an offshore wind turbine is a complex process. In general, it comprises about 33 percent of the total investment cost of the wind farm.

Operation and Maintenance (O& M) costs – Due to limited accessibility, the complexity of offshore repairs and the overall production costs, O&M costs are significantly high. O&M costs could be as high as 30 percent of the total costs of offshore wind farms [5].

Material Challenges

The offshore wind industry faces a series of challenges from the global supply chain, in particular, the supply of: Copper, for cables, transformers, generators etc., rare earth minerals, for high permeability permanent magnets, large casting and forging, for bearings, shafts and gearing systems, high powered semiconductors, for control, power conditioning and AC/DC conversion and high modulus carbon fiber, for wind turbine blades, Consequently, the offshore wind industry will have to compete with other industrial divisions for these materials which may increase the capital cost of offshore wind farms [8].

Environmental Challenges

The approach to the development of offshore wind energy technology is still rooted in an onshore paradigm. However, testing has to be performed to investigate the additional environmental effects impacting turbine in a marine environment beyond what is included in the current standards. The turning blades of turbines disturb or kill birds, therefore more knowledge on the cumulative impact of the offshore wind farm is required. The impact of multiple wind farms on animal groups and the ecosystem is still unknown.

Overcoming the Challenges and Mitigating Risks

To attain sustainable energy supply, wind energy will probably provide renewable contributions to the emerging need for clean energy for the next several decades. Looking boldly forward towards scientific and technological breakthroughs without being constrained by the need for fast returns such as reduced cost of energy is the vision of this paper. Therefore, overcoming the challenges of offshore wind energy will require long-term research driven by problems and curiosity addressing basic research and fundamental knowledge.

The two main approaches for overcoming the challenges of offshore wind energy and mitigating risks are through integrated research and development and through research and educational approach.

Integrated Research and Development Approach

Offshore wind power stations have to fulfill the L^3 conditions: low cost, long lasting and low service requirement [1]. A necessary and sufficient condition is the optimization of all these objectives. Optimization for only one is not an efficient approach. For example, conversion of wind to torque by the rotor, and from mechanical to electrical power by the generator, converters and grid connection needs to be fully comprehended. Thus, integrating knowledge from various discipline will optimize design and lead to the lowest cost of energy (CoE).

Support Structures – The p-y method is the model basis for the current state-of-the-art pile sizing and simulation method. Research studies have shown that this model is too conservative as it underestimates pile displacement and overestimates lateral resistance in sandy soils.

Furthermore, the model also overestimates pile displacement and underestimates lateral resistance in clayey soils [9]. However, an alternative to p-y curve has been developed using a three-dimensional finite element analysis in which the soil was molded as a continuum medium with specific properties and the pile was embedded into the medium. The turbine tower was rigidly connected with the pile and the pile interacts with the inner boundary of the soil cavity [9]. Results showed that this alternate design method is cost-efficient, robust and safe. Foundation types currently employed for offshore wind farms are shown in Figure 1 and due to current design standards, the monopole is limited to shallow waters. The finite element method will lead to the development of more robust monopoles that could be used in deeper waters.

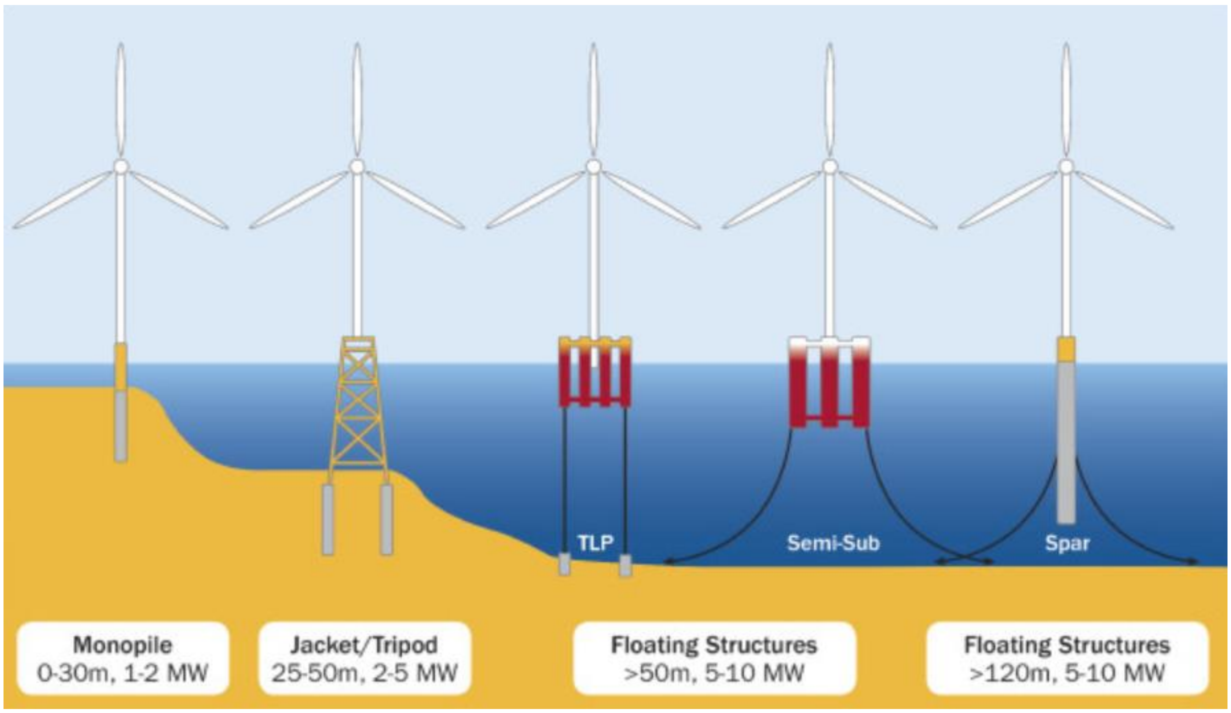

Figure 1 Offshore wind turbine foundation types

Scour Prediction - The cost of scour protection around one turbine ranges from $120,000 to $225,000. However, if long-term predictions can be made, investment in scour protection can be offset. Long-term scour prediction tools such as ‘WiTuS’ can simplify design and reduce investments. A typical scour protection that is cost effective is shown in Figure 2.

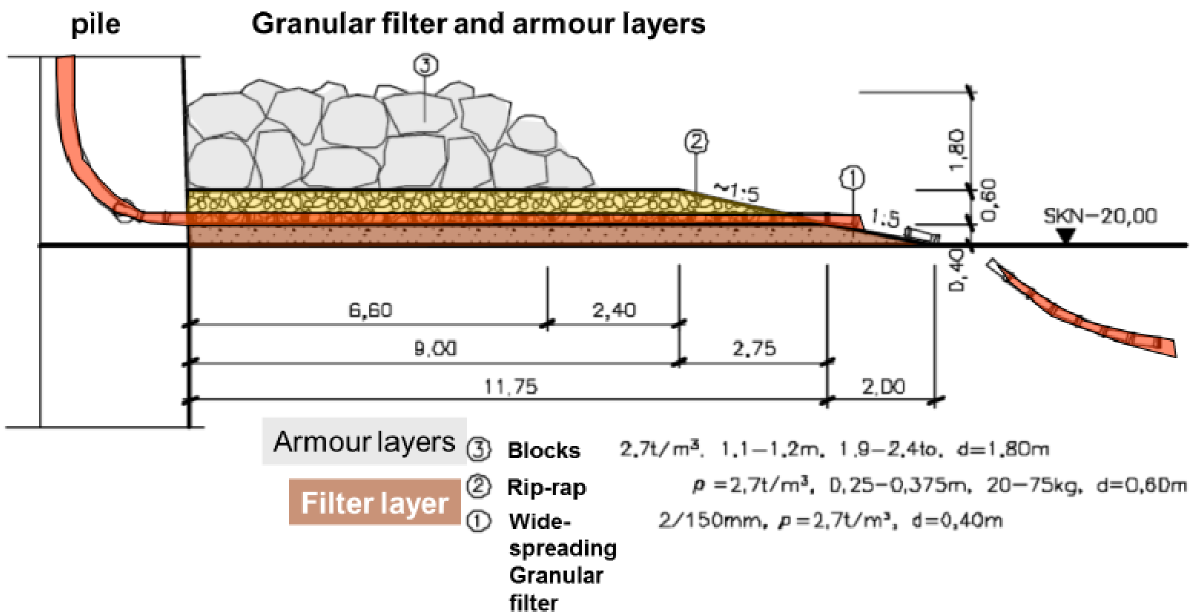

Figure 2 Scour protection solution using granular materials

Critical components causing failure - The critical components causing most downtime for wind turbines are blades, and the electromechanical conversion systems (gearbox, generator, and converter). The problem is more pronounced for offshore due to the high maximum wind and the wet and salty environment. Due to lack of knowledge of loads on gear boxes, the industry has no solution yet. However, some manufacturers have developed hydraulic torque conversion systems which have replaced mechanical gearboxes. In this system, the forces are distributed over larger surface areas than in gearboxes. Another novel concept is the magnetic gearbox which has also replaced the mechanical gearbox. These two systems have fewer breakdowns.

Electrical Infrastructure – Other opportunities that will reduce the cost of energy include; simplifying and optimizing the physical layout of transmission components to minimize the need for specific substation infrastructure, developing more cost-effective and flexible direct current (DC) electrical architecture, and sharing transmission arrangements between wind farms located close together and with trans-national interconnects.

Research and Educational Approach

Elimination of unexpected failures – Failure in wind energy can have a significant impact on downtime, annual energy production (AEP), installation upkeep costs and cost of energy (CoE). In terms of downtime, the consequences of failure in offshore wind energy are more severe because of limited accessibility, the complexity of offshore repair and the overall production cost [1]. Though increasing the reliability of offshore turbine components may alleviate failures, however, this approach will lead to an increase in the levelized cost of energy (LCoE) which may also lead to an increase in capital expenditure (CAPEX). Instead, the prudent approach would be to create a research, and development group whose main focus is to minimize or eliminate unexpected failures. In other words, the R&D group should move away from corrective maintenance, and more towards preventive, and predictive maintenance.

Through engineering education, cooperative research could be organized among the nation's universities with significant wind engineering program to develop wind, and wind farm uncertainty modeling to minimize unexpected failures, and downtime. Furthermore, universities, and institutions with significant wind engineering can take a long-term perspective on addressing, the scientific knowledge base that is required to develop offshore wind energy beyond today's, and tomorrow's applications. Such long-term research perspectives will address basic research, and fundamental knowledge in areas ranging from aerodynamic modeling, (modeling, and prediction of aerodynamic forces on wind turbine), physics, to environmental, and societal aspects.

Advancing Offshore Windfarm Development Through Engineering Education

As previously enumerated, challenges to offshore wind development include technical challenges such as failure mechanisms of electromechanical drivetrain components, achieving more reliable, and more economical power generation, availability, and cost development of various materials to be used as components of the offshore turbine, and mitigation of environmental impacts. However, this gap can be bridged through engineering education. A transition scheme for engineering education curriculum could be developed to meet the needs of engineering graduates who are competent in addressing the needs of offshore wind energy development. Such curriculum will include developing, and incorporating courses relating to wind engineering. For instance, through engineering education, courses, workshops, and assignments relating to wind engineering could be incorporated from the first year to the final year in universities. A framework for such curriculum may follow methods proposed by Desha et. al [10] which is further developed as follows:

Introductory Level –Develop courses relating to renewable energy fundamentals in the first year. This will require some level of commitments from staff to develop materials for lectures, tutorials, homework, and possibly site visits. Calculus, and physics background may be a requirement for this course. The main objective of this course will be to develop students understanding of available sources of carbon-free energy systems, how much energy can be harvested, and to expose students to technological basics of main items such as wind turbine fundamentals, and wind turbine systems, and safety, and how wind turbine generates power.

Intermediate Level - Develop courses relating to wind energy systems in the second year. The objective will be to deepen students understanding of the engineering, political, and economic aspects of renewable energy, and wind energy in particular. Students will be introduced to wind turbine fundamentals, fundamentals of electricity, and power generation, and transmission. The course will also address challenges facing wind energy.

Advanced Level- Implement courses leading to wind turbine design, installation, and construction, power generation, conversion of wind energy to electricity, wind farm modeling,

Conclusion

To accelerate the development, and penetration of offshore wind energy in the energy mix, fundamental, and pioneering research questions have to be solved. This will require cooperative research efforts among universities, and institutions with strong wind energy program. The offshore wind industry will require engineers, and technicians to install, and operate them. Through engineering education, courses in offshore wind technology, safety systems, and survival techniques can be incorporated into the engineering curriculum of our nation’s universities, and institutions. Other challenges to offshore wind can be mitigated through research on support structures, critical component failure, and electrical infrastructure. These will spur an understanding of the offshore wind industry, and will lead to scientific, and technological breakthrough without being constrained by short time horizons.

References

[1] European Academy of Wind Energy (2016): “Long-term research challenges in wind energy- a research agenda by the European Academy of Wind Energy”. Retrieved from: http://www.orbit.dtu.dk/files/120954163/Long_term_research_challenges.pdf Accessed October 19 2017.

[2] Gift, I.I., Lopez-Querol, S., Camacho, J.L. and Bhattacharya, S., (20163).” Improved p-y curves for the Design of Offshore Wind Turbine Foundations”. Retrieved from: http: //www.ngi.no/content/download/4006/431162/file/SP2_sluttrapport_web.pdf. Accessed October 19 2017.

[3] Haiderali, A.E., Madabhushi, G.S.P (2017): “Evaluation of the p-y Method in the Design of Monopiles for Offshore Wind Turbines”. Retrieved from: *https://www.onepetro.org/conference-paper/OTC-24088-MS* Accessed October 19 2017.

[4] Jose, N. M., Mathai, A., (2015): “A Study on Lateral Deformation of Monopile Foundation of Offshore Wind Turbine”. Retrieved from: https://www.ijerst.com/SECM-2016/16_17_(105-110).pdf Accessed October 19 2017.

[5] Blanco, M.I. The Economics of Wind Energy. Journal of Renewable and Sustainable Energy Reviews, 13, Science Direct, Amsterdam, Netherlands 2009, 1372-1382.

[6] Knodel, B. (2016):” A high-level overview of offshore wind project development identifying current technologies, challenges, risks and costs”. Retrieved from: www.ieeepesboston.org/files/2011/06/OffshoreWindPresentation.pdf Accessed October 20 2017.

[7] National Renewable Energy Laboratory (2015): “2014 Cost of Wind Energy Review”. Retrieved from: https://www.nrel.gov/docs/fy16osti/64281.pdf Accessed October 20 2017.

[8] Edward, I. (2011): “Overcoming challenges for the offshore wind industry and learning from the oil and gas industry”. POWER cluster. REPORT No. 012345-R001A; 2011; 36(7):1887-901. Retrieved from: http://www.power-cluster.net/Portals/6/Overcoming%20OW%20Challenges%20summary.pdf . Accessed October 21 2017.

[9] Madabhusi, G., and Haiderali, A.E. (2013):” Evaluation of the p-y Method in the Design of Monopiles for Offshore Wind Turbines.” Retrieved from: *https://www.onepetro.org/conference-paper/OTC-24088-MS* Accessed October 21 2017.

[10] Desha, C.J.K., Hargroves, C.K., Smith, M.H. The importance of sustainability in engineering education: A toolkit of information and teaching material. Retrieved from: *www.naturaledgeproject.net/documents/icdpaper-final*. Accessed September 30, 2016