Modelling Offshore Wind Farm Operation and Maintenance

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The Benefits of Condition Monitoring

By

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A real warrior is the one who is brave enough to face the darkness in life
and bring back light to the rest of the world.

CONTENTS

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I would like to express my very great appreciation for the Centre for Doctoral Training for Wind Energy, University of Strathclyde, the only wind energy focused Centre for Doctoral Training under the British Engineering and Physical Sciences Research Council (*EPSRC*), which provided me with the great opportunity to explore the field of wind energy by providing a thorough training process covering all relevant knowledge, study opportunities on the specific PhD topics, and outreach activities. I would like to thank my academic supervisors, Professor David Infield and Professor William E. Leithead for their valuable and constructive suggestions. I would like to thank Dr Julian B. Feuchtwang for sharing his knowledge on the cost model development.

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BIOGRAPHY

Xi Yu, PhD in Wind Energy Systems, PhD supervisor, graduated from the Centre for Doctoral Training for Wind Energy under the British Engineering and Physical Sciences Research Council (EPSRC) Scheme, with a research focus on offshore wind energy. Dr Yu has worked with EDF (UK Centre, London) in wind energy research and development for five years, and with Vattenfall (UK Centre, Edinburgh) in wind energy research and development for over one year and is still in a good relationship with these centres. Dr Yu has been involved in projects all over the UK and the North Sea, including the world's largest offshore wind power project at Navitus Bay, the Swedish offshore wind project Lillgrund, the British offshore project Teesside, and the UK's largest onshore wind farm Whitelee. In these projects, Dr Yu carried out development of operation and maintenance strategies based on condition monitoring systems, wind farm cost effectiveness analysis, failure rate analysis, reliability analysis, and so on.

The onshore/offshore failure rate translator developed by Dr Yu has effectively improved the simulation confidence level of inaccessible offshore failure rate data. Her wind farm cost effectiveness estimation model has been recognized by EDF, Vattenfall, and academics in this area for its high quality offshore wind turbine component simulated failure rates, detailed operation and maintenance strategy classification, and proper corresponding transportation strategy categorization. The benchmark results of the offshore wind farm cost effectiveness estimation models both in commercial and academic areas show that the cost model developed by Dr Yu has a relatively high estimation quality with high reliability, accuracy, computing speed and wide range of consideration.

The condition-based offshore operation and maintenance strategy in addition to the reactive maintenance developed by Dr Yu has met both the wind farm availability and the cost effectiveness requirements for companies' wind farms and has saved considerable time, economic costs, manpower and material resources.

The animation included a method to distinguish wind turbine yaw and wind direction sensor error developed by Dr Yu. This has assisted wind farm service departments by quickly detecting potentially problematic wind turbines and guiding the service engineers and technicians to implement timely maintenance, therefore achieving a positive outcome.

Dr Yu innovatively developed wind turbine component risk priority numbers specifically for offshore use. She was one of the few pathfinders in the field of quantifying the risk priority ranks for offshore wind turbines. The research results have been published in the offshore wind energy literature.

Dr Yu has been repeatedly invited to present at international offshore wind and renewable energy conferences and became a supervisor for a PhD student in this area.

Dr Yu has participated in the International Three Minute Thesis (3MT) Presentation Speech Competition and was the winner of the University of Strathclyde Division, presenting her research results from the areas mentioned above in 2016.

ABSTRACT

Offshore wind energy production is progressing rapidly and is playing an increasingly important role in electricity generation. Since the Kyoto Protocol in February 2005, Europe has been substantially increasing its installed wind energy production capacity. Compared with onshore wind energy production sites, utilizing offshore sites allows the installation of larger turbines, more extensive sites, and encounters higher wind speeds with lower turbulence. On the other hand, harsh marine conditions and limited access to the turbines are expected to increase the costs of operation and maintenance (O&M—O&M costs presently make up approximately 20–25% of the levelized total lifetime cost of a wind turbine). Efficient condition monitoring has the potential to reduce O&M costs. In the analysis of the cost effectiveness of condition monitoring, cost and operational data are crucial. Regrettably, wind farm operational data are generally kept confidential by manufacturers and wind farm operators, especially for offshore sites.

To facilitate progress, this book investigated accessible Supervisory Control and Data Acquisition (SCADA) and failure data from a large onshore wind farm and created a series of indirect analysis methods to overcome the data shortage, including an onshore/offshore failure rate translator and a series of methods to distinguish yawing errors from wind turbine nacelle direction sensor errors. Wind turbine component reliability has been investigated using this innovative component failure rate translation method from onshore to offshore, and the translation technique to Failure Mode and Effect Analysis (FMEA) for offshore wind installations was applied. An existing O&M cost model has been further developed and then compared to other available cost models. It is demonstrated that the improvements made to the model (including the data translation approach) have improved the applicability and reliability of the model. The extended cost model (called StraPCost+) has been used to establish a relationship between the effectiveness of reactive and condition-based maintenance strategies. The benchmarked cost model has then been applied to assess the O&M cost effectiveness for three offshore wind farms at different operational phases.

Apart from the innovative methodologies developed, this book also provides a detailed background and understanding of the state of the art for

offshore wind technology and condition monitoring technology. The methodology of the cost model developed in this book is presented in detail and compared with other cost models in both commercial and research domains.

CHAPTER 1

INTRODUCTION AND MOTIVATION FOR THE RESEARCH

It is generally accepted that renewable energy has been taking an increasingly important role in energy generation worldwide, especially since the Kyoto Protocol was brought into force in February 2005 when the adoption of renewable energy formally became governmental action. Wind energy, as an important form of renewable energy generation, has been given increasing attention all over the world, within which offshore wind energy generation is now progressing rapidly. Europe has been substantially increasing its installed offshore wind capacity in recent years. The offshore market in the UK has been enlarged rapidly during this period with large projects given political and economic support.

Compared with onshore wind installations, offshore wind farms allow the installation of turbines of both larger structural size and rated capacity. Offshore installations can access more extensive sites with higher wind speeds and lower turbulence. These obvious advantages have attracted a large amount of commercial attention. On the other hand, harsh marine conditions and limited access to the turbines are expected to increase the cost of operation and maintenance (O&M). O&M costs make up 20–25% of the total lifetime cost of an onshore wind turbine 0, and a typical 500 MW offshore wind farm normally requires in the order of £25–40 million for O&M annually [2]. Maintenance costs include preventive and corrective maintenance, and account for the main proportion of the O&M costs. It is therefore important to find a way to reduce O&M costs, especially within the maintenance component.

To reduce maintenance costs, one train of thought is to improve the maintenance strategy. One way of achieving this is to apply condition-based maintenance as a planned preventive method and reduce the dependence on reactive maintenance as a corrective method, since this usually costs more. Efficient condition monitoring has the potential to reduce O&M costs, but it is important to make sure that the investment in condition monitoring systems is worthwhile. The indicative cost for a condition monitoring—

including Supervisory Control and Data Acquisition (SCADA)—system is in the order of £0.4–0.8 million for a typical 500 MW wind farm per year [3]. This is a relatively low cost compared with the overall O&M costs but still considerable for the entire turbine life time. A promising approach is to use information from the SCADA system as much as possible to reduce the costs of any additional condition monitoring hardware.

To study the cost effectiveness of condition monitoring, cost and operational data are important. However, being a relatively new technology in energy generation, wind farm operational data are generally kept confidential by manufacturers and wind farm operators, especially for offshore sites. The lack of historical cost and operational data (especially failure rate) from offshore wind farms makes it difficult to investigate the reliability and undertake the desired cost effectiveness analysis.

This chapter covers the novelty of the research in Section 1.1, an overview of the book in Section 1.2 with a process diagram highlighting the main research points, and publications in Section 1.3.

1.1 Novelty of the research

This book has investigated accessible SCADA and failure data from a large onshore wind farm and SCADA data from selected offshore wind farms, and innovatively created a series of indirect analysis methods to overcome the problem of data shortage, including an onshore/offshore failure rate translator and a series of methods to distinguish yawing errors from turbine nacelle direction sensor errors. Another novelty of this book is that it has creatively applied this failure rate translator to a Failure Modes and Effect Analysis (FMEA) to rank component risks for offshore wind turbines to fill this gap in the research domain. This data translation approach has been used to improve and further develop an existing O&M cost model. The extended cost model (called StraPCost+) has been used to establish a relationship between the effectiveness of reactive and condition-based maintenance strategies. The cost model has also been benchmarked against a number of cost models already in commercial or academic use and it has been demonstrated as reliable and practical. The cost model has then been applied to assess the O&M cost effectiveness for three offshore wind farms at different operational phases, including the planning phase.

This book provides a detailed background to the subject including a comprehensive literature review. It develops and applies innovative methods to modelling O&M and the impact of condition monitoring.

Highlighted topics include the current condition of offshore wind energy, the state-of-the-art condition monitoring techniques and costs, a detailed introduction of the cost model developed in this book, and the methodology of other cost models in both commercial and research domains with detailed comparisons of model results.

1.2 Overview of the book

Chapter 2 begins this book with a thorough review of the relevant literature including a comparison of onshore and offshore wind farms and their O&M requirements. It then presents a technical introduction to condition monitoring including the benefits, performance and costs. It lists the different condition monitoring techniques in use. Finally, this chapter reviews the current situation regarding turbine and component failure rate and provides the motivation for the failure rate analysis developed in this book.

Chapter 3 begins with a technical introduction to the actual wind farms used in this book. It then provides a detailed environmental and generational analysis of an offshore wind farm that is investigated in detail in this book. This chapter principally presents a series of yaw error and turbine nacelle direction sensor error identification methods developed in order to improve the interpretation of operational data. This technique filters out the data with misleading failure information and improves the data reliability for further failure rate analysis and cost effectiveness analysis in the next chapters.

Chapter 4 investigates wind turbine component reliability. It presents a method of failure rate translation from onshore to offshore data that is developed and used in this book and discusses its wider potential applications, in particular, the translation of an FMEA component risk ranking from onshore to offshore. It quantifies for the first time the risks associated with key component ranks in an offshore operational context.

Chapter 5 comprehensively introduces the cost model developed and improved for offshore wind farm performance and O&M cost estimation. This chapter begins with a detailed technical introduction to the existing cost model. A number of other cost models in the research and commercial domain are reviewed and compared with this existing model. The next section presents the improvement of the original cost model, called StraPCost+, including the application of the onshore/offshore failure rate translator developed in Chapter 4. This chapter then compares the StraPCost+ model with other accessible cost models using an offshore wind farm case study and discusses the results. As an innovative function among all cost models, StraPCost+ provides an estimation of condition-based maintenance. This chapter then presents a series of detailed condition monitoring system detection effectiveness analyses from StraPCost+. The last section in this chapter presents a series of sensitivity analyses to examine the impact of changing key factors: the wind and wave parameters, the weather window threshold, overall turbine annual failure rate, condition monitoring detection statuses and distance to shore.

Chapter 6 presents two real site case studies using StraPCost+, with a comparison of other cost models. It firstly provides the analysis of an existing offshore wind farm and demonstrates the reliable applicability of StraPCost+. After that, it presents a case study aiming to provide estimates for a planned offshore wind farm, which shows the potential practical use of StraPCost+ in terms of assisting decision making for vessel planning.

Chapter 7 concludes this book and proposes areas of potentially useful future work.

Chapter 8 lists the references used in this book.

A series of Appendices are presented at the end of the book. Appendix-A presents the wind farm statistics. Appendix-B presents results for the cost model analysis. In the book contents, a citation from the appendix is given an indication after the table number of “a” for Appendix-A, and “b” for Appendix-B.

A progress diagram for the main points in this book is presented on the next page to aid understanding of the coherence of each research point.

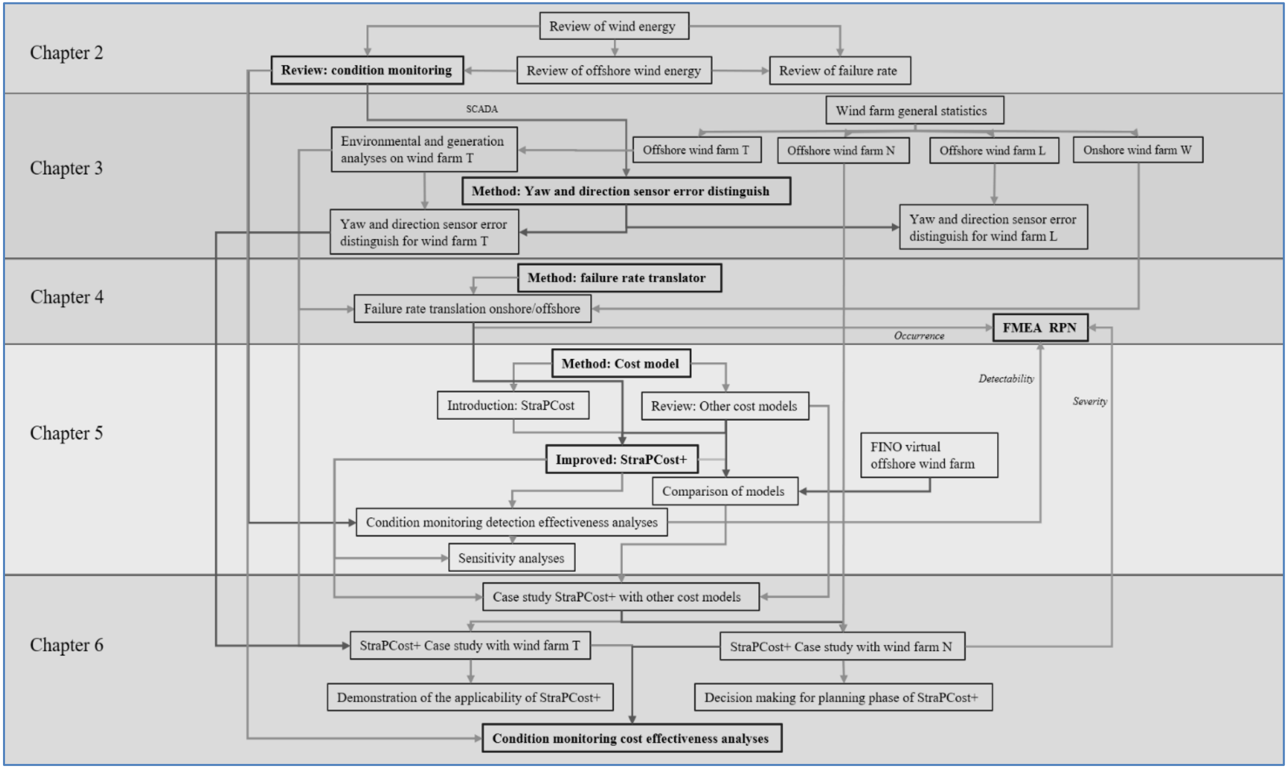

Figure 1. Process diagram for the research points in each chapter in this book.

1.3 Publications

[1] Yu X., Martin R., Infield D., Barbouchi S. and Seraoui R., Determining the Applicability of Onshore Wind FMECAs to Offshore Wind Applications, ***EWEA** Offshore*, 20th Nov 2013

[2] Yu X., Infield D., Barbouchi S. and Seraoui R., Numerical Methods for Applying Onshore Failure Rate to Offshore Operational Conditions and Assessing the Benefits of Condition Monitoring, ***AWEA** 2015*, 18th May 2015

[3] Yu X., Infield D., Barbouchi S. and Seraoui R., Adjusting Onshore Failure Rate Data for Cost Effectiveness Analysis of Wind Turbine Condition Monitoring Offshore, *ACSEE2015*, 11th June 2015 (with Oral Presentation)

[4] Yu X., Infield D., Barbouchi S. and Seraoui R., A numerical method to transfer an onshore wind turbine FMEA to offshore operational conditions, *RENEW2014*, 24th Nov 2014 (with Oral Presentation)

[5] Yu X., Infield D. and Maguire E., Wind direction error in the Lillgrund offshore wind farm in *Renewable Power Generation Conference (RPG 2013), 2nd IET*, 9-11 Sept. 2013 (Oral Presentation)

[6] Yu X., Yue H. and Leithead W. E., Feed-forward pitch control of HAWT using LIDAR, *EAWE 2012*, 12-13 Sept. 2012

CHAPTER 2

LITERATURE REVIEW

In order to have a general understanding of the motivation and the issues investigated later, this chapter provides a thorough literature review covering the topics of wind energy, offshore wind, condition monitoring and failure rate.

Section 2.1, the review of offshore wind, lists the top ten largest operating offshore wind farms in the world and compares the environmental and technical differences between onshore and offshore wind farms.

Section 2.2 discusses condition monitoring, introduces the main categories of maintenance strategies in use, describes the benefits of condition monitoring and lists the different condition monitoring data acquisition and processing techniques in use.

The last section in this chapter, Section 2.3, reviews the current situation of component failure rate which motivates the failure rate analysis undertaken in the next chapters.

2.1. Review of offshore wind

This section presents a general review of onshore and offshore wind farms, an introduction to wind turbines, a comparison between onshore and offshore wind energy, and the current situation of offshore wind energy development in the world and in Europe.

2.1.1 Wind farms

A wind farm is a site that consists of a number of wind turbines, installed onshore or offshore. Both onshore and offshore wind farms have rapidly increased their generation capacity in the past decade. Wind energy delivered in total 3.4% of the world's electricity in the year 2014 [4]. The world's largest onshore wind farms can have thousands of turbines. For example, Gansu wind farm, China has more than 3,500 turbines installed with a current capacity of over 6 GW [5][6]. Offshore wind farms, on the other hand, seek to enhance the total capacity by not only increasing the total number of turbines but also having a higher individual capacity of each turbine, for example 25 MHI Vestas 8 MW turbines have been installed in the Burbo Bank offshore wind farm (DONG Energy), Liverpool Bay, UK [7].

With a large number of turbines, an onshore wind farm can have a total capacity of over several thousand megawatts. Onshore wind farms can be built in a wide range of different terrains such as mountainous areas, plains, coastal areas, deserts and even in polar regions. As stated above, many of the world's largest onshore wind farms are located in China and India; following the Gansu wind farm in China in size, Muppandal wind farm in India has 3,000 turbines generating 1.5 GW of installed capacity [8].

Offshore wind farms, on the other hand, are constructed in bodies of water, where the wind resource quality is better in terms of higher wind speed and lower wind turbulence. DONG Energy, Vattenfall and E.ON are leading operators in the offshore wind industry [4]. The leading countries for offshore wind farms are the UK, Germany, and Denmark [9]. In 2015, the London Array in the UK, inaugurated on the July 4, 2013, remained the world's largest operating offshore wind farm, with 175 Siemens SWT-3.6-120 wind turbines and a total capacity of 630 MW [10].

Table 1 lists the top ten largest operating offshore wind farms in the world. It provides a series of technical details such as distance to shore, maximum water depth, wind farm area, number of turbines, turbine type, installed capacity and commission year. The country of location clearly shows that all of these large offshore wind farms are located in Europe, while seven of them are within the UK. The next section continues discussing this table from the perspective of wind turbine types.

Table 1. List of top ten largest operating offshore wind farms in the world in 2015

No.	Wind farm	Location country	Distance to shore	(Max.) Water depth	Area	No. turbines	Turbine type	Installed capacity	Commission year	reference
1	London Array	UK	27.6 km	0–25 m	100 km^2	175	Siemens SWT-3.6-120	630 MW	2013	[10]
2	Gwynt y Môr	UK	18 km	12-28 m	86 km^2	160	Siemens SWT-3.6-107	576 MW	2015	[11]
3	Greater Gabbard	UK	32.5 km	20–32 m	146 km^2	140	Siemens SWT-3.6-120	504 MW	2012	[12]
4	BARD Offshore 1	North Sea, Germany	90–101 km	40 m	59 km^2	80	BARD 5.0	400 MW	2013	[12]
5	Anholt	Denmark	22.6 km	15–19 m	116 km^2	111	Siemens SWT-3.6-120	400 MW	2013	[13]
6	West of Duddon Sands	UK	20.1km	17–24 m	67 km^2	108	Siemens SWT-3.6-120	389 MW	2014	[14]
7	Walney	Cumbria, UK	19.3 km	19–28 m	28 km^2	102	Siemens SWT-3.6-107	367.2 MW	phase 1: 2011	[15]
			22 km	25–30 m	45 km^2				phase 2: 2012	
8	Thorntonbank	North Sea, Belgium	27.9 km	18–28 m	1 km^2	6	Senvion 5MW	325 MW	phase 1: 2009	[16][17]
			28.2 km	12–24 m	12 km^2	48	Senvion 6.15MW		phase 2: 2012	
			28.1 km	12–26 m	7 km^2				phase 3: 2013	
9	Sheringham Shoal	Greater Wash, UK	21.4 km	15–22 m	35 km^2	88	Siemens SWT-3.6-107	315 MW	2012	[18]
10	Thanet	Kent, UK	17.7 km	20–25 m	35 km^2	100	Vestas V90-3MW	300 MW	2010	[19]

2.1.2 The wind turbine

A wind turbine is a device that extracts energy from the wind and converts it into mechanical energy, and then electrical energy. Wind turbines can rotate both horizontally and vertically, known as horizontal axis wind turbines and vertical axis wind turbines, respectively. The power from onshore wind turbines is usually less than offshore ones mainly because of the quality of the wind, and the fact that onshore turbines usually encounter more noise and visual issues. Offshore wind turbines can be over 6 MW in capacity. Vestas and Siemens are the two largest wind turbine suppliers worldwide, followed by General Electric (GE) Energy, Goldwind and Enercon [4]. From the ten largest offshore wind farms, as shown in Table 1, seven out of the ten use Siemens wind turbines. This indicates that Siemens wind technology is presently favoured by European large offshore wind farm developers. In this book, the main wind farms with accessible data use Siemens 2.3 MW rated wind turbines, for both onshore and offshore wind farms. This shows that this type of turbine is widely utilized in Europe. The consistency of the turbine type for onshore and offshore has provided the possibility—and eased the development—of the onshore/offshore failure rate translation introduced in Chapter 4.

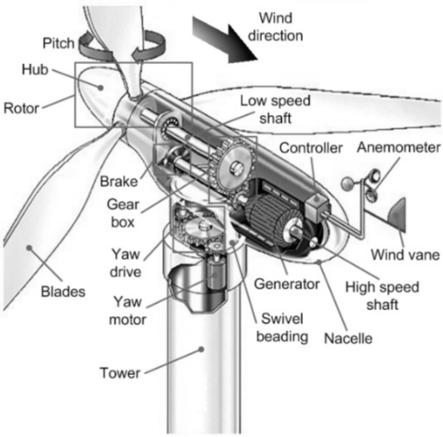

Figure 2. Typical wind turbine structure with detailed drive train system in the nacelle [20]

The complexity of the drive train system increases the frequency and cost of maintenance. A conventional wind turbine drive train mainly consists of a low speed shaft, a gearbox, a brake, a high speed shaft and a generator, as shown in Figure 2. Alternatives to a traditional gearbox arrangement are direct drive and hybrid drives in which a low ratio gearbox is combined with a multi-pole generator. One major branch in direct drive development is permanent magnet generators (PMGs).

Direct drive systems remove the intermediate link, the gearbox, to improve the turbine availability, and hence to reduce the total maintenance cost. Figure 3 shows a low speed direct drive from an Enercon turbine, where the rotor hub is mounted on the fixed axle [21]. To avoid the complexity and thus the high failure rate of the gearbox, wind turbine manufacturers such as Siemens and GE have been devoting themselves to the development of direct drive turbines. The share of direct drive turbines has increased from around 16% in 2006 to 26% in 2013 [22]. However, since direct drive is still a new concept in wind turbine power generation, some research shows that the economic benefits for direct drive turbines are unclear or even lower than the gearbox-driven ones [23].

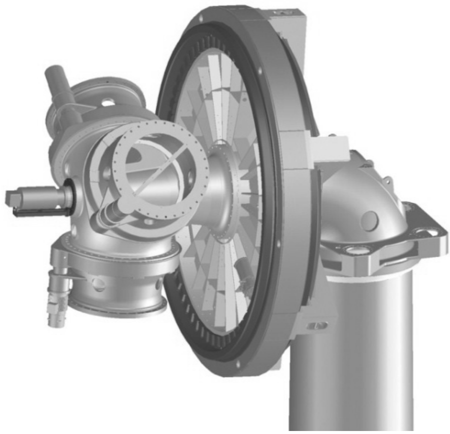

Figure 3. Image of a direct drive of E-48 from Enercon [21]

The hybrid drive system is a compromise between the conventional gearbox drive train and a direct drive system. It uses a gearbox with a reduced number of stages which improves efficiency and reliability and uses intermediate rather than high speed generators. Companies such as Gamesa use multiple permanent magnet induction generators, as shown in Figure 4 [24].

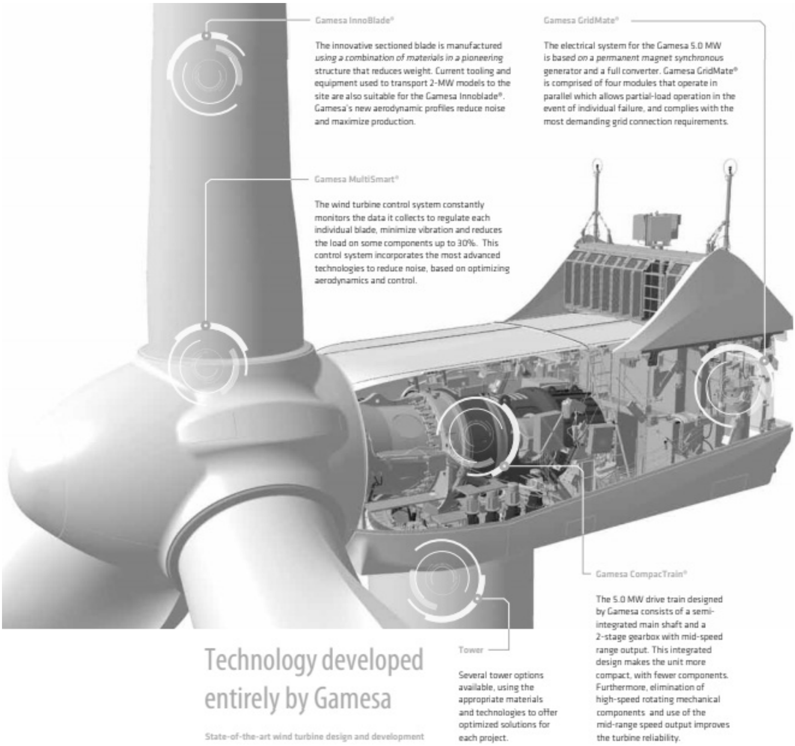

Figure 4. Hybrid drive system with multiple PMGs turbine from Gamesa [24]

The different designs of drive train outlined above provide examples of design improvements of wind turbine components which aim to reduce the failure rate costs and enhance reliability. From the trends outlined, it can be seen that a direct drive arrangement with a large multi-pole (usually PMG) is steadily developing and taking over from conventional geared turbines for large offshore wind turbines. EDF, for example, has selected the Haliade® (GE-Alstom) direct drive 6 MW turbine for their French offshore sites [25].

2.1.3 Offshore vs. onshore

Apart from technical or cost perspectives, there are significant differences between onshore and offshore wind farms. Over the years, the debate between installing a cheaper easy-maintenance onshore wind farm or an offshore wind farm causing less visual pollution and with higher output has never stopped. Compared to onshore wind, offshore wind has rather different characteristics. For example, the total electricity production is generally higher since wind speeds are higher, and they are also more persistent which adds value to the electricity generated. From an environmental perspective, offshore wind farms are exposed to extreme weather conditions, waves, and corrosion due to salt water. In addition, the marine environment makes maintenance much more difficult than onshore, which leads to longer downtime and lower availability. In addition, offshore maintenance and repair is more expensive due to the cost of accessing offshore sites.

Table 2, as first presented in [26], lists the benefits and disadvantages of both onshore and offshore wind farms, and some of the disadvantages address the issues that O&M might encounter. O&M costs for offshore wind could be higher for more challenging offshore sites further from shore. Preventive condition-based maintenance can help to reduce this cost via inspection and maintenance before catastrophic failure occurs.

Table 2. Comparison of characteristics offshore vs. onshore [26]

	Offshore	Onshore
Site related and technological characteristics		
Specific electricity production	High (due to high average wind speeds)	Generally lower than offshore
General restrictions	Water depth, nautical routes, nature reserves, distance from the coast	Wind exposure, residential areas, nature reserves
Environmental conditions	Rather strong and steady wind speeds, salt water and salt spray, waves, extreme weather conditions	Lower, less steady and more turbulent winds than offshore due to surface roughness
Access conditions	Erection only during calm wind and sea conditions, restricted access (e.g. for trouble shooting, maintenance), potentially long distances	Erection in calm wind conditions, road access required, transport of rotor blades more challenging than offshore, but maintenance easier
Environmental impacts	Visual impact and noise of little relevance, potential impacts on sea birds and migrating birds, impacts due to foundation and grid connection	Visual impact and noise often highly relevant
Grid connection	Long distances to coupling points, condition monitoring necessary, separate licence procedure(s), weak costal grids	Low to medium distances, grid integration less problematic because wind farm size is smaller