Reliability Engineering and System Safety 168 (2017) 28–39

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

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

Influence of statistical uncertainty of component reliability estimations on offshore wind farm availability

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ARTICLE INFO

Keywords:
Offshore wind energy
Operations and maintenance
Maintenance modelling
Reliability
Statistical uncertainty
Availability

ABSTRACT

Offshore wind turbine reliability, one of the industry's biggest sources of uncertainty, is the focus of the present paper. Specifically the impact of uncertain component failure distributions at constant failure rates has been investigated with respect to its implications for wind farm availability. A fully probabilistic offshore wind simulation model has been applied to quantify results; effects shown in this paper underline the significant impact that failure probability distributions have on asset performance evaluation. It was found that wind farm availability numbers may vary in the range up to 20 % just by changing the distributions of failure to a different pattern; in particular those scenarios in which extensive failure accumulation occurred led to significant losses in production. Results are interpreted and discussed mainly from the viewpoint of an offshore wind farm developer, owner and operator, with implications underlined for application in state-of-the-art offshore wind O&M (Operations and Maintenance) models and simulation tools.

1. Introduction

The offshore wind sector is today in a phase of rapid growth under multivariate market demands, such as an acceptable cost of energy level at a stable electricity supply and sustainable investment security for its shareholders. Electricity generated from offshore wind turbines will cover a share of up to 7.7% of Europe's overall electricity consumption in 2030 by an installed power of 66 GW capacity [1]. The levelized cost of energy (LCoE) will thereby be driven down to an acceptable level; currently values of 80–100 €/MWh (megawatt hour) for offshore generated electricity is aimed at for assets being located in European and US waters [2–6]. A long-term outlook from the UK government is even referring to cost estimates of around 60 €/MWh by 2050; a value close to what onshore wind generation is achieving today – representing one of the most promising renewable energy technologies [7].

Large investments are needed in order to achieve these ambitious targets. A figure of around € 3billion per GW installed capacity is realistic for future investments according to Rubel et al. [8]. The same report addresses the desire for a commensurate risk-return balance from an investor's perspective in order to attract investments in the field. The European Union presents a scenario in which fewer investments may be made in offshore wind due to a 'struggle of de-risking' the industry [2].

Various different risk sources are thereby relevant for the offshore wind industry. A number of publically available reports address those, such as [9] where the focus is on a methodology for financial assessment of a project; [10] which presents a comprehensive risk assessment framework aimed at new technologies with a strong technical focus; and [11] in which internal and external risk sources, specifically for large-scale offshore wind application, are assessed. All reports refer to, amongst other factors, risks associated with asset reliability. Other important factors, such as ecological risks, political risks, risks in the supply chain, risks related to project financing or risks related to health, safety and the environment are omitted at this point due to the present work having a different focus.

Asset reliability is defined as the 'ability of an item to perform a required function under given conditions for a given time interval' [12]. The reliability of the item, i.e. the asset 'offshore wind farm', depends on, amongst others, the reliability of single wind turbines – respectively their systems, subsystems and components, as well as cabling, grid connectors and on– and offshore substations. A common term used to express the reliability of an item is the so-called failure rate (FR), describing the number of failures per unit of time [12]. As described thoroughly in [13,14], the FR is, for many applications, not constant over time. This characteristic has also been observed for onshore wind energy converters (WECs) which are, from a technology perspective, to some extent

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http://dx.doi.org/10.1016/j.ress.2017.05.021
Available online 5 May 2017

comparable with their offshore counterparts [15]. Time dependence of failures is related to the technical properties of the system or component. Examples of time and loading dependent failures are, for example, the wear out of gear teeth; in contrast the shutdown of a control system often unexpectedly occurs at random time intervals. The latter is a pattern which can specifically be observed for new, unproven concepts for which failure modes and mechanisms are not fully understood [16].

Although it is understood that FRs are not constant throughout the lifetime of offshore WECs, most studies providing publically available reliability figures rely on this simplification [15–19]. All studies mentioned, however, refer to the given fact that there are variations in component and system FRs over time, mostly qualitatively estimating a lifetime failure distribution of an offshore WEC in the shape of a bathtub curve. Carroll et al.'s most recent publication [19], attempts, amongst other factors, to understand the statistical distributions of offshore WEC failure intensities over time. Their studies are based on the operational data of 350 turbines, where two thirds are in operation for three to five years and around one third for more than five years. From the presented data, there is no clear failure pattern observable which would allow for verification of scenarios suggested in former studies. In other words, this means that the statistical distribution of wind turbine reliability over the assets' lifecycle is yet to be understood.

Studies, such as the comprehensive report of Feng et al. [20], illustrate the significant impact that reliability figures have on offshore wind farm availability – a predominant measure of indicating the level of performance of offshore wind operations; availability here is defined as the 'ability to be in a state to perform as and when required, under given conditions, assuming that the necessary external resources are provided' [12]. Positive financial turnovers may only be made in periods of availability, i.e. when the WECs are in operation, thus producing electricity to be fed into a grid.

As many component failures potentially lead to stoppage of the WECs, the relationship between reliability and availability is obvious. This is addressed in several works introducing technical concepts that aim to improve reliability or allowing for early fault detection, minimising the impact of a developing fault. Odgaard [21], presents different fault tolerant control concepts as a way to maximise reliability. Other studies focus on early fault detection for instance by condition monitoring systems [22], or use of SCADA (Supervisory Control and Data Acquisition) information [23].

It should, however, be noted that availability depends on more factors than just reliability. For offshore wind generation in particular, the issue of accessibility is highly relevant. This means that defective components may not be repaired or replaced for a long period of time due to the inaccessibility of the asset. The financial impact of failures may therefore be aggravated during periods of bad accessibility, i.e. during periods of high waves, excessive wind speeds, bad visibility or simply from the absence of the right means of transport, tools, spare parts or personnel [24].

Several offshore wind O&M models and simulation tools attempt to represent offshore wind operations in sufficient resolution, enabling informed asset decision making [25,26]. The magnitude of deviation of expected results delivered by models and reality is generally kept as low as practicable in order to enhance confidence in a decision. Due to the nature of models as such, there are distinct uncertainties in their application. These modelling uncertainties may, for example, arise from an inadequate modelling technique (inappropriate use of data, e.g. due to model idealizations), but also inadequate model input data (use of inappropriate data). The latter has, amongst others, been investigated in [27], in which the concept of expected value of perfect information (EVPI) has been compared to traditional approaches in handling uncertain data, particularly in respect to maintenance scheduling decisions.

The study referred to in [28] has investigated uncertainties in modelling maintenance scenarios in the nuclear energy industry, showing the significant impact that epistemic (systematic) uncertainties caused by low resolution models have on asset availability predictions, particularly regarding component reliability. Nannapenani and Mahadevan [29] suggest a method for including aleatory (statistical) and epistemic uncertainties in reliability estimates with a focus on model-based predictions. One of their main conclusions is that sources of uncertainty need to be addressed, considering application-specific particularities, in order to generate valuable results.

The offshore wind industry in particular faces a challenge in the availability of representative data, allowing for accurate reliability estimates. This is mainly due to the relatively short application of this technology, in line with constantly changing turbine designs due to technological advancement. In addition, site-specific environmental conditions affect failure behaviour significantly, which in turn enhances statistical uncertainty in reliability estimates, considering that these are built upon data from various sites.

This paper aims to address the above described issues with a focus on investigating the impact that different failure distributions may have on offshore wind farm availability levels. A better understanding of interrelations between the different parameters will be enabled in a broad context which may be relevant for, amongst others, existing and future offshore wind farm developers, owners and operators, offshore WEC manufacturers, O&M service providers, insurers or financing bodies. Applied methods can enhance the state-of-the-art O&M modelling and simulation tools in the offshore wind industry. This will improve the predictability of operational asset behaviour, inherently offering risk mitigation opportunities for investments in the field.

The paper is followed by a section introducing the methodology applied for this research, a section about failure modelling, which also contains relevant theory in the field, and a description of the baseline scenario used for the simulations. The results are presented and interpreted in Section 5 – a semi-probabilistic comparison study is presented afterwards, showing that phenomena from overlapping stochasticity are not influencing the results. The paper closes with a discussion and conclusion section.

2. Methodology

A baseline scenario, representing a wind farm operated in waters off the UK east coast, has been modelled in a Monte Carlo simulation tool developed by the first author. A comprehensive description of the basic version of the probabilistic modelling tool applied is available in [30]. Further functionalities were developed in the course of the presented studies in order to adequately model the engineering problem described in this paper. It should be noted that a variety of offshore wind simulation tools focusing on the operational phase do exist in the market; however, modelling techniques and functionalities differ significantly, depending on the exact scope.

An overview of the commercially available tools is provided in [25]. Further developments may be consulted in a verification study referred to in [26]. The methodologies combined in the tool developed for and applied in the present study are unique, with advanced functionalities implemented for failure modelling, emphasising the impact of uncertainties in reliability estimates (further details are provided below). The ability to model the different scenarios, also respecting probabilistic weather time series (with a realistic representation of absolute wind speeds and wave heights but also the persistence of weather windows on site), proves the representativeness of the results in a great variety of conditions.

The purpose of the applied tool in its initial version was to investigate different maintenance strategies for large-scale offshore wind farms with a focus on accessibility. Modifications for the present study are made, as highlighted in the grey box of Fig. 1, on the interaction between the failure modelling module (5) and the O&M simulation module (6); details are provided in Fig. 2. Further explanatory remarks are provided in the text below Fig. 1.

Module 1 – historic, site-specific metocean data: for site definition, historic metocean data has been obtained from the European Centre for