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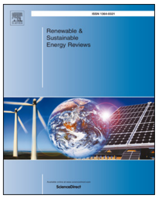

Reliability-based design optimization in offshore renewable energy systems

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ABSTRACT

Offshore wind farm operations and maintenance costs currently total 6 m€/year, or 25–28% of total costs. For wave and tidal energy converters, this cost is projected to be twice that of offshore wind, but has high levels of uncertainty. As the wave and tidal energy industries mature, decreasing O&M costs through reliability-based design optimization is critical to increasing feasibility and competitiveness with other energy technologies. In this paper, we will synthesize existing information on reliability-based optimization in systems analogous to offshore renewable energy systems. We will conclude by highlighting opportunities for future work in this field.

1. Introduction

Offshore renewable energy (ORE) has the potential to be a significant source of future global electricity production, reduce carbon emissions, decrease dependence on energy importation, and stimulate economic growth in coastal and remote areas [1,2]. Available offshore wind, wave, and tidal energy on the US Pacific coast alone is estimated at 8750 million megawatt-hours (MWh) per year, equal to 800 million US households [3–5]. This energy availability, paired with growing population centers along coastlines [6] positions offshore wind, wave, and tidal energy conversion technologies as a viable way of making power in coastal areas. The key to making this technology feasible is providing electricity through reliable technology and at competitive prices.

Currently, offshore wind energy technology has reached commercial-scale installation in Europe, and the cost of energy associated with these systems continues to decrease, but it is still not cost competitive with other renewable energy technologies like solar photovoltaic systems. Tidal and wave energy technologies are even less mature, with less than 1000 MW of installed tidal energy capacity, and no commercial wave energy installations. Both tidal and wave energy are not yet market competitive.

One way to reduce the cost of ORE technologies is through the increased reliability of ORE systems [7–9]. Improving reliability of ORE technologies will enable devices to produce electricity during energy-dense sea-states, lengthen operational life, decrease costly operations and maintenance (O&M), and decrease financial risk premiums. Given that the ORE industry is still in an early development stage, there is an opportunity to use reliability-based design optimization (RBDO) techniques to achieve cost reductions and improve market feasibility. Using RBDO to consider reliability, cost, and performance during subcomponent, device, and system design stages will enable the exploration of optimal solutions, which is of particular interest to the wave and tidal energy industry as they seek technology design convergence.

In this paper, we will describe the current state of the ORE industry, as well as work that includes reliability information in research of ORE systems, with particular emphasis on RBDO techniques. Section 2 discusses fundamental concepts of offshore wind, wave, and tidal energy technologies. Section 3 describes how reliability is used by the ORE industry in the context of each industry. A literature review cataloging the uses of RBDO in ORE comprises Section 4. Lastly, we will synthesize research needs and opportunities within this field in Section 5.

2. What is offshore renewable energy (ORE)?

In this report, *ORE technology* refers to the most mature technologies that have achieved, or are closest to, commercial realization: offshore wind, wave, and tidal energy technologies. Less mature technologies (e.g., ocean thermal energy conversion) are not discussed. The most common offshore wind, wave, and tidal energy device types are briefly explained here. For further information about these concepts, refer to Aquaret [10].

Offshore wind turbines are classified by their turbine orientation (horizontal or vertical axis) and their foundation (fixed or floating). Just like their onshore counterparts, the blades rotate as they interact with oncoming wind: the more consistent the airstream, the more consistent the power output of the turbine. Wind is created by atmospheric pressure differences, which can make this resource variable. Deploying offshore turbines takes advantage of long fetch lengths, resulting in higher speed and more consistent winds compared to land-

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based sites. The most mature technology in the ORE industry is fixed-bottom offshore wind energy technology. Floating offshore wind energy technology is in early-stage development and deployment, with the first grid-connected test installation, Hywind (Scotland), beginning production in October 2017.

Tidal energy technologies primarily consist of barrages or in-stream turbines. The first commercial tidal barrages were installed in the 1960s with the La Rance (France) and Jangxia Creek (China) projects [11]. In-stream turbines account for 76% of research and development efforts, and are focused on horizontal-axis turbines [12]. MeyGen (Scotland) is the first commercial installation of tidal turbines, completing the first stage of construction in April 2018 [13]. Tidal barrages, like run-of-river dams, use the potential energy contained in the difference in hydraulic head between high and low tides to spin turbines in an impoundment. Tidal turbines use the kinetic energy of water moving past an axial or cross-flow turbine as the tide ebbs and flows. Requiring large tidal ranges and flow velocities, tidal energy technologies are often limited by site availability. However, tidal cycles are more consistent than waves or wind, making tidal energy more consistent and predictable than wind or wave energy. First generation tidal devices were mainly bottom-mounted devices, while more recent concepts utilize the middle and upper water column where tidal resource is greatest [12]. This shift has ramifications for the survivability and reliability of devices.

Wave energy converters (WECs) are devices that convert the energy of ocean waves into electricity. WECs are commonly categorized by their location (on-, near-, or off-shore) or mode of operation. Onshore devices have greater accessibility and incur lower O&M costs, but have less available energy to convert. Nearshore devices generally rest on the seafloor in water depths of 10–30 m, thus they require little mooring, and see more exploitable energy than their onshore counterparts. Offshore devices are in water depths greater than 30 m and are typically moored, floating structures. They incur larger O&M costs, are less accessible, and are subject to higher wave regimes than their on- or nearshore counterparts. Devices that are subjected to higher wave regimes see increased gross available energy for conversion, but are also more likely to incur greater damage (both over time due to consistently larger forces, and during extreme events). A number of device types are currently being tested to harness wave energy, including oscillating water columns, overtopping devices, point absorbers, submerged pressure differentials, oscillating surge, bulge wave, vertical axis pendulum, and others.

3. Reliability in ORE

While all three ORE technologies have potential to function successfully in the renewable energy sector, developers need to deliver reliable, efficient technologies that can survive their harsh environment to be economically profitable. This section describes how reliability currently shapes each ORE technology. Due to differences in maturity, offshore wind energy technology has been separated from wave and tidal energy technologies.

3.1. Offshore wind energy

While fixed-bottom offshore wind energy technology has extensive operational experience and is a mature technology, floating offshore wind energy technology is still in early stages of development. Significant research efforts are currently being made to accurately simulate floating offshore wind turbines as well as deploy small-scale demonstration devices. These efforts will result in the ability for researchers to analyze reliability in offshore wind turbines based on simulations, and the ability to leverage data from demonstration installments to better assess reliability in these floating systems. Due to the difference in maturity of fixed-bottom and floating offshore wind turbine technology, the rest of this subsection focuses on fixed-bottom offshore wind energy technology.

Fixed-bottom offshore wind energy technology has benefited from the experience of the onshore wind energy industry, and has reached widespread commercialization in Europe. Although the first site was installed in 1991 in Vindeby, only recently have markets emerged in the United States, East Asia, and India (just as the first European offshore wind turbines are reaching the end of their operational lifespan). In 2016, fixed-bottom offshore wind prices for proposed installations dropped significantly, with developers promising to provide power from facilities at 54.50 €/MWh in The Netherlands, and at 49.90 €/MWh [14] in Denmark. By 2026, the Dutch government expects that its offshore auctions will not require subsidies [15], and in an April 2017 German auction, tenders won at the wholesale electricity price, meaning the wind farms would be supported entirely by market prices, with no subsidy or government support required [16,17].

Europe provides considerable economic and regulatory support for offshore wind, and currently owns 88% of global offshore wind developments [18]. As a result, Europe now has a maturing supply chain, high level of expertise, and strong market competition. Growing investor confidence, decreasing financing risk premiums, and technology improvements further support industry growth. Technology advancements include larger, more reliable turbines; turbine size has increased from 3–4 MW to 8–10 MW, with 13–15 MW models likely to be available by 2024 [19]. Increases in expected operational life of turbines have also been made possible by technology advances, causing the average expected life to increase from 15 years (in 1991) to 30 years [19], with possibilities of life extension (continued operation of old equipment past its expected operational lifespan) and repowering (replacing old equipment for newer equipment with greater efficiency or nameplate capacity).

Despite these encouraging statistics that characterize the current state of the industry, fixed-bottom offshore wind performance and reliability need to improve to become cost competitive with other renewable energy technologies. The levelized cost of energy (LCOE is a metric that incorporates lifetime costs and expected production) for an offshore wind site in 2016 was estimated at 120–130 €/MWh [19], which is 40% more than onshore wind in comparable regions, 20% more than solar photovoltaic cells, and 100% more than that of conventional sources such as coal and gas [20]. Furthermore, expected lives of fixed-bottom offshore wind turbines are proving to be overestimates in some cases. A study looking at the performance of 30 offshore wind installations in Denmark reported an average load factor reduction of 24% in the first 10 years of operation [21] (load factor being defined as the total power output over the maximum possible power output for a given length of time, normalized for wind availability). These results have implications for shorter operational life expectancy for offshore turbines and decreased estimates of lifetime power production.

While decreased performance over time is expected, fixed-bottom offshore wind turbine failures are especially costly. At Horns Rev 1 for instance, two turbines failed and will remain non-operational for the last 10 years of the wind farm life due to the high expense of repair [22,23]. Short weather windows for repairs, limited trained personnel and vessels, and profit loss from lack of production during downtime compound the cost of failure. Developing offshore areas allows for exploitation of greater resource, but potentially increases failure likelihood and decreases accessibility. First, consistently stronger winds increase probability of failure, as turbines are exposed to higher wind and wave loads, both in nominal and extreme conditions. Secondly, accessing equipment that requires repair or maintenance is more difficult by helicopter or boat in areas further offshore, given that wind speed and wave height are strongly correlated.

Failure likelihood and accessibility directly impact availability, or the portion of time the installation is capable of producing electricity. Availability at offshore wind farms is typically between 90% and 95% [24,25], but is sensitive to the location of the farm (distance from shore,