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Review

A review on recent advancements of substructures for offshore wind turbines

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A R T I C L E I N F O

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A B S T R A C T

The sustainable development of offshore wind energy requires thorough investigations on technological issues. The substructure, which acts as the natural link between technologies and environments, is a critical topic for the offshore wind industry. This paper presents a comprehensive review of variable types of offshore wind substructures associate with their corresponding example projects. The study is complemented with a special attention to a novel foundation, namely suction bucket foundation. Main technological issues related to this concept are integrated. In the paper, bearing behaviors of offshore wind turbines (OWTs) with the suction bucket foundation under lateral loads, vertical loads, combined loads, and extreme loading conditions are discussed. Two installation methods are introduced. The geometric and improved design is illustrated by considering capabilities in transportation and installation. Research methods, including field tests, laboratory tests, centrifuge tests, theoretical analysis and numerical simulations, are listed; these methods are employed in previous studies to investigate behaviors of the OWT. This review integrates most relevant aspects and recent advancements together, which aims to provide a reference frame for future studies and projects.

1. Introduction

Due to the rapid developments of economy and urbanization all around the world, the demand for electrical energy experiences a significant increase. By the end of the year 2016, the total electricity generation was 24,353 TWh worldwide, which was about 4 times comparing to the 6131 TWh for the year 1973 [1,2]. It is estimated that the world electricity consumption will increased to 31,657 TWh by the year 2030 [3]. Currently, the electrical energy is mainly produced by fossil fuel, and 80% of the total investment of global energy supply went to traditional oil, gas and coal energy [1]. However, the increasing demand of energy supplies results in threats of energy crisis as well as environmental problems. Fossil fuel on earth is limited with gradual shortages, which can lead to that millions of people will still be left behind without basic energy services in 2040 [4]. The burning of fossil fuels brought significant amount of CO_2 emissions, which reached 31.5 GT in 2016 [1].

To achieve goals of lower carbon emissions and longer service life of energy production, renewable energy has attracted huge amount of interests and experienced rapid developments currently [5]. Renewable energy is the applicable replacement of the conventional energy generation sources, and the switching is benefit to both economy and environment [6]. By the year of 2016, the total renewable energy capacity worldwide is 2017 GW, which accounts 19.2% of the global energy consumption [7]. Reported by International Energy Outlook 2016, nearly 60% of the new power generation capacity will be contributed by renewable energy by the year 2040, and CO2 emissions are expected to decrease to 18,777 MT [4].

Among all renewable energy resources, the wind energy is believed to be one of the most promising types, which has been utilized extensively. Wind energy has the advantage of lowest environmental impacts, cost efficiency and sustainability, etc. The wind energy contributes almost 34% of the total newly installed renewable energy capacity in 2016, and the generation of wind energy experienced a rapid growth during the past ten years worldwide is listed in Table 1 and depicted in Fig. 1 [8]. In the United States, the total wind power capacity is about 76 GW by the end of year 2016, and it accounts 5% of U.S. electricity generation [9,10]. The evaluation of wind power potential is significant process before building the wind farms, and wind resource assessment method includes: cup anemometer, met mast, LiDAR, and SoDAR [11–13]. Offshore wind energy shows a better resource potential: the wind speed is faster and steadier in the open sea areas, which can exceed 10 m/s at a height of 50 m [14,15]. Comparing to onshore counterparts, the offshore wind can be 1.2–2 times faster

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Table 1
Global wind capacity power 2005–2016.

Year	Global cumulative installed wind capacity (GW)	Global annual installed wind capacity (GW)
2005	59	12
2006	74	15
2007	94	20
2008	121	27
2009	159	38
2010	198	39
2011	238	41
2012	283	45
2013	318	36

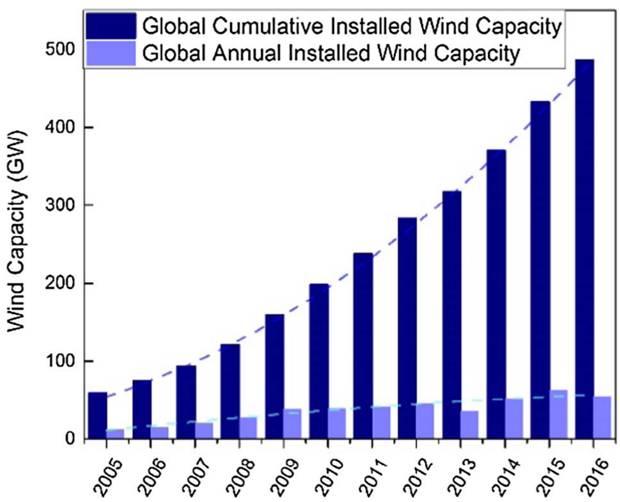

Fig. 1. Global wind power capacity 2005–2016.

and the electrical output will be 1.7 times more powerful, and the energy yield will be generally increases by going further from land [16,17].

Wind turbine is the media that converts the wind energy into electrical energy, and the predominant commercially available equipment is horizontal-axis machine with three blades positioned upwind of the tower [18]. The majority of current wind turbines are land-based projects [19]. The onshore wind turbines are commercially manufactured nowadays, and their sizes grow significantly in order to get better energy productions as well as reduce capital costs (Fig. 2)

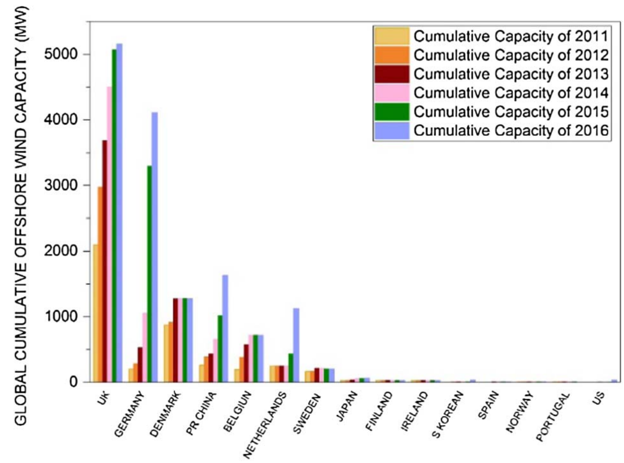

Fig. 3. Global cumulative offshore wind capacity.

[20–22]. However, there are some inverse influences of onshore wind turbines [23]. Firstly, the visual impacts are discussed in the previous literatures, and it is demonstrated that most people, who even support this renewable energy concept, do not favor wind turbines to be located near them or wherever they go often [24,25]. Secondly, mechanical and aerodynamic noises caused by wind turbines are not acceptable, and these annoyances may be worse than those from other environmental noise sources [26–28]. Finally, large requirements of land areas may bring serious conflicts with existing used lands [29].

In order to get better wind sources and minimize the visual or noisy problems, people start to spread their focuses from land-based wind turbines to OWTs [12]. By the end of year 2016, 14,384 MW of offshore wind capacity has been installed worldwide as shown in Fig. 3, and 88% of those are located off the coast of Europe in shallow waters with a depth of less than 20 m while the remaining 12% are installed in China, Japan and South Korean [9,31]. The detailed data is listed in Table 2. Moreover, the visual and noisy annoyances can be largely avoided since the equipment is away from communities; concerning the value of land, moving wind turbines to offshore will bring meaningful benefits. In the United States, the potential wind energy off the coasts is estimated to be more than 900,000 MW by U.S. Department of Energy, and the first commercial offshore wind farm is under construction off the coast of Rhode Island with a capacity of 30 MW [31–35].

Offshore wind farms also bring challenges for the global wind

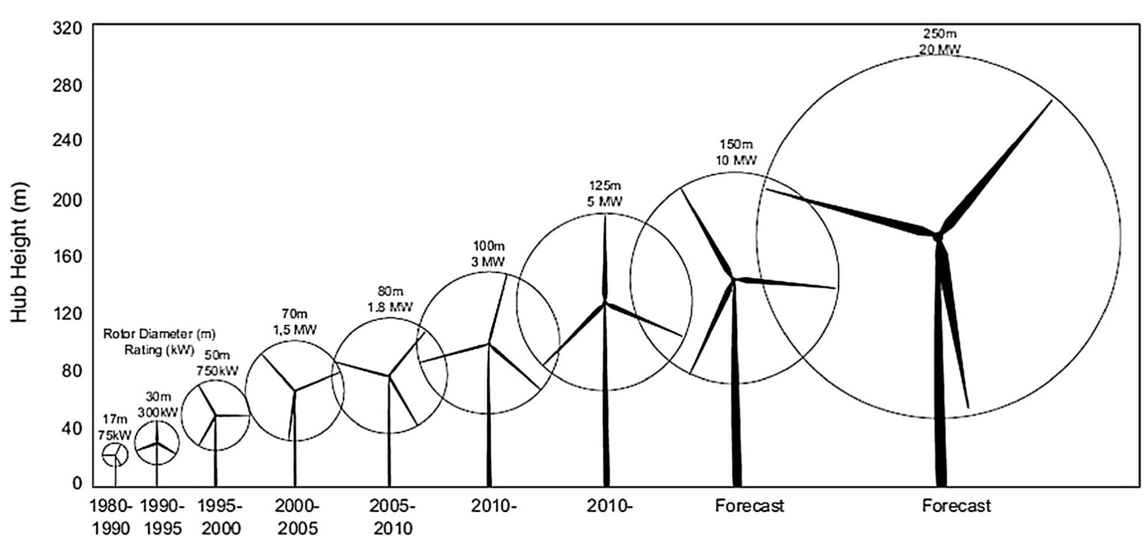

Fig. 2. Growth in size of wind turbines [30].