Renewable and Sustainable Energy Reviews 88 (2018) 16–36

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

A review of foundations of offshore wind energy convertors: Current status and future perspectives

Ki-Yong Oh[a,1], Woochul Nam[b,1], Moo Sung Ryu[c], Ji-Young Kim[c], Bogdan I. Epureanu[b,*]

[a] School of Energy Systems Engineering, Chung-Ang University, 84 Heukseok-ro, Dongjak-gu, Seoul 06974, Republic of Korea
[b] Scho ol of Mechanical Engineering, Chung-Ang University, 84, Heukseuk-ro, Dongjack-gu, Seoul 06974, Republic of Korea
[c] Renewable Energy Group, Korea Electric Power Corporation Research Institute, Munjiro 105, Yuseong-gu, Daejeon 34056, Republic of Korea

A R T I C L E I N F O

Keywords:
Offshore foundations
Offshore wind energy convertors
Offshore wind turbines
Structure-soil interaction

A B S T R A C T

This paper reviews foundations for offshore wind energy convertors considering the significant growth of offshore wind energy since the early 2000s. The characteristics of various foundation types (i.e., gravity, pile, suction caisson, and float type) and the current status of field application are discussed. Moreover, the mechanical characteristics of soil are described in the sense that these characteristics including modulus, strength, damping, and modulus degradation of soil play critical roles for the design of offshore foundations. By using these mechanical properties of soil, theoretical studies to consider structure-soil interaction are classified (into equivalent spring models, distributed spring models, and continuous element models) and explained. Field and laboratory experiments on the response of structure embedded in soil to static and dynamic loads are discussed. Based on the review of previous studies, directions for future research and study on offshore wind turbine are suggested.

1. Introduction

The development of renewable and sustainable energy sources not only mitigates concerns regarding the volatility of oil prices and the emission of carbon dioxide but also reduces the dependency of energy on fossil fuels. Wind energy is one of the promising solutions for sustainable energy because of its maturity and comparatively low cost [1].

In particular, offshore wind power can be a primary energy source in the future considering the high-energy density, lower turbulence, lower wind shear, and fewer civil complaints compared to onshore wind power. Total cumulative capacity in the offshore wind energy converters (OWECs) rose to 8759 MW in 2014 (Fig. 1). Large-scale offshore wind farms have been constructed in Europe, and their power production accounts for more than 90% of power generated by all OWECs. Total capacity has increased to 8.0 GW in 74 offshore wind farms in 11 European countries in 2014. Approximately, 1.5 GW of offshore wind was installed in 2014 [1]. Moreover, dozens of GW-capacity offshore wind farms are scheduled to be constructed over the next decades [2–4].

The United Kingdom (UK) and Germany lead the development of large-scale commercial offshore wind farms. China has become the third largest annual market in 2014. The Chinese government also announced a list of 44 future offshore projects with capacity of 10.53 GW [1]. Several pilot projects and commercial developments have been concurrently conducted in Taiwan, Japan, and South Korea [5,6]. Indeed, wind is a major source of power along with nuclear and fossil fuel (coal) energies, and its share is increasing significantly (Fig. 1).

Technological advances constantly improve the economic feasibility of offshore wind farms. For example, Round I offshore farms in the UK had an average monthly capacity factor of 33.6%, while Round 2 offshore farms increased their average monthly capacity factor to 38.3% [7]. However, many challenges facing the growth of offshore wind farms still remain. Specifically, the construction costs of offshore wind farms are 1.5–2 times greater than that of onshore wind farms [8] because offshore wind farms require expensive foundations, installation, and grid connections (e.g., underwater cabling and offshore transformer stations).

Especially, the cost for a foundation of an OWEC increases depending upon water depth (Fig. 2). The cost of OWEC foundations is about 20% of their total cost, and 45% of the wind turbine cost in shallow water depth. The cost for foundations at the water depth of 40–50 m is 1.9 times higher than the cost for the water depth of 10–20 m. Therefore, selecting a suitable OWEC foundation type and

* Corresponding author.
E-mail address: epureanu@umich.edu (B.I. Epureanu).
[1] These authors contributed equally to this paper.

https://doi.org/10.1016/j.rser.2018.02.005
Received 29 April 2016; Received in revised form 20 February 2017; Accepted 14 February 2018

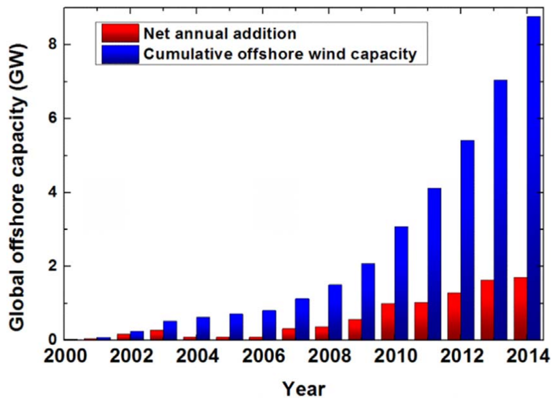

Fig. 1. Global offshore wind power capacity from 2000 to 2014; left bars show the net annual addition each year, while right bars represent cumulative offshore wind capacity every year; data used in this figure is from [1,3].

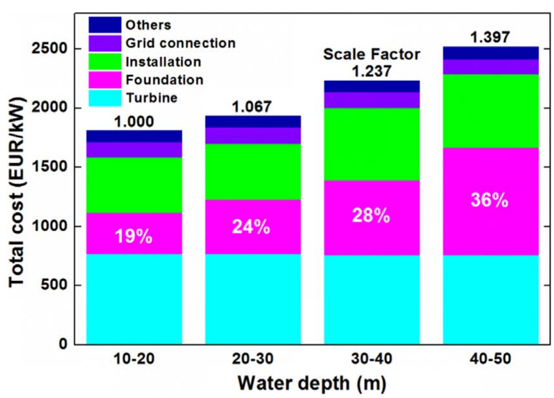

Fig. 2. Cost breakdown of offshore wind farm over water depth; data used in this figure is from [9].

optimally designing it are the most important factors to lower the cost.

Designing foundations for OWECs is more difficult than designing offshore oil and gas platforms. Aerodynamic loads acting on OWECs are significant because of their large blade span. Oil and gas offshore platforms are designed to minimize aerodynamic loads. However, large aerodynamic loads are unavoidable to OWECs because both rotational and thrust forces are applied to their turbine blades. This large aerodynamic load causes significant moments on the foundation of OWECs because the large loads act on the nacelles which are located at the top of the long wind turbine towers. Therefore, the large aerodynamic loads and their interaction with hydrodynamic loads need to be considered to prevent fatigue and failure of the structure. Hydrodynamic loads acting on OWECs and oil (or gas) platforms are also different. OWECs are installed in shallow and transient waters, whereas oil platforms are mainly installed in deep waters. The effect of sediment movement and scour on offshore structures depends upon these conditions. These differences suggest that optimization techniques, design methods, and field experience obtained from oil and gas foundations cannot be directly applied to the design of OWECs and substructures. Thus, intensive efforts in both theory and experiment are required.

This review of foundations of OWECs is aimed for a broad spectrum of readers from academia, research, and industry. The text covers a broad spectrum of topics from basic knowledge to the state-of-the-art research including research perspectives, challenges, and future trends. Section 2 describes basic concepts and future trends of various foundations for commercial OWECs in operation, which might be useful for researchers who wish to catch up quickly with the current state of foundations for large-scale offshore wind farms. The pros, cons and limits of each type of foundation are also explained for the same reason. Section 3 presents the fundamental characteristics of soils. This section includes the dynamic behavior of soils needed for the analysis of structure-soil interaction and the degradation behavior of soils needed for fatigue analysis. Also, we provide basic knowledge about the dynamic and static behaviors of soils over short- and long-term period, which is essential to design OWECs and their foundation and to predict the structural response of OWECs. Material properties of various soils are also listed for readers who need these properties for their studies. Note that understanding the nature of soils should be preceded to design foundations of OWECs because soils play critical roles for the behavior and response of OWECs. Section 4 discusses the principles, current states, and future challenges of modeling methods for structure-soil interaction. Research on modeling methods are categorized into three different model types: equivalent spring models, distributed springs models, and continuum element models. Various experiments on the structure-soil interaction are also discussed because that interaction is highly nonlinear. There experimental observations provide valuable information to develop new modeling methods and to suggest parameters used in modeling. Moreover, modeling and experimental efforts for suction caisson type of foundation are emphasized in a separate section. This type of foundation is the most promising in the future because it is accompanied with relatively small vibration, noise, and suspended sediments during installation [10]. Nonetheless, this type of foundation still faces challenges, which are also described in this section. Lastly, Section 5 suggests future research trends and challenges for the design of foundations of OWECs from several perspectives to secure the safety and reliability of offshore wind farms.

2. Types of foundation

The sea depth is generally classified into three classes: shallow waters (0–30 m), transitional waters (30–50 m), and deep waters (50–200 m) [11,13]. The sea depth is the most important factor for the viability of offshore wind farms because the cost for foundations significantly increases over the depth. Hence, several types of foundations are already developed, and some types are under development considering the sea depth and other conditions (Fig. 3).

Fig. 4(a) shows the current types of foundations used in commercial OWECs with respect to the sea depth and the distance from shore. This figure, which contains reorganized data from Tables 1–3, provides insights into trends for foundation types with respect to the sea depth and the distance from shore (Table 4).

In shallow waters, gravity type (Fig. 3(a)) and monopile type foundations (Fig. 3(b)) are mainly used. Initial offshore wind farms adopted these two types because their reliability is ensured in shallow waters. Especially, the monopile type is most frequently used because of the sea depth at available farm locations and the capacity of installed OWECs. The gravity type is not used for OWECs over 3 MW (Fig. 4(b)) because it has to be very heavy and expensive to be constructed in deeper seas, with depths over 10 m, in order to resist high aero- and hydro- dynamic loads for high capacity of wind turbine.

In transitional and deep waters, a monopile type and a multipod type are mainly deployed. Note that values corresponding to multipod include both tripod and jacket. This observation is also related to the capacity of OWECs. As OWECs with higher capacity, over 5 MW, have been installed in deeper waters, over 30 m, multipod type foundations have been selected to lower costs.

Fig. 4 also shows the trend of foundations for OWECs over the sea depth and the capacity: gravity – monopile – multipod. As the site is deeper and is farther from shore, multipod is more widely used than gravity and monopile foundations because of high economic feasibility. Note that floating type foundations are not included in Fig. 4 because most OWECs with floating type foundations are demo versions. The test floating OWEC foundations target very deep sites (e.g., 100–200 m) and have high rated capacity (e.g., 5–6 MW) [37,38,41]. The current status of applications for different foundations are discussed in the following sub-sections.