Energy 140 (2017) 1121–1130

Contents lists available at ScienceDirect

Energy

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

Economic comparison of technological alternatives to harness offshore wind and wave energies

Laura Castro-Santos [a], Elson Martins [b], C. Guedes Soares [b, *]

[a] Universidade da Coruña, Departamento de Enxeñaría Naval e Industrial, Escola Politécnica Superior, Esteiro, 15471 Ferrol, Spain
[b] Centre for Marine Technology and Ocean Engineering (CENTEC), Instituto Superior Tecnico. Universidade de Lisboa, Lisbon, Portugal

ARTICLE INFO

Article history:
Received 23 April 2017
Received in revised form
9 August 2017
Accepted 25 August 2017
Available online 25 August 2017

Keywords:
Marine renewable energy
Co-located systems
Wave energy
WEC
Hybrid devices
Life-cycle cost
Floating offshore wind

ABSTRACT

The present paper compares in economic terms, four technological alternatives to use offshore renewable energies: floating offshore wind energy technology, floating offshore wave energy systems, floating offshore co-located systems and floating offshore hybrid systems. These alternatives are compared considering different locations and sizes of the farms. Studies such as this can be useful for planning strategies and decision-making, particularly to investors that have to decide if and how to develop and deploy particular technologies in deep waters. The results indicate that the best alternative considering the life-cycle cost and LCOE is the floating offshore wind energy technology. Floating offshore co-located systems have the second best result, being a better alternative than floating offshore wave energy devices or floating offshore hybrid systems.

1. Introduction

Renewable energies are gaining increasing importance considering that global energy demand is increasing [1,2] and they reduce the dependence on traditional fuels [3,4], contributing to achieve the CO_2 targets [5,6]. This is the case of offshore renewable energy, which uses the energy of the oceans [7,8] and the offshore wind [9], which is growing in European [10], although it is not yet enough exploited [4,11]. One of the most important offshore renewable energies is the offshore wind [12] because of the large amount of energy produced by the state of the art turbines. In general one wind turbine produces one order of magnitude more energy than one wave or tidal energy device.

The turbines used offshore are similar to the turbines used onshore (with adjustments to deal with the marine environment) and thus this has become a commercial product already fabricated in series. The main difference offshore is the support structure of the turbine and the logistics of transporting, installing and maintaining the farms. Wave and tidal energy are far from having standard models being produced in series, on the contrary, there is a wide variety of possible devices in this industry, using different modes of capturing energy and transforming it.

During the XX century, solar and wind energy have achieved a great development [13]. However, in the XXI century one can identify important efforts to develop the ocean energy. The European Commission included the wave energy in its research and development objectives [14]. In the wave energy sector, several authors have classified and explained different types of technologies carried out to extract wave energy [15,16]. In this sense, three main types of wave energy devices can be defined [14]: overtopping systems, oscillating water column devices and oscillating bodies. However, all these technologies have been designed for particular operational ranges and efficiencies, whose values depend on the height and period of waves [13,17] and location, such as described in the technology evaluation study performed for the Portuguese nearshore [18,19]. In addition, they have advantages (the wave energy extracted is clean energy [17]) and disadvantages (its costs of accessibility [20,21]).

The offshore wind technology deals with proven technology, but the industry is relatively young, requiring further development [22]. This technology includes the offshore foundations, which can be fixed to the seabed or floating depending on depth, geology and sea state conditions. In this context, floating foundations have been

---

* Corresponding author.
E-mail address: c.guedes.soares@centec.tecnico.ulisboa.pt (C. Guedes Soares).

http://dx.doi.org/10.1016/j.energy.2017.08.103
0360-5442/

developed for larger depths than for fixed platforms. However, they are at an early phase of their life-cycle process. The main types of floating foundations are: spars, semisubmersible and tension leg platforms [23,24]. Expectations are that these devices will tend to be installed further offshore in increased number and capacity, although today most projects developed so far are nearshore in shallow water [25,26].

However, in any energy production scheme it is important to reduce costs such as operation and maintenance (O&M) and increase the energy yield [27–29]. This is the main reason why the combined extraction of renewable energy, for instance wave energy and offshore wind at the same floating platform, is being considered as an option in the future [30].

However, different technologies to harness different offshore renewable energies are at different stages of development. Particularly, that is the case of offshore wind [29,31] and wave technologies [32,33]. In this case, despite the development gap, the wave sector might learn from the experience and knowledge of the offshore wind sector to progress more rapidly [25].

Combined systems of several offshore renewable energies have been classified [27] as: hybrid, island and co-located. Co-located devices are based on wind and wave systems that share the same offshore location and some parts of their farm [34,35], being arrays uniformly, non-uniformly or peripherally distributed, or located independently in diverse offshore zones but near to share some activities, such as the grid system, but being independent. On the other hand, hybrid and islands technologies are a type of platform for several uses. In this sense, hybrid systems combine several types of offshore renewable energies (for instance, offshore wind with wave energy) [36], both in the same platform. Island systems combine more than two kinds of offshore renewable systems on the same structure and are larger than the other devices considered [27,37].

This paper compares, in economic terms, four floating technologic alternatives to harness offshore wind and wave energies, considering different locations and scales: floating offshore wind energy technology, floating offshore wave energy devices, floating offshore co-located systems and floating offshore hybrid systems. At this point there are no studies in the literature comparing these technologic alternatives. Furthermore, these economic comparisons can be useful by providing insights or additional information about if and how to develop and deploy particular technologies.

The paper follows this structure: firstly, the methodology used for economic comparison is developed; then the case study is taken into account, considering specific technologic alternatives in different locations and scales; next, the results for each option considered are presented; and the last section explains the conclusions of the paper.

2. Method

The methodology used for the economic comparison is based on the work of Castro-Santos et al. [38]. The method is briefly described here to provide the background for the rest of this paper. It is based on the life-cycle [39] of the offshore renewable energies. Through a set of input data, based on technologic and economic issues, the life-cycle cost and the Levelised Cost Of Energy (LCOE) are calculated. Total life-cycle cost of a Floating Offshore Renewable Energy Farm (LCS_{FOREF}) is calculated as follows:

$$LCS_{FOREF} = C1 + C2 + C3 + C4 + C5 + C6 \tag{1}$$

being C1 the concept phase, C2 the development and design stage, C3 the manufacturing stage, C4 the installation stage, C5 the exploitation stage and C6 the dismantling stage. Hence, the total cost is calculated considering the cost of all the life-cycle stages.

The concept phase (equation (2)) is composed by the costs of the market study (C11), the legislative factors (C12) and the farm design (C13). The manufacturing cost is composed by the costs of manufacturing the generators (C31), the floating platforms (C32), the moorings (C33), the anchoring (C34) and the electric systems (C35). The cost of installation is based on the cost of installing the generators (C41), the floating platforms (C42), the moorings and anchoring (C43), the electric system (C44) and the start-up (C45) of the farm. The exploitation phase is based on the cost of the insurance (C51), the business and administration (C52) and the operation and maintenance cost (C53). Finally, the dismantling cost involves the cost of dismantling the generators (C61), the platforms (C62), the moorings and anchoring (C63), the electric systems (C64), the cost of cleaning the area where is the farm (C65) and removing all the materials (C66).

$$C1 = C11 + C12 + C13 \tag{2}$$

$$C3 = C31 + C32 + C3 + C34 + C35 \tag{3}$$

$$C4 = C41 + C42 + C43 + C44 + C45 \tag{4}$$

$$C5 = C51 + C52 + C53 \tag{5}$$

$$C6 = C61 + C62 + C63 + C64 + C65 + C66 \tag{6}$$

LCOE is calculated as follows:

$$LCOE = \frac{\sum_{n=0}^{N_{farm}} \frac{LCS_{FOREF_n}}{(1+r)^n}}{\sum_{n=0}^{N_{farm}} \frac{E}{(1+r)^n}} \tag{7}$$

where LCS_{FOREF_n} is the total cost in the period n, E is the energy produced in the period n (assumed equal for all periods in the methodology), and r is the discount rate. The energy generated is calculated considering the kind and quantity of devices taken into consideration, and it is calculated as follows:

$$E = (N_{wi} \times E_{1wi} + N_{wa} \times E_{1wa}) \times \eta_{availability} \times \eta_{transmission} \tag{8}$$

where E_{1wi} and E_{1wa} are the energy produced by one wind or wave energy converter respectively, $\eta_{availability}$ the percentage of availability (in this case it has been considered the same for wind and wave devices to simplify the calculation) and $\eta_{transmission}$ the efficiency of the transmission, N_{wi} and N_{wa} are the number of offshore wind and wave energy devices.

In this context, the energy generated by an offshore wave converter can be determined using two methodologies: multiplying the power matrix of the platform by the matrix that represents the annual probability distribution of the sea states of the offshore location taken into account (method 1) [18] or considering a general equation (method 2, equation (9) [18], based on the assumption of deep water) dependent on the gravity (g), the period (T_{wa}) and height (H_{wa}) of waves, the sea water density (ρ), capture width of a particular technology (D_{wa}) and the efficiency of conversion ($\eta_{efficiency}$). The results obtained using method 1 have more precise values, however the input data are more difficult to obtain. In this paper, the method considered is the second one, because there are no information about the power matrix of the hybrid platforms. T_{wa} and H_{wa} are the average period and wave height ($T_{s\ med}$ and $H_{s\ med}$) of the B3 point of the simulation performed during 2009–2011 by Silva et al. [18].