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Ocean wave energy in the United States: Current status and future perspectives

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ABSTRACT

Ocean waves are a more predictable resource with a higher energy density compared to solar and wind. In addition, and specifically for the United States, resource locations with high wave power are close to major load centers being located along coastlines. These features have sparked a surge of attention in the United States on trying to economically harness ocean wave power. The aim of this article is to provide a concise review of the current state of ocean wave energy conversion technologies and industry status in the United States including research and development as well as commercial activities and governmental support, concluding with a discussion of future industry perspectives. Existing facilities, softwares as well as laboratory and open-water test facilities and resources, active research groups and commercial activities have been identified. Over one third of commercially active wave energy developers worldwide are located within the United States, but only a few have reached a high Technology Readiness Level. These findings, together with a relevant practical resource located within the U.S. and the advantageous nature of the resource compared to other renewable resources, indicate that the United States is well positioned to advance the wave energy industry in the near future.

1. Introduction

Ocean wave energy offers a renewable resource with the advantage of being predictable several days in advance, consistent throughout the day and night, and significantly higher in its energy density compared to wind and solar energies. Moreover, ocean wave power is available in close proximity to the coastal load centers of the United States. In fact, in the United States, half of the population lives within 50 miles of coastlines [1]. The adjacent oceans provide a total technically recoverable wave power resource of 1170 TWh/yr over the U.S. outer continental shelf to the notional 200 m depth contour [2]. This is equal to 30% of the annual electricity consumption of the United States, which is about 4000 TWh/yr [3].

However, currently there is no commercially grid-connected Wave Energy Converter (WEC) capacity installed in the U.S., and only a few megawatts are installed worldwide [4] (Table 1 provides an overview of global installed capacity of wave and tidal energy technologies as of 2014, see also [5]). According to the World Energy Council, state-of-the-art wave energy technologies operate at a LCOE (Levelized Cost of Energy, defined as the energy price at which the produced electricity needs to be sold for the project investment to be profitable) of 49.6 cents/kWh [6–9] (with an upward trend). This is significantly above the Department of Energy's (DOE's) 2030 goal for WECs to operate at 12 to 14 cents/kWh. According to PG&E, which cancelled its WaveConnect™ project in 2010, utility-scale wave farm projects in California were abandoned primarily due to the complexity and higher-than-expected permitting and installation cost, and a lack of cost-competitive WEC technologies [10,11]. Today's state-of-the-art WEC designs face operational and engineering limitations [12], but are also fundamentally restricted by hydrodynamic and design constraints that require trade-offs between Capital Expenditures and Operating Expenditures (CAPEX/OPEX) [108,109].

Although investment and research have been accelerating the Marine Hydrokinetic (MHK) industry worldwide, the industry still finds itself in its early stages of technological development. For example, in contrast to the wind industry in which horizontal-axis wind turbines (HAWT) are being widely used, the wave industry has not converged to a dominant design.

Compared to the U.S., Europe has historically supported the renewable energy industry with much more funding and supportive policies such as feed-in-tariffs. Moreover, most of the driving force within the industry since the 1970s, with investments and R&D in

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Table 1
Global installed capacity of wave and tidal energy technologies as of 2014 (Based on IEA Ocean Energy Systems).

Country	Tidal Installed Capacity [kW]	Wave Installed Capacity [kW]	Tidal Consented Projects [kW]	Wave Consented Projects [kW]
USA	–	–	1350	1365
Canada	20,000	–	20,450	–
UK	5600	3730	96,000	40,000
Sweden	7.5	180	–	10,500
Norway	–	200	–	–
Denmark	–	–	–	115
Netherlands	130	–	3000	–
Spain	–	296	–	300
Portugal	–	700	–	
Belgium	–	–	–	20,000
Singapore	–	16	2.5	
Republic of Korea	1000	500	1300	300
China	4070	350	4700	2860

both academia and industry, were located in Europe. The European Commission report [4] in 2015 highlights a short list of 45 WEC developers that have reached open-sea deployment; 7 are U.S. based, 26 are EU based, 6 are Australian, and the rest are from other international developers. The report also projects an increase in the deployment rate by 2025 and an expected global installed wave energy capacity of 25.9 MW by the end of the decade and consented projects of 1365 kW within the United States, despite a recent report from Bloomberg New Energy Finance indicating a reduction in its projection of global installed capacity for 2014 [6].

Furthermore, the report of the EU Commission predicts that around 14% of this capacity will be installed in Australia and 76% in Europe using various existing wave energy infrastructures ranging from 0–100 m water depth and 0–16 km distance from shore. The report concludes that the main roadblock to the industry is the lack of reliable and operable devices for open waters. But the report also highlights the lack of convergence on a dominant design that would allow a higher rate of knowledge exchange and supply chain engagement. Furthermore, no clear industry trend towards shallow-water or deep-water WEC designs can be predicted, which has significant implications on the supply chain and other elements of the entire value chain of the industry, thus imposing a risk factor in evaluating the economic viability of the WECs.

In this paper, we provide a review of the current status of wave energy research and development (R & D) in the United States. Section 2 outlines the wave energy resources available in the United States. In Section 3, an overview of the U.S. government activities in the field of wave energy conversion is provided. Section 4 highlights the academic research centers and universities with facilities suitable for research on wave energy conversion. Section 5 reviews publically available resources developed in the United States that are supporting investigations of ocean waves and WECs. In Section 6, the nonprofit and commercial activities needed to commercialize wave power in the United States are reviewed. Finally, Section 7 provides conclusions and future perspectives. While the information provided is a snapshot of the present state of wave power in the U.S., our intention is that this review will establish a foundation for further advancements of the wave energy industry through collaborations and economical utilization of existing expertise and resources.

The goal of this paper is to review the status of the research and the industry of wave energy in the United States, and to identify existing domestic facilities, softwares, closed and open-water test facilities, and resources, as well as active research groups and commercial activities. Over one third of commercially active wave energy developers are located within the United States, but only a few have reached a high Technology Readiness Level. These findings together with a relevant practical resource and its advantages indicate that the United States is well positioned to advance the wave energy industry in the near future.

2. Ocean wave energy resource in the United States

For all renewable energy resources, especially ocean renewable energy, it is required to assess and differentiate between the *theoretical resource,* the *technical resource,* and the *practical energy potential* [13]. In the assessment process, the theoretical resource is based on model and input data and can also be defined as the power density of waves approaching the shore [14]. This input power is reduced by extraction filters such as wave converter device specific parameters, cut-in/out constraints, and survival constraints, which results in the technical resource. The technical resource is further reduced by social, economic, and environmental filters that eventually lead to the practical resource [13,14].

For comparison, the theoretical global wave energy potential is about 32,000 TWh/yr [15] (Fig. 1). Excluding areas where the theore-

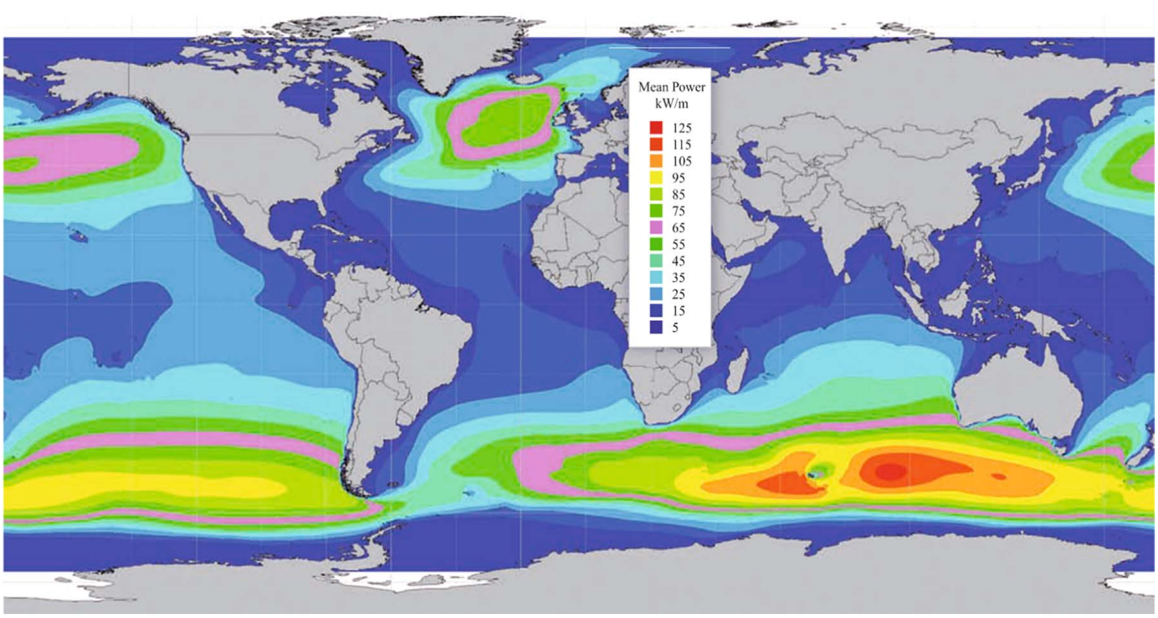

Fig. 1. Global distribution of mean wave power density in kW/m [4].