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A comprehensive evaluation of factors affecting the levelized cost of wave energy conversion projects

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ABSTRACT

The primary objectives of this study are to evaluate the levelized cost of energy (LCOE) for different wave energy conversion strategies and to examine cost reduction pathways such that wave energy conversion projects are competitive, relative to alternative energy industries. The energy production of six different WEC devices was estimated for four sites along the U.S. Pacific coast. The LCOE of pilot-scale wave energy conversion projects was estimated to range between $0.07/kWh and $0.92/kWh higher than the target LCOE of those for early-market offshore wind energy projects. Device capacity factors were generally below the commonly assumed value of 30%. Methods of cost reduction to the target LCOE of $0.30/kWh were explored, including decreasing capital and operational expenditures (CAPEX and OPEX) and increasing annual energy production (AEP) through improvements in the wave energy resource and WEC and WEC array performance, and advanced controls. Results indicate that CAPEX and OPEX should be reduced by at least 45% and AEP should be increased by 200%. A reduction of CAPEX and OPEX by 75%, combined with array evaluation and control strategies capable of increasing AEP by 12%–55% could also result in LCOE for wave energy conversion projects of less than $0.30/kWh.

1. Introduction

The potential contribution of total recoverable wave energy along the U.S. coast has been estimated at approximately 1170 TWh/yr [1], which is comparable to present-day (2016) coal (1240 TWh/yr) and natural gas (1393 TWh/yr) energy generation in the United States (https://en.wikipedia.org/wiki/Electricity_sector_of_the_United_States; *last accessed July 6, 2017*). Thus, wave energy could contribute to over a quarter of U.S. total annual electricity needs. Although wave energy converter (WEC) technology development is in its early stages, advancements are accelerating at a rapid pace and scaled versions of commercial devices are currently being tested at dedicated oceanic test sites such as the Hawaii Wave Energy Test Site, the United Kingdom Wave Hub (e.g., van Nieuwkoop et al. [2]), and the Pacific Marine Energy Center Test Sites [3]. Prior to full commercial-scale deployment of WEC arrays or farms, it is necessary to demonstrate competitive economic performance of these WEC technologies relative to other energy generation technologies.

The levelized cost of energy (LCOE), which is defined as the net present value of the unit-cost of electricity over the lifetime of a generating asset, often given as cost per kilowatt-hour (kWh), provides the fundamental metric by which energy generating technologies are assessed. However, LCOE is difficult to estimate accurately for nascent technologies with little operational experience and large uncertainties in costs. LCOE also depends on many factors that make comparisons between different estimates difficult, e.g., resource and site characteristics, and installed project capacity. Several desktop studies have been conducted to estimate the LCOE of marine and hydrokinetic (MHK) technologies including wave energy (e.g., Neary et al. [4]; Astariz et al. [5]; Castro-Santos et al. [6]; Jenne et al. [7]; OES [8]). In 2013, Bloomberg New Energy Finance reported three different estimates of LCOEs for wave energy conversion projects: 1. high cost of $1.06/kWh, 2. central cost of $0.50/kWh, and 3. low cost of $0.28/kWh, assuming WEC capacity factors of 25%, 30%, and 35%, respectively [9].

High-fidelity techno-economic assessments based on LCOE were conducted for reference model (RM) WEC point designs, including the RM3 point absorber by Neary et al. [4], the RM6

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Abbreviations

AEP	annual energy production
AF	availability factor
Bref-HB	bottom-referenced heaving buoy
Bref-SHB	bottom-referenced submerged heaving buoy
CF	capacity factor
CAPEX	capital expenditures
E	energy
F-2HB	floating two-body heaving converter
F-3OF	floating three-body oscillating flap
F-HBA	floating heave-buoy array
F-OWC	floating oscillating water column
H_s	significant wave height
JPD	joint probability distribution
kWh	kilowatt-hour
LCOE	levelized cost of energy (or electricity)
MHK	marine and hydrokinetic energy
MR	mass ratio
MWD	mean wave direction
NDBC	National Data Buoy Center
NOAA	National Oceanic and Atmospheric Administration
OPEX	operational expenditures
P	power
PC	project capacity
RCW	relative capture width
SNL-SWAN	Sandia National Laboratories – Simulating WAves Nearshore
SWAN	Simulating WAves Nearshore
T_p	peak wave period
$T_{servicing}$	time period for device servicing
$T_{shutdown}$	time period for device protective shutdown
T_{total}	total device shutdown time
USD or $	United States dollars
WEC	wave energy converter
n	system lifetime
r	discount rate
t	year from the start of the project

oscillating water column by Bull et al. [10], and the RM5 oscillating surge flap by Yu et al. [11]. LCOE estimates for these studies were based on detailed cost breakdown structures, and modeled LCOE reductions due to the economy-of-scale effect as the WEC array size (number of devices) and project installed capacity increased. The range of LCOEs of these three RM WECs was reported to average between $0.83/kWh for 100-unit arrays to $0.93/kWh for arrays of 50 devices to an average of $4.25/kWh for a single WEC device [7]. For projects with installed capacities of 10 MW, which represents a typical small commercial scale project, the LCOE averaged $1.11/kWh. Structural and mooring costs were identified as the main cost drivers; and performance improvements from advanced controls, not implemented in these studies, are expected to provide significant reductions in LCOE [4,7]. The LCOE for a 20 MW array of WECs for several European locations was estimated to range between $0.36/kWh to $1.87/kWh (2016 Euro to USD monetary conversion) [12], which is comparable to assessments derived from U.S. studies.

Ocean Energy Systems (OES; [8]) examined the LCOE of ocean thermal, tidal, and wave energy for various stages of energy technology development, from the initial developmental phase to commercial-scale projects. Results for initial phase WEC projects ranged between $0.25/kWh to $1.75/kWh. The highest values in this range were based on the RMs that were conservatively designed using commercial off-the-shelf components, conventional materials, and without advanced controls to improve performance. Cost estimates from technology developer responses and RM results converged for commercial-scale projects, to values between $0.12/kWh and $0.47/kWh, with decreases in OPEX driving the overall cost reduction.

LCOE estimates for nearly all wave energy conversion techno-economic studies are significantly higher than the LCOE of other energy generation projects. The LCOE of conventional energy generation projects such as coal, natural gas, and nuclear has been reported to range between $0.05/kWh to $0.28/kWh and alternative energy sources (e.g., wind and solar) are reported to cost between $0.03/kWh and $0.22/kWh [14]. Offshore wind projects, as a comparable marine renewable energy industry, have been reported to cost approximately $0.17/kWh [15]. While it is not surprising that the present economics of WEC technologies are not competitive, costs must be reduced, and performance improved, to make wave energy conversion economically viable.

Several studies have identified potential methods for reduction of wave energy LCOE such that it is cost-competitive. Bull and Ochs [16] identified advanced controls, improved power conversion, structural design optimization, and array optimization as the most promising wave energy cost-reduction pathways. Improved mooring designs, optimized device profiles, improved system reliability, and planned maintenance were named as secondary techniques to decrease the cost of wave energy. Neary et al. [4] also offered recommendations on methods of reducing high LCOEs, including reducing unknowns in device performance and cost uncertainties (e.g., environmental compliance), design optimization modeling, and advanced control systems.

1.1. Objectives

The primary objectives of this study are to evaluate the LCOE for different wave energy conversion strategies and explore cost reduction pathways such that the LCOE of wave energy conversion is competitive with conversion of other alternative renewable energy sources. The sensitivity of LCOE to resource, device archetype, and array configuration is investigated. The average annual energy production (AEP) and LCOE of six different devices was estimated for four different wave energy sites along the U.S. Pacific coast. Potential reductions in the LCOE due to decreases in CAPEX and OPEX and increases in AEP from WEC array configuration modifications and implementation of control strategies were explored and evaluated.

2. Methods

Levelized cost of energy (dollars per unit energy; here, $/kWh) may be defined as the quotient of total capital and operational expenditures of wave energy generation to the amount of energy generated over the system's lifetime, following OES [8]:

$$LCOE = \frac{CAPEX + \sum_{t=1}^{n} \frac{OPEXt}{(1+r)^t}}{\sum_{t=1}^{n} \frac{AEPt}{(1+r)^t}} \quad (1)$$

where n is the system lifetime in years, t is the year from the start of the project, and r is discount rate (%), which accounts for the value of money as a function of time. CAPEX describes costs (here, units of $) of the WEC project's fixed assets and OPEX includes ongoing