Ocean Engineering 169 (2018) 673–681

Contents lists available at ScienceDirect

Ocean Engineering

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

A symbiotic approach to the design of offshore wind turbines with other energy harvesting systems

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ARTICLE INFO

Keywords:
Wave energy
Offshore wind turbine
Uranium
Nuclear power
Symbiotic system

ABSTRACT

The capital cost of a 5 MW floating wind turbine (FWT) runs as high as $20.7 million, leading to an energy cost of $0.20/kWh, four times that of natural gas (Myhr et al., 2014). Although a single type of energy harvesting device may be too expensive to deploy, if it can operate symbiotically with others, the combined cost of energy might be acceptable. In this study, we show that attaching a wave energy converter (WEC) to the FWT may simultaneously produce an average of 240 kW wave power, reduce the WEC levelized cost of energy by 14% by eliminating redundant components, and reduce the FWT tower lifetime equivalent fatigue stress by 23% by reducing platform motion. Furthermore, the offshore wind turbine may also serve as a structure for the harvesting of valuable elements from seawater, such as uranium, lithium, and cobalt. The major cost drivers for the harvesting of uranium from seawater have been identified to be those associated with the mooring and deployment of the metal adsorbing polymers (Schneider and Sachde, 2013; Byers and Schneider, 2016). In the case of uranium, a symbiotic system coupled with an offshore wind turbine was found to reduce the seawater uranium production cost by at least 11% and up to 30% (Byers et al., 2016, 2018; Haji, 2017).

1. Introduction

With stronger winds, larger turbine sizes, and plenty of space versus onshore, offshore wind turbines have the potential to satisfy significant energy demands with renewable power (Kluger et al. 2015). At ocean sites with depths greater than 50 m, floating wind turbines (FWT's) are more economical than monopile wind turbines but are 2–3 times more expensive than onshore wind, with levelized costs of energy (LCOE) ranging from $0.12–0.27/kWh for offshore versus $0.07/kWh for onshore (Myhr et al., 2014; Jonkman, 2010; Tegen et al., 2013). Much of the FWT cost is due to the challenge of platform stabilization, which is solved using a large steel and/or concrete platform mass, active water ballast, or taut mooring lines (Myhr et al., 2014; Roddier et al., 2010; Butterfield et al., 2005). FWT platform motion is undesirable because it complicates the rotor aerodynamics and control, and reduces aerodynamic efficiency (Butterfield et al., 2005; Sebastian and Lackner, 2013; Tran and Kim, 2015). Furthermore, platform motion increases stresses on the blades, rotor shaft, yaw bearing, and tower base (Matha, 2009). This study hypothesizes that the cost of offshore wind power may be reduced by attaching additional offshore energy machines to the floating wind turbine platform (Astariz and Iglesias, 2015). If these auxiliary machines stabilize the platform, then the platform steel, active ballast, or taut mooring lines may be reduced.

This study considers using a wave energy converter (WEC) as one of the auxiliary machines attached to the FWT platform. One of the benefits of wave power is higher predictability and less variation than wind, which is important for electric grid operation (Georgilakis, 2008; Astariz and Iglesias, 2016). However, wave energy converters typically produce electricity with high levelized costs of energy ranging from $0.28-$1.00/kWh. The main reasons for this high cost are the challenges of system robustness in varying sea conditions as well as costly components. Site permitting, transmission lines, mooring lines, and the WEC steel frame comprise over 50% of a typical WEC cost (Yu et al., 2015). A WEC attached to a FWT could share or eliminate many of these costly components. In addition, this study hypothesizes that a carefully designed WEC attached to a FWT could reduce the detrimental wave-excited FWT platform motion. Several previous studies have investigated combined FWT-WEC dynamics (Aubault et al., 2011; Muliawan et al., 2013; Kelly et al., 2013; Perez-Collazo et al., 2015). Unfortunately, these studies found that the attached WEC design increased the FWT lateral motion rather than decreased it. This study investigates how to design the combined FWT-WEC system to reduce the FWT platform motion.

Furthermore, many metals critical to products and industries of the 21st century which are becoming more scarce and expensive in their land-based form, exist in essentially unlimited quantities in seawater.

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https://doi.org/10.1016/j.oceaneng.2018.07.026
Received 21 December 2017; Accepted 10 July 2018
0029-8018/

Given the environmental issues surrounding land-based mining, deep sea mining of many elements is becoming an attractive option but holds its own unforeseen environmental disruption issues. The use of treated polymers having a high capacity to selectively adsorb minerals has proven to be a promising method of mineral recovery from seawater even at low concentrations (Loganathan et al., 2017). Offshore systems for the extraction of uranium from seawater have been developed since the early 2000s. The system currently studied by a nation-wide consortium of national lab and university partners involves the passive recovery of uranium using polymer based adsorbents. High Density Polyethylene fibers undergo a radiation induced graft co-polymerization process involving amidoxime, to attract uranium, and a polar co-monomer to increase hydrophilicity. After further chemical conditioning adsorbent fibers are braided into 60 m strands for marine deployment. Braids are moored to the ocean floor for the duration of their soaking campaign. After sufficient seawater exposure they are winched up so the adsorbed uranium may be eluted off the braids (Tamada et al., 2006; Schneider and Linder, 2014). This deployment and elution process is repeated multiple times before the adsorbent's ultimate disposal, where its lifetime is dictated by the degradation it suffers with each re-cycle. However, because this deployment scheme requires the adsorbent be brought to a mothership for the elution process and redeployed afterward, it has significant practical and economic deployment challenges stemming mainly from the cost-prohibitive nature of the system's mooring and deployment capital, and operating costs (Schneider and Sachde, 2013; Byers and Schneider, 2016). Thus, combining an ocean mineral harvesting device with an existing offshore structure, such as a floating wind turbine or an oil rig, could drastically reduce the production cost of minerals from seawater while also increasing the structure's overall resource extraction potential. This study investigates the design and testing of a symbiotic system to harvest uranium from seawater that is coupled to an existing offshore wind turbine and the cost benefits that result. This paper also examines other minerals which can be extracted from seawater using a similar system design.

In summary, this paper considers several design aspects of combining a floating wind turbine, wave energy converter, and ocean mineral harvesting device into one symbiotic machine. This paper is organized into the following sections: First, Section 2 considers the dynamics and cost optimization of a wave energy converter attached to a floating wind turbine. Then, Section 3 considers the design and cost of a uranium harvesting device attached to a floating wind turbine, including experimental findings. Finally, Section 4 describes overall conclusions and future work for the symbiotic system design.

2. Design of a wave energy converter array attached to a floating wind turbine

2.1. FWT-WEC design motivation

As described in Section 1, this study hypothesizes that combining floating wind turbines (FWTs) and wave energy converters (WECs) into one system can significantly decrease the cost of both wind and wave power. The two main challenges to doing this are ensuring that the WEC power harvesting motion remains unconstrained by the FWT and the WEC reduces rather than increases the FWT platform motion. Additional challenges are that the WEC's performance must be robust to the changing sea conditions, including very rough seas.

For these reasons, this study considers the FWT-WEC design shown in Fig. 1 (a). The design uses the 5 MW Hywind wind turbine on the floating OC3 spar platform (Jonkman, 2010). This study restricts the WEC array to contain three WECs, spaced apart by 120° encircling the FWT. This design uses a hinged 2-bar linkage to attach each WEC to the FWT. The linkage causes the FWT and WEC to move together rigidly in surge and pitch and to be essentially uncoupled in heave for sufficiently small heave motions. The WEC harvests power in the heave direction. With careful design in this configuration, the WEC's inertia may be designed to reduce the platform lateral motion, while the WEC may experience significant heave motions to harvest wave energy without transmitting vertical loads to the platform.

The WEC itself is designed as a floating oscillating water column (Falcão et al., 2012). Oscillating water columns have been successfully tested in the ocean for over 20 years (The European Commission, 2002; The European Commission, 1998; Osawa et al. 2002). In this study, the WEC spar encircles a partly submerged tube with a 4 m radius that is open to water at the bottom and to air at the top. The top opening contains an air-driven Wells turbine that generates electricity as the water column motion forces air to oscillate through the tube. The Wells turbine is an appealing starting point for WEC analysis due to its simplicity and approximately linear properties. This study varies the Wells turbine coefficient, k_{Wells}, as part of the optimization procedure. The WEC's waterplane area is adjusted so that the WEC resonates at 0.06 Hz, a common frequency at the chosen ocean site. A sealed buoyancy toroid, with its top face submerged 3 m below the waterline, encircles the tube. The toroid has an outer radius r and length $l = 2r$. As r is varied as part of the optimization procedure, the amount of concrete ballast inside the toroid is adjusted to maintain neutral buoyancy.

Typical WECs have capacity factors of 0.3 (Georgilakis, 2008). To achieve a similar capacity factor, this study limits the power produced in the most powerful sea states to match the power produced in the next calmer sea state, so that a capacity factor of at least 0.3 is achieved. This power limitation may be physically implemented by an air bypass valve (Falcão and Justino, 1999). Reducing the power in this way improves the levelized cost of energy; that is, so the storms that occur 2% of the time do not require a costly increase in the power handling capacity that is not used during 98% of the machine lifetime. Future work could further optimize WEC capacity factor based on a chosen sea site.

2.2. FWT-WEC dynamics model

This study models the dynamics of combined floating wind turbine - wave energy converters (FWT-WECs) using linear coupled equations of motion and long-wavelength approximations in the frequency domain:

$$\mathbf{I}(\omega)\vec{x}'' + \mathbf{D}(\omega)\vec{x}' + \mathbf{K}(\omega)\vec{x} = \vec{f}(x) \quad (1)$$

where indicates a time derivative. The vector $\vec{x}$ contains 23 coupled degrees of freedom: the FWT platform's three translational motions and three rotational motions, the tower's two lowest fore-aft bending modes, each of the three WEC's three translational motions, each water column heave motion, and each tube's air pressure. The air pressure is linearly related to the relative heave motion between the water column and tube by the proportionality coefficient, $C = \frac{k_{Wells} V_{Chamber}}{\gamma P_{atm}}$, where k_{Wells} is the Wells turbine ratio of pressure drop to air flow, $V_{Chamber}$ is the equilibrium air chamber volume, $\gamma = 1.4$ is the air specific heat ratio, and $P_{atm} = 101.3$ kPa is atmospheric pressure, as described in Falcão et al. (2012). Nondiagonal terms in the matrices couple the degrees of freedom. Symmetry of this design causes FWT-WEC sway, roll, and yaw to equal 0. $\mathbf{I}(\omega)$ is the platform and WEC inertias and hydrodynamic added masses. $\mathbf{D}(\omega)$ accounts for the FWT platform and WEC hydrodynamic damping and the Wells turbine power takeoff.

The approximate hydrodynamic added mass, damping, and wave forcing on the platform are modeled using the WAMIT panel method results for the NREL OC3-Hywind floating wind turbine (Jonkman, 2010). The hydrodynamic added mass, damping, and wave forcing on each WEC are modeled using the long wavelength approximations from the G.I. Taylor and Haskind relations (Kluger, 2017). Hydrodynamic coupling between the FWT and WECs is neglected. A detailed derivation of the model is described in Kluger (2017), Kluger et al. (2016) and Kluger et al. (2017).

K accounts for the hydrostatic stiffnesses and linkage coupling between the FWT and WECs. As shown in Fig. 1(b) and (c), the FWT and

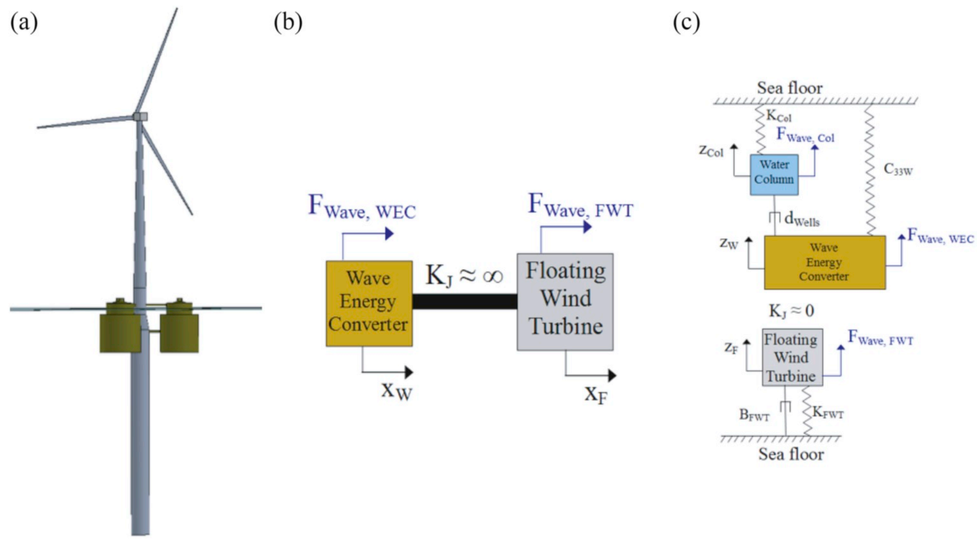

Fig. 1. Combined floating wind turbine (FWT) oscillating water column wave energy converter (OWC WEC) array. (a) CAD illustration of a 3-OWC array attached to the FWT by hinged linkages. (b) Surge-mode free body diagram of a single WEC and FWT. (c) Effective heave-mode free body diagram of a single WEC and FWT.

WEC move rigidly together in the lateral directions (modeled by a large stiffness coupling between the WEC and FWT surge and pitch motions) and are essentially uncoupled in the heave directions. Since the WEC pitches rigidly with the FWT, the WEC pitch inertia, hydrodynamic, and hydrostatic properties are added to the FWT pitch properties.

The model assumes that the wind is steady and causes an effective constant damping coefficient for the FWT platform lateral motion (Kluger, 2017; Kluger et al. 2016). The waves are modeled by a Bretschneider spectrum. The Weiner-Khinchine theorem is used to compute the response statistics of the FWT-WEC when excited by the stochastic ocean waves (Kluger, 2017).

Platform surge and pitch motions cause tower bending and fatigue. This study models the two lowest eigenmodes of the tower based on NREL documentation for the 5 MW reference turbine (Jonkman, 2007). ANSYS eigenmode finite element stress analysis is used to correlate the bending motions to stress at the tower root. The procedure described in Kluger et al. (2016) is used to convert the stress statistics from each sea state to a lifetime equivalent peak-peak fatigue stress amplitude that causes the same damage over the 20 year machine lifetime as the stochastic waves. Power harvested by the WEC array in each sea state is calculated by assuming a 60% power takeoff efficiency (Brito-Melo et al., 2002).

2.3. WEC cost model

One of the main goals in this study is to reduce the WEC levelized cost of energy (LCOE). The WEC LCOE is,

$$\text{LCOE} = \frac{(\text{ICC})(\text{FCR})+\text{AOE}}{\text{AEP}}, \tag{2}$$

where ICC is the installed capital cost, FCR = 0.117 is the fixed charge rate accounting for the cost of financing, taxes, and depreciation, AOE = $\$215P_{\text{Cap,kW}}$ is the annual operating expenses for a WEC with a power capacity of $P_{\text{Cap,kW}}$, and AEP is the annual energy production (Tegen et al., 2013). The ICC is a function of the power capacity, steel mass, and concrete mass,

$$\text{ICC}_{\text{WEC,\$}} = 5020P_{\text{Cap,kW}} + 1.3\text{C. F. } M_{\text{Steel,kg}} + 0.1M_{\text{Concrete,kg}} \tag{3}$$

where C.F.= 2 is a manufacturing complexity factor, $M_{\text{steel,kg}}$ is the steel mass, and $M_{\text{concrete,kg}}$ is the concrete mass. Equation (3) is based on Sandia National Laboratories reference WEC models (Neary et al., 2014). The breakdown of the cost elements that contribute to (3) are plotted in Fig. 2. Notably, attaching the WEC to the FWT allows the elimination of mooring line and infrastructure (maintenance vessel) costs from the WEC.

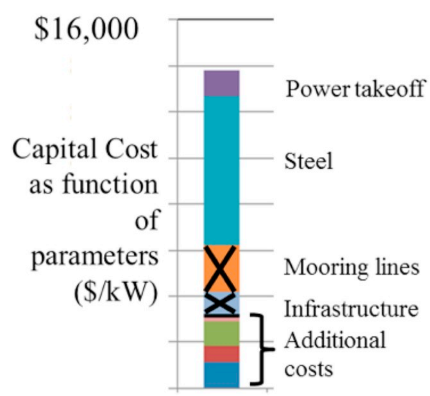

Fig. 2. Breakdown of WEC installed capital cost in a combined floating wind turbine - wave energy converter (FWT-WEC) based on (Neary et al., 2014).

This study assumes that all surface areas of the WEC are comprised of 29 mm thick steel sheet. It is also assumes that the steel linkage arms have lengths of 13 m and cross-sectional areas that conservatively provide yield stress safety factors = 2 when subject to a 6 m wave amplitude hydrostatic pressure. These safety parameters are based on baseline WEC designs by Sandia National Laboratories and the National Renewable Energy Laboratory (Neary et al., 2014; Bull et al., 2014). Details of this cost model are described in Kluger (2017).

2.4. Optimization results

The model described in Sections 2.1–2.3 is used to compute the response statistics of combined FWT-WECs. It is assumed that the FWT-WEC experiences the 8 Bretschneider sea states listed in Table 1 over a 20 year lifetime. Fig. 3 shows the optimization results when the submerged float radius r, submerged float length $l = 2r$, and Wells turbine coefficient k_{Wells} are varied.

Fig. 3 shows that the WEC decreases the FWT tower fatigue stress when its radius is larger than 8 m, while the WEC increases the tower fatigue stress when its radius is smaller than 8 m, compared to a standalone FWT with an equivalent lifetime fatigue stress of 31.2 MPa.

This behavior is related to the FWT-WEC lateral dynamics, as shown in Fig. 4. Attaching WECs with small radii to the FWT increases the

Table 1
Annual sea and wind states 17 nautical miles South West of Eureka, CA, based on National Oceanic and Atmospheric Administration buoy 46022 data from 2005 to 2014 (National Oceanic and Atmospheric Administration, 2016). H_S is the significant wave height, T_P is the dominant wave period, U is the mean wind speed, and p is the state occurrence probability. Sea conditions are modeled with the Bretschneider spectrum.

State	$H_S(s)$	$T_P(s)$	U (m/s)	p
1	1	8	8	0.09
2	1	11	8	0.18
3	1	16	8	0.30
4	3	8	16	0.06
5	3	11	16	0.13
6	3	16	16	0.22
7	6	11	20	0.01
8	6	16	20	0.01

FWT's surge wave forcing more than it increases the FWT's resistance to motion (inertia and damping effects) at large frequencies, resulting in a larger FWT lateral response. On the other hand, attaching WECs with larger radii and submerged lengths to the FWT increases the FWT's resistance to motion more than it increases FWT wave forcing at large frequencies, resulting in smaller FWT lateral responses at these frequencies. Bretschneider sea states with dominant wave periods between 8 and 16 s have non-negligible wave excitation on the structure at larger frequencies between 0.1 and 0.2 Hz. High-frequency stresses have a significant effect on the tower lifetime fatigue stress. Therefore, the smaller WECs significantly increase lifetime fatigue stress on the FWT tower while the larger WECs decrease it.

As shown in Fig. 3, increasing the float radius and Wells turbine coefficient generally increases the wave power harvested. The WEC levelized cost of energy has a minimum value of \$0.55/kWh, for $r = 9$ m and $k_{\text{Wells}} = 800$ Pas/m.

A FWT-WEC array that comprises three WECs that each have a float radius $r = 10$ m and Wells turbine coefficient $k_{\text{Wells}} = 400$ Pas/m is

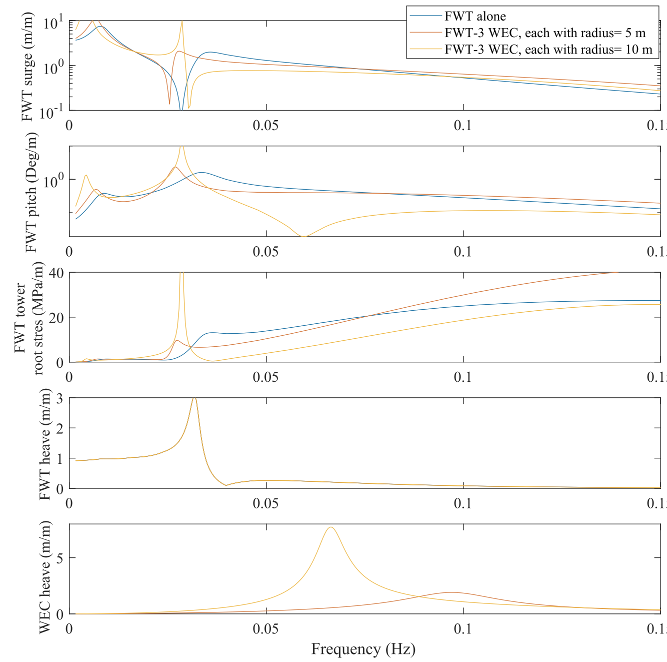

Fig. 4. Response amplitude operators of the floating wind turbine (FWT) alone, a combined FWT-WEC Array with three $r = 5$ m radius WECs, and a combined FWT-WEC Array with three r = 10 m radius WECs. The neutrally buoyant WECs each have submerged lengths, $l = 2r$ and Wells turbine coefficient $k_{\text{Wells}} = 400$ Pas/m.

chosen as the optimal system. This WEC array produces an average annual power of 240 kW. It has a LCOE of \$0.61/kWh. This LCOE is a 14% reduction compared to the standalone WEC system (which has added mooring line, electric transmission line, and maintenance vessel costs). It reduces the tower effective fatigue stress to 24.1 MPa from

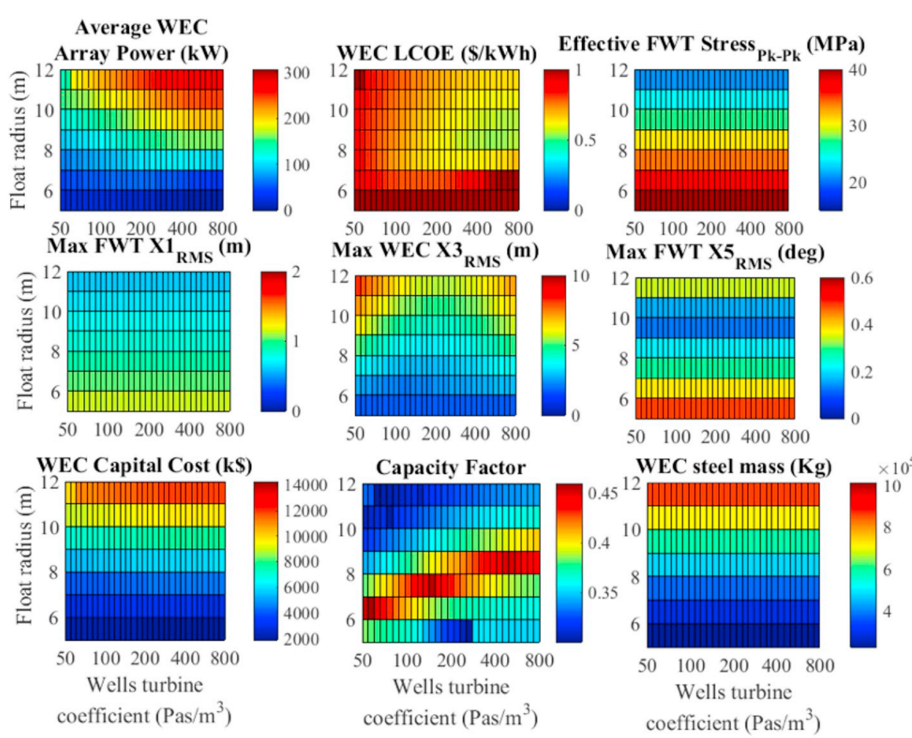

Fig. 3. Combined floating wind turbine - wave energy converter (FWT-WEC) optimization results for varied submerged float radius and Wells turbine coefficient. Max FWT $X1_{\text{RMS}}$ is the root mean square FWT platform surge motion during the sea state that causes the largest surge motion. Similarly, FWT $X5_{\text{RMS}}$ is the maximum FWT pitch response and WEC $X3_{\text{RMS}}$ is the largest WEC heave response.

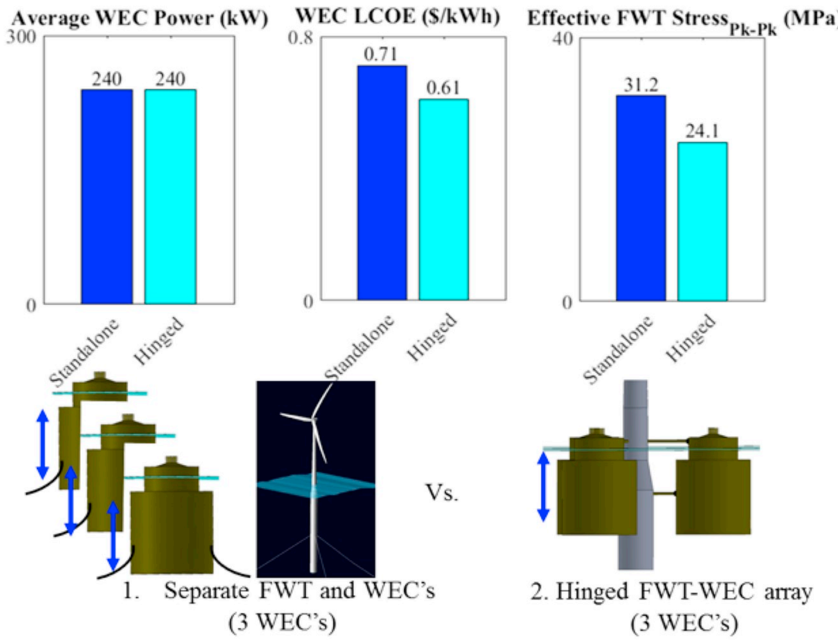

Fig. 5. Performance comparison of the standalone floating wind turbine (FWT) and wave energy converter array (WEC) to a combined FWT-WEC based on a 20 year lifetime off the coast of Eureka, California. The array comprises three WECs that each have a float radius r = 10 m and Wells turbine coefficient k_{Wells} = 400 Pas/m.

31.2 MPa for the standalone system (23%). These performance statistics are shown in Fig. 5. Other notable properties of this WEC array are that it has a capital cost of $10 million, capacity factor of 0.36 and steel mass of 2100 tonnes. While this steel mass is large, most of this mass oscillates, which contributes to harvested wave power. The steel cost may be offset by reducing the FWT platform mass. Additionally, as discussed in Khosravi et al. (2014) and Campos et al. (2016), fabricating the WEC with concrete instead of steel may reduce the WEC LCOE by up to 50% due to lower capital cost and longer lifetime. Future studies will investigate a concrete WEC design. More complex turbines, such as the self-rectifying impulse turbine, Dennis-Auld turbine, and biradial turbine have higher peak efficiencies and/or bandwidths (Falcão and Henriques, 2016). These turbines as well as turbine control will be considered in future investigations.

3. Attaching a uranium harvesting machine to a floating wind turbine

3.1. Motivation and previous work for uranium extraction from seawater

In addition to adding a WEC to a FWT to generate more power and reduce tower fatigue stress, a uranium harvesting machine might also be added to further return on the offshore platform investment. Given that one gram of uranium-235 can theoretically produce as much energy as burning 1.5 million grams of coal (Emsley, 2001), nuclear power has the potential to significantly reduce carbon dioxide emissions from power generation. However, the Organisation for Economic Co-Operation and Development (OECD) predicts that global conventional reserves of terrestrial uranium could be depleted in a little over a century (OECD Nuclear Energy Agency, 2016). This is expected to result in uranium from lower quality sites leading to higher extraction costs and greater environmental impacts. Additionally, current reserves of uranium are not evenly distributed throughout the world, leading to global cost insecurity. Considering that the ocean contains approximately 4 billion tonnes of uranium, present as uranyl ions in concentrations of approximately 3 ppb (Oguma et al., 2011), finding a sustainable way to harvest uranium from seawater could provide a source of nuclear fuel for generations to come.

To date, passive uranium adsorption by chelating polymers has been found to be the most viable uranium recovery technology in terms of adsorption capacity, environmental footprint, and cost (Kim et al., 2013; Zhang et al., 2003; Seko et al., 2003; Anirudhan et al., 2011). Using this technology, the polymers are deployed in the ocean and remain submerged until the amount of captured uranium approaches the adsorption capacity. Then the uranium and other trace metals are stripped from the polymer through an elution process. The polymer may be placed in successive elution baths of increasing acid concentration to recover uranium and remove other elements that have bonded to the polymer. Afterward, it is regenerated by an alkali wash to free its functional groups, thereby allowing the polymer to be reused. The output is transformed into yellowcake through a purification and precipitation process similar to that for mined uranium.

Previously proposed deployment strategies relied on the ability to bring the adsorbent back to shore for the elution process and redeploy it afterward. For these strategies, the adsorbent production and mooring costs of these systems were found to be the most expensive components of the recovery process (Schneider and Sachde, 2013; Byers and Schneider, 2016).

3.2. Symbiotic design strategies for uranium extraction from seawater

Designs proposed by Picard et al. (2014) for a uranium harvesting device (shown in Fig. 6), aimed to reduce system costs associated with the deployment, mooring, and recovery of the adsorbent by coupling the uranium harvester with an existing offshore structure, such as an offshore wind turbine. In the proposed system, referred to in the rest of this paper as the Wind and Uranium from Seawater Acquisition symBiotic Infrastructure (WUSABI), a platform at the base of the wind tower supports an autonomous elution and chemical storage tank system along with a belt of adsorbent that loops in and out of the water. The adsorbent belt cycles through the seawater beneath the tower and eventually through an elution plant located on the platform, thereby allowing for an elution procedure that can be precisely timed depending on the type of adsorbent used. The system was sized to collect 1.2 tonnes of uranium per year, an amount sufficient to supply a 5 MW nuclear power plant. Thus, pairing this system with an existing 5 MW offshore wind turbine could potentially double the energy harvested per square meter of ocean.

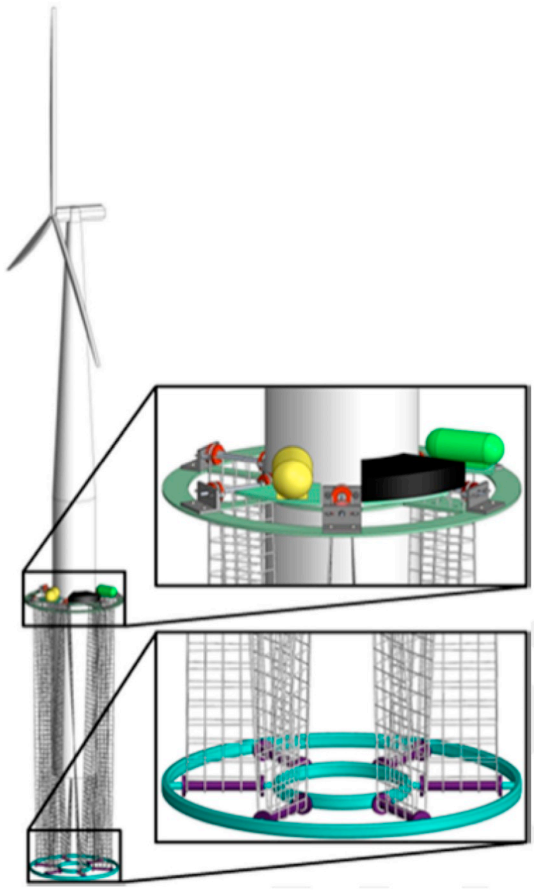

Fig. 6. Three-dimensional view of continuous uranium recovery system with adsorbent belt looped around the turbine mast proposed by Picard et al. (2014). The elution plant is housed on the upper platform out of the seawater.

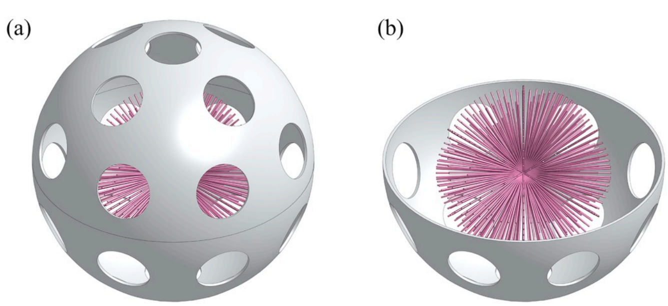

Fig. 7. Decoupling of mechanical and chemical requirements via a tough, outer protective sphere encapsulating a soft, inner adsorbent. The outer sphere features holes to allow adequate seawater flow to the adsorbent interior (Haji et al., 2015).

However, it has been found that adsorbents with high tensile strength and durability often have low uranium adsorption properties (Xing et al., 2013). Thus, the device proposed by Picard et al. (2014), which requires the adsorbent to be braided into a belt held in tension, could face difficulties in an ocean environment. Hence, a two-part system to decouple the mechanical and chemical needs of an adsorbent for seawater harvesting of uranium using a shell enclosure was developed (Haji et al., 2015). In these designs, shown in Fig. 7, the uranium adsorbent material with high adsorbent capacity is enclosed in a hard, permeable outer shell with sufficient mechanical strength and durability for use in an offshore environment and chemical resilience against elution treatments. This decoupling of the chemical and mechanical requirements of the adsorbent has allowed for further exploration and development of novel adsorbents that need not be very strong.

This shell enclosure can be incorporated into a Symbiotic Machine for Ocean uRanium Extraction (SMORE) which utilizes adsorbent shells that are incrementally spaced along high strength mooring rope, resembling conventional ball-chain belts. These ball-chains are then strung together to create a net using cross-members which add rigidity and reduce the likelihood of tangling of individual lengths (Haji, 2017; Haji and Slocum, 2016; Haji et al., 2017b). Two versions of this device, shown in Fig. 8, were tested at a 1/10th physical scale in a nine-week ocean trial, one in which the adsorbent ball-chain net was continuously moving through the ocean to increase water flow and the other in which the adsorbent ball-chain net was only subjected to the ocean currents at the test site (Haji et al., 2017b).

One challenge in the ocean deployment of uranium adsorbing fibers is the fact that biofouling of the adsorbent fibers has been found to have a detrimental affect on their ability to uptake uranium (Park et al., 2016). At the end of the 56-day ocean test, it was found that the stationary system had a significantly higher amount of biofouling on its shells than the continuously moving system, as shown in Fig. 9. This may have been because movement of a surface can limit the amount of fouling (Railkin, 2003). Additionally, the shells of the moving system rubbed up against portions of the prototype as they moved through the ocean, which may have continually removed growth. If either of these factors caused a drastic reduction in biofouling, it lends credence to a few design ideas for mitigating biofouling in such a uranium harvester. Specifically, a bristle brush could be added at various parts of the structure to gently brush the shells as they pass, further reducing chances of growth. Additionally, UV light has been shown to have strong antibacterial properties (Lakretz et al., 2010) and thus adding UV LEDs to a point in the adsorbent net's path could also prevent the formation of biofilm and hence reduce biofouling.

It is important to ensure that the incorporation of the uranium harvester to the FWT will not adversely affect the dynamics of the FWT, which could result in reduced power output by the turbine, increased material requirements for the turbine, or changes in the turbine's operation and maintenance. Experimentally determined hydrodynamic responses of various designs of SMORE have shown no significant shift in the resonant peaks of the FWT (Haji et al., 2018). This is key because an offshore wind turbine is tuned such that its resonant frequencies are in the range of 0.0077–0.0313 Hz, which are well below the significant ocean wave frequencies.

3.3. Reduction in seawater uranium production price

The rational behind coupling a uranium harvester with an offshore wind turbine is that the development of offshore wind or uranium harvesting by itself bears a high capital cost for the structures, but if the mooring function can be shared, the overall cost for each will be lower. An independent cost-analysis of this symbiotic deployment strategy was recently conducted and the results were compared to a reference strategy in which the adsorbent polymer was braided into a buoyant net and deployed like a kelp-field across the ocean floor, serviced by boats for deployment, retrieval for onshore elution, and redeployment (Tamada et al., 2006; Schneider and Linder, 2014). It was found that the symbiotic deployment proposed by Picard et al. (2014) could reduce the seawater uranium production cost in 2015 dollars by at least 11%, from $450–890/kgU for the reference scheme to $400–850/kgU (Byers et al., 2016) and up to 30% with further design optimization (Byers et al., 2018).

The components of the production cost of uranium from seawater are broken down into the following categories (Byers, 2015; Schneider and Sachde, 2013; Schneider and Linder, 2014):

1. Adsorbent Production
2. Mooring and Deployment
3. Elution and Regeneration (also referred to as Back End)

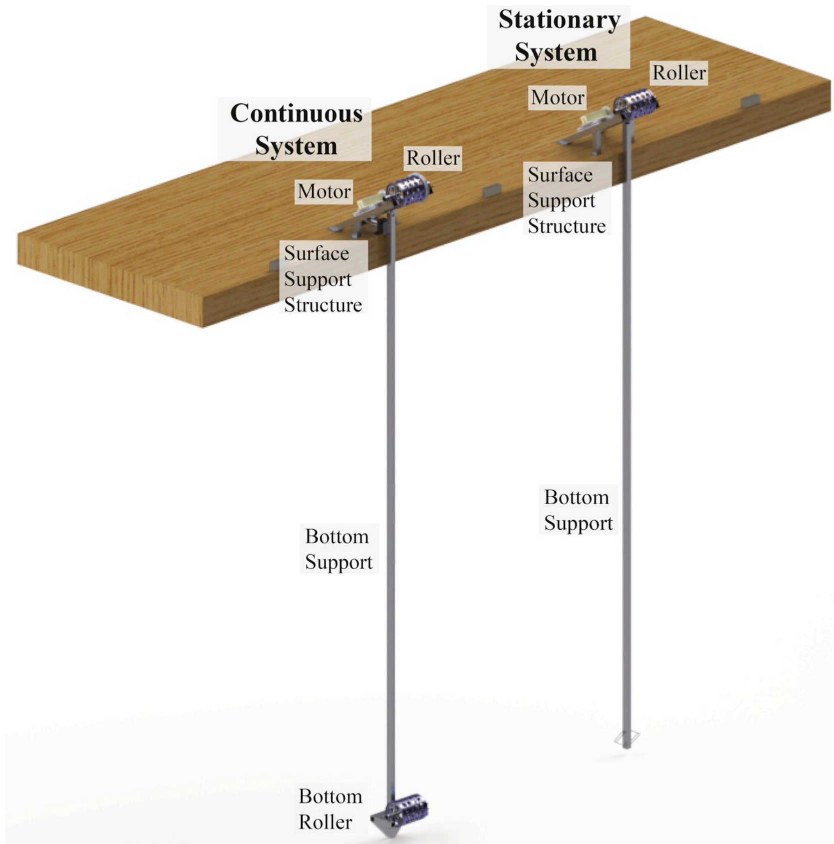

Fig. 8. Three-dimensional model of 1/10th physical scale model for ocean testing of the SMORE design. Both a stationary and continuous version of the design were fabricated and mounted to a wooden float for ocean testing (Haji, 2017; Haji et al., 2017b).

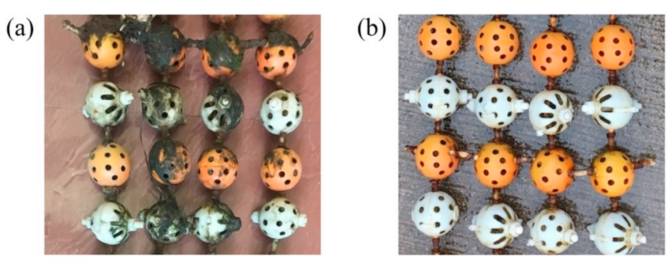

Fig. 9. Biofouling on the (a) stationary net and (b) continuously moving net at the end of the ocean test (Haji et al., 2017b).

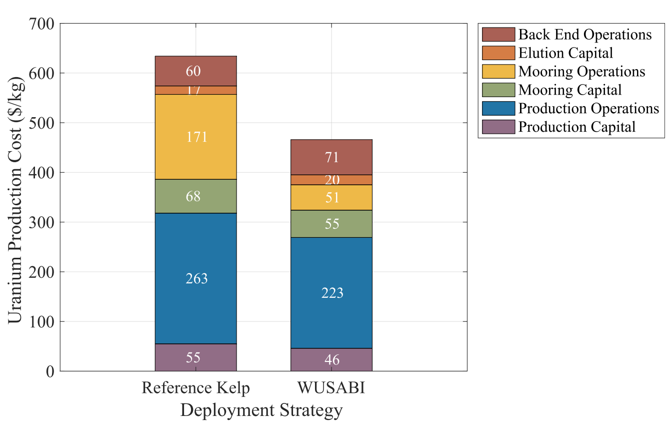

Fig. 10. Cost analysis of WUSABI as initially designed by Picard et al. (2014), compared to the reference kelp deployment strategy (Byers et al., 2016).

These savings were due mainly to the fact that such a symbiotic scheme has lower deployment and mooring operations costs, as hypothesized. This can be clearly seen in Fig. 10 which shows the cost breakdown for an example deployment scenario in which no biofouling affects on the uranium adsorbent are accounted for and time-dependent degradation of the adsorbent with subsequent elution treatments is assumed (Byers et al., 2016). Specifically, for this deployment scenario, the WUSABI deployment scheme had an over 55% reduction in mooring and deployment costs as compared to the reference kelp scheme. Similar cost reductions have been observed for symbiotic uranium harvesting strategies utilizing shell enclosures to encapsulate uranium adsorbing fibers (Haji et al., 2017a, Haji, 2017).

3.4. *Applications to extraction of other minerals from seawater*

In addition to the extraction of uranium from seawater, the symbiotic device investigated here could be used to extract other valuable metals. For instance, the adsorbent fibers used in these studies also extract vanadium, a prominent steel alloy, from seawater. Additionally, the current fiber has been seen to adsorb cobalt (Tamada, 2009) which is present in harvestable quantities at depths below 100 m (Saito and Moffett, 2002). Cobalt is increasingly becoming a strategic element for extraction as it is located in only a few places on land and is a critical element in Li-ion batteries as well as steel. A symbiotic system paired with an offshore wind structure could prove to be a cost-effective method for extracting cobalt as it exists in the ocean in large quantities at depths easily reached by a floating offshore wind turbine (Haji and Slocum, submitted). Work has also shown that lithium, another metal critical to battery technology, may be extracted from seawater with a membrane-type adsorbent (Umeno et al., 2002).

The current elution processes for the uranium adsorbing fibers described in this study removes all metal ions from the fibers before redeployment into the ocean. This presents a unique opportunity to filter out select ions from the aqueous solution using techniques similar to those used in separation of metals in conventional mining processes. Such co-extraction could reduce the production cost of all minerals harvested. Thus, minerals could be co-extracted or harvested individually, depending on the requirements of the symbiotic system.

Most recently, the Department of Energy (DOE) has shown interest into the development of symbiotic systems for extracting rare and high-value minerals from seawater to enhance the United State's critical materials independence and security. In the DOE-hosted forum in December 2017, marine and hydrokinetic (MHK) technology developers and researchers at the forefront of marine energy generation met to discuss and determine industries in which symbiotic systems could be developed to maximize their benefits for each application. Given the complexity of developing structures in a harsh ocean environment, symbiotic efforts such as these could make a host of new energy and materials technologies viable.

4. Conclusions and future work

Considering the high costs involved with offshore floating wind turbines (FWT's), a promising strategy is to employ a symbiotic design that can reduce the stress on the FWT while also generating electricity from the ocean waves. Using a linear frequency-domain long-wave-length dynamics model and first-order cost model, this study predicts that attaching a wave energy converter (WEC) array to a floating wind turbine may simultaneously produce 240 kW average power (a 9% offshore power increase compared to a standalone 5 MW FWT with a 53% capacity factor (Myhr et al., 2014)), reduce the WEC levelized cost of energy by 14% (by eliminating the standalone WEC mooring line and infrastructure costs), and reduce the FWT lifetime equivalent tower root stress by 23%. Future work on this project may consider fabricating the WEC out of concrete, using more efficient turbines, and implementing turbine control in order to reduce the WEC cost and increase its power output.

Moreover, harvesting minerals from seawater is shown to be very promising in the wake of diminishing and expensive land-based resources for metals critical to 21st century industries. The work presented in this paper on the harvesting of uranium from seawater can be readily applied to a host of other valuable metals such as vanadium, lithium, and cobalt. As shown for seawater uranium harvesting, the production cost of the extracted metal has the potential to be significantly decreased by combining the system with an offshore wind turbine, while also doubling the resource harvested per square meter of ocean.

The symbiotic approach of sharing structure and maintenance equipment/personnel among multiple collocated energy systems to reduce capital and operating costs could also be applied to other current and proposed offshore structures to increase offshore energy profitability (Slocum, 2015). Future work on this project may consider applying unused offshore hydrocarbon production platforms as energy harvesting and mineral production hubs, and even as support for aquaculture efforts (Buck et al., 2004).

Acknowledgements

This work was supported in part by the MIT Energy Initiative, the Naval Engineering Education Center for support under Grant No. 3002883706, the National Science Foundation 1122374 for support of JMK and MNH through the Graduate Research Fellowship Program under Grant No. 1122374, the U.S. Department of Energy Office of Nuclear Energy under Contract No. DE-NE0008268 and by the National Academies Keck Futures Initiative.

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