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A Symbiotic Approach to the Design of Offshore Wind Turbines with Other Energy Harvesting Systems

Maha Haji[+‡], Jocelyn Kluger[+‡], Themistoklis Sapsis[†], Alexander Slocum[*]
Massachusetts Institute of Technology
77 Massachusetts Ave., Room 3-445, Cambridge, MA, 02139, USA

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 [2]. 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 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 [16,17]. 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% [40-42].

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 [1]. At ocean sites with depths greater than 50m, floating wind turbines (FWT's) are more economical than monopole 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 [2-4]. Much of the FWT cost is due to the challenge of platform stabilization, which is solved using a large steel platform mass, active water ballast, or taut mooring lines [2, 5, 6]. FWT platform motion is undesirable because it complicates the rotor aerodynamics and control and reduces aerodynamic efficiency [6-8]. Furthermore, platform motion increases stresses on the blades, rotor shaft, yaw bearing, and tower base [9]. 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. If these auxiliary machines stabilize the platform, then the platform steel, active ballast, or taut mooring lines may be reduced.

This study considers attaching a wave energy converter (WEC) to the FWT platform. Wave power has higher predictability and less variation than wind, which is important for electric grid operation [10]. However, wave energy converters typically produce electricity with 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's cost [11]. A WEC attached to a FWT could share or eliminate many of these costly components. In addition, this study hypothesizes that a WEC attached to a FWT could act as an ocean wave absorber to reduce wave-excited platform motion. Several previous studies have investigated combined FWT-WEC dynamics [12-14]. These studies found that the attached WEC design increased the FWT lateral motion. This study investigates how to design the combined FWT-WEC system so that the FWT platform has reduced 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. 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. On the other hand, 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

[‡]Co-first authors
[*]Professor, corresponding author, slocum@mit.edu
[†]Assistant Professor
[+]Post Doctoral Researcher

at low concentrations [15]. However, to date no large-scale adsorbent installations for mineral extraction have been realized in the open ocean, partly due to the cost-prohibitive nature of the system's mooring and deployment capital and operating costs [16, 17]. 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.

2. Design of a Wave Energy Converter Array Attached to a Floating Wind Turbine

2.1 FWT-WEC Design Motivation

As described above, the hypothesis of this study is that combining FWT's and WEC's into one system can significantly decrease the cost of energy for both systems. The two main challenges to doing this are allowing the WEC power harvesting mode to remain unconstrained by the FWT and requiring the WEC to reduce rather than increase 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 Figure 1. The design uses the 5 MW Hywind wind turbine on the floating OC3 spar platform [3]. This study restricts the WEC array to contain 3 WEC's, 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 heave and pitch and essentially uncoupled in heave for 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 large heave motions to harvest wave energy without transmitting vertical loads to the platform.

The WEC itself is designed as a floating oscillating water column [18]. Oscillating water columns have been successfully tested in the ocean for over 20 years [19-21]. In this study, the WEC spar encircles a 4 m radius tube open to the 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 forces air to oscillate through the tube. This study varies the Wells turbine coefficient as part of the optimization procedure. The WEC's still waterline area is selected 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 a 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 WEC's have capacity factors of 0.3 [10], where the WEC power produced in strong seas is limited to match the power produced in the next calmer sea state so the WEC has a capacity factor of at least 0.3. The reason for reducing the power in this way is to improve 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 required during 98% of the machine lifetime. Future work could optimize WEC capacity factor based on a chosen sea site. This power reduction could be achieved by an air bypass valve [22].

2.2 *Floating Wind Turbine – Wave Energy Converter Dynamics Model*

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

$$\boldsymbol{I}(\omega)\vec{x}'' + \boldsymbol{D}(\omega)\vec{x}' + \boldsymbol{K}\vec{x} = \vec{f}(\omega), \tag{1}$$

where ' indicates a time derivative. The vector $\vec{x}$ contains 23 coupled variables: the FWT platform's 3 translational motions and 3 rotational motions, the tower's 2 lowest fore-aft bending modes, each of the 3 WEC's 3 translational motions, each water column heave motion, and the air pressure in each tube. The air pressure is coupled with the relative heave motion between the water column and tube. Nondiagonal terms in the matrices couple the degrees of freedom. Symmetry of this design causes FWT-WEC sway, roll, and yaw to equal 0. $\boldsymbol{I}(\omega)$ is the platform and WEC inertias and hydrodynamic added masses. $\boldsymbol{D}(\omega)$ accounts for the FWT platform and WEC hydrodynamic damping and the Wells turbine power takeoff. The approximate hydrodynamic added mass, damping, and forcing of the platform is modeled using the WAMIT panel method results for the NREL OC3-Hywind floating wind turbine [3].

The hydrodynamic added mass, damping, and forcing on each WEC is modeled using the long wavelength approximations from the G.I. Taylor and Haskind relations [23]. Hydrodynamic coupling of the FWT and WEC's is neglected. A detailed derivation of the model is described in [23-25].

K accounts for the hydrostatic stiffnesses and linkage coupling between the FWT and WEC's. As shown in Figure 1, the FWT and WEC move rigidly together in the lateral directions (modeled by a large stiffness coupling between the WEC surge and FWT lateral motion) 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.

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 [26]. ANSYS eigenmode finite element stress analysis is used to correlate the bending motions to stress at the tower root. The procedure described in [24] 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. Power harvested by the WEC array in each sea state is calculated by assuming a 60% power takeoff efficiency [27].

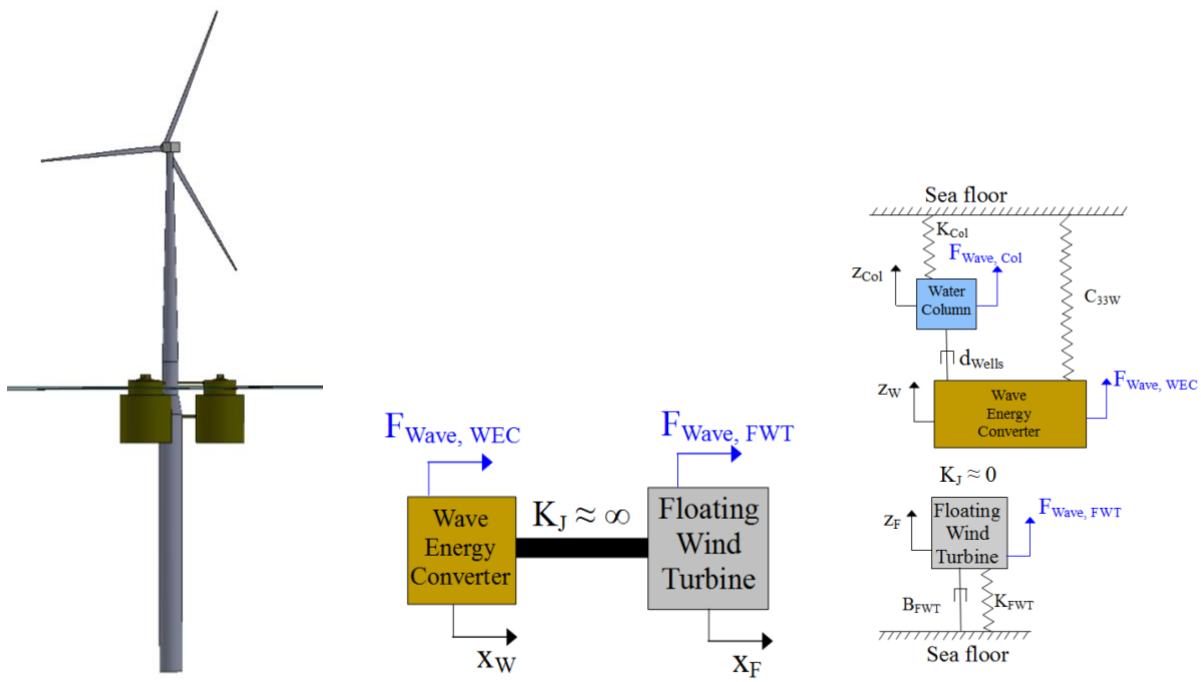

Figure 1. Combined floating wind turbine (FWT) – oscillating water column wave energy converter (OWC WEC) array. Left, CAD illustration of a 3-OWC array attached to the FWT by hinged linkages. Center, surge-mode free body diagram of a single WEC and FWT. Right, heave-mode free body diagram of a single WEC and FWT.

2.3 Wave Energy Converter Cost Model

One of the main goals in this study is to reduce the WEC levelized cost of energy (LCOE). The WEC LCOE is [4],

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

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* = $\$215P_{Cap,kW}$ is the annual operating expenses; and *AEP* is the annual energy production. The *ICC* is a function of the power capacity, steel mass, and concrete mass,

$$ICC_{WEC,\$} = 5020P_{Cap,kW} + 1.3C.F.M_{Steel,Kg} + 0.1M_{Concrete,Kg}, \quad (3)$$

where $P_{Cap,kW}$ is the array power capacity *C.F.= 2* is a manufacturing complexity factor, $M_{Steel,Kg}$ is the steel mass, and $M_{Concrete,Kg}$ is the concrete mass. Eq. (3) is based on Sandia reference WEC models [28]. The breakdown of some cost elements that contribute to Eq. (3) are plotted in Figure 2. Notably, attaching the WEC to the FWT allows the elimination of mooring line and infrastructure (maintenance vessel) costs from the WEC.

This study assumes that all surface areas of the WEC are comprised of 29 mm thick steel sheet. It is also assumed 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.

Details of this cost model are described in [23].

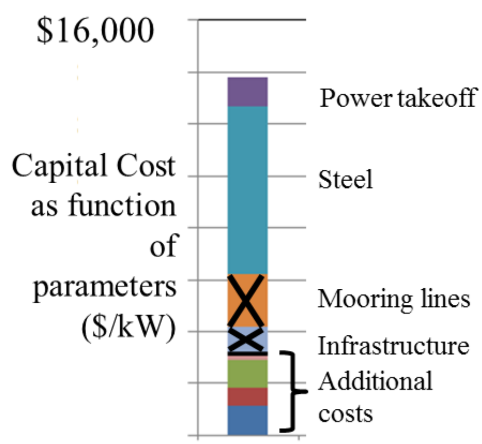

Figure 2. Combined floating wind turbine – wave energy converter (FWT-WEC) installed capital costs.

Table 1. Sea and wind states based on Eureka, CA National Oceanic and Atmospheric Administration buoy data from 2005-2014 [29]. 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 (m)	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

2.4 Optimization Results

The models described in Section 2.1-2.3 are used to compute the response statistics of combined FWT-WEC's. It is assumed that the FWT-WEC experiences the 8 sea states listed in Table 1 over a 20year lifetime. Figure 3 shows the optimization results when the submerged float radius *r*, submerged float length $l = 2r$, and the Wells turbine coefficient, k_{Wells} are varied. Figure 3 shows that increasing the float radius and Wells turbine coefficient generally increases the power performance. In real life, these parameter maximum values are restricted by physical constraints. The WEC levelized cost of energy has a minimum value of $0.55/kWh, for $r = 9$ m and $k_{Wells} = 800$ Pas/m. Increasing *r* decreases the FWT tower fatigue stress. When the WEC radius is less than $r = 8$ m, the WEC array increases tower fatigue stress compared to the standalone FWT rather than decrease it. This is related to the lateral wave forcing effects being larger than the mass inertia effects for the smaller volume WEC's. Decreased tower fatigue stress generally corresponds to decreased platform surge, X_1, and pitch motion, X_5.

A FWT-WEC array that comprises 3 WEC's that each have a float radius $r = 10$ m and Wells turbine coefficient $k_{Wells} = 400$ Pas/m is 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 31.2 MPa for the standalone system (23%). These performance statistics are shown in Figure 4. 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 increases harvested wave power. The steel cost may be offset by reducing the FWT platform mass.

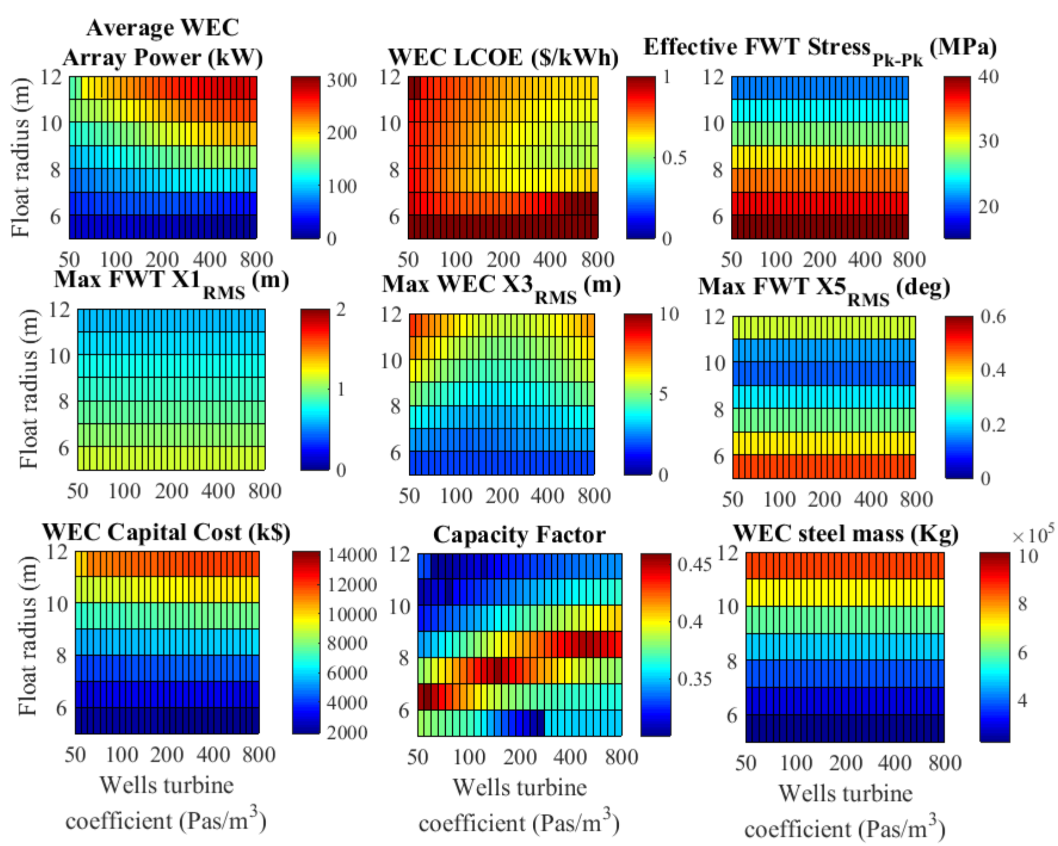

Figure 3. Combined floating wind turbine – wave energy converter (FWT-WEC) optimization results for varied submerged float radius and Wells turbine coefficient. *Max FWT* $X1_{RMS}$ is the root mean square FWT platform surge motion during the sea state that causes the largest surge motion. Similarly,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

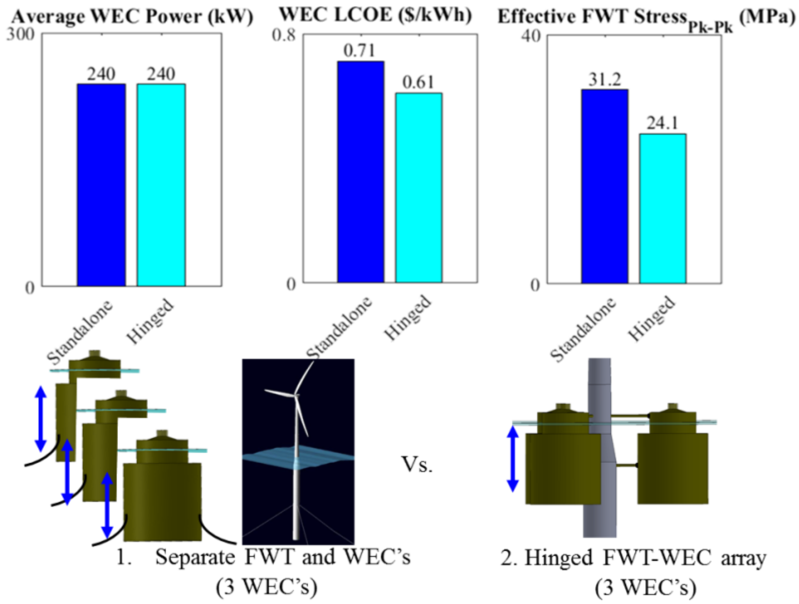

Figure 4. Performance comparison of standalone a floating wind turbine (FWT) and wave energy converter array (WEC) to a combined FWT-WEC based on a 20 year lifetime off the coast of Eureka, California. The array comprises 3 WEC's that each have a float radius $r = 10$ m and Wells turbine coefficient $k_{Wells} = 400$ Pas/m.

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 [30], 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 [31]. 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 [32], 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 [33-36]. 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 [16, 17].

3.2 Symbiotic Design Strategies for Uranium Extraction from Seawater

Designs proposed by [37] for a uranium harvesting device, 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, 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 5MW offshore wind turbine could potentially double the energy harvested per square meter of ocean. 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 [38, 39]. It was found that the symbiotic deployment proposed by [37] could reduce the seawater uranium production cost in 2015 dollars by up to 11%, from $450-890/kgU for the reference scheme to $400-850/kgU [40-42].

However, it has been found that adsorbents with high tensile strength and durability often have low uranium adsorption properties [43]. Thus, the device proposed by [37] 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 [44]. In these designs, shown in Figure 5, 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.

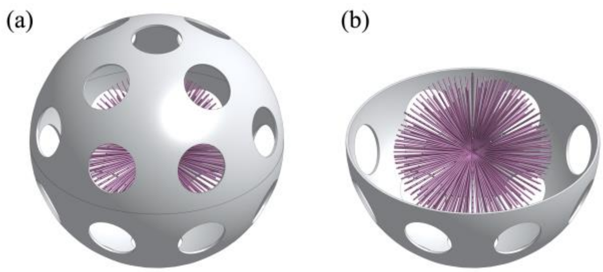

Figure 5. Decoupling of mechanical and chemical requirements via a tough, outer protective sphere encapsulating a soft, inner adsorbent. The outer sphere features holes to allow adequate seawater flow to the adsorbent interior [44].

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 incrementally spaced cross-members which add rigidity and reduce the likelihood of tangling of individual lengths [42, 45, 46]. Two versions of this device, shown in Figure 6, were tested at a $1/10^{th}$ 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 [46].

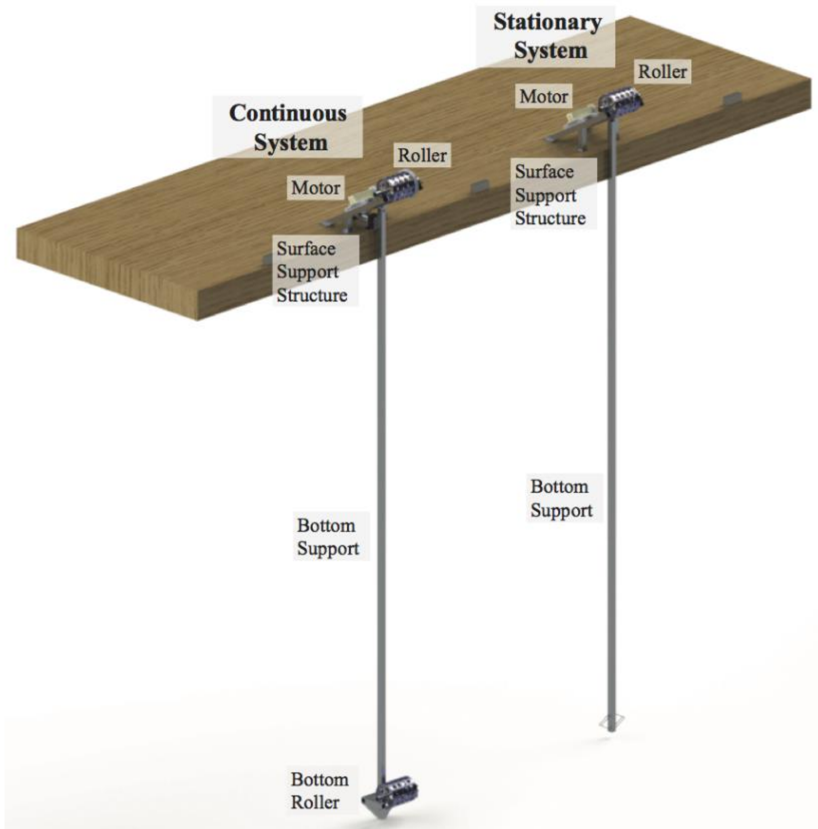

Figure 6. Three-dimensional model of 1/10th physical scale model for ocean testing of the SMORE design. Both a stationary and continuous version of the design were fabricated and mounted to a wooden float for ocean testing [42, 46].

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 Figure 7. This may have been because movement of a surface can limit the amount of fouling [47]. 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 [48] 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.

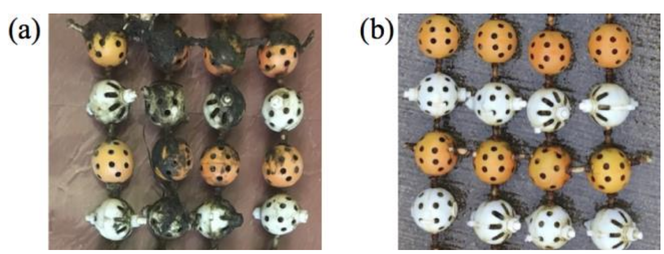

Figure 7. Biofouling on the (a) stationary net and (b) continuously moving net at the end of the ocean test [46].

3.3 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 [49] which is present in harvestable quantities at depths below 100 m [50]. 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. Work has also shown that lithium, another metal critical to battery technology, may be extracted from seawater with a membrane-type adsorbent [51].

4. Conclusions and Future Work

Using a linear frequency-domain long-wavelength 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 [2]), 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%.

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.

Considering the high costs involved with offshore floating wind turbines (FWT's), a wise strategy to pursue is a symbiotic design that can reduce the stress on the FWT while also generating electricity from the ocean waves to help smooth out the power production curve. In addition, it has been shown that and the same system can also serve as a base for a machine that can extract valuable minerals from seawater such as cobalt, lithium, and uranium. This approach could also be applied to other current and proposed offshore structures to share load-bearing structure and maintenance equipment/personnel, thereby reducing the combined system's capital and operating costs while increasing the overall profitability. For example, unused offshore hydrocarbon production platforms could become energy harvesting and mineral production hubs.

Acknowledgements

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