

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

Maha N. Haji^{a,*}, Jocelyn M. Kluger^a, Themistoklis P. Sapsis^a, Alexander H. Slocum^a

^a*Department of Mechanical Engineering, Massachusetts Institute of Technology, United States*

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 [38]. 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 [51, 10]. 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% [11, 22, 18].

Keywords: wave energy, offshore wind turbine, uranium, nuclear power, symbiotic system

*Corresponding author

Email addresses: mhaji@mit.edu (Maha N. Haji), jociiek@alum.mit.edu (Jocelyn M. Kluger), sapsis@mit.edu (Themistoklis P. Sapsis), slocum@mit.edu (Alexander H. Slocum)

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 [31]. 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 [38, 26, 57]. 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 [38, 48, 8]. FWT platform motion is undesirable because it complicates the rotor aerodynamics and control and reduces aerodynamic efficiency [8, 52, 60]. Furthermore, platform motion increases stresses on the blades, rotor shaft, yaw bearing, and tower base [36]. 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 [2]. 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 [17, 3]. 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 [63]. 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 [4, 37, 27, 45]. 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. Given the environmental issues surrounding land-based mining, deep sea mining of many

40 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 [35]. 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 [56, 50]. 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 [51, 10]. 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.

70 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

80 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 figure 1(a). The design uses the 5 MW Hywind wind turbine on the floating OC3 spar platform [26]. 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

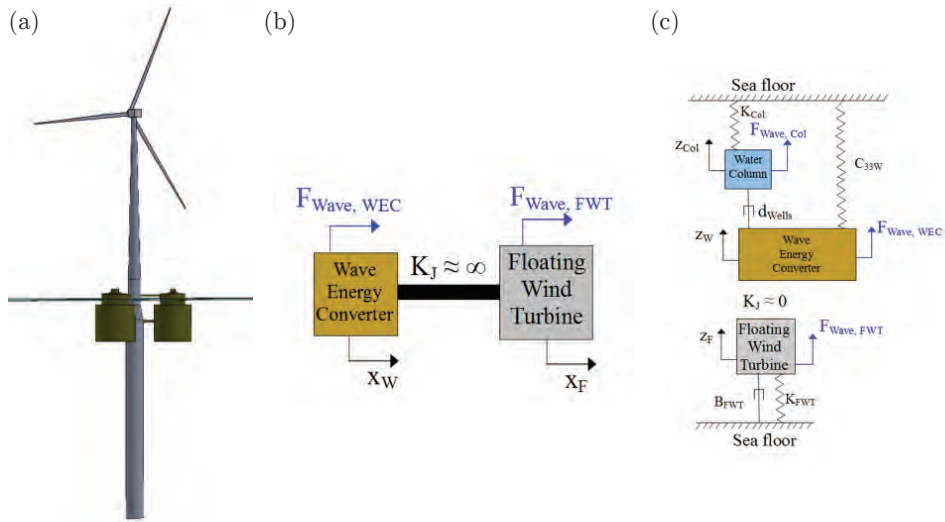


Figure 1: Combined floating wind turbine (FWT) oscillating water column wave energy converter (OWC WEC) array. (a) CAD illustration of a 3-OWC array attached to the FWT by hinged linkages. (b) Surge-mode free body diagram of a single WEC and FWT. (c) Effective heave-mode free body diagram of a single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

WEC'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.

100 The WEC itself is designed as a floating oscillating water column [16]. Oscillating water columns have been successfully tested in the ocean for over 20 years [59, 58, 43]. 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.

115 Typical WECs have capacity factors of 0.3 [17]. 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 [15]. 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

125 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, $C = k_{Wells} V_{Chamber} / \gamma P_{atm}$, 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 [16]. 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 [26]. 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 [30]. Hydrodynamic coupling between the FWT and WECs is neglected. A detailed derivation of the model is described in [30, 32, 33].

\mathbf{K} accounts for the hydrostatic stiffnesses and linkage coupling between the FWT and WECs. As shown in figures 1(b) and 1(c), the FWT and 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 [30, 32]. 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 [30].

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 [25]. ANSYS eigenmode finite element stress analysis is used to correlate the bending motions to stress at the tower root. The procedure described in [32] 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 [5].

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,

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

where ICC is the installed capital cost, $\text{FCR} = 0.117$ is the fixed charge rate accounting for the cost of financing, taxes, and depreciation, $\text{AOE} =$
 175 $\$215P_{\text{Cap,kW}}$ is the annual operating expenses for a WEC with a power capacity of $P_{\text{Cap,kW}}$, and AEP is the annual energy production [57]. The ICC is a function of the power capacity, steel mass, and concrete mass,

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

where $\text{C.F.} = 2$ 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
 180 National Laboratories reference WEC models [40]. The breakdown of the cost elements that contribute to (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
 185 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. These safety parameters are based on baseline WEC designs by Sandia National Laboratories and the National Renewable Energy Laboratory
 190 [40, 7]. Details of this cost model are described in [30].

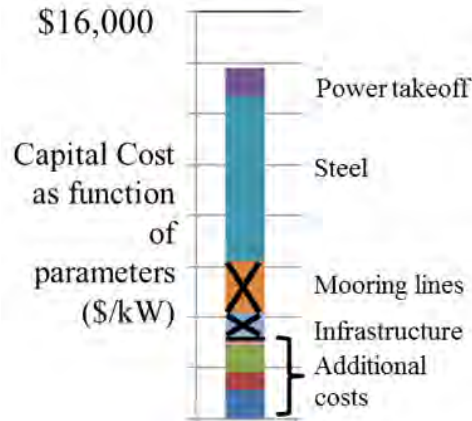


Figure 2: Breakdown of WEC installed capital cost in a combined floating wind turbine - wave energy converter (FWT-WEC) based on [40].

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 2005-2014 [39]. 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

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
195 lifetime. Figure 3 shows the optimization results when the submerged float radius r , submerged float length $l = 2r$, and Wells turbine coefficient k_{Wells} are varied.

Figure 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
200 with an equivalent lifetime fatigue stress of 31.2 MPa.

This behavior is related to the FWT-WEC lateral dynamics, as shown in figure 4. Attaching WECs with small radii to the FWT increases the FWT's surge wave forcing more than it increases the FWT's resistance to motion
205 (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
210 with dominant wave periods between 8-16 seconds have non-negligible wave excitation on the structure at larger frequencies between 0.1-0.2 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.

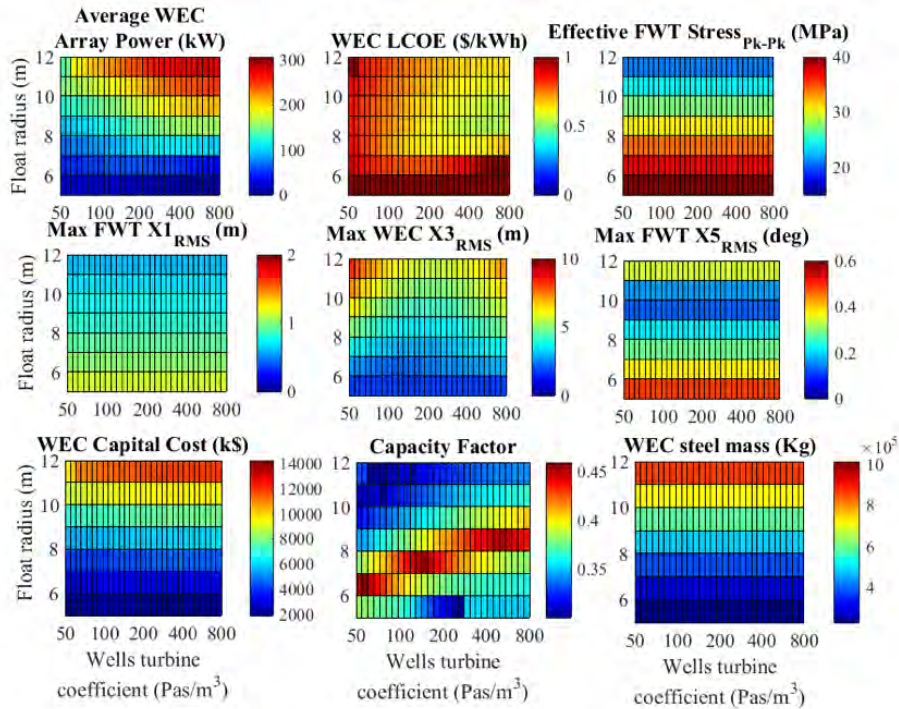


Figure 3: Combined floating wind turbine - wave energy converter (FWT-WEC) optimization results for varied submerged float radius and Wells turbine coefficient. Max FWT $X1_{RMS}$ is the root mean square FWT platform surge motion during the sea state that causes the largest surge motion. Similarly, FWT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

215 As shown in figure 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 $k_{Wells} = 800$ Pas/m.

220 A FWT-WEC array that comprises three WECs 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%).
 225 These performance statistics are shown in figure 5. Other notable properties of this WEC array are that it has a capital cost of \$10

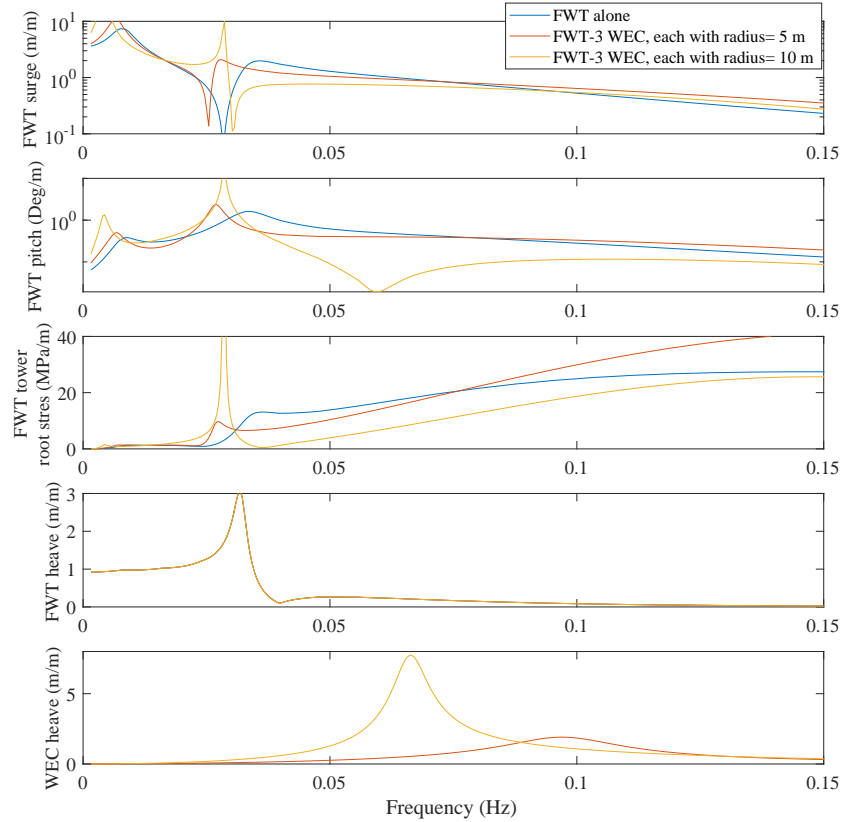


Figure 4: Response amplitude operators of the floating wind turbine (FWT) alone, a combined FWT-WEC Array with three $r = 5$ m radius WECs, and a combined FWT-WEC Array with three $r = 10$ m radius WECs. The neutrally buoyant WECs each have submerged lengths, $l = 2r$ and Wells turbine coefficient $k_{\text{Wells}}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

million, capacity factor of 0.36 and steel mass of 2100 tonnes. While this steel
 230 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 [28] and [12], fabricating the WEC with
 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
 235 impulse turbine, Dennis-Auld turbine, and biradial turbine have higher peak
 efficiencies and/or bandwidths[14]. These turbines as well as turbine control

will be considered in future investigations.

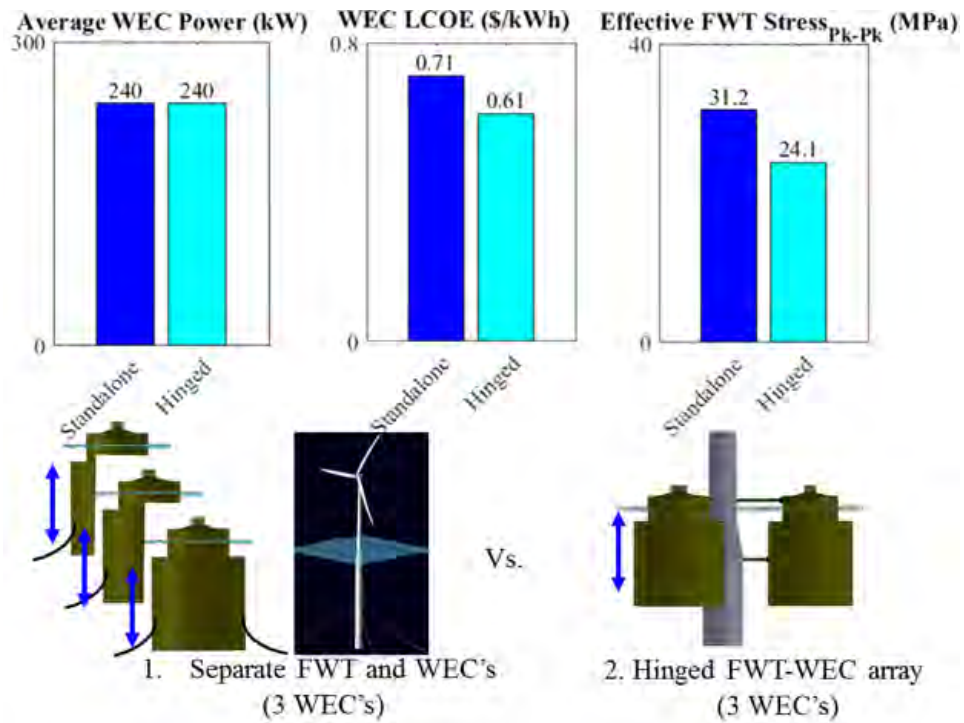


Figure 5: Performance comparison of the standalone floating wind turbine (FWT) and wave energy converter array (WEC) to a combined FWT-WEC based on a 20 year lifetime off the coast of Eureka, California. The array comprises three WECs that each have a float radius $r = 10$ m and Wells turbine coefficient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

3. Attaching a Uranium Harvesting Machine to a Floating Wind Turbine

240 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 [13], 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 [41]. 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 [42], 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 [29, 64, 53, 1]. 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.

270 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 [51, 10].

275 3.2. *Symbiotic Design Strategies for Uranium Extraction from Seawater*

Designs proposed by [46] for a uranium harvesting device (shown in figure 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. 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

280
285

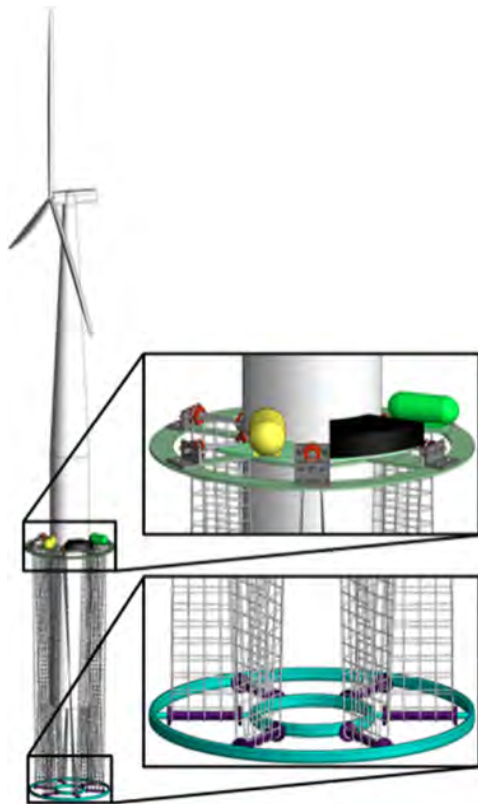


Figure 6: Three-dimensional view of continuous uranium recovery system with adsorbent belt looped around the turbine mast proposed by [46]. The elution plant is housed on the upper platform out of the seawater.

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.

However, it has been found that adsorbents with high tensile strength and durability often have low uranium adsorption properties [62]. Thus, the device proposed by [46] 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 [21]. In these designs, shown in figure 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 incrementally spaced cross-members which add rigidity and reduce the likelihood of tangling of individual lengths [18, 19, 23]. Two versions of this device, shown in figure 8, were tested at a 1/10th physical scale in a nine-week ocean trial, one in which the adsorbent ball-chain net

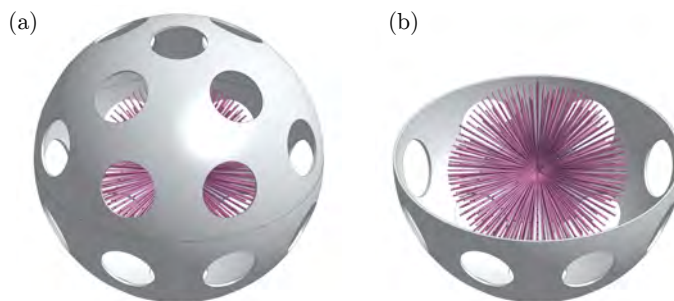


Figure 7: Decoupling of mechanical and chemical requirements via a tough, outer protective sphere encapsulating a soft, inner adsorbent. The outer sphere features holes to allow adequate seawater flow to the adsorbent interior [21].

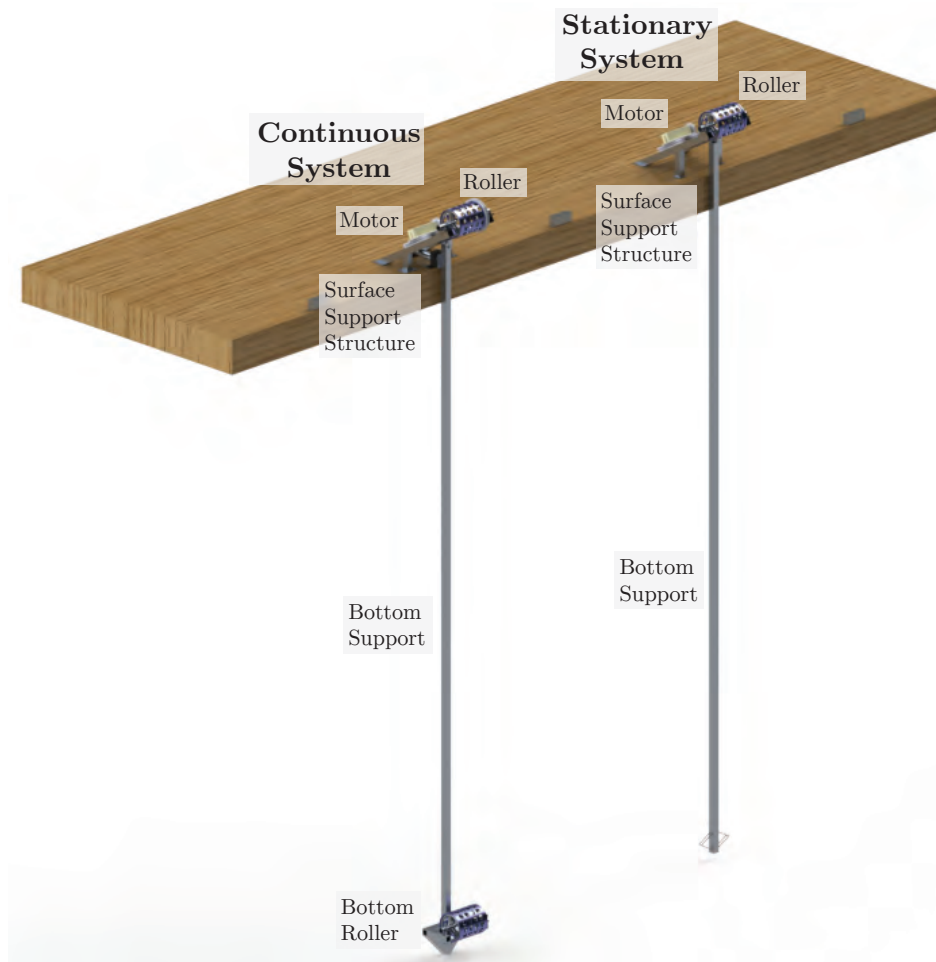


Figure 8: Three-dimensional model of 1/10th physical scale model for ocean testing of the SMORE design. Both a stationary and continuous version of the design were fabricated and mounted to a wooden float for ocean testing [18, 23].

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 [23].

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 [44]. 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 sys-

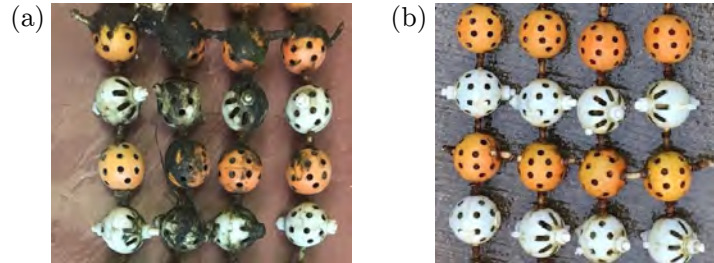


Figure 9: Biofouling on the (a) stationary net and (b) continuously moving net at the end of the ocean test [23].

tem, as shown in figure 9. 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 [34] 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 [24]. 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 rationale 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

350 across the ocean floor, serviced by boats for deployment, retrieval for on-shore elution, and redeployment [56, 50]. It was found that the symbiotic deployment proposed by [46] 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 [11].

355 The components of the production cost of uranium from seawater are broken down into the following categories [9, 51, 50]:

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

360 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 figure 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 [11]. Specifically, for this 365 deployment scenario, the WUSABI deployment scheme had an over 55% reduction in mooring and deployment costs as compared to the reference kelp scheme.

3.4. Applications to Extraction of Other Minerals from Seawater

370 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 [55] which is present in harvestable quantities at depths below 100 m [49]. Cobalt is increasingly becoming a strategic 375 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 [20]. Work has 380 also shown that lithium, another metal critical to battery technology, may be extracted from seawater with a membrane-type adsorbent [61].

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 385 the aqueous solution using techniques similar to those used in separation of metals in conventional mining processes. Such co-extraction could reduce

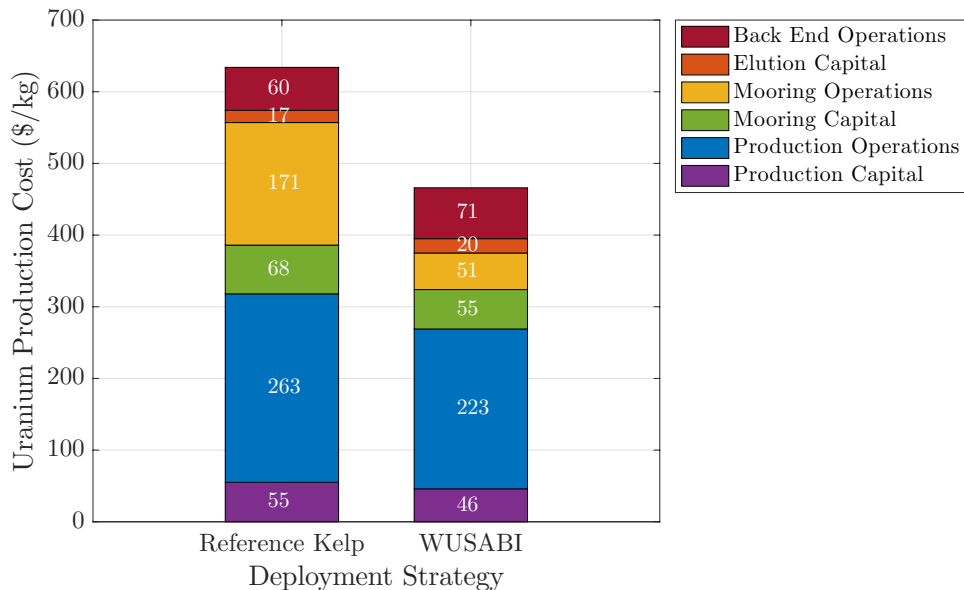


Figure 10: Cost analysis of WUSABI as initially designed by [46], compared to the reference kelp deployment strategy [11].

the production cost of all minerals harvested. Thus, minerals could be co-extracted or harvested individually, depending on the requirements of the symbiotic system.

390 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
 395 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.

400 4. Conclusions and Future Work

Considering the high costs involved with offshore floating wind turbines (FWT’s), a promising strategy to is 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-wavelength dynamics model and first-
405 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 [38]), reduce the WEC levelized
cost of energy by 14% (by eliminating the standalone WEC mooring line
410 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.

415 Moreover, harvesting minerals from seawater is shown to be very promis-
ing 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
420 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 equip-
425 ment/personnel among multiple collocated energy systems to reduce capital
and operating costs could also be applied to other current and proposed off-
shore structures to increase offshore energy profitability [54]. Future work
on this project may consider applying unused offshore hydrocarbon produc-
tion platforms as energy harvesting and mineral production hubs, and even
430 as support for aquaculture efforts [6].

5. 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 for support of JMK and MNH through
435 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.

- 440 [1] T. S. Anirudhan, A. R. Tharun, S. Rijith, and P. S. Suchithra. Synthesis and characterization of a novel graft copolymer containing carboxyl groups and its application to extract uranium (VI) from aqueous media. *Journal of Applied Polymer Science*, 122(2):874–884, 2011.
- [2] S. Astariz and G. Iglesias. The economics of wave energy: a review. *Renewable and Sustainable Energy Reviews*, 45:397–408, 2015.
- 445 [3] S. Astariz and G. Iglesias. Output power smoothing and reduced downtime period by combined wind and wave energy farms. *Energy*, 97:69–81, 2016.
- [4] A. Aubault, M. Alves, A. Sarmiento, D. Roddier, and A. Peiffer. Modeling of an oscillating water column on the floating foundation windfloat. *Proceedings of the International Conference on Ocean, Offshore, and Arctic Engineering*, 2011.
- 450 [5] A. Brito-Melo, L. M. C. Gato, and A. J. N. A. Sarmiento. Analysis of wells turbine design parameters by numerical simulation of the OWC performance. *Ocean Engineering*, 29:1463, 2002.
- [6] B. H. Buck, G. Krause, and H. Rosenthal. Extensive open ocean aquaculture development within wind farms in Germany: the prospect of offshore comanagement and legal constraints. *Ocean Coastal Manage.*, 47(3):95, 2004.
- 455 [7] D. Bull, C. Smith, D. Jenne, P. Jacob, A. Copping, S. Willits, A. Fontaine, D. Brefort, G. Copeland, M. Gordon, and R. Jepsen. Reference Model 6 (RM6): Oscillating Wave Energy Converter. Technical report, 2014.
- 460 [8] S. Butterfield, W. Musial, J. Jonkman, P. Scлавounos, and L. Wayman. Engineering challenges for floating offshore wind turbines. *Proceedings of the Copenhagen Offshore Wind Conference*, 2005.
- 465 [9] M. Byers. Optimization of the Passive Recovery of Uranium from Seawater. Master’s thesis, The University of Texas at Austin, 2015.
- [10] M. F. Byers and E. Schneider. Optimization of the Passive Recovery of Uranium from Seawater. *Industrial & Engineering Chemistry Research*, 55(15):4351–4361, 2016.

- 470 [11] M. F. Byers, M. N. Haji, A. H. Slocum, and E. Schneider. A Higher Fidelity Cost Analysis of Wind and Uranium from Seawater Acquisition symBiotic Infrastructure. *Transactions of the American Nuclear Society*, 115, 2016.
- [12] A. Campos, C. Molins, X. Gironella, and P. Trubat. Spar concrete
475 monolithic design for offshore wind turbines. *Proceedings of the Institution of Civil Engineers- Maritime Engineering*, 169:49–63, 2016.
- [13] J. Emsley. *Nature’s Building Blocks: An A to Z Guide to the Elements*. Oxford Univ. Press, 2001.
- [14] A. Falcao and J. Henriques. Oscillating-water-column wave energy converters and air turbines: A review. *Renewable Energy*, 85:1391–1424,
480 2016.
- [15] A. Falcao and P. Justino. OWC wave energy devices with air flow control. *Ocean Engineering*, 26:1275–1295, 1999.
- [16] A. Falcao, J. Henriques, and J. Candido. Dynamics and optimization
485 of the OWC spar buoy wave energy converter. *Renewable Energy*, 48: 369–381, 2012.
- [17] P. Georgilakis. Technical challenges associated with the integration of wind power into power systems. *Renewable and Sustainable Energy Reviews*, 12:852–863, 2008.
- 490 [18] M. N. Haji. *Extraction of Uranium from Seawater: Design and Testing of a Symbiotic System*. PhD thesis, Massachusetts Institute of Technology, 2017.
- [19] M. N. Haji and A. H. Slocum. Design of a Symbiotic Device to Harvest Uranium from Seawater through the use of Shell Enclosures. *Transactions of the American Nuclear Society*, 115, 2016.
495
- [20] M. N. Haji and A. H. Slocum. An Offshore Solution to Cobalt Shortages. *in prep. for Renewable and Sustainable Energy Reviews*, 2018.
- [21] M. N. Haji, C. Vitry, and A. H. Slocum. Decoupling the Functional Requirements of an Adsorbent for Harvesting Uranium from Seawater through the use of Shell Enclosures. *Transactions of the American Nuclear Society*, 113, 2015.
500

- 505 [22] M. N. Haji, M. Byers, E. Schneider, and A. H. Slocum. Cost Analysis of Wind and Uranium from Seawater Acquisition symBiotic Infrastructure using Shell Enclosures. *Transactions of the American Nuclear Society*, 116, 2017.
- [23] M. N. Haji, J. Drysdale, K. Buesseler, and A. H. Slocum. Ocean Testing of a Symbiotic Device to Harvest Uranium from Seawater through the Use of Shell Enclosures. *Proceedings of the 27th International Ocean and Polar Engineering Conference*, 2017.
- 510 [24] M. N. Haji, J. M. Kluger, J. W. Carrus, T. P. Sapsis, and A. H. Slocum. Experimental Investigation of Hydrodynamic Response of an Ocean Uranium Extraction Machine attached to a Floating Wind Turbine. *accepted to the International Journal of Offshore and Polar Engineering*, 2018.
- 515 [25] J. Jonkman. *Dynamics modeling and loads analysis of an offshore floating wind turbine*. PhD thesis, University of Colorado, Boulder, 2007.
- [26] J. Jonkman. Definition of the Floating System for Phase IV of OC3, Technical Report TP-500-47535. Technical report, U.S. Department of Energy, May 2010.
- 520 [27] T. Kelly, T. Dooley, J. Campbell T, and J. Ringwood. Comparison of the Experimental and Numerical Results of Modelling a 32-Oscillating Water Column (OWC), V-Shaped Floating Wave Energy Converter. *Energies*, 6:4045–4077, 2013.
- 525 [28] N. Khosravi, L. Barker, V. O’Donoghue, J. Benzie, M. Newlands, and M. Jones. Use of concrete as the primary construction material for the Pelamis wave energy converter. *1st International Conference on Renewable Energies Offshore*, 2014.
- [29] J. Kim, C. Tsouris, R. T. Mayes, Y. Oyola, T. Saito, C. J. Janke, S. Dai, E. Schneider, and D. Sachde. Recovery of Uranium from Seawater: A Review of Current Status and Future Research Needs. *Separation Science and Technology*, 48:367–387, 2013.
- 530 [30] J. Kluger. *Synergistic Design of a Combined Floating Wind Turbine - Wave Energy Converter*. PhD thesis, Massachusetts Institute of Technology, 2017.

- 535 [31] J. Kluger, T. Sapsis, and A. Slocum. Combined Offshore Wind, Wave, Storage System Power and Cost Predictions. *Proceedings of the North American Wind Energy Academy Symposium*, 2015.
- [32] J. Kluger, T. Sapsis, and A. Slocum. A reduced-order, statistical linearization approach for estimating nonlinear floating wind turbine response statistics. *Proceedings of the Twenty-sixth International Ocean and Polar Engineering Conference*, 2016.
- 540 [33] J. Kluger, A. Slocum, and T. Sapsis. A first-order dynamics and cost comparison of wave energy converters combined with floating wind turbines. *Proceedings of the Twenty-seventh International Ocean and Polar Engineering Conference*, 2017.
- 545 [34] A. Lakretz, E. Z. Ron, and H. Mamane. Biofouling control in water by various UVC wavelengths and doses. *Biofouling*, 26:257–267, 2010.
- [35] P. Loganathan, G. Naidu, and S. Vigneswaran. Mining valuable minerals from seawater: a critical review. *Environmental Science: Water Research & Technology*, 37:37–53, 2017.
- 550 [36] D. Matha. Model Development and Loads Analysis of a Wind Turbine on a Floating Offshore Tension Leg Platform. Master’s thesis, University of Colorado, Boulder, 2009.
- [37] M. Muliawan, M. Karimirad, and T. Moan. Dynamic response and power performance of a combined spar-type floating wind turbine and coaxial floating wave energy converter. *Renewable Energy*, 50:47–57, 2013.
- 555 [38] A. Myhr, C. Bjerkseter, A. Ågotnes, and T. A. Nygaard. Levelised cost of energy for offshore floating wind turbines in a life cycle perspective. *Renewable Energy*, 66:714–728, 2014.
- 560 [39] National Oceanic and Atmospheric Administration. Station 46022 historical data, Accessed 2016. URL http://www.ndbc.noaa.gov/station_history.php?station=46022.
- [40] V. Neary, M. Previsic, R. Jepsen, M. Lawson, Y. Yu, A. Copping, A. Fontaine, K. Hallett, and D. Murray. Methodology for Design and Economic Analysis of Marine Energy Conversion (MEC) Technologies. Technical report, Sandia National Laboratories, 2014.
- 565

- 570 [41] OECD Nuclear Energy Agency. Uranium 2016: Resources, Production and Demand. Technical report, OECD Nuclear Energy Agency and the International Atomic Energy Agency, 2016.
- [42] K. Oguma, T. Suzuki, and K. Saito. Determination of uranium in seawater by flow-injection preconcentration on dodecylamidoxime-impregnated resin and spectrophotometric detection. *Talanta*, 84(5): 1209–1214, 2011.
- 575 [43] H. Osawa, Y. Washio, T. Ogata, Y. Tsuritani, and Y. Nagata. The Open Sea Tests of the Offshore Floating Type Wave Power Device “Mighty Whale”: Performance of the Prototype. *21st International Conference on Offshore Mechanics and Arctic Engineering*, 2002.
- 580 [44] J. Park, G. A. Gill, J. E. Strivens, L.-J. Kuo, R. Jeters, A. Avila, J. Wood, N. J. Schlafer, C. J. Janke, E. A. Miller, M. Thomas, R. S. Addleman, and G. Bonheyo. Effect Of Biofouling On The Performance Of Amidoxime-Based Polymeric Uranium Adsorbents. *Industrial & Engineering Chemistry Research*, 55:4328–4338, 2016.
- 585 [45] C. Perez-Collazo, D. Greaves, and G. Iglesias. A review of combined wave and offshore wind energy. *Renewable and Sustainable Energy Reviews*, 42:141–153, 2015.
- [46] M. Picard, C. Baelden, Y. Wu, L. Chang, and A. H. Slocum. Extraction of Uranium from Seawater: Design and Testing of a Symbiotic System. *Nuclear Technology*, 188(2):200–2017, 2014.
- 590 [47] A. I. Railkin. *Marine Biofouling: Colonization Processes and Defenses*. CRC Press, 2003.
- [48] D. Roddier, C. Cermelli, A. Aubault, and A. Weinstein. Windfloat: A floating foundation for offshore wind turbines. *Journal of Renewable and Sustainable Energy*, 2(3):033104, 2010.
- 595 [49] M. A. Saito and J. W. Moffett. Temporal and spatial variability of cobalt in the Atlantic Ocean. *Geochemica et Cosmochimica Acta*, 66: 1943–1953, 2002.
- 600 [50] E. Schneider and H. Linder. Updates to the Estimated Cost of Uranium Recovery from Seawater. In *Proceedings of the 19th Pacific Basin Nuclear Conference*, pages 1153–1161, 2014.

- [51] E. Schneider and D. Sachde. The Cost of Recovering Uranium from Seawater by a Braided Polymer Adsorbent System. *Sci. Glob. Sec.*, 21(2):134–163, 2013.
- 605 [52] T. Sebastian and M. Lackner. Characterization of the unsteady aerodynamics of offshore floating wind turbines. *Wind Energy*, 16:339–352, 2013.
- [53] N. Seko, A. Katakai, S. Hasegawa, M. Tamada, N. Kasai, H. Takeda, T. Sugo, and K. Saito. Aquaculture of uranium in seawater by a fabric-adsorbent submerged system. *Nuclear Technology*, 144(2):274–278, 2003.
- 610 [54] A. H. Slocum. Symbiotic offshore energy harvesting and storage systems. *Sustainable Energy Technol. Assess.*, 11:135, 2015.
- [55] M. Tamada. Current status of technology for collection of uranium from seawater. *Japan Atomic Energy Agency*, 2009.
- 615 [56] M. Tamada, N. Seko, N. Kasai, and T. Shimizu. Cost estimation of uranium recovery from seawater with system of braid type adsorbent. *Transactions of the Atomic Energy Society of Japan*, 5(4):358–363, 2006.
- [57] S. Tegen, E. Lantz, M. Hand, B. Maples, A. Smith, and P. Schwabe. 2011 Cost of Wind Energy Review, Technical Report TP-5000-56266. Technical report, National Renewable Energy Laboratory, 2013.
- 620 [58] The European Commission. European wave energy pilot plant on the island of pico, azores, portugal. phase 2: Equipment, technical report. Technical report, 1998.
- [59] The European Commission. Islay limpet wave power plant, technical report. Technical report, The Queen’s University of Belfast, 2002.
- 625 [60] T. Tran and D. Kim. The platform pitching motion of floating offshore wind turbine: A preliminary unsteady aerodynamic analysis. *Journal of Wind Engineering and Industrial Aerodynamics*, 142:65–81, 2015.
- [61] A. Umeno, Y. Miyai, N. Takagi, K. Sakane R. Chitrakar, and K. Ooi. Preparation and Adsorptive Properties of Membrane-Type Adsorbents for Lithium Recovery from Seawater. *Industrial & Engineering Chemistry Research*, 41:4281, 2002.
- 630

- 635 [62] Z. Xing, J. Hu, M. Wang, W. Zhang, S. Li, Q. Gao, and G. Wu. Properties and evaluation of amidoxime-based UHMWPE fibrous adsorbent for extraction of uranium from seawater. *Science China Chemistry*, 56(11):1504–1509, 2013.
- 640 [63] Y.-H. Yu, D.S. Jenne, R. Thresher, A. Copping, S. Geerlofs, and L. A. Hanna. Reference Model 5 (RM5): Oscillating Surge Wave Energy Converter, NREL/TP-5000-62861. Technical report, National Renewable Energy Laboratory, 2015.
- 645 [64] A. Zhang, T. Asakura, and G. Uchiyama. The adsorption mechanism of uranium (VI) from seawater on a macroporous fibrous polymeric adsorbent containing amidoxime chelating functional group. *Reactive and Functional Polymers*, 57(1):67–76, 2003.