Cost Analysis of Wind and Uranium from Seawater Acquisition symBiotic Infrastructure using Shell Enclosures

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INTRODUCTION

At current consumption rates, global conventional reserves of uranium, estimated to be 7.6 million tonnes, could be depleted in a little over a century [1]. As these reserves decrease, extraction of uranium is expected to shift to lower quality sites, resulting in higher extraction costs and greater environmental impact. Fortunately, the ocean contains approximately 4.5 billion tonnes of uranium, as uranyl ions at low concentrations of about 3 ppb [2, 3].

Uranium from seawater is a widely studied topic due to the long term security it can assure the nuclear fuel cycle. Additionally, harvesting uranium from seawater could reduce some of the environmental impacts associated with the recovery of land-based uranium. Seawater uranium is meant to create a cost ceiling that provides economic stability and potential savings, not to act as a direct competitor to terrestrial uranium.

A recent review of uranium recovery technologies by [4] found uranium adsorption by chelating polymers to be the most promising in terms of adsorbent capacity, environmental footprint, and cost. In this technology, chelating polymers are deployed in seawater and remain submerged until the amount of captured uranium approaches the adsorption capacity. Then, an elution bath is used to strip metal ions, such as uranium, off the adsorbent polymer. A polymer may be immersed in a number of elution baths before it is regenerated by an alkali wash to free its functional groups, allowing for the reuse of the polymer. The output from the elution process undergoes purification and precipitation typical for mined uranium to produce yellowcake.

Offshore systems for the extraction of uranium from seawater have been developed since the early 2000s. The system currently studied by a nationwide consortium of national laboratory and university partners utilizes continuous adsorbent polyethylene fibers that are braided around a porous polypropylene float which can be made into long lengths [3]. 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 [5].

Detailed economic analysis by [6, 7] have identified the adsorbent production and mooring as the most expensive components of the recovery process. Based on these results, [8] proposed an alternative deployment method that is attached to an offshore wind turbine and continuously takes the adsorbent, that is fabricated into a belt, from the ocean through an elution process and before submerging it back into the sea. However, it has been found that adsorbents with high tensile strength and durability often have very low uranium adsorption properties [9]. Hence, the Wind and Uranium from Seawater Acquisition sumBiotic Infrastructure (WUSABI) previously studied by [8], which requires the adsorbent into a belt held in tension, could face difficulties in an ocean environment. Instead, the design by [10], further referred to in this paper as WUSABI-Koosh, utilized a two-part system to decouple the mechanical and chemical needs of an adsorbent for seawater harvesting of uranium. In these designs, 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, as shown in Figure 1 [11].

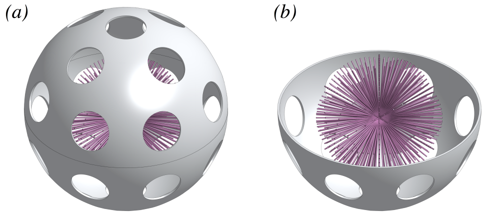

Fig. 1. Decoupling of mechanical and chemical requirements through the use of a a tough, outer protective sphere encapsulating a soft, inner adsorbent. The outer sphere features holes to allow adequate seawater flow to the adsorbent interior [11].

The integration of the design of a uranium harvesting system into an offshore wind turbine tower is pursued because the development of offshore wind or uranium harvesting by themselves bears a high capital cost for the structures, but if the mooring function can be shared, the overall cost for each will be lower. Furthermore, initial design analysis and prototyping of these symbiotic systems has proven they are technically feasible [8, 10]. This paper presents preliminary cost analysis for comparison to uranium recovery via alternative deployment schemes.

METHODOLOGY

The production cost of uranium from seawater was calculated using discounted cash flow techniques to follow the life-cycle costs a unit mass of adsorbent accrues throughout its lifetime as was done in previous cost analyses [6, 7, 12]. All costs are presented in 2015 dollars.

In the remainder of this section, the reference deployment scheme (used as the base case for cost estimates to date) will be described in more detail, as will the deployment scheme proposed by [10].

Reference Deployment Case

The reference deployment scheme refers to the kelp-field like structure described first by [3] and later modified for economic improvements by [13]. In this system, the adsorbent polymer is braided into buoyant 60 meter long strands which are attached to metal chains that act to anchor the braids to the sea floor as well as hold rows of adsorbent braids together. After sufficient seawater exposure, the soaking campaign is terminated. Work boats then transfer the braids to a mothership that houses the chemical bath for the elution of uranium from the polymers. The adsorbents are then redeployed back to the field by the work boats. The adsorbents can be reused as many times as is economically feasible, dependent upon the degradation they suffer with each deployment and elution cycle.

Although many adsorbents have been tested under a wide variety of laboratory conditions, there still exists some uncertainty in the adsorbent's performance in open ocean conditions. For this reason, the uranium production cost is considered as a range rather than a single point. As was done in [12], two parameters that will be studied that characterize the best and worst case scenarios are: (1) the rate of adsorbent degradation and (2) the affect of marine biofouling.

With regards to adsorbent degradation, early experiments on amidoxime adsorbents by [14] reported a 5% loss in uptake after each elution cycle and reuse. This loss was independent of campaign length or the number of times the adsorbent was reused. On the other hand, experiments by [15] using similar amidoxime adsorbents showed that degradation of the adsorbent upon reuse is a function of the length of the campaign and can be quite severe [15]. Therefore, these two empirically derived models will serve as the lower and upper bound of degradation rates respectively.

Recent work found that exposure to marine organisms that colonize the adsorbent surface can lead to a 30% loss in uptake [16]. This estimate is believed to be an upper bound on the loss in uptake due to biofouling given the fact that the studies were conducted in a laboratory with warm and bright conditions, therefore leading to an abundance of growth that may not be seen in a real ocean environment. Furthermore, it is thought that biofouling could potentially be mitigated to fully restore adsorbent performance, thereby leading to a lower bound of 0% loss in uptake due to biofouling. With these two combined, a range of 0-30% loss in uranium uptake due to biofouling is used to enclose the range of possible uranium production costs.

Both of these uncertainties lead to a range of uranium production costs and are believed to represent the best and worst case scenarios, for the current technology. All performance scenarios were subjected to an optimization algorithm [6] used to find the deployment parameters, specifically length of campaign and number of adsorbent uses, that give rise to the minimum possible recovery cost. The resulting range for this reference kelp-field deployment scheme is \$450-890/kg U, achieved with a 45 day campaign length of and 13 adsorbent uses in the best case scenario and 15 days and 10 uses in the worst case. This range will serve as the baseline to which the current deployment scheme is compared.

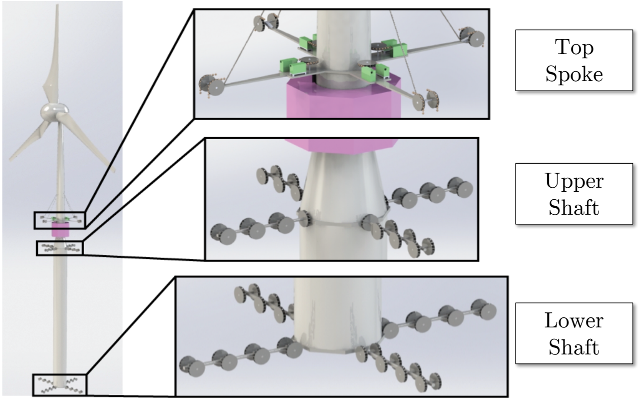

Fig. 2. Depiction of WUSABI-Koosh design with labels indicating terminology used in the cost-analysis to refer to each part of the device.

WUSABI-Koosh Deployment

The design as depicted by [10] can be seen in Figure 2 with labels indicating the terminology of each part of the device used by this cost-analysis. The structure consists of a top spoke providing support to all of the tanks for adsorbent elution and the drive gears that move the adsorbent ball-chains through the system. The upper and lower shafts house the majority of the gears that provide tension for the ball-chain as well as constitute the under-platform loop paths that the chain follows. All support structures are made of 316 stainless steel. The speed of the ball-chain is calculated such that a unit mass of adsorbent will reach the elution tanks at the end of its soaking campaign so that it may be exposed to the elution chemicals for the necessary period before continuing to travel for another deployment cycle. The driving gear can be tuned to speed up or slow down the ball-chain speed, resulting in a faster or slower immersion time of the adsorbent.

As was done by [8] for the WUSABI system, the capital cost of the WSUABI-Koosh structure was calculated primarily by the raw materials required to construct the device. Each harvester unit (i.e. each symbiotic wind turbine device) was sized to support and process the mass of adsorbent required to recover 1,200 tonnes of uranium per year (enough to supply a 5 GW nuclear reactor) from an entire wind farm consisting of 100 turbines.

The adsorbent production cost remained mostly unchanged from previous economic analyses with the kelp-filed deployment scheme. There was however a required cost to wind the adsorbent into koosh balls, fabricate the shells, and to construct the overall ball-chain lengths suitable for deployment with this system.

The method of calculating elution and purification costs also remains mostly unchanged from previous analyses. While the elution of uranium off the braids takes place at sea on the turbine, the necessary purification process was still assumed to take place on land. Therefore, the labor and facility costs for adsorbent elution are reduced. All costs incurred after the bicarbonate elution are calculated in the exact same way as in previous economic estimates [6, 7, 12].

	Kelp-Field			WUSABI-Koosh		
	Cost ($/kg U)	Uses	Days of Campaign	Cost ($/kg U)	Uses	Days of Campaign
Worst Case	$870	10	15 days	$910	20	11 days
Best Case	$430	13	45 days	$590	20	74 days

TABLE I. Optimized deployment parameters leading to the minimum achievable uranium production cost.

The same range of parameters applied to the reference kelp field deployment was used to calculate the resulting uranium production cost for the WUSABI-Koosh scheme. Just as in the case of the baseline design, the cost calculation was subjected to an optimization procedure to find the best number of adsorbent uses and length of soaking campaign to minimize the production cost, $590-910/kg U achieved with a 74 day campaign length and 20 adsorbent uses in the best case scenario and 11 days and 20 uses in the worst case.

Comparison of Deployment Schemes

Figure 3 shows the cost range for the best and worst case scenarios of both deployment schemes as a function of number of adsorbent uses.

In both the best and worst case scenarios, the WUSABI-Koosh scheme resulted in a higher recovery cost, unlike the previous WUSABI scheme developed by [8], as shown by a higher fidelity cost-analysis by [12]. In particular, in the best case scenarios of both schemes, the WUSABI-Koosh deployment costs over 37% more than the reference scheme.

Figure 4 shows the cost breakdown for both deployment schemes for an intermediary case assuming no biofouling and the worst case, time-dependent degradation. In this scenario, the kelp-field deployment resulted in a cost of $634/kg U with a 15 day campaign length and 11 adsorbent uses, while the WUSABI-Koosh scheme resulted in a cost of $758/kg U for a campaign length of 11 days and 20 uses. As can be seen from the figure, the majority of the cost difference between the two deployments are due to the mooring capital cots of each system. While the adsorbent production cost appears lower in Figure 4, the cost to produce a unit mass of adsorbent suitable for the WUSABI-koosh scheme is actually higher than the kelp-field deployment given the cost of fabricating koosh balls out of adsorbent braids. The capitally intensive nature of the koosh scheme, however, allows for a greater number of economically advantageous reuses, resulting in a higher lifetime uranium recovery for a given mass of adsorbent. Therefore, when considered on a per kg of uranium recovered basis, the higher lifetime recovery capacity results in a lower contribution to the final uranium production cost.

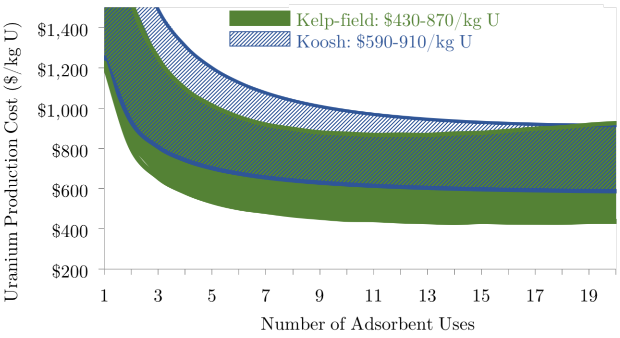

Fig. 3. The range of costs for both deployment schemes as a function of number of adsorbent uses

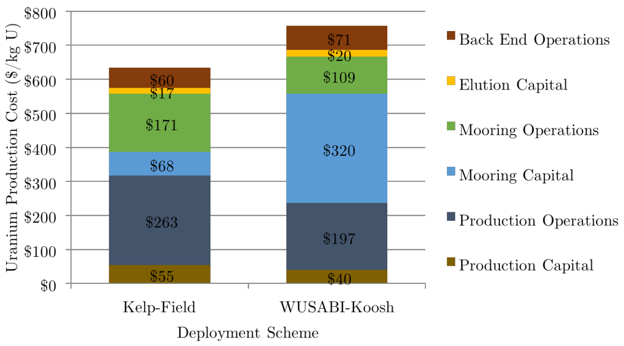

Fig. 4. Breakdown of cost components contributing to the total cost of each deployment scheme for an intermediary case assuming no biofouling and worst case, time-dependent degradation.

This difference in mooring capital costs becomes evident by examining each of the various components contributing to these costs in both schemes, as seen in Figure 3 with the operat-

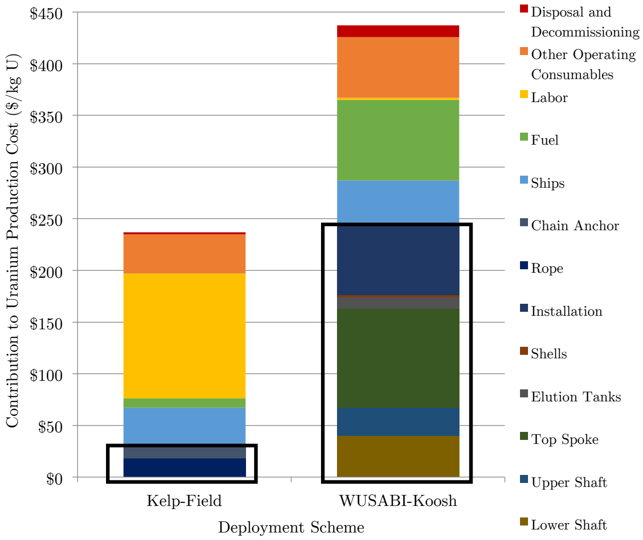

Fig. 5. Cost components contributing to the mooring cost for deployment schemes. The equipment and installation costs for each deployment scheme is outlined in black.

ing costs. As in the WUSABI scheme, the autonomous nature of the WUSABI-Koosh deployment results in significantly lower labor costs, as compared to the kelp-field deployment. On the other hand, as seen by the section outlined in black for each deployment, the equipment and associated installation cost (taken to be 40% of the delivered equipment cost) of the WUSABI-Koosh device is substantially more than that for the kelp-field deployment. In particular, the gears (reflected in the Top Spoke, Upper Shaft, and Lower Shaft cost components) required to loop the ball-chain around the turbine are found to be 31% of the total delivered equipment costs.

CONCLUSIONS

Unlike the WUSABI scheme presented by [8], the WUSABI-Koosh deployment version of coupling the recovery of uranium from with an existing offshore structure, such as a wind turbine, notably increased the cost of seawater uranium. Further investigation into the cost differences found that mooring capital of the WUSABI-Koosh scheme to be the driving factor. Within this, the cost of gears to provide tension and looping for the ball-chain of shell enclosures housing the adsorbent fibers were found to be by far the most expensive components. This identification of major cost drivers will inform future designs using adsorbent shell enclosures that minimize the capital cost of the system. In particular, the gears are currently assumed to be made of 316 stainless steel. Cost reductions could be realized by considering manufacturing the gears from a lighter, and less expensive material, eliminate or reduce the number of gears in a future design, or decrease the density of the gear design itself.

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