A Higher Fidelity Cost Analysis of Wind and Uranium from Seawater Acquisition symBiotic Infrastructure

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INTRODUCTION

The vastness of the worlds oceans makes the low concentration of naturally existing uranium, 3.3 ppb, appealing as a recoverable natural resource. Although ample uranium is available currently through conventional means, uranium from seawater is a widely studied topic due to the long term security it can assure the nuclear fuel cycle. It is important to mention that seawater uranium is not meant to act as a direct competitor to terrestrial uranium, but instead create a cost ceiling that provides economic stability and potential savings. Additionally, seawater uranium could circumvent some of the environmental impacts associated with recovery of any land based resource.

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 meter 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. 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.

Previous economic analyses have identified the adsorbent production and mooring as the most expensive components of the recovery process [1] [2]. Therefore, a later publication by Picard et al. [3] proposed an alternative deployment method in an effort to reduce seawater uranium production cost. The Wind and Uranium from Seawater Acquisition symBiotic Infrastructure (WUSABI) couples uranium recovery with off shore wind to reduce mooring capital cost. The uranium harvesting structure attached to the underwater base of the wind turbine supports elution tanks and an adsorbent pulley system. This allows for a nearly autonomous mooring and elution procedure as adsorbent is in constant motion, reaching the elution tanks at the end of its soaking campaign.

Although the original publication did include a short economic section, further analysis was carried out to provide a higher fidelity production cost estimate for uranium recovered by this system. Sufficient detail was provided in [3] regarding the capital and operating costs of the novel uranium harvesting units. The adsorbent production and uranium elution and purification steps however were estimated by simpler methods, for example applying a previously reported [1] cost for producing a unit mass of adsorbent. This methodology, although satisfactory for the zeroth-order approximation desired in the original publication, overlooks many of the complexities and feedbacks embedded in the full cost model, which are necessary to provide a more accurate estimate. Perhaps more importantly, given the constant updates regarding adsorbent synthesis and performance this value quickly become outdated. Syncing an improved estimate for the WUSABI harvesting units with the existing economic analysis for adsorbent production and elution, which evolves in tandem with the technology, provides a more robust production cost estimate that will remain current over time. In addition to the updates and higher level of detail provided in this independent analysis, consistency in methodology allows for accurate comparison of uranium production costs across recovery methods.

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 [1] [2]. All costs are presented in 2015 dollars.

The remainder of this section will first describe in more detail the mooring and deployment scheme that has been considered in cost estimates to date, and thus serves as the base case. Then the novel WUSABI case is analyzed.

Reference Deployment Case

The reference deployment scheme refers to the kelp-field like structure described in the initial proposal of the passive recovery system [4] that was later slightly modified for economic improvements [5]. This system uses a polymer rope interlaced with metal chains to both hold rows of adsorbent together and moor the net buoyant braids to the ocean floor. Upon realization of the soaking campaign work boats equipped with windlasses winch up the adsorbent braids. Rather than traveling all the way back to shore, the braids are transferred to a mothership for elution of uranium. Work boats then carry the adsorbents back to the field for another deployment. The adsorbents can be reused as many times as is economically feasible, dependent upon the degradation they suffer with each deployment and elution cycle.

Given the constantly evolving nature of recovery technology, there exists some degree of uncertainty in adsorbent performance characteristics when placed in true marine conditions. Therefore, it is most appropriate to consider the uranium production cost as a range rather than a single point. Two particularly important parameters that characterize the best and worst case cost scenarios are: rate of adsorbent degradation and marine biofouling.

Recent experimentation by Pacific Northwest National Lab (PNNL) indicates that exposure to marine microorganisms that colonize the adsorbent surface can lead to a 30% loss in uptake [6]. Given the bright warm laboratory conditions at which these experiments were carried out, this is believed to serve as the maximum decrease in uptake that would be suffered as a result of oceanic biofouling. The lower bound is derived from the notion that it would be possible to completely mitigate biofouling to fully restore adsorbent performance. Therefore, a range of 0-30% loss in uptake is used to enclose the range of possible production costs.

The worst case scenario regarding adsorbent degradation upon reuse similarly comes from recent PNNL experimentation [7]. These experiments indicated that degradation is a function of length of campaign and was more severe on the first reuse as compared to all subsequent reuses. This contrasts to previous experiments [8] on similar amidoxime adsorbents that experienced a constant 5% loss in uptake, independent of length of campaign or adsorbent use number. Therefore these two empirically derived models will serve as the upper and lower bound of degradation rates respectively.

These uncertainties give rise to the range of uranium production costs believed to represent the best and worst case scenario, for the current technology. Both performance scenarios were subjected to an optimization algorithm [2] 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 best case. This range will serve as the baseline to which the WUSABI deployment scheme will be compared.

WUSABI Deployment Case

The WUSABI deployment case analyzed here largely follows the design and cost estimation methods used in the original proposal of the system by Picard et al [3]. The design as depicted by [3] can be seen in Figure 1. The structure consists of a top platform providing support to all of the tanks for adsorbent elution and the pulleys that move adsorbent through the system. The bottom platform hosts the HDPE rollers that guide the adsorbent as it is controlled by the pulleys. All support structures are made of 316 stainless steel. Over the course of the soaking campaign the adsorbent, fabricated into a net, is in constant motion moving up and down the length of the turbine. The speed of the net 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 soaking campaign.

While the original description of the system did include a short economic section, this analysis provides a higher fidelity cost analysis following the detailed methodology [1], [2] used on other recovery technology perturbations. Additionally, the evolving nature of the chemical technology requires updates to be made to important factors including adsorbent performance and the elution procedure. These changes were implemented by modeling the most recent adsorbent behavior and recalculating the tank number and volume required by the currently referenced elution method as described in [9], [10].

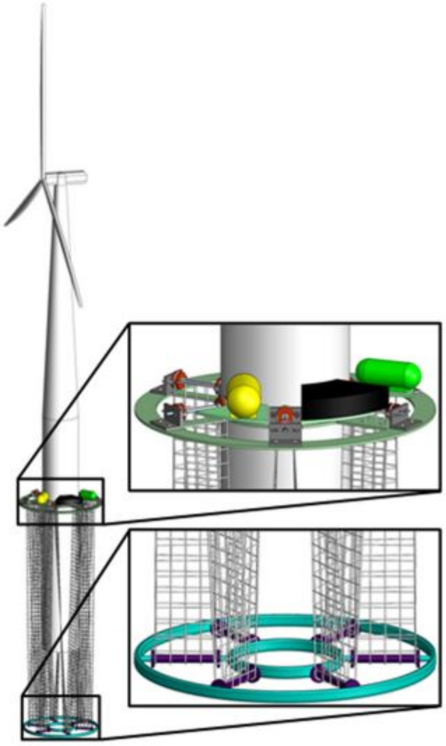

Fig. 1. Depiction of the symbiotic design proposed by [3].

Mirroring the methodology set forth by [3] the capital cost of the WSUABI structure was calculated primarily by the raw materials required to construct the support systems. Each harvester unit was sized to support and process the mass of adsorbent required to recover 1,200 tonnes of uranium per year from the entire wind farm consisting of 214 turbines. The material costs were taken from [3] and adjusted to 2015 dollars.

The adsorbent production cost remained mostly unchanged from previous economic analyses with the kelp-filed deployment scheme. There was however a required cost to construct the adsorbent braids into the 2-D net suitable for deployment with this system. This cost, derived from the Picard publication, includes both the manufacturing of adsorbent into the net and the material cost of the structural wire required.

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 [1], [2].

The same range of parameters applied to the reference kelp field deployment was used to calculate the resulting uranium production cost for the WUSABI scheme. Just as in the

	Kelp-Field			WUSABI		
	Cost($/kg U)	Uses	Days of Campaign	Cost ($/kg U)	Uses	Days of Campaign
Worst Case	$890	10	15	$850	13	16
Best Case	$450	13	45	$400	17	92

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

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, $400-840/kg U. Savings of up to 11% can be realized by use of this deployment method.

Comparison of Deployment Schemes

Figure 2 shows the cost range for the best and worst case scenarios of both deployment schemes as a function of number of adsorbent uses.

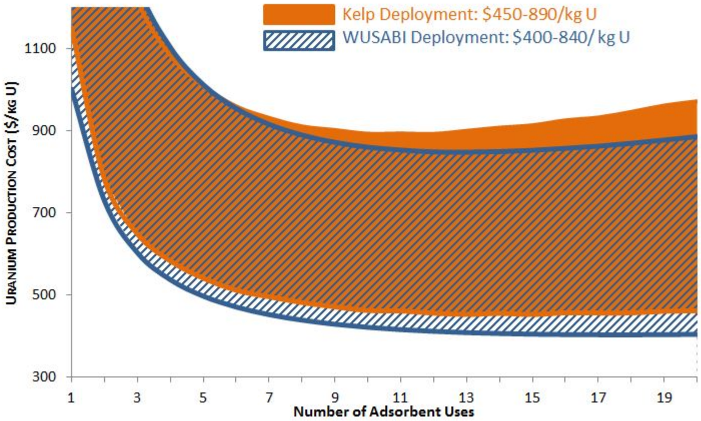

Fig. 2. The range of costs for both deployment schemes as a function of numer of adsorbent uses

In both the best and worst case scenarios, the WUSABI scheme resulted in a lower recovery cost, in part due to a higher number of optimized uses, as seen by the shape of the curves in Figure 2. Additionally, the symbiotic scheme can sustain a longer campaign length as seen in Table I since the cost of each deployment event is lower. The lower deployment capital cost favors a large field with longer soaking times as opposed to a smaller field with a higher turnover rate. This is especially evident in the case of the constant degradation rate as no penalty is suffered from longer deployments.

This becomes evident by examining the various components of the capital and operating cost of both schemes, seen in Figure 3. The autonomous nature of this system results in significantly lower labor costs, which is responsible for the majority of the cost savings as compared to the baseline scheme. This breakdown is also useful in highlighting major cost drivers of the WUSABI system, clearly indicated as elution tanks and ships. Therefore future work will involve methods of reducing these costs.

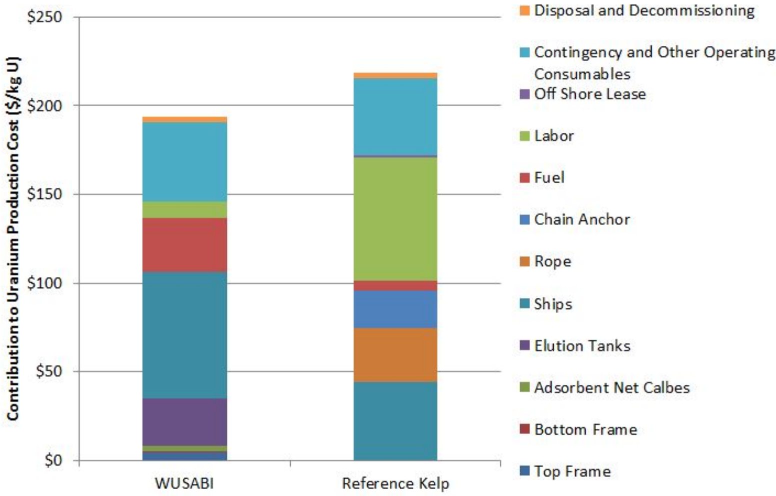

Fig. 3. Cost components contributing to capital and operating cost for deployment schemes

CONCLUSION

Coupling the recovery of uranium from seawater with offshore wind power generation has the potential to notably reduce the cost of seawater uranium. This is especially impactful if the best case scenario regarding adsorbent performance can be realized, meaning oceanic biofouling can be mitigated to realize negligible effects on uptake and adsorbent degradation rate can be restored to previously observed levels.

Beyond providing a higher fidelity, independent economic analysis of the WUSABI system, this work was significant for its identification of major cost drivers. The illumination of the high cost contribution of elution tanks and ships will guide future work efforts to reduce cost.

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