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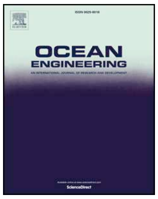

Cost optimization of a symbiotic system to harvest uranium from seawater via an offshore wind turbine

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ABSTRACT

The recovery of uranium from seawater has the potential to transform the perceived sustainability of energy generated by uranium intensive nuclear fuel cycles, while providing environmental benefits as compared to land-based mining. Combining a seawater uranium harvester with an existing offshore wind turbine allows for denser energy recovery per unit ecosystem, as well as lowering the uranium production cost. The analysis presented in this paper focuses on the economic impacts on uranium recovered by adsorbing material deployed with such a symbiotic system as compared to a reference kelp-field like deployment. The Wind and Uranium from Seawater Acquisition symBiotic Infrastructure (WUSABI) was subjected to an independent economic analysis and design optimizations in an effort to reduce the seawater uranium cost. In addition to providing greater transparency to previous economic analyses of this system, this work alters chemical tank materials and establishes a novel means of calculating and optimizing the interval in which symbiotic systems are serviced. The perturbations proposed in this work could achieve a cost savings of 30% as compared to uranium produced from the reference kelp-field like deployment system. Additional design sensitivities are also explored to identify major cost drivers and guide future work regarding deployment location of the turbine field.

1. Introduction

Extraction of uranium from seawater has been researched for decades, with one of the first studies conducted by Davies et al. (1964) after World War II in an effort to secure a uranium supply for Britain at a time when the existence of and access to abundant uranium resources was uncertain. Although evidence indicates that conventional terrestrial mining can satisfy world requirements at moderate cost for the next several decades, the ability to economically recover the 4 billion tonnes of uranium naturally existing in the ocean would assure very long-term availability and accessibility of this critical material. In addition to establishing supply security, this would reduce the uncertainty associated with fuel costs, providing policy and decision makers with increased confidence in the long-term viability of nuclear power. Seawater uranium can also be considered a hedge against the possibility of future uranium scarcity or price hikes, and may be achieved at a considerably lower cost and without concerns for proliferation associated with breeder reactors which utilize plutonium.

A review article (Lindner and Schneider, 2015) details the evolution of technologies proposed since the 1960s for recovering uranium from seawater as well as their production cost estimates. Two primary components of seawater uranium production cost are adsorbent synthesis and ocean deployment of the adsorbent. In general, the synthesis cost and the adsorbent's capacity for taking up uranium are seen to be the most significant drivers of seawater uranium production cost, but deployment cost is also significant; and deployment costs grow in relative importance as the adsorbent material improves. Modern adsorbents are characterized by increasing durability and can thus be reused in the sea multiple times, with deployment costs incurred upon each reuse.

Both Lindner and Schneider (2015) and a recent review of proposed uranium recovery technologies by Kim et al. (2013) identified uranium adsorption by chelating polymers (Zhang et al., 2003; Seko et al., 2003; Anirudhan et al., 2011) to be the most promising in terms of cost, adsorption capacity, and environmental footprint. Other techniques including membrane filtration, coagulation, and precipitation (Kanno, 1984; van Reis and Zydney, 2007; Tularam and Ilahee, 2007) were found to have issues such as high operating costs, poor durability, or toxicity. Further Lindner and Schneider (2015), noted that the deployment strategies involving active pumping of seawater required an implausibly large portion of the uranium contained in the circulated water be captured for the strategy to approach economic viability. For

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that reason, recent work has focused on systems where passive mechanisms, typically natural circulation present in the oceans, provide sufficient seawater exposure to the adsorbent. These passive strategies envision deployment of adsorbent at moderate depth and distance from coastlines, so costs associated with the system to moor the adsorbent to the seabed can be substantial. This work assesses the potential cost savings from leveraging existing structures, specifically offshore wind turbines, to serve as mooring platforms for the adsorbent.

Given that the focus of this analysis is the cost savings associated with the novel marine deployment structure, the adsorbent synthesis and necessary post-processing is modeled identically in all cases, and not covered in great detail. All uranium production costs presented here are calculated using the consistently strong performing and well documented amidoxime-based ligands under continued development by Oak Ridge (ORNL) (Das et al., 2016; Byers and Schneider, 2016a, 2016b). These adsorbent fibers consist of high density polyethylene synthesized by radiation-induced graft polymerization to attach a hydrophilic functional group and the amidoxime ligand, which affords the uranium affinity. The fibers are then braided before being sent out to sea for their soaking campaign, after which they are removed to the surface so the uranium may be eluted off. These robust adsorbents can then be regenerated with a sodium hydroxide rinse and returned to the ocean for multiple subsequent soaking and elution cycles (Kuo et al., 2017b; Pan et al., 2017). This uranium recovery methodology will be applied to both the leading conventional deployment strategy as well as the novel symbiotic system, both of which will be described in more detail in section 2.

2. Alternate recovery strategies

This analysis builds upon the technology identified by Kim et al. (2013) developed by a consortium led by ORNL and Pacific Northwest National Labs (PNNL). Under this approach, polymer fibers are grafted with uranium chelating ligands to allow for the passive extraction of uranium from seawater by adsorption. The optimal immersion time in seawater of the polymer-based adsorbents is on the order of several days to weeks. This reflects a trade-off between factors including diminishing adsorption rates as the saturation capacity is approached, and the required extent of the adsorbent field in order to produce uranium at the desired rate, as well as the cost incurred each time the adsorbent is deployed. Once the adsorbent is recovered from the sea, elution is used to strip the uranium from the polymers. The adsorbent polymer may undergo a number of elution cycles before being disposed of or recycled for the scrap value of the polymer. The output from the elution process undergoes purification and precipitation typical for mined uranium to produce yellowcake.

Several of the polymer adsorbent system concepts have been subject to marine tests to evaluate performance, feasibility and cost-effectiveness. The Japanese Atomic Energy Agency (JAEA) first developed a system of buoy floated stacks of adsorbent fabric. However, due to the weight of the mooring equipment, mooring operations were found to account for more than 70% of the cost of this concept (Sugo et al., 2001; Seko et al., 2003). In addition, the adsorbent was to be brought back to shore for the elution process and redeployed afterward. These stand-alone intermittent operation systems have significant practical and economic deployment challenges (Seko et al., 2003) and to date none have proven economically viable.

To address this problem, a buoyant braid adsorbent made of polyethylene fibers on a polypropylene trunk was proposed by Tamada et al. (2006). This system requires adsorbents to be braided into 60 m long segments. Braids are shipped out to sea where they are moored to the ocean floor using anchoring chains to form a kelp-field like structure. After sufficient exposure to seawater, their soaking campaign ends and the braids are winched up to the surface by workboats for elution. This design was found to achieve a reduction of 40% in the cost of uranium recovery compared to the adsorbent stack system, resulting in an estimated uranium production cost of $1000/kg U (Tamada et al., 2006). An independent cost-analysis by Schneider and Sachde (2013) of the system yielded a production cost of $1230/kg U (both figures are in year 2011 dollars). Much of the difference in cost was attributed to the second paper's inclusion of an experimentally observed 5% degradation of adsorbent capacity per use cycle. Further sensitivity studies confirmed that the major cost divers of such a system were the adsorbent capacity, number of recycles, and capacity degradation. For instance, if the capacity of the adsorbent was increased from 2 kg U/tonne adsorbent to 6 kg U/tonne adsorbent and the number of recycles was increased from 6 to 20, with no degradation and unchanged adsorbent production costs, the uranium production cost was estimated to drop to ca. $300/kg U. In comparison, the market price of uranium has ranged from a 2016 low of near $60/kg U to a peak of $300/kg U in 2007 when demand for nuclear power was higher. Rothwell (2016) cites that nuclear reactors which require reprocessed uranium for fuel (also known as breeder reactors) have a breakeven price of $210-$560/kg U. Hence, one goal is to determine if the production price of seawater uranium would become cost competitive with breeder reactor technologies, which currently account for almost 5% of new nuclear fuel (World-Nuclear.org, 2016).

To date, the use of buoyant adsorbents in the kelp-field like structure has been regarded as the best available and served as the status quo in many previous analyses (Das et al., 2016; Byers and Schneider, 2016a, 2016b; Sugo et al., 2001; Tamada et al., 2006; Schneider and Sachde, 2013; Schneider and Linder, 2014) of recovery system costs. However, this paper focuses on performance modeling as well as cost and system analysis of a proposal by Picard et al. (2014), who proposed a deployment method that couples a uranium adsorbent system with offshore wind turbines. The Wind and Uranium from Seawater Acquisition symBiotic Infrastructure (WUSABI) utilizes existing marine infrastructures to moor the adsorbent as well as to provide a platform and supply of energy to enable the chemical processing involved in recycling the adsorbent and recovering uranium from it.

These innovations are aimed at reducing the cost floor imposed on uranium production by the existing deployment cost. This cost floor exists because a significant portion of the deployment costs, notably ship operation, maintenance and personnel expenses, are incurred each time the adsorbent is brought to the mooring site, emplaced, and then later winched up and brought to shore for elution, or processed on a vessel. The extent to which these expenses influence the final uranium production cost will be explored in more detail in section 3.4 and can be seen in Fig. 9.

A previous publication (Byers et al., 2016) conducted an independent economic analysis of the WUSABI design as described by Picard et al. (2014) so that this mooring and deployment strategy could be incorporated to the robust existing cost model, which consistently updates to reflect progress made in adsorbent technology. That work illuminated major cost drivers, most notably identifying the required chemical storage tanks and ships as making up a substantial portion of the deployment cost. Therefore, this work considers design changes to reduce these costs, as well as provide greater transparency to the higher fidelity economic analysis that is used with the current cost model. Significant design developments carried out here address the material of the storage tank by substituting a more cost effective alternative. Tank size was also manipulated to find the optimal frequency of turbine servicing, which affects not only tank but also service fleet size.

This paper will initially provide background on the cost-analysis of the current braid deployment system described above, which will serve as a base case. To achieve this, a recent cost analysis publication (Byers and Schneider, 2016b) will be referenced to highlight major cost drivers (e.g., adsorbent fabrication and performance) beyond deployment which affect uranium production costs. Then the symbiotic design, as adapted from Picard et al. (2014), is presented in sufficient detail to conduct a cost-analysis of a refined WUSABI strategy. The lifecycle cost of a unit mass of adsorbent moored by WUSABI will be calculated with