An Offshore Solution to Cobalt Shortages via Adsorption-Based Harvesting from Seawater

Maha N. Haji[a,*], Alexander H. Slocum[a]

[a]*Department of Mechanical Engineering, Massachusetts Institute of Technology*

Abstract

The predicted dominance of electric vehicles and the need for grid-scale energy storage have heightened concerns that cobalt, a key constituent of lithium-ion batteries, could become a critical limiting factor. With limited terrestrial resources and over half the global production coming from politically challenging regions increasing risk, a shortage of cobalt could be experienced by the early 2020s. Fortunately, the oceans contain about 70 times more cobalt than on land and can be harvested sustainably with passive adsorption technologies; and a symbiotic system using existing offshore structures to harvest cobalt could enhance the economic feasibility of seawater cobalt harvesting. Our study finds that retrofitting just 76 unused oil platforms in the Gulf of Mexico could extract an average of 27.3% of the nation's 2017 cobalt consumption. New Offshore Opportunity for Underwater Cobalt Harvesting has the potential to reduce the cobalt supply pinch point in lithium-ion battery production.

Keywords: cobalt; lithium-ion; seawater mineral extraction; recycled plastic;

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1. Introduction

By 2025, sales of electric vehicles (EVs) are forecasted to reach 11 million units and by 2040 to be 55% of all new car sales [1]. Simultaneously, lack of grid-scale storage capacity may limit renewable energy penetration. The expansion of the EV market coupled with the increased need for stationary

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[*] Corresponding author

Email addresses: `mhaji@mit.edu` (Maha N. Haji), `slocum@mit.edu` (Alexander H. Slocum)

storage has resulted in significant demand for lithium-ion batteries and their cobalt cathode [2].

The shift to larger form-factor batteries for grid-scale energy storage and EVs has also resulted in new supply chain dynamics for materials used in lithium-ion batteries such as cobalt [3]. [4] studied the projected EV-related commodity demand for elements of lithium-ion batteries if EVs accounted for all passenger vehicles (∼100 million units), according to Chevrolet Bolt specifications (24 kg cobalt per battery). Their results showed that relative to today's market size, cobalt demand would increase by over 1900%, an increase second only to lithium (whose demand would increase by over 2900%). Such EV penetration requires drastic expansion of the battery raw material supply chain.

In scaling the lithium-ion battery supply chain, cobalt will likely be the limiting factor for massive growth [3]. Even as lithium-ion batteries with less cobalt demands become more mainstream (with batteries using higher ratios of nickel cathodes than either magnesium and cobalt), raw materials demand in 2025 to supply an estimated 14.2 million EVs still highlights the cobalt cathode to require the highest percent of proven reserves [4]. Unlike other materials of lithium-ion batteries where current production capacity is the primary bottleneck, cobalt faces the issue of limited reserves [4]. In a 100% EV world (where all vehicles sold globally are Chevrolet Bolts), cobalt is expected to deplete the most incremental annual commodity demand reserve at 33%, followed by aluminum at 10% and lithium at 7.2%. The projected 2040 demand levels could deplete the current total available global terrestrial cobalt reserves (7.1 million tonnes [5]) within nine years if all resources were diverted to battery production alone [6]. Extracting all 25 million tonnes of identified global reserves of cobalt [5] (the vast majority of which are unavailable with current mining technology) would result in only another 30 years of supply [6]. Analysts forecast shortages of cobalt by the early 2020s due to increased demand for various industry sectors (Figure 1) and view cobalt as one of the largest potential risks to EV sales over the next 5-7 years [1]. Although newer battery technologies are striving to reduce demands of cobalt, with the Tesla Model 3 using 4.5 kg cobalt per battery [7] (as compared to the Chevrolet Bolt at 24 kg), these batteries are not expected to have material impacts until 2022 onward [8]. Additionally, research suggests that recycling is unlikely to provide a significant short-term supply of cobalt given long battery lifetimes and multiple end uses [3].

Cobalt production is usually driven by markets for other, more abundant, metals rather than the need for cobalt as it is extracted largely as a

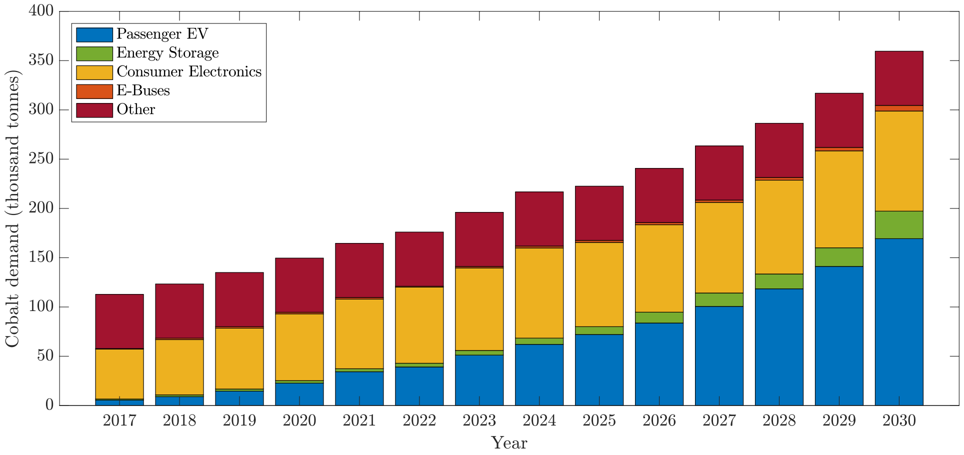

Figure 1: Estimated cobalt demand until 2030 for various industry sectors [1]. Rising cobalt demand could result in supply shocks in the early 2020s according to [1].

byproduct of mining other metals. In 2015, 50% of cobalt production could be attributed to the nickel industry and 35% to the copper industry, with only 6% due to primary cobalt production [9]. This leads to limited flexibility in adjusting the amount of cobalt mined. Changes in demand for cobalt, therefore, often result in either oversupply or shortages while changes in demand for metals such as nickel or copper greatly affect the resulting cobalt supply.

Half the global production of cobalt comes from the Democratic Republic of the Congo (DRC), further complicating the mineral's supply risk (Figure 2). This war-torn country has been in constant conflict for decades and cobalt's negative impact on local populations includes grueling and unsafe working conditions, meager pay, and numerous health problems due to exposure to associated toxic metals [10]. Moreover, refining of cobalt is geographically concentrated, particularly in China [4]. The vast majority of valuable minerals in the US, including cobalt, are imported from other nations [11] with China being the leading supplier of cobalt imports in 2015 [4]. This reliance on a single overseas supply constitutes a national security concern for any country.

Possible supply disruptions caused by government policy or socio-political instability due to the location of reserves in unstable regions as well as the reliance on the co-production of other elements are the main risk factors of cobalt supply [12, 13, 14]. These issues are reflected in the price of cobalt which has increased over 200% in the past two years alone (Figure 3) and

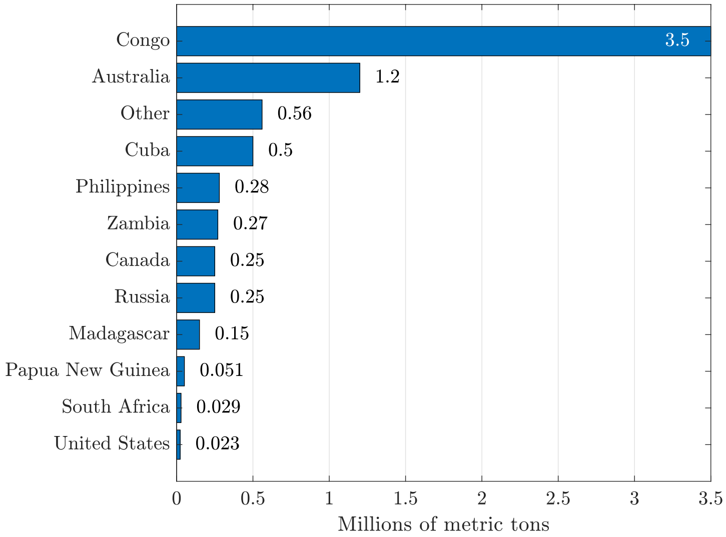

Figure 2: Known cobalt reserves by country [5].

could upend the price of lithium-ion storage systems [15]. If the supply of lithium-ion batteries is to keep pace with demand, new, stable sources of cobalt will need to realized. Supply pressures have already resulted in mounting interested in mining cobalt-rich mineral deposits on the seafloor, however these deep-sea mining efforts are expected to have significant environmental costs that will very likely last millions of years [16, 17]. Here we present an alternative technology in which dissolved cobalt can be passively extracted from the ocean, with the aim of avoiding many of the environmental issues of land-based mining.

This paper presents a New Offshore Opportunity for Underwater Cobalt Harvesting (NO OUCH) that uses existing unused offshore platforms in the Gulf of Mexico (GOM) as support structures for mineral adsorption systems to increase the cobalt supply so critical to the success of EVs and other lithium-ion battery reliant technologies. Presented first is an overview of seawater cobalt sources and the mineral's global concentration with focus on the GOM. Following is a review of current cobalt extraction technologies. Finally, the methodology and results of the symbiotic use of offshore oil rigs in the GOM for cobalt harvesting machines is presented. The results are discussed in light of current production goals for EVs and the impact an offshore cobalt harvesting farm could have to meet ambitious lithium-ion battery manufacturing goals.

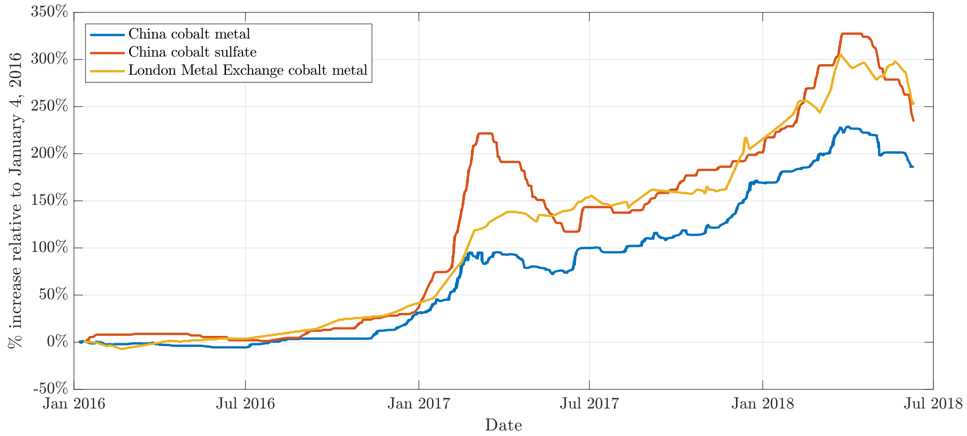

Figure 3: Cobalt prices since 2016 normalized to price on January 4, 2016. Source: London Metal Exchange, Asian Metal. Cobalt prices have risen over 200% in the past two years alone due to market growth and increased demand.

2. Seawater Sources of Cobalt

Supplies of many valuable elements, including cobalt, are greater in seawater than in the Earth's crust (Figure 4) with cobalt 70 times more abundant in the ocean than on land [11]. While land-based minerals are concentrated in specific geologic and geographic areas, seawater minerals are generally distributed evenly in seawater. Table 1 details the concentrations of various metal ions in seawater, including cobalt. With a seawater concentration of about 0.39 μg/L [18], dissolved cobalt amounts to 507 million tonnes over the entirely of the world's oceans [11] as compared to conventional terrestrial reserves of 7.1 million tonnes [5].

Although the concentration of cobalt (Co^{2+}) in seawater is much smaller than other metal ions, both copper (Cu^{2+}, with a seawater concentration approximately twice that of Co^{2+}) and uranium ($\left[\mathrm{UO_2(CO^3)^3}\right]^{4-}$ with a seawater concentration about eight times that of Co^{2+}) have proven extractable, with the latter economically competitive with breeder reactors [19, 20].

The distribution of cobalt in the oceans can vary due to geography, season, and water depth [21], as well as due to processes such as ocean mixing and continental run-off [22, 23, 24, 25]. Cobalt is depleted in the surface ocean by biological utilization and in the deep ocean by remineralization[26], leaving a maximum in many regions around the globe in the upper-mid ocean where concentrations can be increased by a factor of four to nine[27].

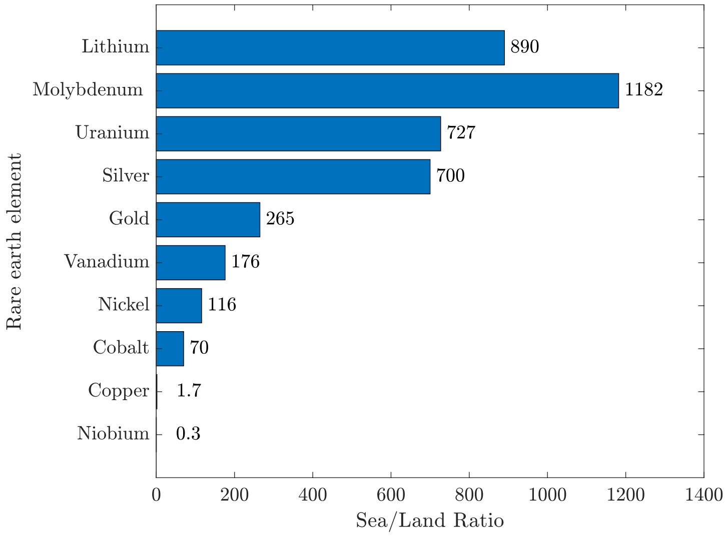

Figure 4: Ratio of seawater abundance to terrestrial reserves of various Rare Earth Elements [11].

Table 1: Composition range of seawater at 35 ppt salinity with respect to major and minor cations in order of abundance [18]

Element	**Concentration (mg/L)**
Na^+	10800
Mg^{2+}	1290
Ca^{2+}	411
K^+	392
Sr^{2+}	8.1
Li^+	0.17
Rb^+	0.12
Ba^{2+}	0.021
Fe^{2+}	0.0034
$\left[UO_2(CO^3)^3\right]^{4-}$	0.0033
Cu^{2+}	0.0009
Co^{2+}	0.00039

The recently launched international research program GEOTRACES aims to improve an understanding of biogeochemical cycles in the oceans by mapping the distribution of trace elements and isotopes and to understand the processes controlling this distribution. As part of this study, the

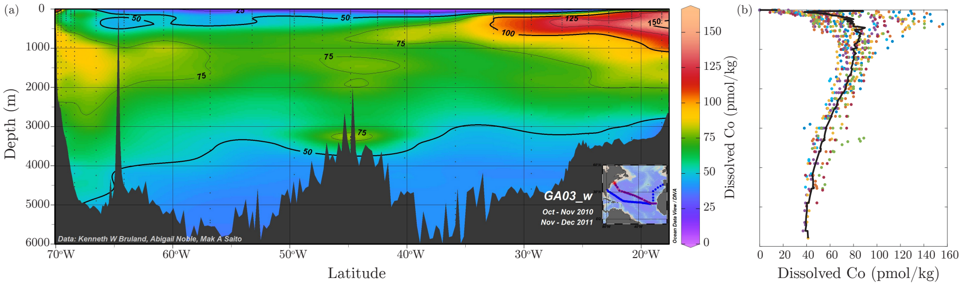

Figure 5: (a) Full depth section of total dissolved cobalt measured along GEOTRACES transect GA03 [28]. (b) Dissolved profiles of total cobalt for GEOTRACES transect GA03. The black line indicates the depth-averaged value across all stations along the transect [28].

concentration of dissolved cobalt has been measured in many locations in the Atlantic, Southern, and Pacific Oceans [26]. These measurements further confirm the increased concentration of cobalt in the upper ocean, just below surface waters. Figures 5(a) shows the dissolved cobalt concentration (pmol/kg) as measured along a transect in the North Atlantic over the course of the research program [28]. Figure 5(b) details all of the dissolved cobalt concentration (pmol/kg) taken along the transect as a function of depth. As can be seen from the figure, there is a sharp increase in the dissolved cobalt concentration between ∼200-2000 m below the ocean surface. In the case of this transect, the dissolved cobalt concentration at depth was observed to be as much as 7.4 times than at the surface.

While the maximum concentrations of cobalt measured as part of GEOTRACES are almost 50 times smaller than the average ocean content of 0.39 μg/L reported by [18], the cobalt concentration in the Atlantic has been observed to be lower than most other oceans. On the other hand, the GOM has been known to have regional average concentrations of cobalt as high as 0.84 μg/L [22], making it a prime location for cobalt extraction. Such low concentrations of cobalt in the ocean could make it highly challenging to selectively extract economically. However, to date, no metrics exist for determining the economic feasibility of passive extraction of a mineral. Future research should determine these metrics, considering such factors as seawater concentration, mineral market price, and future market price (based on projected demand, projected supply, and geopolitical factors that influence each). At present, economic feasibility studies of seawater mineral extraction are based on detailed life-cycle cost analysis of specific systems, such as by [20] and [29]. Such analysis for the case of passive uranium extraction from seawater, another element with low concentration in seawater, have shown advances in chemical adsorbents and mechanical systems enable drastic cost reductions, bringing the production cost of uranium from seawater on par with breeder reactors [19, 20].

3. Extraction of Cobalt from Seawater

Extensive research has been done on the removal of heavy metal contaminants from aqueous solutions largely motivated by the fact that the presence of heavy metals in industrial wastewater have significant impacts on human health and the environment [30, 31, 32, 33]. Excess amounts of cobalt can cause bone marrow hyperplasia, pancreatic failure, congestive heart failure and cardiomyopathy. For this reason, selective adsorption of cobalt from aqueous solutions has been studied in the past with promising results. Starting in the 1970s, [34] observed that after two hours of interaction, over 50% of cobalt could be extracted from artificial seawater with cobalt concentrations of both 9.5 ppb and 110 ppb using natural iron-manganese hydroxides and that 100% of the cobalt could be sorbed within 20 days. Similarly, a screening of 14 ligands and two macroporous resins for cobalt sorption found certain ligand and resin combinations could recover over 90% of the cobalt in artificial seawater [35].

Cobalt's natural removal from seawater through biological processes and remineralization have been an inspiration for the development of novel adsorbents. Work has investigated adsorbents ranging from algae, activated sludge, bacteria, and minerals to more common materials such as lemon peels and even bone char. The results of some of these studies, summarized in Table 2, show cobalt adsorption capacities ranging from 0.69-190 g/kg adsorbent. In particular, nanosized zero-valent iron (nZVI) has been increasingly gaining interest as an efficient sorbent for various types of aqueous pollutants, including cobalt, with exceedingly high adsorption capacities of 172 g/kg [36]. Note that these results were obtained for a variety of solutions ranging from those spiked with single or multiple metals with a large range of Co and other constituent concentrations. The summary in Table 2 is meant to describe the landscape of current materials under research for cobalt extraction from aqueous solutions and is not meant to be a direct comparison between adsorbent types.

Furthermore, given that other salts have much higher concentration in seawater (such as Na, Ca, and Mg), the selectivity of a cobalt adsorbent in seawater conditions should be investigated. Experimental studies have shown that in addition to initial metal ion concentration [37, 38, 36] and the presence of other metal ions [39], the adsorbent uptake of Co can depend on a number of factors including solution pH [40, 41, 42, 38, 43, 36, 44, 39], temperature [42, 38, 43, 39] and contact time [42, 36, 44, 39]. Each of the adsorbents detailed in Table 2 may have varying selectivity when in seawater and is the topic of further research.

Table 2: Comparison of maximum sorption capacity[a] of various adsorbents for the Co^{2+}

Adsorbent	**Adsorption capacity (g/kg)**	**Ref**
PFB1 (fungi)	190	[43]
Rhytidiadelphus squarrosus (moss)	7.25	[45]
Hypogymnia physodes (foliose lichen)	9.90	[46]
Evernia prunastri (fruticose lichen)	5.72	[47]
Parmotrema tinctorum (foliose lichen)	22.10	[48]
Oscillatoria angustissima (blue-green algae)	15.32	[37]
Chlorella sp. (green algae)	14.50	[49]
Ulva lactuca sp. (green algae)	43.07	[50]
Pilayella littoralis (brown algae)	33.00	[40]
Sargassum wightii (brown algae)	20.63	[51]
Mg-treated *Sargassum* sp. (brown algea)	80.55	[38]
Pre-treated 2-*Hypnea Valentiae* (brown algea)	2.80	[44]
Jania rubens (red algae)	1.92	[52]
Pterocladia capillacea (red algae)	3.10	[52]
Galaxaura oblongata (red algae)	4.37	[52]
Alginate beads (ABs)	71.5	[53]
Nanographite carbon in an alginatematrix (NCB)	89.5	[53]
Magnetic AB containing Cyanex 272R	32.65	[54]
Aerobic granules	52.4	[55]
Activated sludge from sewage treatment plant	36.01	[45]
Activated sludge from municipal WWTP	10.31	[41]
Activated sludge from distillery WWTP	15.09	[56]
Anaerobic sludge from paper mill WWTP	12.32	[57]
Chryseomonas luteola TEM05 (bacteria)	45.5	[58]
Nanosized zero-valent iron	172	[36]
MWCNTs/iron oxide composites	10.6	[39]
Magnetic chitosan nanoparticle	1.62	[59]
Alginate-chitosan hybrid gel bead	3.18	[60]
Hydroxyapatite/chitosancomposite	10.63	[61]
Synthetic hydroxyapatite	1.23	[62]
Modified bentonite	138.08	[63]
Kaolinite	51.32	[42]
Arca shell	7.82	[64]
Almond green hull	45.5	[65]
Lemon peel	22	[66]
Sunflower biomass	0.69	[67]
Bone char	6.42	[68]

[a] Note that these results were obtained for a variety of solutions ranging from those spiked with single or multiple metals with a large range of Co and other constituent concentrations. The summary in this table is meant to describe the landscape of current materials under research for cobalt extraction from aqueous solutions and is not meant to be a direct comparison between adsorbent types..

4. Offshore Structures for Cobalt Harvesters

Previous work has shown that the cost of harvesting rare earth elements (REE), such as uranium, from seawater can be greatly reduced by pairing the system with an existing offshore structure [69, 20] thereby forming a symbiotic system as net costs for both are thus effectively reduced. Offshore oil platforms, particularly decommissioned platforms, offer an extremely viable pairing for cobalt harvesting technology. The GOM is a prime candidate for the application of this technology given that it has some of the highest concentrations of dissolved cobalt in the world in addition to thousands of offshore oil platforms. Furthermore, the potential to "re-use" offshore platforms as part of a mineral harvesting system represents a new economy for the region which could increase regional robustness as oil prices remain volatile.

Location of cobalt adsorbents in the water column will be key to the technology's success. Since cobalt is removed from the upper ocean through biological processes and remineralization in the deep ocean, the adsorbents should be placed out of these regions to ensure exposure to larger oceanic concentrations of cobalt for extraction and reduced environmental impact. Additionally, placing adsorbents in regions where organisms are abundant could result in biofouling (growth of marine organisms) on the adsorbent, which has been shown to significantly reduce uptake of minerals in the case uranium adsorbents [70]. The euphotic zone, the depth to which light penetrates the ocean and hence the location of increased bio matter, is used as a guide for the minimum depth adsorbents should be placed. Note, however, that adsorption prefers warm water temperature [38, 71], which decreases with depth; thus depending on the region, there may be an optimal depth for adsorption.

4.1. Platform selection

In the GOM, the euphotic zone extends approximately 100 m deep. Thus, only offshore oil platforms in water depths of 150 m or greater are selected for this study as this depth leaves enough room for the cobalt mineral harvesting to occur in at least the lower 50 m of the platform's structure. Additionally, only the structure types with significant surface expression and considerable subsea structure are considered for addition of a cobalt harvesting system (Figure 6). For the initial development of oceanic cobalt harvesting, only those platforms with expired or inactive leases were considered for repurposing.

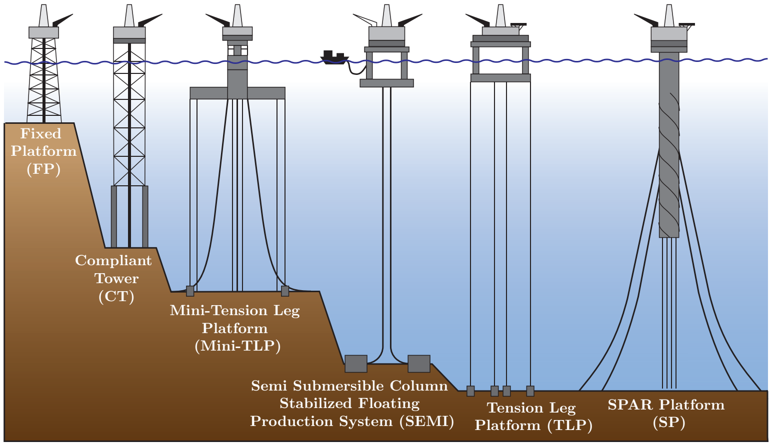

Figure 6: Types of offshore oil platforms reported in the dataset from [72] that are considered amenable to cobalt harvesting. In this study, the fixed platform (FP), compliant tower (CT), tension leg platform (TLP), mini-tension leg platform (MTLP), spar platform (SPAR), and semi submersible column stabilized floating production system (SEMI) are considered to be viable structure types for the addition of a cobalt harvesting system.

4.2. Mechanical design

In order to decouple the mechanical and chemical requirements of the harvesting system and adsorbent and allow for further optimization of each, a hard permeable shell with sufficient mechanical strength and durability for use in an offshore environment can be utilized to enclose a cobalt adsorbent with high adsorption capacity (Figure 7(a)) as has been done for uranium adsorbents in the past [73]. Previous work on the design of systems to harvest uranium from seawater coupled to offshore floating spar wind turbines using these shell enclosures resulted in the Symbiotic Machine for Ocean uRanium Extraction (SMORE) whose design utilized a set of rollers to move the adsorbent through the water column [74]. In this design, the shells enclosing the adsorbent are incrementally placed along high strength rope, resembling conventional ball-chain belts. To decrease the likelihood of tangling between ball-chain lengths and increase the rigidity of the overall component, the lengths of rope are connected together via cross-members to create a ladder-like (or narrow net-like) structure, as shown in Figure 7(b). The ball-chain ladder is then strung between a set of upper and lower rollers along the length of the offshore structure to cycle the adsorbent through the water column, shown in Figures 7(c)-(d) [74]. The roller mechanism allows 10 lengths of adsorbent shells to be strung around on each of four 6.6 m long rollers (for a total of 40 lengths) around a floating spar wind turbine

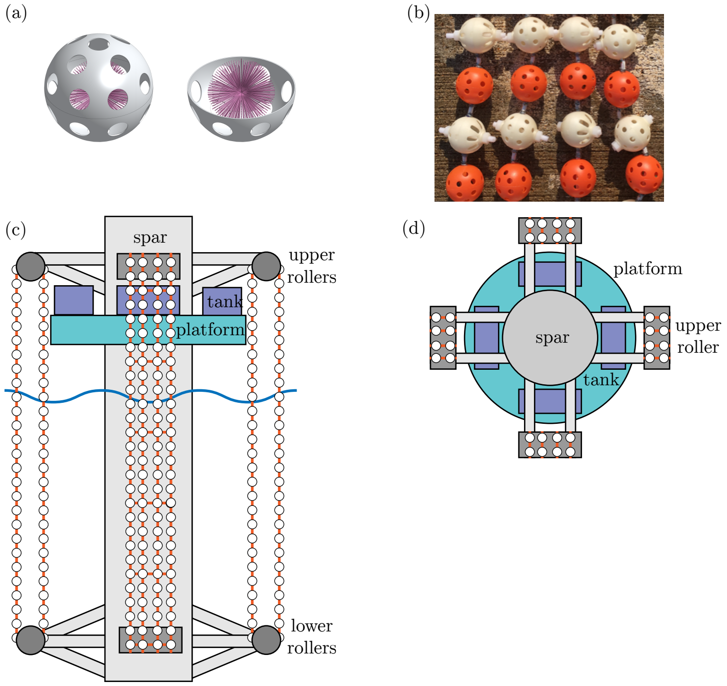

Figure 7: Design details of a Symbiotic Machine for Ocean uRanium Extraction (SMORE) as a starting point for the design of a cobalt harvesting system. (a) Hard permeable shell enclosure encapsulating the polymer adsorbent [73] (Copyright 2018 by the American Nuclear Society, La Grange Park, Illinois). (b) A 1/10th physical scale adsorbent ball-chain ladder as used in SMORE. (c) Side and (d) top views of SMORE which uses rollers to move ball-chain lengths of adsorbent through the water column [74].

with a spar diameter of 9 m.

A system such as SMORE could be readily adapted for passive harvesting of cobalt in the case of polymer-based adsorbents with similar mechanical characteristics to the polyethylene fiber adsorbents used for uranium harvesting [75, 76]. On the other hand, if the cobalt harvesting material is vastly different, new enclosures to decouple the mechanical and chemical requirements may need to be designed. Moreover, it has been shown that a system such as SMORE can be added to an offshore floating structure, such as an offshore wind turbine, without significantly impacting its response in ocean waves [77]. Therefore, adaptations to the SMORE design for use on offshore oil rigs could yield systems viable for cobalt harvesting with little impact to a rig's structural integrity and hydrodynamic response. Given that offshore oil platforms are much larger than offshore wind turbine structures, for the case polymer-based cobalt adsorbents, modifications to SMORE could utilize multiple roller mechanisms to accommodate more lengths and hence 40 lengths per platform is taken as a lower bound. An upper bound of 320 lengths is considered assuming that eight rollers can be used around the perimeter of each of the four legs/corners of a platform. The results are presented as a range based on these two design choices.

4.3. Shell Size and Adsorbent

Based on the current cobalt adsorbent developments, with further research and development into new selective adsorbents, we believe an ocean-ready adsorbent uptake of 10 g/kg adsorbent can be readily achieved and is therefore taken an a conservative estimate. The cobalt adsorbents saturate within 20 days [34, 35] and if the cobalt harvesting machine has an annual uptime of 75%, each tonne of adsorbent would harvest 137 kg. Work has shown that once adsorbed, over 95% of the cobalt can be recovered from the adsorbent using both acids and organic eluates [35] so a 90% recovery rate of cobalt from the adsorbent is assumed. It is estimated that each 0.5 m diameter shell can hold 5 kg of cobalt adsorbent based on previous work for the encapsulation of uranium adsorbing polymers [73].

5. Results and Discussion

Of the 2,073 offshore oil platforms in the GOM [72], 530 are in depths of 150 m or greater, of which 510 are of one of the structure types detailed in Figure 6 (dots in Figure 8). Of these, 76 no longer have active leases (red dots in Figure 8) and are considered here for the development of cobalt harvesting systems.

The 76 platforms considered represent a total available water depth of 12.7 km, resulting in space for about 0.85 million shells and 4.23 thousand tonnes of adsorbent in the case of only 40 lengths around a platform, and about 6.77 million shells and 33.87 thousand tonnes of adsorbent considering 320 lengths are used. From these platforms, 521 and 4,172 tonnes of cobalt could be harvested annually for the 40 length and 320 length design, respectively. Table 3 presents a summary of this analysis.

The ocean harvestable cobalt amounts to 6.1-48.5% (an average of 27.3%) of the reported 8,600 tonnes of US cobalt consumption in 2017 [5] depending on the number of lengths used. With the current spot price of cobalt of about $97/kg [1], the monetary value of the cobalt harvested is approximately $50.5-404.7 million, on average almost $0.67-5.3 million per platform annually. If all 510 platforms (both active and inactive) in the GOM that

Table 3: Total cobalt harvestable from offshore platforms to be decommissioned

2017 US cobalt consumption[5]	8,600 tonnes		
Number of platforms of standard structure in 150m depth[a] [72]	510		
Of these, nonproducing [72]	76		
Platforms to use	Nonproducing		
Total water depth available for mineral harvesting	12.7 km		
Number of lengths[b]	40	320	lengths
Total harvesting length	508	4,064	km
Shell diameter	0.5 m		
Spacing between shells	0.1 m		
Total number of shells	0.85	6.77	million
Amount of adsorbent per shell[c]	5 kg		
Total amount of adsorbent	4.23	33.87	thousand tonnes
Cobalt adsorbent saturation time[d]	20 days		
Adsorption capacity[d]	10 g/kg adsorbent		
Desorption efficiency[e]	90 %		
Harvester uptime	75 %		
Total cobalt harvested annually	521	4,172	tonnes
% of US 2017 consumption	6.1	48.5	%
Cost of cobalt today[1][f]	$ 97/kg		
Monetary value of cobalt harvested	$ 50.5	$ 404.7	million
Cobalt require per Tesla Model 3 battery[7]	4.5 kg		
Number of Model 3 batteries producible from harvested cobalt	116	927	thousand batteries

[a] Standard structure refer to the types detailed in Figure 6.

[b] 40 lengths is based on the SMORE design of a symbiotic floating offshore wind turbine spar and uranium harvester [74]. This is considered an extremely conservative estimate since offshore oil platforms are much bigger and therefore afford more space for mineral harvesting than offshore wind turbines. 320 lengths is taken to be an upper bound.

[c] Conservative estimate based on the results of research on using adsorbent shell enclosures for uranium harvesting devices [73].

[d] Estimate based on cobalt adsorbent research summarized in Table 2.

[e] Estimate based on results from [35].

[f] Shanghai spot price, correct as of March 6, 2018 [1].

have standard structures and are in 150 m of water depth or more were retrofitted in this way, over 5,001-40,011 tonnes of cobalt could be harvested annually, or 58.2-465.2% of US consumption in 2017 and about 4.5-36.4% of the world's cobalt production in 2017. Such a field represents a monetary value of \$0.49-3.88 billion annually (Table 4).

There is an economic pull to develop this resource: Elon Musk has promised to produce an ambitious 500,000 Tesla Model 3 EVs in 2018 alone. According to [7], each Model 3 battery requires 4.5 kg of cobalt. If the supply of cobalt for Tesla's Gigafactory were assured, many positive ripple effects would result. Retrofitting these 76 platforms would provide enough cobalt to produce 16-927 thousand Model 3 batteries, or from about 0.23-1.85 times those to be manufactured in 2018. A farm of 510 platforms would produce enough cobalt for 1.11-8.89 million Model 3 cars annually.

There are other potential positive ripple effects for local communities in the Gulf: utilizing offshore platforms that are no longer used for hydrocarbon production means that they do not have to be removed (yet), which results in more value for their owners. The shells that enclose the cobalt adsorbing material and the backbone of the cobalt adsorbent can be made from plastic such as high-density polyethylene (HDPE), which is a widely recycled plastic, but in need of a simple application where blemishes and color variability do not matter. A substantial amount of recycled plastic could be utilized by a NO OUCH system. Table 5 summarizes the results for the case retrofitting all decommissioned platforms (76) as well as the case in which all platforms (510) in the Gulf of Mexico that are of standard

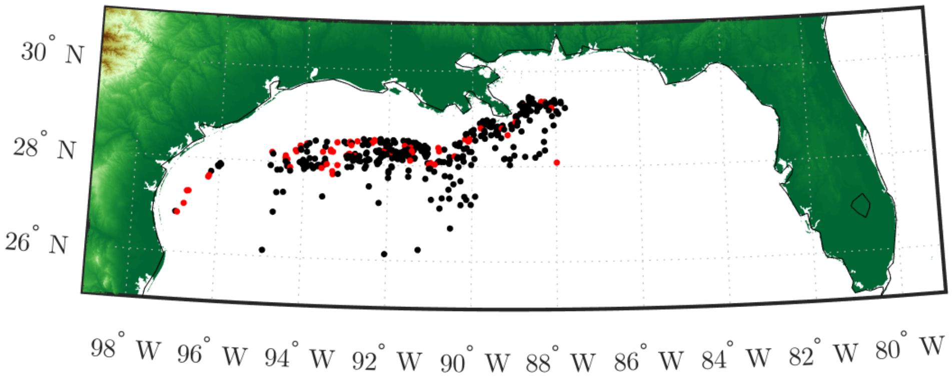

Figure 8: Offshore oil platforms with active (black dots) and inactive or expired (red dots) leases with structures amenable to cobalt harvesting (as defined in this study) in the GOM in water depths of 150 m or greater. Data from [72].

Table 4: Total cobalt harvestable from all offshore platforms

2017 US cobalt consumption[5]	8,600 tonnes		
Number of platforms of standard structure in 150m depth[a] [72]	510		
Total water depth available for mineral harvesting	121.8 km		
Number of lengths[b]	40	320	lengths
Total harvesting length	4,872	38,967	km
Shell diameter	0.5 m		
Spacing between shells	0.1 m		
Total number of shells	8.12	64.96	million
Amount of adsorbent per shell[c]	5 kg		
Total amount of adsorbent	40.60	324.80	thousand tonnes
Cobalt adsorbent saturation time[d]	20 days		
Adsorption capacity[d]	10 g/kg adsorbent		
Desorption efficiency[e]	90 %		
Harvester uptime	75 %		
Total cobalt harvested annually	5,001	40,011	tonnes
% of US 2017 consumption	58.2	465.2	%
Cost of cobalt today[1][f]	$ 97/kg		
Monetary value of cobalt harvested	$ 0.49	$ 3.88	billion
Cobalt require per Tesla Model 3 battery[7]	4.5 kg		
Number of Model 3 batteries producible from harvested cobalt	1.11	8.89	million

[a] Standard structure refer to the types detailed in Figure 6.

[b] 40 lengths is based on the SMORE design of a symbiotic floating offshore wind turbine spar and uranium harvester [74]. This is considered an extremely conservative estimate since offshore oil platforms are much bigger and therefore afford more space for mineral harvesting than offshore wind turbines. 320 lengths is taken to be an upper bound.

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[e] Estimate based on results from [35].

[f] Shanghai spot price, correct as of March 6, 2018 [1].

structure and in 150 m or greater of water depth. As can be seen from the results, a sizable portion of the HDPE plastic bottles recycled in the US could be utilized by NO OUCH systems. Given the apparent all-around win for such a system, these and other aspects of a NO OUCH infrastructure need to be modeled to understand their full economic and environmental impact.

Table 5: Total recycled plastic utilized by a NO OUCH system

Platforms used	Decommissioned			All	
Number of platforms	76			510	
Shell enclosure diameter	500 mm				
Shell enclosure thickness	6 mm				
Shell openness % due to holes	50 %				
Total harvesting length[a]	508	4,064	4,872	38,796	km
Total plastic volume for shells	7,884	63,074	75,615	604,916	m^3
Plastic density[b]	970 kg/m^3				
Plastic required for shells	7,650	61,180	73,350	586,770	tonnes
Plastic to adsorbent mass ratio[c]	0.29				
Plastic required for adsorbent	1,230	9,820	11,770	94,190	tonnes
Plastic used by NO OUCH	8,880	71,000	85,120	680,960	tonnes
Plastic bottles collected for recycling in 2016[d]	504,440 tonnes				
% of plastic collected utilized by NO OUCH	1.76	14.08	16.87	134.99	%

[a] From Table 3 for decommissioned platforms and Table 4 for all platforms.

[b] Density of HDPE. Adsorbent base could likely be made out of polyethylene or polypropylene.

[c] As used in analysis by [20] for uranium adsorbent.

[d] Results from [78] for HDPE plastic bottles recycled.

6. Conclusion

Cobalt supply is one of the largest risks to massive scaling of lithium-ion battery production. In order for batteries to keep pace with demand, new, stable sources of cobalt will need to realized. As with many REE, cobalt exists in greater abundance in the ocean than on land. Adsorbents developed for the removal of cobalt from waste water streams show great promise for use in extracting cobalt from seawater. Furthermore, the GOM presents a unique opportunity for the development of ocean cobalt extraction given its concentration of cobalt is one of the highest worldwide and existing offshore oil platforms in the region could be readily retrofitted with harvesting systems to yield significant positive results.

Adapting technology developed for the extraction of uranium from seawater, this study showed that conservative estimates for extractable cobalt from the region utilizing only decommissioned oil platforms could result in the extraction of almost 521 tonnes of cobalt annually, or about 6.1% of the US's reported cobalt consumption in 2017 with more ambitions designs yielding 4,172 tonnes of cobalt annually, or about 48.5% of the US's reported 2017 consumption. Perhaps most impactful is that such installations would provide enough cobalt to produce 116-927 thousand Tesla Model 3 batteries, or 0.23-1.85 times those to be manufactured in 2018.

Further work needs to be done to develop a cost estimate for extraction of cobalt from seawater using symbiotic systems. As an example, extraction of uranium from seawater has relied on a long history of study by a consortium led by Oak Ridge National Laboratory and Pacific Northwest National Labs. Detailed cost models developed have shown that the primary components of seawater uranium production are adsorbent synthesis and ocean deployment of the adsorbent. Symbiotic deployment strategies have been shown to decrease seawater production costs by 30% [20, 19], leaving the adsorbent synthesis as the primary driving factor of cost. With an adsorbent with a uranium uptake of 4.6 g/kg adsorbent, the uranium production cost from a symbiotic deployment scheme was found to be ca. $300/kg U, which is promising as it is cost competitive with breeder reactors [20, 19]. The methods developed used to create the uranium production cost model could be leveraged to develop a cobalt cost model. Given that a myraid of adsorbents already exist for passive cobalt extraction, it is likely that production of cobalt from seawater via a symbiotic system may also yield favorable economics. Encouraging as this may seem, it warrants detailed further study of cobalt adsorbents, eluates, and costs.

Alternatives to lithium-ion batteries with reduced cobalt requirements as well as lithium-ion battery recycling for increased supply of cobalt should be continued topics of research and development with the aim of avoiding cobalt shortages. In parallel with these efforts, however, we suggest that more selective chemical adsorbents for the passive extraction of cobalt from seawater should be the topic of future research as one or the other or both may be critical for the full electrification of the automotive fleet.

The New Offshore Opportunity for Underwater Cobalt Harvesting (NO OUCH) presented in this paper has the potential to reduce supply vulnerabilities related to cobalt for lithium-ion batteries and help ensure a future of reduced carbon emissions through the expanded use of EVs and renewable power generation systems. The China Sea and Indian Ocean offer similar warm water opportunities as the GOM. By locating cobalt harvesting systems along these coasts, most of the world's population would have ready access to critical elements for electric batteries, thereby perhaps avoiding conflicts and achieving rapid electrification of transportation while pursing large scale battery energy storage for the stabilization of renewable energy-based grids.

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