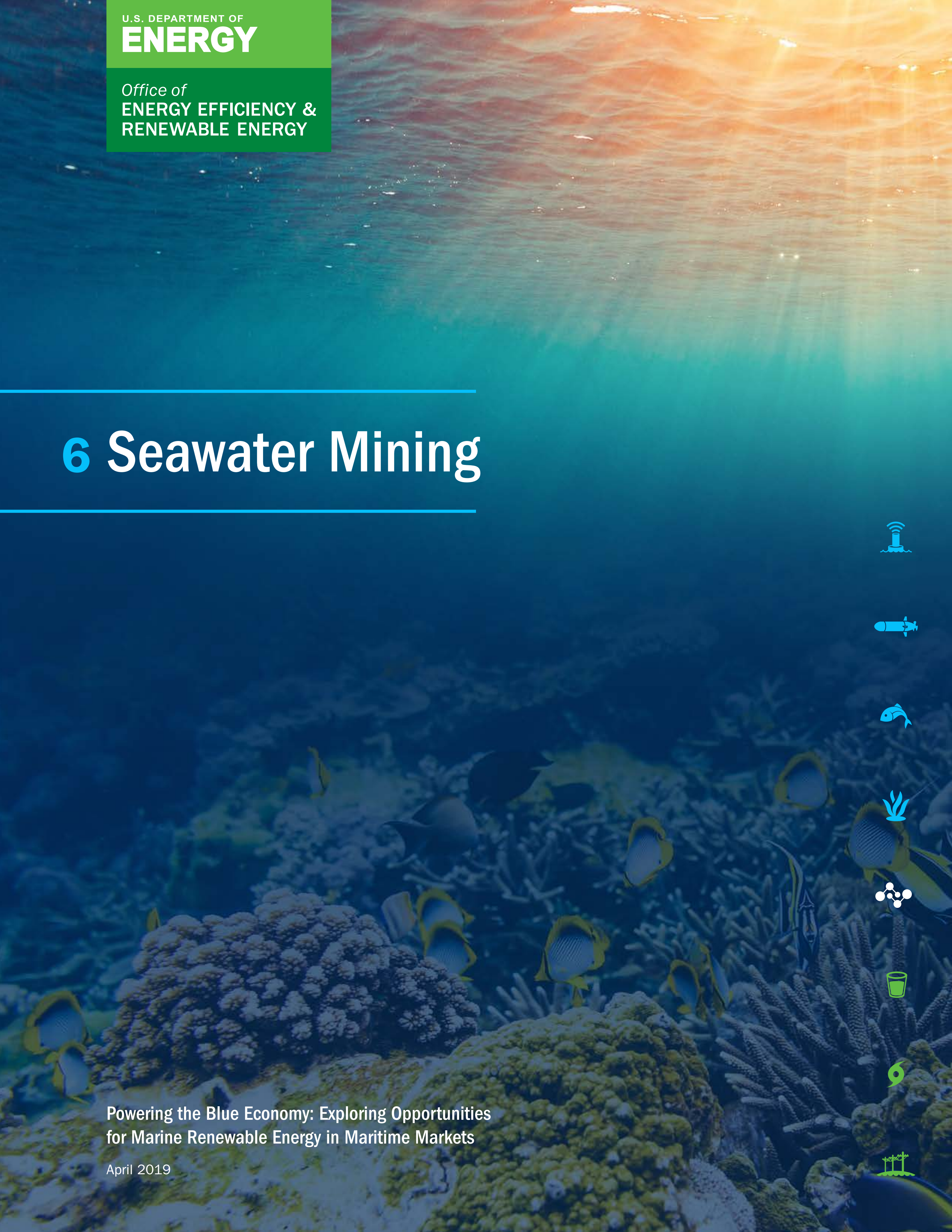

U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

6 Seawater Mining

Powering the Blue Economy: Exploring Opportunities
for Marine Renewable Energy in Maritime Markets

April 2019

6. Mining Seawater Minerals and Gasses

Key Findings

- Seawater contains large amounts of minerals, dissolved gases, and specific organic molecules that are more evenly distributed, albeit at lower concentrations, than in terrestrial locations. Lithium and uranium extraction are two of the more valuable materials under investigation.

- Passive adsorption, and to a lesser extent electrochemical processes, are two different methods to extract elements and minerals directly from seawater. Several gases (e.g., carbon dioxide, hydrogen, and oxygen) can be electrolytically produced directly from seawater. Most systems are in early stages of development, but a strong market demand exists for many of the end products.

- Power required for each method varies. Potential uses for power will be to assist in deploying and retrieving long adsorbent films, extracting elements via electrochemical mechanisms or electrolysis, pumping seawater, powering safety and monitoring equipment, as well as potentially powering the machinery or technology needed to remove elements from adsorbent material.

- Marine energy could open up unexploited opportunities in seawater mining, which could further expand mineral and gas markets. It is believed that linking a marine energy converter to a seawater mineral extraction technology could substantially enhance or enable the extraction process because of colocation benefits and greater power generation potential than other renewable technologies.

- By linking a seawater extraction technology to a local power source, a significant reduction in the overall costs to extract materials from seawater could be achieved.

Opportunity Summary

Seawater contains large amounts of minerals, dissolved gases, and specific organic molecules. Some of the most valuable minerals include the 17 rare earth elements (REEs), precious metals, lithium, and uranium. Although land-based minerals are concentrated in specific geologic formations and geographic areas, seawater minerals are generally distributed evenly in seawater with some higher concentrations near continents as a result of terrestrial runoff and interaction with margin sediments. Minerals can be recovered from seawater using adsorption methods that do not require filtering vast amounts of seawater, while recovering other elements and compounds can require more energy-intensive processes.

Extracting minerals from seawater is a more environmentally friendly enterprise than terrestrial mining (Diallo et al. 2015; Parker et al. 2018). Moreover, seawater extraction will not require fresh water for processing nor create volumes of contaminated water and tailings for disposal. Most REEs, as well as uranium and other minerals used in the United States, are imported from other nations, which raises supply chain concerns for both industry and national security. Dissolved gases like hydrogen can become important sources of energy storage and will be used in the future for maritime transportation. Critical materials are needed for many modern-day technologies, such as wind turbines, solar panels, and electric vehicles.

An energy source is needed to extract minerals or dissolved gases, preferably one that is locally generated, reasonably consistent, and that does not add to the complexity or maintenance needs of the extraction operation. Marine energy power harvested at sea has the potential to meet seawater mining needs to power an electrolyzer, perform electrochemical extraction, mechanically drive an active adsorbent exposure system, and power on-site logistical needs (Figure 6.1).

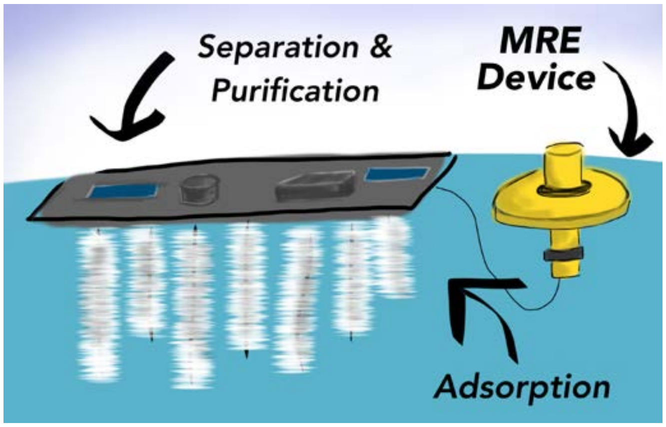

Figure 6.1. Marine energy application overview for mining seawater. *Image courtesy of Molly Grear, Pacific Northwest National Laboratory*

Application

Description of Application

The United States is import-reliant (imports are greater than 50% of annual consumption) for 31 of the 35 minerals designated as critical by the U.S. Department of the Interior (2018). The United States does not have any domestic production and relies completely on imports to supply its demand for 14 critical minerals (Diallo et al. 2015; U.S. Geological Survey 2018). Currently, China and Canada are the top two suppliers of critical minerals to the United States. In response to this concern, the U.S. government has published a list of critical minerals for the nation (Executive Order 13817). This reliance on foreign supply constitutes an industrial and national security concern (Congressional Research Services 2017). Development of a domestic source of critically needed materials from seawater would directly address the resource need and mitigate industrial and national security supply concerns.

The total mass of many of the critically needed elements is far greater in seawater than in the Earth's crust, including the 17 REEs and several dissolved gases. Although land-based minerals are concentrated in specific geologic and geographic areas, many seawater minerals are generally distributed evenly in seawater. Exceptions include elevated concentration of some elements (e.g., zinc, cadmium, copper, nickel, cobalt, and some REEs) below 500 meters (m), which is caused by an uptake of biologically required elements during primary production processes in surface waters and input from deep-sea hydrothermal vents. Many elements are also elevated near the ocean margins from riverine runoff or interactions between seawater and margin sediments.

Some of these REEs could be extracted from seawater by passive adsorption or electrolysis, decreasing dependence on foreign suppliers and improving industrial supply chain resiliency. Ammonia and hydrogen are other potential products that could be produced from a freshwater or seawater source using renewable marine energy (European Marine Energy Center [EMEC] 2017a) and can be used as an energy storage medium. Producing gases (e.g., hydrogen, carbon dioxide, and oxygen) directly from a seawater source using marine renewable energy to power an electrochemical production process may be possible in the future as well. The need to move away from high carbon fuels for commercial shipping is imminent with the announcement of the International Maritime Organization's requirements that all international shipping reduce sulphur emissions from fuel oil (International Maritime Organization 2018). Recent work for the U.S. Maritime Administration is examining the use of hydrogen fuel cells for ferries and other maritime uses (Pratt and Klebanoff 2018).

Power will be needed for harvesting minerals from seawater, deploying and retrieving long adsorbent films, extracting elements via electrochemical mechanisms or electrolysis, and powering safety and monitoring equipment, as well as potentially powering the machinery or technology needed to remove elements from adsorbent material. Existing seawater extraction technologies are mostly in the research and development stage, but look promising for colocation and pairing with offshore energy technologies.

To extract elements in low concentrations from seawater requires processing large volumes of water, which can be energy-intensive and potentially cost-prohibitive (Bardi 2010). The most economical approaches to date are those that use passive adsorption technology, thereby avoiding the energy needed to process or pump large volumes of seawater (Kim et al. 2013; Diallo et al. 2015). In a passive extraction system, the natural ocean currents deliver fresh seawater to the adsorbent for extraction of the elements of interest. Typical passive adsorbent systems are envisioned as farms resembling a kelp forest that are deployed and retrieved by a work vessel (Figure 6.2).

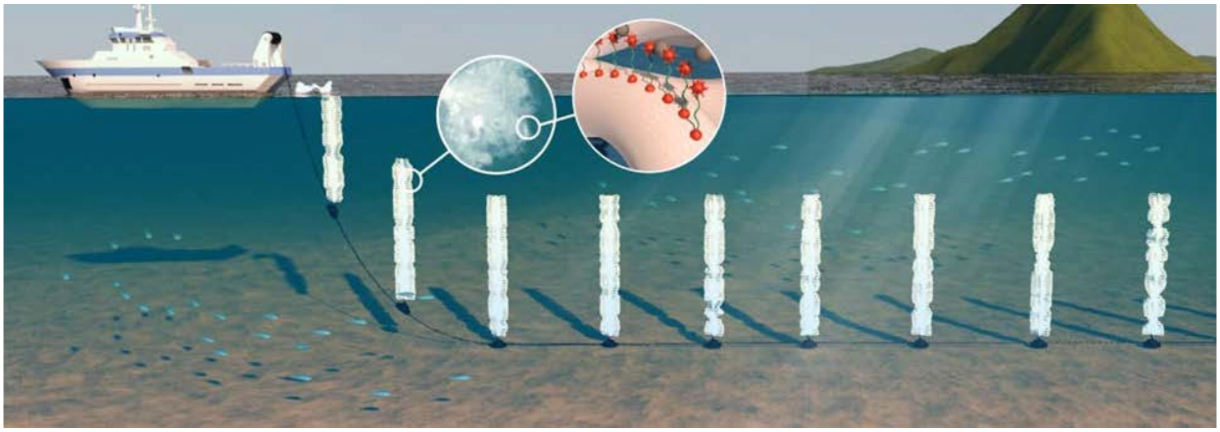

Figure 6.2. Conceptual deployment of amidoxime-based polymer adsorbent in coastal seawater for the passive extraction of uranium and other elements from seawater. *Source: Byers et al. (2018b)*

The cost of performing the extraction process can be reduced by linking the extraction technology to an on-site power source, such as marine renewable energy. Three examples of how a local marine power source could be linked to a seawater mineral extraction scheme are described. These applications focus primarily on uranium extraction, as this is the technology that has been investigated the most, but the approach could also be applied to a broad suite of other elements, including cobalt (Haji and Slocum 2018).

Power Requirements

Extraction of minerals from seawater requires power to operate mechanical adsorbent exposure mechanisms, pump seawater, and operate the electrochemical cell in electrochemical extraction systems. As no commercial or pilot operations are currently in use, any power requirement assessments are currently based on laboratory-scale operations, as explained in this section, for several processes under development. A variety of systems and subsystems could use marine energy power, including electricity (Table 6.1).

Intermittency of power is acceptable for the extraction of minerals and gases from seawater for periods of time of a few days. For both electrochemical and passive recovery processes, the collection simply ceases during a power loss, and the collection technology is not impaired, allowing operations to slow down or cease. Storage backup can help to maintain adequate power for essential parts of at-sea systems like navigation lights and safety gear.

Table 6.1. Systems and Processes Likely To Require Power To Extract Elements and Dissolved Gases from Seawater, and the Relevant Techniques under Development

System	Energy Process	Type of Seawater Extraction or Material Usage
Passive extraction process	Electrifying adsorbent materials	Extraction of uranium from seawater using electrochemically enhanced adsorbent approaches
	Electrolysis and electrochemistry	Direct electrochemical extraction of lithium from seawater; extraction of dissolved gases via electrolysis
Mechanical movement of adsorbent materials	Movement of belts or roller chains into and out of seawater and into and out of extraction baths	Mechanically driven adsorbent exposure system
Surface infrastructure and anchoring systems	Floating dynamic positioning systems without vessels needed for deployment or anchoring	Mechanically driven seawater extraction system
Production of dissolved gases	Electrolyzers to separate hydrogen and oxygen from seawater	Energy storage through hydrogen production; hydrogen-powered propulsion systems
	Electrolytic cation exchange process	Synthetic fuel production

Electrochemical Adsorption of Uranium from Seawater

Liu et al. (2017) describe a process that enhances the ability of amidoxime-based[12] adsorbent materials used to extract uranium from seawater through an electrochemical process (Figure 6.3). Compared to simple passive adsorption processes, applying an electrical field to the adsorption material improves the rate and capacity of the adsorption process (a four-fold and three-fold increase, respectively), while also helping to avoid adsorption of unwanted elements.

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[12] The amidoxime functional group, $-C(NH_2)=N-OH$, has a high affinity for sequestering uranium from a solution.

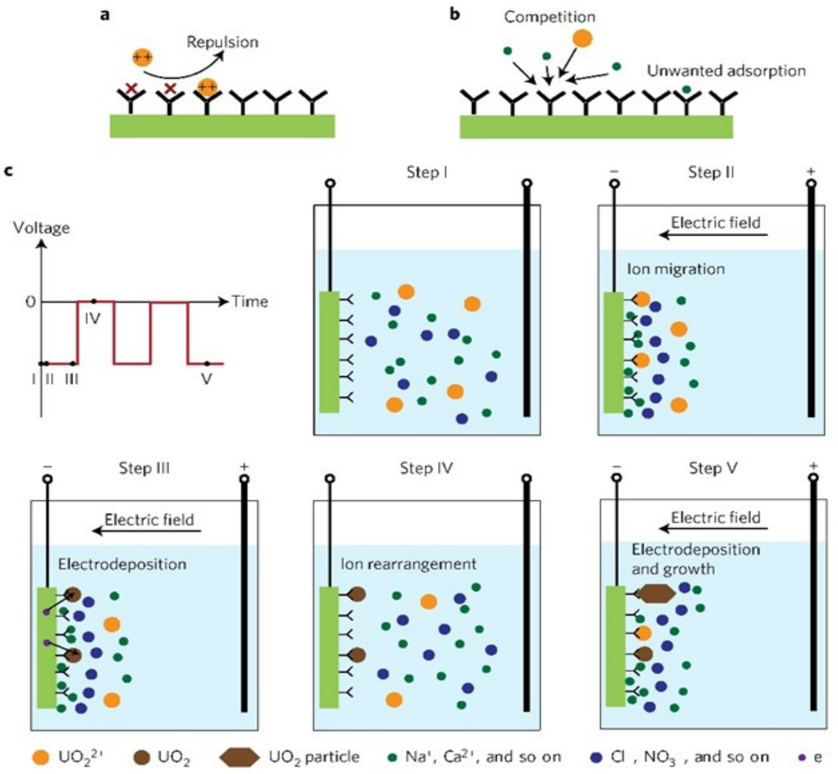


Figure 6.3. Schematics of physicochemical and half-wave rectified alternating-current electrochemical extraction.

Source: Liu et al. (2017)

A Mechanically Driven Seawater Extraction System

A potentially significant reduction in the cost to extract elements from seawater can be achieved by using power generated at sea from a marine energy device. Power is needed to extract elements by a mechanically driven system that will expose the adsorbent material to seawater, return it to the surface platform, and allow for extraction of the elements through a solvent bath. This approach achieves cost reductions by eliminating the work vessels needed to anchor the structures to the seabed and the transport vessels needed to continually deploy and retrieve the adsorbents.

Illustrated in Figure 6.4 is a symbiotic system described by Picard et al. (2014) for the extraction of uranium from seawater. The extraction system consists of a continuous belt of adsorbent material 4,000 m in length. The adsorptive belts containing uranium pass through solutions to extract the uranium from the adsorbent, then they are reconditioned in another solution and returned to the sea for another cycle of adsorption. This system was designed to harvest 1.2 tons of uranium per year, enough to power a small (~5-megawatt) nuclear plant.

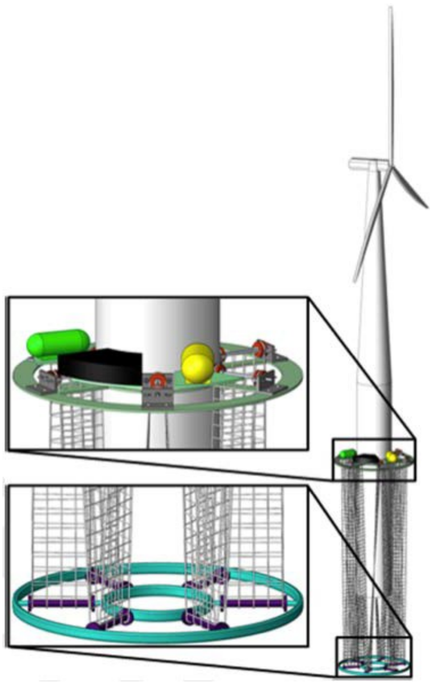


Figure 6.4. A conceptual model of a continuous seawater adsorbent extraction and elution system for the extraction of uranium from seawater integrated into an offshore wind platform providing the power to drive the system.
Image from Picard et al. (2014)

The costs for the extraction of uranium from seawater using the passive adsorption process (kelp) and the symbiotic system described by Picard et al. (2014) (see Figures 6.4 and 6.5) predicted that by linking the seawater extraction system to a local power source, a significant reduction in the overall costs to extract uranium from seawater could be achieved (Byers et al. 2016, 2018a).

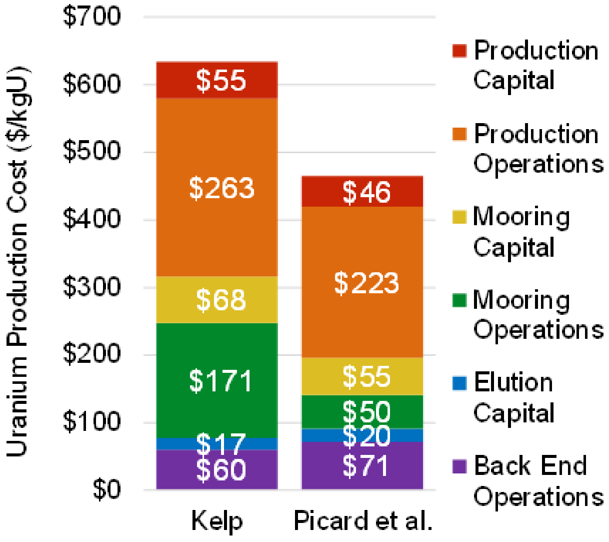


Figure 6.5. Comparison of the costs to extract uranium from seawater using a passive adsorption technology (Kelp) and a continuous adsorbent belt system attached to an offshore wind platform providing infrastructure support and power (Picard et al. 2014). *Image courtesy of Margaret Byers, University of Texas at Austin*

Haji et al. (2017a, 2017b) built on the previous systems described by Picard et al. (2014), Haji and Slocum (2016), and Haji et al. (2016) to design a mechanical exposure system they call Symbiotic Machine for Ocean uRanium Extraction (SMORE) that uses adsorbent shells that are incrementally spaced along a continuous moving roller chain (Figure 6.6). A 1/10 scale model of this concept is depicted in Figure 6.6.

Figure 6.6. Adsorbent material encapsulating a protective sphere (left), and symbiotic machine for ocean uranium extraction (right). *Source: Haji et al. (2017a)*

Figure 6.7 compares the production cost to extract uranium from seawater by passive adsorption (kelp) and the SMORE system described by Haji et al. (2017a, 2017b). Incorporating a SMORE system using on-site power results in a 31% reduction in the production costs to extract uranium from seawater.

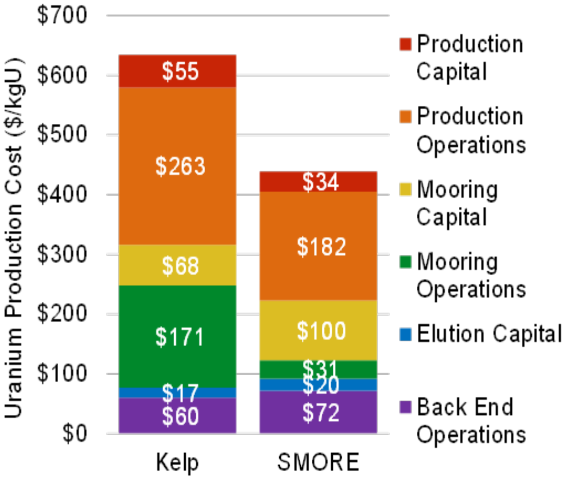


Figure 6.7. Comparison of the production costs to extract uranium from seawater by passive adsorption (Kelp) and the SMORE system. *From Haji et al. (2017a)*

Another concept for operating an on-site seawater extraction system is depicted in Figure 6.8 (Chouyyok et al. 2016), using a free-floating structure. This system is similar to the previous conceptual system in which the adsorbent material is incorporated into a fabric-type belt that rotates into the sea for exposure and then returns to the surface where it passes through tanks containing solutions to strip off the uranium. Marine-energy-derived power could be used to drive the belt, deploying the adsorbent material into the water from one end of the barge, move it slowly through the water under the barge, retrieve the belt at the other end of he barge, move the adsorbent material on the belt through extraction bathes on deck, then continue the movement to redeploy the belt and adsorbent materials overboard again.

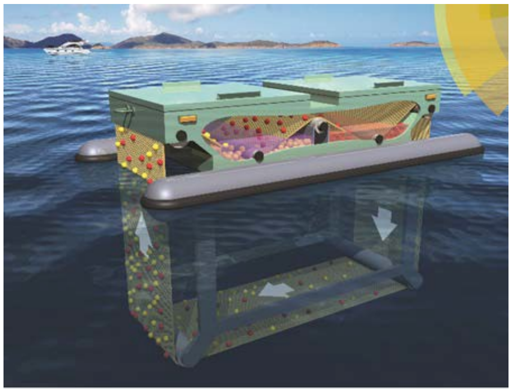


Figure 6.8. Conceptual process for the continuous collection of uranium from seawater using high-performance thin-film adsorbents coated onto a flexible woven belt structure. *Source: Chouyyok et al. (2016)*

Direct Electrochemical Extraction

A promising, but yet unproven, technology for the extraction of elements directly from seawater is electrochemical extraction (Figure 6.9). Any element that has multiple reduction-oxidation states can potentially be extracted from aqueous solutions, such as seawater, using more traditional electrochemical approaches. Pacific Northwest National Laboratory is currently developing a laboratory-scale system to demonstrate the technology.

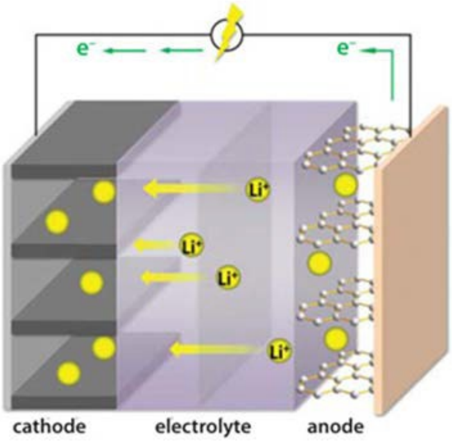


Figure 6.9. An electrochemical cell for the direct extraction of lithium ions from seawater. The cell is based on lithium-ion battery technology that has a high selectivity for lithium ions. *Source: Used with permission from Kam and Doeff (2012)*

Extraction of Lithium from Seawater

The abundance of lithium in seawater (178 µg/L) is at least 1–2 orders of magnitude higher than most critical elements and has a total mass 17,800 times more than terrestrial reserves (Diallo et al. 2015). The abundance of lithium in seawater could be recoverable, and current estimates of terrestrial lithium reserves could last 371 years, based on current demand projected into the future (Diallo et al. 2015). A preliminary analysis by Dr. Erich Schneider at the University of Texas at Austin has concluded that mining seawater for lithium is feasible from a cost perspective (E. Schneider, personal communication, November 2017). A more comprehensive cost analysis is warranted to assess the potential of mining seawater for lithium.

Production of Gases

Several gases (e.g., carbon dioxide, hydrogen, and oxygen) can be electrolytically produced directly from seawater. A current application of this technology is for production of carbon dioxide and hydrogen as precursors to synthetic fuel production. This same technology could likely be applied to the production of hydrogen as a means of energy storage as well.

Energy Storage Through Hydrogen Production

The European Marine Energy Center is producing hydrogen gas as a means to store unused renewable energy produced from tidal and wind energy (EMEC 2017b). The hydrogen gas is being produced in the outer Orkney islands, off the northeast coast of Scotland, by 500- to 1,000-kilowatt (kW) solid oxide fuel cells—or electrolyzer, for short—that runs in regenerative mode to achieve electrolysis of fresh water and produce both hydrogen and oxygen (Figure 6.10). The hydrogen is transported to the main Orkney island for use in the intraisland ferry system and land transport. The hydrogen is compressed and transported to a fuel cell where it is converted back to electricity for local use. The electrolyzers used by EMEC to generate hydrogen and oxygen are 500- and 1,000-kW units, which can produce approximately 2,400 and 4,800 m^3 of hydrogen per day (200 to 400 kg/d). There are units on the market that range from tens of kilowatts to 1,000-kW stand-alone units to multiunit systems that are greater than 10,000 kW. The typical energy needs of electrolyzer units are around 5 kilowatt-hours per m^3 of hydrogen. Because the hydrogen is produced from a renewable energy source, it is a clean fuel, with no carbon emissions. EMEC is currently exploring a use for the oxygen that is also produced from this process. Applications of this type are most suitable for islands and island communities as well as remote locations where the cost of power is high and there are often remote areas requiring energy.

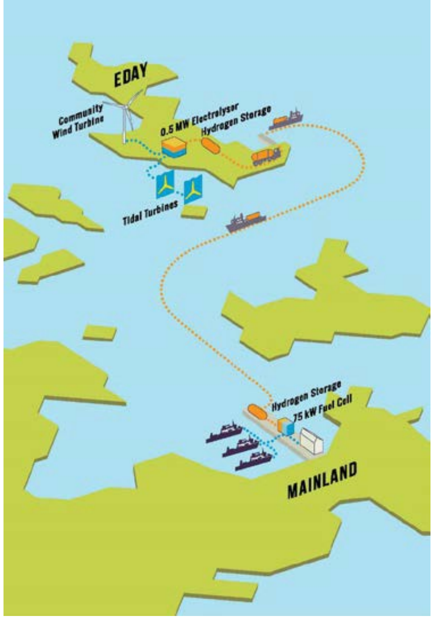


Figure 6.10. Schematic of production, transport, and storage of hydrogen gas from renewable generation for use in fuel cells at EMEC in Orkney, United Kingdom. *Source: Surf 'n' Turf, European Marine Energy Center*

Synthetic Fuel Production

The U.S. Naval Research Laboratory has developed technology for extraction of carbon dioxide gas and hydrogen gas directly from seawater using an electrolytic cation exchange process (Willauer et al. 2017; U.S. Naval Research Laboratory 2016, 2017, 2018). The U.S. Navy has an interest in using these gases as precursors to synthetic fuel production (Willauer et al. 2012). The conversion of carbon dioxide and hydrogen to synthetic fuels is accomplished through a thermochemical conversion process using a catalyst (Dorner et al. 2011; Bradley et al. 2017). The ability to produce synthetic fuels at sea can offer significant logistical and operational advantages to the Navy by reducing its exposure to market volatility and its dependency on at-sea resupply. Key operational parameters for the production of synthetic jet fuel are given in Figure 6.11.

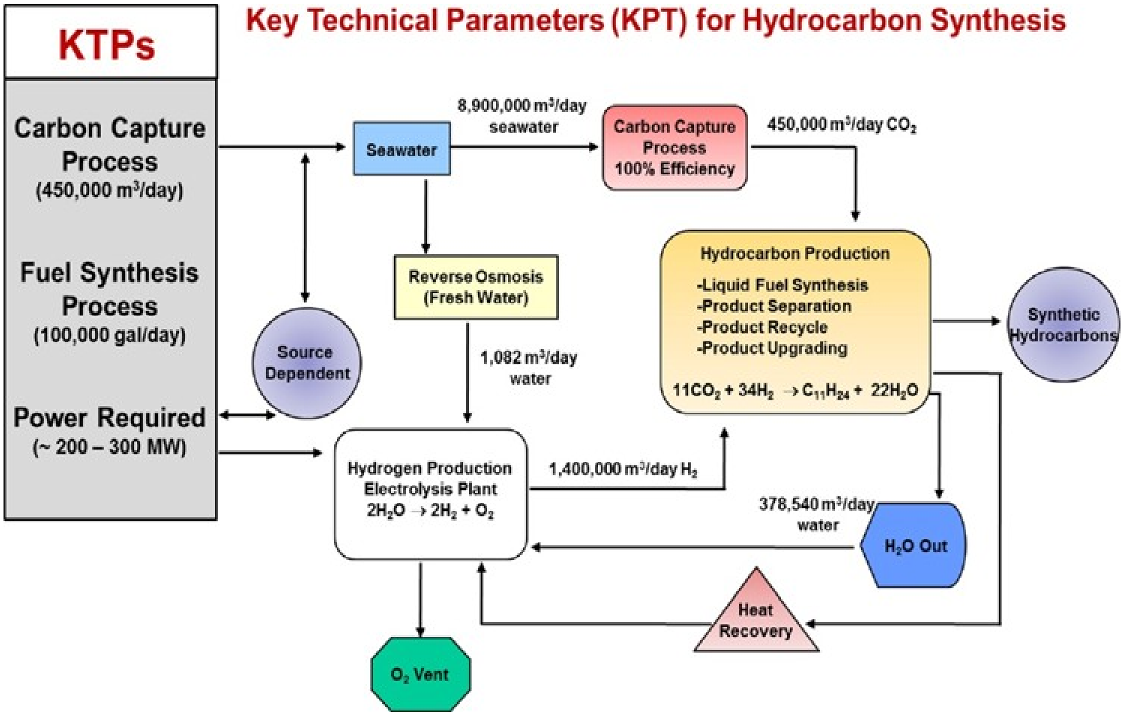


Figure 6.11. Operational parameters for the synthesis of 100,000 gallons of jet fuel per day.
Reproduced from Willauer et al. (2012), with permission of AIP Publishing

This technology has the potential to mitigate the effects of carbon-dioxide emissions from burning fossil fuels because the carbon source for the production of the fuel and other energy-rich molecules is seawater. Moreover, by not burning fossil-derived fuel, harmful emissions of sulfur and nitrogen compounds are also mitigated. The process becomes completely carbon-dioxide neutral if the power required to drive the process (200–300 megawatts) also comes from a renewable energy source.

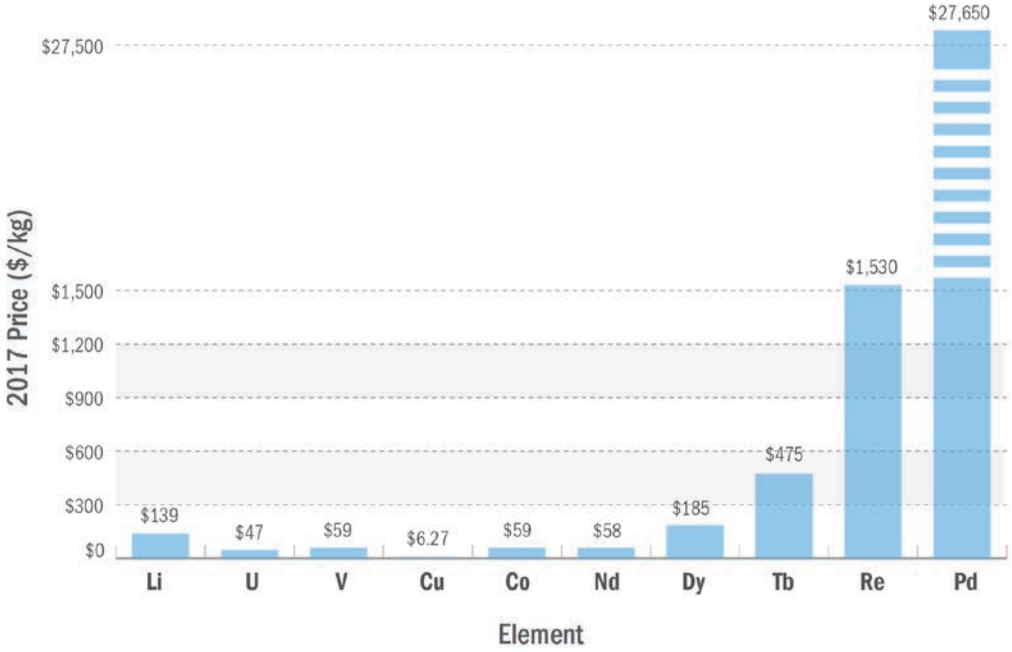
Markets

Description of Markets

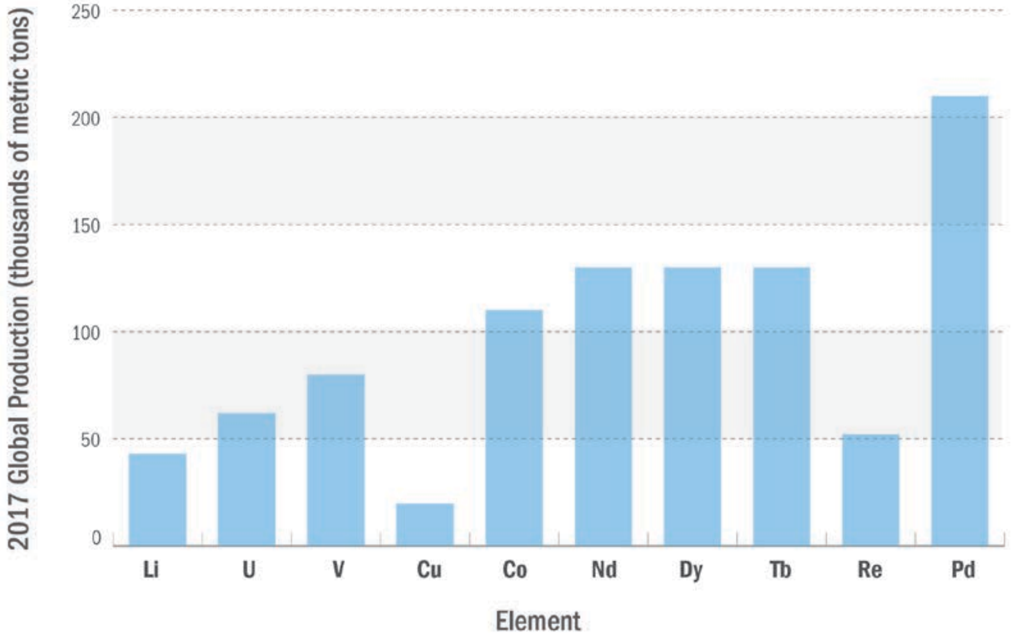
Critical minerals are often defined as those mineral resources that are essential to the nation's economy or for national defense purposes, and for which there is potential for supply disruptions. The target elements are those needed for development and deployment of clean energy technology (U.S. Department of Energy [DOE] 2011), advanced military applications (U.S. Department of Defense 2015), and essential civilian and industrial uses. Of particular importance are those elements in which the United States does not have significant domestic resources, or that possess a significant risk of supply disruption. Elements that are considered critical include the REEs (e.g., neodymium, dysprosium, europium, yttrium, and terbium), lithium, tellurium, gallium, and indium.

In 2016, the market for REEs was 155,000 tons, dominated by China, whereas U.S. consumption was 20,000 tons (Massachusetts Institute of Technology 2017). The current global market for REEs is estimated to be $10 billion and is growing at an estimated compound annual growth rate of 6%. The global market is estimated to be roughly $20 billion by 2030 (Mordor Intelligence 2018). The global uranium market is relatively saturated at the moment because of reduced build-out of nuclear power plants but is expected to recover over the next decade as a result of increased power needs in the United States and internationally. Global demand for uranium is currently 67,000 tons per year, or about $8.7 billion (World Nuclear News 2017).

As an example, if initially 10% of the present worldwide market for minerals could be extracted from seawater, the markets would be substantial (see Figure 6.12a, b, and c), ranging from $123 million for copper to as much as $5.8 trillion for the precious metal palladium (Figure 6.12c).



(a)



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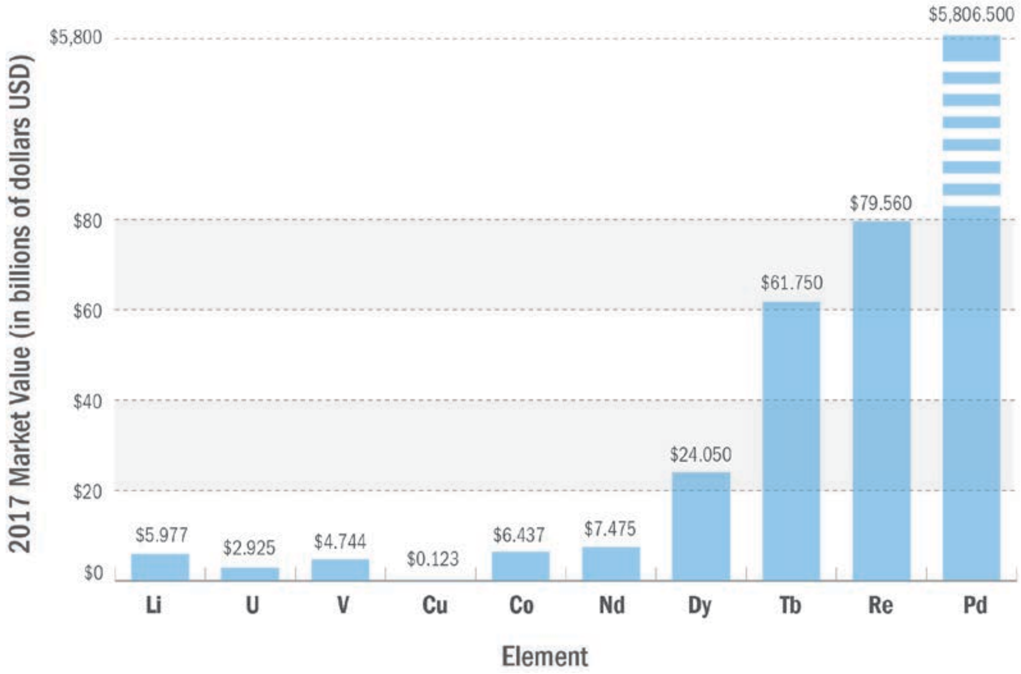

(c)

Figure 6.12. Estimates of global markets for 10 key elements that could be extracted from seawater. Figure 6.12a shows the 2017 market price for 10 elements; Figure 6.12b provides the 2017 global production of the 10 elements; and Figure 6.12c shows the potential market value of the 10 key elements, based on 2017 market prices (Figure 6.12a), and assuming that 10% of the global production of an element (Figure 6.12b) could be extracted from seawater.

The demand for critical minerals is growing, based on likely future scarcities and security concerns for obtaining minerals, such as uranium, from international sources that may not be readily accessible to the United States. Demand for industrially important minerals, such as lithium and REEs, will continue to grow with increases in consumer and industrial electronic uses, further stressing terrestrial supplies, particularly from nations that are considered to be security risks. The development of lower-cost domestic extraction of minerals from the ocean will make these sources more economically attractive; help alleviate international supply concerns; and relieve permitting, waste disposal, and public opinion concerns for terrestrial mining operations.

As fuel cell technologies improve, the demand for hydrogen as an energy storage and transport medium will increase. Therefore, producing hydrogen from a seawater source will relieve stress on dwindling freshwater resources and provide a cost-effective alternative to traditional extraction sources.

The early stage of processes to extract minerals from seawater could allow the marine energy market to develop in parallel with commercial extraction technologies, providing synergies for both industries. A similar situation exists for the extraction of dissolved gases from seawater, although the market drivers are not scarcity or security concerns as much as cost and potential for introduction of gases into fuel cell and synthetic fuel production pipelines.

Customers

Customers for marine-energy-connected systems for mineral and gas extraction from seawater are broad. Numerous battery manufacturers (e.g., Tesla, NEC, LG Chem, and Panasonic Sanyo) need lithium, cobalt, and nickel for manufacturing lithium-ion batteries to supply companies making electric vehicles and mobile phones. Need for these materials is rising rapidly and traditional supply sources may not meet demand (Shankleman et al. 2017). Extraction of REEs and uranium could attract customers among many of the large international mining and chemical companies, such as MP Mine Operations LLC, Galaxy Resources, Albemarle Corporation, Polymet Mining, Uranium Energy Corporation, and NexGen Energy Ltd.

The U.S. Enrichment Company, a subsidiary of Centrus, is a nuclear fuel enrichment company supplying enriched uranium to the nuclear power industry. In addition, the following companies refine uranium internationally: AREVA (France, United States), China National Nuclear Corporation (China), GE Hitachi Nuclear Energy (Japan, United States), Global Laser Enrichment (United States), Japan Nuclear Fuel Limited (Japan), Tenex (Russia), and URENCO Group (United Kingdom, Germany, Netherlands, United States) (World Nuclear Organization 2018a).

The fuel of the future for cruise liners, ferries, and container ships will likely be hydrogen (van Biert et al. 2016; Tullis 2018; The Marine Executive 2017). Marine energy could supply the power to drive an electrolyzer, to produce hydrogen, oxygen, carbon dioxide, and other potential gases. With the current technology, a freshwater source for electrolysis will be needed, but future technologies may be able to use seawater directly. Domestic and international chemical companies and transport organizations are likely partners for gases, such as hydrogen and ammonia, to power fuel cells or synthesize fuels at land-based operations.

The National Nuclear Security Administration needs a reliable supply of low-enriched uranium for defense purposes. It is unclear if the United States requires highly enriched uranium. There is no current domestic source of low-enriched uranium or highly enriched uranium, but the National Nuclear Security Administration has a stockpile to last until 2038, after which a new plant will be needed for low-enriched uranium production. For defense purposes, the United States can only use uranium that has been enriched by U.S.-origin companies. In addition, there is a stockpile of uranium from decommissioned plants operated by DOE in Oak Ridge, Tennessee; Paducah, Kentucky; and Portsmouth, Ohio (World Nuclear Organization 2018b).

There are no industrial transport companies currently using hydrogen fuel at a commercial scale. There are, however, pilot projects involving towboats, passenger ships, ferries, and short-haul truck routes (Table 6.2) (The Verge 2018).

Table 6.2. Pilot Projects Underway Using Hydrogen as a Transportation Fuel (The Verge 2018)

Project Name	Project Type	Project Partners
RiverCell – Elektra	Towboat	Technical University of Berlin, BEHALA, DNV GL
ZemShip – Alsterwasser	Small passenger ship	Proton Motors, GL, Alster Touristik GmbH, Linde Group
Nemo H2	Small passenger ship	Rederij Lovers
Hornblower Hybrid	Ferry	Hornblower
Hydrogenesis	Small passenger ship	Bristol Boat Trips
MF Vagen	Small passenger ship	CMR Prototech, ARENA-Project
Class 212A/214 Submarines	Submarine	CMR Prototech, ARENA- Project, ThyssenKrupp Marine Systems, Siemens
SF-BREEZE	Passenger ferry	Sandia National Laboratories, Red and White Fleet
Ports of Los Angeles and Long Beach	Short-haul trucks	Ports of Los Angeles and Long Beach, Toyota
United Parcel Service	Short-haul trucks and vans	United Parcel Service, General Motors, City of Sacramento

Power Options

As an on-site power generation source, marine energy could reduce or avoid the need for diesel generators or cabled connections from shore, which are both costly and not portable if the system needs to be relocated. Marine energy could reduce offshore installation operating costs, creating a more economically viable installation.

There are no incumbent power sources for seawater mineral extraction; however, in the future, at-sea operations could be satisfied by diesel generators, wind, solar, or marine power sources. There will be a need for battery backup storage for all renewable sources to smooth generation and provide more reliable power. Warm tropical regions, which are better suited for seawater mineral extraction, would benefit from solar generation. Marine energy could produce power at the seawater extraction site without the need to refuel or risk spills from diesel. Marine energy also has certain advantages over solar and offshore wind for offshore seawater mining operations as low-profile infrastructure is preferred for survivability, removing the detrimental effects of salting of photovoltaic panels and corrosion of wind components, and to reduce visual impacts. Seawater mining operations are likely to be in open water. The marine energy industry is in a unique position to design devices that can accommodate these operations.

Geographic Relevance

There are many opportunities for mining REEs, uranium, lithium, other minerals, and producing gases throughout coastal areas and the open ocean, where sufficient tidal and current resources are present. U.S. wave resources are abundant off the coasts of Hawaii, Alaska, the West Coast, and the Northeast. Moreover, these areas will also have the necessary surface currents to meet the minimum requirements for passive adsorption systems.

Unlike terrestrial sources of elements, the concentration distribution of many elements in the ocean are fairly homogenous. Of course, there are exceptions. Many elements, such as the transition elements and many REEs, exhibit lower concentrations in surface water and are elevated in the deep (greater than 1,000 m) ocean, likely because of emissions from hydrothermal vents and interactions with primary productivity processes.

Concentrations of many minor-to-trace elements tend to be higher near the ocean margins as a result of continental runoff and proximity to margin sediments.

It is unlikely that any seawater extraction technology will occur in the deep ocean (> 1,000 m deep), because of the difficulties of developing technologies that work under extremely high pressure, as well as the added logistic and engineering challenges of operating an extraction system so far from the surface power source and surface support and retrieval system necessary to transport the extracted materials to the surface. Hence, it is reasonable to assume that any seawater extraction operations will be restricted to the upper few hundred meters of the ocean.

Seawater temperature is another factor that can greatly impact some extraction technologies. For example, the adsorption of uranium onto amidoxime-based adsorbents is approximately four-fold higher in 30°C seawater than at 20°C (Kuo et al. 2018). Hence, warmer seawater locations are likely preferable relative to temperate locations for most elements and technologies.

In the United States, preferred locations for passive mineral extraction that coincide with marine energy resources (largely wave resources) include the warmer waters off Hawaii, the Caribbean, and the Pacific islands.

Marine Energy Potential Value Proposition

Marine energy could open up unexploited opportunities in seawater mining, which could further expand mineral and gas markets. Both technologies (seawater mining and marine energy development) are at early technology readiness levels; synergies may exist if the technologies were set to mature simultaneously. Seawater mining would also improve the diversity of the U.S. mineral supply chain, eliminating reliance on any one supplier, and provide a price ceiling on the cost of terrestrially obtained critical materials. Costs for REEs and uranium are likely to be less sensitive to energy costs than other markets and are driven more by security and scarcity concerns.

Linking a marine energy power source to a seawater mineral extraction technology could substantially enhance or enable the extraction process. This can occur through providing power to run a mechanical adsorbent exposure system or enabling the use of an electrochemical extraction process. Similarly, marine energy could enable extraction of dissolved gases from seawater directly through catalytic conversion or through an electrolyzer by providing the power needed to continuously supply a charge across the electrodes. Auxiliary power needs could be satisfied by marine energy, including power for safety, lighting, crew support, and small electric vessels servicing the at-sea installations needed to extract gases.

The extraction of uranium from seawater appears to be the most promising opportunity to link marine energy to seawater mining as an adsorption technology, and a prototype engineering system has been developed to expose the adsorbent to seawater. The exposure system requires a localized power source to drive it. This promising immediate opportunity to link marine energy to seawater mining is likely to coincide with the technology under development by DOE’s Office of Nuclear Energy to extract uranium from seawater. The need to find new sustainable supplies of nuclear fuel is driven by predicted scarcities and elevated costs on land by 2035, with terrestrial supplies expected to be exhausted within 60–100 years (DOE 2010; Hall and Coleman 2013; Red Book 2017).

Extraction of Lithium from Seawater

Lithium could be extracted from seawater through electrolytic processes yet to be developed. In addition, there are fibrous adsorbents currently under development for extracting lithium from natural waters (Nishihama et al. 2011; Chung et al. 2004, 2017; Park et al. 2016). If these adsorbents could be made similar in physical format to those described previously for uranium, they could likely be directly substituted into the active-exposure technology requiring linking to a marine energy device under development for the extraction of uranium from seawater. Alternatively, marine energy could provide the power to actively pump seawater through a flow-through membrane adsorber for recovery of lithium (Park et al. 2016).

Extraction of Multiple Elements with a Common Extraction Technology

The most favorable economic outcome of linking marine energy to the extraction of critical elements from seawater will be realized when the technology is adapted to obtain multiple elements of interest from a common extraction technology.

As noted previously, most adsorption technology is targeted at a given element, but will also retain many other elements if they are present. To illustrate this point, consider the uranium adsorption technology. Figure 6.13 shows the elements that the adsorbent retains after 56 days of exposure in natural seawater. Uranium is the fourth most abundant element retained by this adsorbent in terms of adsorption capacity (g of element/kg adsorbent). Calcium and magnesium are more abundant on the adsorbent than uranium, primarily because their seawater concentrations are six orders of magnitude more concentrated than uranium (Calcium = 416,000 parts per billion [ppb]; magnesium = 1,295,000 ppb; uranium = 3.3 ppb). Note that the adsorbent retains significant amounts of several other elements, including vanadium, copper, nickel, zinc, cobalt, and chromium. The adsorbent also retains REEs at lower relative percentages. Currently, these “nontarget” elements are simply discarded in the uranium extraction process. If the nontarget elements are also of economic value, then the overall cost of obtaining the target element could be reduced. All that would be required is to develop isolation technology to recover the elements of interest from the aqueous solution being discarded from the uranium extraction process. It would be important to explore how much of a cost reduction could be obtained by harvesting the nontarget elements for their economic value.

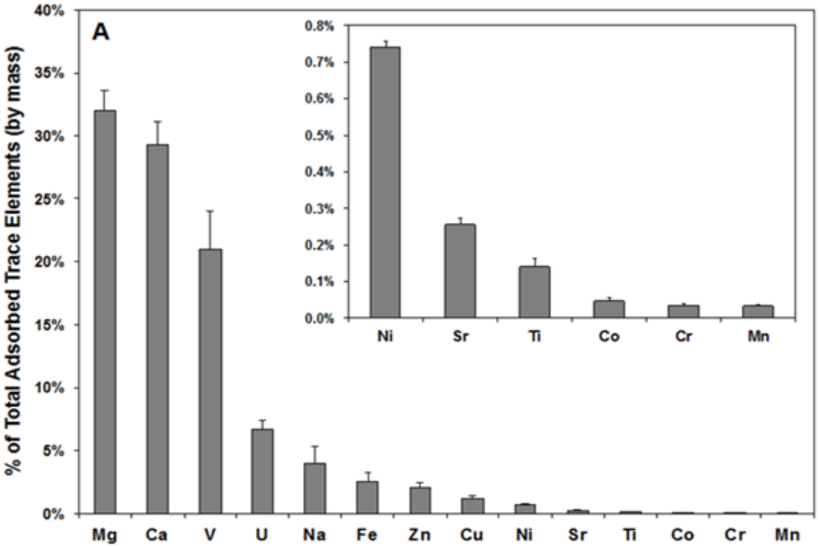

Figure 6.13. Relative abundance of elements absorbed by the Oak Ridge National Laboratory amidoxime-based polymeric uranium adsorbent AF1 after 56 days of seawater exposure. *Figure from Kuo et al. (2016)*

Production of Gases from Seawater

Through electrolysis or catalysis, seawater can serve as a resource for the production of hydrogen, oxygen, and potentially other gases. This process has no location limitations, with the exception that with current electrolyzer technology a freshwater source is required. This means that to use seawater directly, it must first be purified of salts using a technology like reverse osmosis. As technologies advance, production of gases directly from seawater is possible.

Path Forward

Extraction of minerals and gases from seawater will require extensive research and development to create viable industries. Marine energy power generation could be an important catalyst to move these technologies from the pilot stage to full scale.

However, the coupling of marine energy and seawater extraction technologies would also require extensive development, deployment investigations, and potential design evolutions. Additionally, it is essential to understand the power requirements of the various seawater extraction technologies operating at the commercial scale. Currently, there are crude estimates of the power requirements for many technologies at the laboratory bench scale, but the reliability of this information is highly uncertain.

To date, there has been a significant focus on the development of technology for the extraction of uranium from seawater, but little attention has been paid to exploring other obtainable critical elements and the cost of their extraction relative to current terrestrial mining operations.

Technoeconomic analyses are needed that identify target elements and costs for extraction from seawater using a variety of extraction approaches. These analyses should include costs associated with extraction of a single target element as well as an investigation into how those costs would change if multiple elements could be recovered with the same technology.

There is a major potential synergy in linking seawater extraction with desalination operations. The brine discharge from a desalination plant has a salinity that is typically 2–3 times that of the original seawater and it is often higher in temperature than the original seawater. These are both favorable features for enhancing adsorption technologies. The potential adsorbent enhancement (in terms of adsorption capacity, i.e., grams of the element per kilograms of adsorbent) is likely to be 4–8 times that of natural seawater exposure (Sodaye et al. 2009; Kuo et al. 2018; G. A. Gill, personal communication, 2018). Because the desalination plant has its own seawater delivery and disposal system, it should be reasonably simple to integrate a seawater extraction technology. Finally, the power from the marine energy system could be used to operate any mechanical or electrochemical systems that the seawater extraction system would require. In this synergy, the waste product from the desalination operation (brine) would become a resource for mineral extraction, thereby lowering the overall cost of the production of fresh water.

Potential Partners

The concept of directly extracting minerals from seawater has been around for centuries, but to date there are no commercial activities in this space, with the exception of extraction of the major salts from seawater (e.g., sodium, potassium, and magnesium). There is, however, a great deal of interest to research this topic (within both DOE and U.S. Department of Defense) as a potential domestic source of critically needed materials.

Within DOE, the Office of Nuclear Energy's Fuel Cycle Research and Development Program has a subprogram to develop technology for the extraction of uranium from seawater with the goal of addressing future resource availability (DOE 2013; Gill et al. 2016; Kung 2016; Tsouris 2017; Parker et al. 2018). The DOE Office of Energy Efficiency and Renewable Energy's Geothermal Technologies Program is also exploring extraction of critical elements from hydrothermal systems using advanced adsorption technologies in support of obtaining domestic supplies of critical materials (DOE 2017). The Advanced Manufacturing Office at DOE will also benefit from development of seawater extraction technology to obtain the critical materials needed to develop clean energy technologies, such as structural metal alloys, magnets, light-emitting devices, lasers, catalysts, pigments, batteries, and other high-tech applications (King et al. 2016), as well as support for their desalination initiatives. There are likely partnering opportunities with the U.S. Department of Defense for advanced weapons and warfare manufacturing as well.

Terrestrial mining companies are potential commercial partners that may be looking for additional sources of minerals, including those in abundance in seawater, particularly uranium, lithium, and REEs. The startup company LCW Supercritical Technologies (LCW Supercritical Technologies 2017) has patent-pending technology for the adsorption of uranium and other elements from seawater and other aqueous solutions. This technology has not yet been licensed for commercial application. There is also significant international interest in developing technology for the extraction of uranium and other elements from seawater. Countries that are currently doing research and developing technology include Japan, China, and India (Kavakli et al. 2005, 2007; Tamada 2010; Guo et al. 2015, 2016; Gao et al. 2016; Hara et al. 2016; Zhang et al. 2018).

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