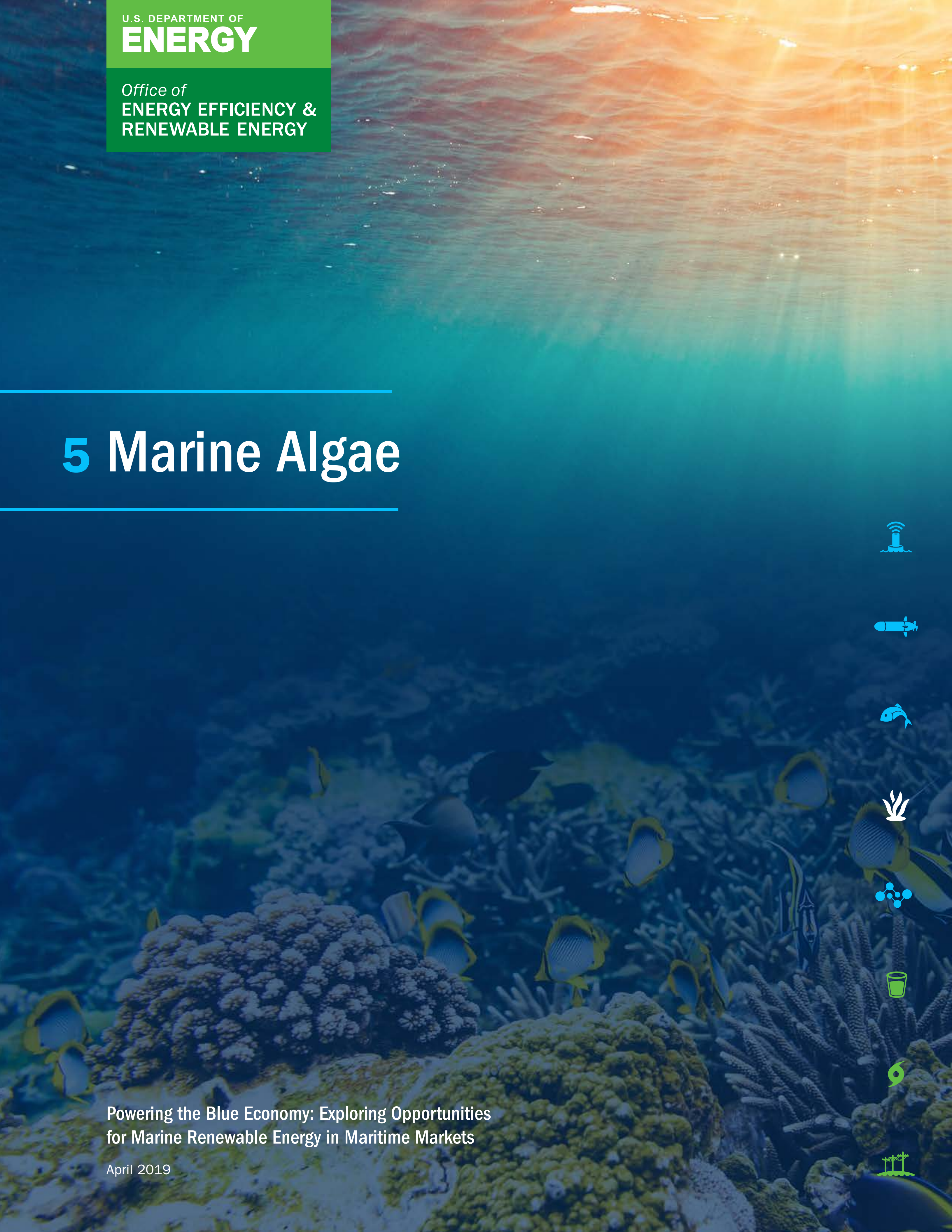

U.S. DEPARTMENT OF
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RENEWABLE ENERGY

5 Marine Algae

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

April 2019

5. Marine Algae

Key Findings

- Macroalgae (seaweed) and some microalgae can be grown at commercial scale at sea to provide biomass for biofuel production; specialized chemicals for food processing, cosmetics, and pharmaceuticals; soil additives and fertilizers; animal fodder; and other end products.
- Algae grown at sea has a competitive advantage over terrestrial-based crops grown for biofuels because it does not require land, irrigation systems, added nutrients, or fertilizers. Macroalgae grown in farms for human and animal consumption are common around the world, but farms dedicated to crop production for biofuels are in the experimental stage. With the world's largest Exclusive Economic Zone, much of which has potential for growing algae, the United States has the potential to become a leader in sea-grown biofuels.
- The power requirements for large-scale macroalgae growing and harvesting operations at sea are not well understood but will likely resemble those for aquaculture operations including power for safety, navigation lights, and maintenance equipment; pumps for nutrients and ballast control; refrigeration and ice production; drying operations; marine sensors; recharging of autonomous underwater vehicles, and recharging transport vessels.
- Marine energy systems have the potential to be integrated into and codeveloped with algal growing and harvesting systems. By replacing fossil fuels with marine energy renewable energy, the biofuels industry could reduce harm to air and water quality; reduce supply chain and transport risks; and potentially reduce operational costs. The low surface expression of most WECs will increase survival at sea, provide low visual impacts, and be more easily integrated with algal facilities.

Opportunity Summary

Algae refers to a diverse group of organisms including macroalgae, microalgae, and cyanobacteria ("blue-green algae"). Macroalgae (seaweed) and some microalgae can be grown at commercial scale at sea to provide biofuels, animal feed, and other co-products. Micro and macroalgae have high levels of structural polysaccharides and low concentrations of lignins that can be made into feedstocks for the production of liquid biofuels. Many algal species contain organic chemicals that are used in many industrial and agricultural processes, ranging from food processing to supplementing animal feed.

Current projected costs for marine algae are several times higher than terrestrial biomass, but improvements in yields, scale, and operations could see algae become cost competitive with terrestrial crops (National Renewable Energy Laboratory 2017). Seaweed farming has been growing rapidly and is now practiced in about 50 countries (traditionally in Japan, the Republic of Korea, and China). Further, 27.3 million tons of aquatic plants (seaweed included) were harvested in 2014, totaling $5.6 billion (Food and Agriculture Organization [FAO] 2016).

Although many small algal cultivation sites need little power, the larger marine farms proposed for production of biofuels will need energy for harvesting, drying, monitoring, and maintenance activities, as well as for maneuvering and buoyancy controls for larger farm structures. These power needs could be satisfied wholly or in part via energy generated from marine energy devices by designing marine energy systems into growing and harvesting systems to provide off-grid power needs. Marine energy provides a unique advantage over other forms of energy generation by being less geographically limited at high latitudes where some macroalgae species thrive and could also provide shelter to more exposed sites by attenuating wave action while simultaneously generating power.

Application

Description of Application

Microalgae and Cyanobacteria

Marine algae includes microalgae and cyanobacteria. Microalgae comprise unicellular plants that can be grown rapidly under natural or artificial light. Cyanobacteria are unicellular organisms that sit at the junction of bacteria and plants; they can be grown in a manner similar to other microalgae. Large-scale microalgal operations are still under development, favoring growth in raceways or ponds on land. However, there has been some interest in growing microalgae in containers in nearshore waters, likely in conjunction with existing facilities (Roesijadi et al. 2008), where designs may consist of open raceway ponds as well as photobioreactors, and hybrids of these two system designs. Commercial products derived from microalgae and cyanobacteria include products for human and animal nutrition, polyunsaturated fatty acids, antioxidants, coloring substances, fertilizers, soil conditioners, and a variety of specialty products including bioflocculants, biodegradable polymers, cosmetics, pharmaceuticals, polysaccharides, and stable isotopes for research purposes (U.S. Department of Energy [DOE] 2016).

Microalgae may be grown at sea in semiporous containers nearshore, largely to save space on land, reduce the need for supplemental artificial nutrients, and take advantage of natural sunlight for growth (Hoffman et al. 2017). However, these methods are in a very early stage of research and development and have not yet established the need for a power alternative to the electrical grid or waste energy from other industrial processes (Figure 5.1).

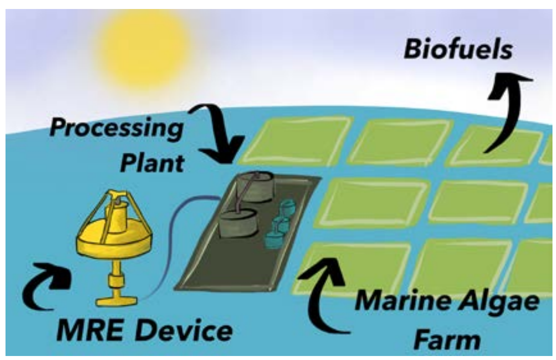

Figure 5.1. Marine renewable energy application overview for a macroalgae farm.
Image courtesy of Molly Grear, Pacific Northwest National Laboratory

Macroalgae

Macroalgae, more commonly known as seaweeds, are typically cultivated offshore or near coastal facilities (DOE 2016). As described in Titlyanov and Titlyanova (2010), commercial cultivation of seaweeds may be carried out in a seabed, on lines and ropes, and on nets. For seabed cultivation, pieces of the seaweed are anchored to sandy or muddy bottoms of shallow lagoons and bays and are harvested several months after planting. The crop may be either completely or partially collected, with 10% to 40% of the crop being left to provide material for the next cultivation cycle.

Seaweeds may also be grown on the seabed enclosed within fences, without being fixed to the bottom. For line/rope cultivation, plantlets are fixed on ropes suspended at the surface of the water or several meters below the surface. The ropes may be several to hundreds of meters long and are fixed to buoys or rafts, which are anchored to the bottom. The ropes are arranged in parallel rows at intervals from 10 centimeters to 1 meter apart. For net farming, seaweed may be cultivated using nets or racks made of bamboo poles, with ropes attached with algal spores or transplanted sporelings stretched between. Small flat-bottom boats are used to manually insert the sporelings on the ropes on the surface. The ropes sink deeper as the seaweeds grow and become heavier.

Products derived from macroalgae include food for human consumption, algal hydrocolloids (e.g., thickening agents such as agar, alginate, carrageenan), fertilizers and conditioners, animal feed, and macroalgal biofuels (DOE 2016). Highly cultivated macroalgae (seaweed) crops for human consumption include *nori* (*Porphyra spp.*), *wakame* (*Undaria pinnatifida*), and *kombu* (*Laminaria japonica*) (FAO 2009).

DOE's Advanced Research Projects Agency-Energy (ARPA-E) Marine Research Inspiring Novel Energy Resources (MARINER) program provided funding starting in 2018 to develop several alternate means of growing macroalgae at sea in sufficient quantity to create feedstock for biofuels, with the intent of producing other value-added products along the way. In addition to funding a series of technical tools to assist with the growing and harvesting operations (e.g., numerical modeling for siting; autonomous vehicles for hauling product; sensors and autonomous underwater vehicles for determining water quality, light, and nutrient availability, and measuring growth; and selective breeding and genomics technologies), ARPA-E MARINER expects to move the successful growing and harvesting operations toward commercial viability.

Large macroalgal farms for human and animal consumption are commonplace in Asia, Oceania, and parts of northern Europe (Okinawa Institute of Science and Technology 2016; Seakura 2018; Seaweed Energy Solutions 2018; Zeewaar 2018). Although less common, plans are now underway to cultivate large amounts of macroalgae at sea for biofuel production in the United States and other countries. There are no large operational macroalgae farms for biofuel production, although tests were made at sea during the 1970s off California (ARPA-E 2018). Although still in the early research and development stage, it is clear that macroalgae farms aimed at growing biomass for biofuels at sea will be large (covering hundreds to thousands of hectares) and will require infrastructure and power that resemble large seafood aquaculture operations at sea (ARPA-E 2018). Smaller macroalgae farms may also be created in the open ocean to grow smaller volumes of product for extraction of high-value chemicals and other products (Figure 5.2).

Biofuels

Biofuels from microalgae are in the development and demonstration stage; the lipid makeup and structure of macroalgae suggests that the same pathways will allow seaweeds to be used for biofuels in a similar manner. Growing microalgae and macroalgae can provide several types of biofuels, including biogas produced by anaerobic degradation of biomass; biodiesel produced from lipids accumulated in cells of algae; ethanol; hydrogen from photobiological transformations; or algae biomass that may be used for direct combustion (Dębowski et al. 2013). The average photosynthetic efficiency is 6%–8%, which is much higher than that of terrestrial biomass, which is 1.8%–2.2% (Chen et al. 2015). Additionally, the electricity produced from biogas derived from macroalgae can be cost competitive with solar thermal, solar photovoltaics, and biomass-generated electricity (Ghadiryanfar et al. 2017). Algal biomass is compatible with an integrated biorefinery that produces a variety of fuels and valuable coproducts (DOE 2016). Ethanol, biodiesel, biogas, renewable gasoline, diesel, and jet fuels are all possible products from algal biomass (DOE 2016). There is a particular need for long-chain hydrocarbons, which are not readily available from land-based biofuels. In addition, the supply of feedstock for biofuels must be of consistent quality and availability to avoid price volatility and attract consumers.

Figure 5.2. Line cultivation of macroalgae. *Image courtesy of Creative Commons*

Chemicals and Bioplastics

Microalgae contain a wealth of organic compounds that are important for the production of certain antibiotics and pharmacologically active compounds like docosahexanoic acid (Oilgae 2017). The pigments found in algae (e.g., carotenoids, phycobilins, and chlorophylls) can be used as coloring agents in natural dyes for food, cosmetics, and research, or as pigments in animal feed (DOE 2016). Other products include agar, which can be used as a food ingredient, in pharmaceuticals, and for biological/microbiological purposes; alginate, which can be used in textile printing, as a food additive, in pharmaceuticals, and for medical purposes; and carrageenan, which can be used as a food additive, in pet food, and in toothpaste (DOE 2016). Microalgae have also been used to produce antioxidants for the health food market, the most prominent being β-carotene from Dunaliella salina (DOE 2016). Algae have also been used to make bioflocculants and biodegradable polymers (DOE 2016).

Human Food and Animal Fodder

Demand for macroalgae as human food is strong in many countries in Asia and Oceania and is developing in the Americas and Europe. The residual biomass from macroalgae, a result of postprocessing for other uses, can serve as an important animal fodder supplement. Moreover, preliminary tests show promising results on methane reduction from cattle that are fed small additional amounts of specific algal species (Kinley et al. 2016). Algae can also be used in fish feeds as an alternative to fishmeal (The Fish Site 2013).

Other

Other products produced from algae include fertilizers, bioactive compounds, polysaccharides, and stable isotopes for research (DOE 2016).

Power Requirements

Because the largest operating macroalgae farms are nearshore and rely primarily on human labor for seeding and harvesting, the power requirements for large-scale macroalgae growing and harvesting operations at sea are not well understood. However, the requirements for power will likely resemble those for aquaculture operations, including energy to power safety, navigation, and maintenance equipment; pumps for nutrients and structure controls; refrigeration and ice production; drying operations; marine sensors; recharging of autonomous underwater vehicles; hotel loads for living quarters (if the structures are manned), and transport vessels (Roesijadi et al. 2008). Some macroalgae farms are said to be using light-emitting diode lighting to boost production, which also requires a power source. Troell et al. (2004) estimate that the energy performance of seaweed farms is comparable to sheep and rangeland beef farming.

Like aquaculture operations, macroalgae grow and harvest operations will not be dependent on consistent, reliable power generation on a daily or monthly basis. Battery or other storage can smooth and provide power on demand to meet the reasonably small power needs of aquaculture operations.

Markets

Description of Markets

Aquatic plant farming (most of which is seaweed) has been growing rapidly and is now practiced in about 50 countries, with China, Indonesia, the Philippines, Republic of Korea, Japan, and the Democratic People's Republic of Korea as the dominant producers (FAO 2016; Ghadiryanfar et al. 2017). Indonesia is the major contributor to growth in aquatic plant production in the world, specifically tropical seaweed species. Indonesia's share of the world's farmed seaweed production increased from 6.7% in 2005 to 36.9% in 2014. Globally, approximately 28.5 million tons of seaweeds and other algae were harvested in 2014 for a number of purposes, including human consumption (Figure 5.3; FAO 2016). In 2004, the combined microalgae and macroalgae global market was estimated at $10–$12 billion (Oilgae 2017). Six macroalgae species and one microalgae species contributed most of the global aquatic plant production in 2014 (Table 5.1; FAO 2016).

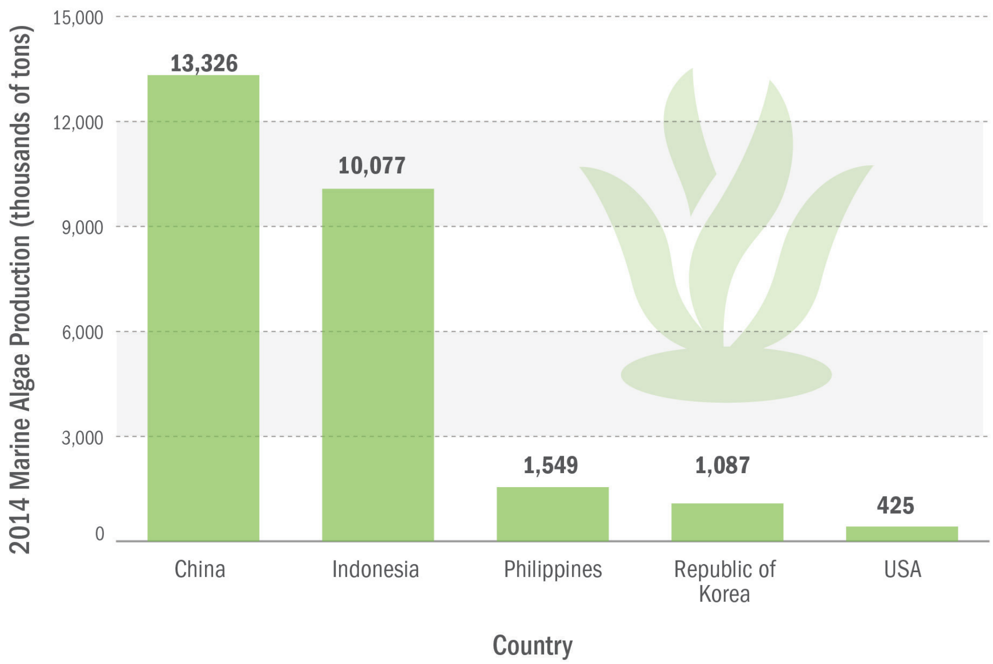

Figure 5.3. Global macroalgae production by nation

Table 5.1. Global Macroalgae Production by Aquatic Plant Type

Marine Algae Species	2014 Production (thousand tons)
Kappaphycus alvarezii and *Eucheuma spp.* (red macroalgae)	10,992
Laminaria japonica (kelp)	7,655
Gracilaria spp. (red macroalgae)	3,752
Undaria pinnatifida (kelp)	2,359
Porphyra spp. (red macroalgae)	1,806
Sargassum fusiforme (brown macroalgae)	175
Spirulina spp. (blue-green microalgae	86

The leading vendors of macroalgal products worldwide in 2016 were Cargill, DuPont, Group Roullier, Irish Seaweeds, and Qingdao Gather Great Ocean, Algae Industry Group (Technavio 2017).

Marine Algae Market Segments

The potential products from macroalgal growth at sea can serve several end markets, including biofuels, industrial chemicals and bioplastics, and human food and animal fodder.

Biofuels

The current worldwide production of terrestrial and marine biofuels is approximately 1,324 million tons of oil equivalent[11] annually (International Energy Agency 2017); marine algal biofuels make up only a small portion of this as most grow operations are at the development stage. For context, the U.S. goals for natural gas production are 691 million tons of oil equivalent (World Energy Council 2017). In 2016, the global biofuel market was valued at $168.18 billion and is projected to reach $246.52 billion by 2024 at a compound annual growth rate of 4.92% (Biofuels International 2016).

Chemicals and Bioplastics

The global value per annum of algal hydrocolloids, specifically agar, alginate, and carrageenan, is estimated to be $132 million, $213 million, and $240 million, respectively. The antioxidant β-carotene, produced from microalgae, had an estimated $392 million in sales in 2010 (DOE 2016). The natural food colors market in North America is expected to expand between 2014 and 2020, with a compound annual growth rate of 7.1%, reaching $441.4 million by 2020 (DOE 2016). The global carotenoid market value (in general) was $1.5 billion in 2014 (DOE 2016). DOE (2016) estimates that the market size for specialty products, such as bioactive compounds, polysaccharides, and stable isotopes for research, is likely to be very small because of their specialized applications (DOE 2016).

Human Food and Animal Fodder

The global value of seaweed per annum for human food is estimated to be $5 billion (DOE 2016), and the global seaweed market as a whole is projected to reach a value of $17.59 billion by 2021 (Algae World 2016). The global value for animal feed is estimated to be $5 million (DOE 2016).

Additional Drivers for Algal Markets

Growing and harvesting systems for microalgae biomass used for biogas production could be integrated with wastewater treatment facilities (Dębowski et al. 2013). This would allow nutrient-rich wastewater to be used as a culture medium for algal growth, resulting in reduced costs for water and nutrient supplements.

Microalgae could perhaps be harvested from naturally occurring marine algal blooms (DOE 2016); however, these blooms are unpredictable, and care would need to be taken not to upset the ecological balance in the harvest waters.

Future Growth

The market for marine algae is divided into biomass from microalgae, which will likely also be derived from macroalgae in the future; specialized chemicals for the food products, cosmetics, and pharmaceutical industry; soil additives and fertilizers; animal fodder; and other end-use products as shown in Table 5.2 (Nayar and Bott 2014). In each market, significant growth is expected (Transparency Market Research 2018).

The "first generation" biofuels, including ethanol, biodiesel, and pure plant oil, are the most common types of biofuels produced but are considered unsustainable (Ghadiryanfar et al. 2016). As a result, "second generation," or advanced biofuels—made from lignocellulosic biomass and agricultural waste—have been a focus of recent production. These biofuels have the potential to compete with food crops for land and freshwater. Algal biofuels are considered "third generation," and macroalgae grown at sea will not compete with land-based foods and crops. Algal-based biofuels can serve as a viable fuel alternative to petroleum-based fuels. In the United States, the Energy Independence and Security Act of 2007 established the Renewable Fuels Standard, which mandates the blending of 36 billion gallons of renewable fuels by 2022, of which only 15 billion gallons can be produced from corn-based ethanol (DOE 2016). Only 5% of the fuel used in the transportation sector in 2014 came from biofuels, but that percentage is expected to grow in the future

[11] A tonne of oil equivalent (toe) is a unit of energy defined as the amount of energy released by burning one tonne of crude oil.

(DOE 2016). This presents a significant opportunity for biofuels derived from algae to help meet these longer-term needs of the Renewable Fuels Standard and impact the energy supply for transportation fuels.

Table 5.2. Global Production of Macroalgal Products Estimated in 2014 (Nayar and Bott 2014)

Product	Industry	Specific Uses	Market Value (million $USD)
Carrageenan	Food products	Gelling and thickening agent, specifically for dairy and meat	527
Alginate	Food products	Food thickening agent Substrate	318
	Textiles	Fabric color paste	
	Pharmaceuticals	Tablet compounds	
	Cosmetics	Thickening agent and moisture retainer	
	Metallurgy	Flux binder for welding rods	
Agar	Food products	Food gelling and thickening agent	173
	Pharmaceutical industry	Laxatives	
	Biomedical industry	Laboratory growth medium	
	Dentistry	Impression material	
Soil additives	Agriculture	Soil conditioning	30
Fertilizer	Agriculture and residential plantings	Soil additive, growth enhancement for plants	10
Seaweed meal	Agriculture and residential plantings	Soil additive	10
Miscellaneous			5
Total			1, 073

In the pharmaceutical industry, the significance of marine-algae-derived drugs is expected to increase (Transparency Market Research 2018). The increasing preference for veganism and nonanimal-derived products drives the marine algae extracts/products market (Transparency Market Research 2018). Additionally, because of its advancement in healthcare and biotechnology, North America and Europe are likely to present lucrative opportunities in the marine extract/product market (Transparency Market Research 2018).For macroalgae production to become a viable industry, growers will need to improve biomass yields and reduce costs through scaling, reducing labor needs via automation, and optimizing logistics.

Potential Customers

The potential list of customers of marine algae cultivated using marine energy is extensive. The potential customers within the biofuels industry include those companies interested in algal-based fuels, such as military, aviation, and commercial transportation enterprises. Within the chemicals and bioplastics industries, potential customers include companies related to pharmaceuticals, cosmetics, health food and supplements, and fertilizers. For seaweed grown for human consumption, potential customers include specialty food manufacturers. For seaweed used in animal fodder, potential customers include animal feed manufacturers.

Power Options

As there are no macroalgae biofuel farms currently in existence, there is no competitive power source to displace; the market is undeveloped, and marine energy could have a first-mover advantage. Offshore wind and solar energy could potentially be competitors of marine energy for algae-based biofuels, depending on the location of the production site. Offshore and land-based wind and solar installations have been proposed for integration into coastal and inland photoautotrophic microalgae sites (DOE 2016). These renewable sources could supplant or supplement electrical grid or other industrial sources of energy for drying microalgae (DOE 2016); however, depending on the location of the site, tidal energy could also be a potential alternative to provide additional energy for the drying process.

Geographic Relevance

Areas of the South Atlantic and Gulf of Mexico, as well as the West Coast, Alaska, Hawaii, and other Pacific Islands have been identified as preferred geographic regions for macroalgal biomass production, with portions of Hawaii, California, Arizona, New Mexico, Texas, Louisiana, Georgia, and Florida as potential areas with adequate sunlight for optimal open cultivation of microalgal biomass within the United States (ARPA-E 2018; DOE 2016).

Additionally, areas of the southwestern United States have been identified as the most suitable for closed systems for growing microalgae, such as photobioreactors (Figure 5.4; Quinn et al. 2011; DOE 2016).

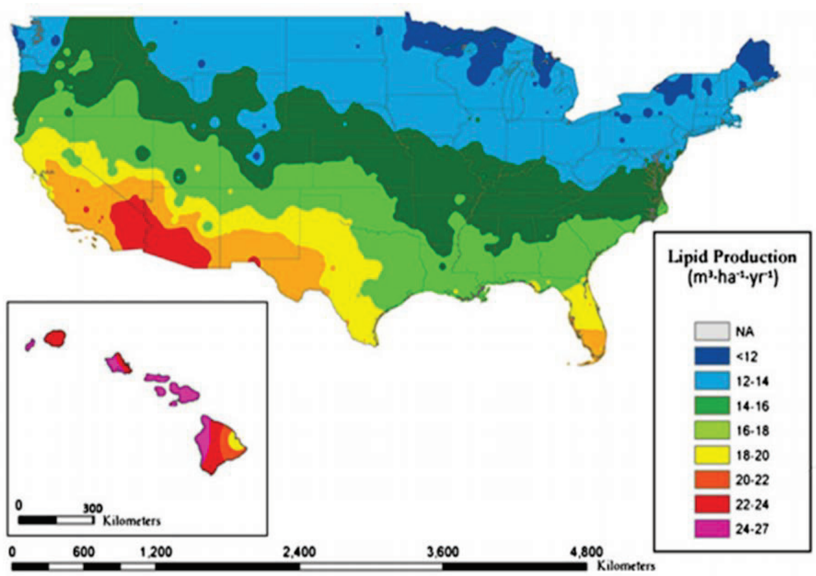

Figure 5.4. Modeled microalgae lipid productivity potential in the United States. *Image courtesy of Quinn et al. (2011)*

Based on concerns about the potential environmental effects of harvesting natural populations of seaweed nearshore, many countries have developed regulations limiting natural harvests (DOE 2016). By moving offshore, seaweed farms could alleviate nearshore environmental pressures and establish larger-scale operations, which will expand the market opportunities. In particular, European, Canadian, and Latin American seaweed industries rely on harvesting natural resources (Buschmann et al. 2017).

Marine Energy Potential Value Proposition

Marine energy systems could be integrated into growing and harvesting systems to provide off-grid power needs. By replacing fossil fuels with renewable marine energy, the biofuels industry could reduce harm to air and water quality, reduce supply chain and transport risks, and potentially reduce operational costs. Marine energy devices at sea will have a durability advantage over other renewable and fossil-fuel sources of power. Biofuels grown at sea will bypass future constraints on terrestrial biomass, such as competition for land and freshwater availability, nitrogen fertilization, and logistics.

Marine energy has a potential advantage over solar and offshore wind when biofuel installations require low-profile infrastructure to avoid shading the algae from sunlight or improve its storm survivability characteristics, or reduce visual impacts when close to shore. With proposals for free-floating biofuel operations, the marine energy industry is in a unique position to design devices that can accommodate the farms. The proposed offshore locations for macroalgae farms could benefit most from wave energy.

Coinciding with aquaculture opportunities, macroalgae growing operations could be sited along most coastlines and offshore waters of the United States. Typically, offshore operations would favor waters where there is an abundant nutrient supply and sunlight. These waters could coincide with abundant wave resources as well as energetic ocean currents. Technologies designed to convert wave or ocean current energy could likely be adapted for both anchored and free-floating growth lines. There are sufficient tidal resources at locations in the United States that coincide with some nearshore operations. Growing seaweeds for food, fibers, and other products requires adequate light and high concentrations of nutrients, so high-latitude growing operations are favored. There are also potential low-power salinity/thermal gradient-based energy sources that might be useful for powering energy needs of algal growing operations at sea.

With the world's largest Exclusive Economic Zone (National Oceanic and Atmospheric Administration 2015), much of which is viable for growing microalgae and macroalgae, the United States has the potential to become a leader in growth at sea for biofuels. Many of these waters overlap with significant marine energy resources that could develop systems in conjunction with the growing and harvesting operations.

Path Forward

Increased demand for cleaner fuels, including air-quality mandates and petroleum spill protections, will spur biofuel markets. High-value coproducts including complex polysaccharides like algin, laminarian, mannitol, fucoidan, and agar can be extracted from macroalgae, leaving the residue for animal feed. The market for these co-products may spur expansion of macroalgae growth at sea, allowing for early marine energy markets.

Although algal biofuels offer promise as a source of U.S. transportation fuels, the state of technology for production is continuously maturing with ongoing investment. Additional research, development, and demonstration are needed to achieve widespread deployment of affordable, scalable, and sustainable algae-based biofuels (DOE 2016). For macroalgae specifically, there needs to be considerable scale-up from current activities, improvement in strain selection, and major technological improvements in efficiency of water movements for microalgae to make a substantial contribution to the biofuels marketplace (DOE 2016).

Ideally, the macroalgae for biofuels and the marine energy industries could develop together, but this will require careful attention and collaboration to ensure that the needs of both industries are met, including matching power resources, market needs, growing seasons, and consumer-demand cycles that will drive energy needs. The marine energy industry and researchers must closely track the design and development of offshore macroalgae grow and harvest operations underway with ARPA-E MARINER funding to determine power needs and understand the requirements for integrating marine energy devices into the anchored or floating lines and enclosures and the constraints that seaweed growers are operating under for siting locations and deployment timing.

Efforts to prove that marine energy devices can be adapted for less-energetic areas (e.g., slower currents, reduced sea states) may become important, allowing for additional provision of marine energy to a broader base of macroalgae growing locations. As the first macroalgae operations are deployed, it would be useful for marine energy developers to design and deploy small-scale devices to test the feasibility and interface for providing power. The development of marine energy as a power source for offshore aquaculture operations could provide important direction for integration with the biofuels grow operations.

Potential Partners

Potential mission-driven partners for the marine energy industry include government agencies like DOE ARPA- E MARINER, National Oceanic and Atmospheric Administration Fisheries, U.S. Coast Guard, and the U.S. Department of Defense—specifically the Defense Advanced Research Projects Agency, the U.S. Air Force, U.S. Navy, and U.S. Army.

Private companies and consortia include the Sustainable Bioenergy Research Consortium (Boeing). Energy companies include Shell, BP, Exxon-Mobil, and commercial airlines.

Other private companies may also see the expansion of biofuel stocks from the ocean as opportunities for partnerships, including the transportation industry, especially commercial air carriers (e.g., Southwest, Alaska, and South African Airlines); airplane and turbine manufacturers (e.g., Boeing, Airbus, Rolls-Royce, and General Electric); ground and sea transportation companies (e.g., Maersk, Wärtsilä, Cummings, and CAT); biofuel refineries; chemical manufacturers (e.g., DuPont, Ashland, and Tata Chemicals); food and feed manufacturers (e.g., Whole Foods Cargill, BioProcessAlgae, TerraVia, and Earthrise Nutritionals); and pharmaceutical companies (e.g., Algae to Omega, Florida Algae, and Amgen).

A number of fuel refiners and catalyst developers (e.g., UOP, Chevron, Eni, Statoil, Total, and Neste) have begun to explore converting vegetable oils and waste animal fats into renewable fuels, whereas Neste, UOP, Syntroleum, Eni, Sinopec, AltAir, and Valero/Diamond Green Diesel have built large-scale commercial refineries to produce green diesel (DOE 2016). These organizations may also serve as potential partners for an algae farm or marine energy developer pursuing the market.

By developing and adapting marine energy devices to provide power for macroalgae growth for biofuels operations, the marine energy industry could move further along the route to commercial-scale development while gaining much-needed revenue. Although marine energy devices most useful for macroalgae growth adaptation are likely to be small, there may be some large aquaculture operations that could use the power from full-scale devices. The testing and experience at sea will support progress toward larger devices.

Similar marine energy devices to those used for macroalgae growth operations will also be useful for encouraging the growth of aquaculture farms and devices for powering navigation markers as well as recharging underwater vehicles and autonomous ocean observation sites.

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