Liquid Fuels from Offshore Macroalgae Cultivation and Hydrothermal Liquefaction

IGA-410

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Introduction

Liquid fuel use in aviation and maritime poses a long-term problem for current decarbonization strategies. While land based transportation can be electrified, aviation and shipping are dependent on the high energy density of liquid fuel. Currently, however, non-oil alternatives are either equally carbon intensive (clean coal), extremely expensive (bioconversion of biomass), or both (Fischer Tropes conversion of biomass). Of these options, bioconversion of terrestrial biomass may eventually be improved to yield economically viable liquid fuels. Under idealized scenarios, biofuels from terrestrial biomass require extensive land use. Only under generous scenarios could enough terrestrial plants be grown on land not used for agriculture to supply aviation and maritime demand, see Fig. 1. As such, another source of liquid fuels is needed.

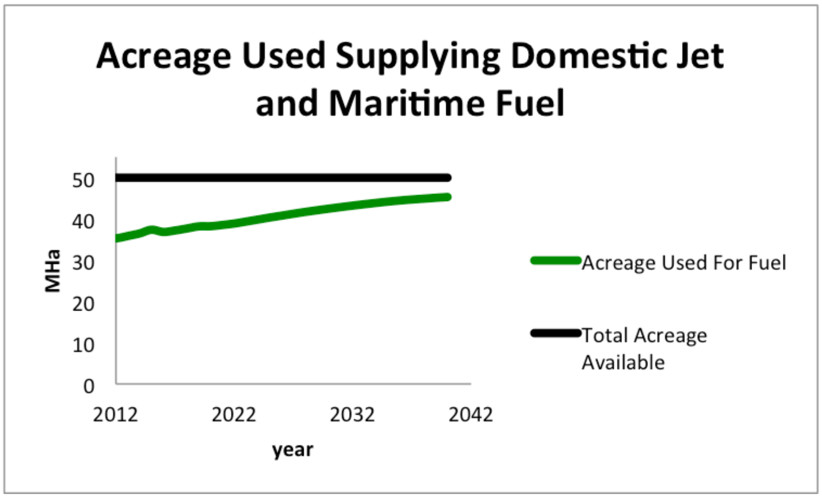


Figure 1. Estimate of acreage used for conversion of switch grass to fuel under generous boundary conditions.

The problem with producing carbon neutral liquid fuels is two fold. First, they require fixed carbon, a resource that is essentially limited to living organisms. These organisms take up space and resources that are used for other essential human needs, such as food. Therefore, carbon neutral liquid fuels must either compete with food, or find new spaces and resources. This is a cultivation problem. The second problem is one of conversion. Liquid fuels are much more energy dense than living organisms, so the organisms energy needs to be concentrated. Some methods of concentration (or conversion) are highly effective, but only when they are used on appropriate biomass. This, then, is both a technological problem, as well as a cultivation problem. Only by integrating these two steps will we be able to achieve economically viable, carbon neutral fuels.

Macroalgae and Hydrothermal Liquefaction (HTL) present a promising integration of cultivation and conversion. Macroalgae, commonly referred to as seaweed, is ubiquitous in the world's oceans and lakes. Wild stocks have been harvested for food throughout human history, while the last century has seen the development of macroalgae aquaculture. Yet, macroalgae production has been limited to fulfilling food demand, which can be achieved with near shore cultivation techniques. Near shore areas are both spatially and economically limited, and cannot provide sufficient biomass for large-scale liquid fuel production. Instead, this report investigates offshore cultivation of macroalgae. Offshore areas have the potential to produce extraordinary amounts of biomass, but the technical feasibility is an open question. We examine what is necessary to develop offshore macroalgae aquaculture as well as to determine its potential to provide biomass for liquid fuels. We conclude that offshore macroalgae aquaculture should initially be developed as a high value food resource, which will help offset the high capital cost of the new industry. The success or failure of initial macroalgae farms will help determine the technical feasibility of extensive offshore aquaculture.

The conversion of macroalgae presents unique problems compared to conversion of terrestrial biomass, primarily due to liquid content and chemical composition. HTL takes advantage of these differences. HTL is a thermochemical conversion processes that turns highly watered biomass into a mix of low BTU solids, aqueous phase organics, and biocrude. Through combined systems, the biocrude can be upgraded to light or heavy oil (depending on the feedstock). As a technology, HTL has been primarily investigated in labs and has not been implemented commercially. This paper examines the potential of HTL, as well as competing bioconversion technologies, and the policies necessary to bring mature versions to market. We conclude that sewage plants can serve as ideal testing and demonstration facilities for HTL, and, as a result of producing products that can be sold in current markets, government subsidies on production will not be necessary to encourage development of HTL.

First, however, we look at the need for liquid fuels and the biomass potential of offshore areas.

Necessity of Zero-Carbon Liquid Fuels

Climate change poses a serious threat the economy, national security, and health, of the United States. Climate mitigation strategies are being pursued for all anthropogenic carbon sources. The most successful of these strategies relies on switching a given end use from a high carbon energy source to a low carbon source. Generally, this is easiest when the end use consumes high quality energy (see alternative electricity generation in US). It becomes more difficult when the end use requires a high-density fuel, such as gasoline. For example, there has been luck with developing electric cars, but electrifying trucks is much harder due to the enormous batteries required. Trucks, however, are terrestrial, and both electrification by overhead lines and transport by electric trains are among the ways of removing their dependency on liquid fuels. Aviation and shipping, however, are dependent on high energy density fuels. Discussion of alternative aviation fuels is limited to drop in kerosene (jet fuel) replacements (Rye, Blakey, and Wilson 2010). The maritime industry has raised the possibility of LNG and liquid hydrogen, but the former is not carbon neutral and the latter poses serious difficulties. Drop in diesel replacements are considered the most likely decarbonization strategies (Remley 2014).

Aviation and maritime fuel consumption accounts for 3.1% of all energy consumption. If trucks are included, that figure rises to 6.2% of US energy consumption. Due to the lack of alternatives for aviation and maritime activity, alternative fuels must be developed. As such, development of zero-carbon liquid fuels is necessary for a zero-carbon future.

Potential Biomass Resources

To make a serious dent in the United States liquid fuel market, domestic macroalgae cultivation will have to be many times current world cultivation and expand into currently uncultivated environments. The US, however, has significant offshore marine resources, with the largest offshore area of exclusive economic interest of any country. Significant portions of this are unconstrained (e.g. not protected marine environment) with viable sunlight and water temperature for macroalgae growth, Figure 1.

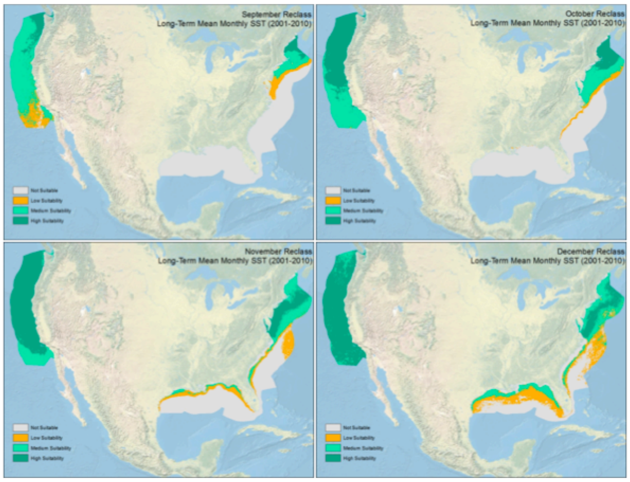


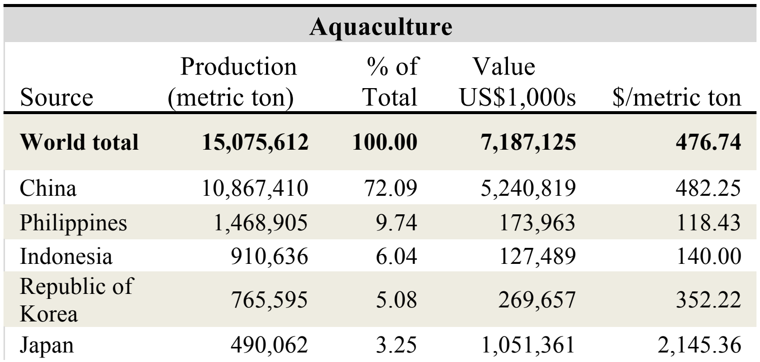
Figure 1. Suitability of offshore areas for macroalgae cultivation, green indicating greater suitability (Roesijadi et al. 2011)

Based on observed macroalgae productivity and conversion efficiencies, about 11,000 km^2 would produce about 5% of aviation and maritime fuel. To account for 20%, about 0.27% of US controlled ocean would be used. For scale, that is around 1/3 to $\frac{1}{2}$ the area of Arkansas. This is a large amount of ocean, but the fuel demand is large as well. As this report outlines, it may be possible to develop such cultivation.

The rest of the report begins by outlining the current state of macroalgae cultivation, followed by a look at biomass to fuel conversion technologies, and then a review of policy. The future of macroalgae cultivation is described, then the requirements for future biomass conversion technologies, and finally policy recommendations to achieve these goals are given.

Current Cultivation and Demand for Macroalgae

Macroalgae come in three different types: brown, green, and red. The different types of algae can vary by their chemical composition, but the intra-group variation is large as well. Macroalgae as a food source accounts for around 95% of demand, while the rest of the demand is divided between specialty uses such as biotechnology and cosmetics. Currently, the market for macroalgae is highly fragmented and therefore the price varies considerably by type of algae and country of origin. Country by country variation can be seen in Figure 2.



Aquaculture				
Source	Production (metric ton)	% of Total	Value US$1,000s	$/metric ton
World total	**15,075,612**	**100.00**	**7,187,125**	**476.74**
China	10,867,410	72.09	5,240,819	482.25
Philippines	1,468,905	9.74	173,963	118.43
Indonesia	910,636	6.04	127,489	140.00
Republic of Korea	765,595	5.08	269,657	352.22
Japan	490,062	3.25	1,051,361	2,145.36

Table 1. Production and cost metrics for aquaculture macroalgae for the top 5 producing countries (Roesijadi et al. 2010).

Macroalgae aquaculture has only been present since about 1950, when modern techniques for macroalgae cultivation were developed. Previously, harvests of wild macroalgae were the primary means of production. The development of macroalgae cultivation in the 1950's coincided with an increase in scientific interest in the life cycle and maintenance of macroalgae. This began with classification of macroalgae based on appearance as well as growth characteristics, followed by development of methods to culture some macroalgae in lab settings. The lab cultivation of juvenile macroalgae opened the possibility for profitable aquaculture, which now dominates macroalgae production.

Macroalgae is primarily produced and consumed in Asia. While there is a significant-amount of wild seaweed cultivation, the majority of macroalgae comes from aquaculture. Currently, macroalgae aquaculture is performed near shore, and is labor intensive due to a lack of mechanized harvesting (Lüning and Pang 2003; Roesijadi et al. 2010). Before near shore cultivation occurs, juvenile algae are grown in vats that must be temperature, light, and chemically controlled. This generally requires coastal property to minimize transport to near-shore cultivation areas. Once the macroalgae are harvested, they are generally dried for to decrease transportation costs as well as for preservation(Titlyanov and Titlyanova 2010).

Near-shore cultivation has been effective in providing adequate supply for current demand, but it imposes a limit on future supply that is well below what is necessary for use of macroalgae as a fuel substitute. However, the availability of near shore space places a limit on this style of cultivation. Macroalgae cultivation is in competition with other forms of aquaculture, boat and ship traffic, as well as the visual preferences of coastal populations (Roesijadi et al. 2011). For countries with underdeveloped coastal areas and populations that have high macroalgae consumption, this limitation is somewhat mitigated. However, the areas with near shore environments suitable for macroalgae cultivation United States are developed. Combined with a general lack of support for macroalgae consumption by the populace, near shore cultivation of algae in the United States is considered highly constrained and not suitable for the scale of production required of biofuel feedstock.

Offshore cultivation of macroalgae is nonexistent in the United States, and it is extremely limited abroad. This is not for a lack of areas suitable to grow macroalgae, see Figure 1, but rather due to a lack of demand. Despite this, there have been a number of pilot projects run in the US and abroad. The first occurred during the 1970's oil shock. It was run by the DOE off the coast of the southern California coast with the goal of producing biogas (Roesijadi et al. 2011). At the time, the offshore environment proved too challenging for the cultivation techniques, but the potential for offshore growth was considered promising. More recently, and an offshore cultivation experiment was run in the North Sea that had success with a number of novel cultivation techniques, shown in Figure 2 (Buck and Buchholz 2004).

Figure 2. Novel ring method for offshore macroalgae cultivation (Buck, et. al. 2004)

Harvesting remains a largely manual process for all types of macroalgae cultivation. In the early 1900s, before the development of macroalgae cultivation, the U.S. built harvesting ships for mechanized gathering of wild macroalgae, but near-shore aquaculture removed the need for such ships (Lüning and Pang 2003). While manual harvesting feasible at current production levels and in near shore areas, scale up of algal cultivation will require mechanization of both harvesting and planting. The demanding environment of offshore cultivation also increases the need for mechanization.

Both offshore and near shore cultivation operations require land-based facilities for cultivation of juvenile macroalgae. This imposes different requirements on the cultivation operations, with near shore operations often located proximally to their land facilities, while offshore facilities require land-based facilities near their port of call. A final issue with offshore cultivation is that current cultivation methods have seasonal harvests. As such, ships are only used for a limited duration, making specialized ships a waste of money. Further, unless all the biomass can be process very quickly, seasonal harvests require the macroalgae be preserved (Roesijadi et al. 2010).

Wet Biomass to Biofuel Conversion Technologies

Biomass is only useful if it can be converted to fuel. Conversion of biomass, and algae in particular, to biofuels is an extensive area of research. Macroalgae are less studied, and differ in important ways from traditional biomass. Compared to terrestrial plants, macroalgae have a very high water content (approximately 85% compared to 18% for land plants). This makes conversion techniques that require dried mass too energetically expensive Figure 3.

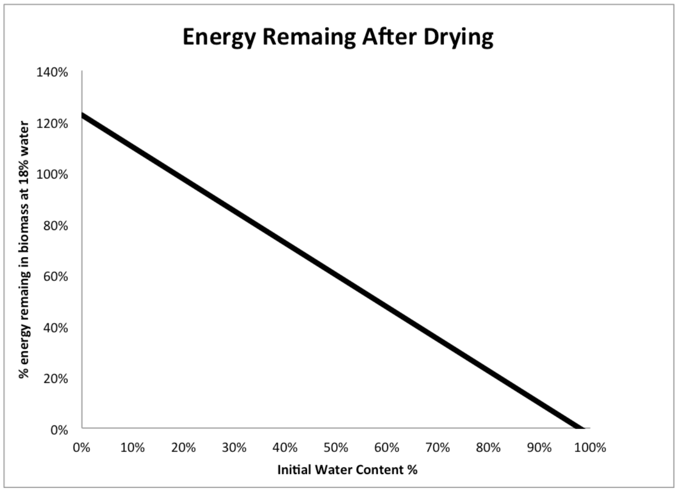


Figure 3. Energy balance of biomass dried to 18% water content relative to initial water content.

Macroalgae also have unique chemical compositions. Most species have very little of the highly stable cellulose that is widely present in land plants, but also have low lipid content relative to microalgae. These features, high water content, low lipid content, and no cellulose, limit the technologies capable of converting macroalgae to fuel. The technologies that are capable of this conversion fall into two categories: biological and thermo-chemical. The current state of each is summarized in Table 2 and reviewed below.

Products	Methane	Ethanol	HTL Biocrude
Scale (metric ton/yr, dry basis)	500,000	500,000	500,000
Conversion rate, dry seaweed	0.124 m^3/kg	0.254 kg/kg	0.2278 kg/kg light crude; 0.0976 kg/kg heavy crude
Byproducts	n/a	Electricity 212,778 MWh/yr	n/a
Project Investment, million USD[2]	41.5	243	151.1
Operating cost, excluding seaweed cost, million USD/yr[2]	4.2	29.3	19.1
Net production (per yr)	61.8 million m^3	127,000 metric ton	113,900 metric ton light crude 48,800 metric ton heavy crude

Note: [1]Based on brown seaweed, *Laminaria sp.;* [2]Converted from 1 Euro = 1.3 USD

Table 2. From left to right, cost of anaerobic digestion, fermentation, and HTL.(Roesijadi et al. 2010)

Biological conversion occurs in two forms: anaerobic digestion and fermentation. Anaerobic digestion is a common way of dealing with sewage waste (another high water biomass mixture) and produces high BTU biogas that can be used directly for heating or can be further upgraded to various fuels. Fermentation for industrial production of ethanol is common, with corn being a common feedstock in the United States. Both of these strategies are adaptable to macroalgae, although the high salt content of marine algae poses a technical hurdle. Biological conversion can in theory yield a wide range of products, including drop in fuels such as isobutanol. However, in practice, yields from these more complex conversions have been limited while work on methane and ethanol has shown good results (Lee et al. 2008). Anaerobic conversion (see figure 4) and fermentation also occur over a relatively long time scale, often weeks (Toor, Rosendahl, and Rudolf 2011). Biological methods, however, are straightforward to implement and cost less than 1/3 of HTL.

Thermochemical conversion places biomass under heat and pressure in the presence of a catalyst. These processes mimic the natural transformation that occurs underground where high pressure, high temperature, and a lack of oxygen results in biomass being converted to fossil fuels.

One type of thermochemical conversion, HTL, processes high water content biomass (80-85%) in 'subcritical water.' Unlike with dry processes, processing terrestrial plants with HTL requires significant additional water (Toor, Rosendahl, and Rudolf 2011). As a result, it in not an attractive conversion technique for crops such as switch grass. Macroalgae, however, generally have water content around 85%, making HTL an ideal processing technology. Further, unlike other processes (including biological conversion) HTL is resistant to the high salt concentrations of marine seaweed.

HTL produces biochar (a low BTU solid), an aqueous fraction, and biocrude. The biocrude is highly oxygenated, and requires upgrading. The aqueous fraction consists of organics dissolved in water. It can be submitted to a process similar to HTL called hydrothermal gasification (HTG) that produces a mix of CO2 and methane. The methane can then be used to upgrade the biocrude to a mixture that is predominantly light oil. HTL is currently a pilot technology, with the most detailed life cycle analysis investigating conversion of wood pulp by HTL (Elliott et al. 2015). Further, while the small scale studies indicate that algae would produce enough methane to upgrade its biocrude, that is not guaranteed.

HTL facilities are capital intensive, and that cost is increased when HTG and upgrading facility are also needed. However, unlike bioconversion, HTL occurs quickly (residence time can be as little as 30 min) and can be operated as continuous flow systems (a necessity for industrial operations) (Toor, Rosendahl, and Rudolf 2011).

Maritime Aquaculture Policy

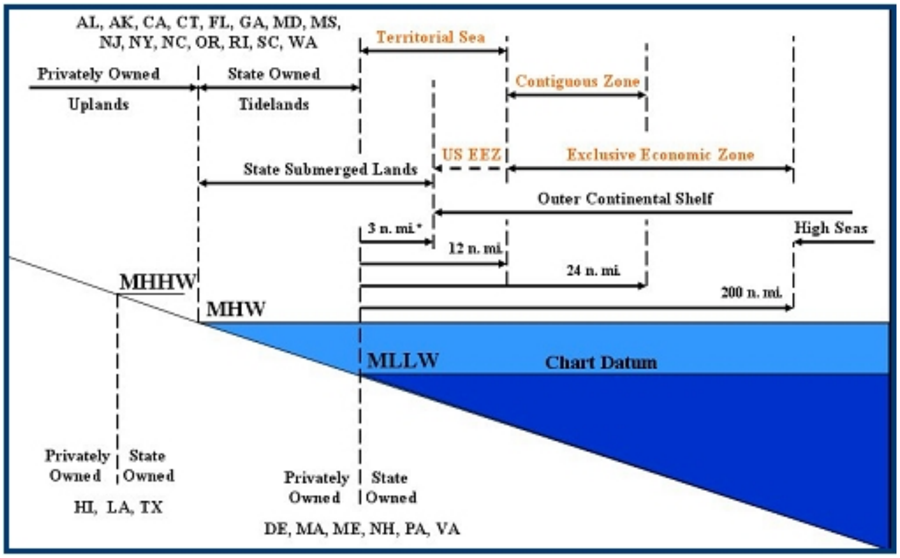


Figure 3. Schematic of maritime boundaries (NOAA 2013).

While HTL may eventually be developed to convert macroalgae, the current policy on offshore macroalgae cultivation is opaque. The territorial boundary of a country, located 12 miles off a country's coast, marks the end of its sovereign territory Figure 3. In the

United States, state, county, and city governments generally regulate areas within 3 miles of the coast, although this regulation may be passed onto federal agencies.

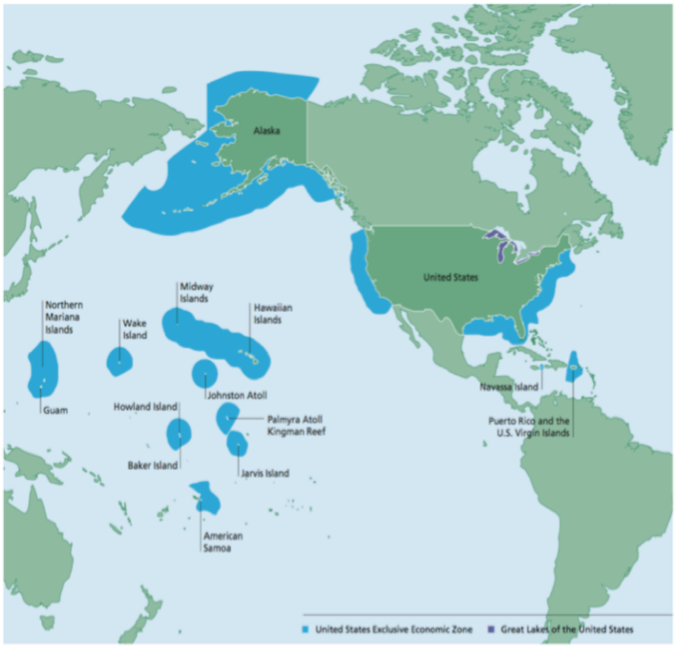


Figure 4. US EEZ (NOAA 2013).

Near shore areas are, as a result, highly constrained in their use, particularly for large-scale operations. Between 3 miles and 200 miles off of the coast is a country's Exclusive Economic Zone (EEZ). Countries maintain exclusive rights to all economic activity in their EEZ, including mining, fishing, and environmental protection. The United State's EEZ is the largest in the world, and encompasses marine environments from the equator to the arctic, Figure 4. The EEZ is regulated by a number of agencies including the BLM, EPA, and the UGS. For established uses, such as drilling, particular agencies are authorized to negotiate leases and grant permits. Offshore aquaculture, however, falls into a grey area.

Currently, there is no permitting or leasing process for offshore aquaculture. It is, in fact, unclear if any agency has legal authority to grant an offshore aquaculture lease (Roesijadi et al. 2010). Historically, this has been a non-issue. Around the mid 1990s, however, there was increased interest in offshore fish farming (in most literature, aquaculture is used to describe fish farming) and policy makers began to look at explicitly encouraging offshore aquaculture. Two different commissions arrived at the same conclusion, that the permitting process needs to be simplified, and that the National Oceanic and Atmospheric Administration (NOAA) should be in charge of aquaculture regulation. Further, NOAA was tasked with studying potential impacts. While a bill was introduced to congress to make these changes in both the 109th and 110th congress, it was not passed and little progress has been made. This has stymied a hope for "blue revolution" in offshore fish farming, but has also made offshore macroalgae farming highly uncertain (Roesijadi et al. 2011). Currently, there are only three offshore farms in the US, all of which raise fish. The lack of policy guidance also prevents integration of algae farms with synergistic projects, such as offshore wind turbines.

Biomass conversion technologies have research support under a number of different federal departments. These projects primarily focus on conversion of terrestrial biomass and microalgae. There has been limited support for conversion of macroalgae, either biologically or thermochemical. Wet biomass thermochemical technologies are currently underfunded relative to dry mass conversion. Historically, funding and policy has focused on production of ethanol. This is clear in the ethanol-gasoline mixture requirements, as well as subsidies for corn, the main ethanol feed stock in the US. Funding agencies, however, have begun to focus more on advanced biofuels, and US climate goals have begun to incorporate them as well.

Future of Conversion Technology

The state of macroalgae cultivation, HTL technology, and aquaculture policy, is muddy. Currently, for HTL-HGS-upgrading, production costs have been estimated at between \$2.18 (personal calculation) and \$2.70 per gallon gasoline/diesel (Roesijadi et al. 2010). At the time of estimation (2008), the average market cost of gasoline and diesel was \$2.80. This allow for between \$6 and \$37 per DWT of macroalgae before the total production cost is greater than the market price. As HTL has not been demonstrated at commercial scale and the lowest estimated production cost of near shore macroalgae is minimally \$23 dollars, macroalgae with HTL is not currently commercially viable (Roesijadi et al. 2010). However, serious exploration of cultivation and HTL has the potential to change this equation.

Offshore macroalgae cultivation and biomass conversion to fuel are in their infancy as industrial scale technologies. The exact nature of what they would look like as industrial mature technologies is an open question, but a number of bounds are clear if they are to meet their promise of contributing to the liquid fuel mix. These are outlined here, and policies to facilitate the transition are discussed below.

Offshore macroalgae cultivation must be feasible on the scale of terrestrial agriculture with production cost no more than $25 per dry weight tonne. Innovation on multiple fronts is necessary to achieve this goal. First, costs must be reduced for the land based portion cultivation of macroalgae (Lüning and Pang 2003). This will require increased knowledge of the biology macroalgae, as well as either technical innovations in laboratory culture or use of non-destructive harvesting and growth methods for offshore cultivation. Second, scalable planting (setting macroalgae in offshore plots) techniques must be developed. Third, offshore farm systems must be able to produce macroalgae constantly throughout the year. Continual harvesting reduces the capacity factor of the system, creating more consistent utilization of boats and conversion facilities. Fourth, cheap, stable offshore structures are necessary. Fifth, mechanized harvesting and cleaning is key to scalable farming systems. Finally, efficient processing and transport to conversion will be required, likely through grinding up the macroalgae and then pumping[1].

The conversion technology must be able to process mass at a rate equal or greater than the rate of harvest. The technology must be resistant to salt water, as desalting at scale will be prohibitive, and the structures should be resistant to corrosion due to coastal air. The waste from conversion must be cheap to dispose of or, ideally, industrially useful. Conversion technologies should not depend on rare or limited catalysts. Finally, conversion cannot be threatening to coastal environments.

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[1] Grinding and pumping of macroalgae is not discussed here, but over short distances they represent minimal cost and energy contributions (Roesijadi et al. 2010).

Policy Towards Offshore Macroalgae for HTL Conversion

Policy for the development of offshore macroalgae aquaculture falls into three categories: ocean management, crop development, and aquaculture development.

As discussed, ocean management is the current roadblock for offshore aquaculture in the United States. To remedy this, it is imperative that a straightforward permitting procedure is implemented and agencies are given legal authority to lease land to aquaculture operations. While a permitting procedure can be implemented through executive order, legal authority will require an act of congress. This should be a priority. Any legislation or executive order must also give direction on how environmental assessments of offshore aquaculture will be performed. Due to the lack of experience, little is known about the intersection of offshore aquaculture with the local environment. The few studies that exist have been limited to the effects of fish farms, and direction on environmental studies should take into consideration the significant differences between fish farms and macroalgae farms (Holmer 2010). Direction should also be given about multi use permitting, such as using offshore wind turbines as anchor points for algae farms.

Due to the specialized ships that will be required for macroalgae aquaculture, the Jones Act is problematic. The Jones Act states that only US built and flagged ships can be involved in trade between US ports. For industries that use specialized ships that are only built outside of the US, this is an issue. Notably, offshore wind development in the

US has had difficulty finding US built ships for wind turbine construction, despite the availability of foreign built ships. Moreover, the Jones Act has long been criticized as anti-competitive and economically harmfully (Vaughn n.d.). Its repeal will enhance the development of offshore resources.

While there is extensive worldwide experience with macro algae cultivation, none of the widely cultivated species are native to the US. Due to the impossibility of containment in offshore macroalgae farms, the use of non-native species should be approached with caution. The lack of experience with near shore aquaculture of macroalgae in the US makes development of native species an important policy goal. Crop development requires biological research into new species, large-scale cultivation of the new species, and market development for the new crop. Each of these poses unique challenges in aquaculture of macroalgae and are discussed below.

Land grant universities are the centers of agriculture research in the US. These universities have long histories of both developing new crops as well as improving agriculture techniques. Aquaculture research at these institutions is limited, with a focus on fishery development. In the 1960's, a sea grant program was developed that is administered by NOAA. The program has a broad purview to perform research that leads to a greater understanding of the oceans and great lakes as well as harness the productivity potential for the benefit of the US. Sea grant programs have worked on fishery development and have recently begun funding macroalgae research. This funding, however, is limited, with base funding totaling $45 mil compared to $245 mil for land grant universities (Land-Grant But Unequal 2013, National Sea Grant College Program Policy for the Allocation of Funds, FY 2014 and Beyond 2014). The difficulty is compounded by the lack of crop development expertise at sea-grant universities. To speed up the development of macroalgae crops, congress should approve a USDA administered research program at marine state sea grant universities. Ideally the funding would be no less than $5 mil per year, so as to allow the development of new research programs across a number of universities. The USDA will be able to bring a farming focus to the research program, while the strong marine research culture at sea grant universities should facilitate crop development. A national institute, modeled after the National Agriculture Institute should be established that collates information about growth characteristics of macroalgae species and cultivation technology, as well as develop leaders in the field (National Institute of Food and Agriculture 2016). Research should focus on developing crops that can either be harvested continually throughout the year or sets of crops that can be harvested at different points during the year.

While demand for liquid fuels is eventually expected to drive macroalgae production, other drivers of demand may be useful in incentivizing early offshore macroalgae aquaculture and crop development. Food, as mentioned earlier, is the worldwide driver of macroalgae production(Rebours et al. 2014). And it is the case that the limited number of macroalgae aquaculture that is occurring in the US is based on demand for macroalgae as a food source. Currently the US does not consume significant amounts of macroalgae(Roesijadi et al. 2011). Changing these preferences, or changing macroalgae to fit the preferences, would increase demand for macroalgae and provide a much-needed market for the development period of offshore cultivation. Americans growing acceptance and taste for Asian foods may be able to provide a significant local market. Such preference switching should be encouraged by incorporating macroalgae into USDA and FDA food evaluations and health guidelines. Funding should also be provided to study potential health benefits of macroalgae consumption. Marine states should be encouraged to view offshore cultivation of macroalgae as local farming, and high profile chefs should be encourage to incorporate macroalgae into their dishes.

Novel preparations of macroalgae or novel uses may provide alternative markets. The sliminess of macroalgae's that so many people dislike gives algae unique chemical properties that can be used to modify foods and create news ones (Machado and Tomkins 2014). There is some work being done on this currently, but it remains to be seen if it will create any significant demand. Alternatively, there is some evidence that mixing macroalgae into cow feed can reduce methane production (Machado and Tomkins 2014). This is currently being studied in farm trials (personal communication) and if successful it could provide a significant market for macroalgae. Marine states agriculture departments should develop educational material for aquaculturists about these markets as well as communicate with their dairy state counterparts to encourage dairy farmer education.

Due to the high startup cost of offshore macroalgae farms, easy access to capital will be key to development of the industry. Currently, startup funding is available for land farms, through the Farm Service Agency (FSA), as well as various fishery activities, through NOAA (Usda 2016). However, both of these programs have stipulations that preclude loans being use for macroalgae funding. The FSA has the greatest capacity for dealing with start-up loans, and as such both the Consolidate Farm and Rural Development Act and the Agriculture Improvement Act should be amended to included both near and off-shore macroalgae aquaculture.

Mechanized harvesting and planting equipment will likely be created in response to specific demands from farmers already engaged in offshore aquaculture. As such, it is not worth explicitly encouraging developing of equipment before offshore farming has developed. Attention should be paid, however, to the mechanical properties of macroalgae species investigated for cultivation so as to simplify future mechanization efforts.

Development of Mature Conversion Technologies

Development of offshore macroalgae cultivation is only one part of the equation. Anaerobic digestion, fermentation, and HTL all hold potential to convert macroalgae to fuel. However, of the three, only HTL can currently produce drop in liquid fuel from biomass (Toor, Rosendahl, and Rudolf 2011). While national energy policy should not ignore the conversion potential of anaerobic digestion and fermentation, the feasibility of either technology to convert macroalgae to a liquid fuel is questionable. Therefore, policy recommendations are focused on HTL. Further, national research priorities should be redirected to biomass to liquid fuel technologies.

The technical feasibility of HTL has been demonstrated at lab and pilot scale and at least one company is attempting commercialization scale plants (Steeper Energy 2016). However, the capital costs remain high and the ability to integrate HTL, HTG, and bio-crude upgrading remains unproven (Roesijadi et al. 2011). Two paths to HTL commercialization are outlined and should be pursued in tandem.

Sewage sludge is initially composed of 1% solids, but is routinely thickened to 10%. The thickened sludge, despite chemical differences, can be converted to fuels using the same technologies used for wet biomass. As such, sewage plants serve as ideal proving grounds for wet biomass conversion technologies. Currently anaerobic digestion is the most common method of treating sludge. Anaerobic digestion, however, has downsides for waste treatment, including the need to further treat sludge to remove pathogens. HTL avoids the latter issues, since it sterilizes the treated biomass, and lab experiments have shown success with HTL of wastewater sludge. HTL does require more energy input than anaerobic digestion, but it generally converts more carbon to usable fuel, which can offset the extra consumption (Roesijadi et al. 2010). Treatment plants should be encouraged to add small pilot processing facilities, with financial aid from research institutions or governments. Certain treatment plants, such as Boston's Deer Island, already are working with outside companies to allow technology testing at their facility (personal communication). These collaborations should be encouraged both for

HTL as well as other wet biomass processing technologies. To encourage research, these systems should be designed to accept additional biomass. This allows them to serve both as disposal of sewage, disposal of other biomass, and as testing facilities for conversion of a wide range of biomass.

The second path to commercialization is for private companies to develop HTL plants and proceed with biomass conversion. Due to the high capital cost of HTL, this will be difficult. The DOE should develop funding and loan structures to support these early endeavors.

Comparison of Algae-HTL-Fuel with Other Systems

Offshore macroalgae cultivation in combination with HTL provides a number of advantages over competing technologies. First, if cultivation is possible on the scale that is predicted, it can provide significant quantities of zero carbon liquid fuel without interfering with food supplies. Second, HTL oil can be dropped into the current oil infrastructure without modification. Unlike alternative fuels, such as CNG or hydrogen, an economy based off of HTL oil will not require massive infrastructure conversion. Third, because HTL oil can be dropped into the current infrastructure, HTL does not need to reach a critical mass to create demand. Rather, a single HTL plant would be able to sell its product. Likewise, demand for macroalgae as food will allow smaller macroalgae aquaculture to be viable before large-scale culture occurs. The ability for HTL plants and macroalgae farms to be built individually, instead of requiring many for market access, means that individuals and companies can drive the creation of the algae-HTL economy (as opposed to the government subsidizing a novel market).

Conclusion

Developing zero-carbon liquid fuel is key to mitigating climate change and achieving a zero carbon future. Offshore macroalgae cultivation is a potential source of biomass while HTL is a potential conversion method. Technologically, offshore macroalgae cultivation and HTL are in their infancy, and fuel produced from macroalgae by HTL will currently only break even under ideal circumstances. However, a number of policy recommendations were made to promote their rapid maturation. For the offshore cultivation of macroalgae, it is imperative that a straightforward permitting structure be implemented, as well as clear legal guidance given for which agency can distribute leases. The Jones Act should be repealed to allow specialized aquaculture ships to be purchased from abroad.

Native crop development is important for offshore cultivation. Current programs to pursue such research are inadequate. A USDA administered research program for macroalgae crop development should be implemented, with funding focused to sea grant universities. A national institute should be established to collate crop and cultivation techniques. To increase demand, food programs should be encouraged to incorporate macroalgae. Finally, the legislation authorizing the FSA should be amended to make offshore farming eligible for startup and guaranteed loans.

Research into all bioconversion technologies should be continued, but HTL should become a focus. Sewage treatment plants should be encouraged to collaborate on testing pilot scale plants, as well as commercial scale if the technology is viable. Further, the DOE should be given authority to fund companies to build commercial scale HTL, either through direct grants or guaranteed loans.

Offshore Macroalgae aquaculture and HTL have the potential to produce significant amounts of the liquid fuel consumed by the US. However, both will require permissive federal and local policies, which are not currently in place. Fortunately, both technologies are dual use and can be commercially viable before they are used to produce biofuels, limiting the need for federal and states subsidies. All avenues to liquid fuels should be pursued, but these two technologies represent a unique path that has been heretofore underexplored.

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