arpa·e
CHANGING WHAT'S POSSIBLE

Macroalgae Research Inspiring Novel Energy Resources (MARINER) Program Overview

B. PROGRAM OVERVIEW

1. Summary

The United States has the world's largest marine Exclusive Economic Zone, an area of ocean along the nation's coast lines which is equivalent to the total land area of all 50 states. The nation has the potential to utilize this resource to build and grow a thriving marine biomass industry for the production of fuels, chemicals, feed, and food. Growing macroalgal biomass in the oceans offers a unique opportunity to sidestep many of the challenges associated with terrestrial biomass production systems, particularly the growing competition for land and freshwater resources, which are likely to result from the 50 to 100% increase in demand for food expected for 2050.[1] The overall goal of this program is to develop the critical tools that will allow the nascent macroalgae industry in the United States to leverage this tremendous resource and grow into a world leader in the production of marine biomass. The program will focus on developing advanced cultivation technologies that enable the cost and energy efficient production of macroalgal biomass in the ocean at a scale suitable as feedstock for the production of fuels and chemicals. The challenge is to dramatically reduce capital and operating cost of macroalgae cultivation, while significantly increasing the range of deployment by expanding into more exposed, off-shore environments. Specifically, this program is interested in new designs and approaches to macroalgae cultivation, with harvesting and transport being an integral part of such systems. These new systems may leverage new material and engineering solutions, and autonomous and robotic operations, as well as advanced sensing and monitoring capabilities. To further accelerate the development and deployment of such systems, the program will also focus on the development of computational modeling tools and ocean- deployable sensor platforms, as well as advanced macroalgal breeding tools. ARPA-E expects that the MARINER program will support development of technologies that will accelerate the deployment of advanced ocean farming systems capable of delivering renewable biomass feedstock at a cost competitive with terrestrial biomass feedstocks.

Introduction:

Macroalgae refers to a set of exceptionally diverse multicellular, non-vascular marine plants. Also referred to as seaweed, macroalgae broadly describes a number of green, red, and brown species that can be found in disparate geographic locations across the planet's vast oceans. Coastal human populations for hundreds of years have harvested macroalgae from native, near-shore ocean environments. In addition to wild harvesting, macroalgae are predominately cultivated and produced on marine "farms." Nearly 25 million metric tons (wet) were produced globally in 2014. Macroalgae is primarily used directly as food for human consumption, but also serves as a feedstock for the extraction of naturally occurring alginate, agar, and carrageenan compounds. Beyond these well established applications, there is a growing number of additional opportunities for large-scale macroalgae utilization, from the production of fuels and chemicals to animal feed.[2,3,4] Yet, to realize this potential will require a significant expansion of production volumes over current levels, as well as drastic reduction in the cost of production, especially when aiming at the conversion of macroalgae to fuels.

Over the previous 25 years, global production of macroalgae has increased 6-fold, driven by an increasing demand for macroalgae and macroalgae products for food consumption. Much of this increase is due to scaling in China and Indonesia, the two countries that dominate world production (Figure 1).[5] Increased production has also been seen in other Asian

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[1] Valin, H. et al. The future of food demand: understanding differences in global economic models. *Agricultural Economics*. 45 (1) 51-67 (2014).

[2] Wargacki, A.J. *et al.* An engineered microbial platform for direct biofuel production from brown macroalgae. *Science.* **335**, 308-313 (2012).

[3] Neushul, M. Marine farming: Macroalgal production and genetics – final technical report. Gas Research Institute, Chicago, IL. (1987)

[4] Ashare, E. *et al.* Cost analysis of aquatic biomass systems - final report. Dynatech R/D Company, Cambridge, MA. (1978).

[5] The state of world fisheries and aquaculture: opportunities and challenges. Food and Agriculture Organization of the United Nations, Rome. (2014) http://www.fao.org/3/a-i3720e/index.html

countries. At least 50 countries around the world are now engaged in aquatic plant farming in ocean waters, according to data from the United Nations Food and Agriculture Organization.[6]

However, even with such impressive growth, the current state of macroalgae mariculture is not capable of achieving the scale, efficiency, and production cost necessary to support a seaweed-to-fuels industry. This will require a transformational change from the low tech, labor-intensive methods used today, to a technology-driven, marine agronomic industry. Innovative engineering and systems-level solutions along with a suite of critical supporting technologies are necessary to build a commercially viable seaweed industry in the United States, capable of delivering a scalable, affordable, and renewable resource.

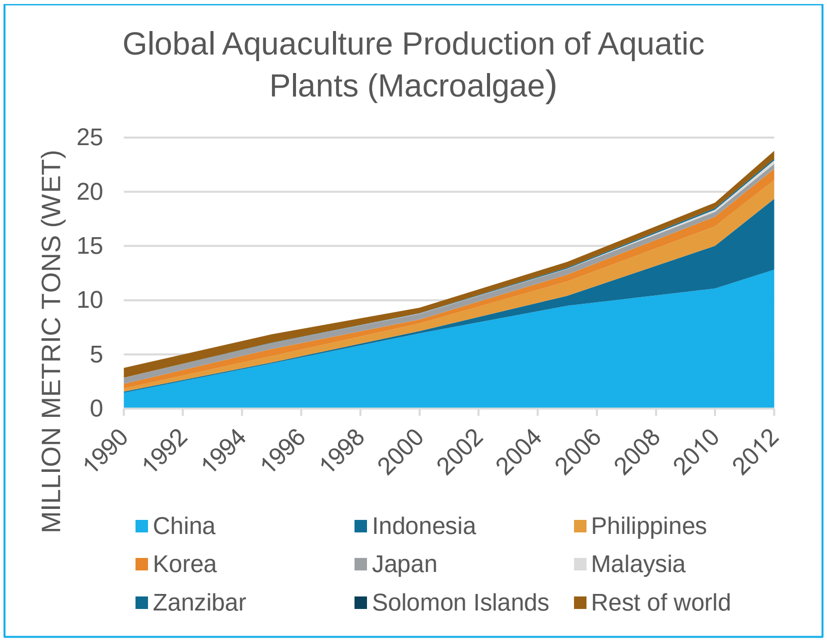

Figure 1. Led by China and Indonesia, global aquaculture production of macroalgae has grown 6-fold over the past 25 years, while capture from wild harvesting has remained static at approximately 1 million wet metric tons (data from wild harvesting not shown).[7]

Motivation:

Biomass-derived energy is the largest form of renewable energy for the nation, contributing about 5% of U.S. primary energy supply. This biomass is being used primarily in the generation of electricity and the production of liquid biofuels. In 2015, the U.S. produced approximately 11.5 billion "Gasoline Gallon Equivalents" (GGE) of liquid biofuels, equivalent to 5% of all the nation's transportation energy demand.[8] Domestically produced biofuels reduce the need for petroleum imports and build industry and jobs in typically rural areas. In the future, biomass-derived energy has the potential to play an even bigger role in the nation's energy portfolio. The ability to produce sufficient quantities of biomass offers the U.S. strategic flexibility to exploit carbon-neutral feedstock for fuels, biogas/synthesis gas, heat & power, and electricity.[9,10]

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[6] FAO. 2016. *The State of World Fisheries and Aquaculture 2016. Contributing to food security and nutrition for all.* Rome. 200 pp.

[7] Cottier-Cook, E.J. *et al.* (2016). Safeguarding the future of the global seaweed aquaculture industry. United Nations University (INWEH) and Scottish Association for Marine Science Policy Brief. ISBN 978-92-808-6080-1. 12pp.

[8] U.S. Department of Energy Energy Information Agency 2015 Energy Outlook

[9] Energy Technology Perspectives 2016 - Towards Sustainable Urban Energy Systems, IEA Webinar, June 2016 http://www.iea.org/media/etp/etp2016/ETP2016_Webinar_ALL.pdf

[10] Williams, J.H., B. Haley, F. Kahrl, J. Moore, A.D. Jones, M.S. Torn, H. McJeon (2014). *Pathways to deep decarbonization in the United States*. The U.S. report of the Deep Decarbonization Pathways Project of the Sustainable Development Solutions Network and the Institute for Sustainable Development and International Relations. Revision with technical supplement, Nov 16, 2015.

Significant investments have already been made to use cellulosic biomass sources, such as agricultural residues, as feedstock for the production of both ethanol and more infrastructure- compatible "drop-in" fuels. The U.S. Department of Energy BioEnergy Technologies Office (BETO) estimates that by 2030, 1-1.5 billion dry tons of biomass – an amount sufficient to displace at least 30% of the nation's demand for petroleum derived liquid fuels – could be available at a farmgate price as low as $60 per dry ton (or a $0.70 feedstock cost per gallon cellulosic ethanol) (Figure 2).[11]

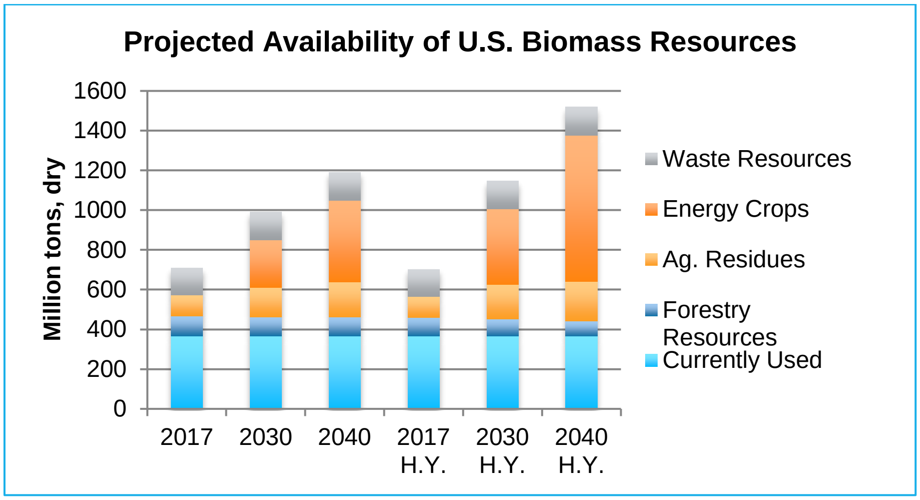

Figure 2. Projected availability of biomass resources for biofuel production potential under basecase scenario and high yield (H.Y.) scenario.

While encouraging, the BETO analysis relies heavily on deployment of "energy crops", such as perennial grasses. Many such feedstocks are under various stages of development. For example, the acceleration of domestic energy sorghum production is a particular focus of the ARPA-E TERRA program.[12] Ongoing research and development in this area is expected to advance adoption, but other risks remain to using terrestrially sourced biomass as feedstock for energy. Such risks include freshwater availability, land availability, and material handling and logistics. In particular, competition for land and fresh water is likely to increase as a growing world population (9 billion by 2050) is expected to increase the demand for food production by 59-98% by 2050.[13] At the same time, the increasing frequency of extreme weather conditions around the world can potentially further constrain the availability of suitable quantities of fresh water and arable land for terrestrial biomass production. Expanding biomass production into the oceans offers an important opportunity to bypass these constraints.

Our planet's oceans cover nearly 70% of the world's surface area; yet, at this time, they supply only 1% of the world's food and even less non-food biomass. Over thousands of years, humans have continuously improved their ability and technologies to extract resources from the ocean. In recent decades, humans have been rapidly developing and deploying new technologies in support of economically viable and environmentally sustainable aquaculture and mariculture. While the gains made in both of these areas have been impressive, the majority of these production gains are being realized primarily in Asia, and not in the U.S. despite compatible and favorable conditions. A recent assessment (funded by ARPA-E) of global geospatial conditions for potential red and brown macroalgae production considered four primary parameters: water temperature, nutrient concentration, bathymetry, and photosynthetically active radiation. The results of this analysis are summarized In Figure 3. Based on this preliminary assessment, ARPA-E estimates that the U.S. has suitable conditions and geography for producing approximately 200 million dry metric tons (DMT) of brown macroalgae and 300 million DMT

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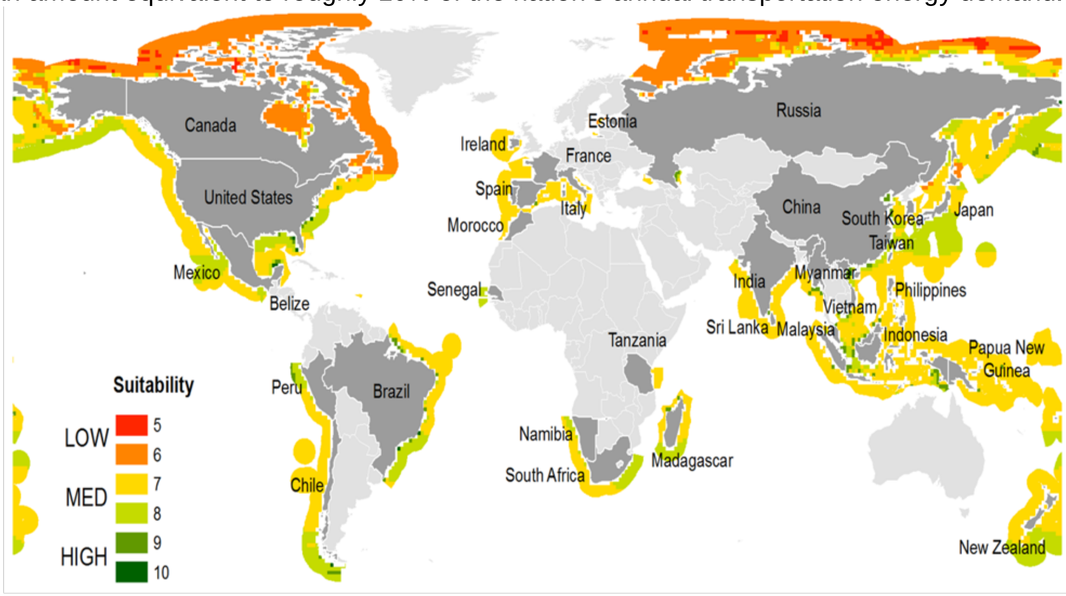
[11] U.S. Department of Energy. 2016. *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks*. M. H. Langholtz, B. J. Stokes, and L. M. Eaton (Leads), ORNL/TM-2016/160. Oak Ridge National Laboratory, Oak Ridge, TN. 448p.

[12] https://arpa-e.energy.gov/?q=arpa-e-programs/terra

[13] Valin, H. *et al.* (2014), The future of food demand: understanding differences in global economic models. Agricultural Economics, 45: 51–67

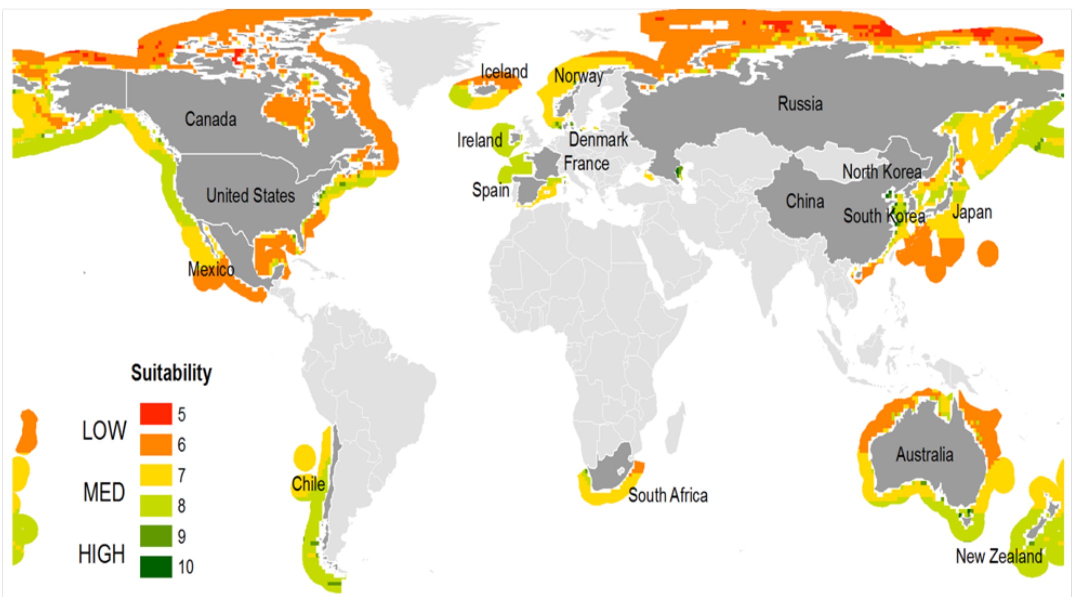
of red macroalgae.[14] Such production volumes could potentially yield approximately 2.7 Quads of energy in the form of liquid fuel – an amount equivalent to roughly 10% of the nation's annual transportation energy demand.[15]



Yield estimates by score:

10: 150 wet MT/ ha-yr , **9:** 133 wet MT/ ha-yr , **8:** 116 wet MT/ ha-yr , **7:** 98 wet MT/ ha-yr

A.



Yield estimates by score:

10: 147 wet MT/ ha-yr , **9:** 141 wet MT/ ha-yr , **8:** 135 wet MT/ ha-yr , **7:** 129 wet MT/ ha-yr

B.

Figure 3. A) Red macroalgae suitability map B) Brown macroalgae suitability map

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[14] Internal ARPA-E funded geo-spatial analysis conducted by Lux Research (Boston, MA)

[15] Energy calculation assumes a conversion efficiency of 230 liters of ethanol per DMT (from experimental data from Dr. Alejandro Buschmann, [Macrocystis production and conversion in Chile] ARPA-E Macroalgae Workshop, Feb. 2016.) which is equivalent to 23.6 billion gallons of gasoline equivalent (GGE) or 2.7 Quads energy. ARPA-E views this value as a conservative conversion factor in light of recent data that suggests a conversion of factor of nearly 600 liters ethanol per DMT is possible (See: Camus, C., et al. Scaling up bioethanol production from the farmed brown macroalgae Macrocystis pyrifera in Chile. Biofuels, Bioprodu. Bioref. 10:673-685 (2016))

The oceans represent the next frontier for production of industrially relevant quantities of biomass feedstock for fuels and chemicals. The U.S. has the technical, engineering, as well as geographic potential to realize this vision – the nation's marine exclusive economic zone (EEZ) is equivalent to the total land area of the United States. Production of biomass resources in the oceans has many advantages. Macroalgae do not require freshwater, nor land, and in many cases do not require "feeding" with nitrogen. The production and application of nitrogen fertilizer is a significant energy component of terrestrial crops – consuming approximately 50% of the energy budget of corn grain production. Additionally, macroalgae are better than terrestrial plants at fixing carbon dioxide, and produce a plant that is nearly 100% harvestable (Table 1).

Table 1. Macrocytsis advantages versus corn.

Plant	Photosynthetic Efficiency	Yield	Recoverable Carbon	Nitrogen Share of "Embedded Energy"
Field Corn (*Zea mays*)	4-6% max[16]	16 DMT/Ha [17]	~70%[18]	>50%[19]
Giant kelp (*Macrocystis pyrifera*)	4-10% max[20]	30 DMT/Ha [21]	>95%[22]	≥0%[23]

In support of ARPA-E's mission, this FOA seeks to significantly broaden the opportunities for macroalgae to be a significant energy contributor to a future low-carbon world, especially for the production of biofuels. ARPA-E supports the development of technologies under this FOA that are capable of providing economically viable, renewable biomass for energy applications that does not compete for land use. Additionally, ARPA-E has determined that near-term economic opportunities exist for macroalgae as a new and substantial source of protein and carbohydrate for livestock feed, which might provide economically viable bridging applications while the market for biofuels evolves and matures. With such potential in mind, ARPA-E is committed to the development of transformational technologies to enable a U.S. based macroalgae industry capable of producing up to 2 Quads of bioenergy by 2050, while also supplying the world's ever expanding need for animal feed. The ARPA-E MARINER Program will meet these goals by developing innovative cultivation & harvest systems able to produce macroalgae biomass that is cost competitive with terrestrial biomass at energy-relevant scale.

Current State Of The Art and Techno-Economics:

As previously mentioned, many Asian countries, notably China and Indonesia, produce the vast preponderance of the world's supply of macroalgae. Macroalgae farming is currently practiced on a cottage-industry scale; the output of a typical

[16] Borak, B., Ort, D.R., Burbaum, J.J. Energy and carbon accounting to compare bioenergy crops. Current Opinions Biotechnology 2013 Jun;24(3):369-75

[17] Theoretical yield based on average U.S. corn grain yield 168 bushels per acre and harvesting all grain and max 50% of above ground biomass (data source USDA National Agriculture Statistics Service Quick Stats (https://quickstats.nass.usda.gov/results/90C69DEC-38D6-31B4-9953-4C6EB5E82D79?pivot=short_desc)

[18] Recoverable carbon refers to the amount of carbon that can be reasonably and sustainably removed from the field. Theorectical value based on average U.S. corn grain yield (iBid) and 100% removal of grain (10.7 DMT total), 50% removal of corn stover (5.4 DMT total), and 0% removal of underground biomass (0.6 DMT total).

[19] Nitrogen share of embedded energy refers to the percentage of energy contained/used to generate nitrogen fertilizer relative to all energy used for corn cultivation and harvest. (See 2015 Energy Balance for the Corn-Ethanol Industry, USDA Office of the Chief Economist, Office of Energy Policy and New Uses, February 2016.)

[20] Fernandez *et al.* Photosynthesis Research 2015 124:293-304.

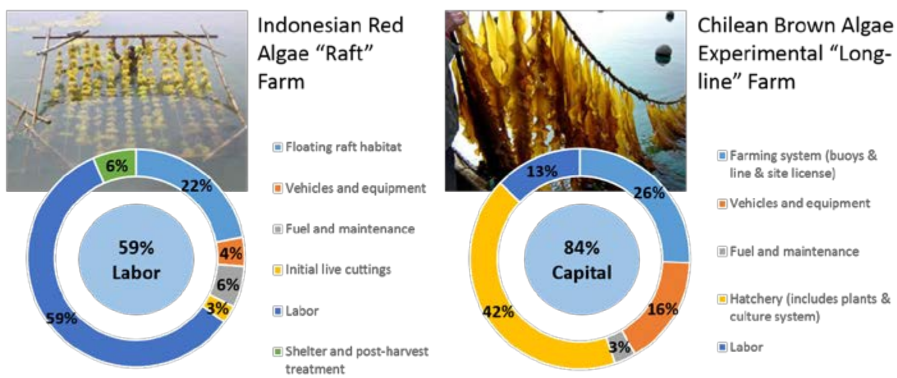
[21] Experimental plot data from Dr. Alejandro Buschmann, (See Macrocystis production and conversion in Chile ARPA-E Macroalgae Workshop, Feb. 2016.) While high yields have been reported in experimental plots for macrocytsis, yields vary widely depending on species, nutrients, and geography, among other factors.

[22] Theoretical assumption that nearly all marine biomass can be harvested considering the lack of requirement to maintain soil carbon "health" in the case of terrestrial crops.

[23] Assumes zero additional fertilizer input in the aquatic system.

farm can be measured in tens rather than hundreds or thousands of dry metric tons. Macroalgae production systems are typified by either "rafts" or anchored "long line" farm designs. The raft design is typically deployed in shallow, often intertidal waters and can be tethered to float, or be fixed at a precise depth. Rafts are often useful for production of macroalgae species such as *Kappaphycus alvarezii*, a red algae that grows vegetatively via branching. Anchored long line designs are representative of the state of the art for brown algae such as *Saccharina japonica* that are capable of growing to 10 meters in length. Such brown algae can be germinated in a hatchery directly on nylon strands, which are then deployed at the aquafarm site by wrapping around long structural support lines. A single support line can be considered analogous to a single row of plants on a typical terrestrial farm. Algae support lines are run in parallel to one another and are spaced apart for optimization of light and nutrient flux.[24,25] The macroalgae is typically harvested by cutting the plant with a blade and lifting the biomass into a boat.

Two examples of macroalgae farm designs are presented in Figure 4. The Indonesian raft farm is capable of producing red algae at a marketable cost for current food applications; however, in this case, the raft farm production cost is dominated by labor.[26] Considering that labor costs inherently do not decrease with scale, the scalability of raft systems to larger farms and to open ocean environments is severely limited. Additionally, current raft production systems are likely limited to tropical latitudes with low energy waves, and therefore also face geographic constraints to scaling. Anchored long line systems on the other hand are typically more capital intensive, but are more productive and efficient. The example shown is from data acquired from an experimental Chilean *Macrocystis* farm.[27] In that case, the current production cost is not competitive because of the high capital investment relative to production volume; this suggests that new technologies are required to improve return on capital for long line systems through increased yield and scale, and to decrease production costs. Current production data from China remains elusive, but ARPA-E believes that the long line systems deployed in China are also very labor intensive and are therefore only profitable at very low labor rates.



	Indonesian raft	Chilean long-line
Total line	33 km line	20 km line
Total Yield	33 dry metric tons (DMT)	56 dry metric tons (DMT)
Cost per DMT	$223	~$500
Productivity	1 DMT/km	2.8 DMT/km

Labor intense –
Does not benefit from economies of scale.
Restricted to calm waters.

Capital Intense –
Can benefit from economies of scale.
More robust for open ocean waters.

Figure 4. Examples of current macroalgae cultivation systems.

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[24] Flavin, K., *et al.* Kelp Farming Manual. Ocean Approved (2013).

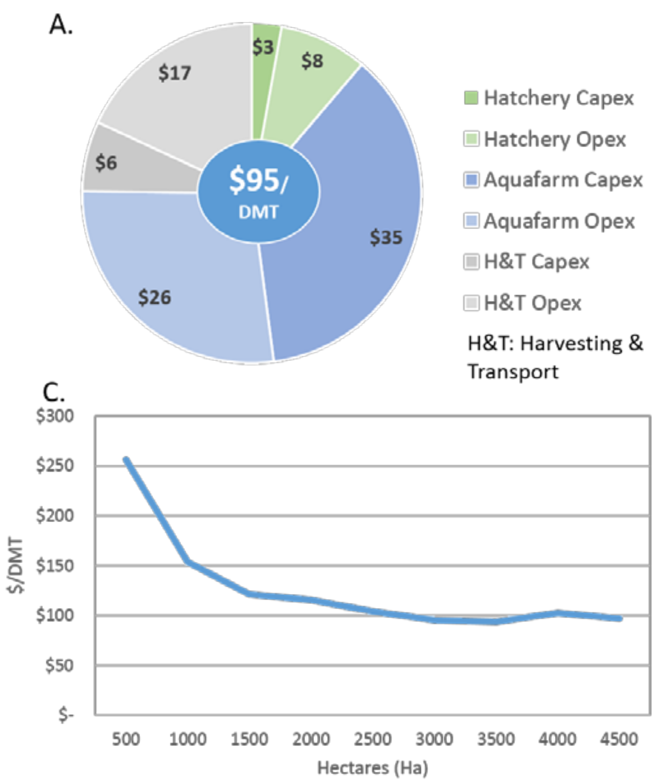
[25] Redmond, S., L. Green, C. Yarish, , J. Kim, and C. Neefus. New England Seaweed Culture Handbook-Nursery Systems. Connecticut Sea Grant CTSG-14-01. 2014. (http://seagrant.uconn.edu/publications/aquaculture/handbook.pdf)

[26] Valderrama, D. *et al.* Social and economic dimensions of carrageenan seaweed farming. FAO Fisheries and Aquaculture Technical Paper 580, Food and Agriculture Organization of the United Nations (Rome) 2013.

[27] Correa, T., et al. Production and economic assessment of giant kelp Macrocystis pyrifera cultivation for abalone feed in the south of Chile. Aquaculture Research 47: 698-707 (2016)

Attempts have been made in the United States over the past 100 years to utilize macroalgae for the production of potash, and as a feedstock for biogas and biofuel production. The techno-economics of these highly-engineered solutions were never rigorously evaluated, and in all cases the solutions failed.[28,29] Such projects were typically initiated in response to a temporary resource crisis. However, much can be learned from these efforts and from the current state of macroalgae production outside of the U.S. in conceiving of new macroalgae systems that take advantage of economies of scale, maximize nutrient uptake, and are sufficiently robust for high(er) energy ocean environments. ARPA-E is interested in new systems that minimize capital costs per unit of output by maximizing yields (i.e. intensification), and that enable production over wider areas by reducing the need for labor, while overcoming nutrient limitations that may diminish farm productivity.

ARPA-E recognizes the significant challenges of developing and deploying biomass cultivation systems in the open ocean. In order to assess the potential for large-scale macroalgae production, ARPA-E simulated various techno-economic scenarios for the cultivation of the giant kelp *Macrocystis* through scenario analyses that are aspirational yet technically reasonable,[30] and that are based on the best information available. While the analysis framework makes several assumptions that may not translate to all ocean environments, farm designs, and/or macroalgae species, it is believed to be a reasonable representation of the variables that need to be considered in planning for high volume cultivation. Figure 5 presents results from a modeled *Macrocystis* farm at 3,000 hectare (Ha) scale. In this case, the target yield was set at 25 DMT/Ha, a value consistent with yields occasionally seen in highly productive systems.



B.

Major Assumptions	
Hectares	3,000
Target yield, DMT/Ha	25
DMT/yr	61,000
WMT/yr	485,000
Capacity factor	90%
Seeding frequency/yr	1
Boat fuel price/gallon	$3.00
Meter culture rope/Ha	6,600
Harvester boats	1
FTEs	47
Labor rate, fully loaded per FTE*	$20,000
Production cost, $/DMT	**$95**

*With a higher labor rate assumption of $40,000 fully loaded per FTE, production cost increases to $99/DMT.

Figure 5. A) Full CapEx and OpEx breakdown necessary to achieve $95/DMT; B) List of assumptions used in the model*; C) Relationship between production cost and scale (at 25 DMT/Ha)

This model is based on the "anchored long line" design described earlier, and is intended to illustrate how costs may be distributed across the three primary operational segments of a hypothetical macroalgae farm: a hatchery where macroalgae is germinated on culture rope until it is ready for deployment; an aquafarm where the culture rope is deployed on structural

[28] Ashare, E. *et al.* Cost analysis of aquatic biomass systems - final report. Dynatech R/D Company, Cambridge, MA. (1978).
[29] Neushul, M. and Harger, B.W.W. Kelp biomass production: Annual technical report. Gas Research Institute, Chicago, IL. (1985)
[30] Camus, C. and Buschmann, A.H. Macrocystis pyrifera aquafarming: production optimization of rope-seeded juvenile sporophytes. Aquaculture 468:107-114 (2017).

rope supports over the intended cultivation area; and a harvesting and transport operation which gathers the mature crop and delivers it to shore.[31] The model incorporates additional assumptions about the operating parameters of each of these segments, including anticipated growth periods, productivity of labor, operational capabilities of necessary equipment (e.g. boats), costs of installation, and consumption rates of electricity, water and fuel. All of these inputs are then used to compute an integrated and internally consistent estimate of overall production capability and associated costs. <u>Note that this model and the derived numbers shown here are for illustration only. ARPA-E anticipates that teams responding to this FOA will develop and justify their own cost models, based on appropriate assumptions consistent with their specific concepts and designs.</u>

In the ARPA-E "anchored long line" model, the costs associated with the aquafarm dominate, strongly suggesting that technologies to reduce aquafarm costs and/or maximize yield per unit of capital are necessary. The model also predicts a non-linear relationship between total production cost and scale, and illustrates the limits of economies of scale under the current set of assumptions. In this particular case, production costs bottom out at 2,500 Ha and remain flat because production capacity is added in modular increments based on the capabilities of existing capital equipment; farms much smaller than 2,500 Ha would have a difficult time competing.

A.

CAPEX Assumptions	Sub-components	Approximate capex ($ MM)	Assumed Lifetime (yrs)	Annual depreciation ($K)
Hatchery	Hatchery - Building	0.95	15	63
	Hatchery - Water System	0.1	10	10
	Hatchery - Tanks + Equipment	0.9	10	90
Aquafarm	Anchors & chain	3.0	50 yrs	60
	Survey	0.9	50 yrs	18
	Culture Rope and Structural Rope	4.8	5	960
	Buoys, Hardware & Installation	8.3	10	830
	Aquafarm - Boats	7.1	30	236
H&T	H&T - Boats	10.0	30	333
	H&T - Docks	6.6	30	220

B.

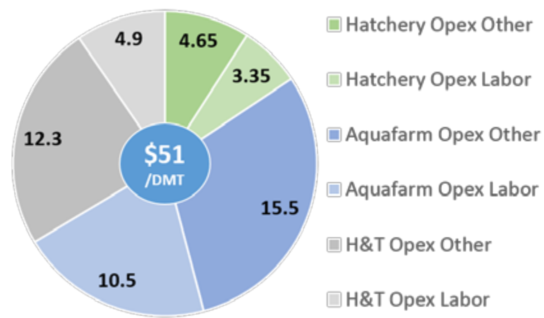


Figure 6. A) CapEx breakdown for farm sub-components; B) OpEx breakdown; all values derived for modeled $95/DMT production system (assumptions can be found in Figure 4B).

[31] This model is based on information provided by Bio Architecture Lab (BAL). BAL has previously received funding from ARPA-E for a macroalgae to fuels project (OPEN 2009).

improvements, macroalgae production at industrial scale will fail.

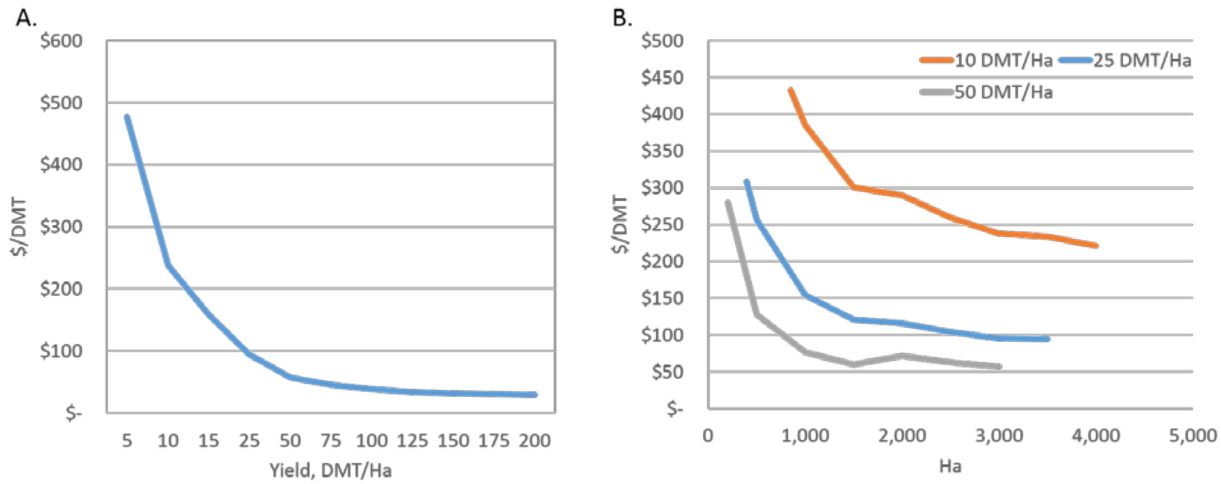


Figure 7. A) Relationship between production cost and yield (at 3,000 Ha scale); B) Impact of yield on cost at increasing scale.

Currently, to our best knowledge, most commercial macroalgae production rarely achieves yields exceeding 10 DMT/Ha. At that level of productivity, the model indicates a production cost floor of $238/DMT (Figure 7B), a value which cannot compete with the anticipated cost of terrestrial energy crops. This analysis demonstrates quite convincingly that the benefits of scale can only be realized if sustained farm level yields can be increased significantly beyond the capabilities of current production systems.

The growth of macroalgae requires light, carbon dioxide, nitrogen, phosphorous, and trace-level micro-nutrients. Of all of these requirements, biologically available nitrogen is the limiting factor to growth and yield. In the open ocean, biologically available nitrogen may be provided by point sources such as anthropogenic waste water discharge or fertilizer runoff, from microbial nitrogen fixation, and nutrient "up-welling" from the deep ocean. Deep water nutrients can potentially also be accessed via pumping or by physically submerging plants to depths where nutrients are available (i.e. below the thermocline). Additionally, macroalgae farms can be actively fertilized. Regardless of which solutions are employed, these new macroalgae cultivation systems must be capable of delivering sufficient quantities of nutrients effectively without environmental damage, and at negligible cost, in order to be highly productive and economical.

PROGRAM VISION

ARPA-E is committed to the development of transformational technologies to enable a U.S. based macroalgae industry capable of producing up to 2 Quads of bioenergy by 2050. The ARPA-E MARINER Program will meet these goals by developing innovative cultivation and harvesting systems, and the supporting tools necessary to produce macroalgae biomass that is cost competitive with terrestrial biomass at energy-relevant scale.

The primary challenges are to dramatically increase yield per unit of capital, reduce overall capital requirements and minimize the operating cost of macroalgae cultivation, and to significantly increase the range of deployment by expanding into more exposed, off-shore environments.

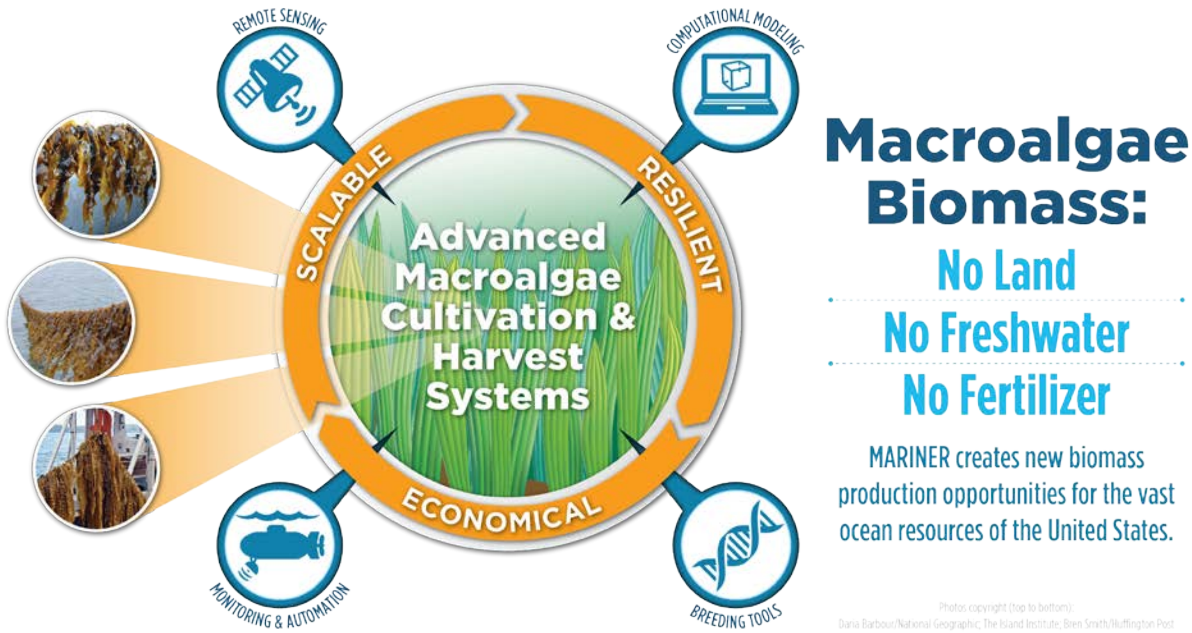


Figure 8. MARINER Program Vision

The technology opportunities envisioned by the program are illustrated in Figure 8. Technologies developed under the MARINER program will address marine system design/engineering and integration with biomass production, hydrodynamic and ocean modeling, sensor technology development, macroalgae breeding tools, and field testing of cultivation systems and sensor technologies.

D. PROGRAM STRUCTURE AND TECHNICAL CATEGORIES OF INTEREST

The MARINER program is focused on supporting the development of biological and engineering solutions for sustainable and cost-competitive production of macroalgae in both near-shore and off-shore ocean environments. Specifically, ARPA-E is soliciting submissions that address one or more of the following categories:

- **CATEGORY 1: Design & Experimental Deployment of Integrated Cultivation and Harvesting Systems**
- **CATEGORY 2: Design & Experimental Deployment of Advanced Component Technologies**
- **CATEGORY 3: Design & Testing of Computational Modeling Tools**
- **CATEGORY 4: Design & Testing of Aquatic Monitoring Tools**
- **CATEGORY 5: Research & Development of Advanced Breeding and Genetic Tools**

ARPA-E anticipates submissions will address only one category. ARPA-E may be open to submissions that address more than one category if such a submission is clearly integrated and thoroughly addresses relevant performance targets for each category. Submissions that address more than one category must show significant synergy between the respective categories addressed. Alternatively, per Section III.C.4 of this FOA, ARPA-E is not limiting the number of submissions from Applicants. Applicants may submit more than one application to this FOA, provided that each application is scientifically distinct.

CATEGORY 1: Design & Experimental Deployment of Integrated Cultivation and Harvesting Systems

ARPA-E is interested in fundamentally new designs and approaches to macroalgae cultivation and production with integrated harvesting solutions. These systems may leverage new material and engineering solutions, autonomous and/or robotic operations, advanced sensing and monitoring capabilities, as well as advanced ecological systems approaches such as co-cultivation of multiple species of algae. In addition to “field-type” cultivation, ARPA-E is also interested in unconventional approaches, for example avoiding the use of cultivation support infrastructure via “ranching” where free floating macroalgae are harvested at locations predicted or determined by satellite imaging and current/drift modeling. Given the enormous size and geographic diversity of the U.S. offshore exclusive economic zone (EEZ), we expect that there will be different system solutions based on the intended area of deployment, macroalgal species to be cultivated, and downstream processing methods. Nonetheless, in all cases ensuring appropriate nutrient management and/or delivery to and within macroalgae cultivation systems will be critical to achieve desirable yield targets.

Category 1 projects will be structured in a two-phase approach, with Phase 1 focusing on system design and techno-economic as well as life-cycle analysis (TEA and LCA), and Phase 2 consisting of building, deploying and testing a pilot-scale system to demonstrate key performance metrics. The initial period of performance for Category 1 awards will be for Phase 1 and will not exceed 12 months. Upon successful completion of Phase 1 and subject to the availability of appropriated funds, only the most promising projects will be selected for a Phase 2 award, which can run up to an additional 3 years. All Category 1 submissions must include budgets and task descriptions that cover both Phase 1 and Phase 2 – Phase 1 in detail and a clear outline of Phase 2.

CATEGORY 2: Design & Experimental Deployment of Advanced Component Technologies

ARPA-E is also interested in new or improved components to significantly improve performance and reduce costs within today’s standard approaches to cultivation and harvesting of macroalgal biomass, e.g. anchored long line cultivation systems. This category seeks technologies that can significantly reduce the overall capital and/or operating cost as well as the energy requirement of the system. ARPA-E is most interested in enabling advances of components with the highest impact on cost and/or energy efficiency, including low energy harvesting and handling technologies, cultivation system components such as lines and anchors, as well as increased productivity of macroalgae hatcheries, specifically for red algae species, which currently face more productivity challenges than do brown algae. Technology for automation of any of these operations is of particular interest. In addition, ARPA-E is interested in innovations that allow these existing systems to be economically deployed over significantly larger and more remote areas, e.g. by enabling the systems to move from relatively protected bays to more exposed stretches of ocean.

CATEGORY 3: Design & Testing of Computational Modeling Tools

To accelerate the design, testing, and operation of new cultivation and harvest systems, ARPA-E is interested in the development of appropriate computational modeling tools. Tools of particular interest are those for hydrodynamic modeling which can simulate the performance of a given cultivation system design in response to ocean current conditions over time and space, and storm events. Another application of interest is nutrient flux modeling within a farm “field.” In addition to the hydrodynamic components such nutrient flux models will need to incorporate models for nutrient uptake by the macroalgae. ARPA-E is also interested in larger scale nutrient flux models, which provide the capability to assess the effect on primary phytoplankton productivity of larger, regional-scale deployment of macroalgae farms. The modeling tools developed under this category should be flexible enough to accommodate a wide variety of cultivation system designs. They are also intended to work in conjunction with advanced marine systems mapping or marine spatial planning tools to identify appropriate deployment opportunities for macroalgal cultivation.

CATEGORY 4: Design & Testing of Aquatic Monitoring Tools

ARPA-E is interested in the development of sensor and analysis tools which allow in-situ monitoring of macroalgae in a farm-sized cultivation system. Specifically, ARPA-E is interested in the ability to monitor growth, spatial distribution, and composition of macroalgal biomass, as well as nutrient concentrations in the waters of a macroalgae farm. Furthermore, ARPA-E is interested in sensors and technologies for biosecurity, including the detection and prevention of disease and herbivory. In-field (ocean) sensor systems should be deployable on autonomous, or semi-autonomous, surface or underwater vehicles, and should include onboard sensor data analysis as appropriate to deliver actionable information to a grower or an automated management system. In addition, tools for the analysis of data acquired via remote (aerial or surface) sensing or satellite imaging are of interest.

CATEGORY 5: Research & Development of Advanced Breeding and Genetic Tools

Finally, ARPA-E is interested in the development of advanced breeding and genetic tools, to accelerate the development of macroalgae cultivars with improved performance parameters including higher yield, improved composition, and temperature and disease tolerance. An important starting point is the development of rapid screening tools to assess genetic diversity in natural populations of macroalgae. In a variety of geographies, this information will be critical for expediting the regulatory approval process for macroalgae farms. In addition, this information is expected to improve the selection of appropriate local or regional breeding stock for subsequent breeding programs. ARPA-E is especially interested in the adaptation of modern breeding methods such as marker assisted selection or genomic selection to the unique life cycles of macroalgae, with the goal of enabling rapid, high-throughput strain development. Development of hybrid seed systems and inbred propogation systems (cytoplasmic sterility systems), and mapping populations (recombinant inbred lines, nested association mapping panels, etc.), are of interest in this category to capitalize on well-described hybrid vigor and to assist in gene identification. However, at this point, ARPA-E is not interested in developing tools to genetically engineer macroalgae.

E. TECHNICAL PERFORMANCE TARGETS

Responses to this FOA must have a well-justified and realistic potential to meet or exceed the following Primary Technical Targets by the end of the project period. A description of each of the Technical Categories together with the applicable Technical Performance Targets is provided below. ARPA-E recognizes that there may be certain solutions that do not match perfectly with the expected performance targets. In those cases, a logical and well-articulated explanation must be provided as a justification for any deviation from the prescribed performance targets.

CATEGORY 1: Design & Experimental Deployment of Cultivation and Harvesting Systems

The final objective for Category 1 is ocean deployment of a prototype macroalgae cultivation system with an integrated harvesting technology. A successful Category 1 prototype will validate all of the following primary technical targets:

Category 1 Primary Technical Targets

ID	Metric	Primary Design Targets
1.1	Full System Size	≥ 1,000 hectares
1.2	Range of Deployment	≥ 100,000 hectares
1.3	Biomass Production Cost	≤ $80/dry metric ton biomass
1.4	Net Energy Return	≥ 5:1
1.5	Nutrient source	Needs to be scalable. Direct application of synthetic fertilizer is not permitted.

Metric Descriptions – Primary Technical Targets

1.1 Full System Size

System size and scalability are critical to establishing a macroalgae ocean farming industry that is capable of achieving an energy-relevant scale. Indeed, this FOA Category requires the development and deployment of technology capable of achieving farm productivity and scale that will eventually supply biomass at costs competitive with terrestrial biomass feedstocks such as agricultural residues or energy crops, both of which are assumed to be collected from millions of hectares of U.S. cropland. ARPA-E requests that Applicants propose and present convincing information and arguments that demonstrate the potential for a proposed system design to scale to ≥ 1,000 hectares. This information must include, at a minimum, a diagram of the farm and description of the scaling factors necessary to achieve the 1000 hectares farm size and a description of the size and number of all critical unit operations, from hatchery to harvesting. In Phase 2, the Experimental Deployment Phase, the underlying assumptions for system scalability will need to be validated experimentally with an ocean deployed prototype.

1.2 Range of Deployment

The Applicants must clearly identify specific ocean areas that are suited for deployment of the specified design. The specific ocean area or areas must in aggregate add up to at least 100,000 hectares. The minimum criteria that must be considered and justified when assessing the availability of suitable ocean area are sufficient nutrient availability and compatibility of the system design with prevailing current and weather conditions.

1.3 Production Cost

For macroalgae biomass to serve as feedstock for biofuel production, production costs must be competitive with terrestrial biomass feedstocks. ARPA-E expects that applicants will demonstrate at the end of Phase 1, via techno-economic modeling, the potential of their proposed system to achieve macroalgae biomass production at a cost of ≤ \$80/DMT of harvested biomass (cost attributed to drying of wet biomass need not be considered at this time).

All submissions must clearly articulate why their design is unique, and specify where significant improvements are expected versus the current state of technology. This must be convincingly demonstrated with exceptional engineering design and techno-economic analysis. Responses to Category 1 must clearly identify the primary assumptions and key calculations that connect farm design to final product cost of biomass (\$/DMT). The techno-economic analysis presented in Section I.B. above for the long-line cultivation system can serve as an example of the type of analysis ARPA-E expects will be included with every Category 1 Full Application submission. In particular, system productivity, e.g. expressed as annual biomass yield in DMT per unit area, is a major driver of macroalgae production cost, and the underlying assumptions, such as species used, geographic location and nutrient availability, need to be made explicit. The expected target yield for the proposed system should be clearly identified, as well as the sensitivity of the production cost to changes in target yield. Finally, it is important that the underlying assumptions are adjusted for the anticipated location of deployment, for example the cost of labor and transportation of product back to shore should be expressed as a function of distance from shore.

1.4 Net Energy Return

The net energy return is defined as the energy content, expressed as lower heating value (LHV), of the final product versus the amount of process energy from all unit operations involved in the production of the final product. Energy from solar radiation should not be included in this calculation. ARPA-E seeks concepts and technologies capable of delivering a net energy return ≥ 5:1, meaning that the final product, i.e. the harvested kelp, will contain 5 times the amount of energy relative to the amount of energy required to produce the biomass product. Energy required for drying the harvested biomass need not be considered in this calculation. This net energy return must be calculated from design and engineering techno-economics. The key assumptions used for these calculations will need to be validated as closely as possible experimentally. Just for clarity, ARPA-E does not require attribution of the energetics of biomass conversion (e.g. hydrothermal liquefaction (HTL)) for this calculation and demonstration.

1.5 Nutrient Supply

Direct fertilization of the macroalgae farm with synthetic or mineral fertilizer is not acceptable. However, supplementing the nutrient supply by recycling nutrients contained in byproducts of macroalgae processing to fuel may be considered. The source of nutrients needs to be specified (e.g. anthropogenic run-off, upwelling, etc.) and clear evidence needs to be provided that this nutrient source will be sufficient to supply a full scale farm (Target 1.1) over the course of the annual production cycle. The source of nutrients also needs to be scalable over the project deployment range of the farm as specified under Target 1.2.

Although Category 1 focuses on integrated cultivation and harvesting systems, ARPA-E will require Applicants to conceptually delineate technical solutions for macroalgal biomass transport and storage for a proposed system solution. Additionally, ARPA-E does not envision funding of concepts under this FOA that address macroalgal biomass conversion to biofuels or other end products. However, ARPA-E acknowledges that the intended use of the harvested macroalgae may influence the design of the most optimal harvesting, transport, and storage solutions to meet expected end use outcomes. Therefore, Applicants should specify which of the following three potential pathways for conversion to fuel they assume will be supplied with biomass from their system: 1) Hydrothermal liquefaction, 2) Anaerobic digestion, or 3) Carbohydrate extraction and fermentation. Conceptual solutions for biomass transport and storage that are aligned with the specification of an anticipated conversion platform will support a more accurate TEA and LCA.

Successful execution of Category 1 projects will occur in two phases over a maximum of 48 months. All Category 1 submissions must include budgets and task descriptions that cover both Phase 1 and Phase 2 – Phase 1 in detail and a clear outline of Phase 2. Details are described below:

Phase 1 (Design Phase): The Design Phase will consist of design and techno-economic assessment including life cycle assessment of a complete macroalgae cultivation and harvesting ocean-farm system. ARPA-E anticipates that the Design Phase will be completed within a budget of \$500,000. ARPA-E will complete a project review of the Design Phase within 12 months from the start of the project. The most promising projects will be selected for advancement to the Experimental

Deployment Phase. At the Design Phase Project Review, all projects will be evaluated based on the following considerations:

- Potential of a full-scale system to achieve final primary Category 1 target metrics;
- Infrastructure robustness/resilience;
- Geographic and macroalgae species factors;
- Siting hazard assessment and mitigation plan;
- Environmentally sound provision of nutrients;
- Weather impact assessment;
- Design considerations for animal welfare;
- Design of Experimental Deployment system and its ability to derisk key technical innovations;
- Status of permits necessary to operate in ocean waters;
- Construction schedule; and,
- Overall execution plan.

Phase 2 (Experimental Deployment Phase): The Experimental Deployment Phase will consist of construction, ocean testing/validation, and performance of a complete cultivation and harvesting system. ARPA-E anticipates that the Experimental Deployment Phase will be completed within 36 months from selection of a project to advance to the Experimental Deployment Phase. The exact size of the Experimental Deployment system will need to be specified during the Design Phase and is expected to be system specific. The key goal is to demonstrate the system at the smallest scale possible, while ensuring that critical design features of the full scale system can be validated and derisked. During the Experimental Deployment Phase, ARPA-E anticipates the potential for integration and/or use of technologies developed under MARINER FOA Categories 2 – 5.

CATEGORY 2: Design & Experimental Deployment of Cultivation and Harvesting System Component Technologies

The final objective for Category 2 is development and delivery of cultivation and harvesting system component technologies. ARPA-E is interested in receiving concepts that address the major techno-economic drivers of the final production cost as spelled out in Section I.B. above in the techno-economic analysis for long line cultivation. In addition, ARPA-E is interested in technology advancements that can significantly expand the scale of macroalgae cultivation without negatively impacting cost and performance. To the extent possible, technologies addressing Category 2 should incorporate automation in order to reduce labor cost. Proposed concepts must be delineated from design to the point of integration with a complete cultivation and harvesting system. Concepts must convincingly articulate a feasible solution capable of meeting at least one of the following primary technical targets:

Category 2 Primary Technical Targets

ID	Metric	Targets
2.1	Performance Enhanced Cost Contribution Reduction	The chosen component technology and/or unit operation cost must be lower by 50% relative to current state of the technology selected for substitution. Prior to improvements, the chosen component technology and/or unit operation should have contributed at least 30% of the overall CapEx or OpEx cost, based on current state of technology.
2.2	Performance Enhanced Expansion of Scale	The chosen component technology needs to enable an increase in farm size or potential area of deployment by at least a factor of 5 relative to current practice.

Metric Descriptions – Primary Technical Targets

2.1 Performance Enhanced Cost Contribution Reduction

Internal ARPA-E analysis, as shown in Figures 5 and 6, based on the current state of technology indicates that the capital expenses of the production system are dominated by farm equipment costs closely followed by the expenditure for boats for harvest and cultivation. The largest operating cost drivers are boat fuel, particularly for harvesting, and labor. Any technology proposed to reduce capital or operating cost should focus on those areas which contribute more than 30% to the overall CapEx or OpEx of the operation. The targeted improvement should achieve at least 50% cost reduction compared to current state of the art. One example would be a new harvest system design that reduces fuel consumption for that operation by at least 50%. The overall effect of the expected performance improvements will need to be demonstrated with a rigorous techno-economic analysis which clearly spells out underlying assumptions. Other potential areas for significant cost reductions are farm system CapEx and nursery CapEx.

2.2 Performance Enhanced Expansion of Scale

To achieve a scale relevant to the energy sector, the production of macroalgae needs to expand by at least two orders of magnitude beyond current total global levels of production. Production of seedlings, particularly for red algal species, is often seen as a bottle neck for expanding production. Innovative technologies to expand production need to demonstrate an improvement of at least 5x over the current state of the art up to a total farm area of 3000 ha. In addition to the need for more productive processes, macroalgae farms are typically confined at present to relatively protected bays. ARPA-E is seeking novel approaches to increasing the resilience of key system components, which expand the range of deployment of existing farm systems by at least a factor of five. The increased resilience will need to be demonstrated experimentally, and the expanded areas of ocean that become available have to be mapped out.

Successful execution of Category 2 projects will occur in a single phase over a period of up to 36 months. Category 2 technologies will be expected to validate primary technical targets in an ocean environment. Preferably, this should be done at a suitable, existing macroalgae farm site or in conjunction with a Category 1 project during the final 12 months of the Category 2 project period of performance in order minimize expenses.

During the in-ocean validation effort, ARPA-E anticipates the potential for integration and/or use of technologies developed under MARINER FOA Categories 1 and 3 – 5.

CATEGORY 3: Design & Deployment of Computational Modeling Tools

The objective for Category 3 is development and delivery of computational modeling tools that facilitate the development and assessment of new macroalgae cultivation systems at the farm level. It is expected that these modeling tools will be developed within 12 months from the start of the project and made available to and tested with systems developed by teams in Category 1 (and Category 2, as applicable). Close communication and collaboration with applicable Category 1 and 2 teams is encouraged to ensure usefulness of the developed tools to the overall program effort.

ARPA-E is interested in tools to model the following farm-level processes:

- Response of farm structural components to hydrodynamic stresses
- Interaction between macroalgae and farm structural components
- Nutrient flux including uptake by macroalgae

In addition, ARPA-E is also interested in models assessing competition for nutrient consumption between macroalgae farms and natural phytoplankton populations on a regional scale.

Primary Technical Targets

ID	Metric	Targets
3.1	Resolution	• 1 m^3 (farm-level processes) • 1 hectare (regional scale models)
3.3	Flexibility	Tool applicable to multiple system designs

Metric Descriptions – Primary Technical Targets

3.1 Resolution

A spatial resolution of 1 m^3 is anticipated in order to enable modeling capabilities for making exploratory, predicative, and dynamic decisions on the macroalgae farm level. A three-dimensional model is required for farm level processes in order to account for the vertical axis present in most if not all farm designs. At the regional scale, two-dimensional models should target a resolution of 1 hectare.

3.2 Flexibility

Farm-level models should be flexible to accommodate different farm designs for modeling dynamics within a farm system.

Successful execution of Category 3 projects will occur in a single phase over a period of up to 24 months. There is a strong preference for projects addressing the modeling of farm structural components in order to have usable models available within the first 12 months that can be applied to Category 1 and 2 projects. For nutrient flux models at the farm or regional scale a plan to validate the models with in-field data should be included. Projects that include in-field data collection may be extended to 36 months.

CATEGORY 4: Design & Deployment of Aquatic Monitoring Technology & Tools

The objective for Category 4 is development and delivery of technologies capable of autonomous or semi-autonomous monitoring of macroalgae farms. The minimum deliverable will be a functional prototype with one or more monitoring properties identified below that has completed testing in an ocean environment. Additionally, ARPA-E is interested in tools that utilize data from remote sensing platforms and/or satellite imaging.

Specific Properties of Interest are:

Properties
Plant level
Biomass growth rate
Macromolecular biomass composition
Presence of disease and herbivory
In-Field level
Biomass distribution variability
Dissolved nitrogen concentration
Presence of disease and occurrence of herbivory
Remote Sensing level
Identification of macroalgae fields
Quantification of algal biomass density
Photosynthetic activity/growth rate
Plant health (indicators of nutrient deficiencies)

Examples of technologies that may be useful for monitoring include:

- Multi-channel/spectral imaging
- Acoustic imaging
- Autonomous biomass sampling
- Autonomous, surface and/or submersed movement

ARPA-E is interested in submissions that propose the various in-ocean sensor technologies deployed on unmanned underwater vehicles (UUV) to conduct field level sampling. Most likely, there will not be enough funds to develop new underwater vehicles under this program. Instead, Applicants should try to utilize or modify existing UUV systems.

Considering the power requirements for analytical equipment and data transfer, ARPA-E is particularly interested in technologies capable of integration with renewable energy captured in-field. ARPA-E anticipates that Category 4 technologies will have an opportunity to be tested in-field at locations/farms developed under Category 1 or 2 of this FOA. Applicants must propose what instrumentation specific technical targets they anticipate will be achieved during the proposed performance period. Submissions also need to describe an appropriate calibration plan to validate sensor accuracy. In addition, sensor technologies proposed under this category must meet the following primary technical targets:

Primary Technical Targets

ID	Metric	Targets
4.1	Instrumentation Target	Precision: +/-5% of target property Accuracy: +/-20% of ground truth value
4.2	Scalability	≥ 20 hectares
4.3	Data Capture Rate	≥ 2 times/sampling location/week; including environmental measurements such as nutrient concentration
4.4	Environmental Operating Tolerance	Temperature range 32-100°F; prototype will be capable of performing 100 hours of data collection in an ocean environment

Metric Descriptions – Primary Technical Targets

4.1 Instrumentation Target

All instruments being developed should at least achieve a precision of +/- 5% of the target property measured. The accuracy should be at least +/- 20% relative to the ground truth value. Applicants need to specify the method used to establish the ground truth value.

4.2 Scalability

All "in-field" monitoring technologies need to be scalable for deployment over areas ≥ 20 hectares without interruption.

4.3 Data Capture Rate

Technologies anticipated to be deployed "in-field" will be expected to capture data at the rate ≥ 2 times/sampling location/week. In the case of a plant-level analysis, "sampling location" means an individual plant. In the case of in-field level analysis, sampling location refers to a given location specified by longitude and latitude data or relative to the coordinates of the farm grid. The sampling frequency value is determined by ARPA-E to be the minimal data capture rate necessary to provide enough data to identify trends and inform models. The Applicant must justify any expected deviation from this technical target.

4.4 Environmental Operating Tolerance

All technologies that will be deployed "in-field" must be compatible with harsh ocean conditions, including but not limited to biofouling, corrosion, and ocean currents. All "in-field" prototypes must demonstrate the capability of performing 100 hours of data collection in an ocean environment. It is expected that the 100 hours of data collection will not necessarily be continuous but tests should be designed to assess feasibility of long-term operation.

Successful execution of Category 4 projects will occur in a single phase over a period of up to 36 months.

CATEGORY 5: Research & Development of Breeding and Genetic Tools

The objective for Category 5 is research and development (R&D) leading to technology transfer of new macroalgae breeding and genetic tools. Macroalgae species have significant genetic diversity (more so than terrestrial, vascular plants), yet suffer from a dearth of knowledge and information on species identification (genotype) and the relationship of genetic information to traits observed in a species environment (phenotype). R&D is needed on breeding and genetic tools (analogous to terrestrial plants) that enable breeders to develop elite cultivars that perform under state-of-the-art agronomic practice and that realize higher species yield potentials. Currently this area of R&D is challenged by macroalgal polyploidy, high "GC" rich sequences, and significant genetic "contamination" with microbial DNA. Specific areas of interest to ARPA-E in Category 5 include:

- Extensive species "barcoding";
- Technology and/or methods to enable high throughput, high accuracy DNA sequencing (e.g. removal/separation and/or deconvolution of microbial genetic contamination);
- Technologies leading to the identification of trait linked genetic markers such as single nucleotide polymorphisms (SNPs); and/or
- Technologies to efficiently produce hybrid macroalgae cultivars.

Ideally, technologies developed under Category 5 will lead to the development of new macroalgae strains with traits more suited for ocean agronomic deployment. However, this outcome may not be achievable during a 36-month period of performance. Rather, ARPA-E will target the development of technologies that will enable macroalgae strain development work which continues beyond the period of performance under the ARPA-E MARINER program. Concepts addressing sequencing and marker identification must meet at least two of the primary technical targets 5.1 – 5.3. Target 5.4 is a requirement for submissions targeting hybridization technologies:

Primary Technical Targets

ID	Metric	Targets
5.1	Macroalgae Species Catalogue	Identification and submission of ≥ 20 macroalgae species "barcodes" from U.S ocean waters to NCBI[32]
5.2	Technologies/methods for Robust Macroalgae DNA Sequencing	Reduction of microbial genetic contamination to ≤ 1% prior to sequencing
5.3	Technologies/methods for Identification of Biomarkers	1. Warm water tolerance: genetic biomarker attributable to increasing the water temperature tolerance of the selected macroalgae species ≥ 2°F 2. Biomass productivity: genetic biomarker attributable to ≥ 10% increase in biomass mass. 3. Pest and disease resistance: genetic biomarker attributable to ≥ 5% in increase in common pest and disease resistance mechanisms. 4. Nutrient uptake & storage: genetic biomarker attributable to ≥ 5% increase in nitrogen storage capacity under relatively low nutrient concentration intervals.
5.4	Macroalgae Strain Hybridization and Propagation	50% increase in throughput relative to state of the art methodology for macroalgae strain hybridization, and micropropagation

Metric Descriptions – Primary Technical Targets

5. 1 Macroalgae Species Catalogue

ARPA-E seeks to genetically identify and catalogue at least 20 macroalgae species native to U.S. ocean waters. Genetic cataloging will be measured by a "barcode" sequence, which is typically a short nucleotide sequence from a standard genetic locus. Target species should be representative of the highest biomass producing brown and red macroalgae.

5.2 Technologies/methods for Robust Macroalgae DNA Sequencing

One of the major challenges with nucleic acid sequencing is the significantly high percentage of "contaminating" foreign DNA. Foreign DNA is typically microbial and can account for up to 50% of the DNA per sample. Technologies are necessary to reduce the level of background DNA contamination and reduce the cost ($/base pair) of macroalgae

[32] https://www.ncbi.nlm.nih.gov/genbank/barcode/

genome sequencing to levels typical of bacteria such as *E. coli*. Additional technical approaches could include the development of chip or bead based genotyping methods, after an informative SNP set is determined.

5.3 Technologies/methods for Identification of Biomarkers

ARPA-E has identified four phenotypes that are envisioned to be critical to deployment of a profitable and sustainable macroalgae cultivation industry. These phenotypes are: warm water tolerance, biomass productivity, pest and disease resistance, and nutrient uptake & storage. ARPA-E seeks the identification of linked DNA markers that can be reliably attributed to desired phenotypes.

5.4 Macroalgae Strain Hybridization and Propagation

The genetic diversity of macroalgae is currently undervalued from an industrial perspective. Preliminary studies indicate that significant potential improvements are possible for numerous phenotypic traits via strain hybridization.[33] ARPA-E seeks technologies that dramatically increase the rate of hybrid development. In parallel, improved methods for other advanced breeding techniques such as micropropagation or double haploid could significantly contribute to genetic gains. ARPA-E anticipates that technologies in this area will be transferred to the community through an open source model.

Successful execution of Category 5 projects will occur in a single phase over a period of up to 36 months.

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[33] Westermeier, R. et al. Macrocystis mariculture in Chile: growth performance of heterosis genotype constructs under field conditions. Journal of Applied Phycology 23:819-825 (2011).