New Approaches to Scalable Ocean Cultivation, Harvest, and Processing of Macroalgae for Energy, Chemicals, Feed, and Food

Workshop Summary Report

Workshop Information

This report is based on the

ARPA-E Macroalgae Workshop
held on February 11-12, 2016
at Capital Hilton, 1001 16th St NW, Washington, DC 20036

Webpage

http://arpa-e.energy.gov/?q=workshop/macroalgae-workshop

Report Format

The workshop was organized as a combination of presentations and breakout sessions, with the detailed schedule shown in the next slides. For most of the presentations, pdf files with the visual materials are provided on the workshop website.

This report provides summaries of the breakout sessions. There were four breakout sessions, each consisting of three discussion groups. For each of these 12 group sessions, this report provides a brief topic introduction and the questions that were posed to the specific group. It then summarizes the output from each group discussion. This summary is a collection of opinions voiced during the workshop and should not be considered as ARPA-E's preferred targets or goals.

Workshop Agenda Thursday February 11, 2016

Time	Session/Speaker	Topic/Comments	Room
8:00 am	Registration w/ coffee		Statler AB
8:30 am	DDT Dr. Eric Rohlfing	Welcome and introduction to ARPA-E	Statler AB
8:45 am	PD Dr. Marc von Keitz	Workshop rationale, description, and operating parameters	Statler AB
9:00 am	Dr. John Benemann	History of US Department of Energy macroalgae projects – major conclusions	Statler AB
9:25 am	Dr. Charles Yarish	Development of open source seaweed culture system technologies in the Northeast US	Statler AB
9:50 am	Dr. Alejandro Bushmann	Macrocystis production and conversion in Chile – lessons learned	Statler AB
10:15 am	MvK	Techno-economic cost considerations & Breakout #1 instructions	Statler AB
10:25 am	Coffee break	Migrate to breakout rooms	
10:45 am	Breakout Session #1	Critical challenges for moving macroalgae cultivation to fuel-relevant scale	
	Group A	System design/Infrastructure & capital	Statler AB
	Group B	Nutrient supply options	Massachusetts
	Group C	Harvest, storage, and transport	New York
12:00 pm	Lunch & Breakout Session #1 report out		Statler AB
12:50 pm	Dr. Jang Kim	Macro algae cultivation in Korea/Asia with emphasis on emerging technology trends	Statler AB
1:15 pm	MvK	ARPA-E perspective of new tech opportunities & Breakout #2 instructions	Statler AB

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Workshop Agenda Thursday February 11, 2016

1:30 pm	Breakout session #2	Advanced tools & Strategies to approach challenges to scale	
	Group A	Advanced marine systems engineering (automation & robotics, integration w/ other marine renewable energy tech)	Statler AB
	Group B	Multi-scale ocean modeling (nutrients, hydrodynamics, etc.) & Remote sensing/monitoring	Massachusetts
	Group C	Advanced breeding tools (genetic screening, biomass monitoring, acoustic imaging, etc.)	New York
2:45 pm	Coffee break		
3:00 pm	Breakout Session #2 read out & Instructions for Breakout Session # 3		Statler AB
3:30 pm	Erick Ask	A US Seaweed Industry – View from the largest US market for seaweed	Statler AB
4:00 pm	Bren Smith	Greenwave and the opportunities for distributed, sustainable ocean farming	Statler AB
4:15 pm	Breakout session #3	Macro Algae Products - revenue, business models & processing	
	Group A	What are relevant energy and co-products from macro algae based on market size, value, and technical feasibility?	Statler AB
	Group B	Complimentary business models to support growth and expansion over the short, medium and long-term (e.g. ecosystem services, multi-trophic aquaculture)	Massachusetts
	Group C	Macroalgae processing & conversion to biofuels and other products: What are the challenges?	New York
5:15 pm	Breakout Session #3 read out		Statler AB
5:45 pm	Day 1 closing remarks		Statler AB
6:30 pm	No host dinner options	Informally coordinated	

Workshop Agenda Friday February 12, 2016

Time	Session/Speaker	Topic/Comments	Room
9:00 am	MvK	Summary of Day 1; Objectives for Day 2	Statler AB
9:10 am	Dr. Mike Rust	Ocean Homesteading? Science and technology needs for smart industry planning and management.	Statler AB
9:30 am	MvK	Strawman FOA & Instructions for Breakout Session #4	Statler AB
9:50 am	Coffee break	Networking opportunity	
10:30 am	Breakout session #4	ARPA-E Funding opportunity	
	Group A	Which key problems/risks need to be addressed first to ensure development of a US macro algae industry suitable for biofuels production?	Statler AB
	Group B	Which target metrics are most useful to measure progress of individual projects towards technical and economic viability?	Massachusetts
	Group C	What are appropriate scales and geographies for potential macro algae field tests?	New York
11:30 am	Break		
11:45 am	Breakout Session #4 read out		Statler AB
12:15 pm	Lunch		
1:00 pm	MvK	Closing Remarks	
1:30 – 4:00 pm	Individual Meetings with MvK and other ARPA-E staff Scheduled in 20 min increments		Massachusetts

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CHANGING WHAT'S POSSIBLE

Group 1 – A – System Design, Infrastructure and Capital Background and Examples of questions for group discussion

Currently, the most prevalent cultivation system for macroalgae is long line cultivation. To lower capital cost in these systems the goal is to maximize the yield of macroalgae per unit length of line while minimizing the number of buoy and anchors required per unit of line length. Overall, we want to explore if the long-line system is a suitable starting point that just needs to be refined or do we need a fundamentally different cultivation system to reach the envisioned scales.

Questions for group discussion:

- What are the key cost drivers in the current long line design?
- What is the maximum sea floor depth in which an anchored long line system can be deployed?
- What are alternative approaches to the long line design, which reduce or eliminate the current anchoring system?
- How susceptible are the long line systems to storm exposure?
- How well can the nursery systems be scaled? What may be some key challenges?
- To what extent are the fundamental components of the cultivation system species specific?

Group 1 – A – System Design, Infrastructure and Capital

Output Summary

- System Design Considerations
  - Near shore farming is a good starting point, reduces effects of wind and storms
  - Need to understand what design parameters are critical for optimizing nutrients and light
  - Deep ocean kelp can withstand storms
  - Long lines are flexible, but lines must be dense enough to use light efficiently
  - Anchored vs. Floating System - Eliminates anchor cost & tension points, but affects productivity and nutrient uptake
  - Need more information on “mowing” vs. whole plant harvesting
  - Change from batch to continuous system (e.g., moving lines?) – allows for smaller and less expensive system
  - Must consider nutrient and light availability
  - Must consider tides as well as currents
  - How to scale a nursery?
    - Nursery space per hectare of kelp?
  - Co-locate with fisheries or offshore wind

- Cost Considerations
  - Anchors
    - Salmon industry may provide some lessons
    - Must reduce number and cost of anchors
  - Lines/Ropes/Nets
    - Line length more important in deeper water
  - Labor (reduced by automation)
  - Offshore systems over-engineered and costly because of regulation
  - Other services that a floating unit could provide in order to offset cost? (e.g., onboard sensors, excess nutrients)
  - Electricity consumption (for nursery)
  - Near shore currently more cost effective – group recommended starting nearshore and moving to offshore
  - Output: Is yield/acre appropriate metric? What metrics are needed for an economic model?
    - “total ecosystem” metrics vs yield/area)
  - Free-floating systems
    - Challenges with nutrient management and optimization
    - Challenges with tracking

Group 1 – A – System Design, Infrastructure and Capital

Output Summary

- Other Considerations
  - Disease
    - Detection
    - Prevention
    - possible “therapies”
  - Predation (invertebrates)
  - Weeds
    - Prevention
    - Control
  - Loss of productivity through sloughing:
    - Dissolved organic material (DOM)- up to 50%in kelp
    - Capture some way?
    - Particulate matter (POM) sloughed off tips of kelp plants- how to optimize increase in biomass- at some point sloughing equals growth.

Group 1 – B – Nutrient Supply Options
Background and Examples of questions for group discussion

After sunlight and CO_2, which we assume to be mostly fixed for a given location in the ocean, nutrients nitrogen and phosphorous are the next limiting factors, which will need to be provided. Current macroalgae cultivation systems either take advantage of anthropogenic sources of nutrients in coastal waters, primarily agricultural run-off and waste water discharge, or natural upwelling of nutrient rich deep ocean waters. A third option, which is being considered, but not currently utilized, is to actively access the nutrient rich water of the deep ocean, by either pumping the nutrient rich water to the surface or by “dipping” the macroalgae down into the nutrient rich deep water zone.

Beyond just the stoichiometric quantity of nutrients needed for macroalgae biomass production, the spatial and temporal supply of the nutrients at a given farm site has a critical influence on macroalgae growth and yield (e.g. Neuschul, 1987).

- Questions for group discussion:
  - How do the different sources of nutrient supply scale relative to the area of macroalgae farms needed at a fuel relevant scale?
  - Are there nutrients other than nitrogen and phosphorous that could be limiting in certain ocean environments?
  - To what extent do we understand the interplay between the hydrodynamic conditions of a farm site and the farm system design?
  - In how many areas do we find suitable hydrodynamic conditions for adequate nutrient distribution given current system designs?
  - What system design parameters could be changed to expand the areas suitable for cultivation?

Group 1 – B – Nutrient Supply Options

Output Summary

- Essential nutrients
  - Varies based on species
  - Nutrient needs are constant through growing season with the first 2 months most important
  - Nitrate and/or ammonia
    - Flow, turbulence considerations – boundary layers will control nutrient conc.
    - Microalgae bloom avoidance always an issue
  - Phosphorus
    - P to N ratio matters; ocean typically not P-limited (also depth-dependent?)
  - CO_2 to a lesser degree
  - S, Mn – plenty available
- Concerns with discussed delivery mechanisms
  - “Nutrients in deep ocean destined for somewhere, can’t just take them”. Is this really a concern?
  - Recycle possible; technologies for fertilizer application may be feasible but costly
  - Nutrients will be likely be depleted in the middle of the system production system/2-D area
  - Suggestion: “Complete nutrient cycle for every nutrient” – Ocean Forests guy
    - Use of deep nutrients may involve moving tremendous amounts of water up in the column

- Location
  - Understanding nutrient location and dynamics may require new technology
  - All/great majority of ocean current studies near-shore
  - Latitude question: sweet spot? Temp vs. solar radiation difference?
    - Different species – *Sargassum* for warmer temps
    - Kelp highly variable seasonally; evolved for northern climates specifically
    - Other species much better evolved for year-round production
    - Tradeoffs between productivity and other considerations
  - Gulf of Mexico
    - Don’t need to go deep for nutrients
    - “Dead Zone” Huge area – spreads from TX to ~AL – size of Connecticut
  - Exclusive area of US ocean is ~2x US land area, but surface waters are nutrient poor
  - Other considerations
    - Upwelling locations
    - Overlap with shipping routes
  - Different species strategies for different locations (east coast vs. gulf, etc.)

Group 1 – C – Harvest, Storage and Transport (HST) Background and Examples of questions for group discussion

The harvest system is closely linked to the species of macroalgae grown as well as the farm design. As the scale of farms grows, the need for mechanization and automation of the harvesting process increases in order to control capital and operating costs (e.g. diesel fuel). Additionally, depending on the anticipated use of the product, a number of transport and storage challenges pose significant impediment to scale.

- Questions for group discussion:
  - What are the key problems/limitations of existing harvesting systems? Are they the same for the different types of macroalgae?
  - What are the material properties of the biomass? And based on these properties, what are the challenges to handling, moving, and storing the material?
  - To what extent does the harvest system design depend on the final use of the product?
  - Price estimates for production in Asia are heavily influenced by low labor and materials costs. To what extent are these techniques transferable to the US? Is automation the only enabler that would allow U.S. manufacturers to compete for these production prices?
  - How do HST costs scale into unprotected offshore waters? What is the relationship between moving further offshore and added costs?
  - What is the status and scale today of mechanized harvest and transport equipment for the macroalgae industry? What existing infrastructure could be adapted to service an industry that grew to a global fuel and chemical scale? For example, might the existing infrastructure of the offshore O&G, fishing, or shipping industries be adapted to the macroalgae industry?

Group 1 – C – Harvest, Storage and Transport

Output Summary

Challenges:

- Transporting billion ton scale of biomass for energy use over distance in open ocean crux of time, cost, reliability issue
- Energy inputs to transportation need to be engineered to be minimized to justify balance of scale bottom line
- Present possibilities only with mowing/boat or tanker transport with high energy costs but future possibilities in pumping or treating at sea. Extremely high capital cost of doing any processing or installing infrastructure in the ocean.
- Short window of “freshness”
- Optimal harvesting techniques dependent on species
- Anchoring techniques informs harvesting strategies
- Water transport – either within biomass (biomass to shore) or as waste water (from off-shore processing are challenging considerations)

Potential and/or partial solutions:

- Co-locate with current or future infrastructure (wind, rigs)
- Using ocean currents to carry biomass and maintain functionality
- Dehydrate before transporting
- Find bioprocessing or feed distribution centers near harvest site.

Group 2 – A – Advanced Marine Systems Engineering (Automation & Robotics, Integration with Other Marine Renewable Energy Tech)

Background and Examples of questions for group discussion

The main operational inputs during open ocean cultivation and harvesting of macroalgae are labor and fuel. The rapid advances in automation, robotics, and autonomous vehicles may enable new system designs for cultivation and harvesting, which could significantly lower production cost and push the suitable operational range further off-shore. At the same time marine renewable energy technology has made significant progress and may offer alternative sources of energy for harvesting and cultivation operations, while also offering the opportunity to share infrastructure, which could potentially reduce cost.

- Questions for group discussion:
  - What new marine engineering approaches enable deployment of macroalgae cultivation to the off-shore environment?
  - Are there advanced methods like robotics or bio-inspired design tools that could allow us to engineer a controlled system with a typical manufacturing learning curve? For example, can we expect to reduce production costs by 15-20% for every doubling of production?
  - What renewable energy sources might be combined at large scale with an offshore algae industry? How could wind and wave energy be integrated? What are the impacts on fuel costs?
  - Explore the possibility for technology to reduce multi-use conflict (e.g. automatic submersion of the farm).

Group 2 – A – Advanced Marine Systems Engineering (Automation & Robotics, Integration with Other Marine Renewable Energy Tech)

Output Summary

- Areas in need of automation include line seeding, anchoring, vertical movement of system, as well as monitoring/sensors for weather, currents, nutrients, CO_2, O_2, light, growth
- Engineering strains that increase usable productivity of algae that leverage synthetic biology, bio-foundry community
- Artificial nutrient upwelling to drive nutrients to the surface/thermocline.
- Any technology designed to transport plants through water should happen at very slow speeds to reduce energy demands

- Open ocean herding using marine autonomous vehicles with satellite remote monitoring and nutrient prediction
- Sensors can be deployed to make a use case for fisherman on ecosystem services, nutrient upwelling and remediating anoxic zones - help ease permitting
- Co-locate systems with jettys, buoys, artificial reefs to protect coastline to reduce cost and improve
- Basic mapping of where to locate marine systems (away from nautical routes and with optimal nutrient/weather/harvesting locales) is crucially important and should be built

Group 2 – B – Multi-Scale Ocean Modeling (Nutrients, Hydrodynamics, etc.) & Remote Sensing/Monitoring
Background and Examples of questions for group discussion

Multi-scale modeling is expected to be important for ocean farm siting, design, and day-to-day management. Mathematical modeling can provide a better understanding of nutrient hydrodynamics within and around an open ocean farm to enable better management practices and optimization of yield per unit area. In order for modeling to be impactful, data acquisition at the macro-level (e.g. geo-spatial satellites) and farm level (e.g. moored sensors) will be critical. Data and modeling advances will provide a more complete understanding if the temporal and spatial variability of ocean nutrients, and other important aspects such as turbidity. The session will address the challenges with current state of technology and identify critical data needs.

- Questions for group discussion:
  - What are the most critical data and modeling needs for significantly improved precision and performance of ocean farm siting and management?
  - What does the current state of technology enable? Where is it limited?
  - Address the trade-offs between macro-level monitoring and “in-field” monitoring? Are there combinations that may be more effective?
  - In the face of uncertainties regarding climate change, how can we expect multi-scale modeling to de-risk open ocean deployment of capital and biology?
  - Could a combination of remote (satellite) sensing and ocean current (drift) modeling enable lower capital cultivation systems, e.g. “ranching” of floating seaweeds, such as *Sargassum*.

Group 2 – B – Multi-Scale Ocean Modeling (Nutrients, Hydrodynamics, etc.) & Remote Sensing/Monitoring

Output Summary

- Data and Modeling Needs
  - Phytoplankton dynamics, but requires high resolution over large areas
  - Nutrients – Forecasting and Improved Management Practices, Potential for real time farm repositioning
  - Temperature/Light/Shading – Need a growth model that predicts yield, but this is a less constrained system
  - Compliance Tools – permission to operate and competing uses
  - Climate models, and application of data
  - Strain Specific Models - Model predicts the best sites, and best site management strategy for production.
  - Mass Yields - Ability to make management interventions and monitor what is growing in the field, allows for optimal design of the system
  - Structural Models - Spacing, how much mass / time, buoyancy, drag, waves, storm surge, bottom conditions, anchoring, minimizes risk of weather incident, this is also useful for siting purposes and allows regulators to determine the risk of the system

- Current Data Models and Sensing/Monitoring Solutions
  - Not much for seaweed, but 13 years of validated data for shellfish
  - Satellite measurement and multiple spectra
  - USNA using wave tanks to model kelp as energy dissipation mechanism
  - Hyperspectral reflectometry, would this be applicable?

- Conclusions
  - Need dynamic data that helps us understand the relationship between biomass growth and ecological conditions
  - There is a tendency to want more, but the question: What information is absolutely necessary for siting and management?
  - Siting – models include hydrodynamics, ecological, nutrients and TEA
  - System Design – models include structural, hydrodynamics and biomass growth dynamics
  - Operational – models include nutrients, growth and structural

Group 2 – C – Advanced Breeding Tools (Genetic Screening, Biomass Monitoring, Acoustic Imaging, Etc.)

Background and Examples of questions for group discussion

Traditional breeding and/or hybridization has long been practiced in agriculture to improve desirable traits. Examples include plant hybrids that are stronger, have deeper roots, or other characteristics such as grain yield and/or composition. Such genetics techniques have also been applied to macroalgae breeding but only to limited degree and with varying success. This session will explore the current state of macroalgae breeding, new tools, as well as ancillary technology needs (e.g. high-throughput genomic sequencing).

- Questions for group discussion:
  - With respect to current methods, how long does it take to generate a hybrid strain? Where are the opportunities to increase throughput?
  - Yield improvements have been realized through breeding. For example, work in China resulted in a 50% yield increase for *Saccharina japonica*. What other traits should be considering top priority for selection?
  - Traditional breeding methods can take > 10 years to achieve some level of success. What additional/ancillary technologies could dramatically improve throughput (e.g. monitoring, non-invasive imaging, etc.)
  - What are the needs surrounding seed stock/germplasm culture?

Group 2 – C – Advanced Breeding Tools (Genetic Screening, Biomass Monitoring, Acoustic Imaging, Etc.)

Output Summary

- Important Traits
  - Yield / area– incorporates temp tolerance, disease resistance, etc.
  - Different traits for food vs. biofuel (fermentable sugars, high biomass focus)
  - Variation can be environmentally triggered (genetic information insufficient)
  - Other – resistance to disease & grazing, structural integrity, holdfast, nutrient uptake
- Sexual reproduction considerations
  - Avoidance of breeding out desirable traits
  - Region of the genome sometimes can ID mating type
  - Biodiversity of key species
  - Genomes don’t follow normal rules; ancient species. Sequencing is challenging.
  - Mowing model could help, but only works for certain varieties (disagreement about this) – transferable traits could help this
  - ID asexual reproduction systems, allow selfing and establishment of clonal populations

- Hybridization/Crossing
  - Seed bank creation to maintain wild seeds
  - Understanding contribution of traits from male vs. female parents
  - Some examples of sterile hybrids
  - Useful information available 25 days after crossing
- Genetic tools considerations
  - General agreement from algae community – GMO undesired
  - Pushback from molecule biology on known vs. unknown variations being selected
  - Regulations over manipulated sterile breed an open question
  - Specific molecular markers for traits of interest
- Sensing/Monitoring
  - Non-destructive, repeatable desired
  - Non-invasive acoustic work promising
  - Key model inputs: temp, turbidity, nutrients
  - Real-time detection of disease would be very helpful

Group 3 – A – What are Relevant Energy and Co-Products from Macroalgae Based on Market Size, Value and Technical Feasibility?
Background and Examples of questions for group discussion

Macroalgae seaweeds have been harvested for centuries for human and animal consumption, and for use as fertilizers. Within the last 100 years, technologies were developed to extract and separate various compounds from seaweed, making seaweed a valued feedstock. Currently, approximately 60% of macroalgae cultivated goes directly to human consumption, and the balance of 40% as a feedstock for the extraction of hydrocolliods (carrageenan, agar, alginate). This session will explore the current and future market conditions for these products as stepping-stones to energy and fuel (at scale).

- Questions for group discussion:
  - What are the possible energy products/uses for macroalgae considering current state of technology? How could we extend the opportunities for macroalgae as a feedstock for biofuels?
  - What co-products can be derived from various macroalgae to biofuel conversion processes? Which of these products have “fuel-scale” market opportunities?
  - What growth opportunities are associated with the market for hydrocolliods and to what extent might that serve as a stepping stone to energy and fuel?
  - Growth in direct human consumption as a stepping-stone to fuels and chemicals appears limited. What are the opportunities to using macroalgae as a protein and carbohydrate source for animals?

Group 3 – A – What are Relevant Energy and Co-Products from Macroalgae Based on Market Size, Value and Technical Feasibility?

Output Summary

- Current Uses
  - Potash
  - Biogas and HTL (funding not consistent)
  - Pharmaceuticals (wound dressing)
  - Fertilizer
  - High end food markets / Animal Feed / Fish meal & other aquaculture foods
- How to increase Opportunities
  - Increase lipid content to increase fuel value
  - Improve carbohydrate to ash fraction
  - Improve quality for pharma markets
  - Blend seaweeds to improve food value (e.g., control levels of arsenic or amino acid content)
  - Replace fishmeal
  - Make kelp catalyst friendly (compounds in algae destroy catalysts)
  - Pretreatment to increase digestibility

- Potential co-products
  - Biochar, Kelp Detritus, Nano-products, HTL, catalyst molecules, water purification, fuel cell substrate, hyper accumulator of heavy metals (mercury, nickel), food coloring, ecosystem services and carbon sequestration

- Needs and Opportunities
  - Forms of biofuels – biogas, green diesel, butanol, biomethane
    - Numerous pathways to fuel; effort should be spent to determine best pathways
  - Cost of certification and approval
    - Money/time required to get animal food approval from USDA and FDA
  - Opportunities in pharmaceutical industry

Group 3 – B – Complimentary Business Models to Support Growth and Expansion Over Short, Medium and Long Term (e.g., Ecosystem Services, Multi-trophic Aquaculture)
Background and Examples of questions for group discussion

Near-term business models might be pursued in parallel with scaling of an industry for commodity scale fuel and chemicals applications. For example, the selection of species for commodity production might be influenced by factors such as very high yield, high-sugar content, and/or adaptability to open water conditions/rough seas. The session will explore how selecting for such traits could influence the opportunity for near-term business models.

- Questions for group discussion:
  - How might an ARPA-E program or other incentives encourage successful short and medium term business models to continue to move towards fuel and chemicals applications? Are we seeing any evolution of current business models towards large-scale production of biomass for fuel?
  - What are the business segments we can enter within a three-year program that could lead towards a) a self-sustaining (earn-to-learn) business evolving towards the fuels and chemicals market or b) a business model that will warrant follow on investment based on commercial merits (e.g. multi-trophic aquaculture)? What would be the differences in our T2M planning between driving towards follow on government or private sector investment within a three-year time frame?
  - Do the potential for carbon markets provide an opportunity for a complementary business? What other types of new business models might develop around ecosystem services (reducing harmful blooms in runoff zones, etc)?
  - How might we develop joint business models with multitrophic-aquaculture while still maintaining a long-term focus on fuels and chemicals?

Group 3 – B – Complimentary Business Models to Support Growth and Expansion Over Short, Medium and Long Term (e.g., Ecosystem Services, Multi-trophic Aquaculture)

Output Summary

- Ecosystem services benefits
  - Carbon offsets (potentially sequestering “fixed carbon in the ocean”- reducing acidification vs. GHG in future burning of biofuel”
  - Shoreline protection from erosion/storms
  - Denitrification (where there is excess)
  - Replacing water use in terrestrial agriculture systems.

- Multitrophic Aquaculture
  - Provides a basis of cost for system but not to scale necessary for (bio)energy
  - Macroalgae production for energy at current scale of current aquaculture systems almost certainly not aligned to best and highest value use for food, etc.
  - Provides habitat for fish stock
  - Captures nutrients otherwise lost
  - Ensures cleaner operations

Group 3 – C – Macroalgae Processing & Conversion to Biofuels and Other Products: What are the Challenges?

Background and Examples of questions for group discussion

The fundamental composition of macroalgae creates numerous challenges to handling, processing and ultimately conversion. Several different approaches have been demonstrated for the conversion of macroalgae to fuel products, including anaerobic digestion, fermentation to ethanol, acetone and butanol, as well as hydrothermal liquefaction.

- Questions for group discussion:
  - What are the key challenges for the biological and thermochemical technology technologies currently available for conversion of macroalgae into fuels and chemicals?
  - Are there comprehensive biorefinery approaches for marine biomass feedstocks?
  - How suitable are these technologies for off-shore deployment and using offshore pipelines to pump product back to shore?
  - What are the known challenges and possible solutions to processing macroalgae at sea? (e.g. fractionation without fresh water, ash removal, etc.)
  - Can we imagine totally new approaches to offshore processing, e.g. fermenting products in floatable bags offshore (and then floating the bags back to shore)?
  - What other existing technologies might be creatively adapted to this problem?

Group 3 – C – Macroalgae Processing & Conversion to Biofuels and Other Products: What are the Challenges?

Output Summary

- Anaerobic digestion
  - Slow kinetics
  - 60/40 CH_4/CO_2 ratio
  - Cost (>$8-$10/mmBTU not including feedstock)
  - Sulfates in seawater difficult to clean up
- Biochemical Saccharification/fermentation
  - High salt content
  - Different carbohydrate composition than terrestrial plants, will require new fermentators
  - Biomass composition will vary over the year
  - Loading levels
    - Need to look at pathogens and herbivores to identify useful enzymes/pathways
- Hydrothermal Liquefaction – Salt will help the separations; challenges from loading level
- Pretreatment – Fractionation as a potential processing step

- Biorefinery approach would include
  - Drying biomass (non-fossil fuel approach for drying, since it takes an equivalent amount of energy to dry the biomass as there is in the algae)
  - Utilization of co-products (Lipids are very low <1%), along with most amino acids. After fermentation, we are left with protein, salt, minor metabolites.

- Processing at sea would include:
  - Fractionation without fresh water
  - Ability to couple renewable electricity with low molecular weight acids derived from macroalgae biomass
  - Concentration (To collect the products (volatiles) using evaporation membranes. Supercritical CO2 is a great solvent)
  - Utilization of waste products and collection of biomass without removing the biomass to a platform or boat (e.g., move the biomass to shore very slowly)

Group 4 – A – Which Key Problems/Risks Need to be Addressed First to Ensure Development of a US Macroalgae Industry Suitable for Biofuels Production?

Background and Examples of questions for group discussion

An ARPA-E focused funding program, like the one we are contemplating here, will invest $30-35 million dollars over a period of 3 to 4 years. Considering the size of the challenge of scaling at least 2 orders of magnitude beyond current world production capacity, ARPA-E's funding can only be considered a seed investment, which will require follow on funding by other sources. The ARPA-E investment needs to derisk the most critical technology challenges and demonstrate that this technology is on a promising development track, to enable the necessary follow on funding.

- Questions for group discussion:
  - What are the key questions that have to be answered before investors will put money into a macroalgae for fuels and chemicals effort?
  - How do we demonstrate a controlled system where costs can be driven down an engineering learning curve? What are good model systems to do this?
  - What are meaningful end-points for an ARPA-E project?
  - Should we demonstrate that labor will be a low cost input as compared with Asian methods? How low?
  - To what extent does our knowledge of breeding/reproductive cycles limit the development of a commodity scale industry? Genetics?
  - In what ways would advances in breeding drive down production costs? Could these advances lead to more integration of breeding with advanced manufacturing or robotics tools?

Group 4 – A – Which Key Problems/Risks Need to be Addressed First to Ensure Development of a US Macroalgae Industry Suitable for Biofuels Production?

Output Summary

- Given size of program, how many key risks tackled? Some to consider:
  - Biomass sloughing problem – large percentage of material lost this way
  - Breeding – takes too long. Instead focus on accelerating process
    - Tools for asexual reproduction
    - 30year timeframe – could start with omics, build organism
    - Non-polyploidal
    - Genetics integral; should be a part of the program
    - Seed bank key (no Ag play has succeeded without)
  - Open ocean structures large bottleneck. Highly site-dependent
- Full techno-economic analysis for all environmental services key – biofuels only part of impact

- Farming in open ocean
  - Ocean moves
  - Seeding, harvesting, etc. with automation challenging
  - Interaction with aquaculture
  - If too much still unknown, spend $5M on data exercise first?
  - Small modular test beds alternative to large open-ocean projects
  - Permitting is a very long process; this has killed deals before
  - “open ocean is the desert” – fertilizer key
- Which organism? Must be carefully managed; large amount of money for the field
- Conversion – esp. storage vs. fermentation vessel-type considerations
- What are the biggest cost drivers? Rudimentary economic analysis needed

Group 4 – B – Which Target Metrics are Most Useful to Measure Progress of Individual Projects Towards Technical and Economic Viability?
Background and Examples of questions for group discussion

ARPA-E Funding Opportunities target high risk technology development. Therefore, performance targets are critical to moving along a trajectory that will ultimately enable scaling in a sustainable manner and profitability. The target metrics are also a very important component of our project management effort. We use them to measure the progress and success of our project teams. We want them to be ambitions, but they also need to be grounded in reality and they need to be aligned with the overall program goals. This session will address and identify the most meaningful target metrics to put us on a trajectory to scale current macroalgae production capacity by two orders of magnitude.

- Questions for group discussion:
  - What is our baseline?
  - What are the performance metrics with the most impact, and what is the unit of measurement?
  - Considering that on average ARPA-E funds 3-4 year projects at less than $5 million dollars, what are some examples of ambitious, but realistic values for performance improvement?
  - Technology development is inter-related, what are the most meaningful system level performance metrics for ARPA-E?
  - How can we structure target metrics to accommodate/encourage out of the box/transformational concepts?

Group 4 – B – Which Target Metrics are Most Useful to Measure Progress of Individual Projects Towards Technical and Economic Viability?

Output Summary

- Target Metrics – System Design
  - Yield
  - Cost ($/dry ash free ton at the point of harvest)
  - Cost ($/GigaJoule)
  - Energy Balance (Joule Input/Joule of final product)
  - GHG footprint
  - Carbon sequestered
  - Comparison with alternative energy options
  - Externalities (ecosystem services, co-products, reduced acidification, clean dead zones, etc.)
  - Increased fish and shellfish production and harvest
  - Nursery Operation (spore production and line seeding), energy/lighting requirements
  - Nutrient recycling

- Target Metrics - Feedstock development
  - General industrialization of the plant germplasm
    - % carbohydrate, % protein, physiology/architecture, extension of growing season, disease/pathogen resistance, nursery productivity
- Target Metric – Processing
  - Yield (Biochemical, EtOH)
  - Hydrothermal liquefaction
- ARPA-E Technical End Point
  - Develop a data collection platform, automation or labor, improved germplasm consistency with multiple varieties
  - Total global ecosystem model, including all of the above, ecosystem services, co-products, reduced acidification, clean up dead zones, etc.

Group 4 – C – What are Appropriate Scales and Geographies for Potential Macroalgae Field Tests?

Background and Examples of questions for group discussion

ARPA-E’s typical investment per project per year is $1 million. What field test scale is possible at this level of funding, and what are the technical benefits ARPA-E could expect to achieve. This session will explore challenges and opportunities for deployment at various U.S. locations. Additionally, we would like to explore regulatory aspects of permitting field tests, as well as larger scale deployments.

- Questions for group discussion:
  - Considering the data needs, what size scale should ARPA-E target?
  - What regulatory challenges might have to be derisked?
  - What tools/models (and the science behind them) are needed to aid industry and government make smart decisions about where and what to do in the ocean? Examples are GIS applications, Marine Spatial Planning (MSP) efforts, and risk assessments.
  - At scale (square mile basis), what, if any, environmental challenges should be anticipated?
  - What type of public acceptance testing might be necessary before introducing a new, commodity scale industry in public waters?
  - What are some design features of an ARPA-E program that would inform regulatory needs?

Group 4 – C – What are Appropriate Scales and Geographies for Potential Macroalgae Field Tests?

Output Summary

- 10 Hectares a good first target
- Should model near shore sites for best location in warm, cold water (South Atlantic/Gulf, Pacific/Northeast)
- Begin regulatory partnerships now to understand species protection requirements
- Minimally impactful harvest
- Don’t overfertilize
- Get out of near ocean to reduce regulatory burden and get to scale as quickly as possible!