Seaweed Biorefining with Energy in Mind

Marc von Keitz, Ph.D.
Program Director @ ARPA-E

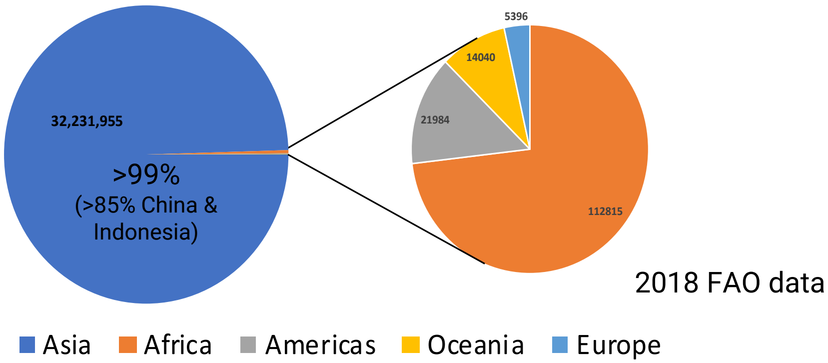
ARPA-E Macroalgae Conversion Workshop

November 16, 2020

Macroalgae (aka seaweed) – the quintessential ocean crop

- ~15,000 different species growing in a wide range of geographies
- Fast growth rate
- Mostly carbohydrate & protein
- Amenable to cultivation & harvest

Asia currently dominates global seaweed cultivation



U.S. Macroalgae Production: Small, but Growing

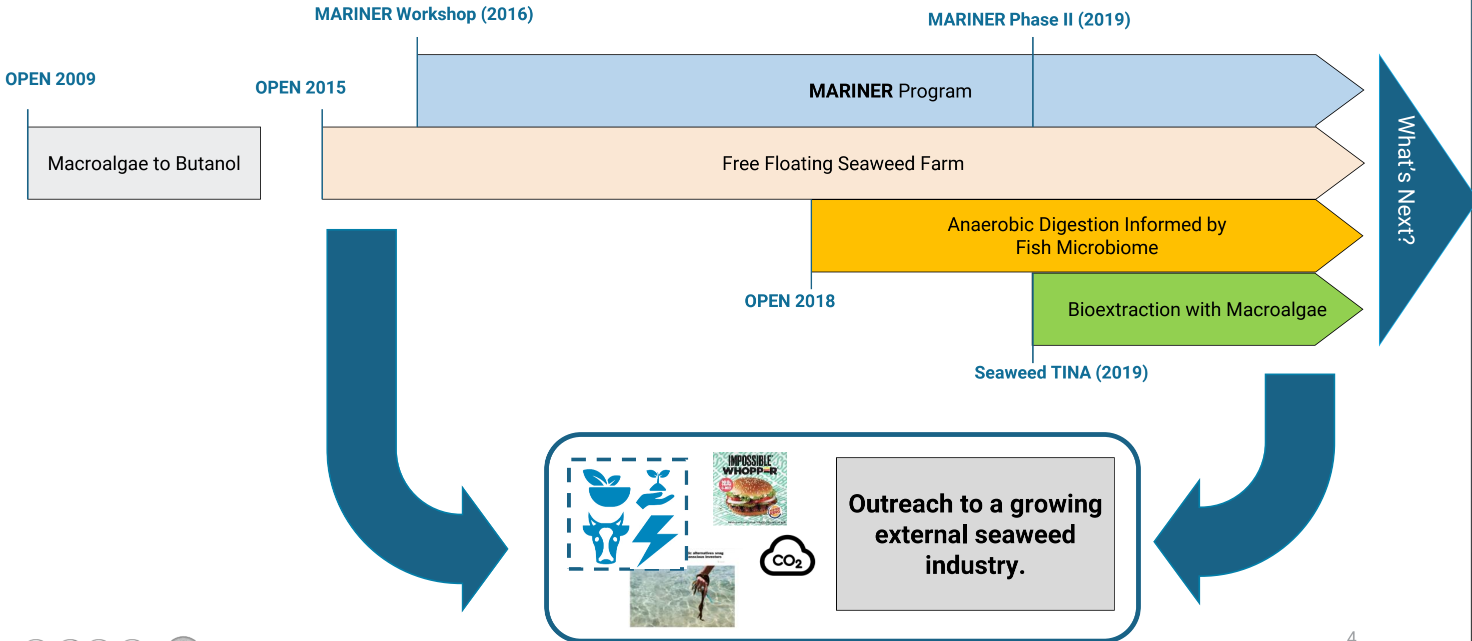
Estimated Edible Seaweed Farmed 2015-2019 (Wet lbs)					
Source	2015	2016	2017	2018	2019
Maine	15,000	24,000	45,000	54,000	325,000
Alaska	Not Available	Not Available	Not Available	30,000	180,000 – 200,000
All Other	10,000 – 15,000	10,000 – 20,000	15,000 – 30,000	20,000 – 40,000	45,000 – 75,000
Total	25,000 – 30,000	30,000 – 40,000	60,000 – 75,000	100,000 – 125,000	550,000 – 600,000

Source: Pentallect Inc. and EPR research; Maine DMR

Recent Trends in Alaska:

- Seaweed Farming Workshops held in cities across the state.
- 16 new seaweed farm applications over 610 acres submitted in 2020.
- Largest farmer (SeaGrove Kelp) plans on 5000 ton capacity by 2023.

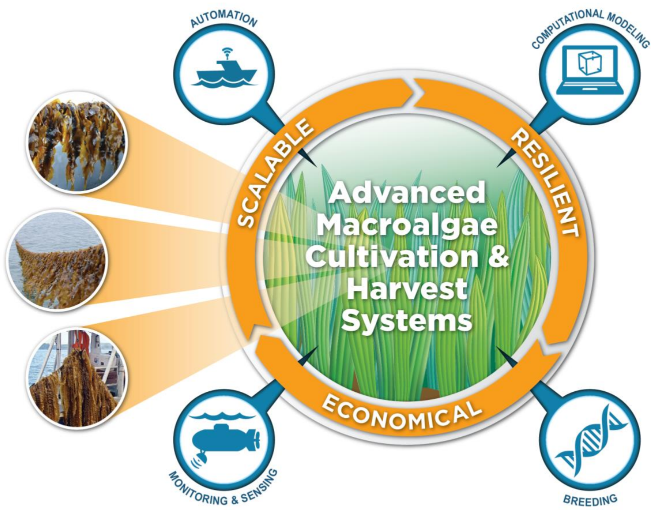
The Story of Seaweed at ARPA-E: A Timeline of Innovation



CHANGING WHAT'S POSSIBLE

ARPA-E’s MARINER Program

Macro**A**lgae **R**esearch **I**nspiring **N**ovel **E**nergy **R**esources



Macroalgae Biomass:

No Land
No Freshwater
No Fertilizer

MARINER creates new biomass production opportunities for the vast ocean resources of the United States.

Photos copyright (top to bottom):
Daria Barbour/National Geographic; The Island Institute; Bren Smith/Huffington Post

- **Launched in 2016**
- **20+ Projects**
- **US$50+ Million**

Metric	Primary Design Targets
Full System Size	≥ 1,000 hectares
Range of Deployment	≥ 100,000 hectares
Biomass Production Cost	≤ $80/dry metric ton
Net Energy Return	≥ 5:1

arpa·e
CHANGING WHAT’S POSSIBLE

1 Ton of Macroalgae (dry) ≅ 1 Ton of CO_2 captured

	Conservative	Medium	Optimistic
Dry weight yield (t/ha)	10	30	50
Carbon Content (% dry weight)	25%	27%	30%
CO_2 captured (t/t biomass)	0.92	0.99	1.10
CO_2 captured in (t/ha)	**9**	**30**	**55**
Area to capture 1 Gt CO_2 (km^2)	**1,091,000**	**337,000**	**182,000**
Cost of biomass production (US$/t dry weight)	200	130	80*
Cost of capturing 1 t of CO_2 (US$)	**218**	**131**	**73**

Numbers presented in this table, while in the right ball park, are primarily for illustrative purposes

* ARPA-E MARINER cost target

arpa·e
CHANGING WHAT'S POSSIBLE

Expanding market opportunities is critical to achieve scale

Human
- Whole foods
- Nutraceuticals
- Proteins
- Hydrocolloids

Energy and Industrial Products
- Biogas via anaerobic digestion*
- Biofuel via HTL or fermentation
- Chemicals and Intermediates

Animal Health & Nutrition
- Ruminants
- Monogastrics

Ecosystem Services
- Nutrient reuptake
- Local deacidifcation
- Wave attenuation
- Carbon storage
- Fertilizers*

Energy products from macroalgae

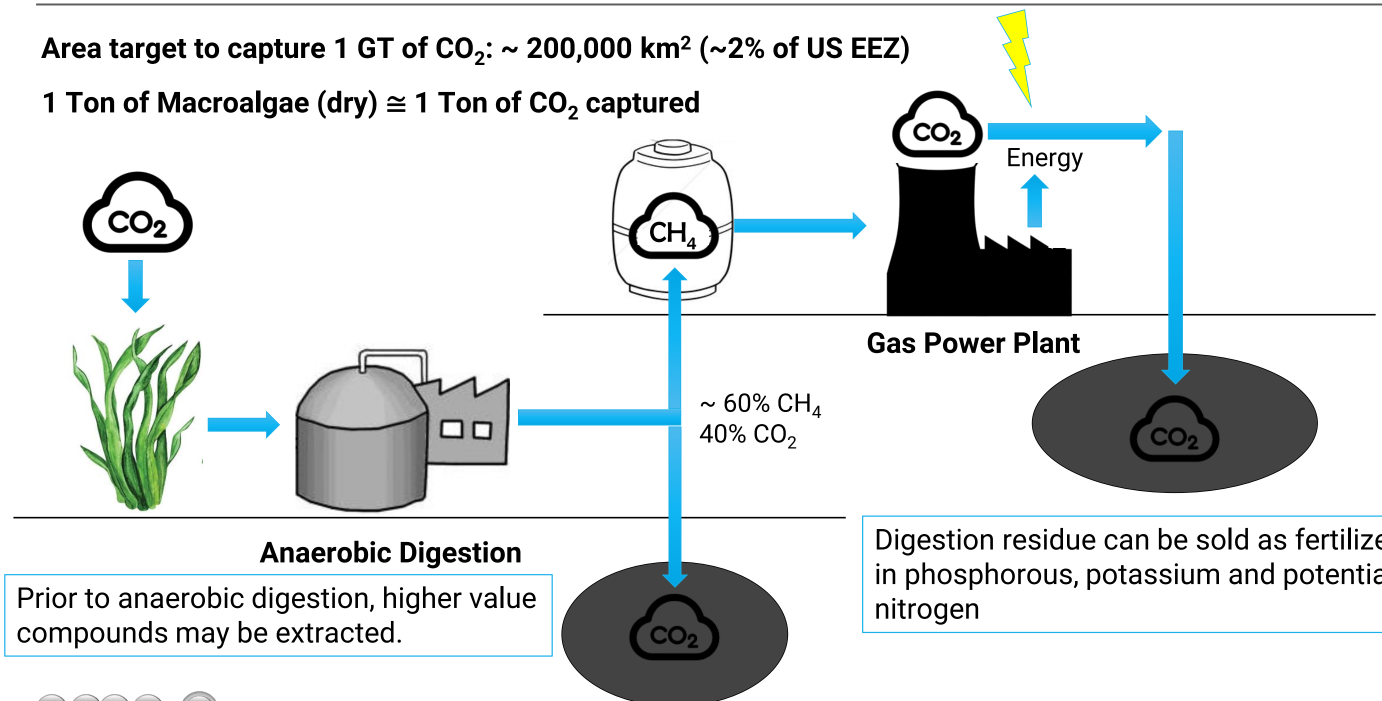
Product	Processing Technology	Year implemented or demonstrated
Acetone	Maceration in digesters	1916
Methane/biogas	Anaerobic digestion	1970's
Ethanol	Engineered *E. coli* ethanologen microbe	2011
HTL liquid/bio-oil	Hydrothermal liquefaction	1988

Digesters at Hercules Chemical Company in Chula Vista, CA

BECCS via a Macroalgae Biorefinery

Area target to capture 1 GT of CO_2: ~ 200,000 km^2 (~2% of US EEZ)

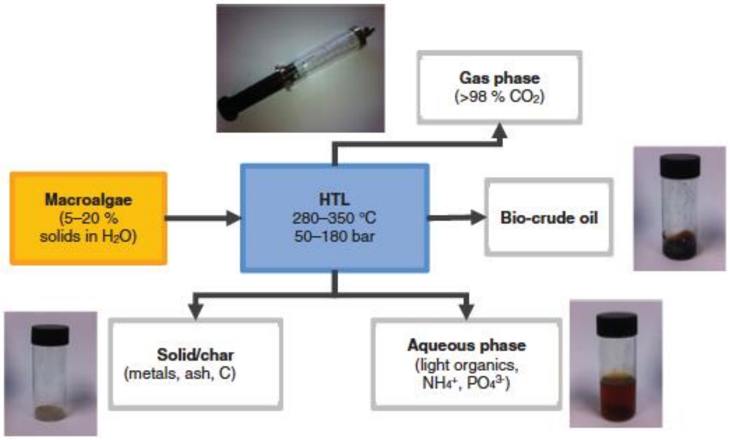
1 Ton of Macroalgae (dry) ≅ 1 Ton of CO_2 captured



Prior to anaerobic digestion, higher value compounds may be extracted.

Digestion residue can be sold as fertilizer rich in phosphorous, potassium and potentially nitrogen

HTL may provide a route to liquid transportation fuels



From: S. Raikova et al. (2019)

Compare to ethanol/butanol fermentation

Energy/Economic Considerations

- Feedstock Cost: f(yield)
- Capital Cost: f(volumetric productivity)
- Operating Cost: f(process conditions & product recovery)

Special considerations for (marine) macroalgae

- High water content (85-95%)
- Water content is saline
- High ash content (as high as 35% of DW)
- Seasonal supply (depending on species and location)

Bioenergy process residues may be a significant source of Nitrogen

Table 4. Compositional data (% dw) for species of seaweed being considered as potential biofuels.

Algae	Ash	Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur
Fucus vesiculosus [1]	22.82	32.88	4.77	35.63	2.53	2.44
Chorda filum [1]	11.61	39.14	4.69	37.23	1.42	1.62
Laminaria digitata [1]	25.75	31.59	4.85	34.16	0.9	2.44
Fucus serratus [1]	23.36	33.5	4.78	34.44	2.39	1.31
Laminaria hyperborea [1]	17.97	34.97	5.31	35.09	1.12	2.06
Macrocyctis pyrifera [1]	38.35	27.3	4.08	34.8	2.03	1.89
Laminaria saccharina [2]	24.2	31.3	3.7	36.3	2.4	0.7
Sargassum muticum [3]	29.45	30.66	3.95	29.56	4.89	1.49

From: J.J. Milledge et al. (2019)

Assuming an average N content of 2% (DW) 1 Giga MT of dry seaweed would correspond to 20,000,000 MT

U.S. Nitrogen use in 2020 for major crops was about 10,000,000 MT of N

Macroalgae may also be a good source of P and K.

Goals of this Workshop

- **Awareness:** Spread the word that ARPA-E is interested in this topic and why
- **Validating/refining FOA approach:**
  - Are we addressing the right problems?
  - Are the metrics ambitious enough, while not totally unachievable?
  - What critical expertise or technology is not on our radar screen?
- **Team building:** Facilitate connection between scientists/engineers from diverse and complementary technical and organizational backgrounds

Technical Focus Areas

1. **Anaerobic digestion** of macroalgal biomass without freshwater
2. **Hydrothermal liquefaction** of macroalgal biomass without freshwater
3. **Nutrient (nitrogen) recovery for fertilizer applications** from process streams
4. **Synergistic integration** of above processes

Workshop structure: Day 1 – Setting the stage

Time (ET)	Session/Speaker	Topic/Comments
12:30 pm		Webex Trainings site opens
12:55 pm	Nancy Hicks	Housekeeping for Virtual Workshop
1:00 pm	Jennifer Gerbi Deputy Director for Technology, ARPA-E	Welcome and introduction to ARPA-E
1:10 pm	Marc von Keitz Program Director, ARPA-E	Seaweed Biorefining with Energy in Mind (Workshop motivation, goals, and operating parameters)
1:40 pm	Jack Lewnard Program Director, ARPA-E	Options for Renewable Natural Gas (RNG) in a Low-Carbon Future
2:00 pm	Dan Fishman Technology Manager, BETO	The Role of Renewable Transport Fuels in the United States
2:20 pm	Mike Reese U Minnesota	Transitioning to Green Fertilizers in Agriculture: Outlook and Opportunities
2:40 pm	Marc von Keitz	Strawman FOA
2:55 pm	Marc von Keitz	Preview/homework for Day 2
3:00 pm	End of Workshop Day 1	

Workshop structure: Day 2 – Technical Deep Dive

Time (ET)	Session/Speaker	Topic/Comments
1:00 pm	Marc von Keitz	Recap Day 1, Objectives for Day 2
1:10 pm	Michael Schuppenhauer LBNL	**Perspective and Challenges of Anaerobic Digestion of Seaweed**
1:25 pm	Hal May, Medical U South Carolina Kevin Sowers, UMD Baltimore County	**Harnessing the Power of Microbial Consortia**
1:40 pm	Lieve Laurens NREL	**Kyphosid Ruminant Microbial Biodigestion of Seaweed (KRuMBS):** Harnessing the Biological Model of Herbivorous Fish Gut Microbiome to Improve Seaweed Bioconversion
1:55 pm	Break for questions.	
2:00 pm	Justin Billing & Dan Anderson PNNL	**Challenges and Opportunities for Hydrothermal Liquefaction of Macroalgae**
2:15 pm	Juan Josse Anaergia	**Marine Macroalgae Anaerobic Digestion for Resource Recovery**
2:30 pm	Brian Saldanha Chemours	**Challenges in Materials of Construction and Equipment Design for HTL Processes in Saltwater Environments**
2:45 pm	Break for questions. Transition to breakout session.	
3:00 pm	**Breakout session**	Discussion of technical needs and target metrics
	Group A_1, A_2	Focus on saltwater anaerobic digestion
	Group B	Focus on saltwater HTL
	Group C	Focus on Nitrogen/Fertilizer recovery strategies
4:15 pm	Break. Transition to main meeting	
4:20 pm	Breakout Session Read-out and Discussion	
4:50 pm	Marc von Keitz	Closing Remarks
5:00 pm	End of Workshop – Please contact us at matthew.mattozzi@hq.doe.gov to schedule meetings with the ARPA-E team.	

Any Questions?