Seaweed Biorefining with Energy in Mind

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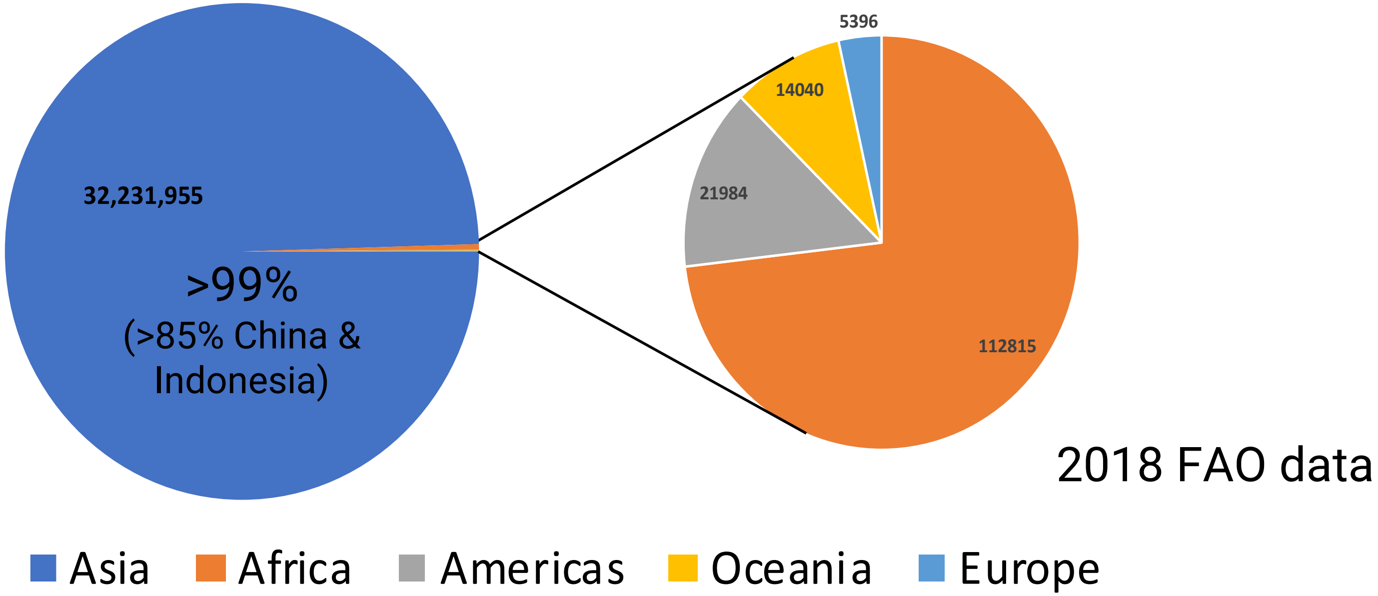
ARPA-E Macroalgae Conversion Workshop

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

OPEN 2009

Macroalgae to Butanol

OPEN 2015

MARINER Workshop (2016)

MARINER Program

MARINER Phase II (2019)

Free Floating Seaweed Farm

Anaerobic Digestion Informed by Fish Microbiome

OPEN 2018

Bioextraction with Macroalgae

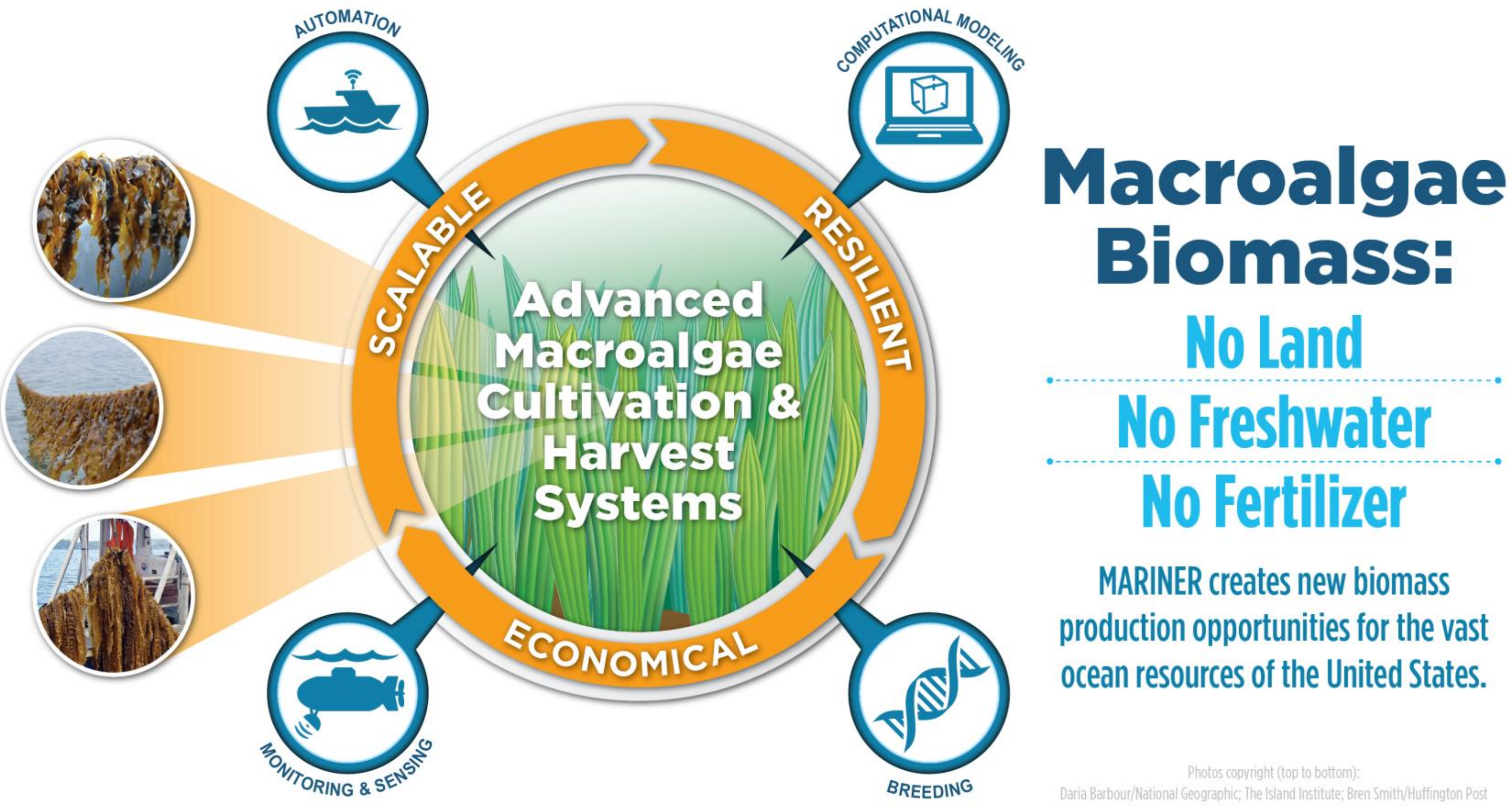
Seaweed TINA (2019)

What's Next?

Outreach to a growing external seaweed industry.

ARPA-E's MARINER Program

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



- **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

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 (km²)	**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**

~ 1.6% of U.S. EEZ

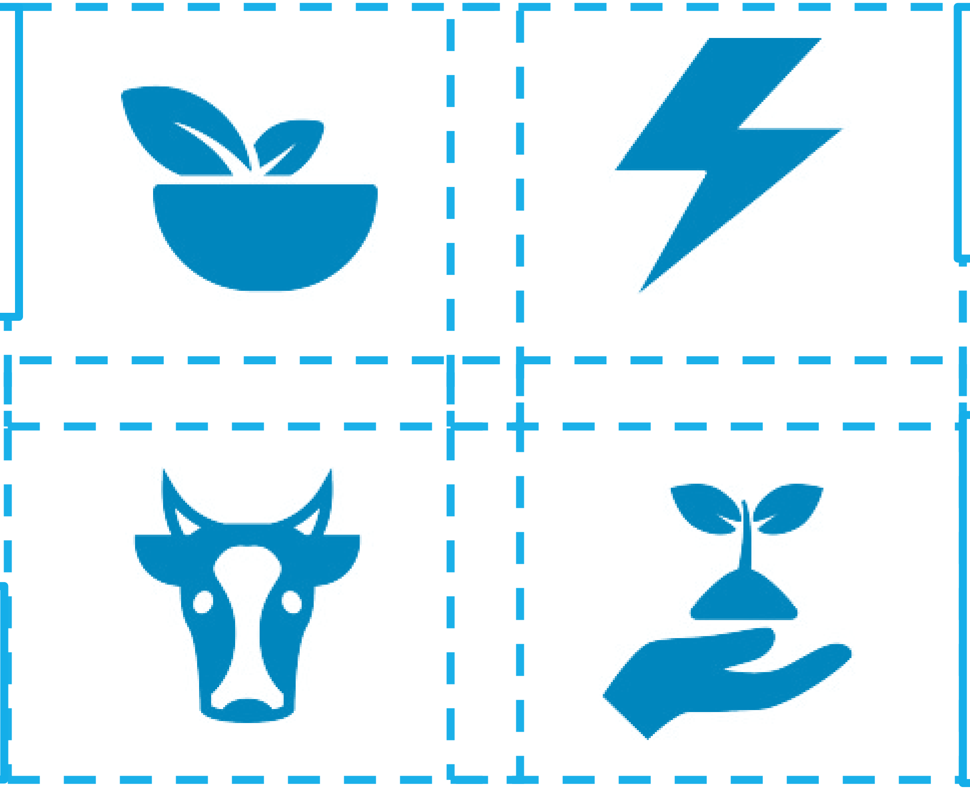
Numbers presented in this table, while in the right ball park, are primarily for illustrative purposes

* 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

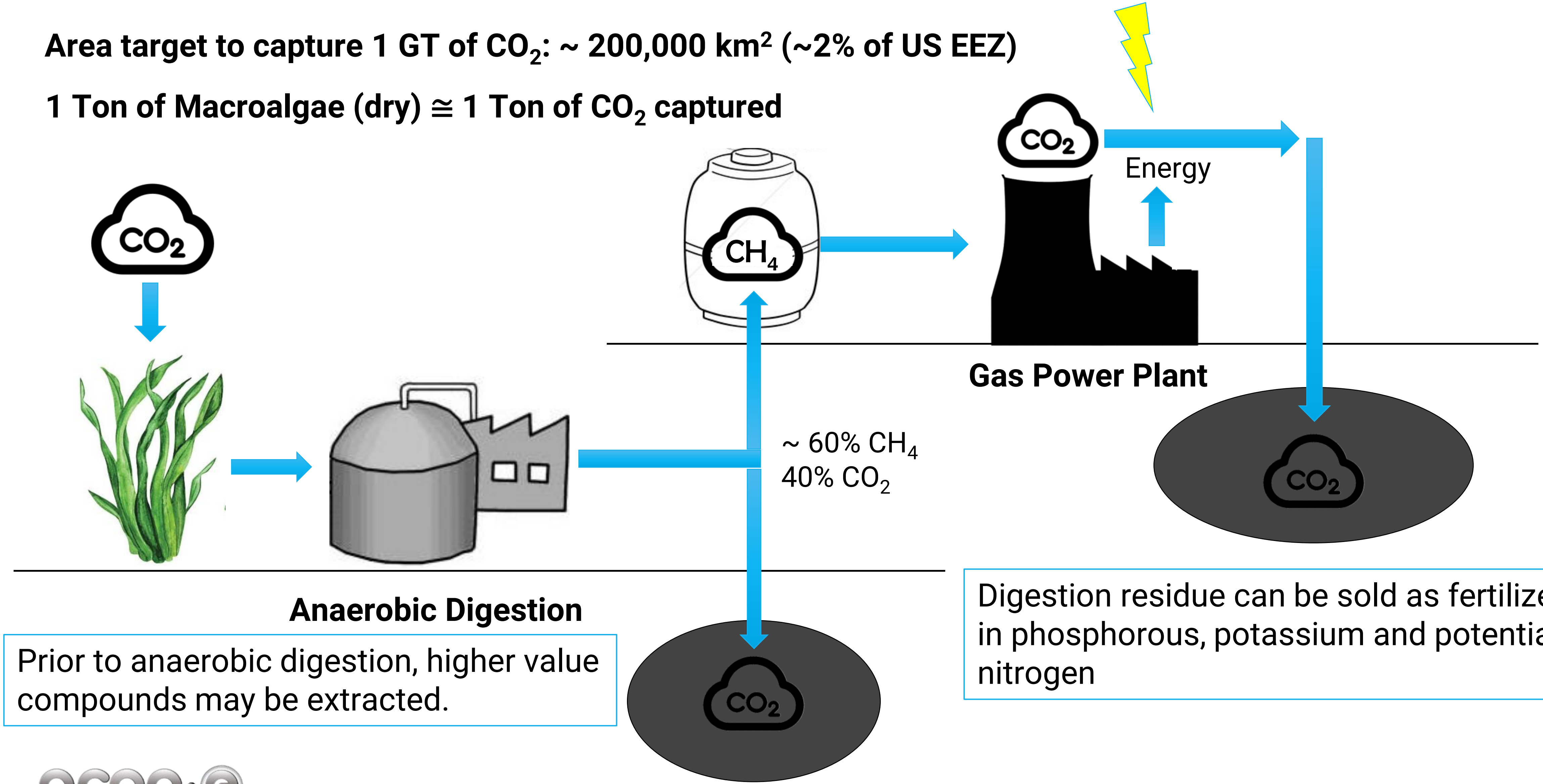
Digesters at Hercules Chemical Company in Chula Vista, CA

CHANGING WHAT'S POSSIBLE

BECCS via a Macroalgae Biorefinery

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

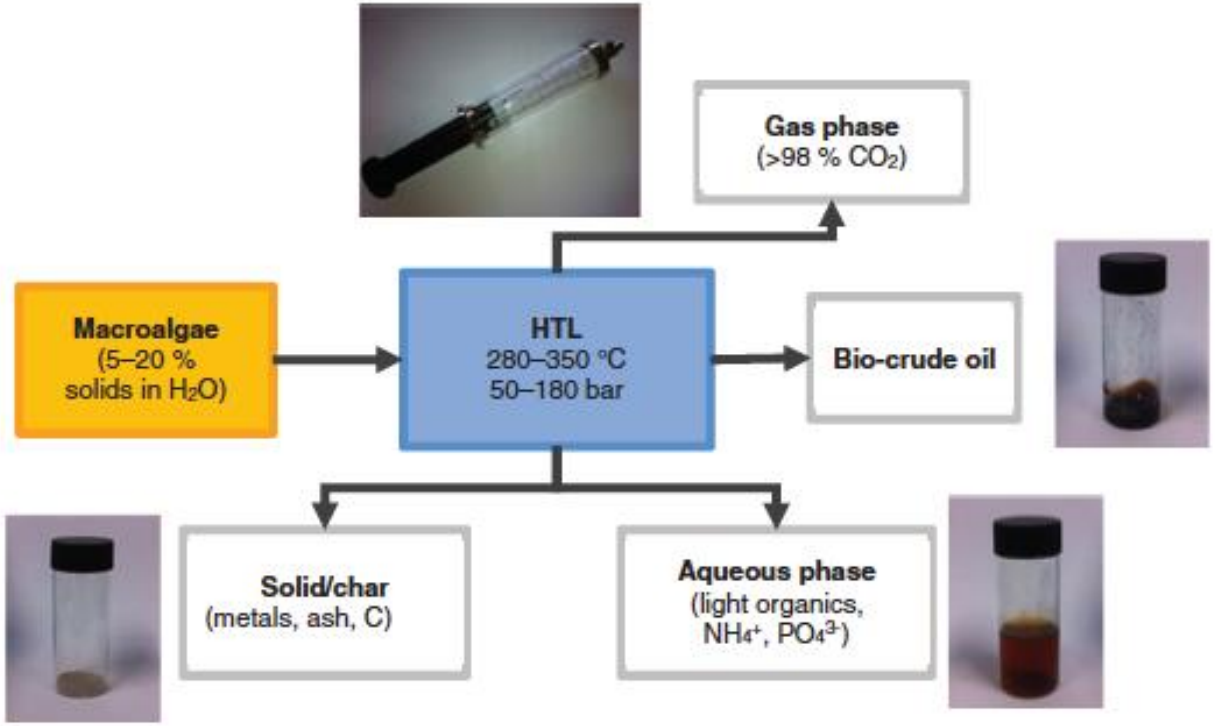
1 Ton of Macroalgae (dry) ≅ 1 Ton of CO_2 captured



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?