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Marine BioEnergy, Inc. Final Scientific/Technical Report

Disruptive Supplies of Affordable Biomass Feedstock Grown in the Open Ocean

ARPA-E Award DE-AR0000689

PI: Brian Howard Wilcox

Sponsoring Agency	USDOE, Advanced Research Projects Agency – Energy (ARPA-E)
Lead Recipient:	Marine BioEnergy, Inc
Project Team Members	Marine BioEnergy, University of Southern California, Glosten, Kelson Marine
Project Title:	Disruptive Supplies of Affordable Biomass Feedstock Grown in the Open Ocean
Program Director:	Dr. Marc von Keitz (2015-2021) Dr. Simon Freeman (2022-2023)
Principal Investigator:	Brian Howard Wilcox
Contract Administrator:	Cindy Wilcox
Date of Report:	9/25/2023
Reporting Period:	5/8/2017-5/31/2023

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Public Executive Summary

The nation and world need abundant, affordable feedstock for liquid biofuels, especially for long-haul vehicles. Biomethane is needed to power the grid on days of low wind and low sun. The open ocean provides a massive, untapped area for growing feedstock. The surface of the open ocean has plenty of sunlight and CO_2, but almost no naturally-occurring nutrients. There are plenty of nutrients at the thermocline and all the way to the bottom.

Marine BioEnergy was founded to commercialize a patented invention to enable open ocean farms to produce feedstock by depth-cycling the farms. The patents address depth-cycling of marine photosynthetic organisms, targeting kelp and seaweeds, hereinafter referred to as kelp. The concept is to surface the kelp during the day to absorb sunlight and CO_2, and submerge the kelp at night to the nutrient-rich waters below the thermocline (~60-300 m deep). The key question was: would the kelp thrive in this novel environment? If yes, Marine BioEnergy will prepare to deploy farms towed by unmanned drone submarines to depth-cycle the kelp and produce disruptive supplies of affordable biomass feedstock that can be used to make carbon-neutral, drop-in fuels to enable the transition to net-zero carbon.

In June 2015, Marine BioEnergy submitted an application to the ARPA-E "Open" call for proposals, resulting in this project. The proposed work was to 1) demonstrate that plants (specifically Giant Kelp, *Macrocystis pyrifera*) will thrive in the daily depth-cycling environment and 2) to develop and analyze a detailed design for a commercial farm system that can produce disruptive supplies of affordable feedstock. These objectives were met by this project.

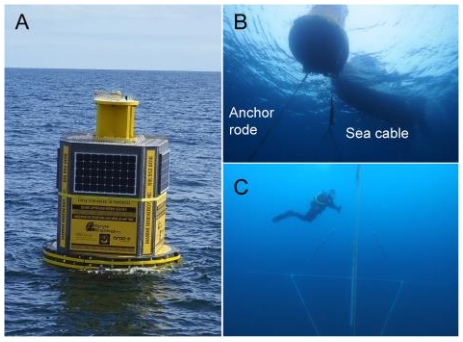

Figure 1: Solar-powered buoy with computer-controlled winch to raise and lower fiberglass kelp growth platform between surface and below-thermocline positions on a daily basis.

Lengthy contract and budget negotiations led to an authorization-to-proceed effective May 8, 2017. The PI built an automated anchored buoy that was deployed in 169 meters of water off Catalina Island (Figure 1). This buoy was solar-powered, with a computer-controlled winch that can raise and lower a fiberglass kelp growth structure featuring a 12-meter horizontal kelp boom, on

which were planted juvenile kelp. The University of Southern California provided marine biology, scientific diving, and related expertise for this project. In the summer of 2019, data was collected on 30+ kelp plants that grew on the depth-cycling structure from late May to early September. The results of this experiment were documented and described in a journal article published in Renewable and Sustainable Energy Reviews in May 2021 (https://doi.org/10.1016/j.rser.2021.110747). The kelp was grown at two locations: the control kelp was grown adjacent to a natural kelp bed at "Parson's Landing" (PL), which was the origin location of all the kelp juveniles used in this experiment. The kelp was also grown on the "Buoy Elevator" (B-E) which is the depth-cycling buoy location. Figure 2 shows the overall results of the experiment, where the depth-cycled kelp grew at an average rate of 5% per day, as compared to a similar number of control kelps that were transplanted adjacent to the natural kelp bed of their origin. The control kelp grew at 3.5% per day over the same period. The overall wet weight of the depth-cycled kelp was about 4 times the corresponding weight of the control kelp grown over the same period at the natural bed. The native kelp beds are renowned for their high rate of growth during periods with consistent upwelling of nutrients. The Elevator Buoy had yielded even better results by providing daily nutrients. This was considered a very successful result – the kelp had thrived in the depth-cycling environment.

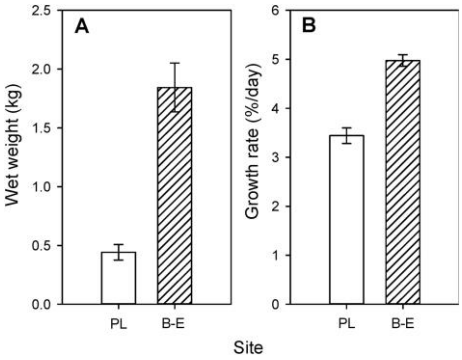

Figure 2: Comparison of kelp growth of controls at Parson's Landing (PL) and the depth-cycled kelp on the Buoy-Elevator (B-E).

Another notable result of this experiment was the determination that the kelp floatation bladders (pneumatocysts) did not develop in the normal way during depth-cycling. Figure 3 shows these results. The key result is that the pneumatocysts of the depth-cycled kelp were filled with liquid, not with gas, and therefore did not exhibit floatation. This is not surprising considering the enormous pressure change involved in depth-cycling (between surface pressure and approximately 8-9 atmospheres of pressure at the night-time position.) Also, as seen in Figure 3, the depth-cycled pneumatocysts were smaller in diameter and had thicker walls than the control kelp pneumatocysts. The fact that the depth-cycled pneumatocysts do not exhibit floatation is considered an excellent result favoring the engineering feasibility of the project, since having the farm exhibit a large change in buoyancy in the top ~50 meters of the daily cycle would be more challenging in terms of system stability and overall engineering.

Success in this first depth-cycling experiment led the then-Program-Director to arrange for additional funds to be added to the contract, leading to an effort to design and analyze a commercial-scale farm system. The team was expanded with Glosten, a Naval Architecture and marine engineering firm; Kelson Marine, a computer-modelling firm specializing in analyzing/simulating and testing the behavior of large flexible structures in the open ocean; Z^2 Engineering, providing propeller design expertise; and 3D Design Concepts, providing CAD design services.

A detailed design was developed, based on solar-powered drone submarines that tow longlines of kelp

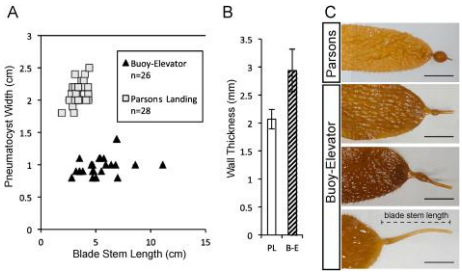

Figure 3: Comparison of pneumatocysts grown on control kelp (PL) and depth-cycled (B-E).

(Figure 4). Each farm will consist of a small number of longlines with spherical floats interspersed along their length. Each longline consists of tubes so that the drone can pump pressurized air or water through the length of the longline to change the buoyancy of the distributed floats. Each day at dusk the drone will pump water into the longlines to further pressurize the air bubble in each float, decreasing the buoyancy of the farm as a whole. The entire length of the farm descends, simultaneously, to the thermocline. The drone releases the pressure on the water line to remove some of the water from each float, stabilizing the depth. At dawn the pressure is released further to allow more water to be removed from each float, causing the entire farm to ascend. The energy required to accomplish this depth cycling is relatively modest. Most of the energy generated each day by the solar panel of the drone is used for propulsion. Large, slow propellers create thrust efficiently, so that economically-attractive lengths of longline can be towed by each drone.

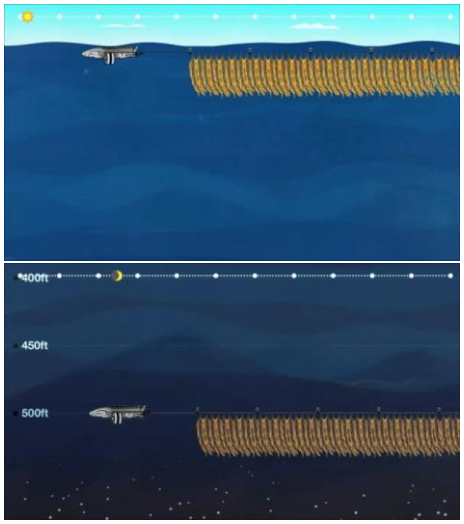

Figure 4: Two still-frames from animation of proposed kelp farms (www.marinebiomass.com). Thermocline can be as much as 300 m deep, but is often as little as 60 m. Drone submarine and other system hardware folds to fit into 40' shipping containers.

The Techno-Economic Analysis indicates that cultivating 0.5% of the oceans will provide enough feedstock to fuel all long-haul vehicles world-wide. To replace all fossil fuels globally requires farming 5% of the open oceans. The TEA shows a ~15-20% Internal Rates of Return on capital invested, without subsidy, competing against fossil fuels. The award period of performance of the project expired May 31, 2023.

Acknowledgements

Marine BioEnergy wishes to acknowledge the financial support of ARPA-E in funding this effort. Program Director Marc von Keitz, Chad Haynes and others at ARPA-E saw the potential, helped launch our project and introduced us to many informative and insightful teams through the MARINER Program. We wish to thank the University of Southern California Professors Sergey Nuzhdin and John Heidelberg, and especially the "doing team" of Dr. Diane Kim, Dr. Ignacio Navarrete, and Marcus Lin, along with kelp consultant Professor Dan Reed from University of California, Santa Barbara. We wish to thank Kyle Beattie and his crew at Glosten (Naval Architect and marine engineering subrecipient), Dr. Toby Dewhurst and his crew at Kelson Marine (ocean dynamics testing and modeling), and Stephen Ziegenfuss of Z^2 Engineering (propeller design). We also wish to thank Jason Carlton and Joshua Morrison at 3D Design Concepts, Inc. for their superb CAD work. Thanks also to technician Waymon Brown and to Captain Nick Gibson and his crew at Pacific Tugboat Services for assistance in getting the depth-cycling buoy deployed and retrieved.

Accomplishments and Objectives

Two major milestones were the objective of this project:

1) to demonstrate that at least one fast-growing species of marine photosynthetic organism (in this case, giant kelp, *Macrocystis pyrifera*) thrives in the daily depth-cycling environment

between the nutrient-poor surface waters and the nutrient-rich water below the thermocline, and
2) to develop and analyze a detailed design of a commercial-scale kelp farm system based on the depth-cycling concept, which also provides the basis for the economic feasibility.

The actual performance against the stated milestones is summarized in the chart below. Note that the initial award was focused on the first milestone, with 10 calendar quarters (2.5 years) allocated to meeting this milestone. Extended contract/budget negotiations with ARPA-E led to "Authority to Proceed" effective 5/8/2017. The actual milestone was met on 9/4/2019, two months early based on 10 quarters after start. When that milestone was met with very encouraging results, the original Program Director arranged for additional funds to be provided (effective 2/23/2022) to achieve the second milestone, using an expanded team that included a Naval Architecture and marine engineering firm and a large-structure ocean dynamics simulation and testing firm. A 51-page detailed design document was submitted in fulfillment of this milestone to the new Program Director and his two top lieutenants, nine days early. Approval of this document was contractually required before work could commence on several additional tasks. This PD didn't offer comments until a few days before the end of the period of performance. Marine BioEnergy was not given the opportunity to respond in order to extend the period of performance and to complete expenditure of funds designated for the sequential tasks.

Table 1: Key Milestones and Deliverables.

WBS	Task/Milestone Title	Task/Milestone Description	Start Q	End Q	Baseline Start(DATE)	Baseline End(DATE)	Task/Milestone Effective Date	Comments
M2.2.2	Depth test the kelp	Depth cycle the test kelp on the deep ocean kelp elevator. First harvest cycle underway.	10	10	3/31/2019	3/31/2019	5/8/2017	Original phase 1 authority to proceed 5/8/2017; 10 quarters later is after actual milestone completion on 9/4/2019.
M2.1.1	Design for the deep ocean kelp farm system approved	Submit design document and the derived detailed-design to Program Director. Conduct design review with ARPA-E management team. After iteration as needed, Program Director will review and approve within two weeks after quarter end.	1	1	6/30/2022	6/30/2022	2/23/2022	Milestone numbering reflects new plan following plus-up 2/23/2022. Design document submitted to new Program Director and two top lieutenants on 6/21/22. No response. Note from PD 12/31/2022 reflected he had not seen document; sent again 1/1/2023. No comments received from PD. Period of performance expired 5/31/2023.

Project Activities

Prior to the accomplishment of the first major milestone (demonstrating that kelp thrives in the depth-cycling environment) all the quarterly reports were concentrated on the development of the depth-cycling buoy. Following that milestone, subsequent quarterly reports often focused on special topics. A list of special topics and their respective quarterly reports is given here:

1QFY20	Detailed discussion of results of first depth-cycling experiment (summer 2019)
1QFY21	Detailed discussion of Journal article submitted for publication.
2QFY21	Detailed discussion of kelp drag and NOAA drifter buoy data and implications.
3QFY21	Discussion of propeller design, among many other topics.
4QFY21	Detailed discussion of economic and technology analogy between kelp farms and wind turbine industry: importance of heavy and expensive gearboxes, steel (for tower in wind turbine and for pressure hull of drone), and fiberglass (for wind turbine blades, longlines for kelp farm). Also, discussion of fiberglass fatigue life.
1QFY22	Detailed discussion of at-sea fermentation of kelp into ethanol, following methodology from Purdue University analysis of engineering and economics of corn ethanol plants.

3QFY22	Detailed discussion of the operating plan during consecutive days of low solar power based on 15 years of daily energy measurements in a foggy coastal site, and current speeds based on >30 years of NOAA drifter buoy data.
4QFY22	Detailed discussion of open-ocean kelp longline tow test conducted 8/4/2022.
1QFY23	Detailed discussion of proposed operational area and plan for first deployment.

Most quarterly reports also summarize the then-current state of the Techno-Economic Analysis.

Project Outputs

A. Journal Articles

Ignacio A. Navarrete, Diane Y. Kim, Cindy Wilcox, Daniel C. Reed, David W. Ginsburg, Jessica M. Dutton, John Heidelberg, Yubin Raut, Brian Howard Wilcox, "Effects of depth-cycling on nutrient uptake and biomass production in the giant kelp Macrocystis pyrifera", Renewable and Sustainable Energy Reviews, Volume 141, 2021, 110747, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2021.110747 (open access)

B. Papers

None

C. Status Reports

Quarterly reports were submitted into the ARPA-E EPIC system prior to the end of each month following each quarterly boundary.

D. Media Reports (reverse chronological order)

24 March 2023
ABLC 2023 Conference Presentation
https://robin.stream/video/ablc-2023-cindy-wilcox-ceo-marine-bioenergy/

20 March 2023
BBC Online Magazine
Video by 4:08 Productions
Executive Producer: Camelia Sadeghzadeh
https://www.bbc.com/reel/video/p0f9qg6l/how-an-aquatic-organism-could-be-key-to-net-zero-aviation
How an aquatic organism could be key to net-zero aviation

19 January 2022
General Electric “The 5 Coolest Things on Earth This Week”
https://www.ge.com/news/reports/the-5-coolest-things-on-earth-this-week-92

31 December 2021
Video segment, Univision, Spanish/English, 9:15 min
https://vimeo.com/659916637/255c946326

26 December 2021
Podcast Interview of Brian H. Wilcox by Mia Funk, One Planet, 44:39 min
https://podbay.fm/p/one-planet-podcast/e/1640512800

28 November 2021
Video segment, ABC7, 4:27 min
(Good explanation of depth-cycling)
https://vimeo.com/648258012/50e1e82242

25 November 2021
Video segment, BBC, 3:41 min
https://www.bbc.com/reel/playlist/2045-memories-of-the-future?vpid=p0b29sn1

9 November 2021
BioFuels Digest
https://www.biofuelsdigest.com/bdigest/2021/11/09/closing-the-gap-in-renewable-energy-the-next-80/

26 August 2021
The inertia, Video interview, 6:56 min
https://www.theinertia.com/environment/how-this-tech-company-plans-to-turn-kelp-into-clean-fuel/

23 May 2021
Long Beach Post News
https://lbpost.com/news/kelp-fuel-biofuel-cultivation-technology-oil

5 April 2021
The Optimist Daily
https://www.optimistdaily.com/2021/04/kelp-could-replace-corn-and-soy-as-a-biofuel-base/

4 April 2021
The Maritime Executive
How Kelp Could Power the World's Transportation Networks
https://maritime-executive.com/editorials/how-kelp-could-power-the-world-s-transportation-networks

1 April 2021
The Conversation
"Move over, corn and soybeans: The next biofuel source could be giant sea kelp"
https://theconversation.com/move-over-corn-and-soybeans-the-next-biofuel-source-could-be-giant-sea-kelp-156728

1 April 2021
Yahoo!News
"Move over, corn and soybeans: The next biofuel source could be giant sea kelp"
https://news.yahoo.com/move-over-corn-soybeans-next-112256391.html

1 April 2021
KABC7 Eyewitness News with Phillip Palmer, 2:57min
https://abc7.com/catalina-island-kelp-as-biofueld-whats-a-biofuel-usc-wrigley-institute-for-environmental-studies/10464956/

27 March 2021
The Log, Lindsey Glasgow
https://www.thelog.com/local/usc-wrigley-study-finds-promising-future-for-kelp-fueling-boats-cars-planes/

22 March 2021
IEEE Spectrum
https://spectrum.ieee.org/energywise/energy/renewables/robots-power-the-quest-to-farm-oceans-for-biofuel
Robots Power the Quest to Farm Oceans for Biofuel:
Study verifies kelp-originated petroleum substitute could scale back demand for traditional fuels

12 March 2021
Springwise, Innovation that Matters, Lisa Magloff
https://www.springwise.com/innovation/agriculture-energy/kelp-elevator-biofuel

11 March 2021
Anthropocene
https://www.anthropocenemagazine.org/2021/03/this-elevator-could-speed-up-seaweeds-route-to-biofuels/

6 March 2021
Tech and Science Post
https://techandsciencepost.com/news/science/kelp-elevator-study-shows-promise-for-producing-biofuel-from-giant-seaweed/

5 March 2021
National Law Review Blog
https://www.natlawreview.com/article/usc-new-aquaculture-technique-leads-to-increased-biomass-kelp-growth

5 March 2021
AIA Architect, Madeleine D'Angelo
https://www.architectmagazine.com/technology/week-in-tech-creating-biofuel-with-an-elevator-for-kelp_o

3 March 2021
Secretary of Energy Granholm mentions Marine BioEnergy technology in first public speech, (as communicated per Marc von Keitz):
"a mighty tool is our highly successful ARPA-E program, which seeds brand-new, out-of-the-box technologies—like seaweed-farming drones to make biofuels"
https://www.energy.gov/articles/remarks-prepared-delivery-secretary-granholm-ceraweek-2021

3 March 2021
Green Car Congress
https://www.greencarcongress.com/2021/03/20210303-kelp.html
3 March 2021
Advanced Biofuels USA
https://advancedbiofuelsusa.info/usc-scientists-may-have-unlocked-kelps-potential-as-a-major-biofuel-source/

2 March 2021
New Atlas, Nick Lavars
https://newatlas.com/energy/kelp-elevator-biofuel-production-four-times/

2 March 2021
USC News
Gary Polakovic
https://news.usc.edu/182840/kelp-as-biofuel-ocean-seaweed-energy-usc-scientists/

2 March 2021
AAAS EurekAlert
https://eurekalert.org/pub_releases/2021-03/uosc-us030121.php

2 March 2021
Science Daily
University of Southern California. “Unlocking kelp’s potential as a major biofuel source.”
https://www.sciencedaily.com/releases/2021/03/210302094053.htm

2 March 2021
KFI AM 640
https://kfiam640.iheart.com/content/2021-03-02-usc-study-shows-promising-potential-for-marine-biofuel/

2 March 2021
Tech Explore
https://techxplore.com/news/2021-03-potential-marine-biofuel.html

2 March 2021
MynewsLA.com
https://mynewsla.com/education/2021/03/02/usc-study-shows-promising-potential-for-marine-biofuel/

2 March 2021
Biotech Asia News
https://www.biotechasianews.com/usc-study-shows-promising-potential-for-marine-biofuel/

2 March 2021
URDUPoint, Pakistan
https://www.urdupoint.com/en/world/us-scientific-grow-kelp-in-ocean-for-bio-fuel-1182035.html

March 2021
QS Study
"Researchers develop a device 'kelp elevator' as a major biofuel source"
https://qsstudy.com/technology/researchers-develop-a-device-kelp-elevator-as-a-major-biofuel-source

16 March 2020
https://www.scientificamerican.com/article/could-our-energy-come-from-giant-seaweed-farms-in-the-ocean/
Could Our Energy Come from Giant Seaweed Farms in the Ocean?
A U.S. agency is funding projects to help create a bioenergy industry based on macroalgae
By Annie Sneed

14 October 2019
By Katharine Gammon,
Copyright on the web site is American Institute of Physics
An experiment off the coast of California may bolster efforts to make biocrude from "the Sequoia of the sea."
https://www.insidescience.org/news/kelp-elevator-could-give-biofuels-lift

13 September 2019
Wild Kingdom
with Stephanie Arne,
Kelp Forest Ecosystem/Farming Fuel
https://www.youtube.com/watch?v=coMEtHwZv7M&list=PLA1UeRQ_bbVvXTkRaiL6Z9S5JFytH38mn&index=11&t=0s
and https://www.youtube.com/playlist?list=PLA1UeRQ_bbVvXTkRaiL6Z9S5JFytH38mn

30 July 2019
"Environmental ingenuity: These creative business ideas aim to be both sustainable and successful"
By Michelle Boston, USC
https://phys.org/news/2019-07-environmental-ingenuity-creative-business-ideas.html

16 March 2018
By Brad Plumer
New York Times
"Kelp Farms and Mammoth Windmills Are Just Two of the Government's Long-Shot Energy Bets"
https://www.nytimes.com/2018/03/16/climate/arpa-e-summit.html

15 March 2017
By Evan Ackerman,– Reporting from the ARPA-E 2017 Innovation Summit
Robotic Kelp Farms Promise an Ocean Full of Carbon-Neutral, Low-Cost Energy" – IEEE Spectrum
https://spectrum.ieee.org/robotic-kelp-farms-promise-an-ocean-full-of-carbon-neutral-low-cost-energy

E. Invention Disclosures
None (the U.S. and International patents for the depth-cycling concept were filed before the application to the ARPA-E Open 2015 program).

F. Patent Applications/Issued Patents
None

G. Licensed Technologies
None

H. Networks/Collaborations Fostered
Good collaboration with Sergey Nuzhdin, Phillippe Alberto, and the other ARPA-E MARINER teams was very helpful in executing this work.

I. Websites Featuring Project Work Results
https://dornsife.usc.edu/news/stories/kelp-elevator-and-sustainable-seaweed-biofuel/
https://marinebiomass.com

J. Other Products (e.g. Databases, Physical Collections, Audio/Video, Software, Models, Educational Aids or Curricula, Equipment or Instruments)
None.

K. Awards, Prizes, and Recognition
None.

Follow-On Funding
Additional funding committed or received from other sources (e.g. private investors, government agencies, nonprofits) after effective date of ARPA-E Award: None.