CALIFORNIA ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

Research and Development for Pilot-Scale Algal-Oil Production

November 2026 | CEC-500-2026-031

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ACKNOWLEDGEMENTS

The author thanks the Bioenergy Technologies Office of the U.S. Department of Energy for funding and guidance; the Global Algae Team including Rodney Corpuz, David K. Hazlebeck, Mark Hazlebeck, Paul Hazlebeck, Brendan Lagather, Daniel Phillips, Aga Pinowska, and Jesse Traller; Specialty Construction, Wallace Group, and Kirk Consulting for extensive contributions to the design and permitting effort; Bill Rickman of TSD Management Associates who led many of the trade-off studies and made major contributions to the design effort; and the Technical Advisory Committee including Bill Barclay, Amha Belay, Phil DeDominicis, Ike Levine, and Greg Mitchell.

PREFACE

The California Energy Commission's Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2015, Governor Edmund Brown, Jr. released Executive Order B-32-15, the California Sustainable Freight Initiative, which established targets to improve freight system efficiency by 25 percent by 2030 and to transition into zero emission technologies. Per the establishment of initiatives and California's continued efforts to meet Federal Ambient Air Quality Standards, state agencies created several funding programs to improve air quality with specific focus on the modernization of California's transportation system. With funding from the Budget Act of 2016, the California Energy Commission implemented a Low Carbon Fuel Research and Development Program, supporting the advancement of low-carbon drop-in fuels production derived from California's biomass feedstocks through the development of intermediate fuels. Renewable biofuels, fuels produced from biomass sources, can be produced to be fully compatible with existing infrastructure and vehicle technologies which can minimize the overall cost of adoption. These intermediate fuels will be used for sustainable low-carbon fungible biofuels production for consumption in California's transportation sector in an effort to further reduce harmful emissions being generated by goods movement vehicles used throughout the state.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

Algae biofuel offers promise as an alternative fuel that can reduce greenhouse gas emissions while driving rural rejuvenation and maximizing benefits from the state's limited water resources. Sharing similarities with vegetable oil and palm oil, algae oil can be readily refined to drop-in fuels such as renewable diesel and jet fuel. Algae biofuel does not compete with food resources and instead increases food production by producing oil and protein simultaneously.

Global Algae Innovations has demonstrated major breakthroughs in algal cultivation and processing at an 8-acre facility, including over 65 innovations to lower the cost of every process step. With these advances, large-scale algae farms are projected to be economically competitive with other commodity proteins and oil. The technology includes direct air capture of carbon dioxide, so the farms can be located anywhere with a suitable climate. The major remaining challenge in reaching commercial algae biofuel production is scale-up and operation of this advanced algae farming technology to validate that it is economically viable and sustainable for producing commodity vegetable oils and protein. This project addressed this challenge by completing the preliminary design and planning for construction and operation of a pilot-scale algae farm. This design effort has improved the ability to obtain funding to build and operate a large-scale algae farm by providing detailed support of the projected costs and benefits, permitting and site selection, and a preliminary design that is ready for advancing to detailed design and construction.

Global Algae Innovations' demonstrated yields for protein and vegetable oil are 24 times greater than soy and palm, the most productive land plants, respectively. This increase in agricultural productivity can support renewable transportation fuel production, rural rejuvenation, carbon dioxide removal, and environmental sustainability.

Keywords: Algae, biofuel, renewable diesel, renewable jet fuel

Please use the following citation for this report:

Hazlebeck, David A. 2026. *Research and Development for Pilot-Scale Algal-Oil Production*. California Energy Commission. Publication Number: CEC-500-2026-031.

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Executive Summary

California set several goals for reducing greenhouse gas emissions which will require significant technological and market changes within the transportation sector. Development and deployment of alternative and renewable fuels will help meet these goals and reduce petroleum dependence.

Algal biofuels hold promise for emission reduction, rural rejuvenation, and maximizing water resources. Furthermore, algal biofuel facilities do not compete with food, but instead increase food production by producing oil and protein simultaneously. Algae oil shares similarities with vegetable oil or palm oil. It can be readily refined to drop-in fuels, used for polymer feedstock, and food.

Global Algae Innovations (Global Algae) was founded with the vision to make a significant improvement in global food and vegetable oil production efficiency on the most expedient timeline possible, dramatically improving the environment, economy, and quality of life for all people. Global Algae has demonstrated major breakthroughs in algal cultivation and processing at an 8-acre facility in Kauai, Hawaii, including over 65 innovations to lower the cost of every process step. With these advances, large-scale algae farms are projected to be economically competitive with other commodity proteins and oils.

Algae farming provides a significant increase in agricultural productivity compared to conventional food and vegetable oil production. Global Algae's current productivity rates are 40 times greater than soy and 9 times greater than palm oil, the most productive land plants. Global Algae's farms can reduce water use by 93 percent and significantly lower land footprint for the same output as conventional crops. Commercial algae farms have potential to provide biofuels, food and feed, high-quality jobs, economic benefits to rural communities, and environmental sustainability.

Project Purpose and Approach

To support the overall goal of facilitating development of a commercial algae farming industry centered in California, this project expanded Global Algae's algae strain library with additional local strains and developed a front-end loaded design of a 160-acre pilot-scale algae facility that incorporated Global Algae's advanced technologies for lower cost and higher productivity algae farming.

The conceptual design included all the top-level process documents and a techno-economic model with a cost estimate, business assessment, and permitting plan. The preliminary design started with site selection that was delayed for over a year due to the COVID-19 pandemic. The final site selected was in Shandon, California.

The purpose of the front-end loaded conceptual design was to prevent re-design during the preliminary or final design effort. The preliminary design started with a set of trade-off studies to finalize various design aspects, such as water management. These trade studies to determine the best and most cost-effective pilot-scale design were important to prevent

changes late in the design. The trade study results updated the top-level process documents, final site layout, and techno-economic model.

Next, the process documents from the conceptual design were updated. A detailed topographical map of the site was generated via an aerial survey with targets placed throughout the site, which was used to develop the site layout and orientation. This determined locations for exploratory trench locations to conduct field examination and analysis for a soils engineering report. This soils engineering report together with the layout and topographical map were used to prepare the grading plan and specifications.

In parallel with the site plan, more detailed process documents were prepared, and the permitting process was nearly completed. The detailed process documents included the piping and instrumentation diagram, single-line electrical, operation and control plan, detailed equipment and utilities lists, and piping layout and electrical distribution.

Key Results

The project successfully achieved its objectives, leading to nine invention disclosures and securing a long-term lease for the selected site. The specific objective, to complete the design of the pilot-scale algae cultivation and processing facility and complete the planning for construction and operation, was achieved along with multiple design improvements for better economics and sustainability.

The success of the project was validated by several follow-on awards and reviews, including multiple projects totaling $11.6M from the U.S. Department of Energy for construction and operation of the first six acres of the facility. Additionally, based on an independent engineer's review of an economic, market, technical, financial, and management feasibility study, the U.S. Department of Agriculture approved a loan guarantee green light to Phase 2 letter for construction of the pilot-scale facility.

The design and Energy Performance Certificate cost estimates were used to improve the fidelity of Global Algae's technoeconomic model for algae cultivation and processing. The model predicts that the technology incorporated into the pilot-scale design will result in cost-competitive production of biofuel, food, and feed at full-scale with jet fuel, diesel fuel, and gasoline production for less than $3/gallon of gasoline equivalent. The model also confirmed the sustainability benefits of the process regarding water, land, carbon dioxide, eutrophication, ocean ecology, and natural habitat preservation and the economic benefits in terms of revenue from land and water resources and job creation. The conclusion is that Global Algae's technology is ready for scale-up, and the technology will have a tremendously positive economic and environmental impact.

Knowledge Transfer and Next Steps

This project was for the design of a pilot-scale algal oil facility. The objective was to use the results to obtain funding for construction and operation of the pilot-scale algae farm. The public-private partnership model, involving various stakeholders, facilitated progress.

The preliminary design will provide the data for preparation of a final business plan including strategy for obtaining financing for construction and operation of the full pilot-scale facility. The next step is raising funds to complete construction and operation of the facility. Results have attracted investments from the U.S. Department of Energy and XPRIZE, as well as interest from the U.S. Department of Agriculture, indicating the potential for further investments. Future plans include obtaining financing through multiple channels, including foundations, commercial investment, strategic partners, and government programs.

CHAPTER 1: Introduction

Algal biofuels offer great promise in solving major environmental issues as well as creating an economic boon and revitalizing rural areas. This promise can be realized through the development of a commercial algae industry for commodities. The existing commercial algae industry produces high value products with technologies that are at least an order of magnitude too expensive for commodities such as animal feed, vegetable oil, and biofuels (Benemann, 2013). Also, conventional algae cultivation technology is not scalable to commodity-level production. Global Algae Innovations developed and demonstrated breakthroughs for algal protein and oil production that overcome the economic and scalability issues with conventional algae technology. These advanced algae cultivation and processing technologies were demonstrated in an 8-wetted acre facility in Kauai, Hawaii, shown in Figure 1.

Figure 2: Global Algae's Research and Development Farm



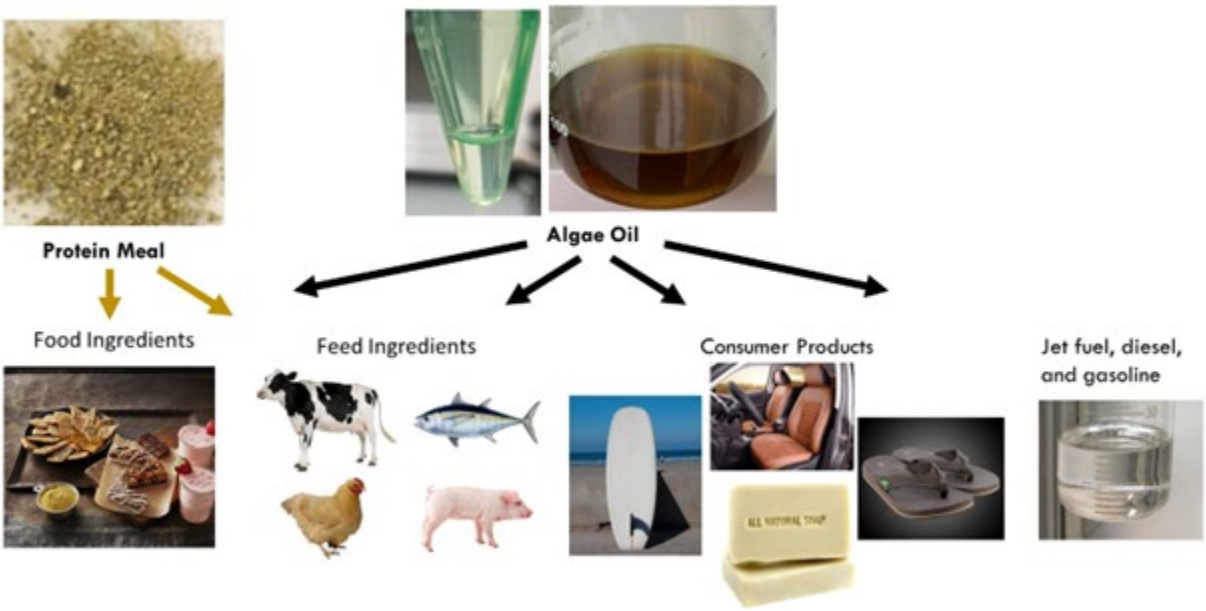
Source: The Image Group (TIG) and Andy Stenz

The primary remaining barrier to development of a commercial algae industry for commodities is scaling-up of these advanced technologies. This project directly addresses this barrier through the design of a pilot-scale facility for algal oil and protein production. Algae oil shares similarities with vegetable oil or palm oil and is well-suited for refining to drop-in jet fuel, diesel fuel, and gasoline (Wang, 2016; Honeywell, 2021), such as renewable diesel under the Standard Specification for Diesel Fuel ASTM D975 and jet fuel under ASTM D7566 Annex 7. U.S. renewable diesel production capacity has grown significantly in recent years from 0.6 billion gallons per year in 2020. As of January 2024, the U.S. production capacity for renewable diesel and other biofuels was 4.3 billion gallons per year, including 1.1 billion gallons per year from refineries located in California.

Algae oil can also be used for polymer feedstock and to supply omega-3's for improved animal and human nutrition. The algae protein powder is a highly digestible and complete protein, making it an ideal ingredient for food and feed. Furthermore, algal biofuel facilities do not

compete with food resources, but instead increase food production by producing oil and protein simultaneously. Figure 2 illustrates some of the products that can be produced in an algae biofuel facility.

Figure 2: Algae Products



Source: Global Algae Innovations

California adopted several aggressive goals for reducing greenhouse gas (GHG) emissions (California Air Resources Board, 2017), including reducing GHG emissions to 40 percent below 1990 levels by 2030 and reducing GHG emissions to 80 percent below 1990 levels by 2050. Achieving these goals will require significant technological and market changes within the transportation sector, which accounts for 39 percent of state GHG emissions (California Air Resources Board, 2024). Both California and the federal government also established numerous goals and mandates to reduce criteria air pollution and increase the prevalence of alternative fuels and vehicles.

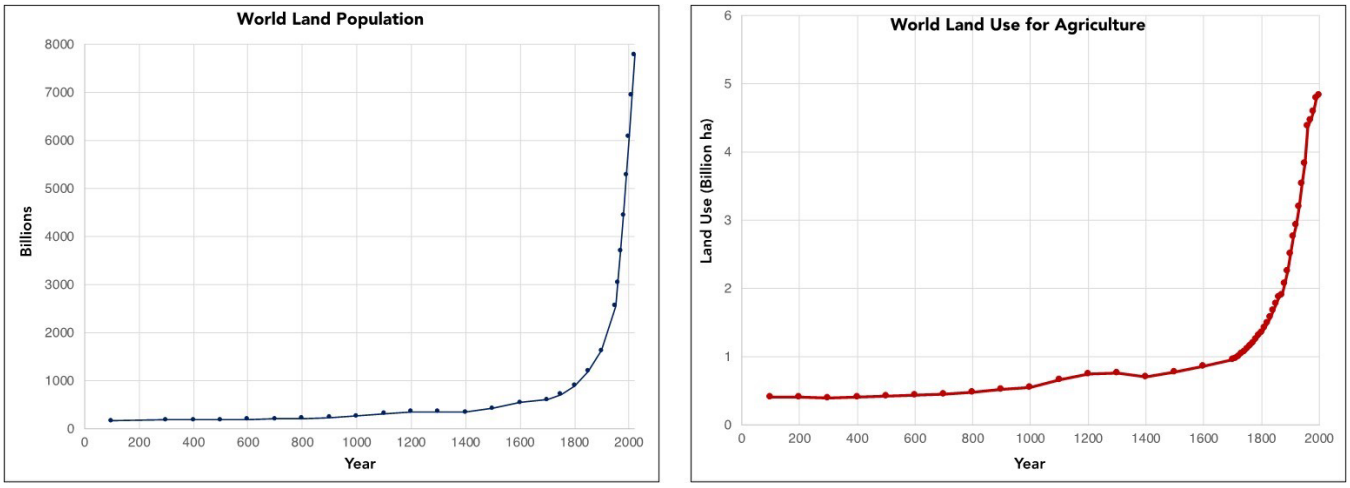
Algal biofuels offer promise as an alternative fuel in enhancing economic and energy security through reductions of imports of energy from foreign sources and reductions of energy-related emissions, including GHGs, while meeting the Renewable Fuels Standard mandate established within the Energy Independence and Security Act of 2007. Algal biofuels offer distinct advantages, such as high per-acre productivity, use of otherwise non-productive, non-arable land, use of poor-quality water sources, and re-use of carbon dioxide. Furthermore, algal biofuels do not compete with food resources and can result in increased fuel and food production through generation of a protein meal co-product. Also, due to the ability of photosynthetic algae to accumulate significant amounts of lipids, algae are particularly well suited for conversion to hydrocarbon-based fuels, such as renewable diesel and jet fuel. The key barriers to unleashing the potential of algal biofuels are development of low-cost production technologies and scale-up of these technologies.

The following sections introduce the potential of algae farming, reasons scale-up of algae farming has not been successful in the past, and the Global Algae Innovation's technology that can contribute to successful scale-up going forward.

Algae's Potential Productivity Benefits

Food production requires significant water and land resources to support a growing population, as illustrated in Figure 3. The primary response has been to use more land and water resources for agriculture, stressing the environment to meet the current production demands of food, feed, and vegetable oil which can be used for renewable fuels.

Figure 3: Population and Agricultural Land Use Curves

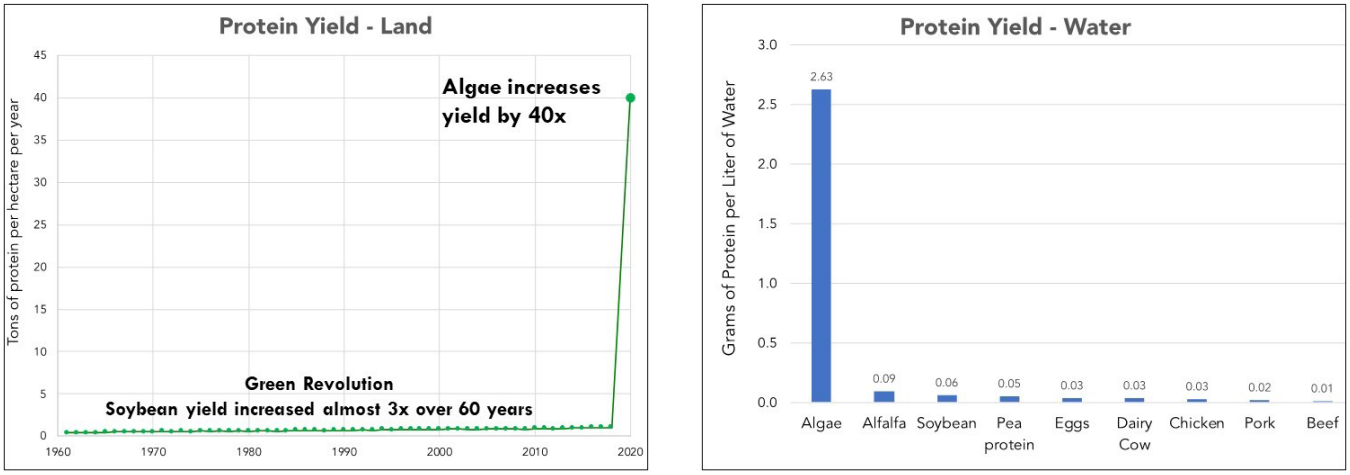


The primary means of feeding the growing population has been devoting greater resources to agriculture. Note: The unit ha stands for hectare, which is equal to 2.4 acres. 5 billion ha is a little more than half the size of the United States.

Source: Our World in Data; replotted by Global Algae Innovations

The Green Revolution (which involved advancements in agriculture such as inclusion of chemical fertilizers, pesticides, and herbicides, crop breeding, and technology adoption) increased productivity 3–5 times, which has prevented catastrophic environmental disaster, but the rate of agricultural productivity increase is now much lower, and food demand is expected to increase two- to three-fold by 2050 (Global Agricultural Productivity Organization, 2022). Global Algae's current productivity rates for protein and vegetable oil from algae are 40 times greater than soy and 9 times greater than palm oil. Figure 4 illustrates the protein productivity based on water and land use relative to conventional sources. By replacing more water intensive crops for production of protein for animal feed, algae farms would reduce water use by 93 percent, helping to restore rivers and watersheds with plenty of water available for feed and for the environment. Furthermore, algae farms do not use pesticides or herbicides and have no run-off, which is the leading cause of ground and surface water impairment. Algae farms also have a significantly lower land footprint for the same protein output as conventional crops, and algae farms can use otherwise non-productive, non-arable land.

Figure 4: Water and Land Productivity of Agricultural Products



Source: Global Algae Innovations' yield data and literature data (Videle 2019; Flachowsky et. al., 2017)

Algae farming offers a significant potential increase in productivity as illustrated in Figure 4. As a result, enabling commercial algae farming can lead to many environmental and social benefits:

- **Water:** Algae farming has greater than 90 percent reduction in water use for protein and vegetable oil production, no use of pesticides or herbicides, and no agricultural run-off or percolation, which is the leading cause of global water impairment.

- **Ocean ecology:** Algae is in the ocean food chain and has all needed nutrients for aquaculture (for example, amino acid profile, taurine, omega-3, carotenoids, vitamins, and minerals), large-scale production as aquaculture feed ingredient could end the need for overfishing (United Nations, 2019).

- **Forests:** Deforestation is driven by protein production. Algae farming is 20–40 times more productive, so it will enable reforestation while meeting the world's growing protein demand.

- **Greenhouse gases:** Greater than 90 percent reduction in GHGs for algae biofuels and algae protein meal relative to conventional technology and combined with algae driven reforestation will be integral to solving climate change.

- **Species loss:** Current rate of species endangerment and loss is unprecedented since the earth's last major extinction event. Algae provides the solution to the major factors causing species loss — water use and impairment, overfishing, loss of habitat, herbicides, pesticides, and climate change (FairPlanet, 2023).

- **Rural rejuvenation:** Algae facilities will create much more revenue per area as well as a full spectrum of high-quality jobs in rural areas that will address unemployment, poverty, and lack of opportunity (Ullman et. al., 2021).

- **Poverty:** Standard of living is driven by productivity. Algae farming provides an unprecedented productivity improvement with 25 times greater production from land and water resources that will lift entire regions out of poverty (World Bank, 2023).

- **Malnutrition:** Algae is the only plant-based food that provides all essential amino acids, vitamins, and minerals. Algae has high protein content with exceptionally high levels of carotenoids, vitamins, minerals, omega-3 oils, and antioxidants.

In California, algae farming can (1) make efficient use of limited water and land resources 2) create high quality jobs and increased revenue in rural areas while enabling restoration of natural habitats, (3) address climate change through biofuel production and reduced GHG emissions, (4) reduce water impairment from agricultural run-off and percolation, and (5) provide an alternative to fishmeal and fish oil in aquaculture, reducing pressure on forage fish populations and enabling restoration of ocean ecosystems.

Prior Scale-up Attempts

Prior algal integrated biorefineries have not been successful in leading to commercial facilities because they did not have the needed innovations throughout the whole process and the cultivation systems have relied on:

- Standard paddlewheel mixed open raceways, which have 2-3x lower productivity and are not scalable since they are modular.

- Photobioreactors, which can achieve more than double the productivity but cost more than double, have higher energy use, and are even less scalable than open raceways (Richardson et. al., 2012; Clippinger et. al. 2019).

- Mechanical attached growth systems, which are very expensive and not scalable but have useful applications in wastewater treatment rather than algae cultivation.

There are algal facilities that are similar scale to the Global Algae pilot-scale for algal biofuels, but they all use standard paddlewheel mixed raceways, and contamination control is accomplished by use of extremophiles or large inoculum volumes. These facilities have been in operation for over 40 years, so if this approach was economical for biofuels, the process would already have been scaled up.

To successfully penetrate the fuel market, the minimum profitable biofuel price must be low enough to compete with gasoline. U.S. Department of Energy (DOE) Bioenergy Technologies Office (BETO) analyses concluded that a minimum fuel selling price (MFSP) of $3/gasoline gallon equivalent (GGE) can compete on an energy-adjusted basis with gasoline derived from oil costing $75–$90 per barrel (U.S. Energy Information Administration, 2015). Given recent declines in oil prices and historical volatility as illustrated by the broad range of oil prices projected by the Energy Information Administration for 2022 ($61–$156 per barrel), bioenergy technology may continue to require policy support and regulatory mandates to enable the new bioenergy sector while it is being established.

DOE developed an algae farm design and state-of-technology analysis (Davis, 2015)[1]. This analysis includes several technology assumptions which are not feasible, including (1) a harvest approach that has never been successfully implemented, (2) low-cost pure carbon dioxide (CO2) is available at the farm, and (3) algal productivity is two to three times higher than typically achieved in paddlewheel mixed open pond cultivation. If actual algal productivity data for paddlewheel mixed raceways from the DOE Algae Testbed Public-Private Partnership (ATP3) is used, the cost is $1,641/mt ash-free dry weight (AFDW), which corresponds to a MFSP of $17.69/GGE. If the actual cost of pure CO2 is used and a proven harvest technology, then the costs would increase to approximately $2,640/mt AFDW, which corresponds to a MFSP of $26.86 /GGE; thus DOE 2015 State of Technology (SOT) projected cost for algal biofuel is an order of magnitude too high to be economically viable, which clearly illustrates why innovation is needed throughout the process (Bioenergy Technologies Office, 2016).

Table 1 provides a summary comparison of the contributions of different process areas to the modeled mature commercial facility MFSP for:

- DOE 2015 SOT with unproven CO_2 and harvesting/dewatering technologies.
- DOE 2015 SOT with state-of-the-art CO_2 and harvesting/dewatering technologies.
- Global Algae's Proposed technology that was demonstrated at the multi-acre scale.

Global Algae's proposed technology has higher nutrient costs per gallon because of the higher nitrogen demand to produce a protein meal co-product. The protein meal co-product is estimated to sell for $1,200/mt. The MSFP for the proposed technology meets the BETO target of less than $3/GGE for algal derived renewable diesel and is more than an order of magnitude improvement over the DOE SOT with state-of-the-art harvesting and CO2 supply.

Since Global Algae has overcome the cultivation and processing technology barriers to commercialization, the key remaining barriers are (1) scale-up, (2) product development and validation at scale, and (3) regulatory approval of food and feed products, which requires operation at scale to produce algal products and testing on the safety and efficacy of the products. These remaining barriers are often called the "valley of death" because obtaining funding for scale-up is difficult. This is particularly true for algae technology because many innovations were required to achieve economic viability, and multiple products must be validated. Economic operation at commercial scale will require a facility size of approximately 3,200 acres, which is 400 times the size of the current facility. An intermediate scale-up to a pilot-scale of 160 acres is needed to validate the scaling and to demonstrate product quality and economics.

[1] R. Davis, et al. 2015. Process Design and Economics for the Production of Algal Biomass: Algal Biomass Production in Open Pond Systems and Processing Through Dewatering for Downstream Conversion. National Renewable Energy Laboratory. NREL/TP-5100-64772.

Table 1: Minimum Fuel Selling Price for Algae Biofuels

Area	DOE 2015 SOT with Unproven Technology	DOE 2015 SOT with State-of-the-Art Technology	Global Algae's Technology
Inoculation	$1.86	$1.86	$0.03
CO_2 Supply	$0.94	$2.68	$0.46
Nutrients	$0.62	$0.62	$0.90
Cultivation	$12.85	$12.85	$3.32
Harvesting	$0.65	$9.28	$0.66
Extraction	$1.95	$1.95	$0.18
Conversion	$0.81	$0.81	$0.70
Co-product	$(0.12)	$(0.12)	$(3.98)
Total	$17.69	$28.06	$2.27

Minimum Fuel Selling Price for DOE state of technology versus Global Algae's technology in dollars per gallon of gasoline equivalent.

Source: Global Algae's technoeconomic model and Davis et. al. 2016.

Production of algae oil at the pilot scale is not economical for fuel or for consumer products. Without government support, the only path forward is production of very high value products such as astaxanthin, omega-3 oils, pigments, nutraceuticals, and so on. Scaling up for these products is beneficial because it validates much of the technology; however, production of these products will not validate the quality and long-term production of algae oil and protein meal, and further scale-up to biofuels will be impeded without validation of these products.

Global Algae's Technology

Global Algae previously demonstrated major advances in algal cultivation and processing such that mature commercial facilities for algal biofuels are projected to be economical and sustainable. Every process step includes innovations relative to classical algae cultivation and processing. This project will complete the preliminary planning and design of a pilot-scale integrated biorefinery incorporating these innovations, and consequently will help address one of the largest challenges in the commercialization of algal biofuels, scaling-up these innovative algal technologies, which is necessary to demonstrate and validate algae systems. Global Algae led the design effort with extensive support from TSD Management Associates, a professional chemical engineer experienced in harvesting and downstream processing of algae.

Global Algae developed an integrated process for algal oil production with numerous innovations relative to standard algal cultivation technology that overcome major technical

obstacles to economical algae production. The integrated process was demonstrated at the 8-acre scale, see Figure 1. Some of these innovations include:

- **Inoculation & Contamination Control**: Novel operational and process designs have enabled growth of multiple strains of cyanobacteria, green algae, diatoms, and red algae without contamination issues.

- **CO_2 Supply**: A patent pending direct air capture CO_2 system that captures CO_2 directly into the raceways from the atmosphere and eliminates the need for a gas distribution and control system as well as a concentrated CO_2 source.

- **Cultivation**: Massively scalable sloped raceways that reduce the number of raceways required for large scale implementation by 100 times and novel, patented operational and design changes that attain 3 times higher productivity than conventional raceways with 1/10th the energy use and much lower manpower requirements.

- **Harvesting & Dewatering**: An ultra-low energy membrane system that incorporates multiple innovations to enable 100 percent harvest efficiency, crystal-clear permeate, and 15–20 percent solids effluent with no flocculent required and 0.04 kWh/kg of algal biomass. Global Algae Equipment started selling the Zobi Harvester®, which utilizes this patented technology.

- **Drying & Extraction**: (1) a new drying and extraction process that reduces drying and extraction energy use by an order of magnitude and (2) a Crown Iron Works extraction process for use in conjunction with drying for a co-product that achieves lysis and extraction with an energy use of approximately 6 percent of the biofuel intermediate energy content. All these technologies were demonstrated at commercial-scale with multi-acre raceways, except the new drying and extraction process, which is at bench-scale.

Together, these innovations reduced the projected commercial-scale cost and energy use by a factor of ten, as illustrated in Table 2. These innovations will further reduce the projected cost of commercial algae biofuel production; thus, further reductions in the MFSP for algal biofuels are expected by the time the pilot facility designed through this project is in operation.

Table 2: Global Algae's Cost and Energy Saving Innovation

Area	Cost Reduction	Energy Use Reduction	Other Notable Metrics Relative to Conventional Systems	Innovation
Inoculation	99%	99%	1000x smaller system	Design and operational approaches for contamination control with 6g inoculum per 140 tons of algae biomass

CO_2 Supply	100%	100%	CO_2 supplied from atmosphere	Direct air capture into the raceways
Cultivation	74%	89%	100x increase in scalability 2-3x higher productivity 40-50% lipid with 25-40% protein	Novel raceway design and operation at multi-acre scale
Harvesting	93%	98%	100% harvest efficiency Crystal clear permeate recycle	Zobi® membrane harvesting system
Drying	49%	94%	Higher quality algae meal	New drying & extraction process
Extraction	91%	78%	Fractionation into multiple products	New drying & extraction process
Overall	89%	94%		

Global Algae's technology provides an order of magnitude improvement in cost and energy use and an improved product spectrum relative to conventional technologies.

Source: Global Algae's Technoeconomic Model

Some of the key research and development (R&D) successes of the Global Algae team include:

- Design, construction, start-up, and operation of the Kauai Algae Farm in **2011**, which is the world's most advanced open raceway algae facility.
- Retrofitting the Kauai Algae Farm to connect to the adjacent power plant flue gas for CO_2 supply and install new technologies in **2014**.
- Operating a large-scale open raceway facility solely on power plant flue gas CO_2 in **2014.**
- Growth of many species of microalgae at large-scale without contamination issues including diatoms, green algae, and red algae in **2015.**
- Doubling algal productivity in **2015.**
- Solving the harvest and dewatering challenge for algal production and commercializing the technology as the Zobi Harvester® in **2016.**
- Production of surfboards from algae oil in **2017.**
- Demonstration of novel drying process **2018.**
- Demonstration of CO_2 supply via direct air capture into raceways in **2019**.
- Increased productivity by 25 percent in **2020**.
- Increased oil content to 40-50 percent in **2021**.
- Demonstration of novel drying and extraction process in **2021**.

CHAPTER 2:
Project Approach

Technology Barrier Approach

"The key barriers to the development of algal feedstocks are the cost, quality, and volume of available sustainably-grown biomass to supply the growing biobased industry for biofuels, bioproducts, and biopower. Design cases and accompanying state-of-technology reports are used to describe discreet barrier areas to achieving large volumes of low-cost, high-quality algal biofuel intermediates. Analysts use modeled scenarios, developed in close collaboration with researchers, to perform conceptual evaluations termed 'design cases'. These design cases provide a detailed basis for understanding the potential of conversion technologies and help identify technical barriers where R&D could lead to significant cost improvements." (Bioenergy Technologies Office 2016). Based on these analyses, the DOE identified the following critical emphasis areas:

- **Productivity and Stable Cultivation**: Developing biology and culture management approaches to unlock algal biomass productivity potential and stable cultivation.

- **Low-cost, Scalable Cultivation Systems**: Developing low-cost, scalable cultivation systems that maximize reliable annual biomass yield and quality and minimize energy use, water consumption, land use, and nutrient additions.

- **Low-cost Harvest Technology**: Developing low-cost, high-throughput harvest technologies that can be integrated with cultivation systems.

- **Integrated Analysis**: Performing integrative analysis to identify critical barriers and evaluating impacts on overall yield to developments in biology, cultivation, and processing.

- **Extraction and Co-products**: Developing higher-value co-products that can be produced and recovered along with biofuel intermediates.

- **Refining**: Demonstrating feasible routes and developing rigorous models to decouple the final upgrading of hydrocarbon-based biofuel intermediates to finished fuels and/or blendstocks to take advantage of existing depreciated refining infrastructure.

This project will have a major impact on the algal biofuel industry because the project incorporates innovations to resolve all of the issues in the critical emphasis areas listed above as well as provides low-cost CO_2 supply, which is another critical area not recognized in the DOE analysis because of the assumption that compressed, pure CO_2 will be available from flue gas at $41/mt (there is no technology currently available to achieve that cost for CO_2 supply). The state-of-the-art and a non-proprietary discussion of the key innovations for each of these critical emphasis areas except co-products and refining are discussed in detail below. Co-

products and refining are utilizing off-site existing facilities with proven capabilities, so no new innovations are required in these areas.

Successful completion of this project followed by successful construction and operation of the pilot-scale facility will validate economical, sustainable technology for algal biofuel production, which will lead to commercial facilities for algal biofuel production. This would create a new industry that would help the US and other countries become independent of foreign oil and reduce global GHG emissions.

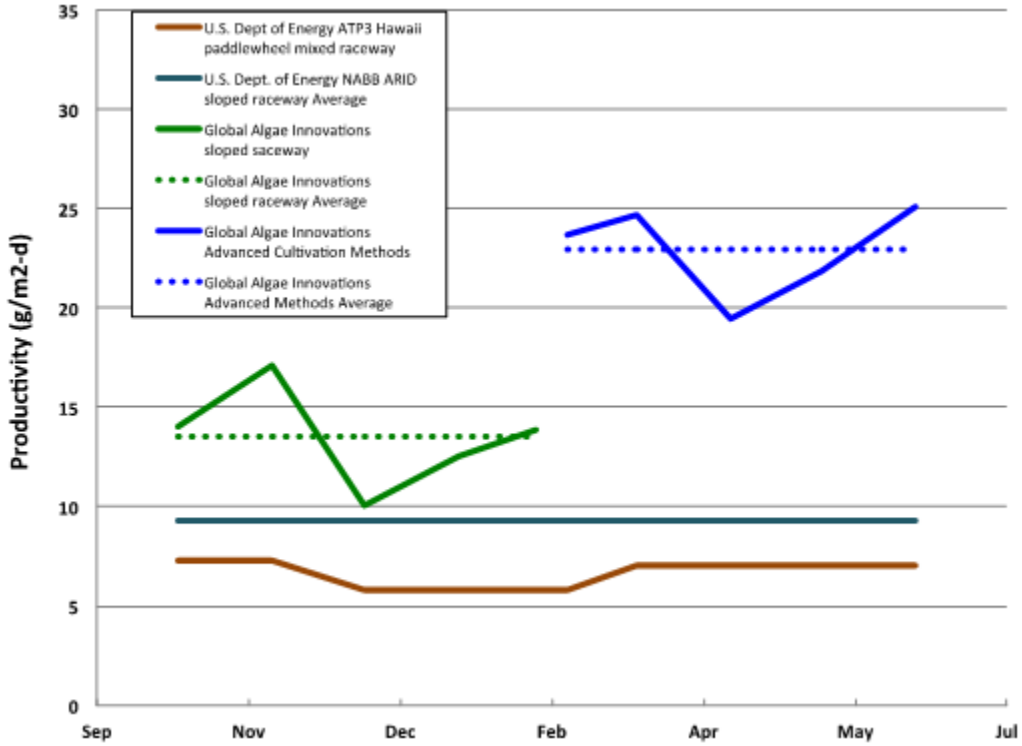
Productivity

Assuming that adequate nutrients and CO2 are supplied, the primary drivers for algal productivity are strain capability, light, mixing, media composition, and condition of the algae. Mixing affects both the accumulation of oxygen in the media and the supply of nutrients and CO2 to individual algae cells. Highly mixed systems have high productivity and poorly mixed systems have low productivity. Generally, state-of-the-art systems are (1) paddlewheel driven open raceways that are relatively inexpensive (~$50,000/acre) but are also relatively deep and poorly mixed or (2) highly engineered systems that are very expensive (~$500,000/acre) but provides good mixing. Examples of these highly engineered systems include photobioreactors, highly sloped open systems with concrete or solid plastic bottoms for very shallow operation, and mechanical attached growth systems. The dilemma is that inexpensive systems have low productivity, and high productivity systems are too expensive, not scalable, and require a very high-energy input (~10x more energy use than conventional).

Global Algae utilizes a gradually sloped system with innovative cultivation operations and equipment designs that achieve productivity similar to the expensive, highly engineered systems, but that require very low energy input and are less expensive and more scalable than paddlewheel driven open raceways.

Figure 5 shows the productivity improvement demonstrated in multi-acre scale operation using sloped raceways with advanced cultivation methods relative to a standard, gradually sloped raceway and a conventional raceway. The productivity improvement is approximately three-fold higher than a conventional raceway and two-fold higher than a standard sloped raceway. In addition to the raceway design and operation, Global Algae has many additional proprietary innovations that improve productivity and/or reduce operational costs in algae cultivation.

Figure 5: Productivity Data in Different Cultivation Systems



Source: Global Algae data and DOE ATP3 program data

Stable Cultivation

As in productivity, there are multiple state-of-the-art approaches to achieving stable cultivation. Extremophiles are used to limit the contamination. For example, *Arthrospira platensis and Arthrospira maxima* (Spirulina) are cultivated at very high pH, or *Dunaliella salina* is cultivated at very high salinity. Another common approach is to use very high inoculation volumes or to perform the entire cultivation in a photobioreactor. This is the approach included in the DOE 2015 SOT analysis, which leads to high inoculation costs. Another approach that has been successfully applied is the use of quantitative polymerase chain reaction (qPCR) to identify contamination before it can be detected by other means, and then to use pesticides or herbicides to treat the contamination before it can take hold. In the project team's case, the use of pesticides or herbicides is not acceptable because of the co-product protein meal, but the qPCR could still be beneficial for other non-toxic targeted treatments.

Stable cultivation without any issues from contamination was validated at 3.2 acre scale in the Kauai facility for several different strains. There are four key innovations that enable this achievement. One example is nutrient preloading and cycling. Nutrient preloading and cycling takes advantage of the natural propensity of algae to over accumulate or "luxury consume" vital nutrients. Global Algae utilizes luxury consumption to load the algae with key nutrients in the inoculation stage and then periodically throughout the cultivation, so these nutrients are locked in the algae cells and are unavailable for competitor organisms.

Low-cost, Scalable Cultivation Systems

The maximum size for a conventional raceway is on the order of 4 ha, and the maximum size of a single cultivation unit in a highly engineered system is less than 0.1 ha. Thus, a 10,000-ha facility would require more than 2,500 conventional raceways or more than 100,000 highly engineered cultivation systems. Each of these systems would require separate controls, piping, instrumentation, and maintenance.

Conversely, the length of a sloped raceway is only limited by a total grade rather than by the height of liquid in front of a paddlewheel. Global Algae's sloped raceways have very low grade, so if pump stations were included at each end, then a 2,000 m long raceway could easily be constructed. Also, the width of a sloped raceway is not limited by the practical width of a paddlewheel because pumps can be used to generate the elevation change. In a 2,000 m long raceway, channel widths of up to 200 m are reasonable for a 10:1 aspect ratio; thus, depending on local topography, an 80-ha sloped raceway is feasible. In this case a 10,000-ha facility would only require about 130 raceways, which greatly reduces the cost relative to conventional or highly engineered systems that are not as scalable.

Other scalability issues with large facilities include energy use, manpower to clean raceways, and handling large rainfall without losing the cultures. Global Algae developed and demonstrated innovations that overcome these issues as well. For example, one contributing factor to lower energy use is that sloped raceways enable use of pumps with higher hydraulic efficiency than the paddlewheels and greater scalability to large flows. Combined with other innovations that lower the energy use and the demonstrated higher productivity, Global Algae has achieved over an order-of-magnitude reduction in the mixing energy use relative to conventional systems.

Low-cost CO2 Supply

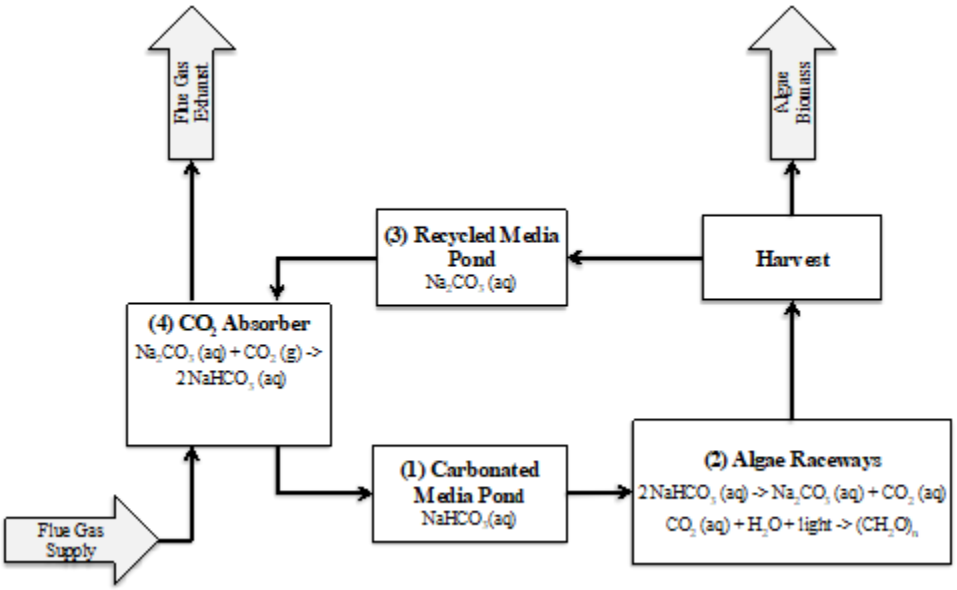
The two state-of-the-art approaches, (1) distribution of flue gas to the cultivation system and (2) capture and compression of the CO2 gas from the flue gas for storage and distribution to the cultivation system, have numerous technical and economic issues for CO2 supply and algal production (Nagarajan 2013; EERE 2010). Both methods require an expensive distribution and control system to provide CO2 to thousands of acres of algae raceways. The first method has major technical barriers including that the technology must be invented to prevent ground level release of the flue gas, cultivation facilities must be maintained during utility outages, and diurnal, daily weather, seasonal variations in CO2 utilization by the algae limit the capture efficiency to less than 15 percent. Even without these barriers, the distribution system is expensive, and a large amount of energy is required to compress the flue gas. The second method, capturing and compressing CO2, overcomes the technical barriers noted above because the CO2 is purified to avoid ground level flue gas emissions, and it can be stored as liquid CO2 to accommodate variations in supply and use; however, because capture and compression costs are added to the vast distribution and control network, this method is even less economical.

Global Algae's advanced CO2 management process overcomes all the obstacles with the conventional CO2 supply approaches. The method includes four cyclic steps, illustrated in Figure 7: (1) the growth media stores/buffers CO2 as sodium bicarbonate, (2) during algae cultivation, photosynthetic uptake of CO2 converts sodium bicarbonate to sodium carbonate, (3) algae is harvested from the media, and the recycled media is sent to the CO2 absorber, and (4) the recycled media is then contacted with flue gas in a packed-tower absorber to absorb CO2 and buffer it by converting the sodium carbonate (Na2CO3) back to sodium bicarbonate (NaHCO3) for storage in step 1.

This method was demonstrated at the 8-wetted acre scale with a slipstream from an adjacent power plant's flue gas as illustrated in Figure 7. All the CO2 for the large-scale cultivation facility depicted in Figure 7 were supplied via this flue gas for the past two years. The CO2 was recovered 24 hours per day with only 2.5 inches of water pressure drop on the flue gas. The carbonated media can be stored indefinitely in a covered pond until it is used for cultivation. This decoupling of the CO2 supply from the cultivation through storage in the carbonated media pond accommodates the variability in flue gas production and cultivation conditions. Furthermore, the CO2 is supplied with the media to the cultivation system, so a separate CO2 supply and distribution system is not required.

During the project, a direct air capture method of CO2 supply was developed and demonstrated in one of Global Algae's ongoing R&D projects. With this approach, direct capture of CO2 from the atmosphere into the raceways is achieved without loss of productivity or added cost for cultivation. Figure 8 illustrates the productivity with the original advanced CO2 supply method and the direct air capture approach. The productivity for each approach was the same, approximately 23 g/m2d. Direct air capture eliminates the cost of supplying CO2 to the farm and enables locating algae farms without the constraint of being physically located next to a CO2 source.

Figure 6: Block Flow Diagram for Advanced CO_2 Management Process



Source: Global Algae Innovations

Figure 7: Application of the Advanced CO_2 Management Process at the Kauai Algae Farm

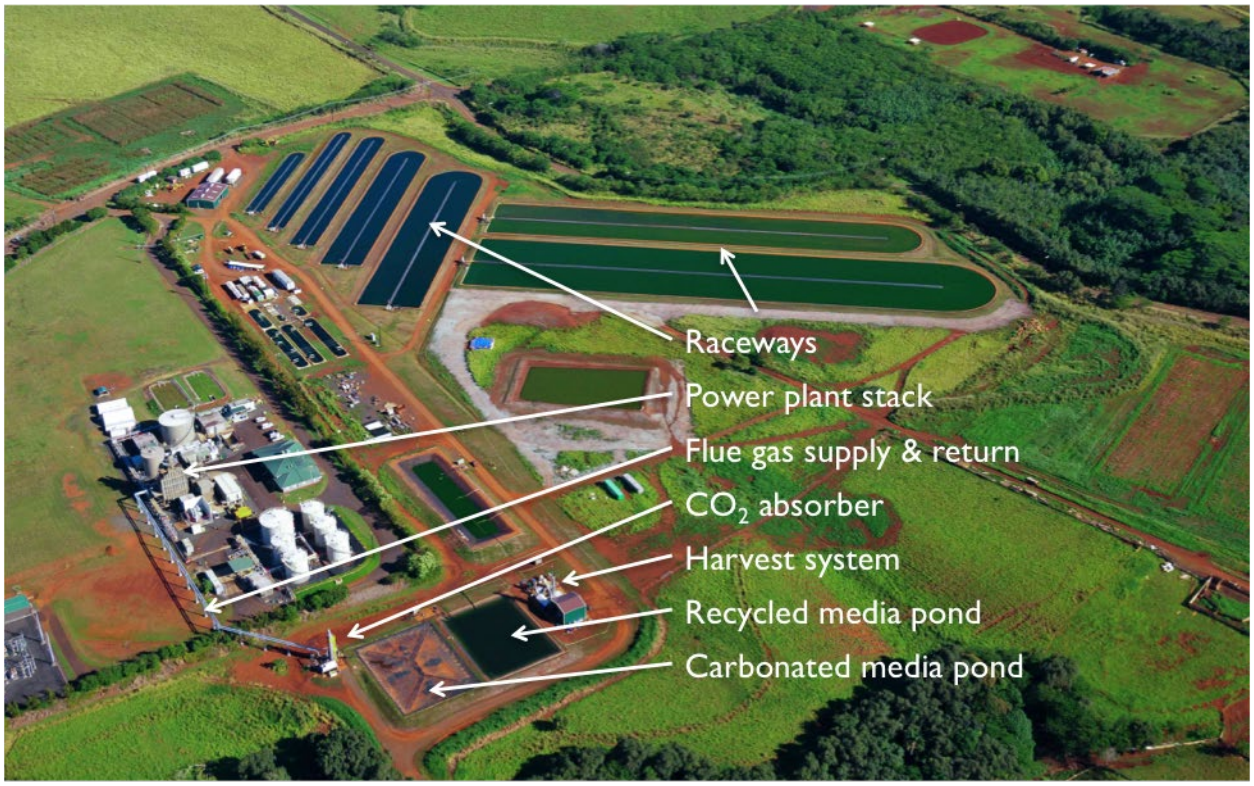


Photo Credit: The Image Group (TIG) and Andy Stenz

Figure 8: Productivity with Direct Air Capture CO_2 Supply

Direct air capture CO2 supply productivity is the same as with CO2 supplied from flue gas.

Source: Global Algae Innovation's cultivation data from the Kauai Algae Farm

Low-cost Harvest Technology

Commercial harvesting is typically accomplished through centrifuge or dissolved air flotation with the addition of flocculants. These technologies are too energy intensive and expensive for large-scale algae production. Use of a clarifier is commonly assumed in techno-economic modeling; however, effective use of a clarifier for harvesting in algae production has not been achieved other than in conjunction with wastewater treatment, which involves high levels of fungus and bacteria to induce flocculation.

A new membrane harvesting and dewatering technology was validated at the Kauai Algae Facility, and it is now commercially available as the Zobi Harvester®. This system incorporates a series of innovations in membrane properties, system design, and operating methods to enable harvesting and dewatering to 15–20 percent solids in a dead-end, low trans-membrane pressure (TMP) filtration system. Because there is no cross flow and the TMP is low, the energy use is only 0.05 kWh/m3. Because a 0.04 µm pore size is used, all the algae and bacteria are harvested, leaving a crystal clear permeate for recycle. Figure 9 shows a Zobi

Harvester installed at another algae company's facility, where it achieved the same exceptional performance at the Kauai Algae Farm.

Figure 9: Photograph of an Installed Zobi Harvester



Zobi harvester with 2 million gallon per day hydraulic capacity installed at a commercial farm.

Photo Credit: Global Algae Innovations

Figure 10 presents photographs of a 20,000 liter/hour Zobi Harvester, of process samples, and of the 15–20 percent algal slurry effluent from the system. Millions of liters of algal culture have been harvested using this system over the past year including multiple green, diatom, cyanobacteria, and red algal strains. The Zobi Harvester reduces the energy use for harvesting and dewatering to approximately 1 percent of the biofuel energy content, achieves 100 percent harvest efficiency with crystal clear permeate, and has successfully harvested over 25 strains of algae tested.

Figure 10: Photographs of a Zobi Harvester Including Feeds and Effluents



On the left, there is a 20,000 l/h Zobi Harvester. On the right, there are samples and the 15-20 percent solids effluent.

Photo Credit: Global Algae Innovations and Bill Rickman

A survey of large-scale algae production was conducted to determine the actual energy use, cost, and throughput of the currently used algae technologies. Table 3 presents a summary of this algae industry survey including the Zobi Harvester employed in this project.

Table 3: Industrial Survey of Harvest Technologies

Technology	Feed rate (m^3/hr)	% of nameplate	Harvest Efficiency	Outlet Solids Conc.	Energy Use (kWh/m^3)	Capital Cost ($k/$m^3$hr)
Crossflow filter	4–5	40%	95–100%	1%	4–7	80–130
Spiral plate separator	0.2–2	30–50%	30–94%	15–25%	3–5	100–200

Disc-stack centrifuge	4–9	25–40%	80–94%	15–25%	3–5	30–50
Decanter centrifuge[a]	0.1–4	NR	NR	14–25%	NR	NR
Dissolved air floatation[a]	45–800	40–70%	0–94%	1–2%	1–1.5	4–10
Liqoflux polymeric crossflow filter	0.5–1	NR	100%	1–2%	NR	40–80
Zobi Harvester®	20	NR	100%	15–20%	0.04	10

Industrial survey of currently used harvest technologies (NR = not reported, a = requires addition of a cationic polymer).

Source: Industrial survey conducted by Global Algae Innovations in 2016.

Extraction

The use of standard Crown Iron Works equipment was a proven approach that will be used for the pilot facility unless a better alternative is developed the in near-term.

Global Algae currently is conducting R&D on a novel extraction and drying process that would further reduce the cost of extraction and drying. The process uses $1/10^{th}$ the energy of traditional drying and extraction. The technology was successfully demonstrated at bench-scale and is currently being scaled up to engineering scale. If this process is validated at engineering-scale, then it will be incorporated into the algal cultivation and processing pilot-scale facility.

Summary

Many of the technologies developed for algal cultivation and processing are too expensive or not scalable. This is because the development is not always driven by an integrated techno-economic analysis model of the entire process or because unfounded assumptions are incorporated into the models. Global Algae has developed a comprehensive techno-economic model for commercial-scale implementation of algae production technology. This model has been used to drive all aspects of the process development by assessing the impact of different approaches on the overall economics of the process. This methodology naturally precludes consideration of technologies that are not scalable, are too costly, or prohibitively increase the costs of other unit operations. It also enables quantification of the benefit of technologies that result in lower overall cost when effectively integrated with other unit operations. As experimental data is generated, the techno-economic model is updated to provide visibility throughout the team on the integrated system's capability to meet target yields and ability to be scaled and operated to produce cost-competitive biofuels and bio-products. The model will also be used to identify areas where additional data is needed to assess the integration.

Application of the techno-economic model reveals the impact need for novel approaches to overcome the cost challenges associated with numerous aspects of conventional algal technology. This project is based on an integrated system approach that addresses all the challenges required to assure all technologies included in the pilot-scale facility are commercially relevant. The techno-economic model was used in all stages of the project planning and preliminary design to move forward only if successful implementation will lead to commercial facilities.

Research and Design Approach

The basic premise of front-end loaded design is that most planning and design should be completed early in a project when the ability to accommodate design changes is relatively high while the cost of making those changes is relatively low. This approach includes many analyses at the conceptual stage with updates and greater fidelity added at the preliminary stage to avoid costly design changes in the later stages of engineering. Thus, a business assessment, potential site selection, permitting assessment, risk assessment, safety and hazards analysis, life cycle assessment (LCA), and cost estimates are completed in the conceptual design phase to provide early identification of any constraints or needs that may affect the design. The preliminary design starts with development of a more detailed permitting and regulatory compliance plan and detailed trade studies supported by data from the preparatory R&D. With this firm foundation in the design basis, the preliminary design can then be completed with confidence that significant changes are unlikely.

With this approach, the conceptual design and preliminary design phases are longer because the front-end loaded process intentionally adds some cost and time to the early part of the project, but this is minor compared to the potential cost and effort required to make changes later in the project. The more a project is defined, the less likely it is to experience cost performance issues due to the greater accuracy of the supporting cost estimate.

The conceptual design started with business assessment that informs the top-level design documents. These documents are then used to perform various assessments to enable the design to accommodate all the potential business, regulatory, technical, and risk issues. The design documents contain more analyses that considers potential and necessary design changes to accommodate unexpected issues prior to the preliminary design stage.

The preliminary design started with site selection that was delayed for over a year due to the COVID-19 pandemic. A site selection matrix was prepared with each site rated on nine attributes weighted based their importance in success of the pilot facility. The final site selected was in Shandon, near Paso Robles in San Luis Obispo County, shown in Figure 11. It was the only site of the top three rated locations where land with the proper topography could be acquired during the COVID-19 pandemic. The site is in an agricultural community with high solar insolation, good access for support based on its proximity to California Polytechnic State University, San Luis Obispo, good temperature range for algae cultivation, good topography, and adequate water availability.

Figure 11: Satellite View of Site Selected for the Algae Pilot Facility



Site selected for the algae pilot facility is located off of state route 46 and state route 41 east of Paso Robles.

Photo Credit: Google Earth

Site selection was followed by preparation of a permitting and compliance plan and with trade-off studies followed by process design, equipment design, and then the remaining design documents and analyses. These design documents are used to complete preparation of the Phase 2 plan. The results of this task were the preliminary design documents, risk management and project management plans, a permitting and regulatory compliance plan, techno-economic analyses, a life-cycle analysis, a safety and hazards analysis, and a business plan.

Table 4 presents a summary of the key project risks and mitigations that are incorporated into the technical scope. A formal risk management system was used to identify risks, assess the risk level, handle the risks, and track resolution of the risks throughout the project. At the beginning of the project, this risk table was used as a starting point to create a comprehensive list of risks for the project. The risks were analyzed to determine the risk level, and then determination was made on how to handle the risk (for example, mitigate, accept, avoid, or transfer).

The strain library development task was added as a result of the preliminary risk assessment presented in Table 4. While Global Algae has a good library of production strains, strain performance is an area of risk for any algae facility. Since the planned pilot-facility is a larger-scale facility that will operate through various seasons in a new location, it is prudent to expand the library to ensure that plenty of production strains are available. It takes a significant amount of time to develop a library of robust production strains from local isolates, so this task could not wait until the Phase 2 project to begin. Global Algae phycologists provided guidance on methodology for collection of new algae strains and then jointly collected the strains with the University of California, San Diego researchers, providing hands-on training on implementation of the methodology as well as isolation of new strains. Global Algae provided preferred locations to Imperial Valley Economic Development Corporation who arranged site access as required. The collection effort produced over 1,000 algal isolates, of which 350 were cultured and cataloged. Screening tests identified 30 as potential production candidates, and the 30 production candidates were added to Global Algae's strain library. Of

these candidates, the genomes were sequenced for the 10 most promising strains. Then these most promising strains were cultivated to measure biomass and lipid productivity.

Table 4: Initial Risk Table

Risk	Risk Probability	Risk Impact	Handling	Actions or Comment
Cannot find a site	Low	High	Mitigate	• Already engaged Imperial Valley leadership • Begin site identification at project start • Consider alternative locations in SD county
Permitting time too long	Moderate	High	Mitigate	• Permit assessment early in conceptual design • Engage regulators and local leadership at the conceptual design stage • Develop additional migration in the permitting and regulatory compliance plan
Loss of cost share	Low	High	Mitigate	• Produce sample poly-ol products during the preparatory R&D to attract new investors if needed
Poor strain performance	Moderate	Moderate	Mitigate	• Conduct climate-controlled testing to simulate all seasons in preparatory R&D • Add sub task to build production strain library of local isolates so that they are available for unforeseen issues in particular seasons or operational conditions • Install algae traps now to collect and isolate additional local strains
Scale-up problems	Low	Moderate	Accept	• Scale-up methodology is documented and reviewed as part of the design
Schedule delays	Moderate	Moderate	Mitigate	• Weekly objectives added to corporate dashboard for rapid intervention if needed as described in Section 3.6.3
Phase 1 over budget	Moderate	Moderate	Mitigate	• Monthly check of financial and labor hour status vs. schedule progress for early intervention if needed as described in Section 3.6.4

Pilot scale cost is too high	Moderate	High	Mitigate	• Include an effort to develop a business strategy that will work with a smaller pilot-scale facility if cost estimate is too high during the initial business assessment • Review options when the conceptual design cost estimate is complete

Source: Global Algae Innovations

CHAPTER 3:
Results

The goal of this project was to facilitate scale-up of an economically viable, sustainable algal biofuel process to pilot-scale and to utilize the pilot-scale facility to validate the algal biofuel scaling and production metrics for this process. The objective for this project was to complete the design of the pilot-scale algae cultivation and processing facility and complete the planning for construction and operation. The key objectives were to:

- Verify that the technology package is ready for scale-up.
- Expand the algae strain library with local Californian strains.
- Prepare a front-end loaded design package for a pilot-scale algal oil facility that will lead to commercial-scale facility, including a techno-economic analysis (TEA) documenting the favorable economics of the process, and a LCA confirming the biofuel produced will qualify as an advanced biofuel.
- Develop a business plan for the pilot-scale facility and the path to full commercialization.
- Create robust project management, risk mitigation, and permitting & regulatory compliance plans that ensure successful completion of a future construction phase.

The objectives were all achieved, so the project was ready to move to detailed design, construction, and operation once adequate financing is obtained. As a result of the successful completion of the objectives, the U.S. Department of Energy awarded Global Algae a $4 million contract for the construction of the first four acres of the facility, another $4 million contract to scale-up the novel drying and extraction to engineering-scale to process the algae produced in the first four acres, and a $3.6 million award for the expansion to six acres of raceways, downstream processing, and operation. Additionally, based on an independent engineer's review of economic feasibility, market feasibility, technical feasibility, financial feasibility, and management feasibility, the U.S Department of Agriculture (USDA) approved moving a loan guarantee application from Phase 1 to Phase 2 for construction and operation of the pilot-scale facility.

The biggest challenges were the delay in site selection and expansion of engineering staff because of the COVID-19 pandemic and the need to orient the raceways in the north-south, more narrow direction of the property because of the detailed topography. As discussed above, the site selection delay was handled by delaying the project. The limited staffing was eventually handled by moving more of the work from Global Algae to the Specialty Construction, which caused delays by a few months. The challenge of orienting raceways in the narrow axis of the site was handled by designing the last six raceways to be serpentine and splitting two of the larger raceways into four raceways that are operated in parallel.

A summary of the results for each objective follows.

Verification

The project started with verification tests that involved cultivation of algae in 8-acres at Global Algae's current R&D facility, extraction of algal oil using the Crown Iron Work's process, and conversion of the oil to jet fuel, diesel fuel, and gasoline at Emerging Fuels Technology. The verification was conducted by a U.S. Department of Energy independent engineering firm to (1) verify the process and operational data supports the technology claims, (2) verify the technology readiness levels for each unit operation, (3) observe a verification test and confirm that the anticipated technical metrics are achieved, and (4) determine if the overall process is ready to move to pilot-scale. The independent engineer confirmed technology performance and technology readiness levels and that the verification test achieved the anticipated technical metrics. The independent engineer recommended that the overall process move to pilot-scale with two constraints:

1. Outdoor photobioreactor testing should be done since Global Algae's contamination control is so good that the R&D facility only needs inoculum from a laboratory system.
2. The raceway size should be limited to 26-acres since long-term productivity data is not available for the largest raceways at the Kauai facility.

Figure 12 presents a photograph of the farm in operation during the verification test. Figure 13 presents photographs of the samples during fuel refining verification test and final fuel produced during the test. Table 5 summarizes the findings and final design status for each process area.

Figure 12: Global Algae's R&D Farm in Operation During the Verification Test



Photo Credit: BBDO

Figure 13: Samples Collected of Fuel Processing During the Verification Test





On the left is algae oil, hydrogenated algae oil, distilled hydrogenated oil, and distilled final product after cracking and isomerization. On the right is final biofuel product exiting the distillation column.

Photo Credit: Global Algae Innovations

Table 5: Summary of Verification Results

Unit Operation	Baseline	Issues	Anything Lacking?	Readiness to Proceed	Final Design
Inoculum System	Laboratory system with scaling through open raceways	May require different type	Outdoor data on photobioreactor (PBR)	PBR testing needed	Baseline system
CO_2 Supply	5' x 50' absorber on flue gas with carbonate shuttle	None	No	Yes	Direct air capture
Cultivation	23 g/m^{2}d, 0.66 ac Mechanical, 3.2ac	Limit to 20x	Larger scale data	Yes, at 26-acre	26-acre maximum
Harvesting	Zobi Harvester®	None	No	Yes	Zobi Harvester®
Dryer	Dedert ring dryer	Testing not witnessed	No	Yes	Novel drying system
Extruder	Anderson International extruder	Testing not witnessed	No	Yes	Novel extraction system, on-site; baseline, off-site
Extraction	Crown Iron Works Immersion system	Testing not witnessed	No	Yes	
Conversion	Refining to jet or diesel fuel	None	No	Yes	Baseline, off-site

Source: DOE Independent Engineer's Verification Report

Strain Library

In October 2019, a sampling trip to the Imperial Valley was planned and executed. Geographic areas of interest were first identified via satellite imagery and then refined based on local guidance and legal access. Assistance was provided by the Imperial Valley Economic Development Corporation, who aided in the selection of sites as well as with navigation during the Imperial Valley sampling trip. In December 2019, two sites were sampled at the biological field station on the campus of the University of California, San Diego, and another from a backyard in Clairemont, San Diego. Table 6 provides details on twelve Imperial Valley sites and three San Diego sites including the type of samples collected. Samples were either collected using (1) a plankton tow, which captures and concentrates any material greater than 5 micron, (2) a general water grab, which was a water sample of roughly 700 mL (3) periphyton samples, which constitutes scraping living material from rocks or surfaces, and/or (4) a dry soil sample, which was approximately 200 mL of soil. Water quality at these sites ranged from freshwater to hypersaline. In some cases, the salinity was so high that salts were precipitating out of solution. Figure 14 provides details on the exact sampling locations and Figure 15 provides photographs of a few of the sites.

Table 6: Sampling Sites for Algae Strain Collection

Sample Site	Site Description	Sample Types Taken
IV-01	Shoreline of western lake of Imperial Lakes	Plankton, Water Grab, Periphyton, Wet Soil, Dry Soil
IV-02	Shoreline of eastern lake of Imperial Lakes	Plankton, Water Grab, Periphyton, Wet Soil, Dry Soil
IV-03	Ditch pond located on deserted dairy farm	Plankton, Water Grab, Periphyton, Wet Soil, Dry Soil
IV-04	Former evaporation pond of onion farm, visibly salty soil	Dry Soil
IV-05	Man-made salt pond for Hudson Ranch Geothermal	Plankton, Water Grab, Periphyton, Soil
IV-06	Geothermally active area with ponds saturated with salt	Water Grab, Periphyton
IV-07	Man-made ponds to create habitat for water birds	Plankton, Water Grab, Periphyton, Wet Soil, Dry Soil
IV-08	Man-made ponds to create habitat for water birds	Water Grab, Periphyton, Wet Soil, Dry Soil
IV-09	Swamp area next to Salton Sea	Water Grab, Periphyton, Wet Soil, Dry Soil
IV-10	Small man-made pond 1	Plankton, Water Grab, Periphyton

IV-11	Small man-made pond 2	Plankton, Water Grab, Periphyton
IV-12	Small man-made pond 3	Plankton, Water Grab, Periphyton, Soil
UCSD Field Station (2 sites)	Empty ponds catching rainwater, evaporation pond	Water Grab, Periphyton
Backyard	Mossy area of irrigated soil	Wet Soil

Sampling site details, including description and type of sample taken. In total, 15 sites were sampled; the UCSD Field Station has two areas with drastically differing salinities and therefore is counted as two sites. The sites cover a wide range of environmental conditions, from dry desert to muddy swamp.

Source: University of California, San Diego

Figure 14: Map of Sampling Locations for Algae Strain Collection

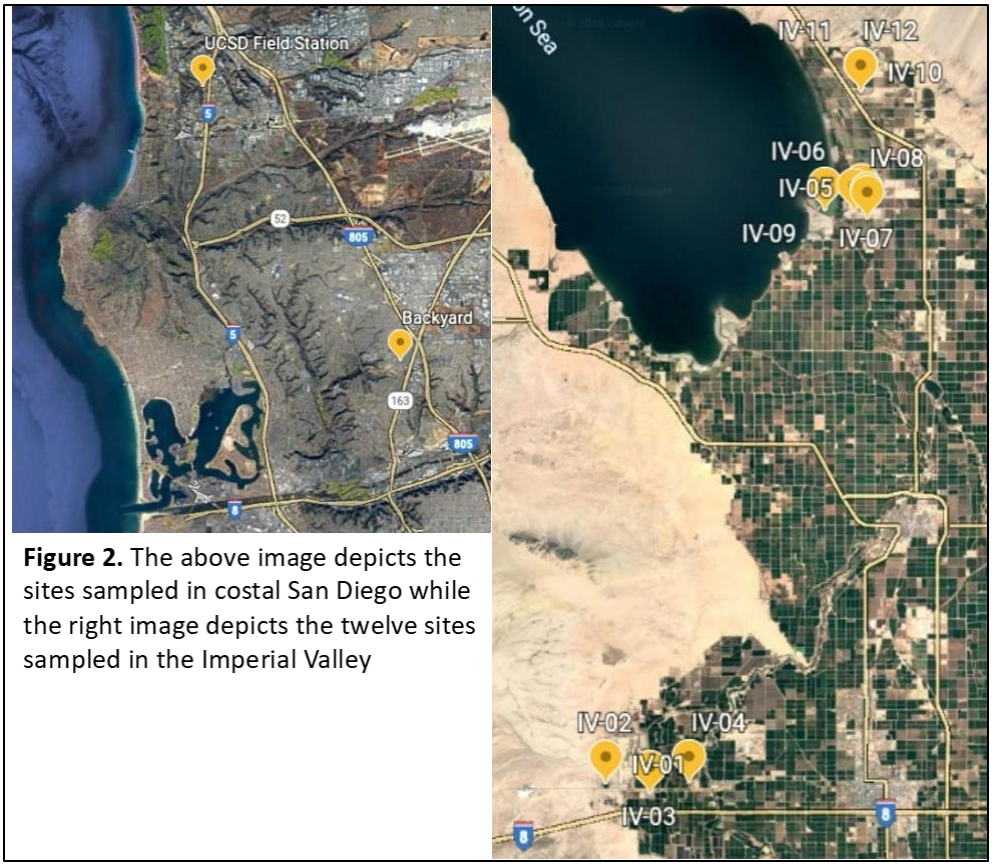


Figure 2. The above image depicts the sites sampled in costal San Diego while the right image depicts the twelve sites sampled in the Imperial Valley

On the left are two sites sampled in San Diego. On the right are twelve sites sampled in the Imperial Valley.

Photo Credit: Google Earth

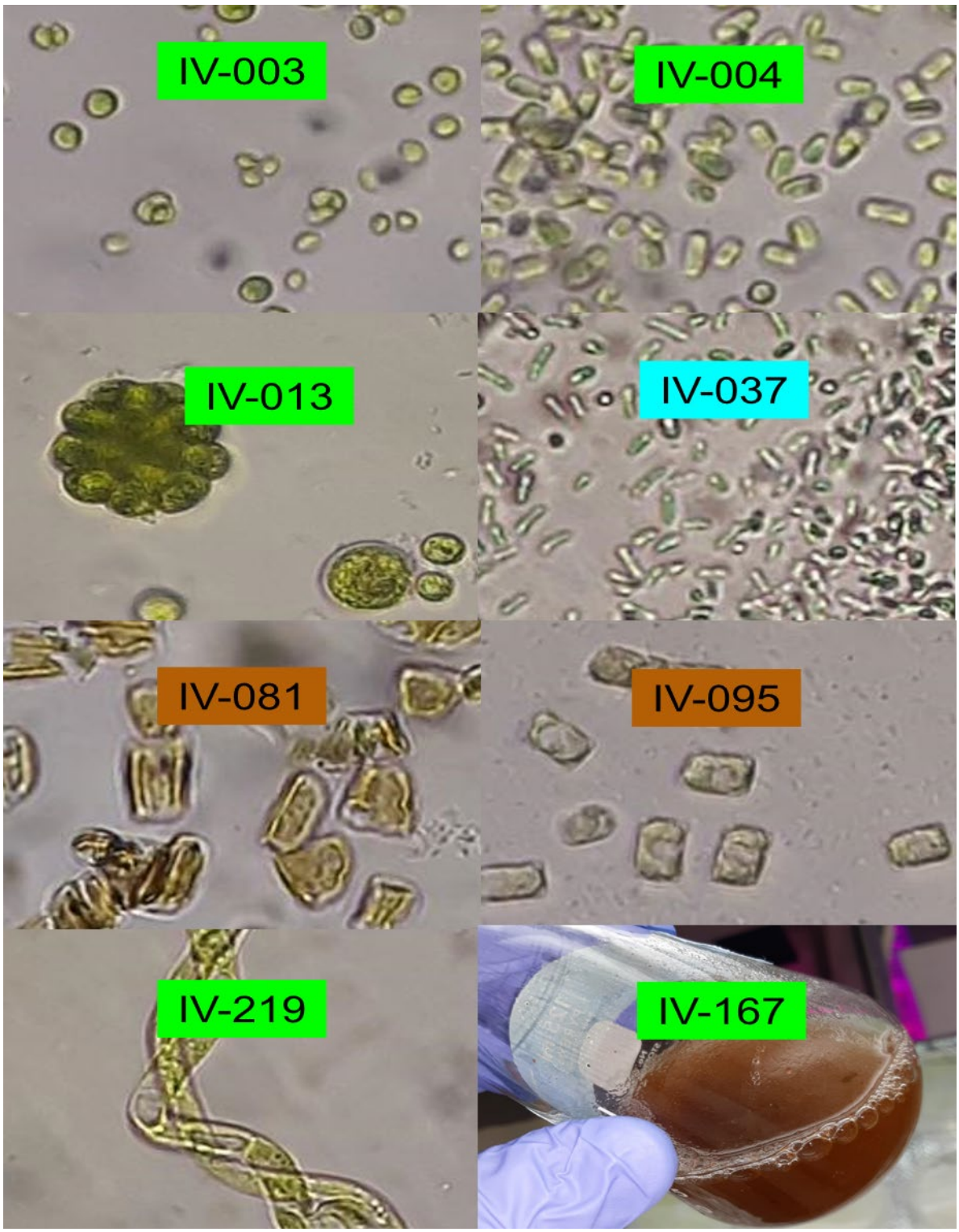
Figure 15: Photographs of Two Sampling Sites in Imperial Valley



Two examples of sampling sites from the Imperial Valley: a man-made lake (left) and a swampy area directly adjacent to the Salton Sea (right).

Photo Credit: University of California, San Diego

Figure 16: Micrographs of Strains Isolated from Imperial Valley



The images above show microscopy examples of strains that were isolated, with representatives from chlorophytes (labeled in green), cyanobacteria (labeled in cyan), and diatoms (labeled with brown). The bottom right picture shows a liquid growth test for a strain showing potential production of carotenoids, hence the red/brown color of the media.

Photo Credit: University of California, San Diego

Initially, over 1,000 individual colonies were picked and transferred from the grow out of the collection samples. After duplicate removal, there were approximately 350 strains isolated and cataloged from Imperial and San Diego counties. Figure 16, above, provides examples of the newly isolated strains. These strains were initially screened for tolerance to high bicarbonate, which narrowed down to 170 strains. The growth rate in high bicarbonate was measured and 70 strains were found to grow vigorously in high bicarbonate. The next screen was testing for growth rate in high pH with no added CO_2, which narrowed the pool to 30 strains. These 30 strains are all considered potential production strain candidates. The strains were sequenced to determine the taxa and were tested for growth efficiency to down-select to the top ten strains for outdoor testing. The 30 production candidate strains were transferred to Global Algae's strain library.

Preliminary Design

The front-end loaded design began with a set of analyses to establish the design basis. The permitting and regulatory analysis provided information on good manufacturing practices, Occupational Safety and Health Administration requirements, and permitting to aid in development of the design basis. A safety and hazards analysis was performed to make sure the design incorporated any safety requirements. A business assessment looked at the costs and potential revenue sources and markets for sustaining operation of a pilot facility as well as potential benefits and opportunities for funding from foundations and strategic investors. Based on this information, flexibility to produce higher value products was incorporated into the design, and the impact of algae farming on multiple areas of sustainability was included in the TEA. All information were synthesized into the design basis document, and then the conceptual design was prepared.

In addition to the assessments discussed above, the conceptual design included the design basis, technology selection, process description, block flow diagram, process flow diagram, mass and energy balance, major equipment sizing, raceway design, facility layout, and technoeconomic analysis model. The technoeconomic model automatically updates the mass and energy balance as well as the equipment sizing, energy use, and costs based on 80 input variables and multiple operating options. The model generates cost and life cycle output that is automatically updated with changes in any input variable or model parameter. The flexibility in the technoeconomic model enabled performance of trade-studies at the start of the preliminary design.

After completion of the conceptual design, all aspects of the design and assessments were reviewed by the Technical Advisory Committee (TAC) in February 2020. The TAC consisted of world leaders in algae technology and commercialization and an expert in business financing. The TAC members were:

- **Dr. Bill Barclay**, retired, founder of Martek Biosciences, which he helped lead to become the world's largest algae company.
- **Dr. Amha Belay**, CEO of Algae4All, who profitably ran the largest algae farm in the continental US as Sr. Vice President and Chief Technology Officer of Earthrise Nutritionals, a company engaged in outdoor algae production for over 40 years.

- **Mr. Phillip DeDominicis**, investment banker with over 30 years of experience in business evaluation, financing, mergers, and acquisitions.
- **Dr. Ike Levine**, Algae Foundation President, who founded one of the first successful macroalgae farms in the US and was CEO of Algal Aquaculture Professionals, one of the world's most prominent algae cultivation consulting groups.
- **Dr. Greg Mitchel**, professor at Scripps Institution of Oceanography, University of California at San Diego, who was a founding director and early Chair of the Algae Biomass Organization, has over 40 years of algae R&D experience, and recently sponsored a study of all current algae cultivation facilities to find the best technologies for expansion into commodities.

Overall, the TAC concurred that the technology selection is likely to achieve the pilot plant objectives and that the assumptions in the technoeconomic analysis were reasonable. There was a robust discussion on the overall process, controls, and interfaces. The conclusion of this discussion was that the design approach is likely to achieve the pilot plant objectives and is likely to be successful in many climate conditions, including deserts and rainy locations. Specific recommendations included:

- Add methods for handling insect contamination.
- Add methods to prevent possible self-ignition of high lipid algae during storage or shipment.
- Add instrumentation to monitor the nutrient composition to prevent accidental over or under feeding of the algae due to operator errors.
- Require hired service for rodent control as part of good manufacturing practices (GMP) for food and feed (for example, rodent traps around the border of the facility).
- Process controls and testing to show no contaminants, heavy metals, etc. is required as part of GMP.
- Maintain a 3-month supply of nutrients and to use multiple suppliers because we will need tons of nutrients, and the supply can be spotty based on other algae facilities.
- Written documentation of all procedures, so it is memorialized and can be used in new facilities during licensing/franchising.
- Consider permitting requirements for any planned algae contamination control treatments.
- Automated methods for microbiota census measurements and algae composition are important, so the new technologies currently under development by Global Algae should be included in the plans for the pilot plant.
- Consider soil-type impacts on the pond design and installation.
- Consider remote spectroscopic and laser measurements for full-scale systems.
- Consider where water is added because of potential precipitants when the incoming water is mixed with the recirculated water.
- Global Algae's technology will radically transform sustainability, but this needs to be shown to non-governmental organizations and the public, who mostly know about algae through news on harmful algae blooms. Suggest running conceptual design information through global models of water, energy, carbon, land use, deforestation, and ocean ecology.

- General public does not understand how much water it takes to make food, so even though we are producing food and feed with a reduction in water use of 95 percent, people may think the water use is too high.
- Need to consider possibility that someone will raise concern about hazardous algal blooms from our facility because public does not understand that most algae do not produce toxins and that Global Algae does not use any algae that produce toxins.

The next step was site selection. Table 7 presents a summary of site selection matrix and weighting of site characteristics. Extensive effort was made to find suitable sites in all the top three locations. A suitable site was found in Shandon in the Paso Robles area, and a long-term lease was established to enable moving on to the preliminary design and permitting. The project team was not able to find any available sites in either of the San Diego locations during the timeframe required to keep the project on schedule. Figure 17 provides a satellite view of the site for the pilot-scale algae farm. A detailed topographical and dimensional map was prepared through an aerial survey with ground targets set throughout the site, shown in Figure 18. This map was used to develop the final farm layout and grading plans for the 19 algae cultivation raceways, harvest ponds, recycled media pond, fertilizer receiving and mixing area, two <10,000 sq. ft. buildings, harvest pad, drying pad, and water supply pond such that there is no net removal or import of soil.

Table 7: Site Selection Matrix

Location	**Access Support**	**Temp Range**	**Days of Sun**	**Water**	**Topo**	**Permit and Reg**	**Fert. Supply**	**Oil and Feed Use**	**CO_2**	**Total**
Weight Factor	8	8	8	6	4	2	1	1	2	120
San Diego: Tijuana Valley	3	3	1	3	2	3	2	2	2	96
San Diego: San Pascal	3	3	1	2	3	3	2	2	1	92
San Luis Obispo: Shandon	**2**	**2**	**2**	**3**	**3**	**3**	**3**	**2**	**1**	**91**
San Luis Obispo: Huasna	2	3	2	2	2	3	3	2	1	89
Imperial Valley: El Centro	1	1	3	3	3	3	3	2	2	85
San Diego: Campo	2	2	1	3	3	3	2	2	1	82
Kern: Bakersfield	1	2	1	3	3	3	3	3	3	74

Source: Global Algae Innovations

Figure 17: Satellite View of Site for the Pilot-Scale Algae Farm



The site is east of Paso Robles off of State Route 46 and the intersection with State Route 41.

Photo Credit: Google Earth

Figure 18: Topographical Map of the Pilot Facility Site

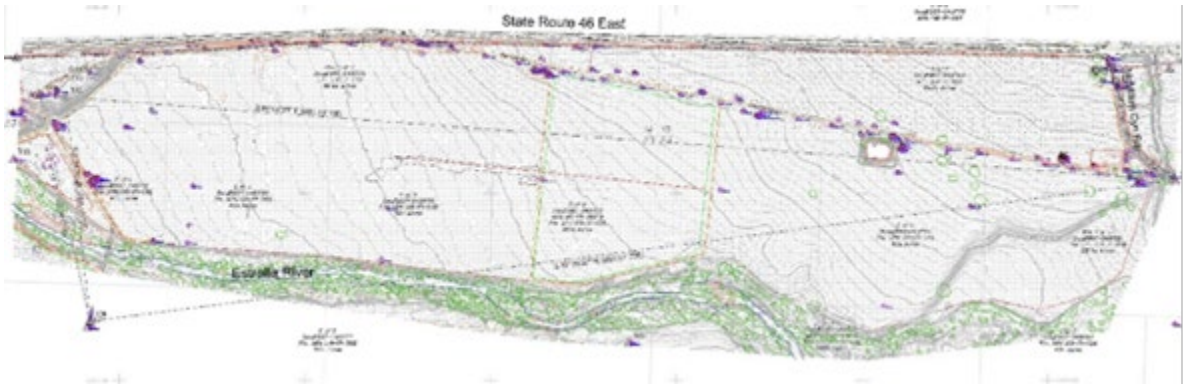


Photo Credit: Global Algae Innovations

After site selection, several trade studies were performed, including:

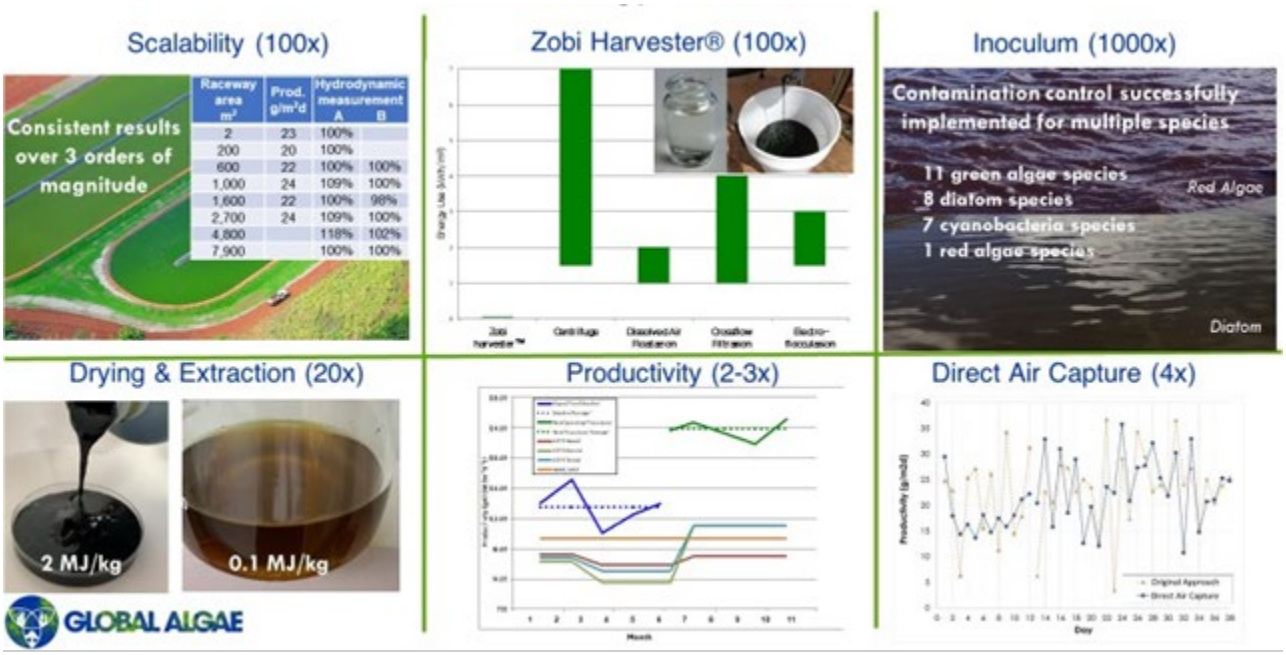
- Inoculation size and smallest raceway
- Nutrient supply options
- Raceway circulation options
- Harvesting concentration mode
- Options for zero discharge or evaporation pond, including cleaning and rinses
- Solids storage and handling for dryer-extraction interface
- Extraction options
- Drying options
- CO_2 supply flexibility
- Evaluate options for variable productivity
- Evaluate options for variable water from rain and evaporation
- Evaluate options for raceway thermal control

Based on the results of the site information, trade studies, TAC recommendations, and recommendations from DOE's independent engineer, the preliminary design started. First the top-level process documents were updated, including the basis of design, technology selection, process description, block flow diagram, and the mass and energy balance. Figure 19 illustrates some of the technology selection, and Figure 20 presents the technical metrics of the selected technology relative to the DOE targets and conventional technology. Figure 21 presents a summary of the mass and energy balance.

Equipment sizing and site layout was completed, followed by the equipment list, the detailed raceway drawings, and the piping and instrumentation diagram. Figure 22 presents a non-proprietary version of the site layout.

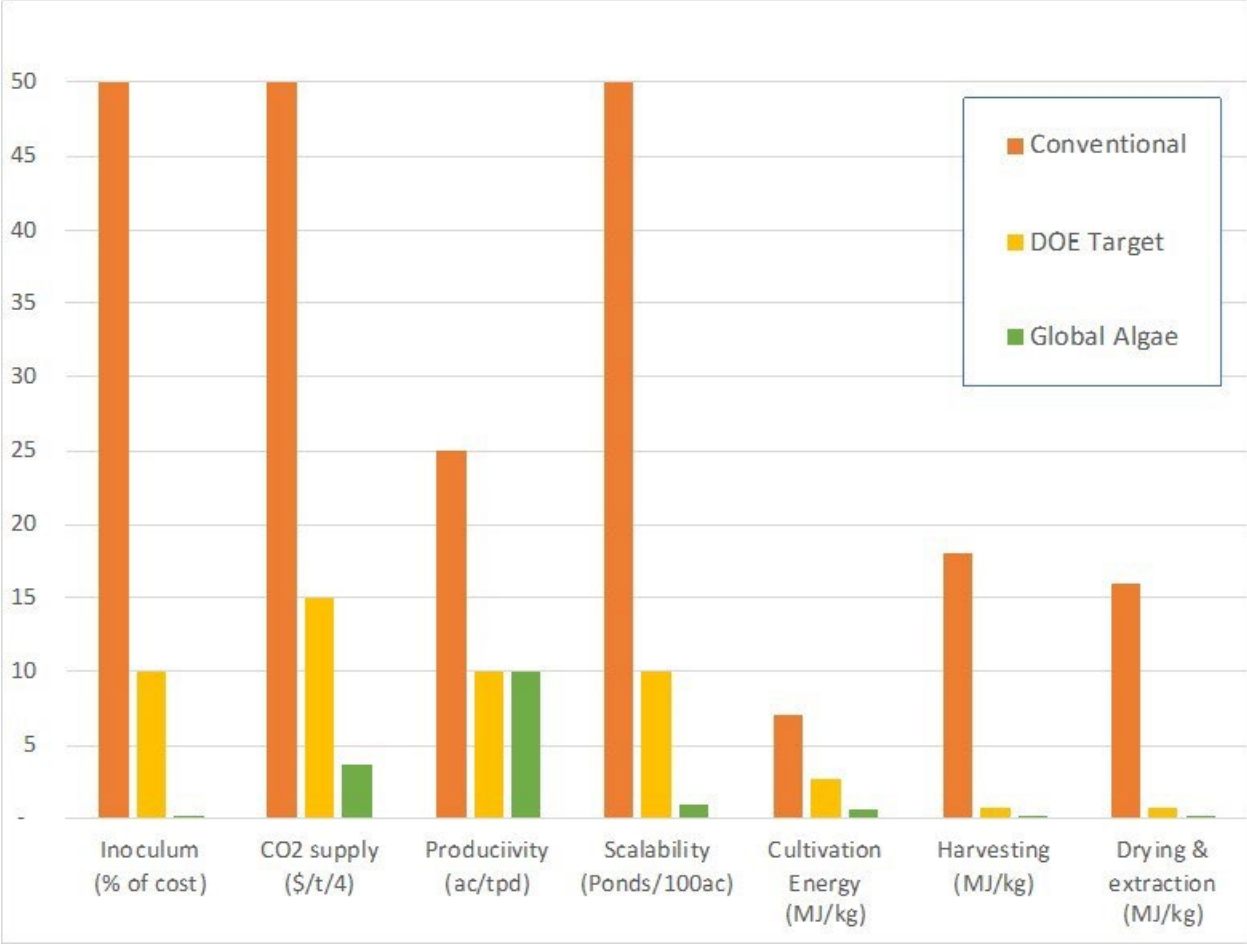
The trade study results, updated top-level process documents, final site layout, techno-economic model, and likelihood of success for the pilot scale facility were reviewed by the TAC in November 2021. The committee consensus was that the pilot plant would be successful, and that the techno-economic estimates were reasonable. In addition, the committee provided extensive recommendations and ideas on how to obtain product regulatory approvals and navigating product development and off-takes, which is hampered because there are no pilot-scale facilities to produce algae for consumer companies to certify the algae ingredients.

Figure 19: Technology Selection Summary



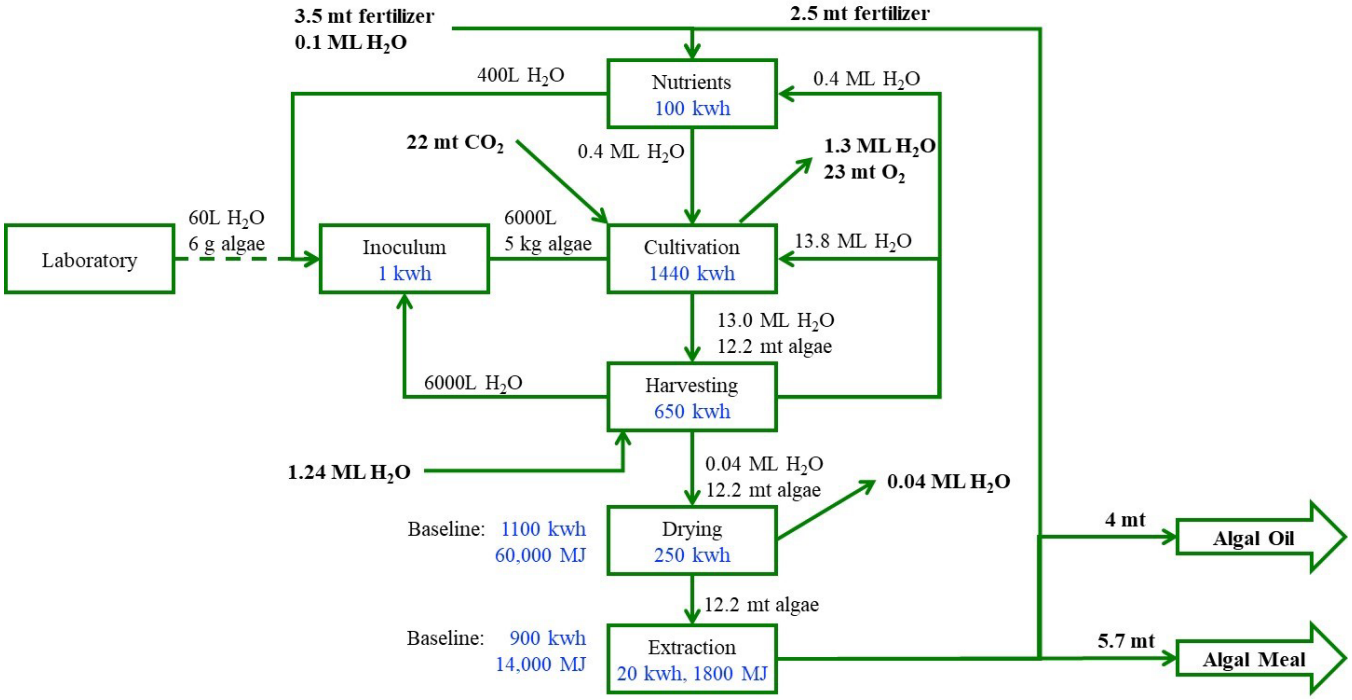
Source: Upper Left, The Image Group (TIG) and Andy Stenz; All others, Global Algae Innovations

Figure 20: Metrics for Technology Included in the Design



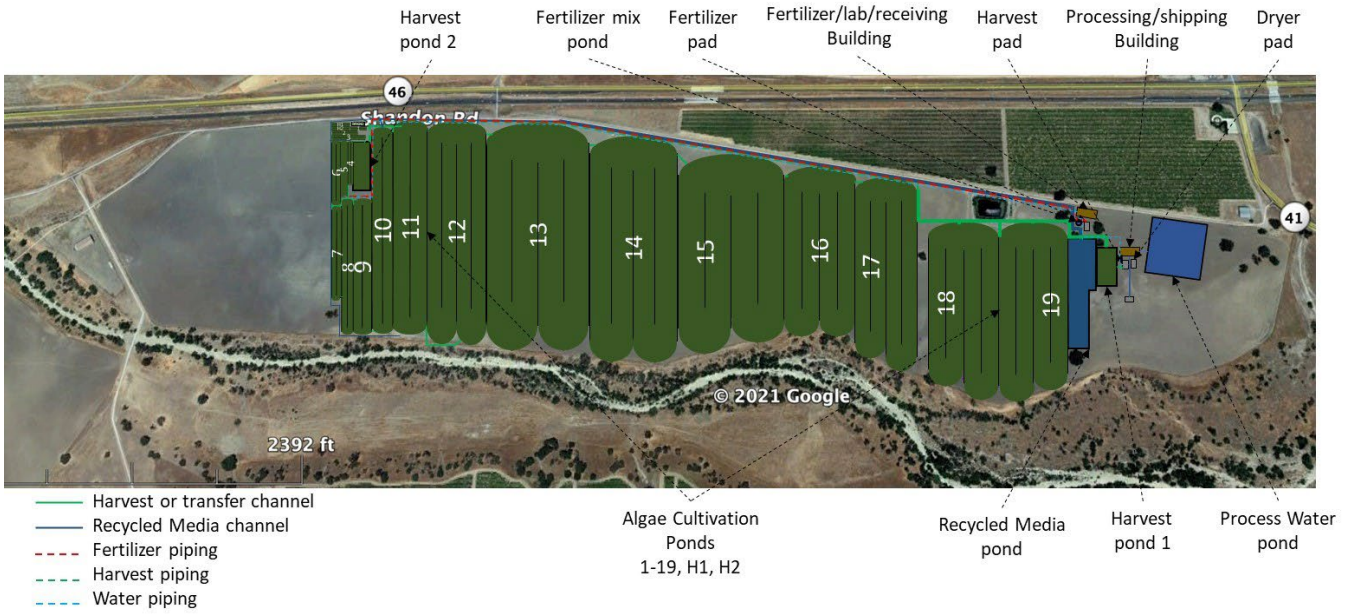
Source: Global Algae Innovations Technoeconomic Model

Figure 21: Mass and Energy Balance



Source: Global Algae Innovations Mass and Energy Balance for the 160-acre farm

Figure 22: Global Algae Pilot-scale Farm Layout

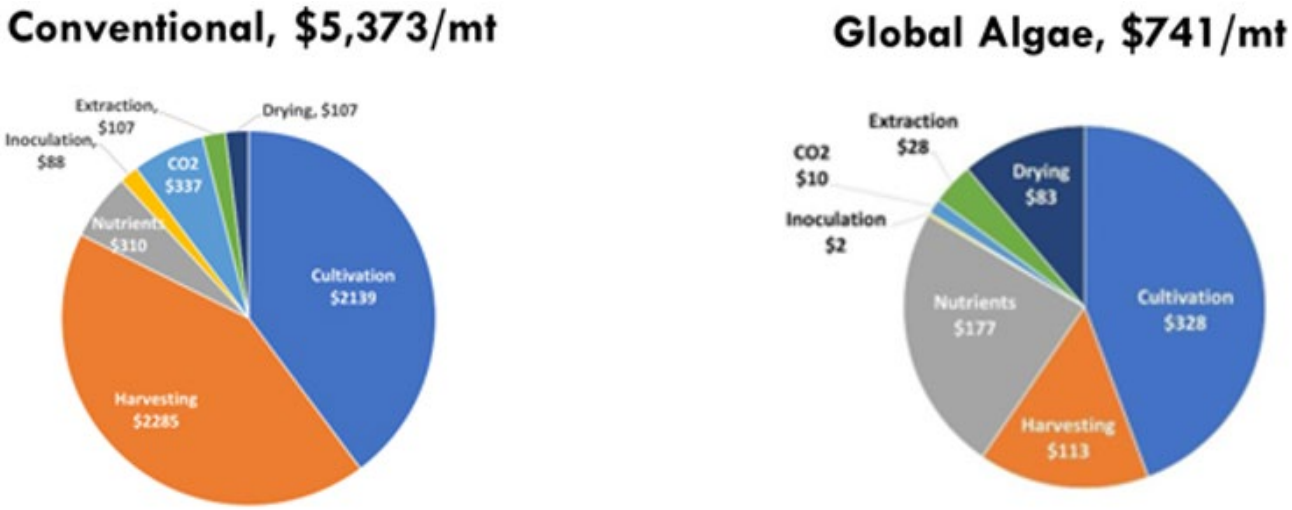


Source: Global Algae Innovations

Specialty Construction, an engineering, procurement, and construction firm, obtained quotes and prepared cost estimates for the farm. Wallace Group and Kirk Consulting also joined the effort to assist Specialty Construction. These estimates were used to improve the fidelity of the technoeconomic model. Figure 23 illustrates the cost estimate for production of algae in

$/metric ton ash-free dry weight for a 5,000-acre algae farm. The capital costs are included through a capital charge factor of 0.1327, which includes depreciation, insurance, and a minimum return-on-investment, so the cost estimate represents the minimum selling price for the algae.

Figure 23: Cost of Algae Production and Processing to Oil and Protein Meal



Source: Global Algae Innovations Technoeconomic Model

Business Plan

The algae biomass is fractionated into algal oil and protein meal. The protein meal is at least 70 percent protein. The algal oil is separated into polyunsaturated fatty acids, mono-unsaturated fatty acids, and saturated fatty acids for the food/feed, polymer feedstock, and biofuel markets, respectively. Table 8 provides a breakdown of the value of these components and the composite value of the algae. The composite value is $1452/ton, which means there is over 90 percent margin over the minimum selling price for a 5000-acre facility. There is plenty of margin for profitable operation of a full commercial scale (for example, a 5000-acre farm, even if the cost of production is 50 percent higher than projected). The market for this product mix will support the first 7 billion gallons of biofuel production per year. Once the risk is reduced from the pilot-scale facility, raising the funds for a full-scale facility will be much easier because the risk will be low, and the profit margin will be high.

The challenge is getting the intermediate scale-up funded because the cost of algae production from the pilot-scale algae farm is estimated to be closer to $5000/mt at this scale. Furthermore, no sales of protein concentrate can be made until the product is approved by the Food and Drug Administration as an animal feed or food ingredient. The pilot-scale facility will be used to validate the techno-economic model and technology metrics as well as to generate protein concentrate for food and feed ingredient testing. Unless the capital costs are paid for through a government or charitable grant based on the benefits of the technology, a higher value product must be made from the facility in addition to the biofuel and co-products. It's likely the plant will produce algae that generate all of the product components in Table 8 part of the time and produce higher value product algae, such as spirulina or omega 3's, part of the

time. The polyunsaturated fatty acid (PUFA) fraction is primarily eicosapentaenoic acid (EPA). There is a small market for much higher value EPA oil as a nutraceutical. Depending on the number of off-takes that can be obtained, this would be an ideal product for the pilot-scale facility because the same products can be made as for the full-scale facility. If the pilot-scale production is too great for the number of off-takes, then an additional high value product will need to be produced, likely *Spirulina*. In this case, the facility would run a week or two each month growing *Nitzschia* for biofuel and co-products and a few weeks growing *Spirulina* as a nutraceutical.

Table 8: Composite Value of Algae Biomass

Component	% of Biomass	Sale Price ($/mt)	Value ($/mt algae)
Protein concentrate	50%	1400	700
PUFA oil	6%	4200	252
Mono-unsaturated oil	16%	2000	320
Saturated oil	18%	1000	180
Recycle	10%	0	0
Total	**100%**		**1452**

Source: Global Algae Innovations algae composition data and market analyses

Funding has been obtained through two U.S. Department of Energy competitive awards that will enable construction and operation of the first four acres of raceways with a harvest system and a drying and extraction system that are sized to handle the output. This will enable production to start at the site, which will reduce the operational risks and enable off-takes to be obtained, both of which will facilitate raising the funds for construction and operation of the rest of the pilot-scale algae farm. In addition to the financial analysis, the business assessment included a review of the sustainability aspects of large-scale algae farming.

Permitting

Permitting started shortly after the site selection was made, and a local engineering, procurement, and construction contractor was selected. The site is in the unincorporated area of the San Luis Obispo County, so they are the cognizant permitting authority. The site is zoned for agricultural use, and the planned operations are algae farming and processing of the algae grown on site to protein and vegetable oil. Both activities fall under the agricultural use definition, so a conditional use permit was not required, and the project is exempt from the California Environmental Policy Act. The County reviewed the plans for the site and concluded that the only permits required were a Water Off-set Permit, an agricultural grading permit, and building permits for the two structures planned for the site. Since the buildings are agricultural support buildings under 10,000 square feet, they do not trigger the need for a conditional use permit or other permitting requirements. Once the facility is in commercial operation, an aquaculture permit will be required from the State of California.

The water off-set permit application was submitted in December 2021. In February 2022, the County provided comments on the permit application. All the comments were accepted and incorporated into a revised permit application submitted in March 2022, and the permit was

approved May 2023. The agricultural grading permit application was submitted in February 2023 and approved in August 2023. This allowed groundbreaking in November 2023 on the first two acres of raceways, which is funded by a subsequent award from the U.S. Department of Energy.

Technology/Knowledge/Market Transfer Activities

The preliminary design of a pilot-scale algal oil facility developed on this project will facilitate financing for construction and operation of a pilot-scale algae farm in California. This farm will produce algal oil as a feedstock for California's biorefineries to make renewable diesel and jet fuel. Successful operation of the pilot-scale farm will lead to commercial-scale farms producing algae oil for California's biorefineries. There are many biorefineries in construction or planning (Hill, Shi, and Collett 2021), and algal oil is an ideal feedstock for these refineries as the algae farms increase the food supply while simultaneously generating algal oil feedstock (Doliente et.al., 2020).

The U.S. Department of Energy awarded three contracts to Global Algae based on the results of this project. The first is a $4 million award to the construction and operation of four acres of raceways with a Zobi Harvester and fertilizer system. The second is a $4 million award to build and operate an engineering scale drying and extraction system that is sized to process the output from the four acres of raceways. The third is a $3.6 million award for the expansion to six acres of raceways, downstream, and operation. These were all competitive awards, indicating that this project was successful, leading to funding for construction and operation of a portion of the facility.

Additionally, the project was submitted to the USDA loan guarantee program. After an independent engineering review of the economic feasibility, market feasibility, technical feasibility, financial feasibility, and management feasibility of the project, the USDA approved moving the loan guarantee application from Phase 1 to Phase 2 for construction of the pilot-scale algae farm.

Global Algae is working to obtain financing through program related investment from non-profit foundations, commercial investment, investment from strategic partners, a USDA loan guarantee, and the California Investment Credit. Products generated through the U.S. Department of Energy projects discussed above, will be provided to customers for product development and testing to enable off-takes, which will improve the ability to obtain financing for the rest of the pilot-scale algae farm.

In addition to these Market Transfer Activities, Global Algae has and will continue to share the results of the project as part of public presentations at conferences (Algae Biomass Organization Summit 2022, Algae Biofuels Algae Biomass Organization Summit 2023, & Carbon to Value Cohort 3 Final Showcase) and private presentations for government agencies and elected officials. In addition, the project resulted in multiple invention disclosures, so patent applications and patents will be published on the results.

CHAPTER 4:
Conclusion

All the project goals were achieved. The new technologies were verified; a site lease is in place; the preliminary design and permitting are complete; and the TAC reviewed the design and concurred that the pilot-scale algae farm is likely to be successful.
The project is ready to move from design to construction and operation of the pilot-scale algae farm in Shandon, CA.

The environmental and economic benefits were confirmed. Approximately 50 percent of the output from algae farms will be algal oil, which is an ideal feedstock for the numerous renewable diesel and jet biorefineries under construction in California. Global Algae's life cycle analysis model projects that algae biofuel will achieve a 90 percent reduction in GHG emissions relative to petroleum fuels, and co-products produced with the biofuel result in greater food and feed production rather than competing for resources with food and feed. The high per acre and per liter of water productivity can make the most of California's limited resources to generate higher revenue and more food simultaneously with the production of algae oil as a feedstock for biorefineries. Expansion of algae farms has the potential to produce algal oil as a feedstock for 4.8 billion gallons of biofuel per year, double the agricultural output of the state, and rejuvenate rural areas by creating a full spectrum of high-quality jobs.

This project facilitated the development of a pilot-scale algae farm in California, which will then lead to development of an algae industry. Global Algae facilities can create high-paying year-round jobs from farm workers through scientists and engineers. The per gallon productivity makes the most of California's limited water resources and uses non-productive land to increase standards of living.

The project has facilitated funding towards construction and operation of the pilot-scale algae farm with $11.6 million in funding from the U.S. Department of Energy for construction and operation of the first six acres and associated downstream processing. The project has also enabled successful completion of Phase 1 of the USDA guaranteed loan program with approval by the Secretary of Agriculture to move into Phase 2.

There is not enough arable land or freshwater in the world to meet the expected world demand of protein (>300 Mt) and vegetable oil (240 Mt) in 2050 with the best currently available crops, soy and palm, respectively (Henchion, 2017; Corley, 2009). Algae offers a 20-30x increase in productivity, which will meet the demand and enable restoration of forests, watersheds, and other habitat. Overcoming the vegetable oil limitation is also crucial for scaling biofuel production to decarbonize transportation. The first and second generation feeds such as palm, soy, and canola will make an important contribution, but the third generation feedstock of algae oil is essential in meeting future biofuel production targets (Doliente et. al., 2020). California is well positioned to become the leader in algae technology and algae oil and protein products.

Some concrete actions that the California state government can take include:

- Seek cost share opportunities for future U.S. Department of Energy algae projects.
- Contribute a portion of the investment funds required to fund an algae pilot-scale farm in conjunction with a USDA loan and other sources.
- Fund a study on the environmental/societal impacts of a large algae industry.
- Fund microalgae animal feed trials at California universities.

In addition to the vital role of algae in renewable fuels, algae farming is expected to be important in the global carbon removal effort. In 2022, the XPRIZE Carbon Removal team of over 70 scientists from all over the world evaluated 1137 teams for the potential of their technologies to achieve gigaton scale carbon removal. This was the largest and most comprehensive review of carbon removal technologies to-date. Fifteen technologies were selected as Milestone Award winners with the greatest potential to achieve gigaton scale carbon removal. Three of the winners are based in California, and Global Algae Innovations' technology was selected as one of the Milestone Award winners. Since these technologies were vetted through an international technology review process as being most likely to help solve the climate crisis on a global scale, California should explore funding opportunities to support pilots of these technologies.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
AFDW	ash-free dry weight
ATP3	Algae Testbed Public-Private Partnership
b/d	Barrels per day
BETO	Bioenergy Technologies Office
CO2	carbon dioxide
DAF	dissolved air flotation
DOE	Department of Energy
EERE	Energy Efficiency and Renewable Energy
EISA	Energy Independence and Security Act of 2007
EPA	eicosapentaenoic acid
GGE	gallon of gasoline equivalent
GHG	greenhouse gases
g/m2d	gram per meter squared day
GMP	good manufacturing practices
ha	hectare
IBR	integrated biorefinery
kg	kilogram
kWh	kilowatt hour
LCA	life cycle assessment
mt	metric ton
MFSP	minimum fuel selling price
MJ	megajoule
PBR	photobioreactor
PUFA	polyunsaturated fatty acid
qPCR	quantitative polymerase chain reaction
R&D	research and development
SOT	State of Technology
TEA	techno-economic analysis
TAC	Technical Advisory Committee
TMP	trans-membrane pressure
UCSD	University of California, San Diego

Term	Definition
USDA	U.S. Department of Agriculture

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Project Deliverables

Project deliverables, including the following interim project reports, are available upon request by submitting an email to pubs@energy.ca.gov.

- Non-proprietary versions of deliverables submitted to DOE
- Algae Strain Summary Report
- Non-proprietary version of the Conceptual Design Report
- Permitting and Regulatory Compliance Plan
- Non-proprietary version of the Facility Planning and Design Report
- Non-proprietary version of the Construction and Operation Plan