Helios-NRG, LLC

Final Scientific/Technical Report for Project Titled:

Novel Algae Technology to Utilize CO_2 for Value Added Products

Grant# DE-FE0031710 This project was funded by the Office of Fossil Energy, National Energy Technology Laboratory, U.S. Dept. of Energy, number DE-FE0031710 from DE-FOA-0001849 - NOVEL METHODS FOR MAKING PRODUCTS FROM CARBON DIOXIDE OR COAL - Area of Interest #2 - Field-scale CO_2 Conversion

Recipient: Helios-NRG, LLC

In addition to Helios-NRG, LLC, partners in this project have included:

University at Buffalo, Dr. Haiqing Lin – anti-fouling dewatering membrane with assistance from the commercial membrane vendor Membrane and Technology Research (MTR)

Linde, Inc – commercial expertise in CO_2 dissolution and background in Techno-economic Analysis (TEA)

Northwestern University – Drs. Jennifer Dunn and Santiago Salas; University of California, Santa Barbara – Dr. Eric Masanet – detailed modeling and Final LCA Report

National Carbon Capture Center – Director – Frank Morten and Project Manager – John Carroll – field test host site

Tresca – vendor for development of automated control system

Project Funding: Total: $1,804,631 Government: $1,387,588 Cost Share: $417,04

Project Period: 5/1/19 – 7/31/23

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Introduction:

Helios-NRG continued the development of a novel, algae-based technology to capture CO_2 from the effluent of coal power plants. In order to off-set the cost of capture, conversion of the algal biomass to value-added products was investigated. The technology was designed for flue gas streams from coal power plants post-sulfur removal, but could be suitable as well from natural gas-fired plants and other industrial point sources. Cost-effectiveness of the technology stems from high utilization, exceptional algae productivity, continuous flow operation, low-cost de-watering, nutrient/water cost reduction, and the production of biofuel and high-value nutraceuticals. A schematic of the overall process is shown in Fig 1.

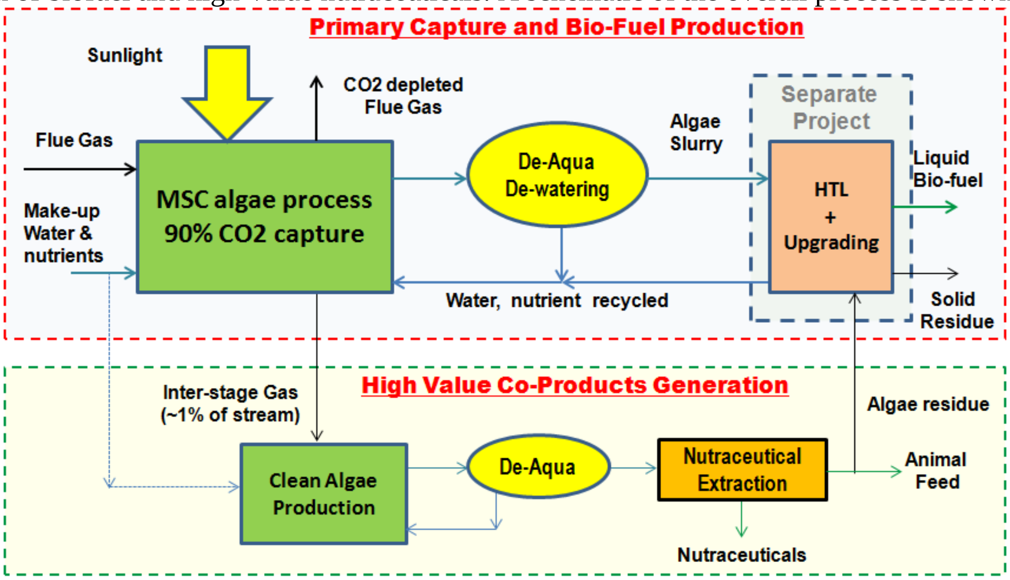

Figure 1: Schematic of the overall process for Carbon Capture and Utilization

Flue gas after de-sulfurization enters a Multi-Stage, Continuous (MSC) flow process, where most of the incoming CO_2 is captured and used beneficially to accelerate the growth of algae. The MSC as demonstrated in this project was operated for the first time with integrated stages, an automated control system, and operation outdoors on actual fossil fuel flue gas at the National Carbon Capture Center (NCCC). Uniquely, the MSC simultaneously enables very high utilization (>80%), stable operation, and high productivity (>25 g/m^2/day). And, unlike traditional batch algae operations, MSC operates in a continuous mode much like most large industrial chemical processes.

The algae culture continuously harvested from the MSC is de-watered using a step-change technology (DeAqua). Another focus of this project is to produce an algae slurry with a solid loading suitable for HTL at 50% lower cost than state of the art. Recycle of up to 98% of the culture media back to the algae culturing system was demonstrated, thus greatly reducing the fresh water use and nutrient make-up requirements. This is critical because the supply of nutrients and water for algae cultivation has been estimated to add at least \$1.20/gal to the cost of producing algal bio-fuels and negatively affect the life cycle assessment (LCA) as fertilizer production requires high use of fossil fuel. The de-watered algae post DeAqua is fed to hydrothermal liquefaction (HTL) + upgrading where it is converted to a biofuel product. The aqueous waste from HTL, which contains residual nutrients, and the CO_2 rich gas from HTL can be recycled back to the MSC process and used for algae growing. Helios-NRG previously collaborated on HTL for algae with Illinois Sustainable Technology Center (ISTC), a division of the University of Illinois, and hence it is not included in this project.

Nutraceuticals are the products focused on in this project. A small fraction of the gas stream, taken from an inter-stage location in the MSC process, is used in a much smaller algae culturing operation optimized for the production of high-value nutraceuticals. These inter-stage gas streams from the MSC would be cleaner in contaminants verses post FGD coal flue gas and well suited for several algae strains intended for human nutraceutical and food applications. Likewise, this process is applicable to animal feed, which also has been part of previous and concurrent product investigations. The goal related to product development in the project was to select and identify two species of algae for conversion into high-value nutraceutical products, develop an induction process for increasing the product concentration over the baseline concentration, and to develop a technique for scaling of production of the product.

Results: the following is the task-by-task discussion of the project.

Task 1: Project Management and Planning
Helios as prime on the project conducted all the oversight of the budget, project planning, in-house work and coordinated activities of the project partners. Below is listed the significant activities related to project management:

- Project Management Plan 5/31/19
- Project Kickoff 8/22/19
- Technology Maturation Plan (TMP) 10/31/19
- Carbon Utilization Peer Review presentation 6/8/21
- NCCC – DOE - Sponsors Meeting 11/16/2022
- Final Project Meeting 7/14/23
- Updated TMP 8/14/23
- LCA 8/14/23
- TEA 8/14/23

The Covid-19 epidemic had a significant effect on the project. Initially, the activities of Helios and other partners were highly reduced due to the quarantine. Then as in-person activities at Helios-NRG came back, all NY state guidelines were followed including social distancing, reduced occupancy capacity in lab and greenhouse and use of masks as required. When possible, work was done offsite from home and meetings held via Zoom. Some of the work was delayed, but eventually with a no cost time extension, all the work in the project was completed, including reports, presentations, and all the milestones and success criteria were met.

Task 2: Design, build, operate MSC system

Subtask 2.1 - Design and build a scalable PBR unit for MSC

The objective of this task is to develop an improved (2nd Generation) multi-stage, continuous system (MSC) for algae-based carbon capture from coal-based post flue gas desulfurization (FGD) flue gas, enabling high algae productivity coupled with high CO2 capture efficiency. A key requirement for this project was to transition the side lit photobioreactor (PBR) design to top lit operation and implement scalable improvements suitable for future large-scale algae cultivation operations.

In prior DOE-funded projects, Helios has extensively qualified and selected a preferred algae strain (H-1903), suitable for this carbon capture application based on its resistance to the detrimental contaminants present in coal-based post FGD flue gas such as acid gas (SO_X, NO_X) and heavy metals. The key design and operating parameters were determined using Helios proprietary algae model developed outside any funded project. Model simulations were conducted based on several MSC configurations with varying liquid and gas transfer rates, as well as incident light available. Performance of the system was mapped and a preliminary design and operational strategy developed.

A scalable single-stage Raceway-PBR with the preliminary desired design features was fabricated and procured such that the overall MSC system be of ~600L. The raceway-PBR tanks were custom-made to size via fiberglass molds with top lips to accommodate the top cover sealing mechanism. The top cover was made of a clear plastic sheet to allow for maximum light entry into the system. The sealing mechanism for the top cover allowed for slight gas pressurization such that top cover is internally supported, allowing for external water run-off. The gas pressure in each of the stages were measured for its potential use in the techno-economic analysis.
Ports for gas distribution, culture flow, sampling, and circulation pump was made through the side wall of the tank, minimizing light loss from the necessary installed components. Preliminary shake-down tests

were conducted to check the single-stage for leaks, culture mixing and gas distribution prior to integration into the MSC system. Algae growth tests were conducted initially in the greenhouse and transitioned to outdoors to determine preliminary algae productivity and CO2 capture efficiency performance as summarized in Table 1. While these experiments resulted in satisfactory performance, several changes to the PBR design to maximize light utilization were identified and incorporated into future designs.

Table 1: Lab and greenhouse testing of individual PBR design

					Overall Performance	
PBR Design	Light		Simulated Feed Gas		Normalized Algae Prod	Total CO2 Cap Eff (%)
	Facility	Intensity Avg (Lux)	CO2	Contaminants		
1	Lab	~9,000	12%	N/A	56%	54%
2	Lab	~9,000	12%	N/A	80%	80%
3	GH	~11,000	12%	SOX/NOX + 5HM	85%	73%
4	GH	~14,500	12%	SOX/NOX + 5HM	123%	74%

Subtask 2.2 - Build and validate performance of scalable MSC system

Based on the preliminary algae productivity and CO2 capture efficiency performance obtained in Subtask 2.1, several improvements in the design and operation of the Raceway-PBR were identified. The tanks were redesigned to incorporate the desired improvements. Additional units were procured for the actual MSC system integration. Modifications to the additional units were made to incorporate the ports for gas and liquid connections as well as for the circulation pump.
The cornerstone of the MSC system is the continuous gas and liquid flow feature, with algae concentration measured over time, enabling efficient upstream/downstream integration in large-scale operations. Several concepts for continuous gas and liquid flow automation through the interconnected MSC system were identified and necessary parts procured. Helios engaged a small specialized company to develop and fabricate the automated control system based on the selected design concept. Post fabrication, solenoid calibrations for the installed liquid flow control system of the interconnected MSC system was performed to refine operation.

The multi-staged Raceway PBR coupled with the 1st generation automated control system was integrated, enabling unattended operation as shown in Figure 2.

Figure 2: Outdoor testing of integrated MSC system with automated control

Preliminary shake-down tests of this first-of-a-kind integrated MSC system were conducted initially on water to determine system functionality, followed by algae growth test promptly thereafter. Initial greenhouse MSC results of the short-term algae growth test with the automated control system were below average as low growth rates due to poor culture health were observed, possibly due to instability/intermittency of the gas transport system in the MSC system. Modification to the top cover sealing was implemented to improve the sealing. Additionally, a new concept for inter-stage gas transfer was identified, evaluated, and incorporated into the automated control system.

While many factors are important in the performance of the MSC system, one of the most important is the intensity of the incident sunlight. Throughout the project, Helios actively measured light intensity variation of the greenhouse facility in use, averaging the measurements throughout the day. Figure 3 shows that sunlight intensity inside the greenhouse varied extensively from day-to-day, but also from season-to-season. A key finding was that there was significant variance between the internal and external measurements of sunlight intensity at the greenhouse. The quarterly average light intensity external to the greenhouse is substantially higher (~ 1.5-2x) than indoor due to lack of infrastructure blockage and losses through the glass, as summarized in Table 2. The substantially lower light intensity available inside the greenhouse potentially limits the overall performance of the MSC tests conducted.

Table 2: Internal and external quarterly average light intensity for greenhouse (GH-1)

	GH-1 Avg Light Intensity (Lux)	
	Internal	External
Q2 2019	9,207	
Q3 2019	10,978	19,717
Q4 2019	3,088	5,890
Q1 2020	4,024	7,027
Q2 2020	11,582	17,401
Q3 2020	11,636	14,819
Q4 2020	3,128	6,626
Q1 2021	5,284	9,034
Q2 2021	11,571	16,198
Q3 2021	10,042	15,005
Q4 2021	3,138	5,792
Q1 2022	5,581	7,274
Q2 2022	11,401	16,092
Q3 2022	10,220	15,086
Q4 2022	4,332	7,812
Q1 2023	4,063	7,049
Q2 2023	9,398	15,748

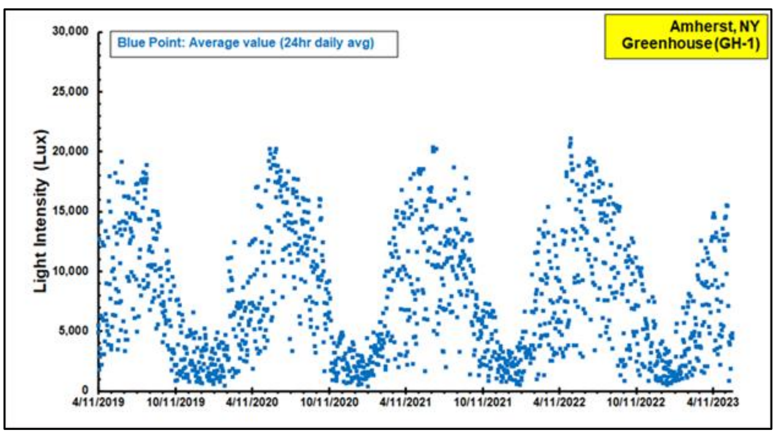

Figure 3: Daily light variation in greenhouse (GH-1)

Several test campaigns were conducted in the greenhouse on the integrated MSC system at various process setpoints to determine its impact the algae productivity and CO2 capture efficiency, correlating the overall performance with sunlight intensity. The tests were highly successful as stable MSC operation with the advanced control system was demonstrated for >75 days with performance marginally below the project target. It demonstrated that the algae productivity and CO2 capture efficiency are strong functions of light intensity; increasing the likelihood of achieving the project targets of 25g/m2/day and 80% CO2 capture in outdoor operation.

The next phase in MSC development was to initiate outdoor operations of the system, more representative of the future National Carbon Capture Center (NCCC) field test. Prior to outdoor operation initiation, the control system box, user interface display unit, wiring of the control system and output to the respective components on the MSC system were weatherproofed. Multiple test campaigns were conducted for the MSC system outdoors based on the learnings from prior greenhouse tests at various process setpoints. The integrated MSC system was successfully operated continuously for >70days, demonstrating process stability, health of the algae, and the robustness of the MSC system despite variations in environmental conditions. As part of a separate practice trial, the MSC system was restarted with a new batch of inoculum. The objective of this test was to further elucidate any potential variation in MSC performance between various algae inoculum as well as to refine the Standard Operating Procedure (SOP) for the integrated system in preparation for the NCCC field test.

As expected, with the significantly higher light intensities outdoors, the MSC performance exceeded the project target. The various test campaigns of the integrated MSC system are summarized in Table 3. Utilization of centrate wastewater (WW) nutrient was another key test objective as wastewater remediation credits can significantly reduce the overall CO2 capture cost. Overall, the tests performed in the indoor GH-1 and outdoor have been successful, setting a positive note for the NCCC field test.

Table 3: Greenhouse and outdoors test of integrated MSC system

Location	Sim. Flue Gas Contaminant	Nutr-WW Replacement	Normalized Algae Prod	Avg CO2 Capture
GH-1 Indoor	SOX/NOX + 5HM	50%	92%	59%
Outdoor	N/A	N/A	139%	81%
Outdoor	SOX/NOX + 5HM	80%	141%	76%
Outdoor	N/A	N/A	142%	77%

Task 3: Optimize Nutraceuticals Production

The activities related to the conversion of algae to nutraceuticals products, where the identity of the algae species and the types of nutraceutical categories in this project are proprietary work by Helios-NRG. The goal was to identify and select two new species of algae which have the potential for producing high-value products (Table 4). The four classes of products include A and B (H-0326), and with their content in algae increased with induction. Induction applies a stressor to the algae which changes the cell metabolism to accumulate more cell product. Product class B, C and D, which do not need induction, are produced in H-1601 algae. Product B and C are extracted from the algae cell while Product D is secreted into the culture media and can be harvested directly without extraction from the cell.

Table 4. Species selection and potential nutraceutical products for this project.

Algae Species for Nutraceuticals			
Species	**Product**	**Induction**	**Comment**
H-0816	A	yes	slow growth, id alternative in this project
H-0326	A, B	yes	selected for use in this project
H-1601	B, C, D	N/A	selected for use in this project

While the H-1903 algae used for carbon capture grows rapidly in 12% CO2, the two nutraceutical species grow slower but adequate for the overall process (Fig 4). Most importantly, the nutraceutical species (H-1601 and H-0326) can grow at lower CO2 levels, representative of an intermediate gas stream from MSC which is a cleaner gas source with much reduced levels flue gas contaminants. This allows the algae to be grown for human consumption without the contamination typically present in coal flue gas.

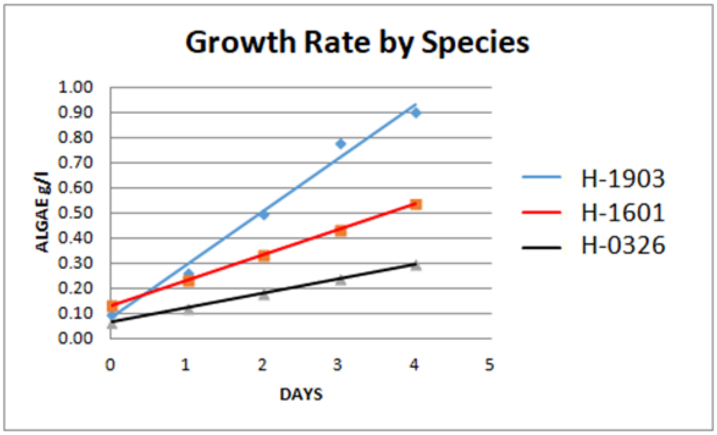

Figure 4: Growth of carbon capture algae vs nutraceutical algae (Note - Carbon Capture 12% CO2, Nutraceuticals intermediate MSC CO2 concentration)

Initial work reported here focuses on species H-0326 which produces nutraceutical A, a product with very high value. The H-0326 growth rate was improved with the adjustment of light, the reduction of shear stress in culture mixing, and the level of CO2. In comparison between H-0326 and H-0816, a species used in another project, the two cultures were grown with similar culturing condition, species H-0326 grew at a rate 5-fold greater than H-0816. Therefore, H-0326 was selected for further study in this project.

The general process for producing nutraceuticals (Fig. 5) include algae cultivation, induction if needed, and dewatering followed by extraction. Throughout this project each of these steps were targeted for improvement.

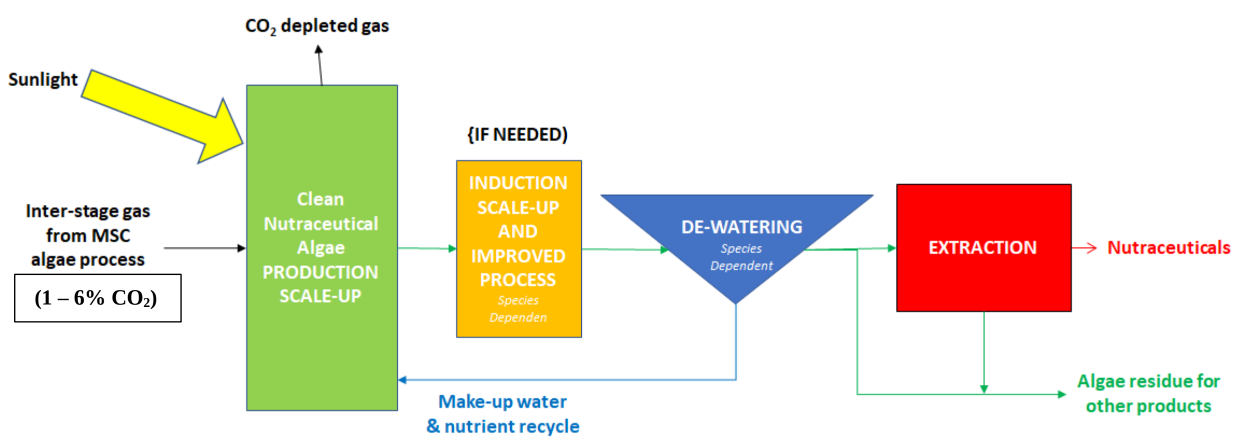

Figure 5: Process to produce crude nutraceutical extracts with high value

A variety of treatments were used to induce H-0326. The process was monitored by a color change in the algae, green when growing, orange upon induction as the concentration of products A and B increases (Fig 6). Initial levels of products, post induction, were qualitatively measured with thin layer chromatography of extracted samples (Fig. 7). Larger cultures were grown and induced, then extracted and analyzed with High Pressure Liquid Chromatography (HPLC) (Fig. 8).

B

Figure 6: Color change from induction of algae species H-0326 (left panel before induction, right panel after induction)

Figure 7: Thin layer chromatography analysis of algae extracts. Left Panel – H-1601 stained for Product B with induction not applicable, and Right Panel – H-0326 induced shows Product A

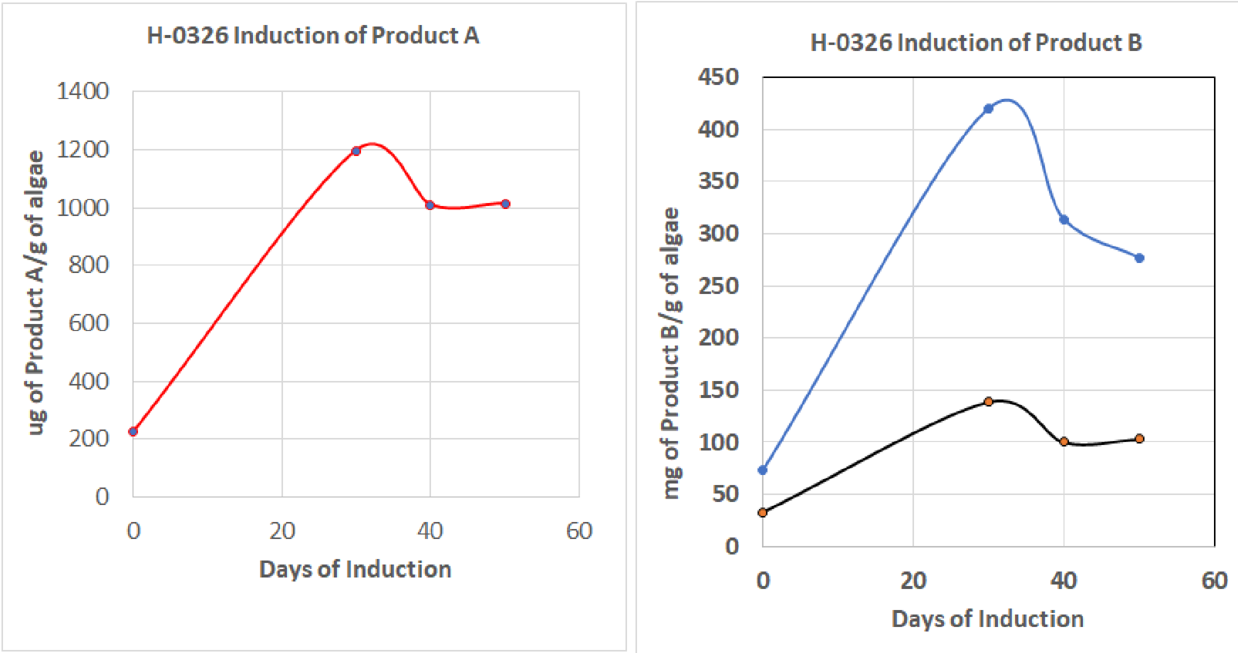

Figure 8: HPLC of analysis over time of induction H-0326. Left Panel – Product A, Right Panel – Product B (note - blue line lower value product, black line high value product)

Levels of product A demonstrated over the course of induction Fig 8, left panel show promise for the production of this valued product; further work will be needed in subsequent projects to determine the best methods for scale-up of the overall process. Similar work will be needed for Product B. Note that Product B is also present in significant levels in H-1601.

We conducted comprehensive tests on samples obtained from cultures of the H-1601 species. Notably, this species did not require any induction. During the culture period, the concentration of Product C in the extract obtained from harvested cells was quantified. It was found that the content of this valuable Product C ranged from 10% to 13% of the total weight, which is significantly higher than what is typically produced by other known species.

We additionally extracted Product D from the cell-free media derived from the same cultures used for the production of Product C. The amount of Product D we recovered varied between 0.22 g/L and 0.32 g/L over the same sampling period. In the future we intend to develop more efficient and cost-effective techniques for recovering these valuable products.

Lastly, since multiple products can be produced by these two algae species, a multiple stage extraction process developed previously could be used for enhanced product recovery. Current bio-processing applications often target only one product from a feedstock. Post nutraceutical product extraction, the remainder of the algae biomass could be recycled back to the HTL process or used in animal feed, enabling a more sustainable processing approach. Bio-refining multiple product lines from algae production line will produce higher value potential. See the TEA for more discussion on these product values and their relationship to offsetting carbon capture costs.

Task 4: Advance DeAqua Gravity Table Performance

Figure 9 illustrate the schematic for a multi-stage DeAqua system for dewatering of algae harvests. Development work of the first two stages, the advance DeAqua gravity table and the anti-fouling membrane module were addressed in this project in Tasks 4, 5, and 6. A commercially available technology can be optionally included in the third stage of the system depending on the degree of dewatering needed.

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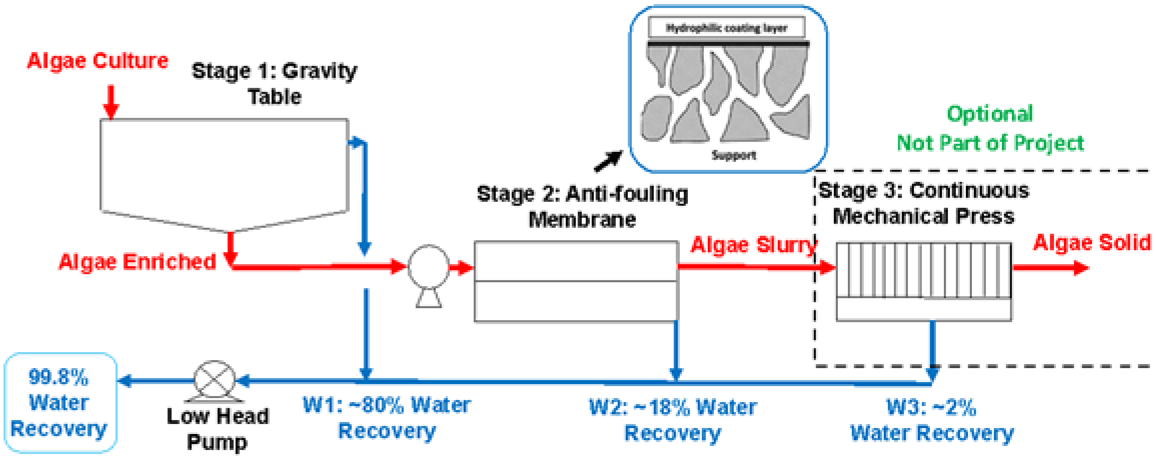

Figure 9: Schematic of DeAqua system envisioned for commercial scale dewatering

The objective of task 4 is to further enhance the algae dewatering performance of the Stage 1 DeAqua, an enhanced gravity table process, from than that achieved in a prior DOE-funded project. A key focus was to improve the energy efficiencies of the Stage 1 DeAqua, by 25%, while maintaining high algae concentration ratio, product recovery ratio and performance index. The concentration ratio is defined as the ratio of the concentration of microalgae in the product to that in the feed. Recovery ratio is defined the ratio of mass recovered in the concentrated product microalgae compared to the initial feed mass. The performance index is defined as the concentration ratio divided by the overall time required for gravity settling.

A second small bench-scale continuous flow test unit with improved designs was fabricated based on the selected parameters of the previous batch and continuous tests. A technique for improving energy efficiencies in the dewatering technology was investigated via culture modification. Various culture modification via use of low-cost additives were performed on harvested algae, where dewatering performance and energetic requirements mapped.

Dewatering tests with the continuous flow lab-scale reactor of the modified culture demonstrated improved energetics of the technology – minimum ~25% reduction in energy requirements while maintaining similar separation performance index, as shown in Figure 10 below. Based on the systematic parametric dewatering tests, an optimum for culture modification metric was determined, as seen by the minimization of dewatering energy requirement while maintaining a high algae product recovery.

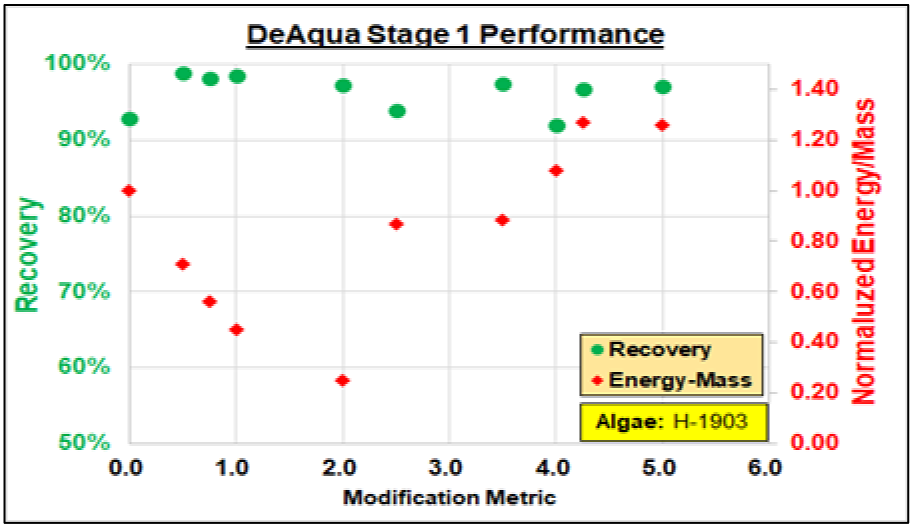

Figure 10: Impact of culture modification on dewatering performance

In order to elucidate the technology feasibility of the improved dewatering performance via additive (modification metric), actual culturing tests are required as the additives need to be non-damaging to the algae itself. Preliminary results of the algae growth rates of the various modified culture looks promising as compared to the unmodified culture (control), indicating no adverse effect, as shown in Figure 11. Additionally, the culture modification was investigated as a method of pathogen control in the culture.

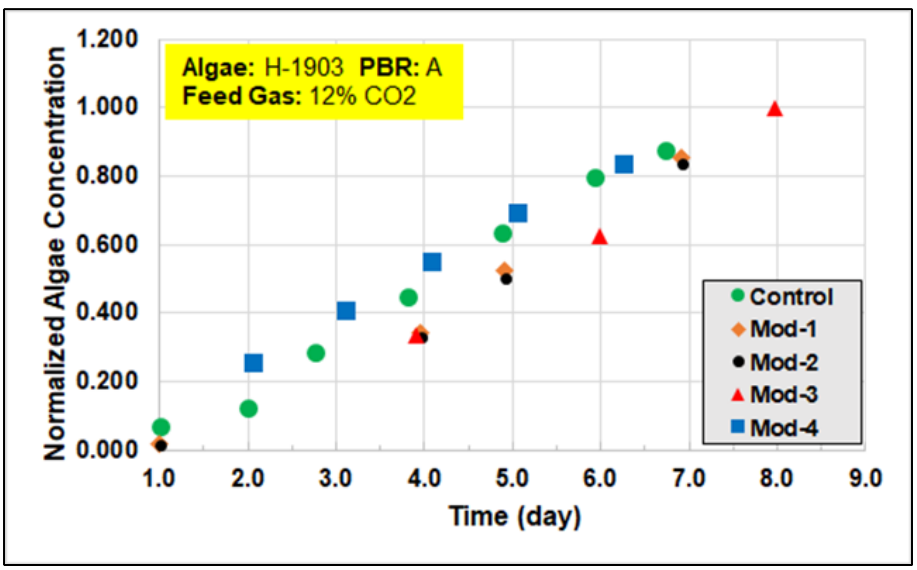

Figure 11: Impact of modification metric on algae growth

A key feature of the dewatering technology is its high water recycle rate (>99%), minimizing freshwater utilization in the MSC system. Helios has utilized low-cost pretreatment techniques such as filtration and UV sterilization to remove potential bio-contaminants from the supernatant culture media post algae dewatering. Parametric tests were conducted to determine the water recycling rate (RR) feasible in the algae culturing process, without affecting the algae growth performance. Overall, the results are encouraging as up to ~98% RR was validated (Figure 12), demonstrating significant reduction of freshwater use, key to the overall cost reduction of algae-based CO2 capture.

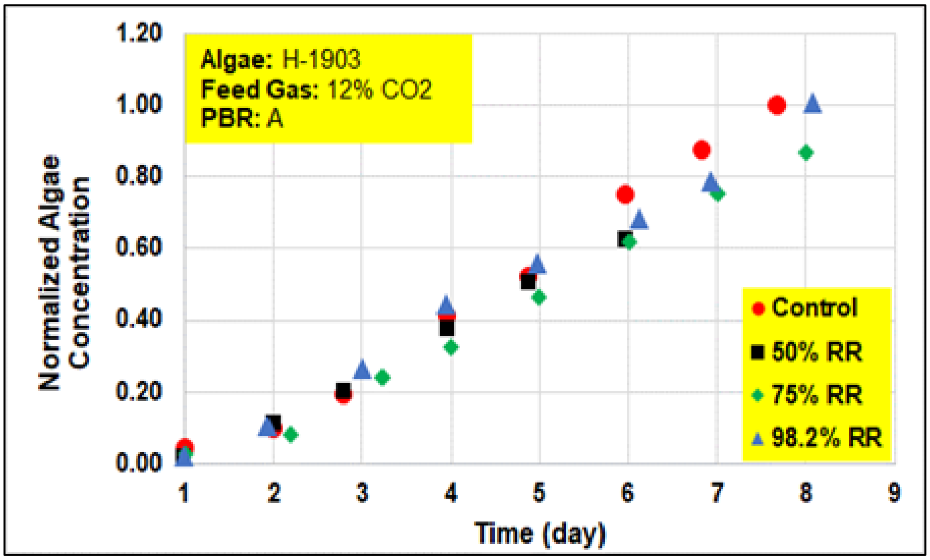

Figure 12: Impact of Recycling Rate (RR) on algae growth

Upon successful dewatering technology demonstration with H-1903 (primary species for CO2 capture and biofuel production), Helios also developed a technology variant for dewatering H-1601 algae, utilized for nutraceutical production. Preliminary tests with the current dewatering unit had shown some limitation in product recovery performance due to poor flow distribution due to clumping arising from the bio-secretion of this algae species. The Stage 1 design was modified to address this issue and the overall dewatering performance improved, achieving ~90% product recovery. The energetics of the dewatering process has also been improved via culture additives, decreasing energy requirement. However, compared to H-1903, H-1601 requires longer time to achieve 90% product recovery, resulting in lower Performance Index performance. The specific energy requirement for H-1601 is also higher than for H-1903, but this is not a significant concern due to the much higher value of the nutraceutical products than biofuel. Overall, the development of the DeAqua Stage 1 is highly encouraging, as shown in Table 5 where all performance specifications exceeded the initial project targets. Advancements in this work resulted in >90% water removed through the Stage 1, as compared to 70%, significantly reducing the dewatering cost and simplifying the overall process.

Table 5: DeAqua Stage 1 Performance of H-1903

	DeAqua Stage 1 Performance Specification		
Project	Conc Ratio	Performance Index	Recovery
Prior work	3-6	0.12-0.37	70%
Initial Project Target	3-6	1.5	80%
Current work	20-25	5.0-12.5	80-95%

Task 5: Advance DeAqua Anti-fouling Membrane

Our objective was developing a bench-scale plate-and-frame module to test the composite membranes tested previously on a scale over 0.2 ft^2. The plate-and-frame modules fabricated was utilized for continuous microalgae dewatering in a crossflow filtration system setup. Additionally, periodic cleaning of the plate and frame modules during the operation was conducted to determine long-term stability of the membranes. The details are shown below.

5.1 Make small plate-and-frame modules for early testing

A lab-scale plate and frame module M10 was procured from Alfa Laval. The membrane area in this module is 168 cm^2 each membrane envelope as shown in Figure 13.

Figure 13: Photo of M10 plate and frame module from Alfa Laval

5.2 Design and fabricate prototype plate-and-frame modules incorporating improved membranes.

A comparison of algae dewatering performance between pristine PES and zwitterionic modified PES (zPES) in the plate-and-frame module is summarized in Table 6 below. It was shown that the hydrophilicity-enhanced membrane (zPES) had a better fouling resistance under a low feed flow rate of 3 L/min with a Reynolds number (Re_m) of 1500 compared to the pristine PES membrane. The water permeance (PW) of zPES at the steady-state in the dewatering process achieved was ~2x of the pristine membrane. However, when both the membranes challenged against a high concentrated algae solution with a content of 10 g/L, similar dewatering performance was observed. The improvements achieved in the zPES membrane developed will serve as a basis for future prototypes of the plate-and-frame module developments.

Table 6: Summary of steady-state water permeance of PES and zPES at different algae contents.

Membrane	Algae content (g/L)	Permeance (LMH/bar)		
		PW	Algae	PW
PES 0.05	1	1128	129	333
	10	1173	52	131
zPES	1	1151	344	619
	10	1173	43	175

Task 6: DeAqua Membrane Module Performance Tests

Subtask 6.1. DeAqua anti-fouling membrane module test

Single-cycle filtration tests were conducted using zPES modified membrane. When the membranes were challenged with 1 g/L algae, the dewatering permeance decreased with the decrease of Re_m. The zPES membrane has a permeance of 200 LMH/bar at a Re of 3000, 155 LMH/bar at a Re of 2000, and 80 LMH/bar at a Re of 1000. The corresponding recoveries, after being cleaned with DI water, were 70%, 50%, and 40%, respectively. Next, a continuous multi-cycle filtration test was conducted with the Re_m number decreasing from 3000 to 1000. The dewatering performance was similar to that observed in the single-cycle filtration tests. After cleaning with DI water, the membrane showed a recovery of 40%, similar to that in the single-cycle test. Finally, the effect of different feed algae concentrations on dewatering permeance was studied. At a high Re_m number of 3000, the membrane showed ~260 LMH/bar for both concentrations tested. However, at the Re number of 2000 and 1000, the membrane exhibited a ~30% higher permeance for the lower algae concentration. Detailed data were summarized in Table 7.

Table 7: Summary of steady-state water permeance of PES and zPES at different operating conditions, including flow condition, Re_m, and algae contents.

Membranes	Flow condition	Re_m	A_W with various algae contents (LMH/bar)			
			Pure water	1 g/L	5 g/L	10 g/L
PES	Dead-end	65,000	1600 ± 300	225	76	80
	Cross-flow	1,000	1300 ± 48	99	60	54
		2,000		116	81	69
		3,000		151	87	85
*z*PES	Dead-end	65,000	1300 ± 98	386	161	166
	Cross-flow	1,000	1300 ± 50	114	69	63
		2,000		120	93	78
		3,000		172	103	92

Figure 14a summarizes the influence of the algae content and Re_m on the steady-state water permeance of PES and *z*PES at a constant pressure of 10 psig in a crossflow system. Increasing algae content decreases water permeance, similar to that observed in the dead-end cells. The *z*PES exhibits 15~30% higher water permeance than PES for 1-5 g/L algae solutions. However, the advantage of the surface modification diminishes at 10 g/L algae solution because of the reduced influence of the surface hydrophilicity. Figure 14b demonstrates that increasing the Re_m increases water permeance for both membranes because of the flow-induced shear force and the self-cleaning behavior [1, 2].

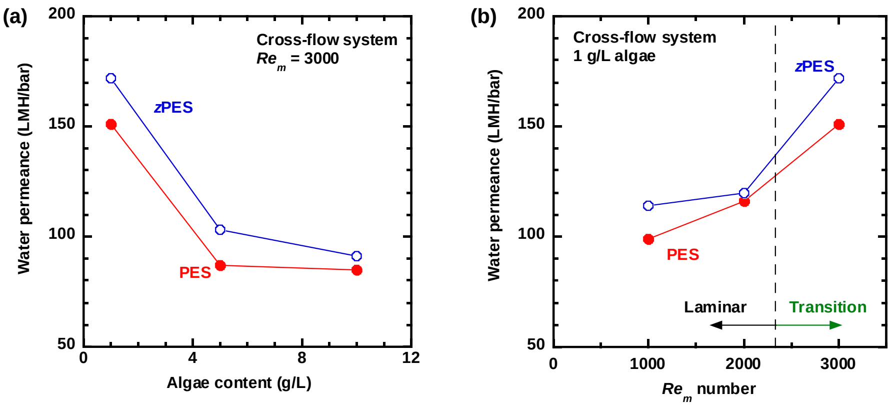

Figure 14: Influence of (a) *Feed content* at Re_m = 3000 and (b) Re_m number at *feed content* of 1 g/L on the steady-state permeance in the crossflow system.

6.2. Module regeneration process test

Cleaning MF membranes is critical for long-term operation, as fouling seems to be inevitable. Figure 15 illustrates a continuous crossflow test of the PES and *z*PES membranes with three cycles of dewatering and cleaning using NaOH solution with a pH of 11. Accelerated fouling was used here to better elucidate the effect of the cleaning. The dopamine-based coating was demonstrated to be stable when tested with the cleaning solutions at pH of 2 – 11 [3, 4]. Both membranes exhibit good chemical resistance to the NaOH solutions. The *z*PES still shows higher water permeance and higher flux recovery ratio (i.e., the ratio of pure-water permeance after the cleaning to before the algae dewatering) than PES. The recovery ratio is ≈70% after the NaOH cleaning and only ≈40% after the water cleaning, indicating that NaOH is more efficient than water in removing the foulants from the surface because of the following factors. First, the NaOH solution can decompose insoluble organic particles on the surface into soluble molecules, which can then be detached [5]. Second, the NaOH solution makes organic foulants surface-negative, which repels the membrane surface with negative charges [6].

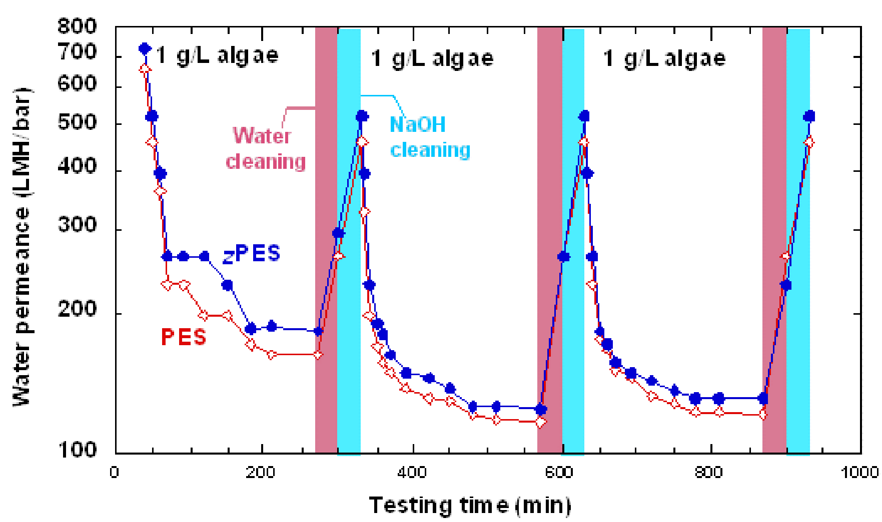

Figure 15: Continuous testing of PES and zPES membranes for three cycles of dewatering 1 g/L algae solutions with water and NaOH cleaning. The measurement was conducted at 10 psi and Rem of 2000. Both water cleaning and NaOH cleaning last 30 min and water permeance was tested after cleaning.

Additionally, Table 8 shows that the NaOH cleaning barely changed the water contact angle or surface hydrophilicity, further confirming the stability of the zwitterionic coating layer. Acidic cleaning agent did not provide satisfactory recovery of the water permeance after algae fouling on the membrane. In a more severe situation, the NaClO removed the coating entirely because the oxidant agent damaged the PDA layer.

Table 8: Effect of different cleaning chemicals on the *z*PES in M10 after filtrating 5 g/L algae solution for 1 h.

Cleaning agent	PW	5 g/L algae	PW after cleaning	Membrane after cleaning	Recovery	Reduction	Water contact angle after cleaning (º)
Water cleaning	1268	184	1007		79%	86%	28 ± 2
HCl pH~3 cleaning	1282	163	516		40%	87%	34 ± 4
NaOH pH~11 cleaning	1203	175	935		78%	85%	29 ± 3
0.04% NaClO cleaning	1417	155	1097		77%	89%	--

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Task 7: Field Test of Carbon Capture

The objective of this task is to validate the performance of the MSC system on an actual coal utility post FGD flue gas, in this project, a flue gas slipstream from the National Carbon Capture Center (NCCC). This work is a first-of-a-kind biological approach for CO2 capture to be conducted at the NCCC. Post contract negotiation, Helios personnel conducted a site visit to determine location, potential layout and utilities connections. Two possible locations, mainly the pilot-scale and bench-scale site were initially identified as potential test sites. Light intensity measurements were performed at both sites with help from NCCC personnel. The average monthly light intensities at the various test sites at NCCC are summarized in Table 9. Based on the significantly higher light intensity measurements, Helios and NCCC decided on locating the MSC test system at the NCCC-Bench site. In addition, NCCC provided adequate lab and office space locations near the field test site which benefited overall operations.

Table 9: Light comparison at various site locations at NCCC

Month	Avg Daily Light Intensity (Lux)	
	NCCC Pilot	NCCC Bench
Sep-21	9,530	18,952
Oct-21	6,331	16,135
Nov-21	3,105	15,304
Dec-21	2,248	8,950
Jan-22	2,524	12,701
Feb-22	3,848	14,600
Mar-22	7,602	19,878
Apr-22	13,244	16,492

Leading up to the NCCC field test, Helios developed a complete system checklist of all needed materials and equipment needed, including procuring anticipated spare parts. The MSC system shipping crate/base was fabricated in preparation for shipping to NCCC. Helios identified several options for logistic carriers for transporting the system to NCCC, obtaining quotes for comparison. Final modifications to the MSC system in terms of electrical weatherproofing and component skid-mounting were performed prior to shipment to NCCC.

Upon arrival at NCCC, the algae inoculum system and the MSC CO2 capture system were installed on-site. The algae inoculum system was established in a nearby indoor laboratory whereby cultures were maintained in a controlled environment to supply algae seed for the MSC tests. The MSC test system was setup at the bench-scale site, as shown in Figure 16, where post FGD flue gas was provided from a mixture of natural gas and coal-fired operation. Supplemental CO2 from pressurized cylinders was added by NCCC to boost CO2 concentration in feed gas to levels representative of coal-based flue gas. Feed gas composition was measured and logged continuously, with the blended CO2 concentration varying between 7.5-12.5%. On-site modifications were implemented with help from NCCC personnel to improve safety and operability.

Figure 16: Integrated MSC system at NCCC bench-scale site (photo John Carroll, NCCC)

Initial shakedown and startup operations were completed and algae CO2 capture tests initiated. It is important to note that the sunlight intensity at the skid site was lower than originally expected due to significant shading from neighboring infrastructure in the early morning and late afternoon. The lower light intensity at the site was expected to impair the MSC performance. In order to elucidate the issue with the lower light intensity, Helios conducted sunlight intensity measurements at the actual test site and another site at NCCC free of light shading. The average light intensity at the shade-free site was up to 45% greater than the actual test site. However, due to site restrictions, the MSC skid system could not be moved to the shade-free site. Hence MSC modifications were implemented to maximize performance at the current test site.

In the beginning of the test campaign, we experienced several setbacks related to the poor algae growth in both inoculum and MSC systems. These were resolved by acquiring new seed inoculum samples from our main facility in Buffalo, NY. Improvements to the MSC cooling system were resolved with help from the NCCC personnel site support. It is important to note such that throughout most of the test campaign at NCCC, the weather was unexpectedly poor as there were stretches of rain/heavy cloud cover, resulting in very poor light intensities, and thus poor MSC performance. It is noted that the levels of acid gases and heavy metal contaminants present in post FGD flue gas supplied at NCCC was significantly lower than those previously used in Helios in-house tests with simulated flue gas.

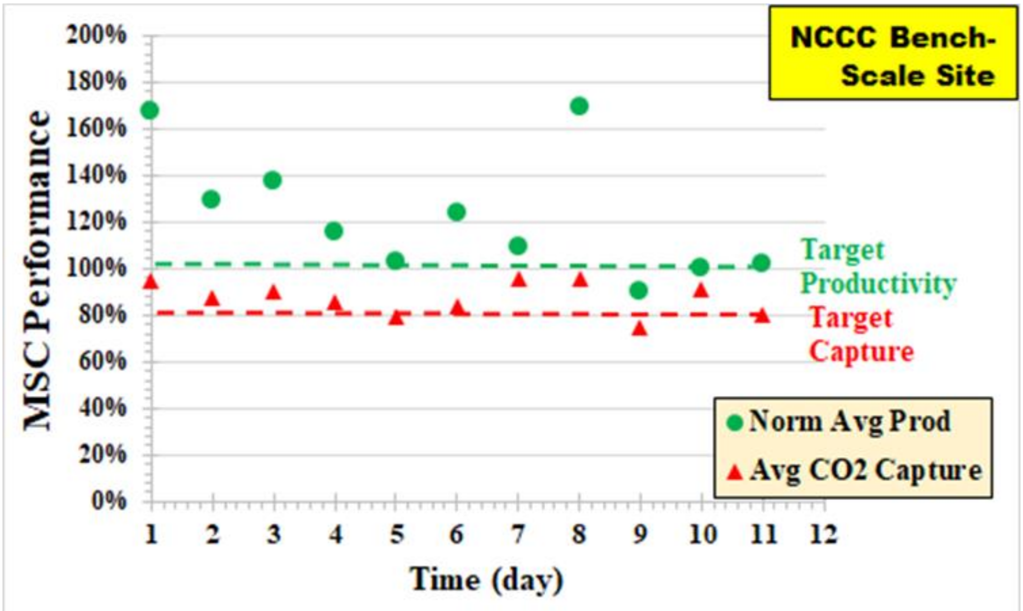


Figure 17: NCCC field test result of MSC system

Despite the complications that arose during the test campaign, the overall tests are completed on time. The results, summarized in Figure 1, show that the project targets for average algae productivity and the CO2 capture efficiency were exceeded. Subsequent to the successful field test, the MSC and related equipment were returned to Helios-NRG and all reporting requirements to NCCC and DOE were completed.

Task 8. Lifecycle Assessment

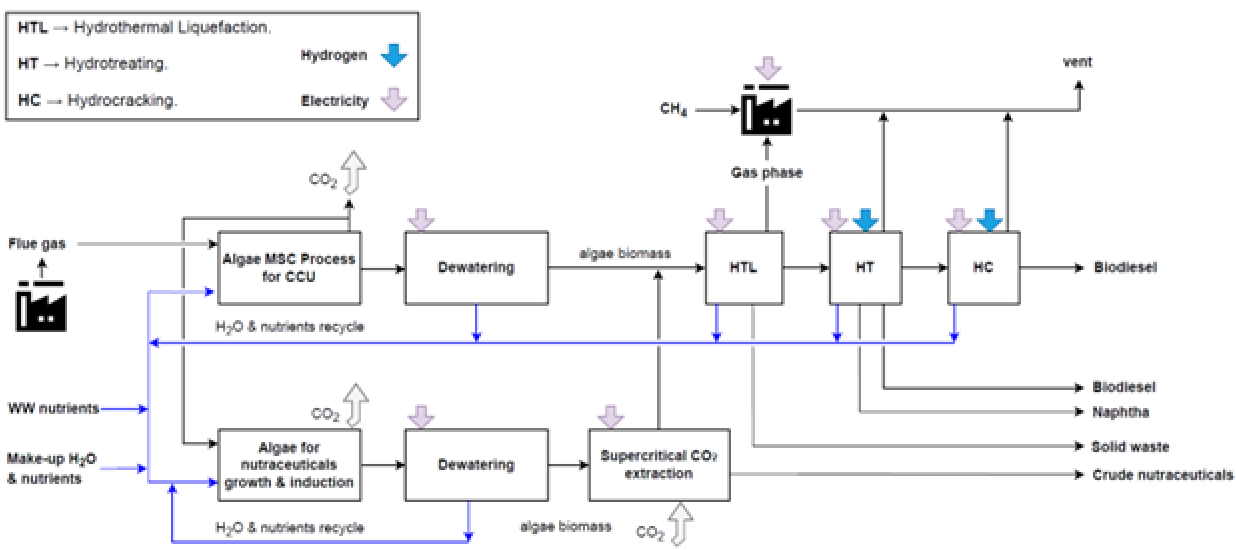
EXECUTIVE SUMMARY

This life cycle analysis (LCA) is required by the United States (U.S.) Department of Energy (DOE) to satisfy the requirements for vendors participating in the DOE Utilization Procurement Grants (UPGrants) program. The vendor completing this study is Northwestern University and University of California Santa Barbara applying for the inclusion of Liquid Fuels and Crude Nutraceuticals from algae under the UPGrants program. This LCA report has been prepared in accordance with ISO 14040/14044 requirements and with the NETL CO2U LCA Guidance Document as modified by the UPGrants addendum.

The objective of this life cycle assessment was to evaluate the life-cycle greenhouse gas emissions of liquid fuels and nutraceuticals produced using technology under development by Helios-NRG, LLC. To accomplish this task, we developed a model in AspenPlus of the conversion technology based on a combination of Helios process data and literature information. We adopted two co-product handling methods (displacement, process-level allocation) and two functional units (MJ biodiesel, L nutraceutical).

Emission factors associated with process inputs and baseline systems were mainly derived from the Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model. The comparison systems include petroleum diesel, soybean biodiesel fuel, and algal fuel as modeled in the GREET model. Furthermore, a baseline nutraceutical life-cycle greenhouse gas emissions estimate was acquired from the literature in which the nutraceutical is produced from krill. The different types of fuel all provide the same service (delivery of one MJ of fuel). The nutraceutical is equivalent on a volumetric basis. Performance of the nutraceutical from the Helios process may be comparable to this nutraceutical.

The system boundary is displayed below.



When the displacement co-product handling technique is used, life-cycle GHG emissions of the biodiesel produced from the Helios process (36 g CO_2e/MJ) fall below baselines of petroleum biodiesel (59% reduction), soybean biodiesel (71% reduction), and algal biodiesel (32%) when the average U.S. grid provides electricity. Petroleum-derived naphtha's life-cycle GHG emissions are 84 g CO2e/MJ. Naphtha derived from the Helios process therefore offers a 57% reduction in GHG emissions as compared to this fuel. Baseline fuel life-cycle GHG emissions are from the GREET1_2022 model. When a low-carbon electricity source is used (nuclear, solar, wind), the algal biodiesel outperforms all baselines. The major GHG emission sources are the combustion of the fuel (e.g., in an engine) and combustion of HTL-derived methane for process heat. CO_2 from both of these processes is biogenic and because the algae is a fast-growing biomass, we incorporate a biogenic carbon credit that offsets these CO_2 emissions. Aside from these emissions, use of electricity in the process and hydrogen consumption drive GHG emissions. When the grid is powered by renewable electricity, hydrogen consumption is left as the main GHG emissions source.

The main conclusion of this analysis is that the liquid fuels produced by Helios have the potential to achieve an over 50% reduction in GHG emissions from baseline liquid fuels.

Goal and Scope

Study Goal

The study was conducted to compare the life-cycle greenhouse gas emissions of products from the Helios-NRG system to baseline liquid fuels and nutraceuticals. The information will be used by Helios to confirm these products are achieving at least a 50% reduction in GHG emissions compared to the baseline. This report also serves to inform the project sponsor, NETL, about the LCA portion of the Helios project.

Study Scope

This section of the report details the functional unit, system boundary, representativeness discussion, and life cycle impact assessment method.

Functional Unit of the Study

This work considers two functional units: MJ of liquid fuels based on lower heating value (LHV) (both naphtha and diesel are produced) and L of crude nutraceutical. The nutraceutical has potential applications in the food and pharmaceutical industries due to its high content of Omega-3 fatty acids and other beneficial compounds.

System Boundary

The system boundary is depicted in Figure 1. It begins with pumping flue gas to algae ponds. Algae grows and is converted to fuel products (biodiesel, naphtha), a solid waste (char), and a nutraceutical. Inputs to the system include electricity and hydrogen.

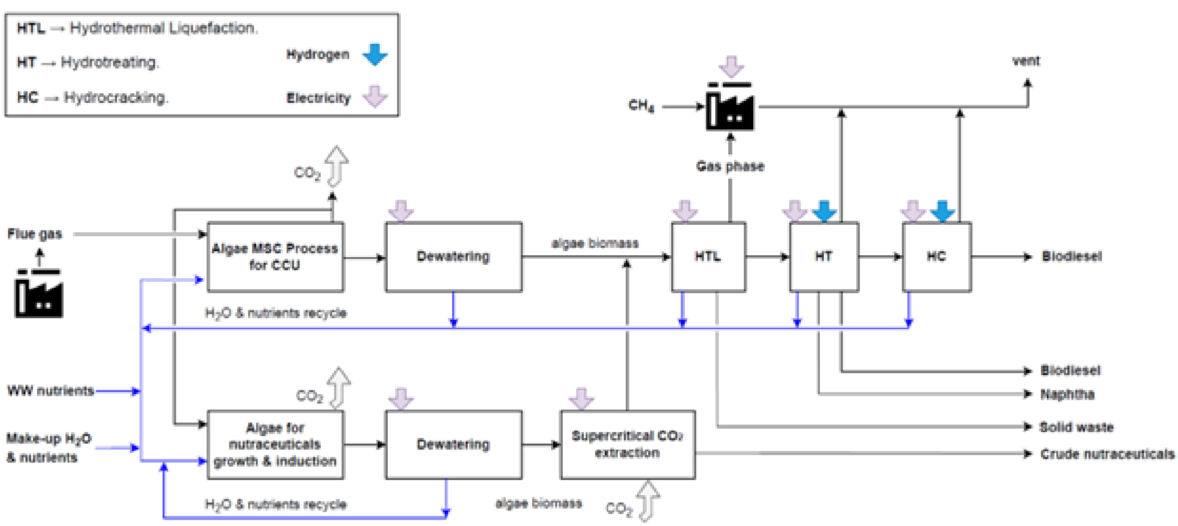


Figure 1. System Boundary

Carbon Dioxide Source and Utilization

The carbon dioxide source is power plant flue gas. The system captures carbon dioxide from the flue gas and grows algal biomass in the presence of sunlight. The algae then undergo a process that produces liquid fuels, crude nutraceuticals, and other potential products. The multi-stage continuous portion of the system exceeded project goals of 80% carbon dioxide efficiency and productivity of 25 grams per square meter per day.

Technology Representativeness

The technology incorporated into this analysis is representative of current technology, both in use at Helios, and in the broader algal fuel and nutraceutical industry.

Geographical Representativeness

While this analysis could be treated to represent a plant located anywhere in the U.S., we did evaluate the influence of electric grid in different sun belt states where algal growth is most promising. The sun belt states include Arizona, California, Florida, Georgia, Louisiana, New Mexico, North Carolina, South Carolina, Texas, and Virginia.

Life Cycle Impact Assessment Methods for Results Interpretation

We used the latest global warming potential (GWP) factors included in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) report. The following impact categories have been modeled and are included in this report:

> GWP (kg CO_2e), based on IPCC AR5, 100-year time horizon; accounting for carbon climate feedback; abbreviation: GWP-100

Completeness Requirements

No unit operations were omitted from the system boundary. Completeness requirements have therefore been met. Please see the system boundary diagram.

Sensitivity Analysis

Our sensitivity analysis emphasized the electric grid. We also included two functional units and two allocation procedures.

Life Cycle Inventory Analysis

Modeling Platform

We built a first principles model to determine the material and energy flows within the system of study. This model used Aspen Plus to evaluate the material and energy flows of the system and Python to extract the results. Emission factors for inputs and energy were extracted from the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model as it was released in September 2022.

Unit Process Description

Flue gas with 15% CO_2 is collected and transported from a coal power plant to algae wetted ponds.

Algae grows in closed multi-stage continuous units. This stream is then fed into a multi-stage continuous algae-based system that captures carbon dioxide from the flue gas. We selected the algae composition in Aspen Plus v 12 as in Figure 2 reports. The technology has demonstrated algae productivity of 25 g/m^2 per day with 80% carbon capture efficiency, applicable to a 5000-acre wetted pond. The algae grow in the presence of sunlight and additional carbon dioxide from the flue gas, which results in high productivity and capture efficiency. Once the micro algae reach a concentration of 0.5 g algae/L, it is harvested and undergoes a dewatering process to reduce its water content to 20%. The recovered water recirculates to the algae growth units to reuse remainder nutrients and minimize the feed of makeup water.

The resultant algae stream then enters a hydrothermal liquefaction (HTL) process, followed by hydrotreating (HT) and hydrocracking (HC), both of which use hydrogen. Finally, biodiesel and naphtha are produced. The feed to the HTL process is algae slurry. The reactor operates at 300 °C and 12 MPa. For processing 10,000 ton/day of algae slurry, 26 MW of thermal energy is required. This is obtained by burning CH_4 that the HTL process generates. 200,000 gal/day of biocrude oil are produced (700 ton/day) with an average heating value of 37.5 MJ/kg. In addition, the following by-products are generated: 110 ton/day of gas (>90% CO_2), 8910 ton/day of wastewater (11.5 g/L total N) and 280 ton/day of biochar. Nutraceuticals are extracted with supercritical CO_2 extraction.

ALGAE FOR NUTRACEUTICAL

	MIN	MAX
Protein	35	45
Lipids	3	5
Carbohydrate	25	30
Fiber	7	15

ASPEN PLUS V12

SP.		Units
FPROT	40	% mass/mass
FOIL	3	% mass/mass
FSUCR	15	% mass/mass
FGLUCAN	15	% mass/mass
FCELL	15	% mass/mass
FFAM	2	% mass/mass
FASH	10	% mass/mass

Figure 2. Algae composition in Aspen Plus Simulations

The data for the case study on liquid fuel and crude nutraceutical production was obtained from various sources, including experimental information from Helios-NRG, literature, and an open-source simulation developed on a commercial modular process simulator (Aspen Plus). Initial data was provided based on current ongoing experiments, and additional information for modelling the overall system, establishing fair assumptions, was obtained from the literature and the Argonne National lab database GREET 2022. To obtain high resolution information on flow rates, thermodynamic properties, and environmental indicators, the open-source simulation proposed by Chen and Quinn (2021) was utilized. This biorefinery simulation processes microalgae to generate liquid fuels, which is relevant to the case study on liquid fuel production. An additional simulation permitted to model the crude nutraceuticals extraction. The liquid fuels production was modeled using Predictive Soave-Redlich-Kwong (PSRK). The nutraceutical extraction was modeled using the non-random two-liquid (NRTL) model.
The process simulations were interconnected with a Python environment to accelerate information retrieval. Figure 3 illustrates the modeling framework. The interaction between Aspen Plus and Python relies on the Component Object Model (COM) implementation. Any language or application that supports COM can be used to read or write data within software packages. The connection between Python and Aspen Plus requires importing the library win32 in Python. This library allows OS Windows to open different applications and execute commands (Espinoza-Vasquez et al., 2023).

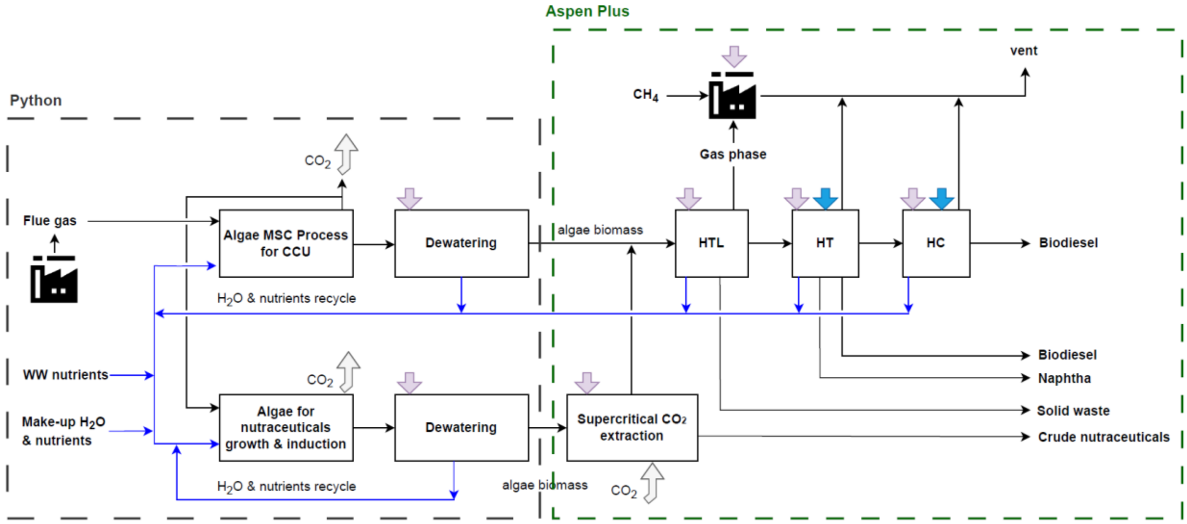


Figure 3. Process simulation strategy connecting Python and Aspen Plus.

The algae growth and dewatering sections were modeled in the Python environment mainly relying on yields and process efficiencies. Utilizing a combination of experimental, literature, and simulation data, the technological representativeness of the proposed product system was established.
The comparison product system corresponding technology representativeness was established by using GREET 2022 and literature values. Such emission levels permitted to set baseline cases.

Data Sources and Quality Assessment

This model described in Section 2.2 was grounded in a model reported by Chen and Quinn (2021). These authors report all relevant parameters and process modeling approaches. This model is suitable temporally (2021) and geographically (U.S.) to this project.
Based on this model we established all material and energy flows required to achieve biodiesel and nutraceutical production as depicted in the system boundary.
We extracted relevant GHG emissions for electricity and hydrogen from the GREET1_2022 model (Table 2). Other data were acquired from the following sources.

Table 1. Key parameters

Description	Value	Units	Source
Flue gas transport (15% CO_2)	0.143	kWh/kg CO_2	Tu et al. 2017
Water to site	0.000437	kWh/L	Davis et al, 2014
Culture to site	0.000025	kWh/L	Frank et al, 2011
DeAqua dewatering	0.129	kWh/gry kg algae (whole biomass basis)	Helios
DAF	0.133	kWh/gry kg algae (whole biomass basis)	Davis et al. 2014
Centrifuge	0.0193	kWh/kg-afdw out (afdw-ash free dry weight basis)	Tu et al., 2017
Super critical CO_2 extraction	12.9	MJ/kg algal oil	Tu et al., 2017

We compared LCA results for diesel against petroleum diesel, soy-based biodiesel, and algal biodiesel from the GREET model. We compared LCA results for nutraceuticals to the value Parker and Tydemers (2012) report of 7.1 kg CO_2e/L.

Table 2. Electricity emission factors for hydrogen and different electricity sources and in different Sun Belt States (GREET[1]_2022)

Parameter	Emission Factor
Life-cycle GHG emissions of hydrogen	9 kg CO_2e/kg H_2
Electricity from U.S. average grid	470 g CO_2e/kWh
Electricity from nuclear power plants	6.9 g CO_2e/kWh
Electricity from Wind energy	10 g CO_2e/kWh
Electricity from solar energy	40 g CO_2e/kWh
Electricity from AL grid	430 g CO_2e/kWh
Electricity from AR grid	600 g CO_2e/kWh
Electricity from AZ grid	480 g CO_2e/kWh
Electricity from CA grid	250 g CO_2e/kWh
Electricity from FL grid	530 g CO_2e/kWh
Electricity from GA grid	490 g CO_2e/kWh
Electricity from LA grid	580 g CO_2e/kWh
Electricity from MS grid	500 g CO_2e/kWh
Electricity from NC grid	440 g CO_2e/kWh
Electricity from NM grid	790 g CO_2e/kWh
Electricity from OK grid	490 g CO_2e/kWh
Electricity from SC grid	320 g CO_2e/kWh
Electricity from TN grid	460 g CO_2e/kWh
Electricity from TX grid	590 g CO_2e/kWh

Results of Inventory Completeness Check

We ensured that carbon and mass balances closed in the system model and therefore conclude that the completeness check is complete. Please see appendix for stream tables from the Aspen Plus model.

Results of Life Cycle Inventory Model Sensitivity Check

We checked sensitivity by applying different sources of electricity, two allocation approaches, and two functional units.

Allocation Procedures

This LCA considers two methodologies for coproduct allocation, displacement and process allocation. In the displacement method, the environmental burden of the production of the coproduct (crude nutraceutical oil) is allocated to the liquid fuel production process, as the main product. In the process allocation approach, the liquid fuel product (green dashed lines in Figure 4) and nutraceutical product (red dashed lines) each bear the GHG emissions associated solely with unit operations used to manufacture them.

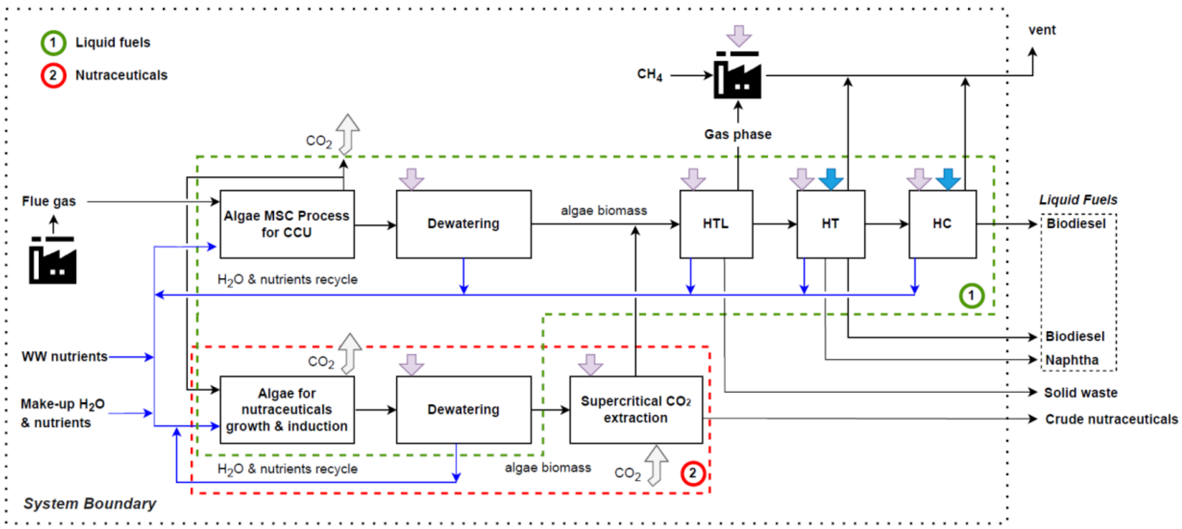


Figure 4. LCA diagram considering process coproduct allocation.

<u>Life Cycle Impact Assessment</u>

Data Quality Assessment

There are no known data limitations that would affect results.

Life Cycle Impact Assessment Results

When the displacement co-product handling technique is used (figure 5), life-cycle GHG emissions of the biodiesel produced from the Helios process (36 g CO_2e/MJ) fall below baselines of petroleum biodiesel (59% reduction), soybean biodiesel (71% reduction), and algal biodiesel (32%) when the average U.S. grid provides electricity. Petroleum-derived naphtha's life-cycle GHG emissions are 84 g CO2e/MJ. Naphtha derived from the Helios process therefore offers a 57% reduction in GHG emissions as compared to this fuel. Baseline fuel life-cycle GHG emissions are from the GREET1_2022 model. When a low-carbon electricity source is used (nuclear, solar, wind), the algal biodiesel outperforms all baselines. The major GHG emission sources are the combustion of the fuel (e.g., in an engine) and combustion of HTL-derived methane for process heat. CO_2 from both of these processes is biogenic and because the algae is a fast-growing biomass, we incorporate a biogenic carbon credit that offsets these CO_2 emissions. Aside from these emissions, use of electricity in the process and hydrogen consumption drive GHG emissions. When the grid is powered by renewable electricity, hydrogen consumption is left as the main GHG emissions source.

displacement credit is associated with nutraceutical production, which is produced in small amounts. Similarly, CO_2 sequestration from char if it is land applied is effectively negligible because char is produced in minimal quantities.

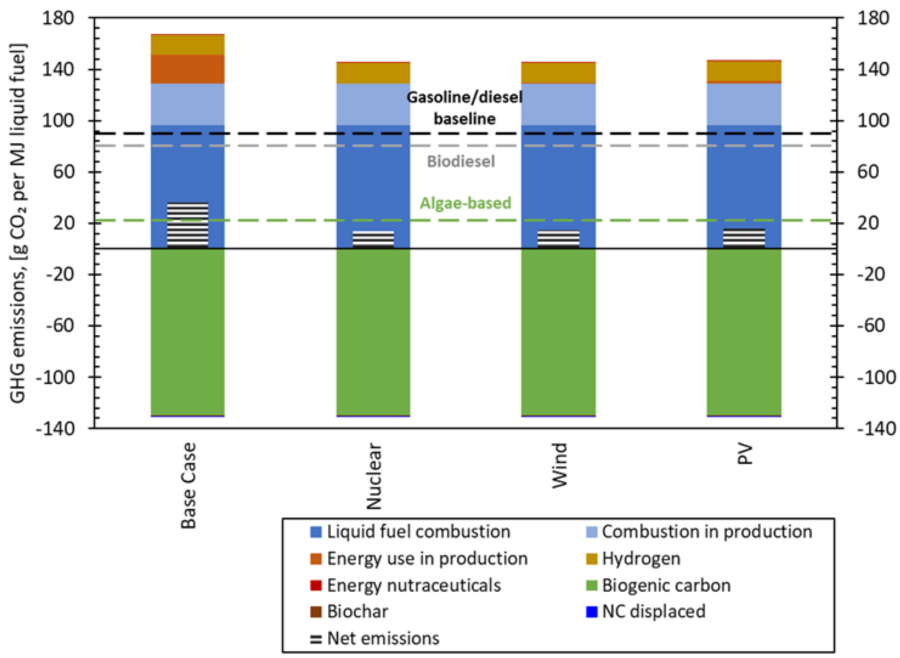


Figure 5. GHG emissions per MJ biodiesel when displacement co-product handling technique is used. Dashed lines represent results for comparator systems of petroleum-based diesel, soy biodiesel, and algal biodiesel in the GREET model. Net GHG emissions of the biodiesel produced fall below all of these baselines.

Life cycle GHG results were insensitive to choice of co-product handling methods. Co-product process-purpose based allocation results are presented in Figure 6 and are nearly identical to those in Figure 5.

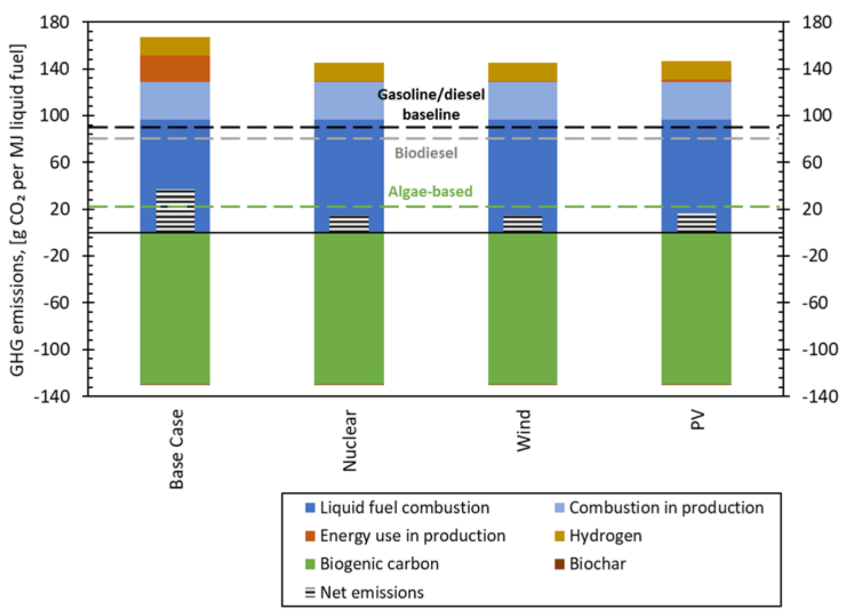


Figure 6. GHG emissions per MJ biodiesel when co-product process-purposed allocation technique is used. Dashed lines represent results for comparator systems of petroleum-based diesel, soy biodiesel, and algal biodiesel in the GREET model. Net GHG emissions of the biodiesel produced fall below all of these baselines.

Life-cycle GHG emission of the nutraceutical co-product when process-purpose allocation is used are presented in Figure 7. Net emissions are very low and well below the baseline of 7.1 kg CO_2e/L (Parker and Tyedmers 2012).

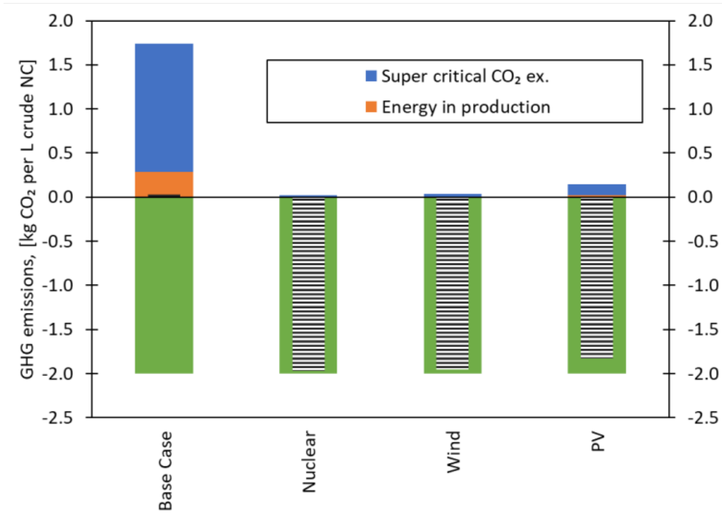


Figure 7. Life-cycle GHG results for production of nutraceutical based on process-level allocation

Life Cycle Interpretation

The main opportunities to improve the LCA results in this study are to obtain additional data from the Helios process regarding yield variations under different processing conditions. Additionally, as new information is published regarding life-cycle impacts of nutraceuticals, existing LCA results should be compared against this new information.

We have assessed the influence of electric grid on results as electricity consumption was a major results driver. We considered the grid in Sun Belt states where algae production is most likely given insolation. Emission factors are provided in Table 2. Results in California were most promising while algal fuel produced in New Mexico had GHG emissions nearly twice the algal fuel baseline (Figure 8). Results in Figure 7 also reiterate the insensitivity of results to co-product handling technique.

The main conclusion of this analysis is that the liquid fuels produced by Helios have the potential to achieve an over 50% reduction in GHG emissions from baseline liquid fuels.

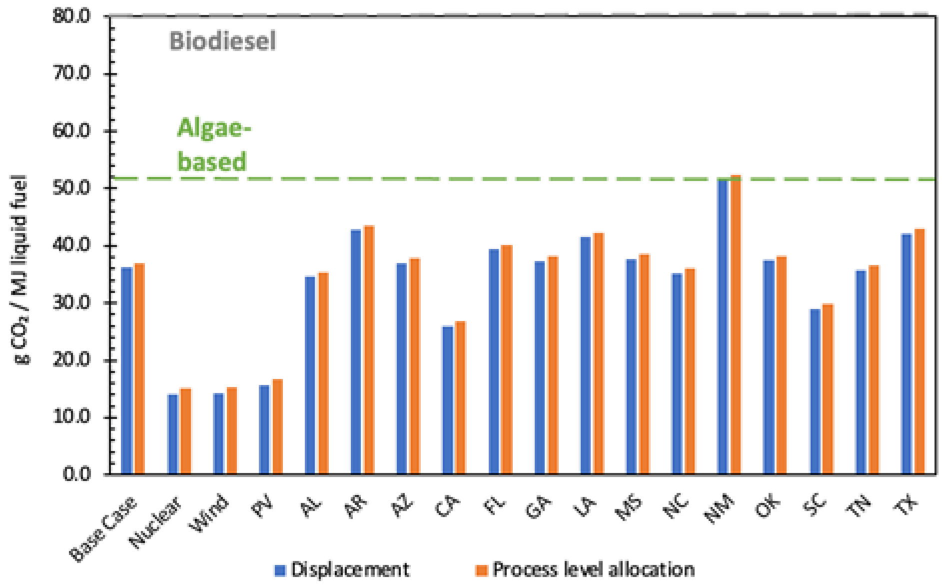


Figure 8. Results dependence on location given differences in electric grid. Differences in algae production were not considered.

Critical Review

The U.S. DOE Carbon Utilization Program will serve as the critical reviewer for this study.

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LCA Acronyms and Abbreviations:

atm	Atmosphere (14.696 psi)
bbl	Barrel
Btu	British thermal unit

CCS	Carbon capture and storage
CF	Capacity factor
CFR	Code of Federal Regulations
CH_4	Methane
cm	Centimeter
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
COE	Cost of electricity
DOE	Department of Energy
EIA	Energy Information Administration
EOR	Enhanced oil recovery
EPA	Environmental Protection Agency
FE	Fossil energy
FGD	Flue gas desulfurization
ft	Foot
gal	Gallon
GHG	Greenhouse gas
GJ	Gigajoule
gpm	Gallons per minute
h, hr	Hour
H_2	Hydrogen
H_2O	Water
Hg	Mercury
HHV	Higher heating value
hp	Horsepower
IEA	International Energy Agency
ISO	International Organization for Standardization
K	Thousand
kg	Kilogram
kJ	Kilojoule
kW, kWe	Kilowatt electric
kWh	Kilowatt-hour
lb	Pound
LCA	Life cycle analysis
m	Meter
M	Thousand
m^3/min	Cubic meters per minute
Mcf	Thousand cubic feet
mD	Millidarcy
MM	Million
mol%	Mole percent
MPa	Megapascal
MW, MWe	Megawatt electric

MWh	Megawatt-hour
N/A	Not applicable/available
N_2	Nitrogen
N_2O	Nitrous oxide
NEMS	National Energy Modeling System
NETL	National Energy Technology Laboratory
NG	Natural gas
NGCC	Natural gas combined cycle
NOAK	N^{th} of a kind
NOx	Oxides of nitrogen
O&M	Operation and maintenance
O_2	Oxygen
PC	Pulverized coal
ppm	Parts per million
PSFM	Power Systems Financial Model
psi	Pounds per square inch
psia	Pound per square inch absolute
psig	Pound per square inch gauge
R&D	Research and development
SC	Supercritical
scf	Standard cubic feet
SO_2	Sulfur dioxide
SOA	State of the art
SOx	Oxides of sulfur
tonne	Metric ton (1,000 kg)
U.S.	United States
°C	Degrees Celsius

Task 9: Techno-economics Analysis

Executive Summary:

The techno-economic analysis is based on a future commercial system covering 5000 acres of wetted area. The system consists of parallel MSC units, with each MSC stage comprising a 10-acre raceway featuring an inexpensive plastic top cover. This innovative design ensures minimal contamination, water evaporation, and facilitates efficient CO_2 capture. The financial and operating assumptions used in this analysis closely align with DOE's 2022 projections for algae technology in CO_2 capture and Utilization, as detailed in later sections.

For the baseline case, we considered an annual average algae productivity of 25 g/m2/day, based on measured MSC system performance in outdoor operations at the National Carbon Capture Center. At this productivity level, the 5000-acre algae farm would produce approximately 187,000 tons of dry algae per year, capturing around 350,000 tons of CO_2 annually. The CO_2 required for the operation is obtained directly from post FGD flue gas from a coal power plant, without the need for purification. We assume a 90% utilization of the by algae. The culture is harvested and dewatered, with 99% of the water removed being recycled back for algae growth. Based on our previous work, we assume a 75% nutrient replacement from wastewater.

The produced algae serves as the raw material for three types of products, all of which have existing markets, generating revenue and mitigating business risks associated with fluctuations in product prices. Products envisioned include biofuels, feed and nutraceuticals. Additionally, there is potential for revenue from credits obtained through wastewater remediation and CO_2 capture. However, the base case assumes no credits from either of these sources, and the sensitivity analysis explores their potential impact.

The estimated net cost of algae production for the base case is slightly below DOE's 2022 projection of $494/ton. This reduction is primarily attributed to cost savings from using wastewater nutrients, employing flue gas instead of purified CO_2, and advancements in dewatering technology. Notably, the productivity of algae has the most significant impact on production costs: a 30% increase in productivity reduces costs by approximately $90/ton of algae, while a 30% decrease in productivity results in production costs increasing by about $160/ton. The sensitivity analysis explores other variables.

The total revenue generated for the base case is estimated to exceed the cost of algae production. This positive result indicates that product generation has the potential to enable cost-neutral operation, thereby facilitating large-scale CO_2 capture. The sensitivity analysis further highlights the impact of variations in key revenue and credit-related metrics. Particularly, remediation credits from wastewater can be substantial, making the profit motive even more compelling. Moreover, significant added revenue potential lies in optimizing the product profile.

In conclusion, the current work suggests the potential to achieve cost-neutral carbon capture. With further improvements, carbon capture could transform into a net profitable business proposition, incentivizing large-scale adoption without relying on legislative credits.

Basis for Analysis:

Table 10 summarizes the basis for the techno-economic assessment performed for the CO_2 capture and utilization technology developed in this project.

Table10: Basis for Analysis

Pond (Raceway) size (acres)	10
Wetted pond area (acres)	5000
Total Area of facility (acres)	7600
Land cost ($/acre)	3000
Pond Cost ($/acre)	31700
Water recycled	99%
% nutrients from waste water	75%
% nutrients purchased	25%
CO2 utilization	90%
CO2 Type	Flue Gas
Operating days /year	330
Facility Life yrs	30
Electricity price (c/kWh)	6.8
Net dewatering efficiency	99%
Algae conc after dewatering (g/L)	Product dependent

To the extent possible, the assumptions used here are the same those used in DOE's 2022 projections for algae technology for CO_2 capture and Utilization[1,2]. This recognizes the high quality of work and the depth of analysis inherent in that extensive work, but is also intended to enable easier comparisons with the results presented therein.

Production of Algae Biomass:

Carbon capture and algae production is carried out using the MSC system developed in this project. Each stage of the MSC is comprised of a raceway with an inexpensive plastic top cover to minimize contamination, water evaporation and enable high CO_2 capture. For purposes of the TEA, each raceway is assumed to be 10 acres in size (670m long x 30m channel width) with a paddlewheel to circulate the culture. The pressure in the headspace above the culture is nominally ambient and hence the plastic cover is not a loadbearing element. The power required for paddle wheel operation is ~12kW per raceway. Work at Helios-NRG in ongoing and prior DOE projects has demonstrated the ability to replace up to 90% of the nutrients required to grow algae from municipal waste water sources. Nutrients from municipal waste water is expected to a be an attractive source for culturing algae since there~17,000 waste water treatment plants in the US and the N and P compounds in waste water must be removed prior to discharge into the environment. The centrate stream produced by the waste water treatment plants, which is concentrated in N and P, represents a valuable source of nutrients for algae. In the present analysis 75% nutrient replacement from waste water is assumed.

[1]Multi Year Program Plan, March 2016, Bioenergy Technologies Office, EERE|US DOE
[2] "Process Design and Economics for the Production of Algal Biomass", Ryan Davis et al, NREL|US DOE, Feb2016

The CO_2 required for the operation is obtained directly from post FGD flue gas from a coal fuel power plant - the basis for the current project. This is different from the earlier DOE work[2] wherein the CO_2 is purified at the power plant and supplied to the algae growing operation. In the base case the algae farm is assumed to be located near the plant. Linde, who is a partner in this project, has carried out a detailed analysis to estimate the cost of transporting the flue gas via pipeline to the culturing site for various distances. Their analysis included the cost of the pipeline, flue gas compression as well as the cost of using Linde's proprietary Solvocarb™ technology (used in waste water systems) for gas injection into the culture. In the sensitivity analysis, shown later, we have incorporated Linde's work to illustrate the added cost of transporting the flue gas various distances to the algae farm. In the analysis we have used the gas dispersion technology currently used in our MSC systems. 90% utilization of the CO_2 from flue gas by algae is assumed based on the performance achieved in this project. The culture harvested is dewatered using different technologies as follows based on the requirements of the final product (Table 11).

Table 11: Algae dewatering for different products

Product	Dewatering Technology	Algae Product	Rationale
Bio-fuel	Enhanced gravity settling + Membrane	Slurry	Low energy, Low cost
Feed	Membrane dewatering + continuous centrifuge	Slurry	Purity, Cost
Nutraceutical	Continuous Centrifuge + drying	Dry biomass	Highest purity

Based on the advances made in this project, this technology is estimated to reduce the cost of dewatering by ~$8/ton-algae for the product mix envisioned. The water removed is recycled back to the algae growing operation and 99% recycle is assumed in current analysis.

Perhaps the most important parameter influencing algae economics is the productivity of the system. The present analysis is hence based on a summer productivity of 35 g/m2/day and we have estimated the productivity during other seasons to reflect the variation in duration and intensity of sunlight available. At the assumed level of productivity, the 5000 acre algae farm would produce ~187,000 tons-dry algae/yr and capture ~350,000 tons- CO_2/yr.

The facility was assumed to have a 90% onstream factor and a useful life of 30 years. Equity financing of 40% of total investment is assumed with an Internal Rate of Return of 10%. The loan is assumed to be for 10 years at an interest rate of 8%. In addition to the annual capital related charges, there are operating costs such as for electricity, water, nutrients and labor to run the facility. The present analysis assumes a total staff of 100 people comprised of a plant manager, 4 engineers and a variety of personnel for operation, maintenance and site support. All the labor and most of the electricity represent fixed costs that are independent of algae productivity. Hence the total annual cost to operate the facility is to a great extent independent of algae productivity. However, the total algae biomass produced per year depends directly on productivity. For this reason, as shown later, the cost of algae production is very sensitive to algae productivity.

<u>Product Revenue and Credits:</u>

The present analysis assumes that the algae is used to generate the following three products with existing market needs.

- Biofuels –The price at which algae can be sold into this application depends on the desired biofuel price which is market dictated. The baseline case assumes a biofuel price of $3/GGE.
- Animal Feed – The high levels of protein, lipid and other compounds (e.g. carotenoids) in algae makes it attractive for blending into animal feeds. The value of algae in these applications depends on both the nutritional profile of the algae as well as the price point of the blended feed.
- Nutraceuticals – The algae selected for this market segment contains high levels of valuable components such as anti-oxidants, omega fatty acids, polysaccharides etc. These are characterized by very high current market prices ranging from $200-2000/kg of product.

In addition to product-based revenue, there is potential for credits from at least two sources:

- Waste Water Credits: Waste water treatment plants incur significant costs to remove nitrogen and phosphorous compounds down to mandated levels prior to discharge. Based on data from a number of municipal waste water treatment plants around the country, researchers at University of Illinois at Urbana Champaign have estimated that the value of the removal of N and P from municipal waste water by algae to be in the range of $210-600 $/ton-algae DW.
- CO_2 Capture Credits: At present there is no CO_2 capture credit in the US and future credits are speculative. For this reason, the base case does not include any CO_2 capture credit. However, a case with a capture credit of $20/ton- CO_2 is used in the sensitivity analysis for illustration.

Base Case Economics:

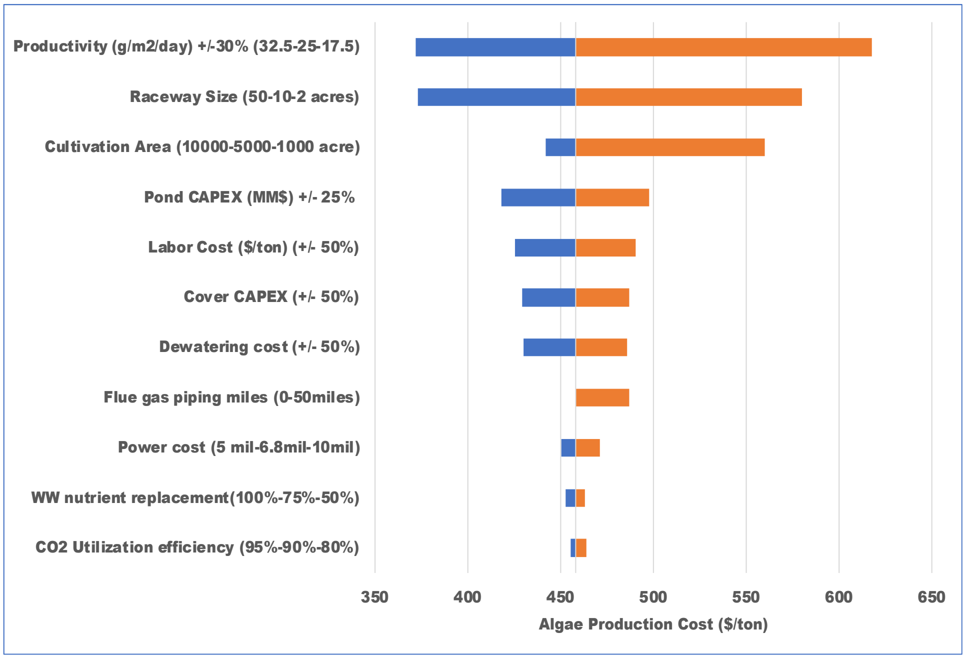

Figure 18: Tornado Diagram: Sensitivity of Algae Production Cost

Figure 18 depicts the sensitivity of algae production cost to several key parameters. The most important factor by far is algae productivity. Increasing the average annual algae productivity by 30% to 32.5 g/m2/day lowers the production cost by ~$90/ton. Conversely a 30% lower productivity than the base case increases the production cost significantly to ~$620/ton. The size of the pond is another important variable. A wetted area of 2 acres, typical of current state of the art, would increase the algae production cost to ~580/ton while using 50 acre ponds, which represents new learning, would reduce production cost by ~$85/ton.

The use of a much smaller farm (1000 acres) increases production cost substantially to ~$560/ton because many of the labor and infrastructure costs are not proportionally reduced in a smaller facility. Conversely, going to a 10,000 acre farm only reduces the algae cost modestly by ~$16/ton. This indicates that the 5000 acre base case provides useful perspective on the economics of a much larger facility as would be required for instance for a 500MW power plant. Transporting the flue gas by pipeline a distance of 50 miles adds ~$30/ton to the cost of algae. The product cost sensitivity to the cost of the top cover, a new feature introduced in this project, is indicated to be modest. Similar is the case for dewatering cost, degree of CO_2 utilization and the fraction of nutrients obtained from waste water.

Waste water credit has the biggest impact and the use of algae for the removal of nitrogen and phosphorous from municipal waste water treatment plan can greatly increase net revenue. Nutraceutical production has significant impact on revenue potential - multiple products makes this an attractive proposition. While the biofuel price can vary significantly due to market factors, at even at a relatively low-cost price of $2/GGE, the net revenue from products can offset 90% of the cost of capture. The ability to make multiple products, reduces the business risk to revenue potential from disruption in any one market. In commercial operation this will be an important factor in developing a viable business proposition. For reasons discussed earlier, CO_2 credits are not used in the base case. However, at the $180/ton currently discussed, this can be a significant added benefit.

Summary

The Helios-NRG technology for converting coal-based flue CO_2 into valuable products has been successfully validated through a series of rigorous test programs. The key component, the MSC (Multi Stage Continuous System), played a pivotal role in this process. The MSC's various stages were seamlessly integrated and controlled by a second-generation automated system, surpassing project goals in terms of both algal productivity and capture efficiency. Notably, the MSC's operational duration improved while maintaining healthy cultures.

The integrated system was rigorously tested under real outdoor conditions with varying sunlight levels and template flue gas. The final MSC test, conducted at the NCCC, successfully met project objectives.

Two species of algae were validated to produce at least one valuable product, each with an average value of $700 per kg. The production process saw continuous enhancements to improve culture health, growth rates, scale-up, induction, extraction, and overall nutraceutical content.

Advancements were also made in the dewatering technology. Stage 1 exceeded project targets for both carbon capture species and nutraceutical algae. A module with anti-fouling membranes (representing stage 2) was developed and tested. This technology achieved an impressive ~98% water recycling rate and reduced overall costs by 50%, addressing two significant obstacles in the commercial use of algae-based technology: high fresh water usage and dewatering costs.

A life cycle assessment (LCA) revealed that the Helios-NRG algae-to-biofuel conversion process results in a greater than 50% reduction in greenhouse gas emissions compared to petroleum products and soybean biodiesel. This reduction increases by an additional ~50% when utilizing low-carbon electrical generation sources like photovoltaic, wind, or nuclear power instead of the average US grid electricity.

Finally, a techno-economic analysis (TEA) highlighted that algae technology's two main cost drivers are algae productivity and the size of algae raceways. The use of covered raceways in the Helios system enables a high productivity of >25 $g/m^2/d$ and near 90% capture efficiency. With product revenue and projected waste water credits, the net cost of this technology falls below the Department of Energy's nominal cost target of <$30/ton-$CO_2$, especially in expected operational sites near fossil fuel power plants and numerous municipal wastewater treatment facilities in the southern US.