Phase1 Final Technical Report

DOE Award: DE-SC-0017077

Project Title : **Novel Algae Technology for CO2 Utilization**

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Period Covered : 2/21/2017 - 11/20/2017

Report Date : 12/4/2017

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Public Summary
Non-Confidential

The United States, the world's largest energy user and second largest CO_2 emitter, is heavily dependent on fossil energy. In 2014, CO_2 emissions from US coal burning power plants was ~ 1562 MM tons/yr, accounting for 76% of the total US power sector emission[1]. Hence, reducing the CO_2 emission footprint from coal plants is widely viewed as a key element in mitigating global warming. Despite significant interest, implementation of CO_2 capture technologies have been hamstrung by high capture costs which significantly increases the cost of electricity.

In this project, supported by a SBIR grant from the US DOE, Helios-NRG in collaboration with the State University of New York at Buffalo (UB) aims to develop a novel, algae based technology to capture CO_2 from coal based power plants and convert it to renewable bio-fuels and other higher value co-products. The use of algae to capture CO_2 and subsequently utilize it to produce products has the promise to enable substantial reductions in the net cost of carbon capture.

The Phase 1 project was aimed at demonstrating technical feasibility of critical components of the proposed concept in the presence of some key flue gas contaminants and advancing the technology. The project is now complete and all the project objectives were met or exceeded. The contaminants in typical flue gas streams post-FGD, including heavy metals, were quantified. The CO_2 levels in this stream is ~12% which is much hgher than the ambient concentrations that all algae have evolved on. In addition this stream contains ~75ppm SOx, 75ppm NOx and small amounts of a large number of heavy metals. Phase 1 demonstrated the ability of two preferred strains of algae to survive and grow in simulated flue (CO_2, SOx, NOx) as well as three of the most toxic heavy metals.These strains were selected based on their suitability for the flue gas enviroment and potential for high carbon capture. These species were then used in carbon capture tests using existing photo bireactors to simulate a new process. The target CO_2 capture efficiency of 70% was exceeded in these tests and stable operation demonstrated. Technology for a new dewatering technology called DeAqua was advanced. This can potentially reduce both the cost and energy for the critical dewatering step. The algae used in the carbon capture tests were shown to contain a number of valuable co-products.

Data obtained in the tests were used to simulate operation of the new process at high carbon capture efficiency. A reasonable set of design and operating conditions were identified that can achieve 90% CO_2 capture from the post FGD flue gas stream. Preliminary economic analysis was performed for CO_2 capture from a 550MW supercritical power plant burning sub-bituminous coal. The results showed the potential of the proposed technology to significantly reduce the cost of CO_2 capture compared to current options. The results showed that the utilization of the CO_2 captured to generate high value products can make a step change in the cost of carbon capture.

Plans to advance the technology in Phase II were developed and potential partners identified.

1. Executive Summary (Confidential):

The United States, the world's largest energy user and second largest CO_2 emitter, is heavily dependent on fossil energy. In 2014, CO_2 emissions from US coal burning power plants was ~ 1562 MM tons/yr, accounting for 76% of the total US power sector emission[1]. Hence, reducing the CO_2 emission footprint from coal plants is widely viewed as a key element in mitigating global warming. Despite significant interest, implementation of CO_2 capture technologies have been hamstrung by high capture costs which significantly increases the cost of electricity.

In this project, supported by a SBIR grant from the US DOE, Helios-NRG in collaboration with the State University of New York at Buffalo (UB) aims to develop a novel, algae based technology to capture CO_2 from coal based power plants and convert it to renewable bio-fuels and other higher value co-products. The use of algae to capture CO_2 and subsequently utilize it to produce products has the promise to enable substantial reductions in the net cost of carbon capture.

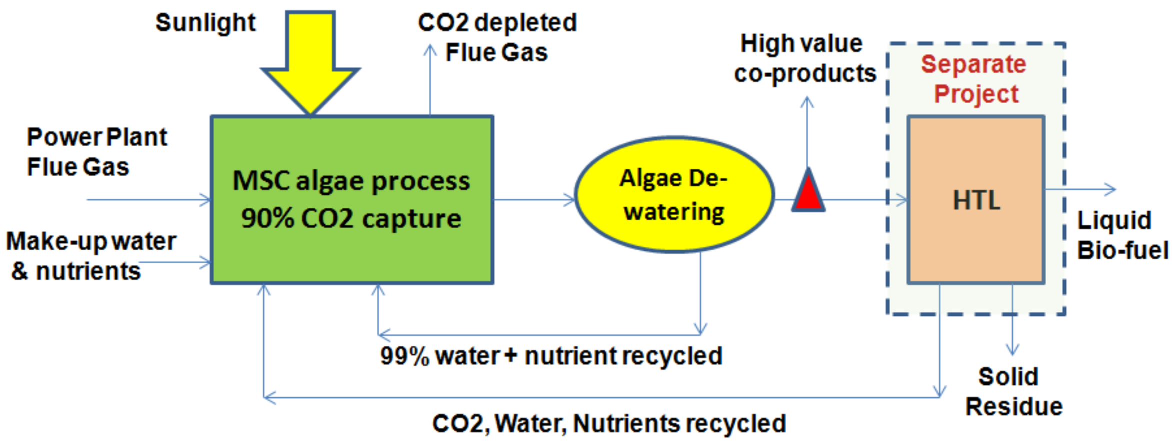

Figure 1: Schematic of Carbon Capture and Utilization Process

A schematic of the overall scheme is shown in Fig 1. Flue gas, after de-sulfurization, enters a multi-stage, continuous flow (MSC) photo-bioreactor (PBR) process where 90% of the incoming CO_2 is captured and used beneficially to accelerate the growth of algae. The algae culture leaving this process is de-watered using a new technology called DeAqua, being developed by Helios-NRG together with UB, to produce an algae slurry with a solids loading ~25% wt at much lower cost than state of the art. Over 99% of the culture media is separated out in this step and recycled back to the PBR thus greatly reducing the fresh water and nutrient requirements.

Most of the algae leaving this stage is utilized in the Hydro Thermal Liquefaction (HTL) process to produce bio-crude oil. The HTL conversion of algae was validated in an earlier DOE funded SBIR project and is not part of this project. The CO_2, water and nutrients from this step are recycled to the PBR to reduce water and nutrient requirements. In addition, high value co-products are extracted from a small slip stream of the dewatered algae.

Unique features of the proposed technology which will enable a step change in carbon capture costs are as follows:

- The MSC process enables high CO_2 capture efficiency (~90%) at high algae productivity which, to our knowledge, has not been simultaneously achieved

- The continuous flow MSC process permits steady state operation wherein the productivity, concentration and capture efficiency are invariant with time - a feature not achieved in traditional operation.
- The algae is de-watered using a low cost technology and the resulting slurry fed directly into the HTL thus eliminating the cost and energy requirements for drying.
- The bio-crude produced can be used in existing refineries and significantly lowers carbon capture costs.
- Generation of higher value co-products such as nutraceuticals and animal feed can reduce carbon capture costs further.

The Phase 1 project was aimed at demonstrating technical feasibility of critical components of the proposed concept in the presence of some key flue gas contaminants and advancing the technology. The project is now complete and all the project objectives were met or exceeded. The contaminants in typical flue gas streams post-FGD, including heavy metals, were quantified. The CO_2 levels in this stream is ~300x of the ambient concentrations that all algae have evolved on. In addition this stream contains ~75ppm SOx, 75ppm NOx and small amounts of a large number of heavy metals. Phase 1 demonstrated the ability of two preferred strains of algae to survive and grow in simulated flue (CO_2, SOx, NOx) as well as three of the most toxic heavy metals - As, Se and Hg.

Species H-1903, which appeared to be slightly advantaged in the species selection task, was used in tests to mimic the operation of a 3-stage MSC process in carbon capture in the presence of the three heavy metals. Since the design and operation of the MSC is well beyond the scope of Phase1, three single stage, batch PBR's were used to replicate the conditions in the different stages of the MSC to achieve 70% capture efficiency. The test conditions corresponding to CO_2 capture were established using a Helios-NRG proprietary model developed prior to the project. The results were highly encouraging and >80% CO_2 capture efficiency was measured in the presence of heavy metal contaminants which exceeded the Phase1 goal of 70% capture. In addition, both the algae concentrations and the CO_2 capture efficiency in each stage was shown to be stable over time - critical features of the new MSC process.

Significant progress was made in advancing the DeAqua technology. This project focused on advancing the technology for the first two stages of the DeAqua process. The viability of using a continuous gravity table for the first stage of DeAqua was demonstrated and concentration ratios in the range of 2.-3.5x were achieved. The key objective for the second stage was to develop robust high-performance membranes for micro-algae dewatering. Commercial membranes suffer from fouling and thus water permeance decreases dramatically with time. It was demonstrated that the commercial membranes can be co-deposited using bio-adhesive polydopamine (PDA) and superhydrophilic graphene oxide (GO) or poly(ethylene glycol) diamine (PEG) to increase antifouling properties and thus water permeance for algae dewatering. When challenged with solutions containing algae from 0.5 g/L to 35 g/L, the modified membranes show water permeance 10-50% higher than the virgin one. Water permeance meeting or significantly exceeding the Phase1 target of 40 LMH/bar was demonstrated. Two approaches have been identified for the module design to achieve high dewatering performance: post-modification of commercial modules, and design and fabrication of plate-and-frame modules with optimized components.

Co-production of nutraceuticals is expected to be highly beneficial in reducing carbon capture costs. Five valuable nutraceuticals, including astaxanthin and β-carotene, were found to be present in the algae species used for carbon capture from the simulated flue stream containing

12% CO_2. It is expected that their concentrations and production rate can be increased through species selection and process refinements in the future.
Preliminary economic analysis was next performed for 90% CO_2 capture from a 550MW supercritical power plant burning sub-bituminous coal. Since photosynthesis is driven by sunlight, the analysis assumes the carbon capture occurs during 14 hours/day of natural sunlight. Details of the economic analysis are provided below under Task 5.

The results show that CO_2 capture with MSC with HTL for bio-crude production and co-production of nutraceuticals can lower ***the net cost of capture to $3-23/ton CO_2.*** Although these numbers are preliminary, they clearly show that the utilization of the CO_2 captured to generate high value products is the key to making a step change in the cost of carbon capture.

Table 1 summarizes the actual accomplishments against the original goals for each of the primary objectives.

Objective	Original Goal	Actually Achieved
1	Identify at least one algae species capable of tolerating the contaminants in coal derived flue gas including heavy metals	Two suitable algae species identified
		Ability to grow in 12% CO2, 75ppm each SOX & NOX demonstrated
		Growth in simulated flue gas with Hg, Se, As demonstrated
	Achieve high CO2 capture from simulated flue gas with Heavy Metals	MSC tests with 1-stg PBR's successful
		>70% CO2 capture efficiency achieved in simulated MSC tests
2	Advance the DeAqua technology for dewatering algae	Continuous gravity table with 2-3.5x concentration enhancement demonstrated
		New de-watering membrane with super-hydrophilic coating developed
		Reduced fouling rate and higher stable flux >200 LMH/bar achieved
		Conceptual module design developed
3	Validate high value nutraceutical synthesis by the algae	Presence of several high value cartenloids including lutein, β-Carotene, zeaxanthin, and astaxanthin verified in algae grown on simulated flue gas
4	Conduct preliminary process and economic analysis	DeAqua economics updated and TEA completed
		CO2 capture cost with algae without products estimated at $72-92/ton
		Co-production of bio-fuel via HTL + nutraceuticals estimated to lower the net CO2 capture cost to $3-23/ton

Table 1: Actual accomplishments vs Initial Goals **(Confidential)**

2. Detailed discussion of work and accomplishments by task:

Task 1 Select algae species best suited for contaminants in flue gas

Subtask 1.1 Define flue gas contaminants including heavy metal and select critical ones

The objective of this task is to determine contaminants present in the gas stream from a coal power plant which might be detrimental to algae. Flue gas varies in its gas composition based on the source of bituminous pulverized coal (PC) and the treatment process implemented at the power plants. The gas stream of most interest is post flue gas desulfurization (FGD) which typically contains ~12% CO_2 (300x of ambient).

In flue gas from coal power plants SOx and NOx are typically identified as the major contaminants present while heavy metals and organics are identified as minor contaminants. Table 2 summarizes typical flue gas compositions for subcritical and supercritical PC power plants post flue gas desulfurization respectively while Table 3 summarizes a typical case for heavy metal concentration in the post FGD stream. In the Phase I project, emphasis was placed on the minor contaminants (heavy metal) for their impact on algae cultivation instead of the major acid gas contaminants (SOx and NOx) as they have been investigated in a prior project (DE-SC-0015719). The selection of heavy metal for the Phase I project were based off their respective toxicity level based off the Permissible Exposure Limit (PEL) measured for humans due to the lack of available data measured for aquatic life. It is important to note that the PEL levels measured for humans will likely vary from that for aquatic life.

Case	Subcritical PC (Case B11A)	Supercritical PC (Case B12A)
V-L Mole Fraction	**Post FGD**	**Post FGD**
Ar	0.82%	0.82%
CO2	12.88%	12.88%
H2	0.00%	0.00%
H2O	14.51%	14.51%
N2	68.54%	68.54%
O2	3.25%	3.25%
SO2	76.5 ppm	76.5 ppm
Nox	76.5 ppm	79.7 ppm

Table 2: Typical flue gas compositions for coal-fired power plant[1]

Metals	Conc (ppb)	PEL (mg/m^3)
As	78.9	0.01
Cd	15.2	0.10
Co	16.2	0.10
Cr	131.5	0.5-1
Cu	132.5	1.00
Hg	10.1	0.10
Pb	54.6	0.05
Ni	252.9	0.50
Se	10.1	0.20
Zn	445.0	5.00

Table 3: Typical heavy metal compositions for post FGD stream[2]

Subtask 1.2 Study impact of flue gas heavy metal contaminants

The objective of this task is to systematically investigate the survival and growth of selected algae species in the presence of selected heavy metals present in post FGD flue gas. Arsenic (As), Selenium (Se) and Mercury (Hg), were selected for this study because coal burning power plants are majority source of these elements in air pollution in the US. Due to inaccessibility of coal-fired flue gas streams for the Phase I project, the selected heavy metal contaminants were added via solution as soluble salts into the algae photobioreactors (PBR). High pressure cylinders of industrial grade CO_2 were procured from Praxair and blended with air to obtain the simulated flue gas stream post FGD for algae cultivation experiments. A test facility with timed light chambers to mimic day/night setting, gas distribution panel and photobioreactors (PBRs) was used for experimental purposes. Two microalgae species (H-1903 and H-0322) were chosen for the contaminant studies. Table 4 outlines the test matrix for studying the impact of the heavy metal contaminants on algae survival.

Test Series	Flue Gas Stream	Algae	Heavy Metal	Metal Conc (ppb)
1	Post FGD	H-1903	As	0
				25
				50
				75
2	Post FGD		Se	0
				5
				10
3	Post FGD		Hg	0
				5
				10
4	Post FGD	H-0322	As	0
				25
				50
				75
5	Post FGD		Se	0
				5
				10
6	Post FGD		Hg	0
				5
				10
7	Post FGD	H-1903 H-0322	As, Se, Hg	75, 10, 10

Table 4: Impact of heavy metal contaminants on algae cultivation test matrix (Confidential)

Systematic studies of adding flue gas to algae cultures and measuring the amounts of heavy metals soluble in the solution and available to effect the the selected algae strains have not been documented, and therefore require detailed investigations to assess their impact on algae growth. The heavy metals were introduced into the algae cultures as fully soluble salts (sodium arsenite, sodium selenite, and mercury (II) chloride). The concentration of these highly soluble heavy metal salts in the algae culture represent the most extreme case as most of the heavy metals present in actual flue gas are typically of a non-soluble chemical form. This is likely to result in the concentration levels introduced to be much higher than resulting from actual flue gas. The individual heavy metal contaminants concentration was increased in steps to determine their impact on algae growth, the cutoff concentration at which growth is inhibited and to determine if additional pretreatment is required to lower the concentrations in flue gas before delivery into algae cultures.

The step-wise addition of individual heavy metal species into the algae cultures was carefully monitored as these cultures were used in later experiments. It is essential to maintain healthy cultures free of infection with microorganisms as these accumulate in batch operated cultures and reduce the overall algae growth due to competition for nutrients and growing space. To ensure reliability and consistency the PBRs and all accessories were sterilized with chemicals or heat prior to use. Alternative methods such as UV sterilization of feed culture media, which are more cost effective for large scale operations, will be explored in a future phase.

Growth rates of control (only 12% CO_2) and experimental cultures (individual heavy metal at various levels) were monitored daily via cell density measurements using a spectrophotometer. Due to the batch PBR operation, the heavy metals were added until a steady state concentration corresponding the incoming flue gas stream was achieved. The test series as indicated in Figure 2(a) and 2(b) shows the algae growth comparison over time with 12% CO_2 (control) and 12% CO_2 + 25ppb As respectively. As a first approximation, the algae growth for both control and experimental cultures are similar despite small discrepancy between some points (likely due to measurement error)

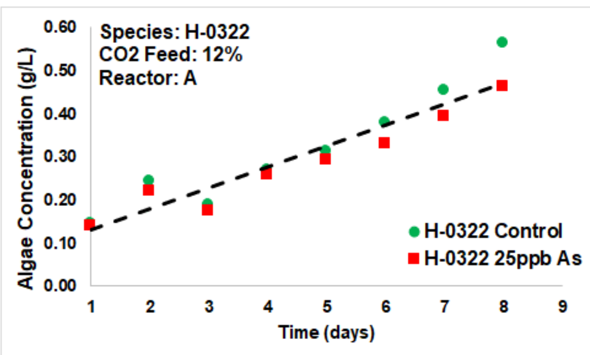

Figure 2(a): Impact of 12% CO_2 and 12% CO_2 with 25ppb As on H-0322 growth (Confidential)

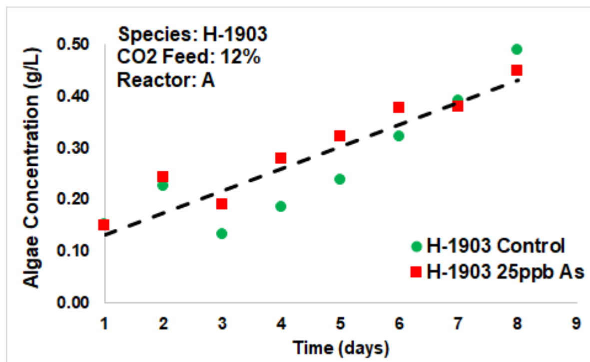

Figure 2(b): Impact of 12% CO_2 and 12% CO_2 with 25ppb As on H-1903 (Confidential)

The concentration of As was next increased to 50ppb followed by 75ppb (representing the highest level reported in Table 4) with 12% CO_2 for both H-0322 and H-1903 algae cultures. The growth results are highly encouraging, demonstrating the potential for algae survival at the As levels expected in post FGD stream.

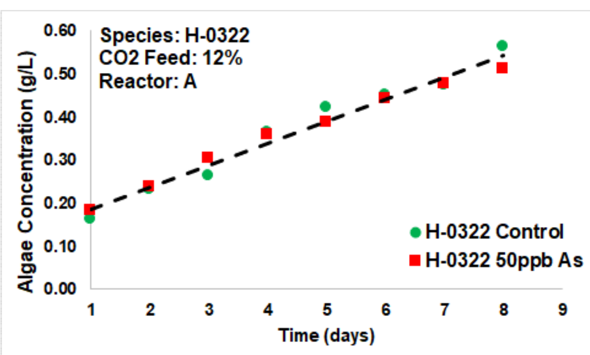

Figure 3(a): Impact of 12% CO_2 and 12% CO_2 with 50ppb As on H-0322 growth (Confidential)

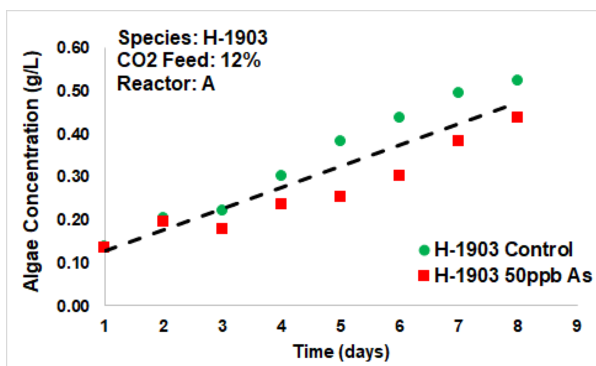

Figure 3(b): Impact of 12% CO_2 and 12% CO_2 with 50ppb As on H-1903 (Confidential)

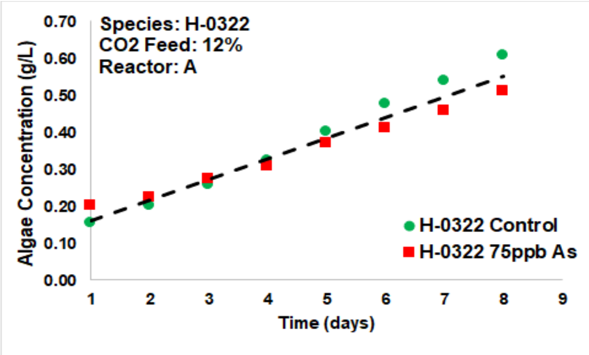

Figure 4(a): Impact of 12% CO_2 and 12% CO_2 with 75ppb As on H-0322 (Confidential)

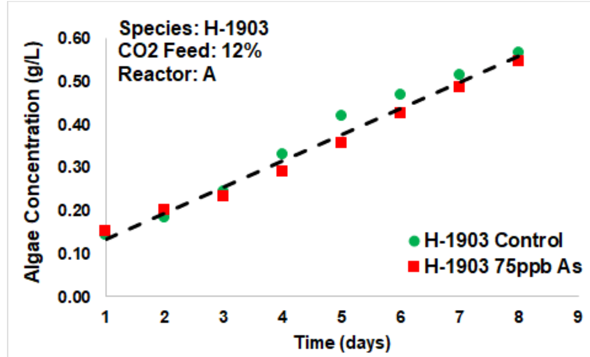

Figure 4(b): Impact of 12% CO_2 and 12% CO_2 with 75ppb As on H-1903 (Confidential)

The next set of tests were aimed at determining algae survival with Selenium at 5ppb and 10ppb Se levels, representative of the highest-level present in flue gas. The results are shown in Figure 5 and 6 respectively. Comparison between both control and experimental growth curves for both species are highly encouraging and shows survival with Se contaminant.

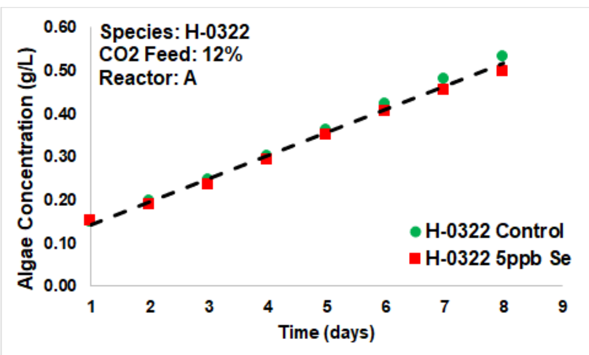

Figure 5(a): Impact of 12% CO_2 and 12% CO_2 with 5ppb Se on H-0322 (Confidential)

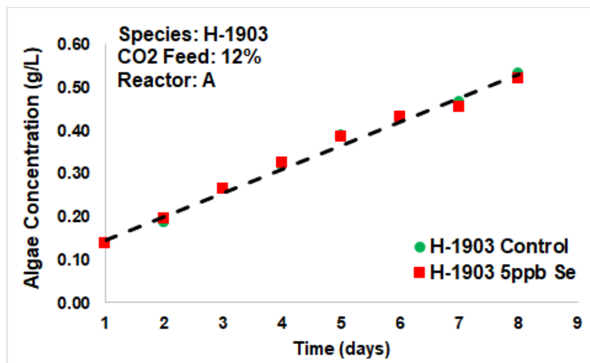

Figure 5(b): Impact of 12% CO_2 and 12% CO_2 with 5ppb Se on H-1903 (Confidential)

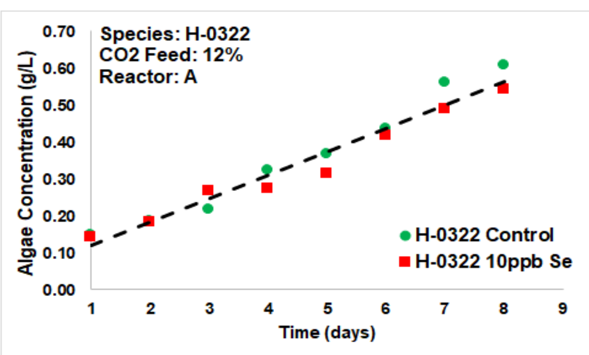

Figure 6(a): Impact of 12% CO_2 and 12% CO_2 with 10ppb Se on H-0322 (Confidential)

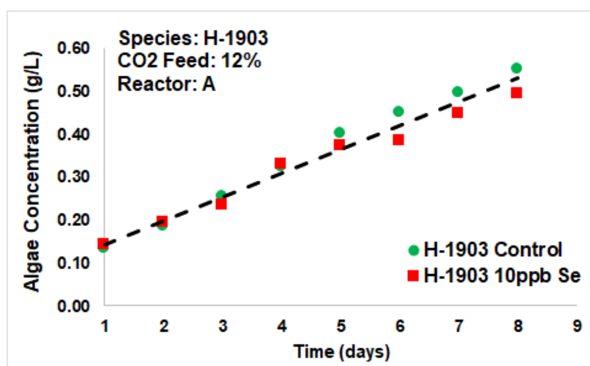

Figure 6(b): Impact of 12% CO_2 and 12% CO_2 with 10ppb Se on H-1903 (Confidential)

The next series of experiments studied algae survivability in 12% CO_2 with 5ppb Hg and 10ppb Hg respectively (Figure 7 and 8).

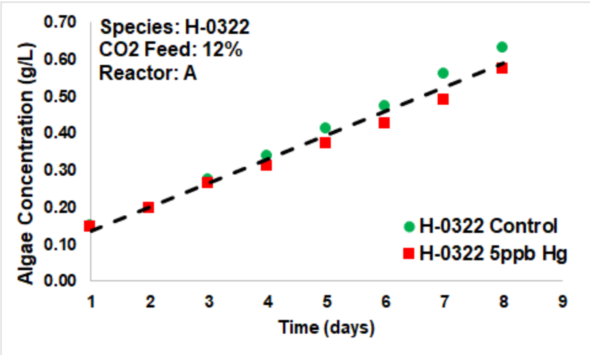

Figure 7(a): Impact of 12% CO_2 and 12% CO_2 with 5ppb Hg on H-0322 (Confidential)

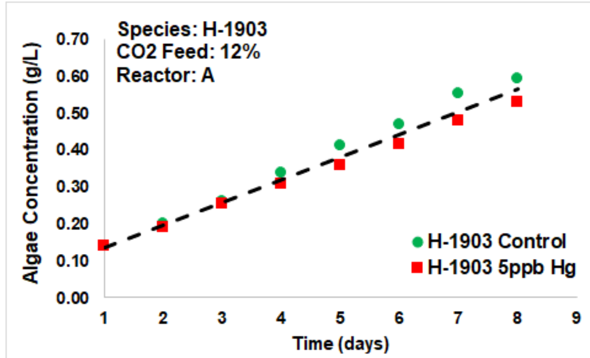

Figure 7(b): Impact of 12% CO_2 and 12% CO_2 with 5ppb Hg on H-1903 (Confidential)

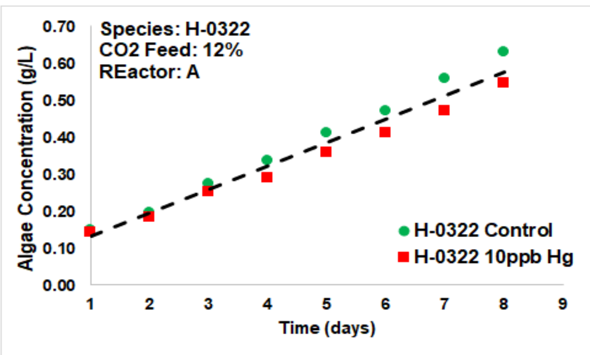

Figure 8(a): Impact of 12% CO_2 and 12% CO_2 with 10ppb Hg on H-0322 (Confidential)

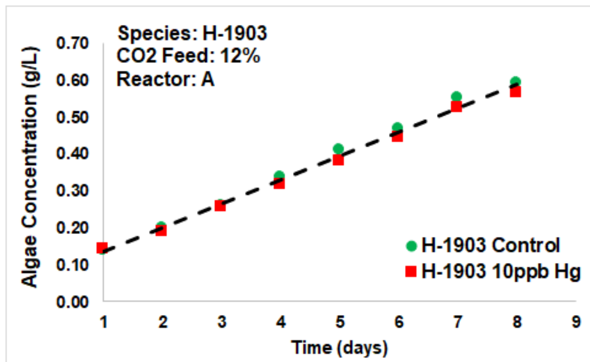

Figure 8(b): Impact of 12% CO_2 and 12% CO_2 with 10ppb Hg on H-1903 (Confidential)

The comparison between the control and experimental growth curves for both 5ppb Hg and 10ppb Hg were similar, demonstrating algae survivability at Hg levels expected in post FGD stream. It is important to note such that all the heavy metal concentrations tested represents a very extreme case due to the high solubility of each of the respective salts added. In Phase II, more realistic heavy metal concentration corresponding to the expected concentration for the metal species present in flue gas will be tested.

Subtask 1.3 Test different algae species

The objective of this task is to identify various strains of microalgae species capable of being employed in the proposed MSC system based on several primary criteria. The microalgae must be able to tolerate high CO_2 concentration, tolerate flue gas contaminants such as SOx, NOx, and heavy metal contaminants, exhibit high growth rates, be capable of exhibiting high CO_2 fixation (capture) and have been well characterized. Additional consideration in strain selection is the potential to co-produce high value nutraceutical compounds (such as astaxanthin and β-carotene), which is further discussed in Task 4.2. Helios-NRG has intentionally focused on naturally occurring microalgae species which do not have the environmental concerns of GMO strains.

The ability of both of these algae species to tolerate a simulated post-FGD flue steam containing 12% CO_2, 75ppm SOx and 75ppm NOx has been demonstrated in a prior project (DE-SC-0015719). In this project, both H-0322 and H-1903 were further advanced for cultivation in the added presence of 75ppb As + 10ppb Se + 10ppb Hg. The growth curves for both H-0322 and H-1903 are shown in Figure 9(a) and 9(b) respectively. The results demonstrate the ability of both species to survive and grow in this demanding environment. However, in comparison to control, some reduction in growth rate is observed towards the end of the experiments. It is important to note such that the heavy metal contaminants of As, Se, and Hg were added into the algae culture as soluble salts, and thus the overall levels are very much higher than that expected from the typical non-soluble heavy metal forms present in actual flue gas.

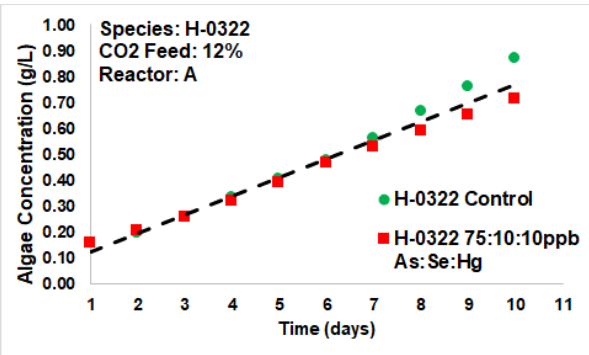

Figure 9(a): Impact of 12% CO_2 and 12% CO_2 with 75ppb As + 10ppb Se + 10ppb Hg on H-0322 (Confidential)

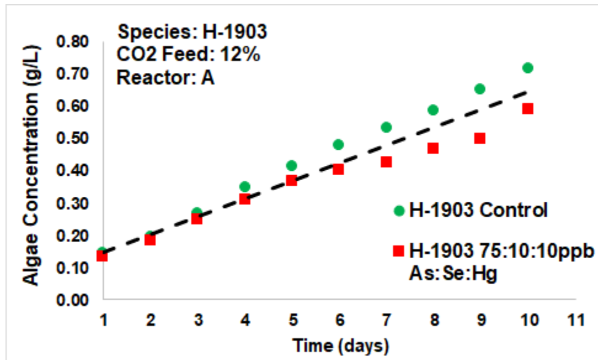

Figure 9(b): Impact of 12% CO_2 and 12% CO_2 with 75ppb As + 10ppb Se + 10ppb Hg on H-1903 (Confidential)

Because the two species tested performed up to the test criteria, there was not any need to test a third species.

Task 2 Measure CO_2 capture efficiency with contaminants

Subtask 2.1 Set up single stage tests to mimic MSC process

Single stage batch reactors were set up based on the simulations from Helios proprietary MSC simulation code and placed in a time-controlled light chamber to mimic natural light/dark cycle. Extensive efforts were made to maintain the health of the algae cultures free of bacteria and pathogens. The PBRs and all accessories were sterilized with chemicals or heat prior to use. The algae concentration for each stage of the MSC was independently established using cultures from other dedicated PBR's. Feed CO_2 concentration to each stage was individually established by metering CO_2 into the feed air stream and the inlet and outlet stream concentrations were measured using an IR analyzer. The PBRs were operated in batch mode with periodic liquid transfers based on simulations to mimic the MSC process and algae concentration monitored daily using a spectrophotometer. Algae cells from each of the stages were examined periodically under a microscope to verify culture health. The algae culture contained As, Se, and Hg at the highest levels from earlier experiments. Make-up solution containing heavy metal was added to replace the amounts lost during the periodic liquid transfer.

Subtask 2.2 Measure single stage CO_2 capture efficiency with contaminants

Model simulation from the Helios proprietary MSC code was utilized to predict the stage algae concentrations for the CO_2 capture based on a feed of post FGD stream with 12% CO_2. The simulation however is not capable of predicting the effect of heavy metal contaminants on CO_2 capture efficiency. This experiment was significantly more challenging due to the high CO_2 concentration along with the heavy metal contaminants present.

The heavy metal contaminants were added in liquid phase as solutions of sodium arsenite, sodium selenite and mercury (II) chloride. Based on prior experience, in this experiment, it was assumed such that the algae culture in each stage uptakes ~60-65% of the incoming heavy metal level. The CO_2 concentration into each stage was individually established such that the feed to Stage 3 was ~12% CO_2, the feed gas into Stages 2 and 1 were based on the CO_2 levels in the streams exiting Stage 3 and Stage 2 respectively, thus mimicking the MSC process. This Figure 10(a) and 10(b) illustrate the results of the MSC capture experiment post FGD with the heavy metals present.

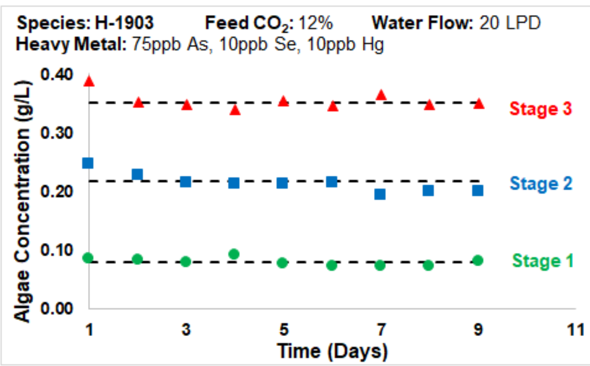

Figure 10(a): Stage algae concentration vs time in post FGD MSC process tests with heavy metals (Confidential)

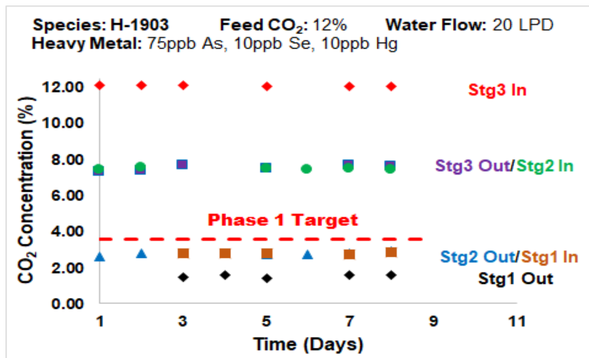

Figure 10(b): Stage and overall CO_2 capture efficiency in post FGD MSC process tests with heavy metals (Confidential)

Figure 10(a) shows that the algae concentration in each stage is stable over time - this validates one of the key assumptions underlying the MSC process. Figure 10(b) illustrates the inlet and exit CO_2 concentration to/from each stage is stable over time. The overall MSC CO_2 capture efficiency based on these single stage tests is estimated to be >80%, substantially exceeding the Phase I target of 70%. Table 5 summarizes the algae MSC process test for CO_2 capture with heavy metal.

Stage	Algae Conc (g/L)	Feed CO2 (%)	Exit CO2 (%)	% Capture In Stage	Average Heavy Metal (ppb)		
					As	Se	Hg
3	0.35	12.08	7.50	37.9%	75	10	10
2	0.22	7.46	2.76	63.0%	30	4	4
1	0.08	2.81	1.52	45.8%	10	1.3	1.3

Table 5: Algae MSC process test for CO_2 capture with heavy metal (Confidential)

The CO_2 capture efficiency in each stage is highest in Stage 2 due to the algae culture concentration being located on the optimal point of the growth rate curve and the geometry of the PBR used in the test. As explained in a later section, this MSC design does not represent an optimum design which would be used for large scale operations, but a design capable of achieving high overall CO_2 capture efficiency with existing PBR's.

Task 3 Advance the DeAqua process for algae dewatering

Subtask 3.1 Advanced design of gravity table

The objective of this task is design, fabricate and validate a continuous gravity table operation for algae dewatering. This dewatering step is to be performed without the utilization of chemicals flocculants, allowing for water and nutrient recycle for cost reduction in the algae cultivation process. This first stage of the overall DeAqua process is envisioned to achieve a 3-5x increase in algae concentration thus removing 65-80% of the water content from the feed algae culture. This work builds on the progress achieved in a prior DOE SBIR Phase1 (DE-SC-0013676) project in which several factors impacting algae settling were systematically studied.

The continuous gravity table is comprised of a specially designed settling tank with one inlet and two outlets. The algae culture from the MSC enters the tank at a low concentration (~0.5-1 g/L) and is split into two streams, with the top fraction being algae depleted and the bottom fraction being algae enriched. The design concept for the continuous dewatering operation mimicked commercial wastewater clarifiers by incorporating offset baffle configurations in the settling chamber. This produces a tortuous path for algae flow, promoting algae settling by gravity as well as preventing the convective feed flow from short-circuiting the settling system. The continuous gravity table experiments were performed with H-1903 and H-0322 algae, both of which have similar intrinsic settling profiles. The algae feed culture for all experiments were of concentrations between 0.5-1.0g/L, similar to the expected product concentration exiting the MSC system. A crucial aspect in improving the performance of the continuous gravity table operation is to significantly minimize the algae concentration exiting in the top fraction The first design was a rectangular gravity table (GS-1) which incorporates several baffles with holes in an offset configuration. A bottom sieve plate is utilized to inhibit the continuous convective feed flow from re-suspending the concentrated bottom product. GS-1 was placed at an angle to promote the settled algae product to migrate horizontally to a common collection point while the top fraction was collected from an overflow top weir. The operational flowrate for the bottom product was set to be ~25% of the feed flowrate while the top overflow flowrate was the remaining. Each settling experiment was conducted until a steady state top fraction concentration was achieved with respect to time. The conceptual design of GS-1 is as shown in Figure 11.

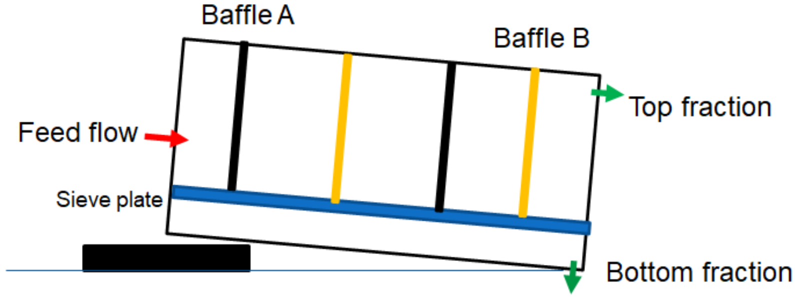

Figure 11: Conceptual design of GS-1 (Confidential)

The first series of tests in GS-1 studied the impact of the presence of baffle and residence time on the algae settling. A preliminary test with continuous feed flowrate corresponding to ~8 hours residence time in GS-1 without any baffles was conducted as a control experiment. The subsequent experiment was conducted by introducing baffles with holes of different configurations, promoting an extended path for algae flow while maintaining feed flowrate corresponding to ~8 hours residence time. An experiment with an increased feed flowrate (reduction of residence time to ~4 hours) with the same baffle configuration was conducted to determine its impact on algae settling performance. The algae settling performance was characterized by the resulting concentration ratio, defined as the bottom product concentration to the feed flow concentration achieved over time. The summary of the continuous algae settling experiment is shown in Table 6.

Test	Algae Species	Baffle(s) /Tank	Hole(s)/ Baffle	Res. Time	Conc Ratio Bottom/Feed
1	H-0322	0	0	8.3	2.6
2	H-1903	4	2	8.6	3.8
3	H-1903	4	2	3.8	2.6

Table 6: Impact of the presence of baffle and residence time on algae settling (Confidential)

In Test 1, the proof of concept for continuous algae separation was achievable for GS-1 without baffle incorporation (Test 1) as seen from the moderate product concentration ratio achieved. The introduction of baffles in the settling chamber (Test 2) improved the algae product concentration ratio when operated under similar feed flowrates and similar residence time. The algae product concentration ratio decreased with higher feed flowrates (lower residence time) due to convective flow re-suspending the settled algae. These tests demonstrated that incorporating baffles in the settling chamber improved the algae settling performance and indicated the potential for further improvement through baffle design. The summary for the impact of varying baffle design in GS-1 is shown in Table 7.

Test	Algae Species	Baffle(s) /Tank	Hole(s)/ Baffle	Res. Time	Conc Ratio Bottom/Feed
1	H-0322	0	0	8.3	2.6
2	H-1903	4	2	8.6	3.8
3	H-1903	4	6	7.8	2.5

Table 7: Impact of baffle design on algae settling (Confidential)

The algae settling experiments were conducted with relatively similar feed flowrates corresponding to a residence time of ~8 hours. The increased number of holes per baffle from 2 to 6 holes per baffle resulted in a decrease in the algae product concentration ratio. This reduction in algae product concentration ratio is likely due to the flow short-circuiting across the gravity table, through the baffles as well as the bottom sieve plate. A new gravity table of similar rectangular design (GS-2) with baffles incorporated utilized a bottom sieve plate of lower height to reduce bypassing. The impact of bottom sieve plate height on the algae settling performance is summarized in Table 8 while a physical representation of the GS-2 with varying bottom sieve plate height as shown in Figure 12.

Test	Algae Species	Baffle(s) /Tank	Hole(s)/ Baffle	Res. Time	Sieve Height (cm)	Conc Ratio Bottom/Feed
1	H-0322	5	4	7.3	1.0	1.8
2	H-1903	5	4	6.9	0.3	2.4

Table 8: Impact of bottom sieve plate height on algae settling (Confidential)

Figure 12: GS-2 with varying bottom sieve plate height (Confidential)

The bottom sieve plate was intended to inhibit the convective feed flow from re-suspending the settled algae product. The settling operation was conducted with a feed flowrate corresponding to ~7 hours residence time with similar baffle design and configuration. The decrease in the sieve plate height as shown in Figure 12 improved the algae product concentration ratio. This is likely due to the increase in flow resistance through the bottom of the sieve plate, thus forcing the flow to pass through the baffles. Based on the continuous operation experiments, algae product concentration ratios of 2-3.5x was achieved based on operations with residence time between 4-8 hours. The baffle design configuration and the sieve plate design in the gravity table are important factors in the algae product concentration. A key finding was that the flat bottom design for the tank is undesirable due to the adhesion of concentrated algae, inhibiting horizontal product mitigation to the collection point. In addition, the freshness of the harvested algae culture plays an important role in the algae settling performance. It was observed such that older cultures exhibited a lower algae product concentration ratio due to secretion of extracellular protein from algae breakdown, inhibiting algae settling. This bodes well for operation of this stage on the culture from the MSC process which, being continuous, will always be fresh.

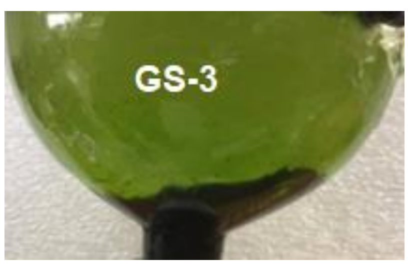

Figure 13: Settled algae at conical bottom of GS-3 (Confidential

A new concept design (GS-3) with a round conical bottom shape, shown in Figure 13, was designed to overcome the challenges in collecting the settled algae product in GS-1 and GS-2. The cylindrical tank with the conical bottom promoted the settled algae to migrate easily to the collection port. It is important to note such that the particular GS-3 tested did not have any baffles. It is expected such that with the incorporation of baffles the performance can be improved. Overall, the design of GS-3 is simpler than GS-1/GS-2 and it significantly overcomes the challenges of collecting the settled algae product. This design is also easier to scale up for larger operations due to the availability of circular commercial wastewater clarifiers. GS-3 design is also beneficial as it can be fabricated to have more tank depth, reducing area footprint. Several other gravity table design and operational concepts to improve algae settling rate have been identified and will be further studied in Phase 2.

Subtask 3.2: Enhance Dewatering Membrane Performance (UB)

The goal of this task was to improve the membrane performance for microalgae dewatering (in the algae concentration range of 1.5 g/L to 35 g/L) via increasing antifouling properties. This was achieved by surface modification of membranes to enhance hydrophilicity. Specifically, we adopted a facile one-step surface coating using bio-adhesive polydopamine and superhydrophilic graphene oxides (GO), poly(ethylene glycol) (PEG) or zwitterionic materials.[4] As shown in Fig. 14, dopamine forms polydopamine (PDA) in the presence of oxygen with fast kinetics and adheres to the membrane surface. The PDA reacts with the functional groups in the hydrophilic materials via Michael addition and then covalently grafts the hydrophilic layer, increasing the hydrophilicity on the surface. A commercial ultrafiltration (UF) membrane, polysulfone (PSf-100) from Alfa Laval with nominal molecular weight cut off (MWCO) of 100 kDa was chosen in this study, and the details are discussed below.

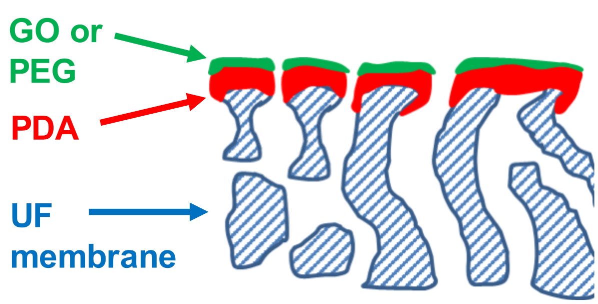

Figure 14: Schematic of membrane surface modification by co-depositing bio-adhesive PDA and superhydrophilic materials such as GO, PEG-NH_2, and zwitterionic materials with methacrylate groups. (Confidential)

Effect of GO coating on membrane performance of microalgae dewatering. GO are hydrophilic due to the functional groups such as epoxide, hydroxyl, and carboxyl groups, and they exhibit electrostatic repulsion against microorganism deposition by introducing more negative charges to a membrane.[5-9] To increase the grafting density of GO, we have also functionalized GO with amine groups using diamines.

The water flux was determined using dead-end filtration cells. The water permeance, A_W (liter per m^2 hr bar, LMH/bar), can be calculated using the following expression:[4,10]

$$A_W = \frac{1}{\Delta p \cdot A_m} \frac{dV_W}{dt} \quad (1)$$

where Δp, A_m and dV_W/dt are the pressure difference across the membrane, membrane effective area and water flux, respectively. Six membrane samples were tested and an average water permeance is reported here. The test was run under a stirring rate of 700 rpm to keep a constant Reynolds number (which is in the transition region). The membranes were usually tested in the order of pure water, algae solutions at desired concentration, and pure water again.

Fig. 15 demonstrates the advantage of the GO+PDA coating on the membrane performance for algae dewatering. As shown in Fig. 13a, the coated membrane showed a lower initial water permeance than the virgin PSF membrane, when challenged with 0.8 g/L algae. However, at steady state, the coated membrane showed water permeance 20% higher than the virgin one. The results also indicate that the steady state water permeance can be achieved, despite the high algae concentration. Similar behavior has also been observed when the membranes were challenged with algae concentration as high as 35 g/L.

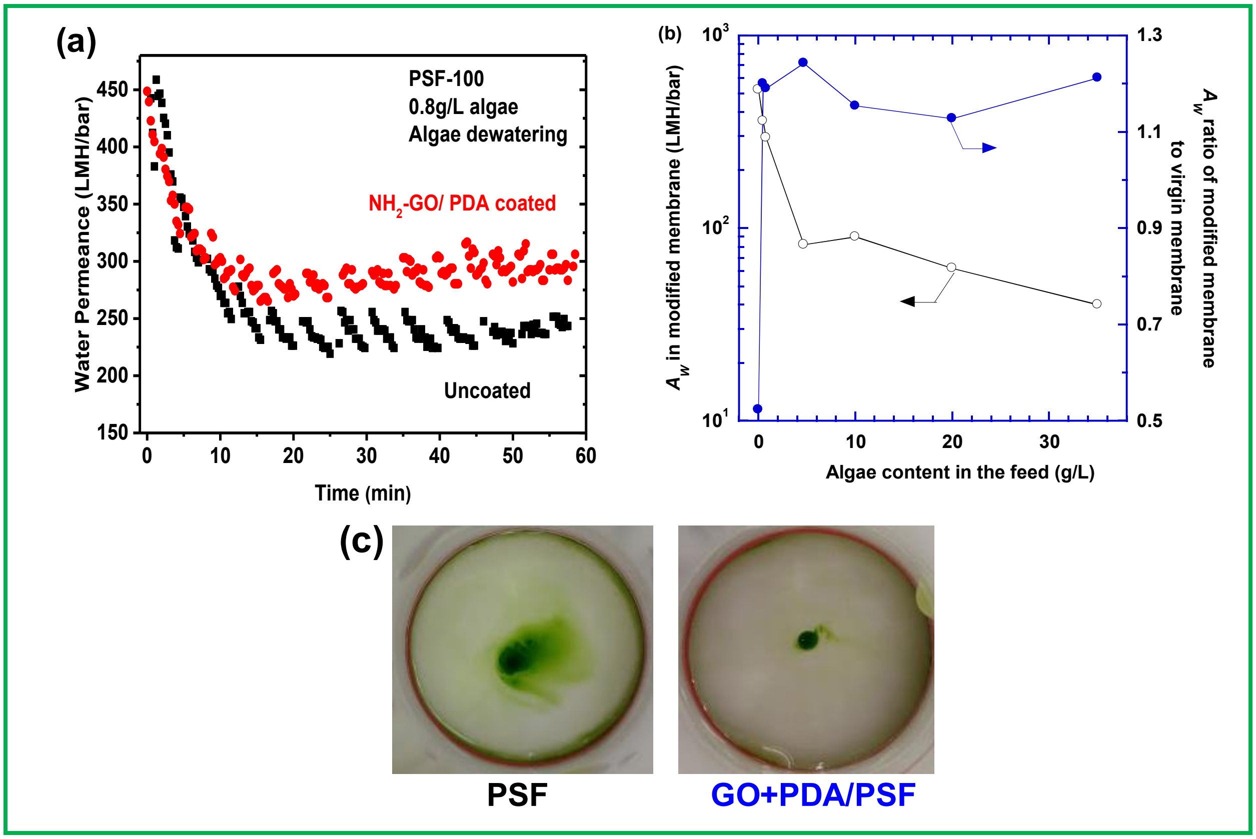

Figure 15 (Confidential): (a) Comparison of virgin PSF membrane and GO+PDA coated PSF membrane for treating 0.8 g/L microalgae. The feed pressure is 1 bar, and the stirring rate is 700 rpm. (b) Effect of algae concentration on the water permeance in PSF and modified PSF membranes. (c). Exampled images of the PSF and GO+PDA coated membranes after testing with 0.8 g/L algae.

Fig. 15b shows that the water permeance decreases with increasing algae concentration (0.5 g/L – 35 g/L), presumably due to increased fouling by the algae. Nevertheless, the coated membrane exhibited improved water permeance over the virgin one. It should be noted that the pure water permeance in the coated membrane is only 50% of that in the virgin PSF membrane. Fig. 15c vividly shows that the coated membrane has lower adhesion of microalgae (as indicated by the green spots) than the uncoated one, suggesting the enhanced antifouling properties by the surface modification.

Effect of PEG coating on the membrane performance of microalgae dewatering. We also modified membranes with 2 g/L dopamine and 1 g/L PEG diamine (PEG) (molecular weight of

2000 g/mol), and evaluated the dewatering performance with algae at four concentrations, i.e., 5.2, 10.3, 20.6, and 35.8 g/L. As an example, Fig. 16a compares the water permeance in the virgin PSF membrane and the PEG+PDA modified one for dewatering 5.2 g/L solution. The uncoated membrane shows higher pure water permeance because the coating adds a layer and thus increases the water transport resistance.[4,11] However, the coated membrane show higher water permeance when dewatering algae, suggesting the enhanced antifouling properties via the coating.[12-15] Similar trend was also observed for other algae solutions.

Fig. 16b shows that increasing algae concentration decreases water permeance. Nevertheless, at the algae concentration studied (0.5 g/L – 35 g/L), the coated membrane exhibited improved water permeance. The permeance improvement by coating is more significant for lower algae concentration. It should be noted that the pure water permeance in the coated membrane is only 70% of that in the virgin PSF membrane.
Fig. 17 compares the virgin and coated membranes after the algae dewatering tests and pure water rinsing. The uncoated membrane shows green spots due to the algae adhesion, while the coated one (which is brown due to the PDA coating) is essentially free of green spots or algae, which further confirms the enhanced antifouling properties in the coated membranes.

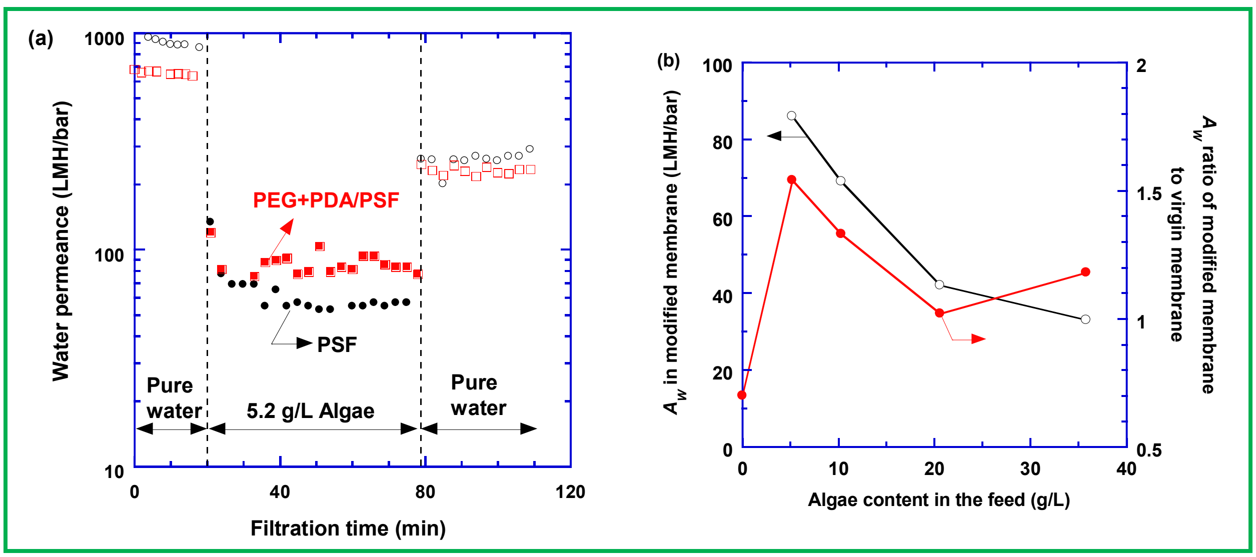

Figure 16: Comparison of water permeance in the virgin PSF membrane and the one coated with PEG+PDA tested in dead-end systems at 20 °C. The feed pressure is 1 bar, and the stirring rate is 700 rpm. (Confidential)

Figure 17: Images of (a) an uncoated and (b) a PEG+PDA coated PSf-100 after algae dewatering test with the algae concentration of 35.8 g/L. (Confidential)

Subtask 3.3: Develop conceptual design of membrane module

Two conceptual designs for the advanced membrane modules were developed. In the first, approach, commercial modules are procured and surface modification performed as a post-modification method. The surface modification is performed in aqueous solution at room temperature and hence can be easily adapted for the module modification. For example, nanofiltration membrane modules have been successfully modified using PDA and zwitterionic materials in our laboratory. It is expected that this approach can be transferred to the modification of the commercial UF membrane modules for algae dewatering.

The second approach is to design membrane modules from bottom up. The membranes, feed and permeate spacers, and other module components can be designed independently to reduce fouling. Plate-and-frame modules can be designed with proper feed spacers to increase turbulent flow and hydrodynamic dragging force, and thus decrease the aggregation of algae on the membrane surface. Additionally it is possible to create patterns on the membrane surface to enhance the hydrodynamic force.

Task 4: Validate production of high value nutraceuticals from algae

Subtask 4.1: Development of procedure for Astaxanthin and β-carotene extraction

The objective of this task is to further the process of obtaining high value products from algae in order to help offset the cost of carbon capture. Nutraceuticals are one category of products with high value to lower overall cost. Most nutraceuticals are insoluble in water and thus identified by their solubility in nonpolar, organic phase solvents. Commercial operations often use solvents such as hexane to extract plant products or employ synthetic chemistry to manufacture these supplements. There is great interest in the market to avoid chemical extraction and chemical synthesis due to the toxicity of the chemicals potentially retained in the product and the environmental issues of handling and disposing.

The extraction of nutraceuticals from algae typically involves a two-step process. First a pretreatment is done to break open the tough outer cell wall using mechanical, thermal, and/or chemical means. Then the organic fraction is extracted and the residue collected post solvent evaporation. Some of the most effective extraction methods are listed in Table 9 for a species of algae known to produce high levels of astaxanthin.

Method of Extraction	% recovery
supercritical CO2 plus 10% ethanol	97
supercritical CO2	79
acid pre-treatment	80
acetone and enzymes	70

Table 9: Reported methods for high levels of Astaxanthin extraction from H. pluvialis.[16]

Subtask 4.1 was successfully completed by the analyses performed by Helios-NRG and an outside testing laboratory. In this study two species of algae were tested for nutraceutical levels following stress induction. The induction includes increased production by the algae simultaneously of triglycerides and the nutraceuticals each species is able to synthesize. For two species H-1903 and H-0322, the algae cultures were first culture in 12% CO_2 and then treated with 100 mM NaCl for a minimum of four days. Helios performed preliminary analysis of the salt induced algae using bead shaking in a hexane/isopropanol solvent. After several rounds of bead shaking in the solvent all the color was released and collected in the organic phase indicating full extraction.

Subtask 4.2: Measure Astaxanthin and β-carotene concentration in at least two species

To examine what components could be found in the induced algae samples Helios-NRG used thin layer chromatography (TLC) to demonstrate the presence of materials of interest. Results are shown in Figure 18 for induced species H-1903. High levels of lipid in the form of triglycerides were detected as well as some β-carotene, astaxanthin and carotenoids. Neither the triglyceride nor the astaxanthin were detectable in the non-induced samples (data not shown). Similar results were found in the induced H-0322 except the astaxanthin was not detectable (data not shown).
Lane A reveals the lipids in the sample after acid charring. Lane B shows the pigments in the sample prior to acid charring the plate.

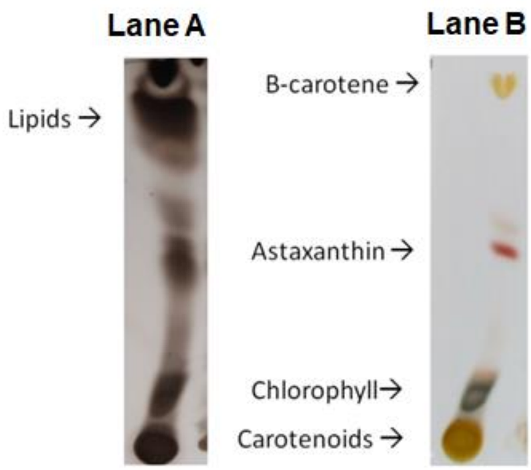

Figure 18: Thin layer chromatography of H-1903 induced non-polar fraction of algae (Confidential)

After the preliminary analysis demonstrated that the induction process was effective, the algae slurries were frozen and shipped to an outside lab for detailed gas chromatographic analysis of the carotenoid and astaxanthin components. The algal cells were broken open prior to extraction with alkaline hydrolysis. The results are shown in Table 10.

	Quantity (µg/mg-algae)	
Compound	**H-1903 Induced**	**H-0322 Induced**
trans - Lutein	1.42	0.37
trans - Zeaxanthin	0.36	0.04
cis- Lutein & Zexanthin	0.17	0.08
b- Crptoxanthin	ND	0.02
trans- b-carotene	0.2	0.01
cis- b-carotene	0.08	0.01
total- b-carotene	0.27	0.02
total carotenoids	2.23	0.52
Astaxanthin-di-esters	ND	0.02
Astaxanthin-mono-esters	ND	0.03
Free- Astaxanthin	0.05	ND
Canthaxanthin	0.05	ND

Table 10: Content of nutraceuticals in two species of algae (Confidential)

The table of nutraceutical content indicates a number of pigments in each species. For species H-1903 the most prevalent component was Lutein and then Zeaxanthin and β-Carotene. For species H-0322, the most prominent compound was also Lutein, and then lower levels of Zeaxanthin, Cryptoxanthin, Astaxanthin and β-Carotene. All of these components have value in the nutraceutical and animal feed market.

Task 5: Process Development and Economics

Preliminary economic analysis was performed using the MSC process for 90% CO_2 capture from a 550MW power plant burning sub-bituminous coal with the flue gas entering the process containing ~12% CO_2. While the long term commercial goal is a 550MW power plant, the technology would likely to be initially deployed on a much smaller scale (possibly ~50MW) in either a small power plant or on a side stream of a larger power plant. The flue gas properties were obtained from DOE's baseline study[1]. Since photosynthesis is driven by sunlight, the analysis assumes that carbon capture occurs during 14 hours/day of natural sunlight. The basis for analysis are summarized in Table 11.

Parameter	Value
Power Plant Size (MW)	550
Flue gas flowrate TPY (Tons/yr)	1.98E+07
CO2 in Flue gas TPY	3.89E+06
Flue gas CO2 conc	12.9%
CO2 capture efficiency by MSC	90%
Hours of sunlight/day	14
Total CO2 Capture by Algae (TPY)	2.04E+06

Table 11: Basis for economic analysis **(Confidential)**

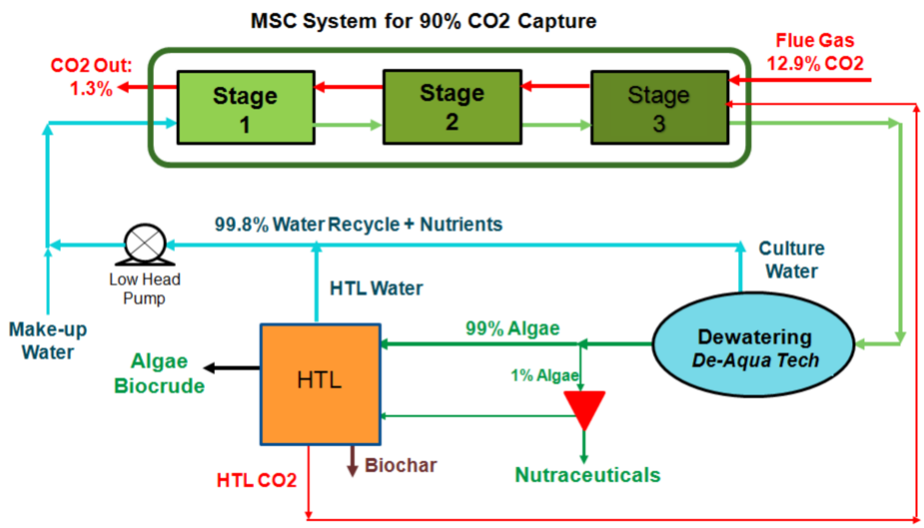

Figure 19: Schematic of overall process for Carbon Capture and Utilization **(Confidential)**

Figure 19 shows a schematic of the overall process. Post FGD flue gas from the power plant enters a 3-stage MSC process wherein the CO_2 captured is used to accelerate the growth of algae. The algae produced by the MSC process is de-watered using the De-Aqua process to produce product algae with dry weight concentrations from 20-45%. The de-watered algae leaving De-Aqua is split into two streams. As shown, about 99% of the algae is fed to HTL where it is converted to a bio-crude product. HTL is not part of the present project, but the conversion of Helios-NRG grown algae to bio-crude using HTL was demonstrated in an earlier DOE funded project. The remaining 1% is used for production of two nutraceuticals (Astaxanthin and β-Carotene) which were shown to be present in our algae species in the current project. While several other valuable nutraceuticals were also found to be present, they are not included in the present TEA and represent potential sources of added revenue. The biomass waste after nutraceuticals production is fed to the HTL process. All the water and nutrients extracted during De-Aqua and the waste water from HTL are recycled to the MSC process. The CO_2 rich gas produced by HTL is recycled.

The experimental data measured in Task 2 were used in the Helios-NRG proprietary model used to predict MSC operation. Developing the global optimum design of MSC for 90% CO_2 capture from flue gas streams is well beyond the scope of the present Phase 1 project and is one of the future objectives. Hence the strategy has been to use the MSC model to identify a reasonable design and set of operating conditions that can achieve 90% CO_2 capture from the post FGD flue gas stream (Table 12) and subsequently use this for preliminary economic analysis.

MSC Stage	Culture Conc g/L	% CO2 Captured	Exit CO2 Conc
1	0.17	22%	1.2%
2	0.40	30%	3.8%
3	0.70	39%	7.4%

Table 12: MSC parameters for 90% CO_2 Capture from post FGD flue gas **(Confidential)**

Cost estimates for the DeAqua process was based on updating earlier work incorporating the progress made in Task 3. For Stage 1, a residence time of 16 hours was assumed in commercial operation which represents a modest improvement over the results achieved in Phase1. A product concentration ratio of 3.5 was assumed in Stage 1 which has been demonstrated in Task 3. The dewatering membrane used in Stage 2 was assumed to operate at 30psig and have an average water flux of 250 LMH/bar, which was measured in Task 3. The dewatering membrane was assumed to have a packaged cost of $60/m^2$, an estimate provided by a commercial vendor. Stage 2 increases the algae concentration to 35 g/L. Stage 3 uses a continuous mechanical filter press which operates at 300psi and increases the product concentration to >250 g/L. As the culture moves from Stage 1 to Stage 2, the culture volume is reduced by ~75%. In going from Stage 2 to Stage 3 the volume is further reduced to ~1% of the initial feed. This enables significant reduction in the size and cost of each successive stage. Table 13 summarizes the energy, capital and operating charges for the DeAqua process per ton of algae.

DeAqua	Energy (MJ/ton)	Capital Charge ($/ton)	Depr Charge ($/ton)	Operating Cost ($/ton)	Total Cost ($/ton
Stage 1	55.5	13.8	3.3	0.8	17.9
Stage 2	130.5	2.1	0.5	1.8	4.4
Stage 3	23.4	0.8	0.2	0.3	1.3
Fixed Costs + Misc	[redacted]			3.1	3.1
Net Total	**209.5**	**16.6**	**4.0**	**6.0**	**26.6**

Table 13: Estimate of energy, capital and operating costs for DeAqua process (Confidential)

The cost for carbon capture with algae was estimated by Helios-NRG assuming an average algae productivity of 35 g/m^2/day in the MSC process. This represents Helios-NRG's baseline target productivity for commercial operations. Total CAPEX of the MSC was estimated by Helios based on the design of our proprietary process using information available in literature and/or quotes. As a sanity check, the capital cost was also estimated using the costs reported by Lundquist et al[17] for open raceway ponds, scaled for our higher productivity, and adding costs for a top cover to capture the gas phase and other modifications. This resulted in a capital cost range of $530-750MM for the 550MW plant including DeAqua. Capital charges were estimated based on 10-year term with 8% annual interest. A 30-year plant life was assumed for depreciation.

The operating costs included the following:

- Cost of make-up water and nutrients - based on the values reported by EISA[18] and assumed 98% recycle of water and nutrients. The expected water recycle in the process shown in Figure 17 is >99%.
- Power for a gas blower and paddle wheel operation - estimated from BETO report
- Cost estimate for de-watering with De-Aqua process - estimated by Helios-NRG based on work in the present project
- Labor and maintenance costs - estimated based on our industrial experience

The total costs are significantly lower than state of the art due to the following:

- High algae productivity of 35 g/m2/day
- Use of waste CO_2 from flue gas
- Reduced dewatering cost through the novel DeAqua process
- High rates of water and nutrient recycle (>99%)

- Production of bio-crude and nutraceuticals which add significant value

The capital and operating costs for the HTL plant were based on the costs estimated by PNNL[19] for diesel production using HTL processing of algae and developed in an earlier project. Since the output of the De-Aqua process can be directly fed into the HTL process, the costs for algae drying were excluded. Further, the output of the process envisioned is bio-crude which will be sold to a refiner. Hence only the costs for bio-crude production were included and the costs for further upgrading and processing to make diesel were eliminated. The selling price of bio-crude was assumed to be 67% of the price of petroleum in 2025[20].

Helios-NRG believes that co-production of high value nutraceuticals can significantly lower the cost of carbon capture. For nutraceutical production, it is assumed that the algae will have 1% by weight of Astaxanthin and 0.5% β-Carotene which is lower than the 1-4% typically reported. Conservative numbers were intentionally used since the level of nutraceutical production in the proposed MSC process has not been quantified. Unrefined nutraceutical production was assumed to involve the following added steps:

- An induction step which would be performed in a deep tank
- Extraction of lipids and nutraceuticals from algae using a super-critical CO_2 process with CO_2 recovery.
- A process for separating lipids, Astaxanthin and β-Carotene

The capital and operating costs for each of these were either estimated by Helios-NRG based on prior experience, literature data, and where possible (e.g. supercritical CO_2 extraction) actual vendor quotes. The selling price of the Astaxanthin and β-Carotene produced were assumed to be 1/10th of the current market price since the products are not purified.

Table 14 summarizes the results of the assessment. It shows that the co-production of bio-fuel and nutraceuticals can significantly lower the cost of CO_2 capture. Thus, the cost of CO_2 capture with MSC alone (no products) results in a capture cost of $74-94/ton CO_2. The addition of HTL and nutraceuticals production increases the overall capital and operating costs. However, this is more than offset by the revenue from sale of these products. Bio-crude sale is estimated to reduce the cost of CO_2 capture by $75/ton and nutraceuticals by $25/ton respectively. ***The net cost of capture with Bio-crude and nutraceuticals production is hence reduced to $3-23/ton CO_2.*** While the numbers shown here are very preliminary, they clearly show that the utilization of the CO_2 captured to generate high value products is the key to making a step change in the cost of carbon capture.

System	Parameter	550MW
MSC + Biocrude (HTL) + Nutraceuticals	Total Capex (MM$)	739-957
	Capital Charge (MM $/yr)	102-132
	Depreciation (MM $/yr)	23-30
	Operating Costs (MM $/yr)	85-90
	Bio-crude production (MM Barrel/yr)	3.2
	Bio-crude value ($/Barrel)	47.6
	Astaxanthin production (kg/day)	150
	β-Carotene production (kg/day)	75
	Selling price of Astaxanthin produced ($/kg)	750
	Selling price of β-Carotene produced ($/kg)	200
	Bio-crude reveue ($/ton CO2)	(75)
	Nutraceuticals Revenue ($/ton CO2)	(25)
	CO2 Capture Cost w/- Biocrude + Nutraceuticals ($/ton)	3-23

Table 14: Summary of economic assessment of proposed technology for CO_2 capture and utilization from flue gas streams **(Confidential)**

For a preliminary life cycle analysis, the CO_2 generated from the process and also from the power consumed by the process were estimated. The CO_2 generated by HTL operations is recycled back to the algae where 90% is captured. Additional CO_2 emitted by the proposed process would arise from power requirements in the MSC process (flue gas distribution and sparging, paddle wheel operation, water and CO_2 recycle etc) and energy used in the HTL process, energy in algae dewatering and supply of make-up water and nutrients (Table 15). Note that ~90% of the CO_2 generated for the added power for the algae+HTL process will be re-captured by the algae. The preliminary analysis indicates that this will reduce the net CO_2 capture efficiency during operation from 90% to ~87%. The total estimated energy consumption by the process of ~2.8 MJ/kg algae is only a small fraction of the energy content of the algae (~18 MJ/kg).

Component	Basis	MJ/kg-Algae
Nutrients for Algae	67% recycle	0.48
MSC operational power	Estimated	0.60
Algae Dewatering (DeAqua)	Phase1 work	0.21
Water Recycle	10ft head	0.08
Flue Gas Blower	2 psig	0.18
HTL	75% heat recovery	1.23
TOTAL		2.78

Table 15: Energy consumption by process resulting in CO_2 emission **(Confidential)**

Task 6: Project Management

This task ensured that all programmatic activities were completed in time and on budget to ensure successful completion of the overall project. Subsequent to signing of the Phase1 contract with DOE, Helios-NRG executed contracts and necessary confidentiality agreements with UB. Schedules for task completion, billing and reporting were established. Meetings were held with Dr Haiqing Lin and his team on a bi-weekly basis. Project expenditures were tracked against progress in tasks. Progress and financial reports were submitted to DOE as required. Final project cost was $ 154,948 vs. a budget of $ 154,948.

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