Helios-NRG, LLC

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Phase1 Final Technical Report

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Project Title : **"Novel Integrated Technology Incorporating Anti-fouling Membranes to De-water Algal Harvests"**

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Public Summary
Non-Confidential

Fuels produced from renewable biomass (bio-fuels) are generally viewed as an important component of a long term solution to address the Nation's energy needs and reduce CO_2 footprint by as much as 50% compared to fossil fuels. Using algae as the basis for bio-fuels has many potential advantages - extraordinary growth rates, short harvest time, very high lipids content and acreage yields substantially higher than traditional crops. However microalgae is grown in dilute solutions and hence must be de-watered in order to be used for energy applications. The commercialization of microalgae for renewable biofuels has been hindered due to the high energy and cost for de-watering cultures.

This project is aimed at developing a multi-stage hybrid process to de-water algae cultures from 0.5g/L to 250g/L with very low energy consumption and total cost. This technology permits most of the water to be recycled back for algae culturing which is important for practical applications. Phase1, aimed at demonstrating technical feasibility, is complete and all Phase1 objectives were met or exceeded.

The work in Phase1 showed that the rheology of the algae solution changes significantly as de-watering progresses. The change in viscosity with concentration is highly non-linear at higher concentrations as the de-watered product transitions from a water like liquid to a slurry to a semi-solid. This has significant impact on technology selection for the de-watering process. In Phase1, significant effort was devoted to developing and demonstrating a novel dewatering membrane, characterized by high anti-fouling properties and high flux. It was shown that by suitable surface modifications, the fouling can be greatly mitigated. These membranes were tested on both algae cultures and a template foulant. Another milestone in Phase1 was the development of a very low energy technology for increasing the culture concentration by a factor of 3-6 at reasonable residence times. This technology is well suited for one of the stages of the hybrid process. Another de-watering technology needed in the hybrid process, was developed that is particularly well suited for achieving very high concentrations of algae in the product while using low energy. An overall process which integrates the different technologies was developed and the inter-stage concentrations defined. The ability of each stage to achieve target performance was validated in lab scale tests. The results demonstrated the ability of the integrated hybrid process to dewater algae from 0.5g/L to over 250g/L. In some cases, concentrations up to 500g/L were achieved.

Preliminary process optimization was performed and the best operating parameters were selected. This resulted in energy and mass balances for each of the stages and confirmed the ability to recycle over 99% of the water. Preliminary economic analysis was completed based on the results from Phase1. The Phase1 results confirmed the potential of the technology to make a step change in the energy and cost for dewatering algae.

Plans to advance the technology in Phase2 were developed and potential partners identified.

1. Executive Summary (Confidential):

In order for algae to become a viable source of renewable energy, the de-watering must be accomplished at very low energy consumption and at very low lost. On the energy side, algae typically has a thermal energy content of ~18-25 MJ/kg dry weight. To be viable, the de-watering technology can only use a small fraction (e.g. 10-15%) of this energy content. On the cost side, in order to be competitive with petroleum at $40/barrel, algae oil will need to be at ~$1/gal. Even for high lipids algae, 8-10 kg of dry algae is required to make 1 gal of algae oil. When one factors in extraction, even with very low cost techniques, Helios-NRG estimates that the cost of dry product algae will have to be ~ 10 c/kg in large scale production for algae based fuel to be competitive with petroleum based fuels. In order for the de-watering technology to have any potential for large scale bio-fuels, Helios-NRG believes that the cost of de-watering will need to be likely <4 c/kg for commercial success.

No current technology meets this dual requirement. For instance the baseline provided by DOE[1-3] of micro-bubble flotation followed by centrifugation is highly energy intensive - just the centrifugation part is estimated to consume over 13 MJ/kg - over 70% of the energy content in algae. *The total de-watering cost using this technology, based on published data[4], is estimated to be 14.2 c/kg-algae which is about 2x of the cost target for the final product algae and about 3.5x of what Helios-NRG believes would represent a reasonable target cost for the de-watering step.*

With support from DOE, Helios-NRG is developing a novel process for de-watering algal cultures with ~0.05% algae weight loading (0.5g/L) to produce a product with at least 25% algae weight loading (dry basis) -this can eliminate one of the major roadblocks to large scale commercialization of algae for energy. We refer to this technology as the DeAqua process (Fig 1). The goal is to make a step change in the energy required for harvesting by achieving a total energy budget of <3 MJ/kg of dry algae while reducing capital cost substantially to achieve a total de-watering cost below 4 c/kg-algae. Specifically the DeAqua process involves the integration of three steps of de-watering technology all of which are characterized by low energy and capital costs compared to current technology. Each of the steps is designed to operate in a range of algae concentrations for which it is ideally suited.

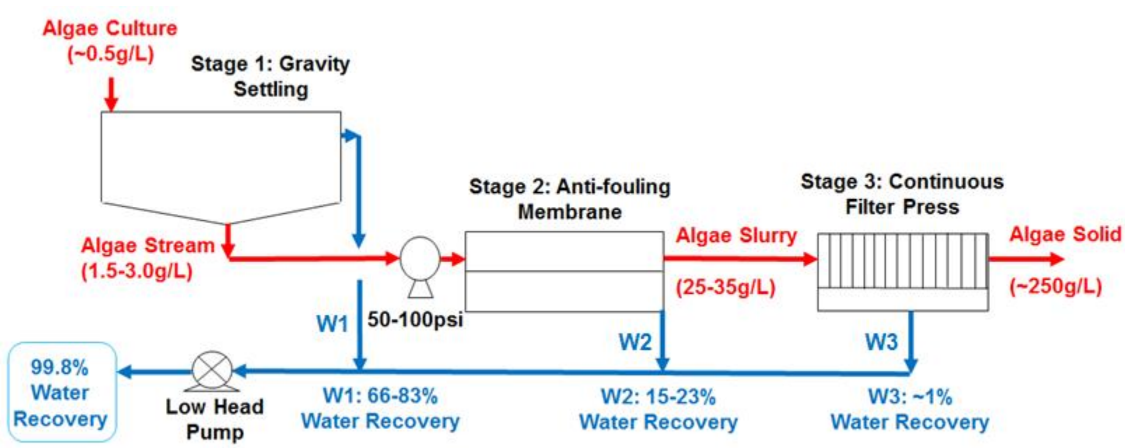


Figure 1: Schematic of Helios-NRG's DeAqua Process for algae de-watering (Confidential)

The total energy budget for the DeAqua process is estimated to be under 2 MJ/kg of operation, which represents a >50% reduction from the current baseline[1-3] (exceeding the DOE target of 20%). *Another key benefit of the DeAqua technology is that the de-watering in each step is performed without the use of chemicals which enables to water extracted to be recycled to the algae culture - highly critical for commercial success.*

The objective of Phase1 was to establish technical feasibility of the DeAqua process. Phase1 is now complete and all the project objectives were achieved and in some cases exceeded. The technology for each stage of the DeAqua process was significantly advanced and feasibility demonstrated. Since the de-watering performance can be impacted by algae type, two microalgae species of very different shapes - *Chlorella vulgaris* (CV) which is spherical and *Selenastrum capricornutum* (SC) which is crescent shaped were used in all the studies. The detailed results and progress against each task is provided in the next section. Here we provide a brief summary of the progress.

For Stage 1 (Gravity Table), the impact of several design and operating parameters on the settling rate of algae cultures was studied. Key considerations in the selection of the parameters to be studied included avoidance of chemical additives, low energy requirements, ease of implementation, and cost effective scalability to large sizes. The parameters investigated included culture depth, tank diameter, type of tank surface, initial culture concentration, addition of de-watered algae for seeding, and impact of light. Fresh cultures were used as the results from healthy cells was very reproducible. The results of the work showed that the settling rate can be accelerated through optimizing the various parameters and a concentration increase of 3-6x can be readily achieved within 12-24 hours which exceeds our initial target of 3x. However, in some cases based on optimizing our best parameters, a concentration ratio of ~2-3x was achieved in ~6 hours. This shows potential to significantly reduce the size of the gravity table, thus reducing the capital cost.

For Stage 2, three commercial water purification UF membranes [polyethersulfone (PE-2), polyacrylonitrile (PAN-50), and polysulfone (PS-100)] were selected and samples procured. Technology was developed for surface modifying these porous membranes to increase hydrophilicity and hence reduce interactions between membrane surface and algae that cause fouling. The polymers selected for surface modifications were polydopamine (PDA), sulfobetaine methacrylate (SBMA) and PDA/SBMA blends were extensively characterized. The coated membranes showed significant increase in hydrophilicity as measured by the water contact angle. Samples of the coated and uncoated membranes were mounted in permeation cells and the water permeance characterized. Finally two species of algae and one template foulant, bovine serum albumin (BSA), were individually passed through a cross flow membrane configuration to test fouling rates. The results are highly encouraging and showed that by hydrophilic surface modification the fouling rate can be greatly reduced. Best results were obtained using the PDA/SBMA blend in which permeance improvements of up to 42% over the untreated case was achieved for algae and 82% for BSA. This work also showed significant potential for further improvement.

For Stage 3, a mechanical press and suitable filter media cloth were procured and a press chamber built. The ability to increase the algae weight loading from ~3-5% (30-50g/L) in the incoming slurry to 26-54% in the final product (a solid or semi-solid depending on loading) was demonstrated for both types of algae, greatly exceeding our target of 25%. At the preferred feed concentration of 30g/L, the energy required for mechanical dewatering was ~190 kJ/kg - well below our target of 250 kJ/kg. In addition, the originally conceived process for Stage 3 was further improved using a 2-step process that permits further reduction in energy requirement for this stage.

Preliminary process optimization and economics were carried out for the DeAqua process (Fig 1) using the technology developed in Phase1. Key parameters were varied to determine preferred ranges for various design and operating variables including the inter-stage concentrations between Stages 1 and 2 and between Stage 2 and Stage 3. The results are very encouraging and indicated that the DeAqua process can de-water algae with very low energy consumption, well below our original target. Significant reduction in capital cost is also indicated.

Table 1: Estimated Cost and Energy for algae de-watering using DeAqua process (Confidential)

		Energy		Total Cost for De-watering (c/kg-algae)
	Capital Cost ($/TPY-Algae)	Mech. Electrical (MJ/kg-algae)	Thermal Equiv (MJ/kg-algae)	
Stage 1	32.5	0.03	0.09	1.03
Stage 2	6.2	0.27	0.76	0.56
Stage 3	4.9	0.06	0.18	0.24
Labor				0.74
Total	43.6	0.36	1.03	2.57

Table 1 summarizes the estimated energy and cost of algae de-watering using the DeAqua process for a 1000 acre farm for a preferred set of design and operating conditions. The details underlying these estimates are discussed in the following section under Task 6. With a projected energy consumption (thermal) of ~1 MJ/kg and a net cost of ~2.6 c/kg, the results demonstrate the potential of the DeAqua technology to meet the ambitious targets set earlier and thus achieve a step change in the energy and cost for algae de-watering.

The substantial progress in Phase1 positions us well to advance the technology in Phase2 to a continuous process which will further improve performance and make it suitable for commercial applications of algae for energy and bio-products.

2. Detailed discussion of work and accomplishments by task:

Task1: Understand impact of algae concentration on viscosity

The goal of Task 1 was to determine the effect of microalgae concentration on the solution viscosity. The viscosity increases with increasing microalgae content, and the increase is more rapid than that predicted using the Einstein equation. These results provide guidelines in designing the operation parameters such as pressures for membrane processes and the need for mechanical handling of the high concentration liquid phase as it becomes like a paste towards the end of the de-water process.
Fig. 2 presents the viscosity values as a function of microalgae volume fraction, assuming an equal density to water (1.0 g/cm^3) for all the algae samples. For samples containing algae less than 0.04 (volume fraction), the viscosity increases linearly with increasing volume fraction, which is consistent with behavior of Newtonian fluids. As the volume fraction increases above 0.04, the viscosity increases exponentially with increasing volume fraction, as illustrated by the SC samples.

To correlate the viscosity of solutions containing hard spherical particles which have interaction together[5], the Einstein equation (Eq. 1) is used[6]:

$$\mu = \mu_w \left(1 + 2.5\phi_{algae}\right) \quad (1)$$

where μ, μ_w, and ϕ_{algae} are solution viscosity, water viscosity, and volume fraction of algae in the water, respectively. Both *Chlorella vulgaris* (CV) and *Selenastrum capricornutum* (SC) samples indicate higher viscosity than those estimated using Einstein equation, even at volume fractions lower than 0.04. This is expected since the algae species are not hard spheres[5], as with SC being crescent shaped, and also there are interacting forces between the algal cells[7].

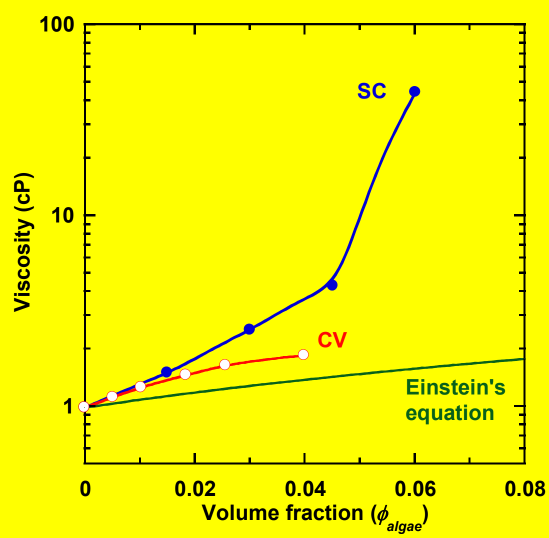


Figure 2: Viscosity values for CV and SC species against volume fraction (Confidential)

The solution viscosity results shown in Fig. 2 indicate that solutions containing higher algae content may be difficult to pump, particularly though fine channels, due to the high viscosity and thus high energy consumption. This suggests that a concentration of ~30-40g/L is likely a reasonable upper bound for the end point of Stage 2 (membrane de-watering step) where mechanical handling takes over in Stage 3 of the DeAqua process.

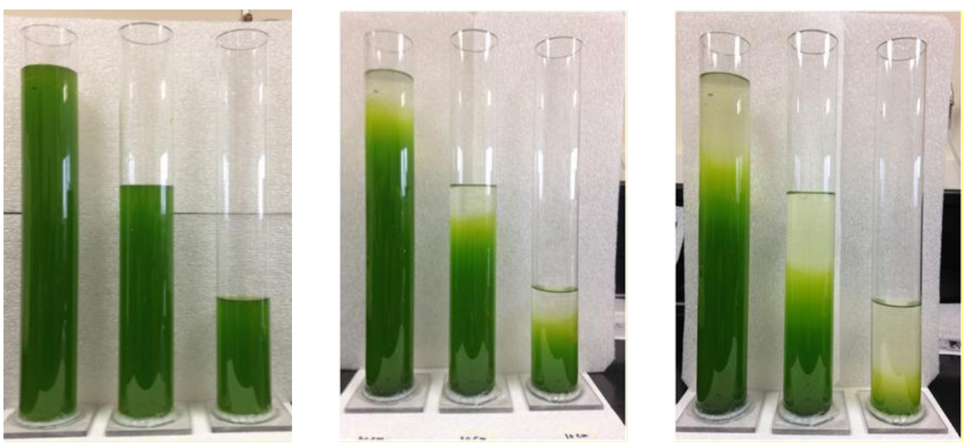
Task 2: Quantify sedimentation rates for different algae and process conditions

The objective of this task was to determine the fastest algae settling rates in the gravity table to achieve concentration ratio of 3 or better without the use of chemicals to enable water recycle for algae culturing within a short duration of time. This would result in taking out 2/3 of the water in the first step.

The impact of several design and operating parameters on the settling rate of algae cultures was studied. Key considerations in the selection of the parameters to be studied included avoidance of chemical additives, low energy requirements, ease of implementation, and cost effective scalability to large sizes. The parameters investigated included culture depth, tank diameter, type of tank surface, initial culture concentration, addition of de-watered algae for seeding, and impact of light. Since the settling rate is potentially impacted by the type of algae, two microalgae species of very different shapes – CV which is spherical and SC which is crescent shaped were used in the tests. The settling experiments were conducted with freshly harvested algae cultures grown in photo-bioreactors (PBR) under natural sunlight as well as under artificial light. It is important to use freshly harvested algae species as the results from healthy cultures is very reproducible. The settling of the algae cultures was studied in batch mode lab-scale tests, by varying the parameters and measuring their impact on settling rate. The efficacy of settling was quantified through the use of the concentration ratio which is defined as the ratio between the initial volume and the final volume of the concentrated algae solution. The results obtained are discussed below:

Effect of Culture Depth and Vessel Diameter

The impact of culture depth and tank diameter on gravity table was studied with SC and CV strains respectively. Over time, the culture separates into two layers - a top clear layer which is mostly algae free and a bottom layer of concentrated algae culture. The depths of these layers were measured as a function of time to obtain the concentration ratio.



0 hr **21 hr** **46 hr**

Figure 3: SC Algae settling at various initial heights (Confidential)

SC algae culture with an initial concentration of 0.8g/L was filled into polycarbonate cylindrical vessels of inner diameter of 4.5cm to initial heights of 10, 20, and 30cm. Figure 3 shows the impact of culture depth on the settling of SC algae. Measurements of the clear depth were taken at periodic time intervals. The results of the impact of culture depth on the settling of algae is summarized in Table 2. It is seen that the settling rate increases significantly with decreasing culture depth as indicated by the highest concentration ratio. Similar trends were observed with CV. This is an important and unexpected result because it suggests that factors such as auto-flocculation likely plays an important role in settling rate.

Table 2: Impact of algae (SC) culture depth on concentration ratio (Confidential)

Time (hr)	Initial Culture Depth (cm)					
	10	20	30	10	20	30
	Clear Depth (cm)			Concentration Ratio		
0	0.0	0.0	0.0	1.00	1.00	1.00
21	3.5	3.5	3.5	1.54	1.21	1.13
46	7.0	7.0	7.0	3.33	1.54	1.30

The CV algae culture with an initial concentration (0.6g/L) was filled into glass sedimentation vessels of 5, 7, and 9cm diameter to identical depths of 9.5cm. The settling rate of the CV species was found to be significantly higher than for SC indicating the importance of tailoring the de-watering technology to the species of algae with most of the selling occurring within the first 21 hours. However, the impact of vessel diameter was negligible which is desirable for future scale-up. The results of varying vessel diameter on the settling of algae is summarized in Table 3 and did not show an initial strong trend.

Table 3: Impact of vessel diameter on settling rate of CV (Confidential)

Time (hr)	Vessel Diameter (cm)		
	5	7	9
	Concentration Ratio		
0	1.00	1.00	1.00
21	19.00	19.00	19.00
46	47.50	47.50	47.50

Algae culture concentration

The impact of initial culture concentration on the settling of algae was studied using various concentration of both CV and SC in polycarbonate vessels each of which were filled to constant depth. Figure 4 illustrates the impact of initial SC culture concentration on the algae settling.

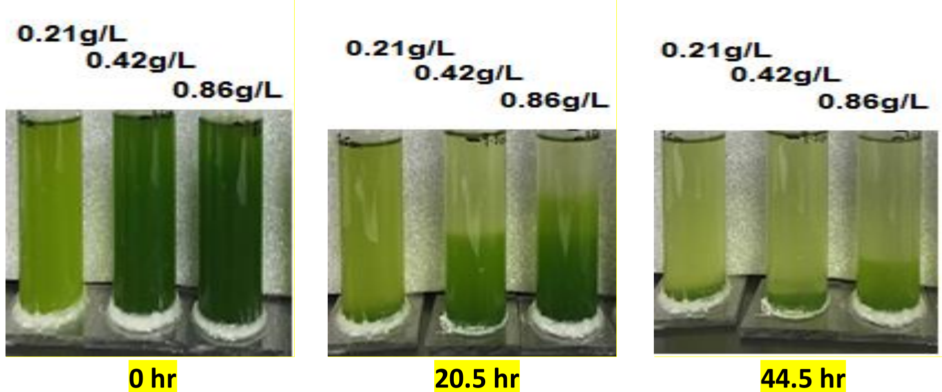


Figure 4: SC Algae settling at various initial culture concentrations (Confidential)

Table 4: Impact of initial SC culture concentration on settling rate (Confidential)

Time (hr)	Initial SC algae Culture Concentration (g/L)		
	0.21	0.42	0.86
	Concentration Ratio		
0	1.00	1.00	1.00
3.5	1.03	1.12	1.06
20.5	4.75	2.11	1.73
27.5	47.50	6.33	2.38
44.5	47.50	47.50	47.50

Table 4 summarizes the impact of initial SC culture concentration on the settling rate starting from an initial culture depth of 9.5cm. It is seen that the settling rate is the highest in the SC culture with the lowest starting concentration, and lowest at the highest concentration. Similar results were obtained with CV. It was found that the settling rate is the highest in the vessel containing the culture with the lowest concentration and lowest at the highest concentration.

Thus for both species the settling rate clearly diminishes at high concentrations. This is most easily explained by the increased cell-to-cell interactions affecting terminal velocity as concentration increases. Studies by Helios-NRG, outside the present project, on several relevant species, has shown that the algae growth rate decreases above concentrations of ~0.5g/L. This finding hence has important ramifications in the eventual applications because it suggests that culture concentrations of ~0.5g/L might be optimal from the perspective of both de-watering as well as algae productivity.

Sedimentation vessel surface material

The impact of varying the sedimentation vessel surface material on the settling of algae was conducted using vessels made of polycarbonate (PC), Plexiglas (acrylic), polyethylene terephthalate (PET), and glass. Initial concentration for CV and SC algae were 0.49 and 0.67g/L respectively and were filled to a height of 9.5cm in all the sedimentation vessels.
The results are summarized in Table 5. It is seen that CV has a higher settling rate than SC independent of vessel surface material. This is because SC cells have a different shape and possibly more motility than CV.

Table 5: Impact of sedimentation vessel surface on settling of CV and SC (Confidential)

Time (hr)	SC Settling Vessel Surface Material					CV Settling Vessel Surface Material				
	Glass	PC	Plexiglas	PET capped	PET uncapped	Glass	PC	Plexiglas	PET capped	PET uncapped
	Concentration Ratio									
0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
5	1.0	1.0	1.0	1.2	1.2	1.0	2.0	2.0	1.7	1.7
23	1.0	1.9	1.9	2.1	3.2	19.0	95.0	95.0	95.0	95.0

We believe that the observed results on the impact of vessel material are the direct consequence of surface charge interaction between the algae species and the surface of the settling vessel. Both CV and SC cells possess a negative surface charge. Because of this, they do not settle well in glass vessels which possess a relatively high negative surface charge resulting in repulsion. In the case of CV, there is slow settling in glass after ~5 hours while SC did not settle in glass tanks during the duration of the test also likely due surface interactions and possibly higher intrinsic mobility.

Much faster CV settling was observed in polycarbonate, Plexiglas and PET vessels than in glass. It is suspected that since the plastics have a different surface charge distribution than glass, that interactions between the wall and the algae needs to be considered in Phase 2. Similar trends were observed with SC, but in general, the settling rates were lower. The capped vs. uncapped results in Table 5 correspond to the settling tanks being closed or open to oxygen in the air - this did not meaningfully impact the settling rate for either species. Overall the PET vessels produced the best settling rates.

Settling vessel shape

The impact of varying the sedimentation vessel shape on the settling of algae was conducted for CV and SC with initial concentrations of 0.95 and 0.64g/L respectively. CV was used to compare the settling rates in an upright vs. and inverted conical vessels, with base diameters of 8 and 3cm respectively. SC was used to compare the settling rate in three shapes - conical, inverted conical and cylindrical with base diameters of 8, 3, and 5cm respectively.

Table 6: Impact of sedimentation vessel shape on settling of CV (Confidential)

Time (hr)	Settling Vessel Cone Shape	
	Upright	Inverted
	Concentration Ratio	
0	1.00	1.00
6.5	1.46	1.27
19	47.50	19.00

Table 7: Impact of sedimentation vessel shape on settling of SC (Confidential)

Time (hr)	Settling Vessel Shape		
	Cylinder	Upright Cone	Inv. Cone
	Concentration Ratio		
0	1.00	1.00	1.00
2.5	1.01	1.32	1.06
5	1.10	1.51	1.20
7.75	1.20	1.73	1.32
10.75	1.36	2.38	1.58
23.75	2.44	47.50	47.50
29.75	6.33	47.50	47.50

The results are summarized in Tables 6 and 7 for CV and SC respectively. For CV the upright conical vessel gave approximately 2.5x faster settling than inverted cone. For SC, the upright conical vessel gave approximately 7.5x faster settling than the cylindrical vessel. Despite the higher intrinsic mobility of the SC cells, a surprising observation was that in these experiments SC exhibited a higher settling rate than CV. We believe that this observation is attributed to the that the CV used in this work was an older culture which likely contained secreted proteins which inhibit settling while the SC was a much younger, fresh culture. This strongly suggests that the continuous process envisioned in Phase2 will yield improved performance. Regardless, in practice only vessel shapes such as cylindrical or rectangular would be commercially feasible. A continuous flow process in phase 2 will be required and the concept of the increased base size could be mimicked to enhance settling, by allowing the algae more space to settle as they move away from the addition end of the vessel towards the removal end of the vessel. In these shapes, a concentration ratio of ~2-5 could be readily achieved in 12 - 24 hours.

Light and dark environment

The settling of algae is impacted by its intrinsic mobility. Since the mobility is affected by the presence of light, this test was aimed at determining if faster settling rates can be obtained in dark settling tanks. Settling experiments were conducted using CV at an initial concentration of 0.71g/L using vessels made of PET and polycarbonate filled to constant depth of 9.5cm. The shapes of the vessels were also varied to provide a comparison with sections above.

Table 8: Impact of dark environment on settling of CV (Confidential)

Time (hr)	Dark		
	Cylinder	Cone	Inv. Cone
	Concentration Ratio		
0	0.0	0.0	0.0
2	1.12	1.36	1.12
3.75	1.19	1.46	1.27
6	1.36	1.90	1.46
22	3.80	31.67	31.67

The settling rate of CV algae was found to be accelerated when in the dark environment. We believe that this occurs because in the dark environment, the lack of light inhibits the mobility of the algae, hence promoting settling. In addition, the clear top portion of the settled culture is much clearer for cultures settled in the dark environment than in the light environment enabling higher yield in sedimentation. Since settling in the dark requires no energy addition, this technique is attractive from the low energy perspective.

Summary of Task 2 Results

The work in this task demonstrated the technical feasibility of Stage 1 of the DeAqua process. It showed that the sedimentation of algae by means of gravity table, can be significantly enhanced without chemical addition and can be performed at very low energy levels. Various factors impacting the gravity table of the algae were systematically explored. The most important factors promoting settling are moderate culture depths, low to medium algae culture concentration, and operation in a dark environment. Utilizing a vessel surface (e.g. liner) that has low negative charge (e.g. PET, PE) further enhances settling rate. Preliminary experiments to explore the impact of altering the pH or adding algae seeding to the harvested culture did not improve the settling rates. In the case of settling operation in the dark, it is seen from Table 6 and 9 such that a concentration ratio of ~3 or higher could be achieved under 22 hours through a cylindrical sedimentation vessel, which is highly encouraging as this would results in the decrease of the residence time required for the settling process to occur. Helios-NRG believes that by integrating the parameters that promote faster settling into an advanced sedimentation vessel design, the settling rate can be greatly increased over state of the art which is shown in Fig. 5. This can enable a concentration ratio of ~4 or higher in 24 hours - a factor of ~3x over current state of the art and resulting in removing 60 to 80% of the water from the culture with very low energy and cost. Achieving a higher concentration ratio in the same time in the improved gravity table (Stage 1 of DeAqua) has a major impact on the overall economics. This occurs both because the process used here is characterized by very low energy requirement and also because it accounts for the bulk of the water being recycled in the process. Further improvement is expected by using a continuous process (Integrated Design) which is amenable for large scale operation and is one of the Phase2 objectives.

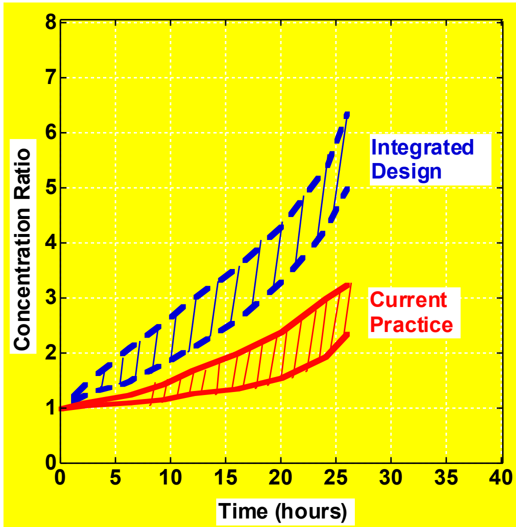


Figure 5: Estimated Concentration Ratio with respect to Time (Confidential)

Task 3: Select commercial membranes, modify surface & characterize (UB)

Membrane selection and coating: To study the effect of modification of membranes on antifouling properties, we have selected the most common commercial ultrafiltration membranes for wastewater reuse. Polyethersulfone and polyacrylonitrile from Sepro, and polysulfone from Alfa Laval were chosen in this study. Table 9 summarizes the information about these membranes.

Table 9: Selected membranes for surface modification to improve antifouling (Confidential)

Membrane Material	Membrane Type	Manufacturer	Pore Size
Polyethersulfone (PE-2)	UF	Sepro	4 kDa MWCO
Polyacrylonitrile (PAN-50)	UF	Sepro	50 kDa MWCO
Polysulfone (PS-100)	UF	Alfa Laval	100 kDa MWCO

Before coating the membranes, the glycerin inside the pores (to preserve pore structure) was removed by soaking in ethanol and then in water. The coating is performed by exposure the membrane surface to the solution containing PDA and SBMA in a rocking platform shaker. The successful coating of PDA and SBMA can be confirmed using x-ray photoelectron spectroscopy (XPS), which indicates the increase of N and P element content on the surface.

Effect of surface modification on contact angles: Fig. 6 shows the effect of coating composition and time on membrane surface hydrophilicity, indicated by water contact angles determined using a Ramé Hart contact angle goniometer. The values were taken as an average of at least five points. In general, the contact angle decreases with increasing SBMA content and deposition time before leveling off. Therefore, the use of SBMA with 2g/L and deposition time of 2 hour would yield sufficiently low contact angle, or good surface hydrophilicity.

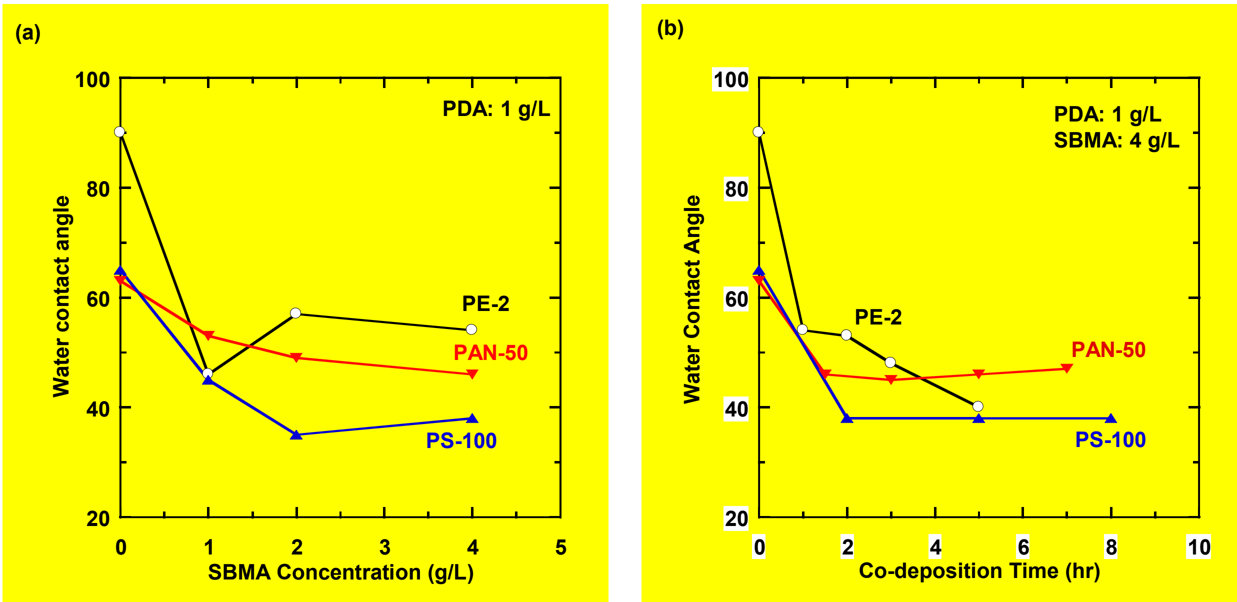


Figure 6: Water contact angle as a function of (a) SBMA concentration with a PDA content of 1g/L and (b) deposition time. For Fig. 6 (b), the deposition time was 1, 1.5, and 2 hour for of PE-2, PAN-50, and PS-100, respectively (Confidential)

In conclusion, commercially available UF membranes were selected and the surface modification conditions (such as composition and deposition time) optimized to improve the membrane surface hydrophilicity. The results show that the hydrophilicity can be greatly increased via the surface modifications.

Task 4: Characterize de-watering properties of advanced membranes (UB)

Effect of coating on pure water flux. The pure water flux was determined using dead-end filtration cells. The water permeance, AW (liter per m^2 hr bar, LMH/bar), can be calculated using the following expression:

$$A_W = \frac{1}{\Delta p \cdot A_m} \frac{dV_W}{dt} \quad (2)$$

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.

Fig. 7a shows the effect of SBMA content in the coating solution on pure water permeance for PE-2, PAN-50, and PS-100. The introduction of SBMA in the coating solution initially decreases water permeance and then the effect levels off for all three membranes. Fig. 7b shows that increasing the deposition time decreases water permeance and the effect levels off after 2 hour coating. In general, the coating seems to have more effect on the membranes with small pores such as PE-2 than those with larger pores such as PAN-50 and PS-100.

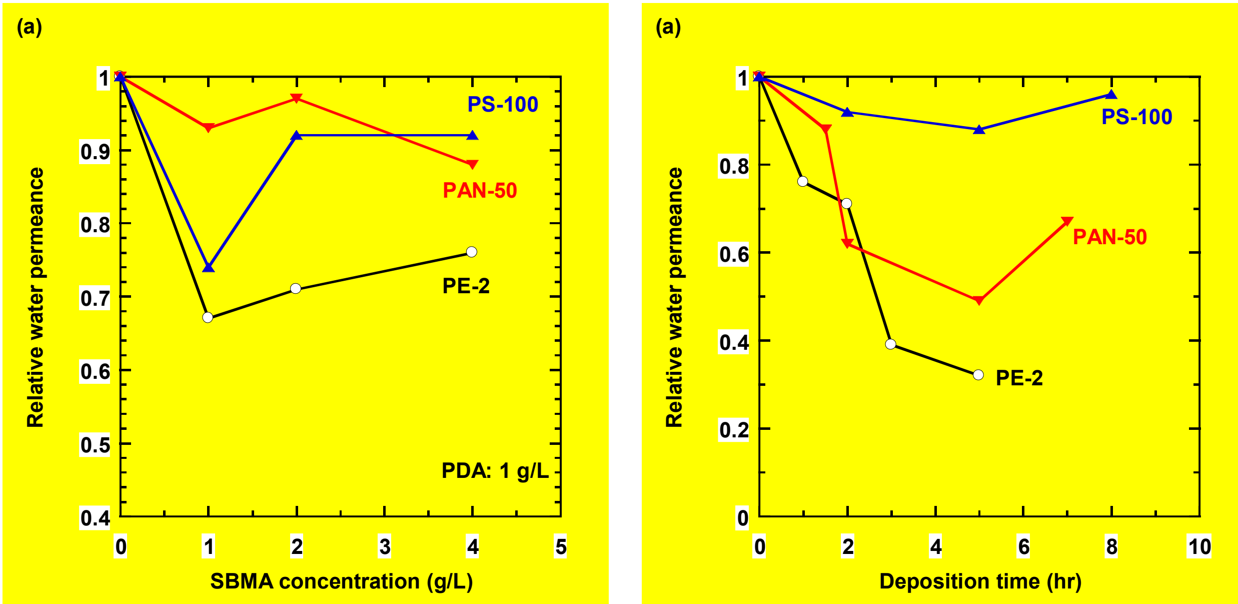


Figure 7: Relative water permeance as a function of (a) SBMA content with PDA content of 1g/L and (b) deposition time. For Fig. 2 (a), the deposition time was 1, 1.5, and 2 hour for of PE-2, PAN-50, and PS-100, respectively (Confidential)

Based on the gained understanding of the effect of SBMA content and deposition time on membrane surface hydrophilicity and pure water permeance, we have selected the most convenient conditions for surface modification to achieve the most improved hydrophilicity and water permeance. The modification conditions are summarized in Table 10.

Table 10: Selected membranes with simple modification process and good improvement of surface hydrophilicity and water permeance. DT: deposition time (Confidential)

Sample Type		**PE-2**	**PAN-50**	**PS-100**
PDA Coated	Conditions	PDA=2g/L DT=1hr	PDA=2g/L DT=1.5hr	PDA=2g/L DT=2hr
	Contact angle (°)	69	55	38
	Relative water permeance	0.64	0.71	0.76
PDA/SBMA Co-Deposition	Conditions	PDA=1g/L, SBMA=1g/L, DT=1hr	PDA=1g/L, SBMA=4g/L, DT=1.5hr	PDA=1g/L, SBMA=4g/L, DT=2hr
	Contact angle (°)	46	46	35
	Relative water permeance	0.67	0.88	0.92

Fouling tests using a crossflow system. A cross flow filtration system was designed and built in our laboratory for antifouling experiments, as shown in Fig. 8. Three filtration cells with a membrane surface area of 19.4cm^2 each were used in series. The membrane feed side Reynolds number was estimated to be ~1000.

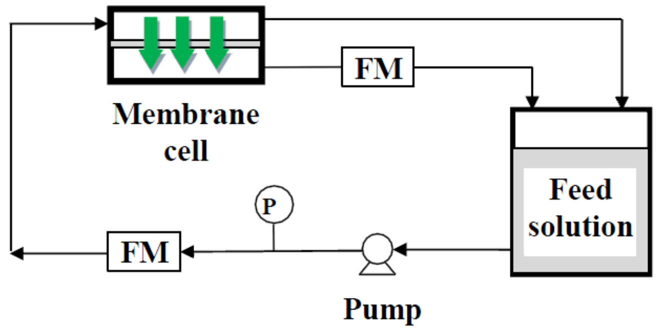


Figure 8: Schematic of a crossflow membrane test apparatus (Confidential)

We have extensively studied the water permeance in the three commercial membranes (unmodified, PDA-modified, and PDA/SBMA-modified ones) for microalgae de-watering (SC and CV at different concentration). As an example, Fig. 9a and 9b show the water permeance as a function of time for algae de-watering. In all cases, the PDA modified membranes reached similar final permeances to those of the corresponding unmodified ones. This occurs as the fouling rate increases due to the increase in the surface charge positivity due to the increase in the amine groups in PDA, which leads to greater interactions between the modified surface and the algae cell. Therefore, the compromised effect between the favorable hydrophilicity increase and unfavorable reduction in the surface negative charges leads to unchanged water permeance after PDA coating for microalgae de-watering.

On the other hand, the coating with PDA/SBMA clearly demonstrates higher water permeance than the unmodified membranes. For example, the PDA/SBMA coated PAN-50 shows 28% improvement in the permeance than the virgin membranes when testing with a solution containing 4.57g/L SC. These results confirm the improvement of antifouling properties from the SBMA coating and the benefits of enhanced water permeances. Similar results have been observed for other two membranes (PE-2 and PS-100).

To further verify the improved antifouling properties by coating with PDA/SBMA, we have also evaluated the membranes for treating water containing BSA, and the results are shown in Fig. 9c. BSA is used as marker for foulants, and it can be convenient to increase the BSA content. The coating with PDA/SBMA again increases the water permeance compared with the virgin membranes, which are consistent to those testing with microalgae solutions.

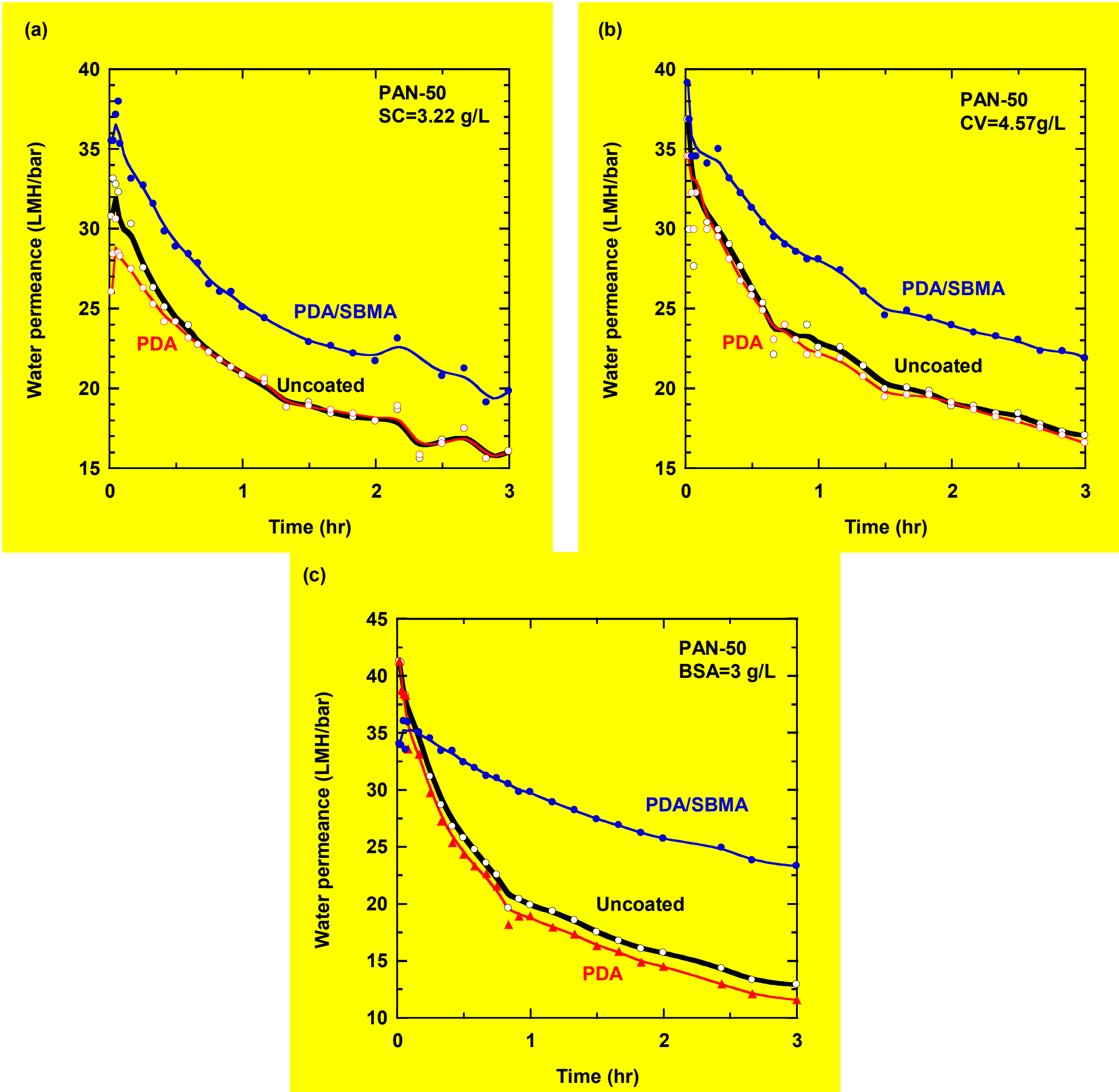


Figure 9: Permeate permeance as a function of filtration time for unmodified, PDA modified, and PDA/SBMA coated PAN-50 membranes when tested with water containing (a) 3.22g/L SC, (b) 4.57g/L CV, and (c) 3g/L BSA (Confidential)

The benefit of surface modification on water permeance in the presence of foulants can be characterized using permeance improvement (β_W), which is defined as:

$$\beta_W = \frac{A_{W,\mathrm{m}} - A_{W,\mathrm{v}}}{A_{W,\mathrm{v}}} \times 100\% \qquad (3)$$

where $A_{W,\mathrm{m}}$ is the final permeance of the modified membranes and $A_{W,\mathrm{v}}$ is the final permeance of the uncoated membrane.

Table 11 summarizes the percentage of permeance improvement is the PDA/SBMA- modified membranes for de-watering microalgae and BSA. In general, the permeance improvement is more significant with increasing microalgae or BSA content. For example, when treating a solution containing 3g/L BSA, the PDA/SBMA coated PAN-50 shows an improvement as high as 86%.

Table 11: Percentage of permeance improvement with the PDA/SBMA modification relative to the corresponding unmodified membranes for PE-2, PAN-50, and PS-100 at different concentrations of SC, CV, and BSA (Confidential)

Foulant	Concentration (g/L)	PE-2	PAN-50	PS-100
SC	1.17	15%	12%	31%
	3.22	26%	24%	20%
CV	2.28	20%	14%	23%
	4.57	18%	28%	23%
	6.86	16%	26%	42%
BSA	0.3	1%	46%	22%
	1	27%	67%	82%
	3	65%	81%	61%
	5	35%	44%	31%

Overall, the results of this task are highly promising because it clearly demonstrates that by modifying the surface of membranes using super-hydrophilic layers the rate of fouling by algae deposition during de-watering can be significantly decreased. Furthermore the impact is greater at higher algae concentrations. We believe that there is significant potential for further improvement by optimizing the coatings, developing a module enabling higher Reynolds number (Re) operation, tailoring the Re to the feed algae concentration to enhance self-cleaning and through beneficial impact in periodic regeneration. These improvements are integral to the Phase2 project.

Task 5: Mechanical De-watering

The objective of this task is demonstrate the feasibility of mechanical de-watering to achieve a solids loading of 250g/L starting from a concentrated algae solution with a solids loading of ~25-35g/L.

The feed to Stage 3 in the process (Fig 1) is an algae slurry with a concentration of ~25-35g/L while the product is a semi-solid with a loading of 250g/L. Hence during Stage 3 de-watering there is a step change in viscosity and rheology of the material. The selection of the best technology for this stage is driven by the requirement to be able the handle this major change in rheology as well as considerations such as low energy and ability to scale to larger sizes in a cost effective manner. After considering various technologies, a mechanical filter press was selected as the best option.

Helios-NRG, LLC obtained a 10 Ton batch hydraulic press (Model HSP-10H) from Baileigh Industrial, Inc. This press is suitable for small lab tests and the applied pressure could be monitored and varied as needed. The filtration cloth media was fitted into a specially designed perforated steel chamber (12.5cm x 12.5cm x 4.0cm). Using this setup, pressures up to 1000psi could be applied, although all tests were done at much lower pressures. De-watering tests were conducted using the two microalgae species, CV and SC, discussed earlier. The CV cells are ~2-5μm in diameter. The characteristic dimension of the SC cells are similar although, because of their crescent shape, an effective diameter is difficult to define. The filtration media (MC-101) obtained from Met-Chem, Inc. is made of non-woven yarn with a pore diameter in the range of 0.5-1μm which was deemed suitable because the size of the algae cells.

The de-watering of the various algae cultures were performed and the volumes of water removed and the mass of algae cake produced recorded. The mechanical energy for the de-watering of algae by mechanical press (W) is calculated as the product of the applied pressure (P) and the volume of water (V) removed as per Eq. 4.

$$W = P \times V \tag{4}$$

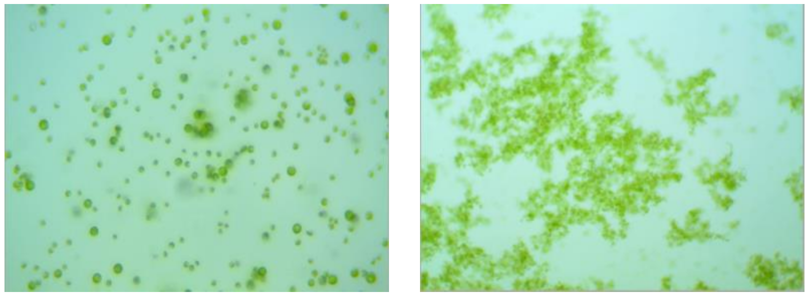
In the mechanical press experiments, which were performed in batch mode, the initial volume used was 0.2L and this was introduced into the steel chamber lined with the filter media. One of the significant findings was that a significant portion of the water in the feed slurry could be removed by simple gravity drain to produce a paste which could then be de-watered to 250+g/l by applying pressure. This is likely the result of auto-flocculation as the culture is concentrated and consistent with the non-linear increase in viscosity at concentrations above ~40g/L. This 2-step de-watering process greatly reduced the energy requirements for this already low energy process. Thus if a water volume of V_1 liters is collected in the first step the effective volume of paste to be pressed is reduced to (0.2- V_1). The mechanical press was used to apply a pressure of ~275psig in most tests. The volume of water removed during pressing (V_3) can be collected and measured. However, this is highly error prone due to the water retained in the filter media. Hence V_3 is estimated using the volume of semi-dry algae cake collected (V_2) which can be estimated from the mass of algae cake (M_1) assuming that the density of the algae is 1g/cm^3. A density of 1 g/cm^3 for is strongly supported by the long sedimentation times required for algae which shows that its density is close to that of water. Hence, V_3 is determined using Eq. 5.

$$V_3 = 0.2 - V_1 - V_2 \tag{5}$$

The energy used by the mechanical press for de-watering is defined by Eq. 6.

$$W = P \times V_3 \tag{6}$$

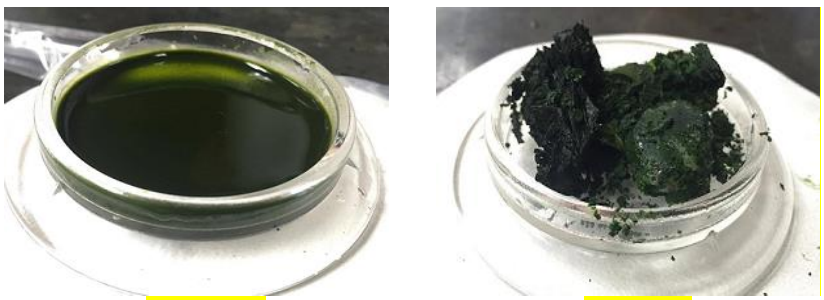
Our work showed the addition of a very small amount of alum potash improved the gravity drain in step 1 of this process. In most cases, the removal of V_1 by gravity drain would typically results in the concentration of the feed solution to increase by a factor of ~3x (~100-150g/L), resulting in the transition of the feed slurry into a paste. The impact of this on cost and water recycle is negligible due to the minute amount of alum required (drops per liter) and because ~99% of the water is extracted in Stages 1 and 2 where no chemicals are used. Figure 10 shows the images of magnified images of *Chlorella vulgaris* (CV) for non-flocculated and flocculated samples. It is seen that the addition of alum results in large clumps of the algae cells. These large clumps enables accelerated drain of the water through the filter media in step 1 enabling an algae paste to be formed rapidly. In the future, we expect that through the selection of better filter media and/or surface treatment, and the use of something like a belt and roller press, that the addition of alum will be entirely eliminated while performing the gravity drain portion of mechanical de-watering.



a: Slurry (10x) b: Flocculated Slurry (10x)

Figure 10: Magnified images of CV algae slurry before and after flocculation

Algae solutions of various concentrations were prepared to determine its effect on the energy requirement for the de-watering process. The semi-dry algae cake from the mechanical press is air dried to determine surface water content. The solids loading of the algae cake was ~54% for CV and ~26% for SC - both of these are higher than our project target of 250 g/L. The visual comparison between an algae slurry of ~40g/L and the algae solid of 250+g/L is shown in Figure 11.



a: Slurry b: Solid

Figure 11: Algae slurry (~40g/L) and algae solid (250+g/L) (Confidential)

The results of the energy requirement for the de-watering of algae by mechanical press for CV and SC algae is as summarized in Table 12 and 13 respectively.

Table 12: Impact of feed CV concentration on mechanical de-watering energy (Confidential)

Conc. (g/L)	Percent Recovery (%)	Mechanical Energy (kJ/kg)	Thermal Equiv for Producing Mechanical Energy (kJ/kg)
20	87.5	42.2	140.7
30	85.7	56.3	187.5
40	95.1	68.0	226.6
50	65.2	70.1	233.6

The mechanical energy for the de-watering of the CV slurry in Table 12 was calculated using Eq. 6, and ranged between 40-70 kJ/kg. In practice, this mechanical energy would be produced using an electric motor (~95% efficient) and the average thermal efficiency of the electrical utilities supplied by the US power grid is about 35%. Hence the thermal energy required to provide this mechanical energy is considerably higher as shown in Table 12. Despite this being a higher number, Helios-NRG believes that this is the legitimate way to make the energy assessment because the reported energy content of the algae is as thermal energy.

Thus the thermal energy required for de-watering is 140-235 kJ/kg - which is below our target of 250 kJ/kg.

Table 13: Impact of feed SC concentration on energy requirement (Confidential)

Conc. (g/L)	**Percent Recovery (%)**	**Mechanical Energy (kJ/kg)**	**Thermal Equiv for Producing Mechanical Energy (kJ/kg)**
30	42.4	58.1	193.5
40	41.6	42.8	142.5
50	25.6	84.0	280.0

Similarly the mechanical energy for the de-watering process in Table 13 is calculated by Eq. 6, ranging between 40-85 kJ/kg, well below the budgeted energy. The net thermal energy required for the SC algae de-watering by mechanical press is of range between of 140 to 280 kJ/kg, which is close to or below the target energy of 250 kJ/kg. We suspect that the data at 50g/L has higher error due to the very low recovery in the test. The low recovery in all these tests is primarily the result of very small scale batch operation where the mass of algae collected is only a few grams as well as leakage from the filter box at the seams. We expect that in continuous belt press operation, as envisioned for commercial operation, the recovery will be ~95% - similar to that currently achieved in other applications.

Summary of Task 5 Results

The work in this task demonstrated the technical feasibility of the mechanical de-watering process used in DeAqua to achieve algae solids loading in the range of 25-55% by weight at low energy. As explained under Task 6, our work in Phase1 indicates that the optimum feed concentration to Stage 3 is ~30g/L at which the energy for de-watering, on a thermal basis, is ~190 kJ/kg - which is well below our target of 250 kJ/kg for both species. We believe that this is a significant achievement. In this Phase1, the mechanical press de-watering process was performed in small batch operation. For algae mechanical de-watering process to be commercially viable the process must be transitioned from a batch process to a continuous process, which will increase recovery and reduce cost. The additional development required for this is one of the key objectives of Phase2.

Task 6: Process Analysis, Economics and Conceptual Design

The objective of this task is to develop an overall flow sheet for the DeAqua process (Fig 1) with energy and mass balances, identify preferred design/operating conditions and determine preliminary economics. The impact of key variables such as inter-stage algae concentrations, operational pressures and sedimentation vessel sizing are assessed and energy and cost for each of the steps calculated.

The preliminary process assessment is based on an algae culture farm area of 1000 acres, which based on Helios-NRG previous work is expected have a productivity of at least 46 tons algae/acre/year. At a concentration of 0.5 g/L, this would result in a flowrate of 92 Million m^3/year of algae culture into stage 1. The DeAqua process is estimated to have an overall water recovery of 99.8%, with the recoveries in Stages 1, 2, and 3 being 66-83%, 15-23%, and ~1% respectively. The total cost per kg-algae for each stage of the process is defined as the summation of the capital cost and energy cost per kg for each of the respective stages. In the discussion below, the energy cost is estimated using input electrical power and a grid power cost of $0.05/kWh.

The capital cost in Stage 1 is from the cost of land required, liner and construction for the sedimentation vessels as well as a system for transporting the overall recycled water to the algae culture ponds. The energy cost in Stage 1 is attributed to the power required to transport the recycle water over a specific head of water, based on the depth of the sedimentation vessel and the height of the algae culture tank (estimated to be 0.5m). Therefore, the depth of the sedimentation vessel in Stage 1 is a key variable in optimizing the overall Stage 1 process. The sizing of the sedimentation vessels were estimated based on work in Task 2, whereby Helios-NRG has determined that 17 hours was sufficient to achieve a concentration ratio of 3. The impact of the sedimentation vessel depth on the cost of algae is summarized in Figure 12.

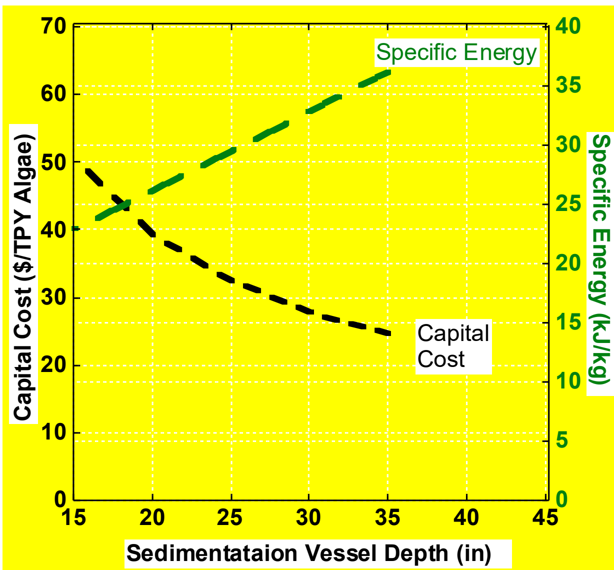


Figure 12: Impact of Vessel Depth on Stage 1 Capital Cost and Specific Energy (Confidential)

As the depth of the sedimentation tanks increase, the required area of the sedimentation vessel decreases thus decreasing capital cost. However, as the vessel depth increases, the length of time for algae settling increases and the power required to pump the recycle water back to the PBR tanks increases due to the increased head. Because Stage 1 is an ultra-low energy step, the cost of algae de-watering in Stage 1 is dominated by the capital cost of the sedimentation vessels as compared to the energy cost. In the present analysis we used a conveyor bucket system for transporting the recycle water since its cost and power were available. Helios-NRG believes such that by utilizing a water channel with vane pump (inexpensive and easily scaled to large sizes) for recycling the water the capital cost in Stage 1 can be reduced, further reducing the cost of algae de-watering using DeAqua technology.

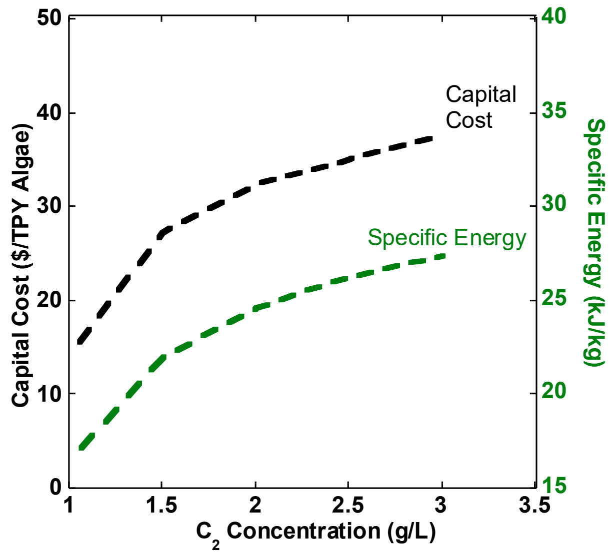


Figure 13: Impact of C_2 concentration on Stage 1 Cost and Specific Energy (Confidential)

The impact of Stage 1 outlet flow concentration, C_2, on the Stage 1 cost is shown in Figure 13. Higher C_2 concentration is achieved by increasing the residence time of the algae culture in the sedimentation vessel which increases the size required and the overall capital cost for Stage 1.The energy requirement cost in Stage 1 is insensitive to the variation in C_2 concentration as the total volume of recycle water is only a weak function of it. However, when seen for its impact on just the volume of recycle water emerging from the gravity table, the increase in C_2 concentration slightly increases the energy requirement.

The capital cost in Stage 2 is primarily compromised of the packaged skid of modified anti-fouling membrane modules and a pump to pressurize the feed stream while the specific energy is based on the power required to pump the algae culture to the feed pressure of membrane operation. Two key parameters were identified to have most impact on the de-watering cost; the membrane feed pressure and the inlet concentration, C_2, of the feed solution into the membrane. The capital cost of the membrane skid is estimated based on the membrane area requirement. In most membrane operations, the water flux through the membrane is linearly proportional to the feed pressure of the system. Hence as the pressure increases, the membrane area required decreases, thus reducing capital cost. The impact of the membrane feed pressure on the cost of algae de-watering in Stage 2 is shown in Figure 14.

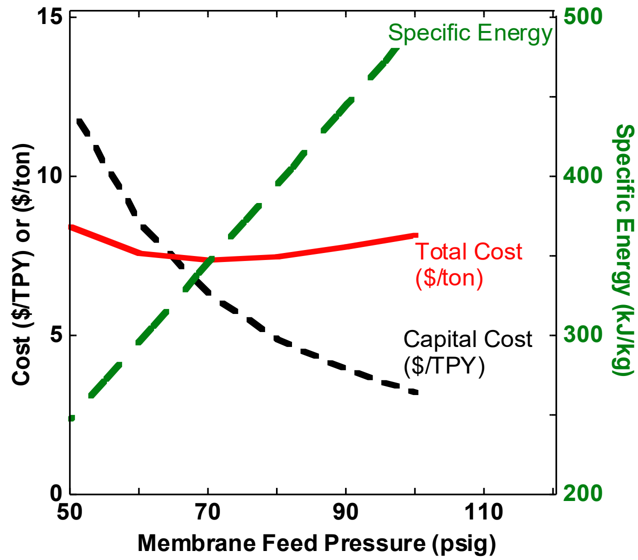


Figure 14: Impact of Stage 2 Feed Pressure on Cost of Stage 2 De-watering and Specific Energy (Confidential)

Figure 14 shows the estimated cost for Stage 2 operation assuming an inlet feed concentration of 1.5g/L and outlet concentration of 35g/L. Due to the large scale of operation and removal of water from an aqueous feed, membrane skid was assumed to cost similar to that of a commercial RO system ($60/m^2 packaged skid). The increase in the membrane feed pressure reduces the membrane area requirement, therefore reducing the capital cost while the pump power requirement increases, increasing the operational cost of the Stage 2. The optimum pressure is indicated to be ~70psig, but will ultimately depend on the flux performance of the commercial membranes and its unit area cost.

Another key variable affecting to the cost of Stage 2 de-watering is the inlet feed concentration of algae culture, C_2, entering the membrane system, estimated to be between 1.5-3.0g/L. Above Stage 1 analysis concluded that the C_2 value has a dominant effect on the Stage 1 capital cost and little effect on its operating cost. In Stage 2, the increase in C_2 value decreases both capital cost and energy cost due to the reduction in membrane area requirement and pumping power. Hence the impact of C_2 must be studied by considering Stage 1 and Stage 2 together. The impact of C_2 on the cost and energy for Stage 1+2 de-watering is shown in Figure 15.

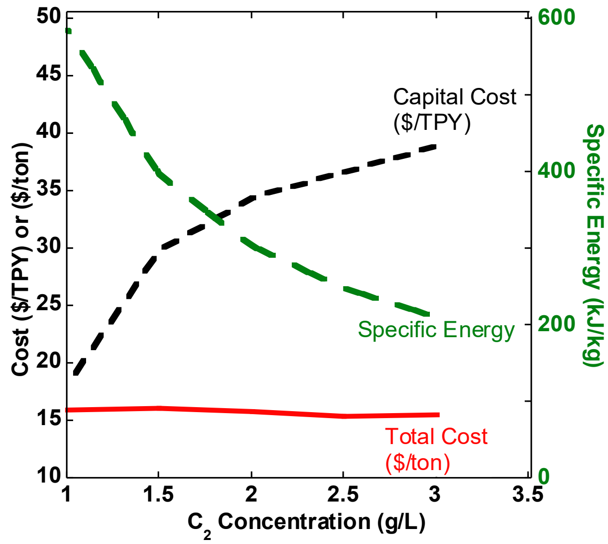


Figure 15: Impact of Stage 2 Inlet Flow Concentration, C_2 on Capital Cost, Specific Energy and Total Cost for Stages 1+2 (Confidential)

In general, the increase in the C_2 concentration results in higher water removal in Stage 1, thus resulting in less volume to be pumped through the membrane system, reducing the membrane area and power requirement for Stage 2. However, when seen in combination with Stage 1 (Figure 15), increasing the C_2 concentration value results in the requirement to increase in the residence time for the culture in the sedimentation vessels, increasing vessel size and thus the capital cost. The total cost of de-watering in Stages 1+2 is hence only a weak function of C_2 with ~2g/L indicated as a good operating point.

The Stage 2 outlet concentration from the membrane system, C_3, is a minor variable affecting the Stage 2 de-watering cost. Variations of C_3 in high concentrations has minimal impact due to the small change in water removal. The increase in C_3 concentration value results in the slight increase in the membrane area requirement as well as the pumping power requirement for Stage 2. The increase in C_3 in Stage 3, results in the decrease in the press power requirement due to the smaller feed stream volume, thus reducing energy cost.

The capital cost in Stage 3 is attributed to the continuous filter press along with its filter media cloth while the energy cost is accounted by the power requirement to operate the continuous belt press. In this stage, C_3 and the operational pressure of the continuous belt press have been identified to have an impact on the de-watering cost. The impact of C_3 concentration on the cost of Stage 2+3 de-watering is shown in Figure 16.

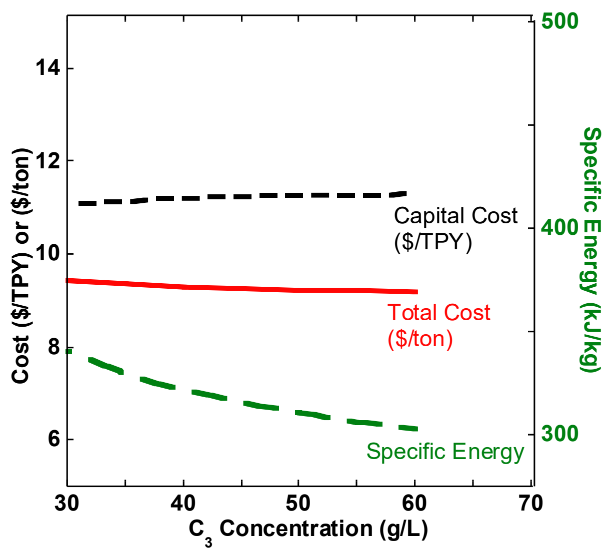


Figure 16: Impact of Stage 2 product conc (C_3) on Cost and Energy for Stages 2+3 (Confidential)

Figure 16 assumes a C_2 concentration of 1.5g/L, a membrane feed pressure of 70psig, mechanical press pressure of 300psig and a product concentration, C_4 of 250g/L. Due to the high concentrations of C_3, the volume of water removed is small, thus weak function of both the capital and energy cost in Stage 2. In Stage 3, the capital cost of the mechanical press is only a weak function of C_3 concentration. The increase in C_3 concentration value decreases the mechanical press work as most of the work would be done in Stage 2. As can be seen, the total cost is a weak function of C_3 which permits C_3 to be selected based on other considerations.

In practice the optimum value of C_3 will likely be determined by practical factors such as processability of the algae slurry. The work in Task 1 clearly showed that the culture viscosity is highly non-linear and increases exponentially above a concentration that is species dependent. This limit appears to be ~40-60g/L for the both species studied. Above this there is high potential for plugging and fouling of the membrane flow channels which must be avoided. However in real operation it is not feasible to ensure completely uniform flow distribution nor permeance in all membrane channels. In practice this will require operation at C_3 concentrations well below the limit stated above. We expect the upper limit of C_3 based on this to be ~30-40g/L. The lower end of C_3 will likely be determined by the processability in the mechanical stage 3 as a low C_3 would result in excessive stream leakage and implementation of a longer filter press belt to sufficiently gravity drain the water, increasing the capital cost. Our work in Phase1 indicated that this is likely to be in the 25-35g/L. Hence based on the work in Phase1, a C_3 concentration of ~30g/L appears to be a rational choice.

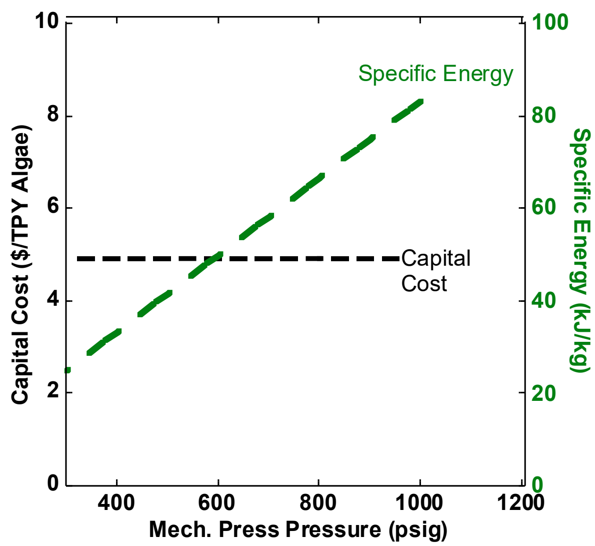


Figure 17: Impact of Stage 3 Mechanical Press Pressure on Cost of Stage 3 De-watering and Specific Energy (Confidential)

The operational pressure of the continuous mechanical belt press accounts for majority of the operational cost. Its impact on the cost of Stage 3 de-watering is shown in Figure 17. The capital cost is insensitive to the mechanical press pressure in the range of operation because most presses are designed for much higher pressures. Increase in the mechanical press operational pressure results in the increase in the cost of Stage 3 de-watering due to the increase in the energy cost.

In our Phase1 Task 5 work, for both species of algae, C_4 concentrations of 260-540g/L, significantly above our initial target of 250g/L, were achieved in many cases. No credit for this was factored into our analysis, although we expect this to add to the economic benefit. In practice this will enable the DeAqua Process to tailor the product algae concentration to the specific needs of different applications.

Overall, based on the preliminary optimization, we have pre-determined the preferred range of several key variables for the DeAqua Process as summarized in Table 14.

Table 14: Preferred range of key variables for the DeAqua Process (Confidential)

Variable	Preferred Range
Stage 1 Sedimentation vessel depth	20-30 in
Stage 2 Mem feed concentration, C_2	2-3 g/L
Stage 2 Membrane feed pressure	60-80 psig
Stage 2 Mem outlet concentration, C_3	25-35 g/L
Stage 3 Mechanical press pressure	~300 psig

Utilizing this preliminary range of operating conditions for the process design (Fig 1) and based on the flowrates for a 1000 acre farm, the inter-stages flow properties were tabulated and summarized in Table 15.

Table 15: Estimated flow properties for a 1000 acre algae farm (Confidential)

	Stage 1			Stage 2			Stage 3		
	Inlet	Outlet	Recycle	Inlet	Outlet	Recycle	Inlet	Outlet	Recycle
Algae Conc. (g/L)	0.5	2.0	0.0	2.0	35.0	0	35.0	250.0	0.0
Volume Flowrate (MMm^3/yr)	92.0	23.0	69.0	23.0	1.3	21.7	1.3	0.2	1.1

The estimated capital and energy requirements for the integrated DeAqua process are summarized in Table 16 for a preferred set of operating conditions (Table15). In our analysis, to be conservative, we have assumed a concentration factor of 4x within 21 hours in Stage 1, although work done in Task 2 indicates such that a factor of ~3x could be achieved within 12 hours or less, which could significantly reduce the overall capital cost. The electric energy shown represents the input power required for the different stages. We have converted this to an equivalent thermal input based on a typical US power plant thermal efficiency of 35%. This is important because algae typically contains ~18-25 MJ/kg of thermal energy and it is essential for the de-watering technology to use only a small fraction of this energy. The preliminary estimate includes the labor cost for a staff of eight full time personnel.

Table 16: Estimated Cost and Energy for DeAqua Process for a 1000 acre farm (Confidential)

		Energy		Total Cost for De-watering (c/kg-algae)
	Capital Cost ($/TPY-Algae)	Mech. Electrical (MJ/kg-algae)	Thermal Equiv (MJ/kg-algae)	
Stage 1	32.5	0.03	0.09	1.03
Stage 2	6.2	0.27	0.76	0.56
Stage 3	4.9	0.06	0.18	0.24
Labor				0.74
Total	43.6	0.36	1.03	2.57

Summary of Task 6 results:

A preliminary assessment of the DeAqua Process including the capital cost and energy requirements has been conducted to determine the feasibility of the overall approach. An internal rate of water recycle of 99.8% was achieved in the process, thus minimizing water consumption. The results are highly encouraging and indicate that DeAqua has the potential to achieve the de-watering at an energy budget of ~ 1 MJ/kg and a total cost of ~2.6 c/kg algae - both well below our initial targets. These represent a step change over current technologies.

The DOE has suggested a baseline of using microbubble flotation followed by centrifugation, both currently available technologies. While combining these is much better than either alone, drawbacks of combining these two methods are 1) centrifugation is limited by high capital and energy costs, and modest volumetric flowrates 2) microbubble flotation generally entails higher costs and in demonstration projects produced variable results depending on species type. Just the centrifugation step, starting from a concentration of 6g/L, is estimated to consume ~4.8MJ/kg of mechanical energy (Table 1) - equivalent to ~13 MJ/kg on a thermal energy basis (assuming a power plant thermal efficiency of 35%) -*a major fraction of thermal energy interest the product algae.* The total dewatering cost, based on a reported work[2], for an integrated two-step process comprising chemical flocculation + centrifugation is estimated to be ~14.2 c/kg algae, significantly above our target.

Task7: Project Management

This task ensured that all programmatic activities were completed in time and on budget to ensure successful completion of the overall project. The Phase1 contract with DOE was signed on 6/8/15. Subsequently Helios-NRG executed contracts and necessary confidentiality agreements with UB, SUNY. Schedules for task completion, billing and reporting were established. Meetings were held with Prof. 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 $149,817 vs. a budget of $149,902.

Discussions were held with Praxair related to application of the technology for non-algae applications of interest to them. Discussions were held with Jordan Walbesser of Hodgson Russ, LLP to develop an IP strategy for the technology being developed including timing and content of patent filings. A market study has been initiated with cost share from Directed Energy to better quantify the market for the technology and identify early opportunities.

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