Techno-Economic Assessment of Open Microalgae Production Systems

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Microalgae represents a promising feedstock due to inherent advantages such as high solar energy efficiencies, large lipid fractions, and utilization of various waste streams including industrial flue gas. This study directly evaluates and compares the economic viability of biomass production from two different open cultivation platforms, 1) algal turf scrubbers and 2) open raceway ponds. Modular sub-process models were developed and leveraged for the economic comparison of the systems on the metrics of harvested biomass. The system boundary was expanded to include downstream processing for the production of renewable diesel through thermochemical conversion for a comparison of the production platforms on a cost per gallon of fuel. Economic results of the two production pathways show a biomass production cost for the algal turf scrubber of \$510 tonne^{-1} and \$8.34 per gallon for fuel. Open raceway pond results give a biomass cost of \$673 tonne^{-1} and a fuel cost of \$6.27 per gallon. Sensitivity analysis show productivity and culture stability to be critical factors in the economic viability. Multiple scenarios are presented with baseline results directly compared to literature and highlight the need for robust growth modelling.

Keywords:
algal turf; open raceway pond; sustainable; algae; TEA

1. INTRODUCTION

Large uncertainties associated with future oil supplies and costs have increased interest in alternative fuel sources. A variety of feedstocks are being investigated for the production of biofuel, with microalgae representing a promising alternative to first and second generation terrestrial crops primarily due to superior productivity and use of non-arable land (Moody et al., 2014; Quinn & Davis, 2015; Wijffels & Barbosa, 2010). As a biofuel feedstock, microalgae is characterized by high solar energy yield, high lipid content, year-round cultivation, can be integrated with various waste streams, and the ability to use low quality water (Pienkos & Darzins, 2009; Quinn et al., 2012a; Richmond, 2004; Venteris et al., 2014). Defining the economic viability of the microalgae to biofuel processes has proven challenging based on the current immaturity of the technology.

A number of techno-economic assessments (TEA) have been completed to analyze the economic feasibility of biofuels derived from a microalgae feedstock (Amer et al., 2011; ANL et al., June 2012; Beal et al., 2015; Benemann et al., 1982; Benemann & Oswald, 1996; Chisti, 2007; Davis et al., 2011; Davis et al., 2014a; Davis et al., 2014b; Jones et al., 2014; Lundquist et al., 2010; Nagarajan et al., 2013; Pienkos & Darzins, 2009; Richardson & Johnson, 2014; Richardson & Johnson, 2015; Richardson et al., 2012; Rogers et al., 2014; Sun et al., 2011; Thilakaratne et al., 2014; Williams & Laurens, 2010). The results range from a low of $2.20 per gallon reported by (Nagarajan et al., 2013) to $31.36 per gallon reported by (Richardson et al., 2012) for commercial scale facilities. Inconsistencies in process boundaries, core modeling assumptions, and variation in processing pathways resulted in two separate harmonization efforts completed by Sun et al. (2011) and ANL; NREL; PNNL (June 2012). A large contributing factor to the variability of results is due to uncertainty in the cost for the production of biomass in the growth system. A small number of studies have focused on understanding the cost to produce and harvest algal biomass. Norsker et al. (2011) report a cost of \$4,520 tonne^{-1} but also report that with optimizations the cost could drop to \$740 tonne^{-1} (assumed photosynthetic efficiency 5%). Davis et al. (2014a) and Jones et al. (2014) have evaluated downstream processing through algal fractionation and hydrothermal liquefaction, respectively, with an arbitrary biomass production cost of \$474 tonne^{-1}. The majority of current TEAs have failed to explore the impacts of different cultivation systems on biomass production costs (ANL et al., June 2012; Barlow et al., 2016; Beal et al., 2015; Davis et al., 2011; Davis et al., 2014a; Davis et al., 2014c; Jones et al., 2014; Lundquist et al., 2010).

The majority of TEAs have assumed the use of an open pond or closed photobioreactor production systems (Davis et al., 2014b; Lundquist et al., 2010; Richardson et al., 2014). An alternative open growth system for producing algae is the algal turf scrubber (ATS). An ATS is an open flow attached growth system. The system employs a substrate that supports attached algal growth. The entire system is constructed on a sloped surface that allows contaminated water to flow over algae which in turn take up inorganic compounds. A critical components of ATS systems is the integration with contaminated water systems such as estuaries or agricultural run-off. The integration of the ATS systems with contaminated waterways reduces the raw nutrient inputs required to maintain high growth rate production while providing an environmental service. ATS systems are based on a native culture which dynamically adapts to changing conditions decreasing culture crash events seen in homogeneous cultures (Lane et al., 2013). ATS systems are relatively simple in design and yield a biomass that can be easily harvested utilizing farm equipment

(Pizarro et al., 2006). ATS systems have currently been used commercially for contaminated water treatment with the produced biomass representing a co-product to water reclamation (HydroMentia, 2016). The stability of the systems and promising productivities make the ATS a system of interest as a biomass production platform for biofuels. The cultivation and harvesting of native cultures while improving culture robustness does yield low lipid algae typically with a high ash content (Christenson & Sims, 2012; Gross et al., 2013; Kesaano & Sims, 2014; Schnurr et al., 2013). The low lipid algae and high ash content represent hurdles that need to be overcome in the commercialization of ATS systems for the production of a bioenergy feedstock. ATS systems are of interest in terms of a growth platform for the production of a biofuel feedstock based on the advantaged described with the need to better understand the economic viability compared to traditional open raceway systems as a function of inherent operational tradeoffs.

Based on the current state of the field there exists a need to quantify the costs associated with microalgae feedstock production in large-scale open systems. A systems engineering process model was developed and integrated with economic modeling to evaluate the cost of producing biomass in an ATS and open raceway pond (ORP) growth systems. Results from this study focus on a direct comparison of the cost for the production and harvest of biomass through the two growth platforms. Modularity in model construction facilitated the integration of downstream processing through hydrothermal liquefaction (HTL) for an economic evaluation of the production of fuel. Multiple case scenarios are evaluated that are intended to represent a conservative near term system and an optimistic scenario envisioned to represent performance that includes advancements from research and development. Discussion focuses on sensitivities of the individual processes, optimization of each system for a final fuel cost of $3 per gallon of gasoline equivalent (GGE), and a direct comparison of results to literature.

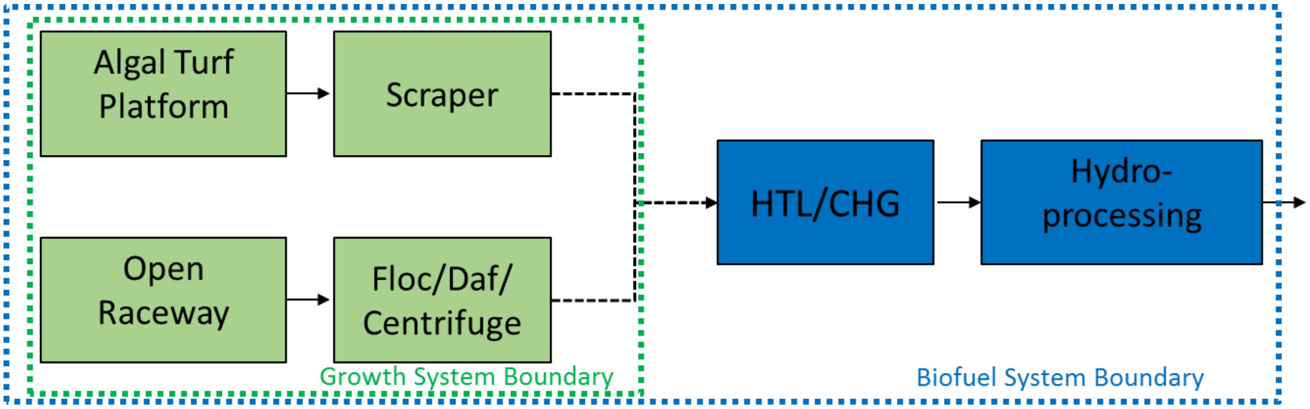

Figure 1: System boundaries allowing for comparisons of ATS and ORP growth systems on the metrics of biomass cost per tonne and fuel cost per gallon.

2. METHODS

An engineering systems model was generated for both the ATS and ORP growth and harvest systems. Biomass production for each system was 500 ktonne ash free dry weight per year (Davis et al., 2014a; Davis et al., 2014b; Jones et al., 2014). Modeling and results for each of the production systems was divided into two efforts corresponding to the evaluation of the costs associated with biomass production and extension of the work for the evaluation of fuel production corresponding to system boundaries defined as 1) growth system and 2) biofuel system, respectively, Figure 1. The first boundary, growth system, was limited to the production and harvesting of biomass to 20% solids. The second boundary, biofuel system, expands work to include the production of renewable diesel through HTL. Energy and mass flows from the engineering process model were combined with economic modeling to evaluate the viability of production through the alternative pathways and directly compare the two growth architectures. Results are presented on a cost per metric ton of 20% solids ash free dry weight biomass for the first system boundary and cost per gallon of renewable diesel for the second system boundary with all results presented in 2014 dollars. Detailed assumptions are presented in the next sections.

2.1 ATS Growth System

Systems modeling was used to develop and assess microalgae growth utilizing an ATS system. Foundational inputs for the ATS growth system are listed in Table 1. The growth rate was set at 20 g m^{-2} d^{-1} with an assumed lipid content of 10% based on data provided by Sandia National Laboratories (SNL) and literature (Mulbry et al., 2009; Mulbry et al., 2012; Mulbry & Wilkie, 2001). This growth rate is based on experimental data collected through SNL and industry represents a conservative annual average productivity. The low lipid is characteristic of polyculture systems (Christenson & Sims, 2012; Gross et al., 2013; Kesaano & Sims, 2014; Schnurr et al., 2013). The ATS module length was set at 152 m (500 ft.) with each ATS unit set to 405 hectares (1000 acres). The module is a slightly sloped growth platform were contaminated water is passed from the top of the system to the bottom. A schematic drawing and images of ATS systems are presented in the supplementary material. ATS systems are designed to integrate with contaminated water systems and do not require additional nutrients to be added to the system with the assumed growth rate observed at pilot scale. The designed system is assumed to limit the delivery of water to a single pass with water delivered through a head rail system. The required hydraulic loading rate is 124 lpm per linear meter. Pumping efficiency was assumed to be 67% with 4 m of pumping head. The power required was calculated using equation 1 where g is gravity, R_H is the hydraulic loading rate, n is the number of ATS modules, W_m is the width of each module and η is the pumping efficiency:

$$P_{ph} = \frac{g * R_H * n * W_m}{\eta} \quad (1)$$

The resulting power that is required is 0.80 MW m^{-1}. Accounting for 14 hours of total pumping per day results in a power consumption of 4100 MWh m^{-1} year^{-1}. The ATS system is designed with a 0.5% slope and utilizes a liner and 3D attachment screen to provide a textured substrate for improved productivity. Capital costs associated with earthworks, roads, piping and land are $371k, $297k, $863k and $3M per 405 hectares respectively (Lundquist et al., 2010). Earthworks is a critical component to the system as a slight slope is required for proper water flow. Liner and attachment screen costs represent significant capital investment at $22 million per 405 hectares. The liners are more robust than a standard pond liner as they must withstand harvesting operations. There are no costs associated with nutrient loading due to the assumption that the ATS utilizes waste and contaminated water systems to provide required nitrogen, phosphorous, and carbon. The system is designed and assumed to operate on native algae to the system resulting in a polyculture. Detailed capital assumptions are included in the supplementary material.

Table 1: Baseline assumptions for the ATS and ORP growth systems for annual production of 500 ktonne of ash free dry weight biomass

Inputs	ATS	ORP	Description
Algae Growth Rate	20	20	g m^{-2} d^{-1}
Algae Lipid Content	10	30	wt %
Harvest Cell Density	200	0.5	g L^{-1}
Module Length	152	100	m
Slope	0.5	0	%
Pond Depth	-	20	cm
Evaporation Rate	-	0.4	cm day^{-1}
Amount of water recycled	-	90	%
CO_2 Losses	-	10	%
Total Harvesting Efficiency	90	90	%

Ash Content	50	8	%
Nutrient Requirements:			
N, dry wt%	-	7.6	wt %
P, dry wt%	-	0.8	wt %
CO_2	-	1.93	kg biomass^{-1}

2.2 ATS Harvest

An advantage of the ATS system is the simplicity of the harvesting of the biomass. Harvest is achieved using current agriculture operations utilizing a tractor plow with further dewatering not needed. The system is assumed to operate perpendicular to the water flow. Capital harvest costs include purchasing machines and operation costs based on hourly labor and diesel fuel costs. Assumptions included 4 machines required per 405 hectare ATS module at a cost of $350K each. It was assumed that the harvest rate was 0.84 hr hectare^{-1} with a harvesting efficiency rate of 90%. Operation costs included farm diesel fuel with a cost assumed to be $3.90 per gallon. The number of employees required was approximately 250 with employment information provided by commercial estimates and detailed in the supplementary material.

2.3 ORP Growth System

Open raceway ponds were evaluated through the construction of a systems engineering model. Key input assumptions for the ORP growth system are listed in Table 1. ORPs are assumed to cultivate *Nannochloropsis salina* at an annual average growth rate of 20 g m^{-2} d^{-1} (Davis et al., 2016; Huntley et al., 2015; Quinn et al., 2012b). The ORP was designed using 4 hectare (10 acre) ponds at a depth of 20 cm with a sufficient number of ponds to satisfy the annual tonnage requirement. The algae is circulated through the ponds at a density of 0.5 g L^{-1} using paddle wheels. Paddle wheel power consumption was set to 1 kW ha^{-1} for continuously circulating the water (Lundquist et al., 2010). Nutrient loading is achieved by providing nitrogen and phosphorus at 7.6% and 0.8% dry weight respectively (Clarens et al., 2010). CO_2 is assumed to be provided via a nearby power plant or other flue gas source. The CO_2 is transferred to the ponds by a sump with a baffle system to limit outgassing. The CO_2 sumps attribute a cost of $4.3k per hectare and CO_2 delivery costs were set to 250 kWh ton^{-1} (EPA, 2013). Evaporation from the ponds was assumed to take place at a rate of 0.4 cm day^{-1} (Batan et al., 2013; Eichinger et al., 2003; Wigmosta et al., 2011).

Infrastructure costs were largely gathered from reports by Lundquist et al. (2010) and Benemann and Oswald (1996) with costs converted to 2014 US dollars. The land required is assumed to be low-value land that is not suitable for traditional terrestrial crops. Similar to the ATS system, a cost of $7.4k per hectare was used. The cost for the ponds and paddle wheels were set at $34k per hectare with costs for a liner included in the baseline scenario. Costs for general machinery are $1k per hectare. The number of employees and their associated salaries were based on a design by Humbird et al. (2011) for a similar plant. Specifics of employee related costs are included with the supplementary material along with a table of detailed capital assumptions.

2.4 ORP Harvest

Harvesting algae from the ORP is done at a rate equal to the growth rate achieved by the system. A key disadvantage of the ORP system in comparison to the ATS system is the need to dewater the algae from less than 0.1% solids to 20% solids. A three stage dewatering process is necessary to provide adequately dewatered feedstock for harvest (Davis et al., 2011). Initial dewatering is achieved using settling tanks to achieve a density of 10 g L^{-1} or 1% solids. The slurry is flocculated with chitosan and collected by a DAF unit to bring the density to 100 g L^{-1} or 10% solids. Chitosan is required at a concentration of 40 mg L^{-1} (Rashid et al., 2013). A centrifuge is then used to realize the desired density of 200 g L^{-1} or 20% solids for harvest. Capital and operation costs associated with each harvesting step are based on Wang et al. (2007). Operating requirements for harvesting include 0.078 kW lpm^{-1} for the DAF unit and 0.066 kW lpm^{-1} for the centrifuge.

2.5 Hydrothermal Liquefaction to Biocrude

To further investigate and compare the overall economic feasibility of the growth platforms, the system model for both ATS and ORP growth platforms was expanded to include a biorefinery based on the conversion of biomass to bio-oil through HTL as shown by the biofuel system boundary in Figure 1. The results from Jones et al. (2014) were leveraged to provide a rough estimate of capital and operational costs to facilitate comparisons to previous work based on a dollar per gallon metric. Ash content for the ATS system was accounted for by multiplying a costing factor equal to the increased amount of mass flow required. Key inputs and assumptions for the HTL and hydrotreating process are shown in Table 2. Hydrotreating to renewable diesel has a fuel yield of 78% with 83% of the product being diesel and the remaining 13% naphtha. Catalytic Hydrothermal Gasification (CHG) is also included to remove carbon content from the aqueous phase post HTL. The processed gas is then utilized to generate hydrogen at a hydrogen plant assumed to be onsite facilitating hydrotreating. In order to account for advantages of each individual system the oil yield and ash content for each system were varied. The HTL yield for the ATS is assumed to be 44% based on experimental data from Sandia National Laboratories (Pate, 2016). The HTL yield for the ORP is assumed to be 44% based on experimental data from Pacific Northwest National Laboratory (Jones et al., 2014).

Table 2: Key assumptions associated with fuel production via HTL processing for both the ATS and ORP systems.

Inputs	ATS	ORP	Description
HTL			
HTL Oil Yield	44	44	%
Ash Content	50	8	%
NG Energy	6.2	3.7	M-MJ d^{-1}
Electrical Energy	192	120	MWh d^{-1}
Capital Cost	270	183	M$
Hydrotreating			
Hydrotreating Oil Yield	78	78	%
Processing Capacity	153	153	kgal d^{-1}
Diesel Yield	83	83	%
Naphtha Yield	17	17	%

2.6 Techno-economic assumptions

Cost data for both systems were determined and were divided into capital, operation, and taxes. Economic model assumptions were held constant throughout to have normalized systems that could provide a direct comparison of the cost benefits of each individual system. The economic model was designed with assumptions for the standard reference of the "Nth" plant design (Short, 1995). Detailed economic inputs are outlined in the supplementary material. These assumptions are modeled to be consistent with the Department of Energy's Bioenergy Technologies Office design cases allowing a standard basis for comparison across studies (Davis et al., 2014a; Jones et al., 2014) . The developed plant is assumed to have a three year startup with capital costs occurring at 8%, 60% and 32% in years one, two and three respectively. During the first three months of operation the output capacity of the plant is half of full production. The economic model minimized the fuel price to provide a zero net present value by simulating a 30 year plant life. An internal rate of return of 10% was assumed with 60% financed as a 10 year, 8% interest loan, and 40% was financed in equity. Net revenue for the system was taxed at a rate of 35%. Detailed inputs are outlined in the supplemental material.

2.7 Sensitivity Analysis and Alternative Scenarios

Modeling inputs and assumptions were varied to generate a sensitivity analysis to identify system inputs that have the largest impact on the basis of economics. A two-tailed distribution based on a 95% confidence interval for the economics was completed to show which parameters are statistically significant. This analysis was further utilized to provide a path towards economically feasible results. Results for the two-tailed distribution are included in section 3.3 with further details included with the supplementary material.

Alternative scenarios were simulated to understand conservative and optimistic system performance. The conservative scenario is intended to represent the performance of current systems while the optimistic scenario is intended to represent the performance of the systems with reasonable research and development advancements. Results from the sensitivity analysis were used to identify key drivers in terms of model inputs for the alternative scenarios.

3. RESULTS AND DISCUSSION

Resulting costs for both the growth and biofuel system boundaries are presented along with comparisons between the ATS and ORP systems. Alternative scenarios are included that provided results based on optimistic, baseline and conservative assumptions for each of the production systems. Sensitivity analysis for each system is detailed with results used to identify a path to $3 gallon gasoline equivalent (GGE).

3.1 ATS and ORP Baseline Biomass Production Costs

Capital and operation costs for both the ATS and ORP systems were used to evaluate the economic viability of each biomass production system. Resulting costs are broken down in Table 3. A total cost of \$510 tonne $^{-1}$ for the ATS system was determined. Power costs related to the required pumping of contaminated water contribute 48% of the total operating costs and is the largest contributing factor in terms of operational costs. The total operating costs for the ATS system are favorable as there is no need to dewater the biomass. Primary costs associated with harvesting are fuel and labor contributing 16% and 11% respectively which are the largest contributors after power requirements. Dominating factors within the capital costs include building costs (infrastructure) and liners which attribute 24% and 27% respectively.

Cost results for the ORP systems are broken down into capital and operation costs in Table 3 with the total biomass cost of \$673 tonne $^{-1}$. The operational costs are dominated by the power, nutrient and dewatering requirements. Power requirements are driven by the need to continually circulate the ponds and dewatering requirements to reach an acceptable harvest density. This results in power consumption attributing 32% of the operation costs with circulation and dewatering contributing 85% and 15% of that respectively. Also involved in the dewatering costs is flocculent required for dissolved air flotation which contributes 21% of the total operating costs. Key factors contributing to capital costs include the pond and paddle wheels, liners, building costs (infrastructure development) and site development corresponding to a combined 52% of the biomass costs.

Table 3: Detailed cost breakdown for the ATS and ORP growth systems.

Costs Factors	ATS (\$/tonne)	ORP (\$/tonne)

Operation Costs		
Power	$ 56.21	$ 65.26
Nutrients (N,P,C02)	-	$ 104.25
Fuel (ATS), Flocculant (ORP)	$ 19.14	$ 56.36
Labor	$ 13.30	$ 14.69
Maint/Insur	$ 29.26	$ 25.53
Tax	$ 53.88	$ 56.36
Capital Costs		
Earthworks (ATS), Ponds + paddle wheels (ORP)	$ 7.30	$ 61.50
Liners	$ 90.20	$ 14.93
Pump System (ATS), CO2 delivery+sumps (ORP)	$ 15.97	$ 10.64
Piping (ATS), Water/Nutrient/Electrical Supply (ORP)	$ 53.48	$ 17.81
Land Costs	$ 5.59	$ 15.95
Engineering/Tech (ATS), Inoculum system (ORP)	$ 42.70	$ 22.26
Building Costs	$ 7.76	$ 81.27
Other Costs	$ 14.47	$ 30.48
Harvest Systems	$ 81.09	$ 50.20
Site Development	$ 20.27	$ 46.17
Total	**$ 510.65**	**$ 673.65**

Key differences between the ATS and ORP growth system drive a 28% difference in costs. The ATS system has large upfront costs due to land works to create a sufficient slope and extensive costs associated with an appropriate liner system. Capital costs for the ORP system are driven by the infrastructure required for developing ponds, similar requirements compared to an ATS system, and dewatering systems. Capital costs for the ATS growth system totaled \$339 tonne^{-1} which is very comparable to the ORP growth system which totaled \$351 tonne^{-1}. The ORP growth system has the disadvantage of being more expensive to operate due to the dewatering processes to reach the required harvest density and nutrient requirements. The operation costs associated with the ATS growth system are \$118 tonne^{-1} while operations costs for the ORP growth system account for \$266 tonne^{-1}. The ATS system has an advantage over the ORP system by not requiring raw nutrients and utilizing an attached growth system to improve dewatering costs of the algae. These advantages drive the total biomass cost to be significantly lower for the ATS system. The baseline case for the ORP system includes minimal inputs for the procurement of CO_2 which represents a required nutrient for accelerated growth and is limited to onsite distribution. Previous resource assessments have highlighted co-location as a limiting factor on the scalability of algal biofuel systems (Quinn et al., 2012a). The ATS system does have siting limitations that are different from those of ORP, specifically contaminated water systems. Preliminary work has been completed with results presented in the supplementary material.

The ATS system has very promising results for biomass production \$510 tonne^{-1}. Barlow et al. (2016) report a biomass production cost of \$2500 tonne^{-1} for an attached growth system with a productivity of 20 g m^{-2} d^{-1}. The resulting \$673 tonne^{-1} for the ORP system is 42% greater than the arbitrary \$474 tonne^{-1} assumed by Davis et al. (2014a) and Jones et al. (2014) with major improvements needed to realize this cost assumption. A critical assumption in regard to the performance of the systems being compared is the annual average productivity, assumed to be 20 g m^{-2} d^{-1} for both the ATS and ORP. Comparison of results from this study to Davis et al. (2016) shows a 27% higher biomass production cost reported in this study. Harmonization of model inputs, primarily growth rate, results in a 2% higher cost reported in this study. This result illustrates the importance of growth rate on results as expected. The ATS system is based on native dynamic cultures which have proven to be robust (Christenson & Sims, 2012; Smith & Crews, 2014). Commercial systems have been deployed with a focus on water remediation with the produced biomass being an unwanted low value co-product (HydroMentia, 2016).

The focus of these systems has been on water remediation and not biomass production. ORPs have been shown to be susceptible to invasive species which would decrease the overall productivity of the system and negatively impact the economics (Richardson et al., 2014). When considering strictly a growth system boundary it is apparent that the ATS system has many advantages driving to a lower overall biomass cost.

3.2 Biofuel Production Costs

The system boundary was expanded to include downstream processing of the biomass through HTL. This supported the economic evaluation of the production platforms on a system boundary that encompasses the production of fuel. Figure 2 shows the resulting costs for both the ATS and ORP systems. Results include growth, harvest, conversion and tax costs for the capital and operation costs for each system. The allocation of the MFSP is based on an average cost for growth, harvest, conversion and tax over the 30 year economic simulation. The ATS system is considerably cheaper when looking at the feedstock costs, however, it is nearly double the cost for fuel production. Due to the high ash content associated with ATS systems, fuel production is much less efficient when compared to the lower ash content achieved with the ORP system. The larger cost for growth in this system boundary is a result of the high ash content and resulting higher capital investment required for the ATS system. When noting these key advantages for the ORP system it is important to realize that due to the robust attached growth cultures for the ATS system the ORP is susceptible to invasive species leading to system shutdown. Resulting costs for both systems illustrate the need for further research and development in order to produce an economically competitive product.

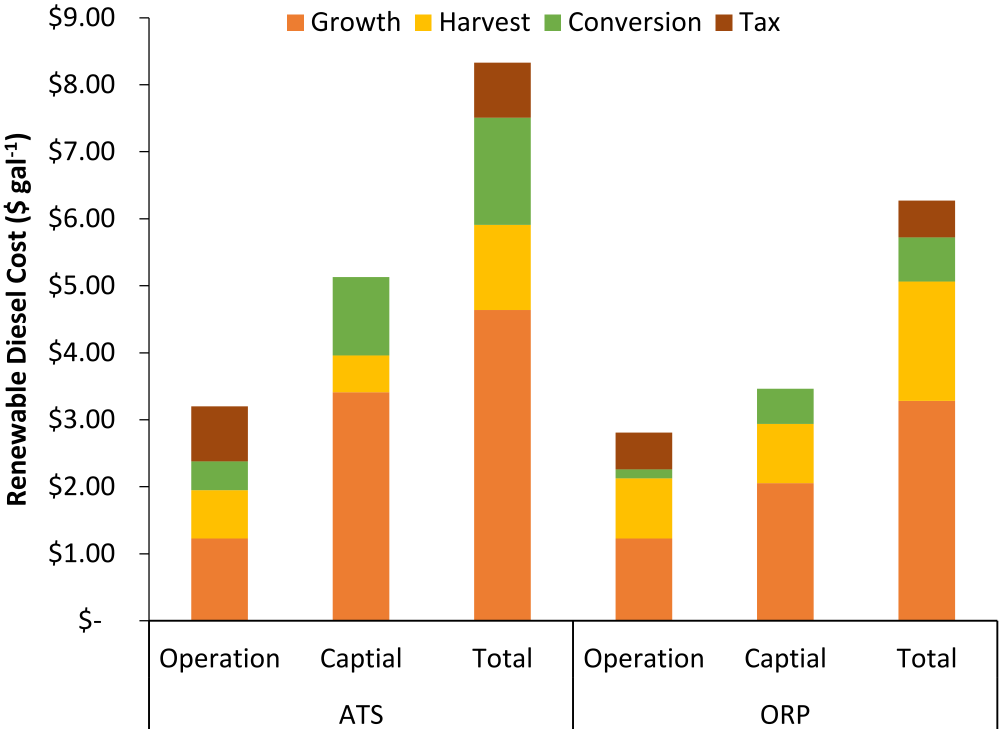

Figure 2: Fuel costs for the ATS and ORP systems broken down by growth, harvest and conversion costs.

Resulting fuel costs from this study are in the lower end of results reported in literature. Fuel costs have been reported as low as $2.20 per gallon (Nagarajan et al., 2013) and as high as $31.36 per gallon (Richardson et al., 2012). The ATS system result of $8.34 per gallon does fall into the middle of the range while the $6.27 per gallon for the ORP system is on the lower end of fuel costs. High ash and lipid content associated with the ATS system cause the ORP system to have advantageous fuel costs even though the biomass cost is higher. Ash reduction could be obtained by relatively simple processes leading to reduction in fuel costs. A 5% reduction in the ash content leads to a total cost of $7.88 per gallon which is a 5.5% decrease in overall cost. The results show the growth system dominates the overall costs associated with the production of fuel corresponding to 56% and 52% for the ATS and ORP systems respectively.

3.3 Sensitivity

A sensitivity analysis was completed for each system to identify the key contributing cost factors in the models. The tornado plot for the ATS and ORP systems are shown in Figure 3 and Figure 4 respectively. It is clear that dominating factors for both systems are lipid content and growth rate. By optimizing these parameters, small changes can dramatically impact results in the economic feasibility of utilizing algae as a feedstock for renewable fuels. Reducing costs associated with varying operation and capital expenses can help drive the cost down but are not as significant as the results obtained with more efficient and productive algae growth. When exploring the individual systems key factors in both systems can be observed. The ATS system is driven largely by liner costs while the ORP system is sensitive to the cost of pond development and paddle wheels. The downstream processing via HTL can also have an important impact on the economics of each system.

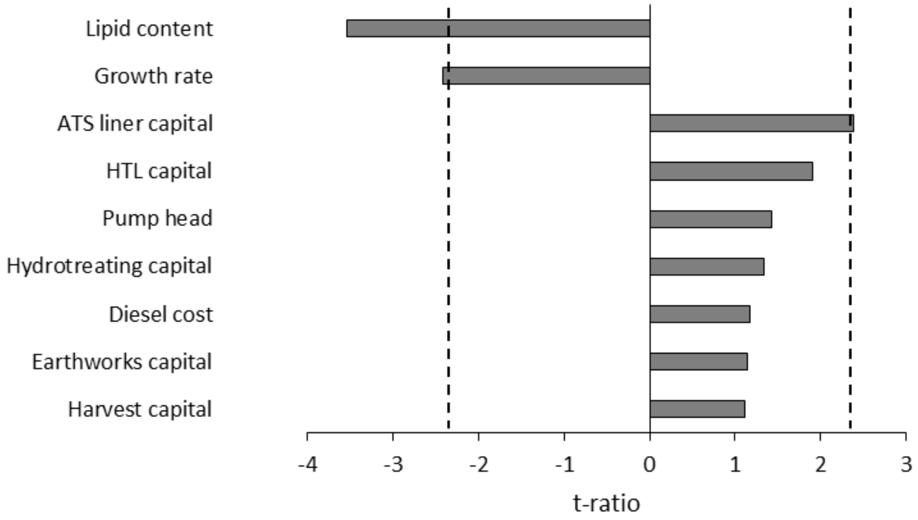

Figure 3: Sensitivity analysis results to varying input parameters for the ATS system, t_{crit}=2.36 (dashed lines). The top 9 variables are reported.

Utilizing the sensitivity analyses a path towards $3 per gallon of gasoline equivalent (GGE) was found for each system. In order for these systems to become realizable in economics of today's world, a number of advancements must be achieved to drive the cost down to be competitive with the cost of crude based fuels. The largest barrier to the ATS system is reducing the ash content. Results form this work highlight the need for experimental work to understand the composition of the ash and potential to decrease ash content in the biomass prior to downstream conversion. Another complicated factor that could have a large impact on ATS systems is subsidies for removing waste nitrogen and phosphorus from contaminated water. Due to a somewhat unpredictable cost benefit that could be tied to these subsidies it would be difficult to rely on these savings over a long period of time to drive costs to be more competitive. The ATS system could also benefit by achieving better growth rates and decreasing capital and operation costs. An alternative scenario was evaluated which included a 74% reduction in ash content from 50% to 13%, a 10% reduction in capital costs, subsidies at 2x fertilizer costs and an improved productivity, 30 g m^{-2} d^{-1}. Savings realized by these improvements reduce the cost of fuel from the baseline of $7.67 per GGE to $3.07 per GGE. It is expected that some changes in the ATS system lead to a larger impact than what can be achieved with the ORP system. This is due to the fact that the ORP system has been developed and optimized for algae growth and many improvements have already been explored and implemented. The ATS system is undeveloped as an algae growth system and there is the potential for improvements through focused research and development.

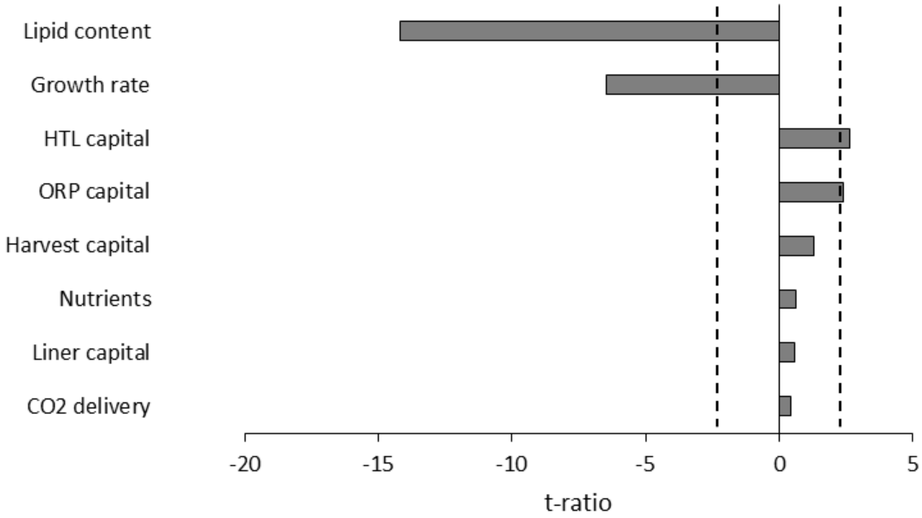

Figure 4: Sensitivity analysis results to varying input parameters for the ORP system, t_{crit}=2.36 (dashed lines). The top 8 variables are reported.

For the ORP system a reduction of 50% needs to be realized in order to achieve the DOE target of $3 per GGE. The largest factor to decrease costs would be to improve the growth rate. There are difficulties that come with being able to increase the growth rate as the ponds are exposed to the elements and can easily be contaminated leading to culture instabilities and culture crashes. It is expected that GMOs or extremophiles will be required to maintain culture robustness in these systems. A path to $3 per GGE for the ORP includes a 15% decrease in capital and operation costs, a growth rate of 30 g m^{-2} d^{-1} and a pond system that does not require a liner. The elimination of a pond liner has been explored and represents a geographically specific constraint. (Benneman and Oswald 1996). Resulting cost savings realizing each improvement leads to a cost of $3.84 per GGE.

3.4 Alternative Scenarios

Alternative scenarios were evaluated that represent a current production system, conservative scenario, and a system with strategic improvements, optimistic scenario. The baseline scenario is intended to represent a near-term realizable production system. The optimistic assumptions for the ATS system include a growth rate improvement of 50% to 30 g m^{-2} day^{-1} along with removing the need for any liner or attachment screen and a 10% reduction in the operation costs associated with the system. Conservative assumptions include a growth rate of 15 g m^{-2} day^{-1} along with increased liner costs and an increase in operation costs. Optimistic case scenario assumptions resulted in a cost of $286 $tonne^{-1}$ for the ATS system. The resulting cost based on the conservative assumptions results in a cost of $769 $tonne^{-1}$. It is important to note that ash and lipid content do not impact biomass production costs and hence are not included in the alternative scenarios for biomass production. A detailed breakdown of the results for the three scenarios is shown in Figure 5.

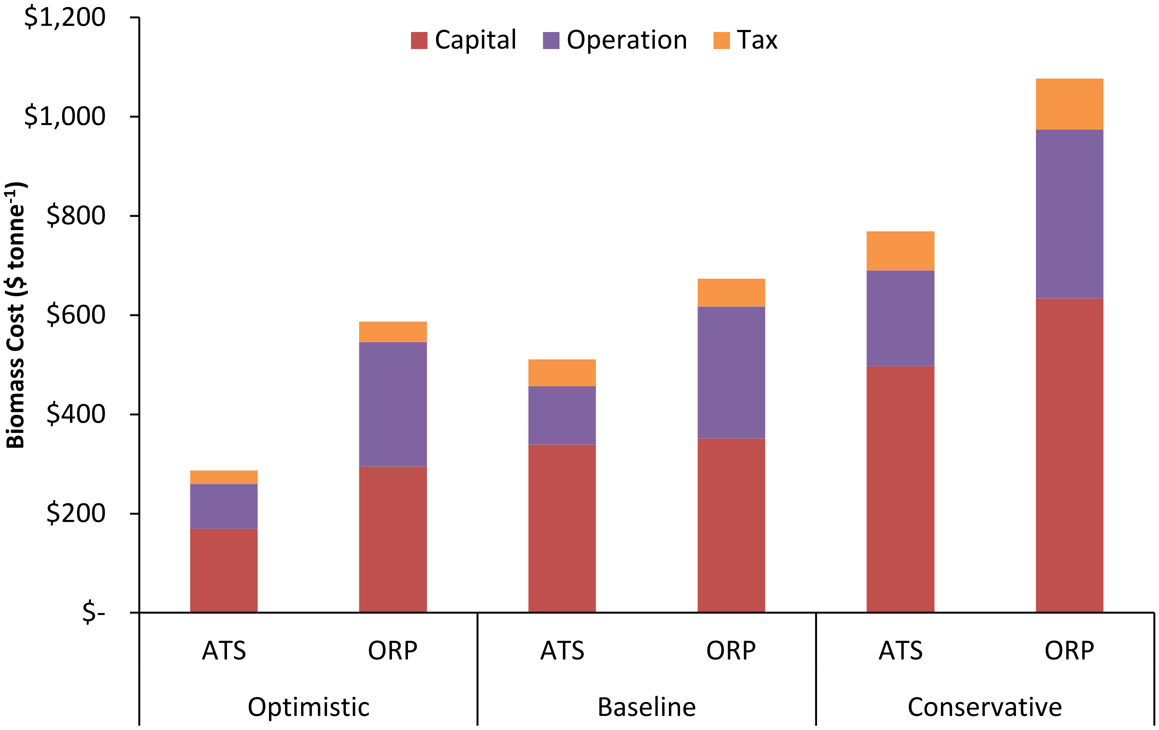

Figure 5: Detailed breakdown for the ATS and ORP growth systems of capital, operation and tax costs for optimistic, baseline and conservative assumptions.

For the ORP optimistic scenario it was assumed that a growth rate of 25g m^{-2} day^{-1} could be achieved and that no liners were required. This case also assumes a 10 % cost reductions in operation cost. For the conservative scenario a growth rate of 15 g m^{-2} day^{-1} was assumed. This scenario also accounted for an increase in operation costs and for a much more expensive liner system. Optimistic assumptions result in an overall biomass cost of $592 tonne^{-1} for the ORP system. When accounting for conservative assumptions the ORP growth systems results in a cost of $1076 tonne^{-1}. The ORP growth system cost break down is shown in Figure 5.

In comparison with the ORP system the optimistic scenario for the ATS system provides a significantly better cost for biomass production. However, with the ATS system being less developed it may have a higher potential but at this point more work needs to be done to determine this possibility. Examining these results show that if the optimistic scenario were achievable that the cost of biomass production could be cheaper than the assumed cost of $474 tonne^{-1} of Davis et al. (2014a) and Jones et al. (2014). This also shows that one must be cautious of the risks associated with not achieving ideal growth and plant assumptions as it drives the cost far beyond the assumed costs. Upon integration of downstream HTL processing the critical impact that lipid and ash content have on costs is very apparent. Even though the ATS system proves superior for the growth system the overall fuel cost result is $8.34 per gallon, whereas the ORP resulting fuel cost is $6.27 per gallon.

4. CONCLUSIONS

The economic feasibility of producing biofuels utilizing microalgae feedstock using ORP and ATS growth system was determined. Growth system economics were explored along with a biorefinery using HTL to produce renewable fuels. Resulting costs of \$510 tonne^{-1} and \$673 tonne^{-1} were determined for the ATS and ORP growth systems respectively. Downstream process integration resulted in \$8.34 per gallon for the ATS system and \$6.27 per gallon for the ORP system. At its current state the economic outputs are not competitive with current fossil fuel prices but there are paths to reach a competitive price. Results highlight that ash and lipid content are inputs with the greatest impact in the ATS growth platform. Key barriers include the need for increasing lipid yields and growth rates for both systems. For ORPs it is also critical to have robust cultures that can withstand being exposed to the elements. The ATS system requires improved productivity along with improved methods in reducing ash content. It is also essential to define the direct requirements of liners for both systems as this can become a driving cost.

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