Algal Turf to Fuel (ATF)

SAND2015-8552C

Updated assessment of the p*roduction of biofuels from chemical, biochemical, and thermochemical processing and conversion of benthic polyculture algal turf biomass*

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Engineering & Analysis Track Session:
Thinking Big: Scale-up Strategies

2015 Algal Biomass Summit
Washington, DC
September 30 – October 2, 2015

ALGAE BIOMASS ORGANIZATION

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[1] Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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Polyculture "Algal Turf to Fuels"

Interesting alternative to planktonic algae production in raceway systems

Algae Turf Scrubber®

Hydromentia – Vero Beach, Florida

- Polyculture – resilient and resistent to crashes
- Growth: 5-20+ g/m^2/day (AFDW)*
- No nutrients or external CO_2 added with single-pass operation
- Harvesting & dewater – simple, but ash reduction needed
- Requires energy for water pumping to maintain flow
- Biomass focus - low neutral lipids
- Similarities with open field agriculture

VS

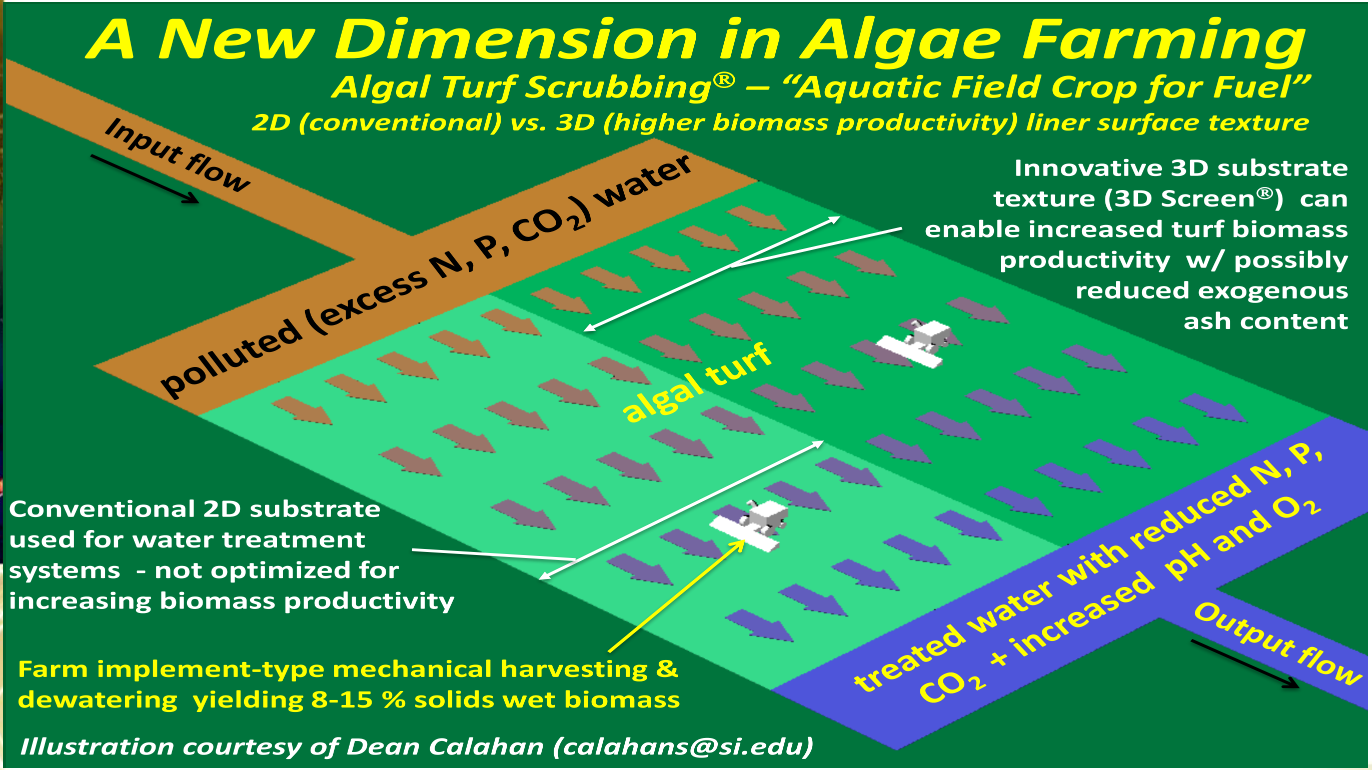
Algae Raceway Pond

NBT – Eilat, Israel

- Monoculture – vulnerable to crashes
- Growth: 5-20+ g/m^2/day(AFDW)*
- Needs fertilizer & CO_2
- Harvesting & dewater more difficult & energy-intensive
- Requires energy for paddle wheel flow/mixing
- Lipid focus (historical)

**** Range of annual average productivity performance depending on system & conditions***

Algal Turf System - Open Field "Algae Farming"
Used to *clean water through production of biomass*



Consists of slightly tilted & lined planar open-field systems using pulsed, shallow, turbulent water flow and mechanical harvesting more compatible with conventional agriculture.

Commercial multi-acre scale systems have been developed and used for water treatment.

Key Points

- Algal Turf to Fuels – Possible solution to key algae challenges:
  - Crashes … Cultivation resiliency with polyculture
  - Costly harvesting & dewatering
  - Costly CO_2 supply &/or distance-limited co-location w/ industrial sources
  - Costly fertilizer/nutrients
- Turf algae pioneered in 1980s (Walter Adey) and commercialized for water treatment (HydroMentia)
- Robust algae biomass growth reported using trace nutrients in surface waters in the environment - *SNL to further assess in FY16*
- Recent SNL Focus:
  - Evaluation of biochem &/or HTL conversion paths
  - Initiation of analysis of scale-up feasibility of “Algal Turf to Fuels”

Features of algal turf biomass production, processing, and conversion to fuels

- Polyculture algal turf biomass has low neutral lipid content (< 10%)
  - Relatively high in protein and carbohydrates
  - Production of fuels using HTL &/or biochemical fermentation of carbs & proteins
- High ash typical in raw harvested material from current systems (ATS system design and operation have *not been optimized for reduced ash*)
  - Ash is combination of biogenic and exogenous environmental material
  - Improvement possible with cultivation and harvesting systems & ops
  - Dilute acid pre-treatment & separation provides ash reduction
  - Simple rinsing can significantly reduce exogenous ash
- Heterogeneous polyculture biomass characteristics
  - Dynamically changes with season, water source chemistry
  - Provides robust and resilient culture immune to “crashes”
- HTL biocrude can be higher in nitrogen (~5+%) due to protein
  - Biochem pretreatmen & conversion of proteins can reduce and recycle nitrogen

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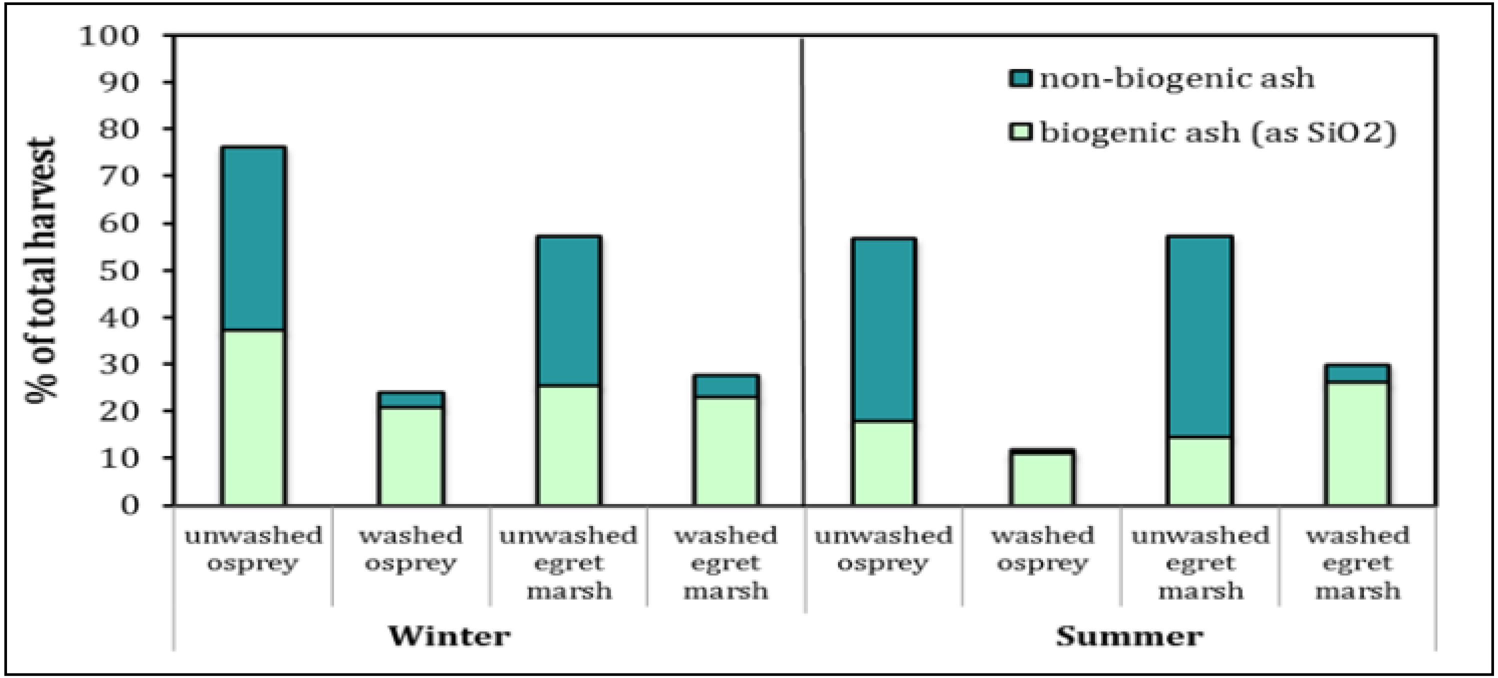
Ash reduction through simple rinsing

(with ≤ 10-15% loss of original biomass content in SNL tests)



Reduction of ash content by rinsing: *Ash content of harvested benthic algal turf biomass before and after washing for winter (Jan 2015) and summer (June 2015) harvests from the Egret Marsh and Osprey commercial scale ATS systems by HydroMentia, Inc.*

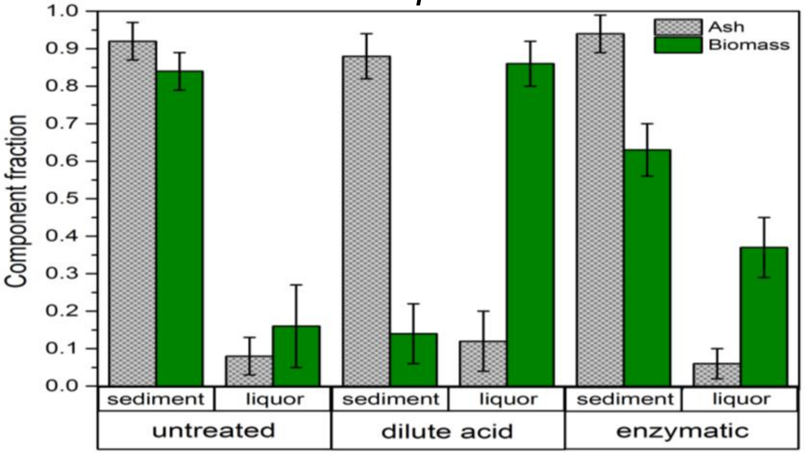
Biomass pretreatment:

Ash removal, solubilization, and hydrolysis

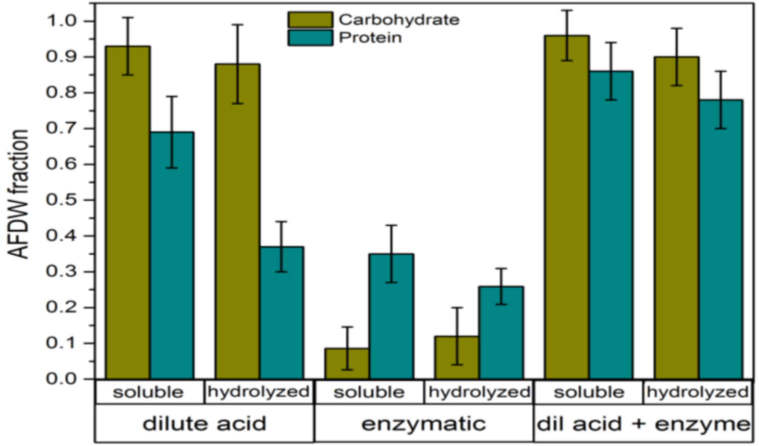
- Dilute acid and enzymatic treatments are each effective for separating ash
- Dilute acid is effective for solubilizing the protein and carb fractions, and carb hydrolysis, but additional enzymatic treatment is necessary for protein hydrolysis

Native biomass *Pretreated residuals*

Ash separation



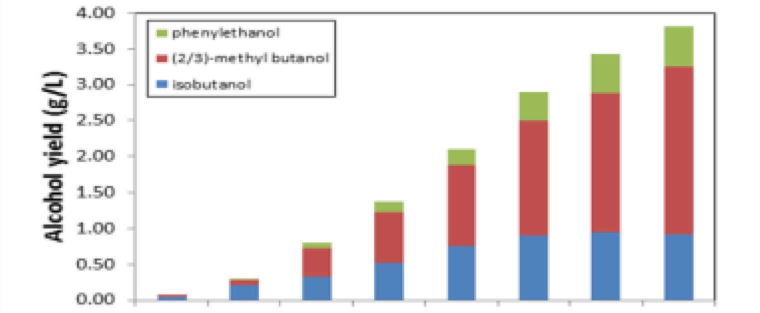
Solubilization and hydrolysis

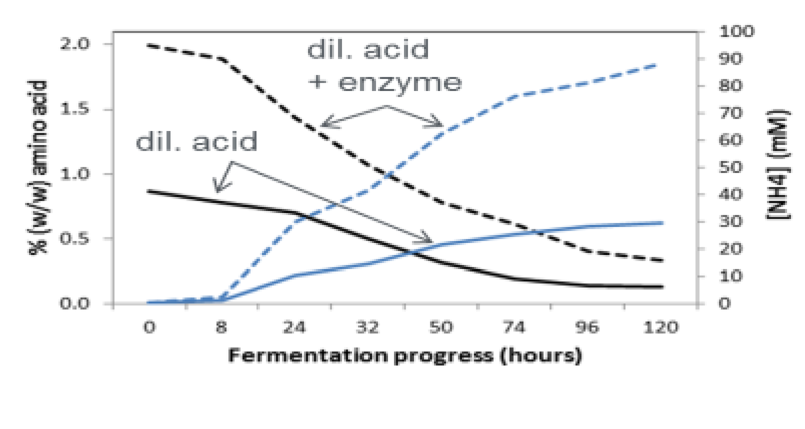


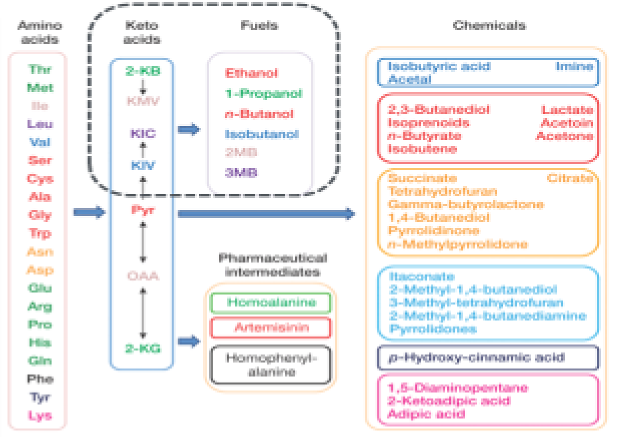
Biochemical conversion

Fermentation of sugars & proteins with promising yields based on non-optimized bench-scale testing

- **70% of theoretical protein conversion & 90% carb conversion achieved with bench scale testing**
- Sugar fermentation strain: *Zymomonas sp.* for utilization of C5 and C6 sugars
- Protein fermentation strain: *E.coli* YH83 for conversion of amino acids to >C2 alcohols + NH_4, developed by collaborator Liao & coworkers (Huo *Nat. Biotech* 2011)







Thermochemical conversion

Improved biocrude yields seen with algal turf vs. monoculture

- HTL oil yield of whole ATS polyculture is **44%**
- HTL oil yield of monoculture (*nannochloropsis*) for same process conditions yields 35%, despite less ash -other monocultures to be investigated
- Literature values of monocultures with continuous HTL systems obtain >50% yields implying much improved performance for polyculture algae
- Whole ATS produced least char
- HTL of fermentation residue yields 22% biocrude
- HTL of fermentation residue reduces **N from 4% to 0.89%**
- High heating value of 38.7 MJ/kg and 39.4 MJ/Kg for whole oil/residue respectively (versus 45 MJ/kg gasoline)

HTL Mass Balance [%]	Whole ATS	Algal Turf Residue*	Whole *Nannoch.*	Carbon partitioning In Whole ATS	Nitrogen partitioning In Whole ATS	Carbon partitioning in residue*	Nitrogen partitioning in residue*
GAS	14%	18%	13%	9%	42%	12%	40%
BIOCRUDE	44%	22%	35%	43%	17%	21%	13%
AQUEOUS	25%	32%	30%	30%	26%	38%	19%
SOLIDS	17%	28%	22%	18%	15%	29%	28%

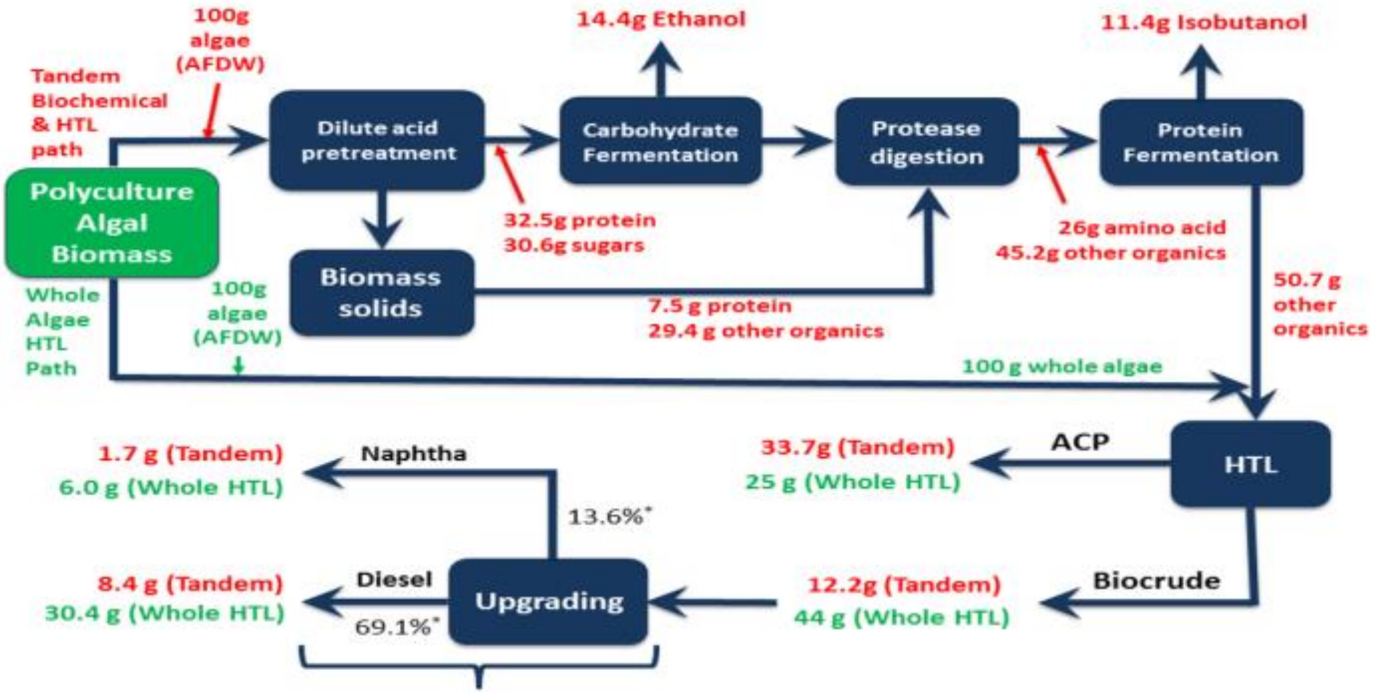
** Algal Turf Residue refers to the material remaining after fermentation of carbs and proteins*

Biochem & HTL Conversion Paths

~2000-3000 GGE/Acre Fuel Potential with Algal Turf Productivity of 15 g m^{-2} d^{-1} (AFDW)

~5000 GGE/Acre Fuel Potential with Algal Turf Productivity of 25-30 g m^{-2} d^{-1} (AFDW)

Two paths shown: Tandem Biochem + HTL or Whole Algae HTL



* Assumed HTL biocrude upgrade conversion factors from: Jones, et al., AHTL Process Design Report, PNNL-23227, March 2014.

Fuel yields based on non-optimized bench tests using algal turf polyculture biomass from HydroMentia with AFDW material composition of:

8g lipid
39g protein
34g carbohydrate
<u>19g other organics</u>
100g basis (AFDW)

Hypothetical Fuel Production

as a function of AFDW algal turf productivity

Hypothetical Fuel Production for Two Processing Pathways		Polyculture Algal Biomass Annual Average Daily Productivity $[g\ m^{-2}\ d^{-1}]$ (AFDW)				
		10	15	20	25	30
Annual Biomass Productivity [kg/acre] (AFDW)		14800	22200	29600	36900	44300
Pathway #1: Tandem Biochemical & HTL Processing & Conversion						
Annual Fuel Production by Type [GGE/acre]*	Ethanol:	470	700	940	1170	1410
	Isobutanol:	470	710	945	1180	1420
	Naphtha:	90	135	180	225	270
	Diesel:	470	700	935	1170	1400
Total Annual Fuel Productivity [GGE/acre]*		1500	2250	3000	3750	4500
Pathway #2: Whole Algal Biomass HTL Processing & Conversion						
Annual Fuel Production by Type [GGE/acre]*	Naphtha:	320	490	650	810	970
	Diesel:	1690	2530	3370	4220	5060
Total Annual Fuel Productivity [GGE/acre]*		2010	3020	4020	5030	6030

* Assuming polyculture algal biomass with ash-free dry weight equivalent content of 8% lipids, 39% protein, 34% carbohydrate, and 19% other organics, with conversion yields obtained at bench scale by Sandia National Laboratories and assumed upgrading efficiencies taken from 2014 PNNL AHTL Report.

Based on process yield results from non-optimized and non-integrated bench scale testing using wet harvested algal turf biomass supplied by HydroMentia and using assumed HTL biocrude upgrading conversion yield factors from 2014 PNNL AHTL Report

Note: 2500 and 5000 GGE/acre are BETO Algae Program near and longer-term goals, per BETO MYPP, March 2015.

Preliminary TEA Financial Assumptions

Effective Tax Rate (T)		
Federal Tax Bracket	35.00%	
State Tax Bracket	0.00%	
Effective State Tax Bracket	**0.00%**	
Effective Combined Tax Rate (T)[1]	**35.00%**	
Real Average Weighted Cost of Capital (r_{wacc})		
Percentage of total project equity financed (E/V)	**40.00%**	
Equity financing rate (r_e)	10.00%	
Percentage of total project debt financed (D/V)	60.00%	
Pre-tax debt financing rate (r_d)	8.00%	
Effective tax rate (T)	37.60%	
Real Average Weighted Cost of Capital (r_{wacc})	**7.12%**	
Capital Recovery Factor (CRF)		
Economic Plant Life (n)	20	Years
Capital Recovery Factor (CRF)	**9.53%**	
Fixed Charge Rate (FCR)		
Fraction of Investment that can be Depreciated (b)	100%	
Depreciation Period (M)	7	Years
Tax Credit (t_c)	0.00%	
Annual Insurance Cost (p_1)	0.00%	
Other Taxes (p_2)	0.00%	
FCR	**10.62%**	

Applied to TEA of:

a) Whole algae HTL;

b) Biochem processing of whole algae & HTL of residue;

Using scale-up assumptions consistent with recent PNNL and NREL assessments.

Preliminary* Process Assumptions for Medium Biomass Productivity and Medium Ash Content Baseline Case

***Comparative TEA is still a work in progress and subject to revision**

ATS Growth	
Growth Rate (AFDW)	20 g m^{-2} d^{-1}
Pumping Duty Cycle	24 hr d^{-1}
Pumping η	67%
Pumping Head	4 m
ATS Length	152 m
Biomass (AFDW) Flow	1340 tons d^{-1}
Capital Cost	\$23.8 m^{-2}

HTL/CHG Processing	
NG Energy	3.95 MM BTU d^{-1}
Electrical Energy	130.6 kWh d^{-1}
Capital Cost	\$183 M
Oil Yield (whole/residue)	44%
Aqueous Yield (whole/residue)	40%
Ash Content	50%
Gas	3%

Harvest	
Harvest Density to processing	20% solids
Ash Content	25%
Harvest Frequency	7 days (ann. av.)
Operation Cost	\$0.23 m^{-2} yr^{-1}
Capital Cost	\$0.35 m^{-2}

Hydrotreating	
Processing Capacity (HTL oil)	212 kgal d^{-1}
Hydrotreated Oil Yield (via HTL oil)	83%
Diesel Yield (via Hydrotreated oil)	83%
Naphtha Yield (via Hydrotreated oil)	16%
Capital Cost	\$69 M

Estimated Costs of Harvested Algal Turf Biomass

Annual Average Biomass Production Costs	Total Cost of Biomass ($/ton)
Total Cost of Biomass with Low Productivity ($/ton per year)	909
Total Cost of Biomass with Medium Productivity ($/ton per year)	455
Total Cost of Biomass with High Productivity ($/ton per year)	303

Where,

Low Productivity = 10 g m^{-2} d^{-1} Annual Average (AFDW Harvested Material)

Medium Productivity = 20 g m^{-2} d^{-1} Annual Average (AFDW Harvested Material)

High Productivity = 30 g m^{-2} d^{-1} Annual Average (AFDW Harvested Material)

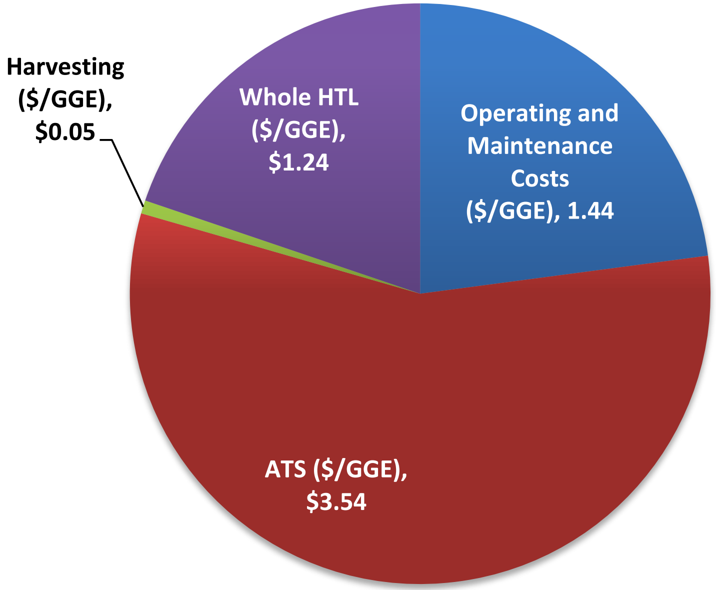
Preliminary TEA Results for Range of Cases
of *Algae Turf Productivity, Processing Path, and Ash Content*

	Case 1: Low Productivity Whole HTL Low Ash	*Case 2*: Low Productivity Biochem + Residue HTL Low Ash	*Case 3*: Medium Productivity Whole HTL Low Ash	*Case 4*: Medium Productivity Biochem + Residue HTL Low Ash	*Case 5*: High Productivity Whole HTL Low Ash	*Case 6*: High Productivity Biochem + Residue HTL Low Ash	*Case 7*: Medium Productivity Whole HTL Medium Ash	*Case 8*: Medium Productivity Biochem + Residue HTL Medium Ash	*Case 9*: High Productivity Whole HTL Medium Ash	*Case 10*: High Productivity Biochem + Residue HTL Medium Ash	*Case 11*: Medium Productivity Whole HTL High Ash	*Case 12*: Medium Productivity Biochem + Residue HTL High Ash
Total Capital Costs ($M)	3381.10	3563.96	1914.7	2097.6	1425.90	1608.8	1973.08	2150.59	1484.28	1661.79	2091.66	2317.80
Capital Costs ($/GGE)	$8.28	$7.34	$4.69	$4.32	$3.49	$3.31	$4.83	$4.43	$3.63	$3.42	5.12	$4.78
Annual Operating and Maintenance Costs ($M)	157.70	178.60	97.71	118.95	77.72	98.61	99.16	122.66	79.17	102.66	103.18	136.74
Naphtha coproduct credit at $3.25/gal ($M/year)	-28.42	-7.65	-28.42	-7.65	-28.42	-7.65	-28.42	-7.65	-28.42	-7.65	-28.42	-7.65
Methane coproduct credit at $5/1000 CF ($M/year)	-8.49	-5.52	-8.49	-5.52	-8.49	-5.52	-8.49	-5.52	-8.49	-5.52	-8.49	-5.52
OPEX & Maintenance after Credits ($M/year)	120.79	165.43	60.80	105.79	40.81	85.45	62.25	109.49	42.26	89.50	66.27	123.58
O & M Costs per gallon fuel ($/GGE)	2.79	3.21	1.40	2.05	0.94	1.66	1.44	2.12	0.97	1.74	1.53	2.40
Estimated total cost per gallon fuel ($/GGE)	**$11.07**	**$10.55**	**$6.09**	**$6.37**	**$4.43**	**$4.97**	**$6.27**	**$6.56**	**$4.61**	**$5.16**	**$6.65**	**$7.17**

Preliminary TEA - Baseline Case

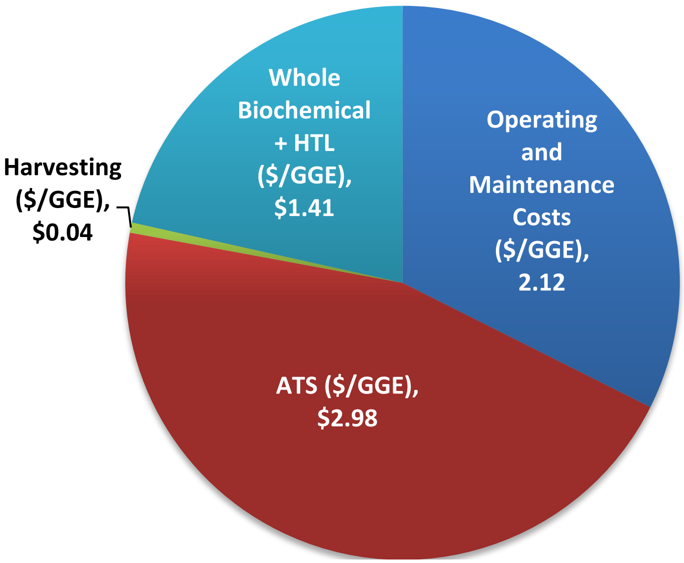
Medium AFDW Algae Productivity (20 g m^{-2} d^{-1}) and Medium Ash (25%)

Case 7: Whole Algae HTL



Total Cost: $6.27 /GGE

Case 8: Whole Algae Biochem Processing + HTL of Residue



Total Cost: $6.56 /GGE

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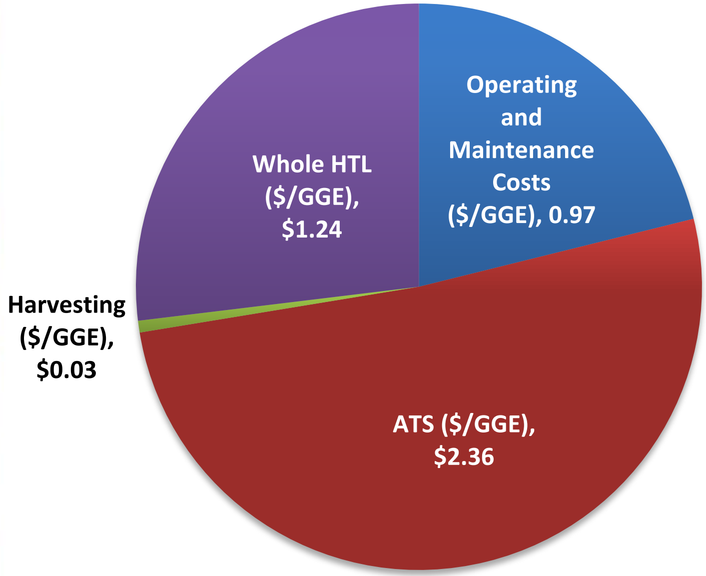
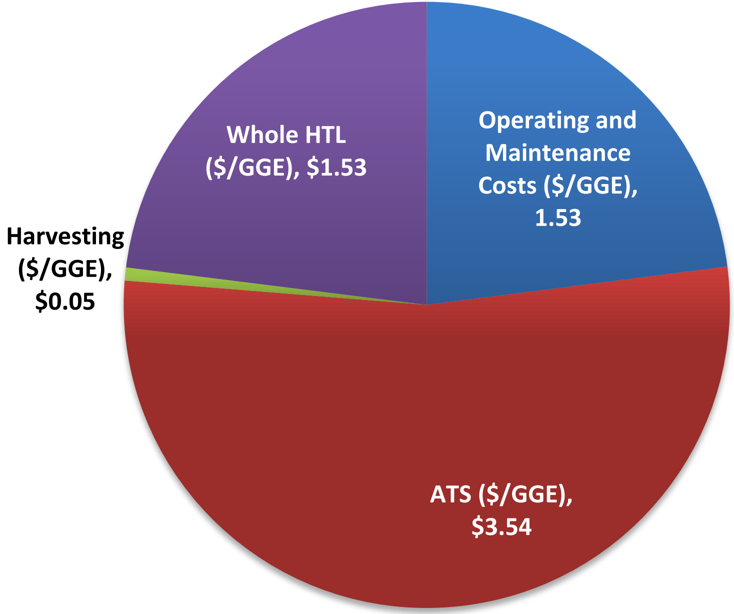
Preliminary TEA – Example Cases
Showing Tradeoffs of Productivity & Ash

Case 9: High Productivity (30 g m-2 d-1), Whole HTL, Medium Ash (25%)



Total Cost: $4.61 /GGE

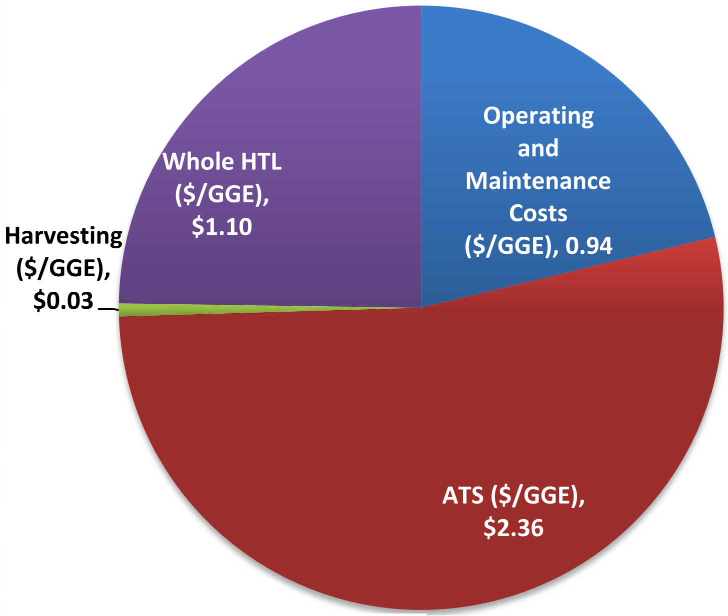
Case 11: Medium Productivity (20 g m-2 d-1), Whole HTL, High Ash (50%)



Total Cost: $6.65 /GGE

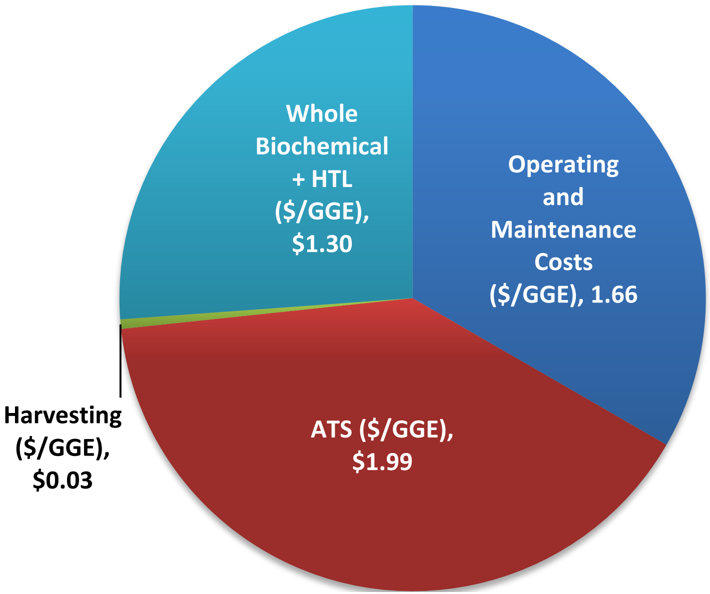
Preliminary TEA – Best Cases
High Productivity (30 g m^{-2} d^{-1}) & Low Ash (13%)

Case 5: Whole Algae HTL



Total Cost: $4.43 /GGE

Case 6: Whole Algae Biochem Processing + HTL of Residue



Total Cost: $4.97 /GGE

Paths to fuel cost reduction (to ~\$3/GGE[1])

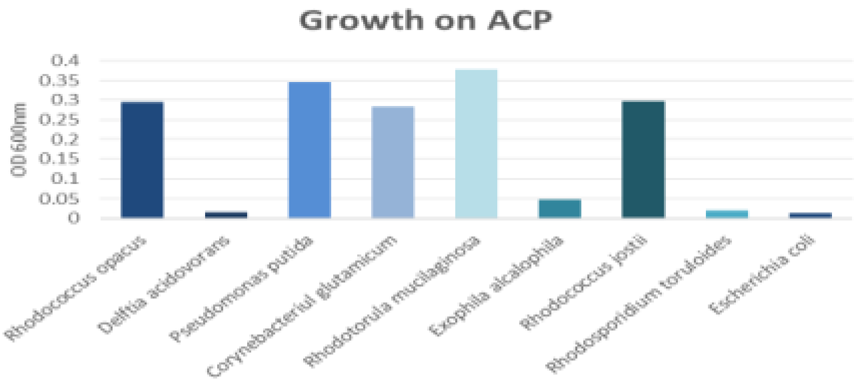
- **Increase biomass productivity**
  - e.g., to 30 g m^{-2} d^{-1} (AFDW) annual daily average
- **Reduce ash content of algal turf biomass**
  - Reduced ash in raw cultivated & harvested material (systems & ops)
  - Ash reduction via pre-processing prior to conversion processing
- **Decrease Capital Costs**
  - Improved system design for more efficient use of materials
  - Less costly materials
- **Decrease or Offset Operational Costs**
  - Co-product and co-service (e.g., water cleaning) value / credits
  - Improved operational efficiencies

[1] *BETO Algae Program Goal, per Multi-Year Program Plan, March 2015.*

Valorization Investigations of HTL Aqueous Co-Product (ACP)

Table below: 20 most abundant compounds in ACP prior to biological conversion. (ND – Not determined)

Compound	Relative abundance [%]
Pyroglutamic acid	46.37
(3-carbamoyloxy-2-phenylpropyl) carbamate	7.09
Lactic acid	6.62
Succinic acid	4.69
Sulfamonomethoxine	4.25
2-Acetolactic acid	2.56
Furafylline	2.25
Desmethylnaproxen-6-O-sulfate	2.03
His Cys Met	1.80
2-Ketovaline	1.26
Lactaldehyde	1.23
3-Hydroxybutyric acid	1.16
2-Keto-glutaramic acid	1.05
4'-Desmethylpapaverine sulfate	1.01
ND	0.95
2-Acetolactic acid isomer	0.92
3-Hydroxyglutaric acid	0.83
ND	0.73
ND	0.72
Adipic acid	0.69



Graph above: Organism growth on ACP derived from algal turf biomass obtained from the upper 3D floway of Great Wicomico River

Investigations underway to assess feasibility and yields for higher value products from ACP using various selected organisms

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Initial Scoping of Scale-Up Potential

Quick Look at Southeastern States Region

Preliminary Screening of Scale-Up Potential

Based on initial screening of potentially suitable land area for siting Algal Turf cultivation within 5 miles of impaired surface waters in the eight state SE region with coldest monthy temperatures > 30°F and land slope ≤ 3%

Scenario: Using ~ 9% of the shrubland acreage identified for ATS biomass production, at fuel yield of 2000 GGE/acre, would provide scale-up to 1 Billion GGE

State	Ag Acres within 5 miles of Impaired Waters	Shrubland Acres within 5 miles of Impaired Waters	Total Ag & Shrubland Acres within 5 miles of Impared Waters
Alabama	2,312,215	388,264	2,700,479
Arkansas	1,705,378	78,175	1,783,553
Florida	6,621,383	876,168	7,497,551
Georgia	3,004,481	445,032	3,449,513
Louisiana	9,865,027	639,112	10,504,139
Mississippi	9,702,977	1,609,786	11,312,763
South Carolina	3,041,534	481,329	3,522,863
Texas	3,797,384	1,078,400	4,875,784
Total Acres	40,050,379	5,596,266	45,646,645

Data sources used:

Temperature Data from PRISM Climate Group, Oregon State Univ.
http://www.prism.oregonstate.edu/

Impaired Streams and Water bodies from the EPA ATTAINS Program
http://water.epa.gov/scitech/datait/tools/waters/data/downloads.cfm

Digital Elevation Model (GTOPO30) from the USGS
https://lta.cr.usgs.gov/GTOPO30

Next Steps for FY16

Pilot scale testing of ATS cultivation/harvesting productivity

- Single pass operation at one or two strategic site(s)
- Direct comparison with raceway pond planktonic algae production
  - No nutrient or CO_2 addition for ATS
  - Nutrient and CO_2 addtion required for open raceway ponds

Harvested algal turf material characterization over time

- Organic biomass elemental analysis & fractions: carbs, proteins, lipids, other
- Non-organic ash content and elemental analysis
- Species profile

Assess Long-Term Algal Turf Productivity and Resiliency

Provide Biomass for Processing and Conversion Testing

Scale-up Analysis: CONOPS, GIS-RA, TEA, Initial LCA

Looking Ahead to FY16-17
Pilot ATS Projects

Plans Underway to Partner with TAMU AgriLife Algae Research Center at Corpus Christi, TX in FY16 to evaluate ATS productivity performance

- Using Gulf Coast Estuarine/Marine Water
- Comparison of ATS with open raceway pond cultivation
  - Single-Pass ATS operation without addition of nutrients and CO_2
  - Raceway pond operation requiring addition of nutrients and CO_2

Possible additional pilot scale project in FY17 at freshwater inland site within Missippippi watershed

Looking Ahead to FY16-17
Pilot ATS Projects … continued

Efforts underway to establish a Salton Sea project partnered with Imperial Irrigation District (IID) and others still TBD in California

- Using inflow river water: partly saline with high Se content
- Combines energy production & environmental remediation (Se removal)

Red Hill Bay site
Adjacent to Alamo River inflow to SS

The entire dry bay area is IID lands leased to USFWS

Conclusions

- Algal turf polyculture biomass processed using biochemical and/or thermochemical conversion offers a promising alternative approach to algal biofuels
- SNL processing and conversion results show promise, and will continue at larger scale in FY16
- Preliminary TEA shows promise for both whole algae HTL and tandem Biochemcial + HTL processing of residue – with application of water clean-up credits yet to be included
- Future work will assess the single-pass performance of pilot scale algal turf polyculture productivity and culture stability relative to open raceway ponds
- Detailed analysis needed on CONOPS, TEA, GIS-RA, & LCA

Thank you! - Questions?

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HydroMentia
WATER TREATMENT TECHNOLOGIES

Smithsonian
National Museum of Natural History

UtahStateUniversity

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