DOE Bioenergy Technologies Office (BETO) 2015 Project Peer Review

Algal Polyculture Conversion & Analysis

24 March 2015

Algae Technology Area

This presentation does not contain any proprietary, confidential, or otherwise restricted information
Goal Statement

Alternative path to affordable & scalable algal biofuels

• New paradigm not focused on monoculture, lipids, and PBRs & raceway pond cultivation approaches
• Emphasis on benthic algal turf polyculture for practical scale-up
  – Robust, resilient polyculture biomass cultivation
  – Potential for high biomass productivity with ease of harvesting & dewatering
  – Potential avoidance of need for supplemental CO2 & commercial fertilizers
  – Potential for tapping water clean-up credits as a co-product / co-service
  – Conversion of all components of low-lipid algal polyculture biomass to fuel intermediates using optimized tandem biochemical and/or HTL processing.

Relevance and Outcomes

• Show feasibility and path for integrated scale-up to meet MYPP\(^1\) targets of 5000 GGE/acre @ $3/GGE

\(^1\) DOE/EERE-BETO, Multi-Year Program Plan, November 2014.
Quad Chart Overview

Timeline

- Project start date: August 13, 2013
- Project end date: September 30, 2017
- Percent complete: 28%

Budget

<table>
<thead>
<tr>
<th></th>
<th>Total Costs FY 10–FY 12</th>
<th>FY 13 Costs</th>
<th>FY 14 Costs</th>
<th>Total Planned Funding (FY 15-Project End Date)</th>
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<td>$13K</td>
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Barriers

- AFt-A. Biomass Availability and Cost
- AFt-B. Sustainable Algae Production
- AFt-D. Sustainable Harvesting
- AFt-H. Overall Integration & Scale-up
- AFt-I. Algal Feedstock Preprocessing

Partners

National Laboratories (level of effort) – Hub

- INL (41%)
- ORNL (18%)
- SNL (35%)
- PNNL (6%)

Collaborators (Hub and otherwise)

- University of California San Diego (Hub)
- University of Kansas (ORNL)
- Boise State University (INL)
- Hydromentia (SNL)
- SI & Ecological Systems Technology (SNL)
- Utah State University (SNL)

Prior to Hub

Hub
1 - Project Overview

History and Context

• FY09/10 - SNL interest in polyculture algal turf began as possible alternative to address challenges for monoculture PBR/pond/lipid pathway to algal biofuels;
• FY13 - SNL-led “Algal Turf to Fuel” team proposal to ABY FOA;
• Late-FY13 - SNL asked to help BETO investigate polyculture potential via new AOP project - Polyculture Conversion & Analysis:
  – Quick-dive polyculture literature search and consulting of colleagues active in field w/ findings reported to BETO 1QFY14: Promising for resilience, Improved productivity TBD
  – Initiated algal turf sample characterization and biochemical & HTL processing of wet algal turf in Q2/FY14 – leveraging work under former SABC (BETO-funded) project;
  – TEA feasibility analysis of “algal turf to fuels” initiated late-FY14 for whole HTL;
• FY15 – Continued SNL testing/analysis; TEA of tandem biochem + HTL
• FY15 – Initiation of coordination & collaboration of SNL project with multi-lab “Polyculture Hub”

High-Level Objectives

• Identify & develop cost-effective and scalable path for producing fuels from low-lipid algal polyculture biomass, with emphasis on benthic algal turf
2 – Approach (Technical)

Emphasis:
• Benthic polyculture algal turf biomass characterization, productivity and quality improvement for fuels;
• Tandem biochemical and/or HTL conversion of low-lipid biomass to fuels;
• Algal turf-to-fuels TEA, LCA, and sustainable scale-up feasibility assessment;
• Hub Collaboration - Comparative assessment of productivity, stability, and conversion efficiency relative to pond-based monoculture & polyculture.

Challenges:
• Improving algal turf biomass productivity & quality (lower ash) without need for supplemental CO2 and fertilizer – nutrient recycling included;
• Affordable & scalable conversion of low-lipid and higher-ash biomass to fuels.

Critical success factors:
• Go/No-Go: Demonstrate annual average productivity of ≥20 g m\(^{-2}\) d\(^{-1}\) (AFDW) and conversion of wet biomass to fuels with target yields of ≥40%;
• TEA & LCA performance – LCA still to come, refined TEA in progress;
• Industry and lab partnering to enable affordable fuels scale-up.
2 – Approach (Management) – SNL

- **Focus on critical success factors that will define path with technical and commercial viability**
  - Biomass productivity, quality, and fuel conversion efficiency;
  - Fuel production cost reduction potential and path;
  - Fuel production scale-up potential and path;
  - Leverage value from co-products & co-services.

- **Risk Management**
  - Leverage mature, commercialized, and scalable algal turf production technology for water treatment;
  - Pursue complementary alternative Biochemical and HTL processing pathways, including nutrient recycling;
  - Coordinate/Collaborate with other BETO labs under Algal Polyculture Hub.
2 – Approach (Management) - Hub

**Coordination Plan**
- Individual laboratory AOPs
- Lab specific milestones
- Joint milestones
- Scaled demonstrations
- Project integration
- Monthly PI calls
- Quarterly HQ calls
- Quarterly reports to BETO
- Go To Meetings
- SharePoint Site
- Common framework for data when possible
- Hub-- Extension of expertise through university collaborators
Algal Turf System - Open Field Algal Farming

Cleaning water while producing biomass

**A New Dimension in Algae Farming**

Algal Turf Scrubbing® – “Aquatic Field Crop for Fuel”

2D (conventional) vs. 3D (higher biomass productivity) liner surface texture

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

Innovative 3D substrate texture (3D Screen®) can enable increased turf biomass productivity w/ possibly reduced exogenous ash content.

Illustration courtesy of Dean Calahan (calahans@si.edu)

Conventional 2D substrate used for water treatment systems - not optimized for increasing biomass productivity

Farm implement-type mechanical harvesting & dewatering yielding 8-15 % solids wet biomass

**Illustration courtesy of Dean Calahan (calahans@si.edu)**
**Based on projections with non-optimized fuel intermediate yields achieved at bench scale at SNL and from the literature, not including potential energy extraction from HTL aqueous co-product (ACP), using algal turf polyculture biomass from HydroMentia with the following AFDW material composition:

- 8g lipid
- 39g protein
- 34g carbohydrate
- 19g other organics

100g basis (AFDW)
3 – Technical Accomplishments/Progress/Results (cont’d)

Algal turf biomass characterization (raw harvested material)
From systems and operations non-optimized for biomass quality

- Composed of multiple phylogenetic groups: Dominant clades include chlorophyta, diatoms & cyanobacteria – details depending on location
- Relatively low lipid content (8% AFDW)
- Relatively high protein content (39% AFDW)
- Relatively high carbohydrate content (34% AFDW)
- Can have relatively high ash content (50+% raw harvest)

Biogenic + Exogenous Ash

- Ash reduced from 52% to ~20% w/ rinsing
- Untapped opportunities to improve and optimize harvested material quality
Biochemical Pretreatment - Solubilization, hydrolysis, & ash separation

- Dilute acid effective for solubilizing the protein & carb fractions + carb hydrolysis
- Relatively low-cost enzymatic treatment necessary for protein hydrolysis
- Dilute acid and enzymatic treatments are each effective for separating ash
- Simple rinsing reduces exogenous ash

**Ash separation**

**Solubilization and hydrolysis**
Biochemical conversion: Sugar & Protein Fermentation

- 70% of theoretical protein conversion achieved at bench scale
- 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 + NH₄⁺, developed by collaborator Liao & coworkers (Huo Nat. Biotech 2011)
Thermochemical conversion – results of non-optimized bench tests

**Improved biocrude yields obtained for polyculture algal turf vs. monoculture**

- HTL oil yield of whole polyculture algal turf is **44%**, with N content of **4.5%**
- HTL oil yield of monoculture (*nannochloropsis*) for same process conditions yields 35%, despite less ash - other monocultures are to be investigated
- Literature values of monocultures with continuous HTL systems obtain >50% yields implying the likelihood of much improved performance for polyculture algae
- Whole algal turf polyculture produced the least char
- HHV of 38.7 MJ/kg and 39.4 MJ/Kg for HTL oil from whole algae & residue, respectively
- HTL of biochemically preprocessed residue yields 22% biocrude, **N content of 0.89 %**

<table>
<thead>
<tr>
<th></th>
<th>Whole Algal Turf</th>
<th>Algal Turf Residue*</th>
<th>Whole Nannoch.</th>
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<tbody>
<tr>
<td>GAS</td>
<td>14%</td>
<td>18%</td>
<td>13%</td>
</tr>
<tr>
<td>BIOCRUDE</td>
<td>44%</td>
<td>22%</td>
<td>35%</td>
</tr>
<tr>
<td>AQUEOUS</td>
<td>25%</td>
<td>32%</td>
<td>30%</td>
</tr>
<tr>
<td>SOLIDS</td>
<td>17%</td>
<td>28%</td>
<td>22%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Nitrogen partitioning in HTL Fractions from Algal Turf Residue</th>
<th>Nitrogen partitioning in HTL Fractions from Whole Alga Turf</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>40%</td>
<td>42%</td>
</tr>
<tr>
<td></td>
<td>13%</td>
<td>17%</td>
</tr>
<tr>
<td></td>
<td>19%</td>
<td>26%</td>
</tr>
<tr>
<td>WHOLE ATS BIOCRUDE</td>
<td>28%</td>
<td>15%</td>
</tr>
</tbody>
</table>

*Algal Turf Residue refers to the material remaining after fermentation of carbs and proteins*
3 – Technical Accomplishments/Progress/Results (cont’d)

Preliminary TEA Results for Algal Turf + Whole Biomass HTL*
Assuming high (unimproved) ash content (50%) harvested biomass @20% solids to HTL

- Algal Polyculture Conversion & Analysis
  - HTL Processing & Upgrading To Renewable Diesel Using 2014 PNNL AHTL Report Results
  - Revised TEA Underway for Tandem Biochem + HTL & Whole Algal HTL w/ SNL Data

Total Cost: 8.54 $/gal (GGE)

Operation Cost: $/gal Fuel
- Power Requirements: $0.83
- HTL Cost of Supplies: $0.25
- Fuel For Harvesting: $0.89
- Pumping Costs: $0.28
- Labor for ATS/Harvesting: $0.20
- Labor for HTL: $0.14

Capital Cost: $/gal Fuel
- ATS Growth System: $3.44
- Harvest: $1.00
- HTL: $0.58
- Hydrotreating: $0.12

• HTL Processing & Upgrading To Renewable Diesel Using 2014 PNNL AHTL Report Results
  ... Revised TEA Underway for Tandem Biochem + HTL & Whole Algal HTL w/ SNL Data
Preliminary TEA Sensitivity Results for Algal Turf + HTL Processing
Assuming high (unimproved) ash content (50%) harvested biomass (20% solids) to HTL

Model Inputs Sensitivity Analysis

- Growth Rate
- Capital ATS Liner Costs
- Capital HTL Costs
- Pump Head
- Capital Hydrotreating Costs
- Cost of Diesel for Harvesting
- Capital Earthworks & Piping Costs
- Capital Harvest Costs

+20% Baseline

-20% Baseline

$/gal

$7.40
$7.70
$8.00
$8.30
$8.60
$8.90
$9.20
$9.50
$9.80
$10.10
Assessment of Scale-Up Potential

Based on initial screening of potentially suitable land area for siting Algal Turf cultivation closely adjacent to impaired surface waters in the eight state Southeastern region, with dual-use role of biomass feedstock production and water quality improvement.

**Screening suggests > 1 billion GGE/yr potential**

**Refined assessment in progress**

<table>
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<tr>
<th>State</th>
<th>Ag Acres within 5 miles of Impaired Waters</th>
<th>Shrubland Acres within 5 miles of Impaired Waters</th>
<th>Total Ag &amp; Shrubland Acres within 5 miles of Impaired Waters</th>
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<tbody>
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<td>Total Acres</td>
<td>40,050,379</td>
<td>5,596,266</td>
<td>45,646,645</td>
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**Data sources used:**
- Temperature Data from PRISM Climate Group, Oregon State Univ. [http://www.prism.oregonstate.edu/](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](http://water.epa.gov/scitech/datait/tools/waters/data/downloads.cfm)
- Digital Elevation Model (GTOPO30) from the USGS [https://lta.cr.usgs.gov/GTOPO30](https://lta.cr.usgs.gov/GTOPO30)
4 – Relevance

- Polyculture algal turf for biofuels is promising alternative for meeting BETO MYPP Algal Program Goals:
  - Practical and scalable cultivation & harvesting systems and operations;
  - Leverages industry commercialization of algal turf for water treatment;
  - Potentially capable of high, stable, and resilient biomass productivity;
  - Potentially avoids cost & logistics of providing supplemental CO$_2$ & nutrients;
  - Dual-use opportunity for water cleaning (N & P removal) credits;
  - Largely unexplored opportunities to improve ATS productivity & quality.
- Biochemical and/or HTL processing promising for converting low lipid content biomass to fuels and coproducts, including nutrient recycling;
- Initial TEA feasibility w/ whole algal biomass HTL processing looks promising, with TEA in progress for tandem biochemical + HTL processing;
- Preliminary GIS land and impaired water source screening assessment suggests promise for single-pass ATS operations capable of >1B GGE ... refined resource assessment in progress.
4 – Relevance - Hub

- Integrated polyculture R&D efforts and the BETO AOP process allows flexibility to adapt and adjust focus based on findings;
- Polyculture Hub activities have been designed to address a subset of these key challenges through collaboration and integration of expertise and capabilities towards established goals;
- Interface with industry on needs and system and process improvements (HydroMentia, others) + close communication and collaboration with BETO ATP3 testbed for monoculture comparison;
- Expected Outcomes:
  - Polyculture options for achieving relatively high biomass productivity, stability, and resilience relative to monoculture;
  - Polyculture biomass production target: \( \geq 20 \text{ g/m}^2/\text{day (AFDW)} \) annualized daily productivity.
5 – Future Work - SNL

- Polyculture algal turf productivity & quality improvement – dynamic interdependencies: engineered system & biology;
- Probiotic polyculture performance enhancement and possible seeding of ATS with selected consortia;
- Meso-scale polyculture cultivation testing/monitoring;
- Refinement and optimization of biochemical & HTL processing and conversion of polyculture biomass;
- Testing and evaluation of larger-scale biochem-HTL polyculture processing (with LBNL-ABPDU and PNNL);
- Comparative performance testing of polyculture vs. monoculture (with ATP³);
- Initiation of LCA and refinement of TEA and GIS feasibility.
5 – Future Work - Hub

**INL**
- Productive polycultures at cool temperatures
- High-throughput to field validation

**SNL**
- Polyculture algal turf biomass productivity & quality improvement
- Biochemical & HTL processing and conversion of polyculture biomass
- Probiotic performance enhancement of polyculture
- Comparative performance testing of polyculture vs. monoculture
- Meso-scale pond testing/monitoring

**PNNL**
- Evaluate polycultures in climate-simulation ponds
- Predictive modeling of polycultures

**HUB**

**ORNEL**
- Stable polycultures resistant to pond crashes
- Meso-scale pond testing
- Predictive modelling of long term grazer:algae population dynamics
Summary

Overview: Benthic polyculture algal turf biomass production, with biochemical and/or thermochemical (HTL) processing to fuel intermediates, offers an alternative path to meet BETO’s Algal Program MYPP goals and milestones.

Approach: Maximize yields, minimize costs, and identify viable path for integrated scale-up of polyculture algal biomass production and conversion using high-efficiency biochemical and/or HTL utilization of all biomass components to optimize production of liquid fuels.

Technical Accomplishments/Progress/Results: Characterized algal turf biomass from several sources; Achieved promising bioconversion yield of algal turf proteins and carbohydrates to mixed alcohols & HTL conversion of residue yielding reduced N-content biocrude at bench scale; Achieved >40% bench scale HTL conversion of whole algal turf biomass; Initial TEA and scale-up feasibility promising.

Relevance: Biochemical and/or HTL conversion of low-lipid, higher ash polyculture algal turf biomass produced without need for supplemental CO$_2$ and nutrients, and/or with nutrient recycling, has promise as an alternative path to affordable, scalable, and sustainable biofuels.

Future work: Increased polyculture algal biomass productivity and quality (reduced ash), larger scale demonstration of linked biochemical / HTL conversion operations, pro-biotic enhancement, dynamic system modeling, LCA, TEA, and GIS feasibility assessment.
Thank you! - Questions?

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Ben Wu - SNL/CA
Deborah Newby - INL
Walter Adey - Smithsonian Institution
Dean Calahan - Smithsonian Institution
Mark Zivojinovich - HydroMentia, Inc.
Justin Hoffman - Utah State University
Jason Quinn - Utah State University
Responses to Previous Reviewers’ Comments

- Project started after last BETO Peer Review
High-Level Concept for Polyculture “Algal Turf to Fuels”

Non-Point Surface Water Sources w/ excess nutrient load
- Chesapeake Region
- Mississippi Watershed
- Gulf Coast Region
- Salton Sea
- etc.

ATL Algae Cultivation
Mechanical Harvesting & Dewatering

Nutrient Recycle

Struvite
Mixed Alcohols, Terpenes, etc.

Fuel Intermediates and/or Commodity Chemical Products

Tandem Biochem & HTL Process Option

Whole Algal Biomass HTL Option

Hydrothermal Liquification (HTL)

Flash Separation
Hydro-treatment
Aqueous Co-Product (ACP)

Light Hydrocarbons
Hydrocarbon Fuel Diesel/Jet/Naphtha

Biocatal Hydrothermal Gasification (CHG)

Biogas

Thermochemical Process Option

Cleaner Water
- Less nutrient loading
- Increased oxygen
- Increased pH

Nutrient Removal Credits

Diagram Legend
- Upstream Operations
- Downstream Processing & Conversion Unit Operations
- Intermediate Products
- End-Use Products
Projected fuel yields (GGE) as function of biomass productivity*

Still to be Included is Value of Product vs. Cost of Production Tradeoff

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<tr>
<th>Fuel Production per Processing Pathway</th>
<th>Polyculture Algal Biomass Annual Average Daily Productivity [g m⁻² d⁻¹] (AFDW)</th>
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<td>Annual Biomass Production [kg/acre] (AFDW)</td>
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Tandem Biochemical & HTL Processing & Conversion

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<th>Annual Fuel Production by Type [GGE/acre]</th>
<th>Ethanol:</th>
<th>Isobutanol:</th>
<th>Naphtha:</th>
<th>Diesel:</th>
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<td></td>
<td>701</td>
<td>935</td>
<td>1169</td>
<td>1403</td>
</tr>
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</table>

Total Annual Fuel [GGE/acre]

| Total Annual Fuel [GGE/acre] | 2248 | 2997 | 3746 | 4495 |

Whole Algal Biomass HTL Processing & Conversion

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<tr>
<th>Annual Fuel Production by Type [GGE/acre]</th>
<th>Naphtha:</th>
<th>Diesel:</th>
</tr>
</thead>
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<td>2529</td>
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<td></td>
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<td></td>
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<td>4216</td>
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<tr>
<td></td>
<td>973</td>
<td>5059</td>
</tr>
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</table>

Total Annual Fuel [GGE/acre]

| Total Annual Fuel [GGE/acre] | 3016 | 4022 | 5027 | 6032 |

* 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
Collaboration in Algal Polyculture Hub Starting FY15

*Initiated in FY14 as stand-alone SNL AOP polyculture project*
  Ryan W Davis, Anthe George, Todd W Lane, Ronald C Pate, Ben C Wu.
• Presentations at 2014 ABBB Symposium and 2014 ABO Summit.
• Joint Hub publication in preparation: Review manuscript to be submitted to BETO that establishes a baseline for the state of the art for algal polyculture overyielding and resilience (FY15 Q2).
• Publications and presentations in preparation for reporting on updated project results achieved in FY15.
• Collaboration on Algal Turf Scrubber® cultivation & harvesting with Walter Adey (Smithsonian Institution) and HydroMentia
• Collaboration discussions with ATP³ re/ testing of polyculture vs. monoculture, LBNL-ABPDU and PNNL re/ larger scale polyculture biomass biochemical and HTL processing, and others in industry re/ commercialization.
Hydrolyzed Carbohydrate Profile*

* Based on algal turf samples from HydroMentia

Note: The carbohydrate fraction was ~34.5% of the non-ash biomass in the samples analyzed.
Thermochemical conversion of raw harvested algal turf:

Bench scale HTL giving > 40% biocrude yields with N content ~ 5%

- 44% biocrude achieved – process unoptimized
- C in aqueous co-product/solids can potentially be recovered to increase yield
- Gas composition mostly NH₃, CO₂ and some CH₄
- Solids yield is mixture of oil and char; char TBD

Based on wet biomass w/ 10% SOLIDS

<table>
<thead>
<tr>
<th></th>
<th>Carbon partitioning</th>
<th>Nitrogen partitioning</th>
</tr>
</thead>
<tbody>
<tr>
<td>GAS</td>
<td>14%</td>
<td>9% 42%</td>
</tr>
<tr>
<td>BIOCRUDE</td>
<td>44%</td>
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<td>AQUEOUS</td>
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<td>17%</td>
<td>18% 15%</td>
</tr>
</tbody>
</table>

Biocrude N content: 4.5%
Thermochemical conversion of biochemically processed algal turf:

Bench scale HTL processing of pre-processed residue ... Reduces N by > 80%

- 24% biocrude from residue w/ reduced N content <1% - process unoptimized
- C in aqueous co-product and solids can potentially be recovered to increase yield
- Higher content ash likely changing heat/mass transfer profiles and affecting yield
- High heating value of 38.7 MJ/kg (versus 46 MJ/kg for typical upgraded HTL oil and 45 MJ/kg for gasoline)

Based on wet biomass w/ 10% SOLIDS

<table>
<thead>
<tr>
<th>Component</th>
<th>Carbon partitioning</th>
<th>Nitrogen partitioning</th>
</tr>
</thead>
<tbody>
<tr>
<td>GAS</td>
<td>18%</td>
<td>12% 40%</td>
</tr>
<tr>
<td>BIOCRUDE</td>
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<td>33% 19%</td>
</tr>
<tr>
<td>SOLIDS</td>
<td>28%</td>
<td>31% 28%</td>
</tr>
</tbody>
</table>

Biocrude N content: 0.89%
Preliminary TEA Assumptions - Non-optimized ash content

- **Economic Assumptions**

<table>
<thead>
<tr>
<th>Input</th>
<th>Value</th>
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<tbody>
<tr>
<td>Equity</td>
<td>40%</td>
</tr>
<tr>
<td>Loan Interest Rate</td>
<td>8%</td>
</tr>
<tr>
<td>Loan Term</td>
<td>10 yrs</td>
</tr>
<tr>
<td>Internal Rate of Return</td>
<td>10%</td>
</tr>
<tr>
<td>Income Tax Rate</td>
<td>35%</td>
</tr>
<tr>
<td>Plant Life</td>
<td>30 yrs</td>
</tr>
<tr>
<td>Build Time</td>
<td>3 yrs</td>
</tr>
<tr>
<td>Annual Fuel Production</td>
<td>46 Mgal</td>
</tr>
<tr>
<td>ATS Cultivation Acreage</td>
<td>15000 acres</td>
</tr>
</tbody>
</table>

Preliminary TEA Feasibility Assessment Unit Ops and Assumptions

### Preliminary TEA Assumptions - Non-optimized ash content

#### ATS Growth

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Growth Rate (AFDW)</td>
<td>20 g m⁻² d⁻¹</td>
</tr>
<tr>
<td>Pumping Duty Cycle</td>
<td>14 hr d⁻¹</td>
</tr>
<tr>
<td>Pumping η</td>
<td>67%</td>
</tr>
<tr>
<td>Pumping Head</td>
<td>4 m</td>
</tr>
<tr>
<td>ATS Length</td>
<td>152 m</td>
</tr>
<tr>
<td>Biomass (AFDW) Flow</td>
<td>1340 ton d⁻¹</td>
</tr>
<tr>
<td>Capital Cost</td>
<td>$10 m⁻²</td>
</tr>
</tbody>
</table>

#### Harvest

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harvest Density</td>
<td>20% solids</td>
</tr>
<tr>
<td>Ash Content</td>
<td>50%</td>
</tr>
<tr>
<td>Harvest Frequency</td>
<td>7 days</td>
</tr>
<tr>
<td>Operation Cost</td>
<td>$0.23 m⁻²yr⁻¹</td>
</tr>
<tr>
<td>Capital Cost</td>
<td>$0.35 m⁻²</td>
</tr>
</tbody>
</table>

#### HTL/CHG Processing

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>NG Energy</td>
<td>3.7 M-MJ d⁻¹</td>
</tr>
<tr>
<td>Electrical Energy</td>
<td>120 MWh d⁻¹</td>
</tr>
<tr>
<td>Capital Cost</td>
<td>$183 M</td>
</tr>
<tr>
<td>Oil Yield</td>
<td>47%</td>
</tr>
<tr>
<td>Aqueous Yield</td>
<td>40%</td>
</tr>
<tr>
<td>Ash Content</td>
<td>50%</td>
</tr>
<tr>
<td>Gas</td>
<td>3%</td>
</tr>
</tbody>
</table>

#### Hydrotreating

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Yield</td>
<td>78%</td>
</tr>
<tr>
<td>Capital Costs</td>
<td>$69 M</td>
</tr>
<tr>
<td>Processing Capacity</td>
<td>153 kgal d⁻¹</td>
</tr>
<tr>
<td>Diesel Yield</td>
<td>83%</td>
</tr>
<tr>
<td>Naphtha Yield</td>
<td>16%</td>
</tr>
</tbody>
</table>

---

1 Cultivation and harvesting assessment customized to ATS, but using scale-up assumptions consistent with the ANL-NREL-PNNL Algal Biofuels Harmonized Baseline Study: Technical Report ANL/ESD/12-4, NREL/TP-5100-55431, PNNL-21437, June 2012.

Preliminary TEA Results for HTL Processing

Assuming lower ash content (13%) harvested biomass (20% solids) to HTL

Total Cost: 6.57 $/gal (GGE)

- Capital Costs: $4.21
- Operation Costs: $1.69
- Tax: $0.67

Operation Cost: $/gal Fuel

- Power Requirements: $0.04
- HTL Cost of Supplies: $0.13
- Fuel For Harvesting: $0.75
- Pumping Costs: $0.50
- Labor for ATS/Harvesting: $0.01
- Labor for HTL: $0.04

Capital Cost: $/gal Fuel

- ATS Growth System: $2.73
- Harvest: $0.81
- HTL: $0.47
- Hydrotreating: $0.19

Algal Polyculture Conversion & Analysis
Example Scenario for Reducing Fuel Cost to ~ $3/GGE

• **Reduce ash content** to ≤13% (Improved case)
  – Reduced ash in raw cultivated & harvested material (systems & ops)
  – Ash reduction via pre-processing prior to conversion processing
• **Increase annual growth rate** to 30 g/m²/day (AFDW)
• **Decrease Capital Costs** by 10%
• **Subsidies at 2x Fertilizer Costs** (*Leverage water clean-up credits*)
• **Results in estimated cost of $3.07/gal**

---

Cost Breakdown - 3.07 $/gal

- **Capital Costs**
- **Operation Costs**
- **Tax**
Turf algal biomass for fuels

Offers significant benefits over raceway monoculture systems

- Polyculture – resilient to crashes
- Growth: 10-20+ g/m²/day (AFDW) annual av. with non-optimized systems & operations
- No added nutrients or external CO₂
  - Using single-pass mode using water with excess N,P,CO₂
- Harvest/dewatering – simple, low-energy
- Biomass focus - low neutral lipids
- Similarities with open field agriculture

VS

- Monoculture – vulnerable to crashes
- Growth – 2 to 15 g/m²/day
- Fertilizer and external CO₂
- Harvesting & dewater more difficult & energy-intensive
- Lipid focus (historical)
Key Points

Algal Turf to Fuels – Promising polyculture algae solution to key challenges:
- Can avoid crashes ... Cultivation resiliency with polyculture
- Can avoid expensive, energy-intense harvesting & dewatering
- Can avoid costly CO₂ supply &/or co-location w/ industrial sources
- Can avoid commercial fertilizer costs

- Turf algae pioneered in 1980s (Walter Adey) and commercialized at multi-acre scales for water treatment (HydroMentia)
- Robust algae production of 20-30 tons ac⁻¹ yr⁻¹ AFDW annual average demonstrated over years of pilot and commercial scale systems operations for water treatment; Non-optimized for biomass production

SNL project emphasis:
- Characterization of algal turf biomass quality – feedback for improvement
- Biochem &/or HTL processing and conversion of total (wet) biomass
  - Optimize product yields vs. costs
  - Recycle major nutrients (N & P)
  - Reduce nitrogen content in biomass residue & subsequent HTL biocrude product
- Feasibility assessment for affordable scale-up
Advantages of algal polyculture turf for biofuels

• Relatively simple cultivation system configuration - more like open field ag
  – Utilizes pulsed, shallow, turbulent flow with excellent solar insolation exposure and gaseous exchange with atmosphere
  – Stable, diversified cultivation … resilient and resistant to crashes
  – Years of commercial experience w/ multi-acre systems for water cleaning

• One-pass operation (typically used for water cleaning)
  – Annual average daily AFDW biomass production of 10 -to- >20 g m$^{-2}$ d$^{-1}$
  – No engineered addition of CO$_2$ or nutrients required under single-pass operation
  – System improvement potential for 25 to ≥35 g m$^{-2}$ d$^{-1}$ AFDW annual average productivity
  – Multi-pass recycle system operation can expand deployment opportunities, but …
    • Requires supply of supplemental nutrients and CO$_2$
    • Imposes added CAPEX and OPEX

• Ease of scale-up and low-energy harvesting/dewatering
  – Scale up to larger acreage simple matter of duplication of multi-acre “field” modules
  – Simple mechanical harvesting approaches consistent w/ agricultural operations
  – Immediately provides 6% to >15% solids content wet biomass
Challenges of algal polyculture turf for biofuels

• Low neutral lipid content (< 10%)
  – Relatively high in protein and carbohydrates

• High ash content (~ 50+%) in raw harvested material
  ... with current systems not optimized for reduced ash
  – Ash is combination of biogenic and exogenous environmental material
  – Improvement possible with cultivation and harvesting systems & ops
  – Simple rinsing has reduced harvested material ash content from 50+% to < 25%
  – Dilute acid pre-treatment & separation provides ash reduction for biochem processing

• Heterogeneous polyculture biomass characteristics
  – Dynamically change with season and water source chemistry
  – Provides robust and resilient culture relatively immune to “crashes”

• HTL biocrude can have high nitrogen content (~5+%) 
  – Biochem pretreatment of proteins can reduce and recycle nitrogen
  – Resulting HTL biocrude from residue has N-content <1%, but yields are lower

• Preliminary TEA feasibility assessment looks promising.
Algal Turf Productivity in Water Treatment Systems

Biomass productivity on Floway #1, comparing 2-D (dashed lines), 3-D (solid lines) and Interface (bold dotted line) growth substrate (screens). The smooth curves are sine functions fit to the two data sets. Note the one-year mean production marked for different screen types (Adey, et al. J. Phycol. 49, 489–501, 2013).

Floway #1 (left) and Floway #2 (right) on the Great Wicomico River off the Central Chesapeake Bay

Productivity of Egret Marsh Commercial Scale ATS

Representative data from HydroMentia.
Normalized plots of dominant 15-20 species found in algal turf biomass provided courtesy of Walter Adey¹

Examples of Algal Turf Polyculture Cultivation & Harvesting

Photos courtesy of Mark Zivojnovich, HydroMentia and Walter Adey, Smithsonian Institution