2017 DOE Bioenergy Technologies Office (BETO) Project Peer Review

1.3.4.101 Thermochemical Interface
PNNL-SA-109025

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TECHNOLOGY AREA REVIEW: ALGAE

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Goal Statement

Develop processing methods for the algae hydrothermal liquefaction (HTL) Pathway to reduce conversion cost, improve sustainability and enable commercialization of algal biofuels supporting BETO’s MYPP strategic goals.

• Technical improvements span the Entire Pathway
  HTL processing, upgrading to finished fuels, water treatment, and nutrient recycle

• R&D Targets based on data driven Process Models and “State-of Technology” (SOT) Analysis

• Conversion Processing will be Validated at Engineering Scale
Quad Chart Overview

Timeline
- Project Start: 10/1/2016
- Project Finish: 9/30/2019
- Percent complete: 6%

Barriers
- Aft-H. Overall Integration and Scale-Up
  - Process integration/TEA; Engr. Scale HTP system being tested
- Aft-J. Resource Recapture and Recycle
  - Aggressively demonstrating reuse of HTL byproduct stream

Budget

<table>
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<tr>
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<th>FY 18 Budget</th>
<th>FY 19 Budget</th>
<th>Total Planned Funding (FY 17-Project End Date)</th>
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<tr>
<td>DOE Funded</td>
<td>$1,591,520</td>
<td>$1,800,000</td>
<td>$1,800,000</td>
<td>$5,191,520</td>
</tr>
</tbody>
</table>

Partners

- Other interactions/collaborations
  - Algal Biofuel Techno-economic Analysis 1.3.1.200 (NREL)
  - BETO Algal Testbeds (UA RAFT and ASU ATP3)
  - Hydrothermal Processing of Biomass 2.2.2.301
  - Characterization and Valorization of Aqueous Waste 2.3.1.310
  - Microalgae Analysis 1.3.2.102
  - Waste-to Energy : Feedstock Evaluation 2.2.1.109
  - Genifuel, Reliance Industries

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1 - Project Overview

Algae HTL Process

**HTL Pathway Model**

FY15 with CHG then recycle to pond

FY16 with untreated recycle to pond

Model Evolution

CHG eliminated / Direct recycle $/gge reduced by 40% 2015 to 2016

**HTL accounts for ~60% of conversion cost**

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight %</th>
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<tbody>
<tr>
<td>Lipid Content of Algae</td>
<td>14%</td>
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<tr>
<td>Biocrude from HTL Wt% (DAF)</td>
<td>43%</td>
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<tr>
<td>Carbon Yield to Biocrude</td>
<td>60%</td>
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</table>

**Wet Processing / High Carbon Yield**

**HTL Aqueous recycled to Ponds**

<table>
<thead>
<tr>
<th>Conversion, $/gge</th>
<th>2014</th>
<th>2015 SOT</th>
<th>2016 SOT</th>
<th>2022 Projection</th>
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<tr>
<td></td>
<td>$3.45</td>
<td>$0.22</td>
<td>$1.14</td>
<td>$1.98</td>
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<tr>
<td>Aqueous recycle</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td></td>
<td>$0.51</td>
<td>$0.29</td>
<td>$1.19</td>
<td>$1.98</td>
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<tr>
<td>HTL Biocrude Production</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>$0.57</td>
<td>$0.59</td>
<td>$0.59</td>
<td>$0.59</td>
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<tr>
<td>HTL Aqueous Phase Treatment</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$0.66</td>
<td>$0.66</td>
<td>$0.66</td>
<td>$0.66</td>
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<tr>
<td>Balance of Plant</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td>$0.31</td>
<td>$0.31</td>
<td>$0.31</td>
<td>$0.31</td>
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<tr>
<td>Nutrient Recycle Credits</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>$0.32</td>
<td>$0.32</td>
<td>$0.32</td>
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**Chlorella Algae, 22wt%**

**HTL Biocrude (Chlorella)**
## 2 - Approach Technical
### FY17- FY19

<table>
<thead>
<tr>
<th>Focus Area</th>
<th>Technical Objectives</th>
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| **Improved HTL Capacity/Capital Cost** | Increase LHSV  
Evaluate Blended Feedstocks (Cost, scale and capacity)  
Scale-up Validation at Engineering Scale |
| **Improved Biocrude Yield** | Improve Separations (solids/liquids and liquid/liquid)  
PFR scale-up improved conversion efficiency  
Use of blended feedstocks (wet wastes/lignocellulosics) |
| **Improved Fuel Yield and Quality** | Catalytic HTL  
Refinery Integration Options with Improved Biocrude |
| **Water Treatment/Reuse** | Direct recycle to Algae Ponds  
Concentration/Recovery Aqueous Phase Carbon for Fuel and Co-products  
Conversion to methane (CHG or AD) |
| **Nutrient Recovery and Recycle for Algal Cultivation** | HTL filter solids reuse (P and other minerals)  
Direct HTL water recycle (Carbon, N, P and Minerals) |
| **Distributed Small-scale Upgrading Process for HTL Biocrude** | Increased LHSV, Fe mitigation, Catalyst and Process Development  
LHSV and Reactor Economy of Scale  
Scale-up Validation at Engineering Scale |
| **Updated Process Models, TEA and LCA** | Integrate Conversion Models with Algae Farm (nutrient/water recycle)  
Use of blended feedstocks (wet wastes/lignocellulosics)  
Processing Improvements Validated at Engineering Scale  
SOT Updates/Pathway Options Analysis |
| **Scaled-up Fuel Production and Characterization** | Integrated engineering scale HTL, HT and distillation processing at best conditions |
2 - Approach (Management)

- **Critical Success Factors**
  - Decreasing HTL Conversion Costs
  - Nutrient Recycle
  - Scale-up Validation
  - Fuel Validation

- **Top Potential Challenges**
  - HTL Capital and Operating Costs
  - Process Turndown (seasonal productivity effects)

- **PM Approach**
  - Regular Milestones (1/Quarter) and Deliverables, Data Input for Process Model and Validation of SOT Technical Targets
  - Go/No Go Decision Points based SOT
  - Regular Meetings with BETO
  - Management and Integration of Supporting Projects and Partners
**3-Technical Accomplishments/Progress/Results**

**Algal HTL Process Development**

- **Evaluated Multiple Algal Feedstocks in Plug Flow HTL**
  
  Feedstock composition and solids impact biocrude yield *(Milestone)*


- **Initial Data Analysis of Algae Composition vs. Biocrude Yields**
  
  Inverse correlation between lipid and protein
  
  NREL algal feedstock compositional targets could enable high yields
- **Demonstrated Dramatic Increase in HTL Throughput**
  2X increase in LHSV = 50% Reduction in Capital Cost

- **Catalytic HTL Evaluated**
  TEA suggests no improvement over SOT for algal feedstocks *(Milestone)*

- **Feedstock Blends Proof-of-Concept**
  Higher biocrude yields observed with blended feedstocks *(Milestone)*
3. Technical Accomplishments/Progress/Results

**Aqueous Phase Treatment & Valorization**

- **Evaluated AD Treatment**
  HTL aqueous phase (WSU subcontract) *(Go/No-Go)*

- **Extended CHG Catalyst Life**
  Sulfur removal below 10ppm for freshwater strains only *(Go/No-Go)*

- **Demonstrated 60% TOC Reduction Aqueous Phase**
  Developing aqueous product recovery and valorization methods

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**Graphs and Data**

- **Gas Production (Normalized)**
  - 40% algae feed: 811 Nm³ gas
  - 50% algae feed: 260 Nm³ gas
  - 60% algae feed: 184 Nm³ gas

- **TOC Reduction with Activated Carbon Treatment**
  (1 g/10 mL carbon loading)
  - Clean Pine
  - 75:25 Pine:Chlorella
  - 50:50 Pine:Chlorella
  - Chlorella
3. Technical Accomplishments/Progress/Results

Upgrading and Fuel Characterization

- Developed Guard Bed Mitigation
  Iron plugging from algal biocrude porphyrins (Milestone)


- Demonstrated 200+ Hrs Hydroprocessing
  Algal HTL biocrude upgrading stability and fuel characterization (Milestone)

- Completed Blended Feedstock Upgrading and Fuel Characterization
  Blends improved diesel fuel properties (Milestone)
Phosphate Recovery and Recycle

- Developed HTL Solids Separation for Phosphate Recovery
  P and other minerals captured for nutrient recycle *(Milestone)*

- Demonstrated Phosphorus Recovery Process
  Dilute sulfuric acid recovery process flowsheet developed for HTL process model *(Milestone)*
Nutrient Recycle

- **Demonstrated Complete Nutrient Recycle using HTL Process Wastes**
  - P and (Ca, Mg, and S) derived from the acid extracted solids
  - N and P derived from the HTL-aqueous phase

- **Demonstrated Recycle for Semi-continuous Pond Simulation**
  - 80% dilution, alternating days for 16 cycles with no loss in productivity *(Milestone)*

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**Bioavailability of HTL Recovered Nutrients**

**Recycled HTL Nutrients in Semi-continuous Culture**

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3-Technical Accomplishments/Progress/Results
HTL Process Model, TEA/LCA, and SOT

- **Updated Process Model and SOT (Milestone)**
  - NREL CAP feedstock and farm scale
  - Remove CHG/ Add direct recycle
  - Add phosphate recovery recycle
  - Regional Upgrading

- **Completed PBR Cost Model (Milestone)**
  - vetted by an industrial entity
  - 800 to 1200 $/US ton (AFDW basis)

- **Modeled Blended Algal and Terrestrial Feeds Path to $3/gge (Milestone)**

Additional cost reduction options towards $3/gge
- HTL Plant scale
- Refinery Integration
- Aqueous carbon valorization

Minimum Fuel Selling Price, $/GGE (2014 $)
Engineering Scale HTL Skid

**System Features**
- Modular/Relocatable
- Feed Prep for All Feedstocks
- HTL Modes - PFR or CSTR/PFR Hybrid
- Heat Recovery
- Capacity 12-18 L/hour Feed
- Ash Solid Separations
- Flexible Product Separations Unit Ops

**Operational Status**
- System Fabrication and FAT completed July 2016
- PNNL Facility Mods & Installation completed October 2016
- Operational Readiness Testing/Documents/Training underway
- 100 Hour Run using Algae Feedstock scheduled March 2017 *(Milestone)*
**Technical Accomplishments/Progress/Results**

**FY 17 Milestones**

**Upgrading**
- Complete upgrading of a biocrude from blended algal and cellulosic feedstocks

**HTL Processing**
- Demonstrate higher LHSV with blended algal feedstocks with continuous solids removal in PF bench scale HTL

**Modeling/TEA/LCA**
- Updated SOT target table showing the FY17 progress towards the performance goals and summarize the supporting experimental information and TEA results in a brief.

**HTL Engineering Scale**
- Complete initial 100hr engineering scale HTL run with an algal feedstock

**Aqueous Phase Treatment**
- Demonstrate water treatment methods to improve biocrude yield by 10-15%

**FY18-19**
- Complete additional 100hr engineering scale HTL run to validate process improvements with mixed feedstocks
Targeted R&D focused on BETO primary technology pathway
- HTL pathway technical needs and cost targets identified
- Developing new enabling technology for critical elements of the pathway

Project has resulted new IP

Project is supporting technology transfer
- 2015 FLC Award, 2015 R&D100 Award
- Multiple collaborations with industrial partners and BETO IBRs

Project is leveraging synergies with Thermochemical Platform
- HTL process development, upgrading and fuel characterization
- Establishment of engineering scale HTL capability

Project has already contributed to multiple publications and invited presentations
## Future Work
### FY17 - FY19

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<tbody>
<tr>
<td>Task 1.1</td>
<td>SOT Targets</td>
<td>LHSV, Yield, Biocrude Quality, Lower Capital</td>
<td>Bench HTL PFR Processing (algal feedstocks/blended)</td>
<td>HTL Parametric Bench Testing</td>
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<tr>
<td>Task 1.2</td>
<td>SOT Targets</td>
<td>LHSV, Catalyst Life, Smaller Scale HT</td>
<td>Bench HT Processing (biocrudes algal feedstocks/blended)</td>
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<tr>
<td>Task 1.3</td>
<td>SOT Targets</td>
<td>COD Reduction, Biocrude Yield, N and P Recycle</td>
<td>Water Treatment (Adsorption/Recovery/Valorization)</td>
<td>Nutrient Recovery, Recycle, Bioavailability</td>
<td></td>
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<tr>
<td>Task 2</td>
<td>Pathway Cost Targets</td>
<td>LCA CO2 Mitigation</td>
<td>Update Process Models, TEA and LCA</td>
<td>Technology-to-Market (T2M) Planning</td>
<td></td>
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<tr>
<td>Task 3</td>
<td>Scale-up validation &amp; integration bench results</td>
<td>Sustained processing for fuel production</td>
<td>Eng. Scale HTL HTL PFR Processing (algal feedstocks/blended)</td>
<td>Eng. Scale HT</td>
<td>55 gal. Fuel</td>
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### Key AOP Interface Activities
- Hydrothermal Processing of Biomass, PNNL (2.2.2.301)
- Aqueous Samples for Char. & Upgrading, PNNL (2.12.2.1)
- Microalgae Analysis 1.3.2.102
- Waste-to Energy : Feedstock Evaluation 2.2.1.109
- Materials/Corrosion Assessment, ORNL (2.12.5.1)
- Provide Data Biofuels Products & Refinery Integr Modeling, NREL/PNNL 4.1.3.30/4.1.3.1
Summary

- **Relevance:** Project directly contributes to meeting the goals and objectives of BETO’s Advanced Algal Systems R&D (HTL Pathway)

- **Approach:** HTL pathway process development and scale-up base on process modeling and SOT technical and cost targets

- **Technical Accomplishments:** Significant advancements made in HTL processing, nutrient recovery/recycle, upgrading/fuel characterization and process scale-up

- **Future Work:** The project will conduct targeted research in FY17-19 based on SOT targets to significantly reduce HTL conversion cost, validate at engineering and enable commercialization

- **Success Factors and Challenges:** The critical success factors and challenges for the project have been identified and are being addressed

- **Technology Transfer:** The project is actively supporting technology transfer to industry through collaborations, IP development and licensing, publications and presentations. Received FLC Award and R&D 100 Award in 2015. Industrial collaborations underway.
Additional Slides
Publications


Presentations

- Scott Edmundson. “Phosphorus Recycle following Algal Biocrude Production via Hydrothermal Liquefaction” at the 6th International Conference on Algal Biomass, Biofuels and Bioproducts in San Diego, California, June 27th, 2016.
Publications, Patents, Presentations, Awards, and Commercialization

Awards
- 2015 FLC technology transfer excellence award
- 2015 R&D 100 Award “Hydrothermal Processing to Convert Wet Biomass into Biofuels”

Patents