# DOE Bioenergy Technologies Office (BETO) 2019 Project Peer Review

# Hydrothermal Liquefaction (HTL) Model Development
## 1.3.5.202

Advanced Algal Systems Review

March 4, 2019

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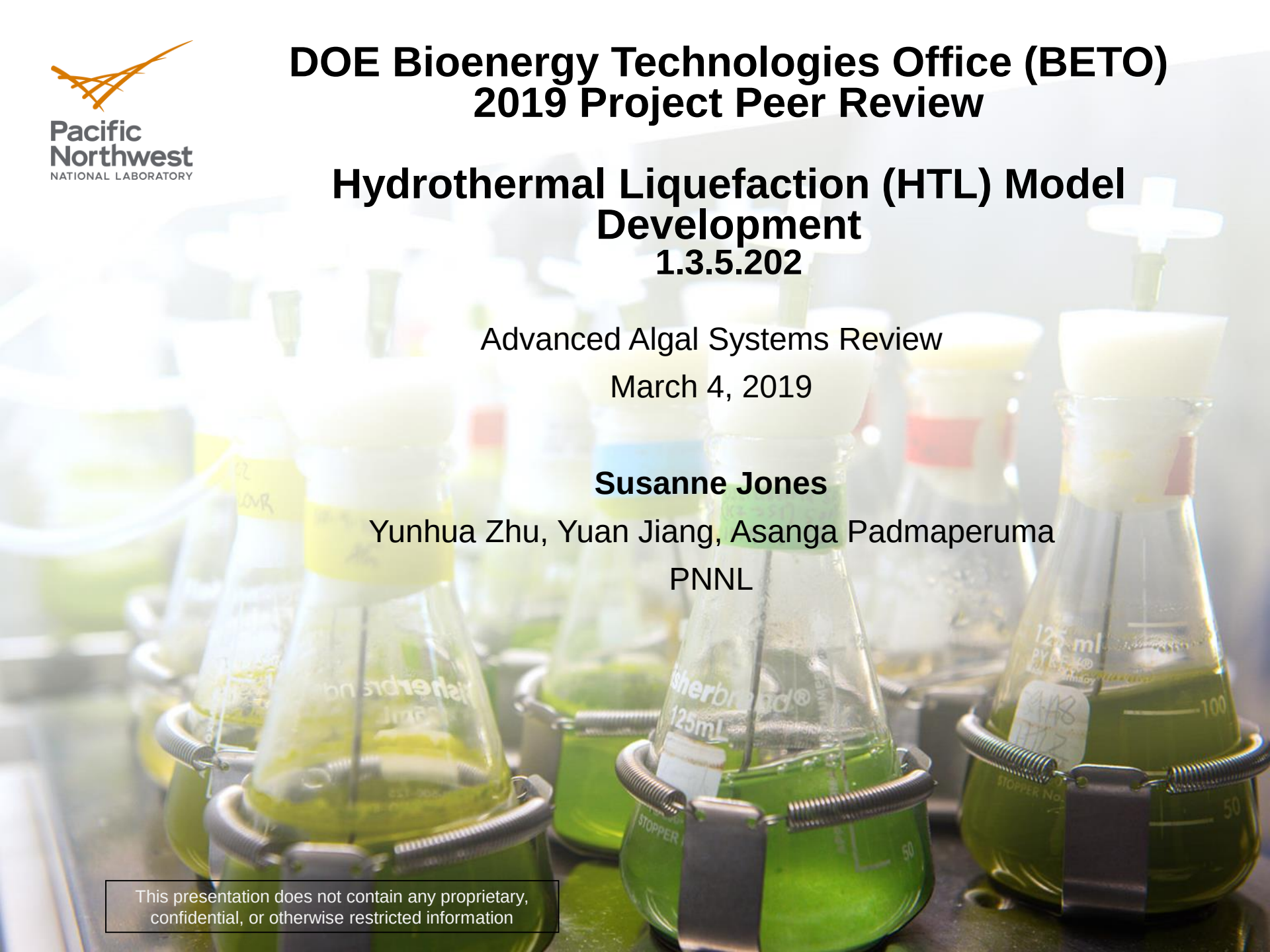
PNNL

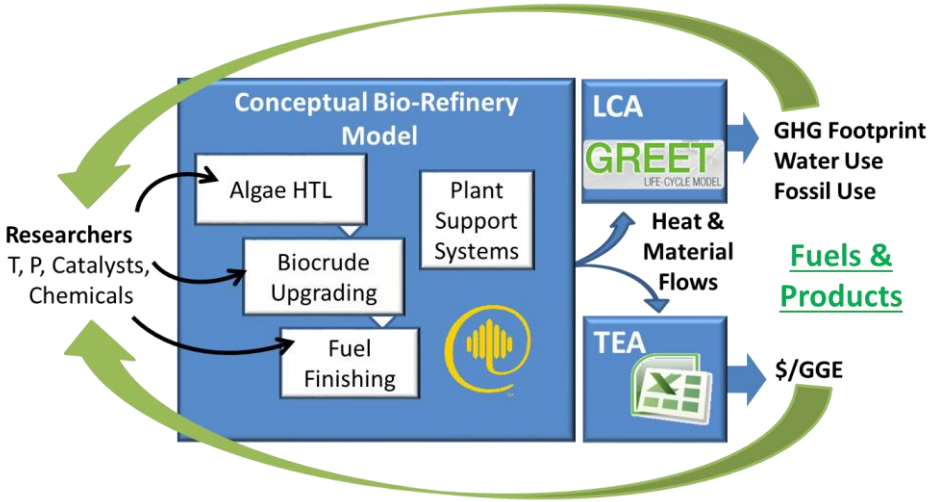


# Goal Statement

## Cost Effective Algae Conversion to Fuels is Challenging

**GOAL: Develop research-driven process models and perform techno-economic analysis to inform HTL algae conversion research for fuels and chemicals**

- **Guide research**
- **Track progress**
- **Reduce costs**




[HTL - hydrothermal liquefaction]

# Quad Chart Overview

Timeline
- Project start date: October 1, 2018
- Project end date: September 30, 2021
- Percent complete: 17%

| | Total Costs Pre FY17 | FY 17 Costs | FY 18 Costs | Total Planned Funding (FY 19-21) |
|---|---|---|---|---|
| **DOE Funded** | $474k | $153k | $170k | $600k |
| **Project Cost Share** | $0k | $0k | $0k | $0k |

**Partners: Collaborators/Interactions**
- **National Lab Interactions**
  - **ANL: life-cycle analysis**
  - **INL: terrestrial feedstock cost & quality**
  - **NREL: algal feedstock cost & availability**
  - **PNNL: experimentalists**

Barriers addressed

**At-E: Quantification of Economic, Environmental and other Benefits and Costs**

**Objectives:** Algae HTL is considered an example route to fuels that is tracked in the MYPP
- ***The Challenge***
  - Producing fuels from wet, algal is expensive
  - HTL addresses this, but yields, biocrude upgrading catalyst preservation, and HTL aqueous carbon valorization need attention
- ***The Solution***
  - Provide TEA to identify impactful areas of research
  - Use TEA to track research progress towards goals
  - Integrate with resource assessments conducted in related projects to understand business opportunities
- ***The Outcome***
  - Annual SOT assessments for the HTL route
  - Annual peer reviewed publication(s) to inform stakeholders

[HTL - hydrothermal liquefaction]

# 1 - Project Overview

**History**

- FY13-17: Algal HTL conversion analysis began as a subtask under an HTL experimental project. A *Design Report* published in FY14 outlined cost reduction targets for the 2022 timeframe
- FY18: algae HTL and wet waste HTL combined into a single analysis project
- FY18: algae HTL project passed merit review for the FY19-21 time frame

**Goals:** use conceptual biorefinery models to enable R&D toward sustainable economic algae conversion to liquid fuels and chemicals

- Identify barriers and cost reduction strategies
- Assess sustainability impacts
- Inform the setting of technical and cost targets
- Track R&D progress

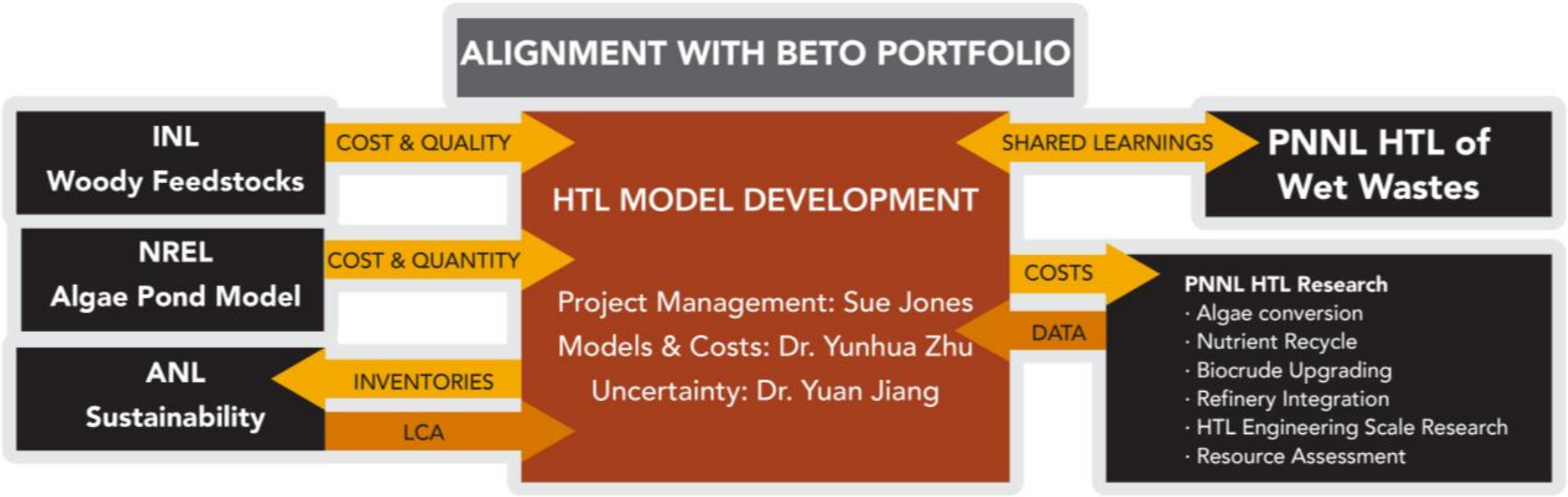
**Value**

- Incorporates multi-variable analysis approach vs 1-variable at a time to understand opportunity space
- Shares learnings from non-algae HTL research (wood, wet waste, bioreactor effluents)
- **Directs limited research dollars to be directed towards high impact research**

# 2 – Approach (Management)

## Approach Structure

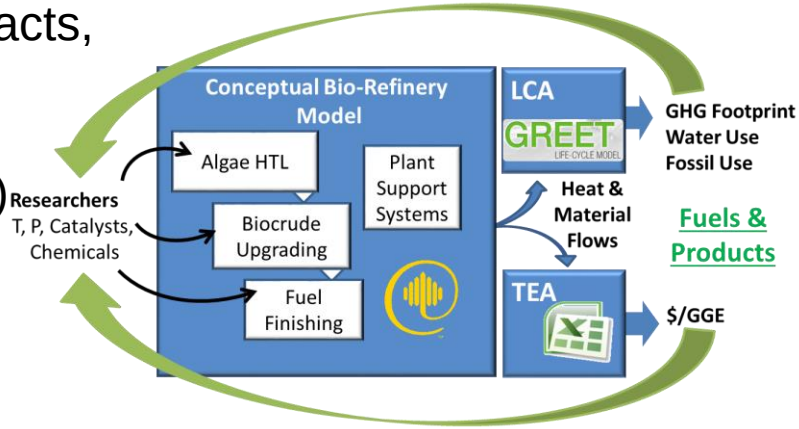
- Annual Operating Plants (AOP) with quarterly progress measures and deliverables in place with quarterly formal reporting to BETO
- Project merit reviewed in FY18 for FY19-21
- Go/No-Go scheduled for mid-FY20 to identify research targets meeting the BETO 2030 cost target
- Publish analysis for use by stakeholders



# 2 – Approach (Technical)

## Technical Approach

- Develop data-driven process models (AspenPlus) and cost models (Excel)
- Work closely with researchers to convey impacts, identify data gaps
- Use well-defined basis for economic analysis published in the BETO Multi Year Plan (MYP)




## Challenges – Data Limitations

- Develop flexible models for quick scenario assessments
- Quantify sustainability impacts concurrently with Techno Economic Analysis (TEA)
- Seek review and input from experts external to PNNL

## Critical Success Factors

- Identify gaps and opportunities: where is research needed? What research has the greatest impact?
- Make results available for public use

Guide Research
Track Progress
Reduce Costs

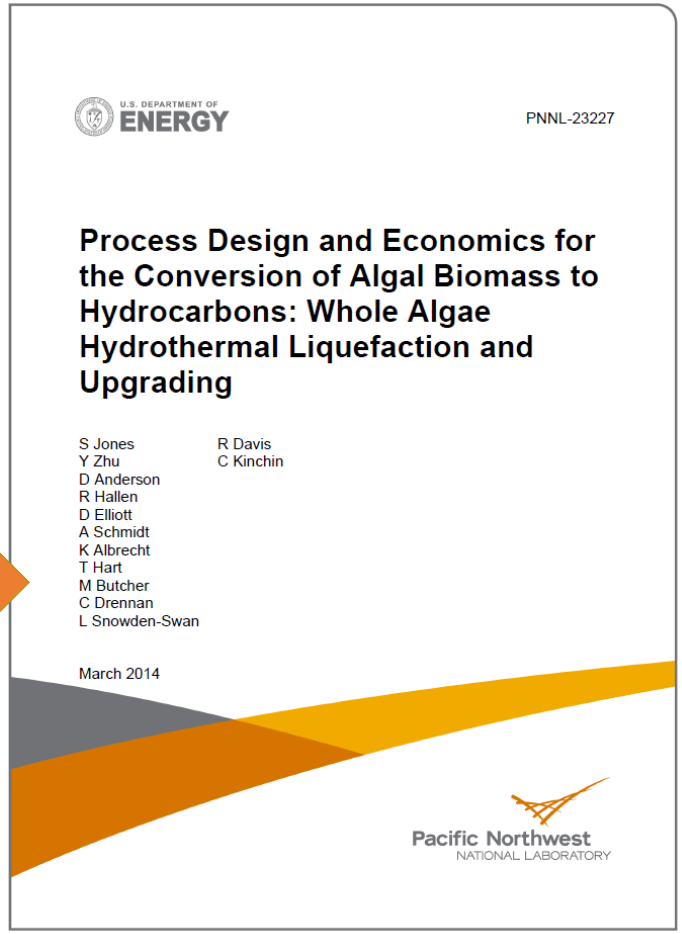
# 3 – Technical Accomplishments/Progress/Results

All milestones met on time, on budget
(see backup slides for details)

Key findings and State of Technology Development (SOT)

# Analysis Basis - Design Cases are a means for prioritizing conversion research and development barriers

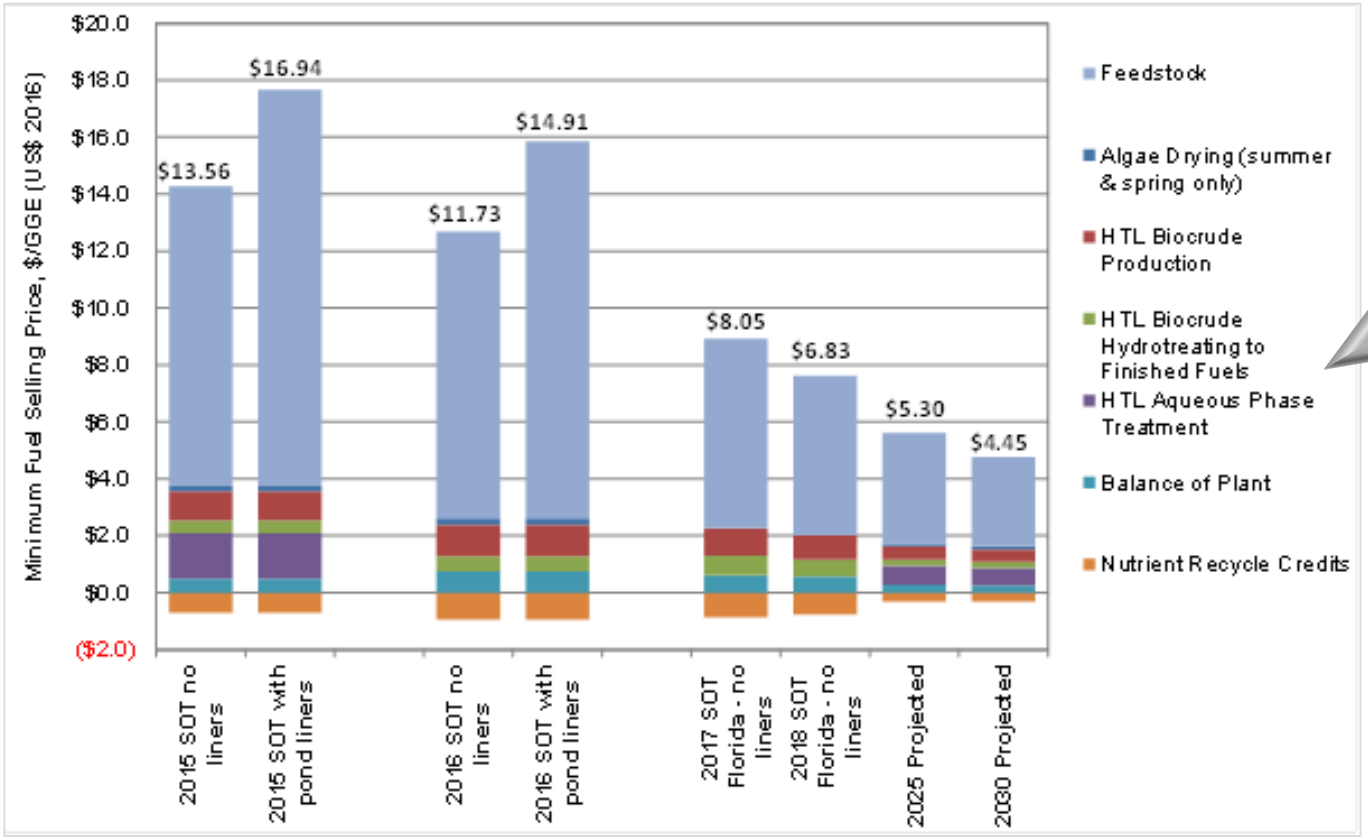
- **Design cases** include major cost drivers, how future targets can be achieved.
- **Detailed** equipment sizing, costs and heat and material balances
- 2 published algal related design cases (NREL, PNNL)
- **Standard assumptions** agreed upon with BETO, **ensures consistency and transparency**
- Reports receive extensive **external review** from experts in the field
- **This project directly supports the Algae Processing pathway towards meeting the 2030 BETO performance goal**




"By 2023, develop technologies …with conversion yields of 80 GGE per ton of biomass."

# How the analysis is used: Annual State of Research Technology (SOT)

- Research progress expressed as a modeled cost of fuel production
- Costs for algal growth, harvest and dewatering are from the NREL pond model
- Conversion related costs are based on PNNL research into HTL conversion, HTL biocrude upgrading, and HTL aqueous testing

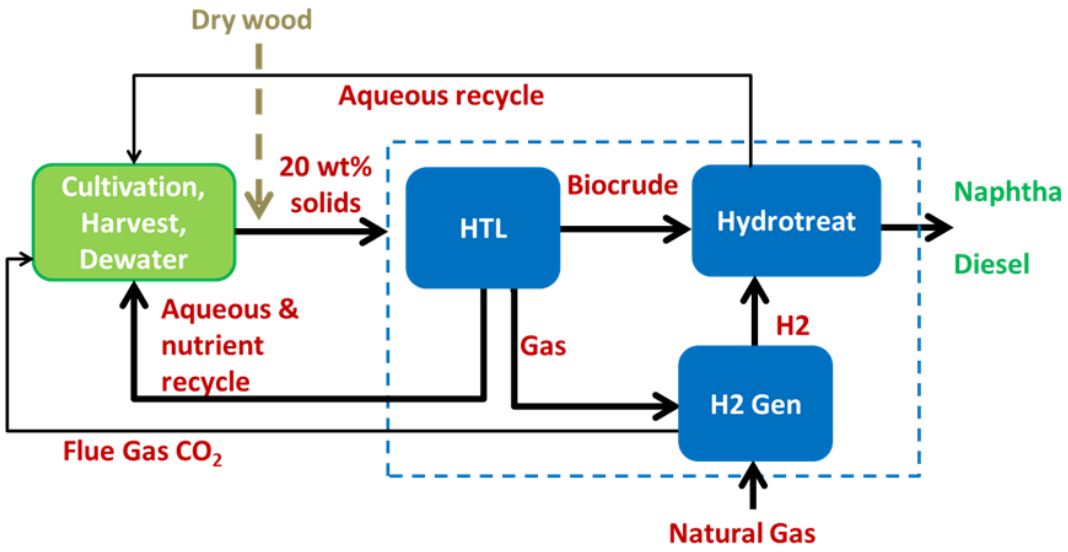



**Modeled costs leading to the out-year target projections are prepared annually and published in the BETO MYP**

# SOT analysis is built on modeled scenarios and experimental work. Example: Algal seasonal variability causes highly variable flow to HTL conversion

## Two Scenarios Assessed

1. Dry a portion of algae grown in summer, store and use during winter
2. Blend dry feedstock (e.g. wood) in during Fall, Winter and Spring to match the Summer algae production rate

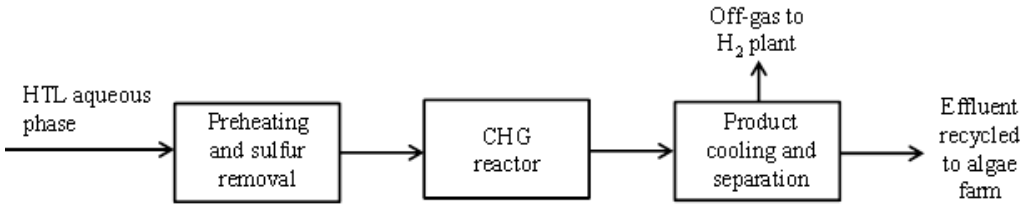



- Inexpensive terrestrial biomass reduces feedstock cost, capital and conversion operating costs
- **A portion of the analysis presented in Seattle (8th International Conference on Algal Biomass, Biofuels and Bioproducts); completed manuscript containing additional analysis**

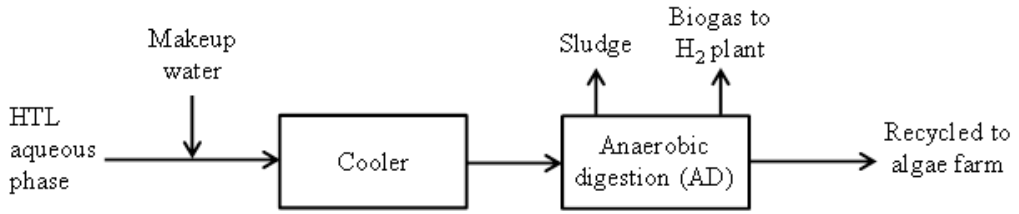
# SOT modeled scenarios example: HTL Aqueous Phase Treatment Options

## Three Scenarios Assessed

1. Direct recycle to algae ponds
2. Pretreatment and catalytic hydrothermal gasification, then recycle to ponds:



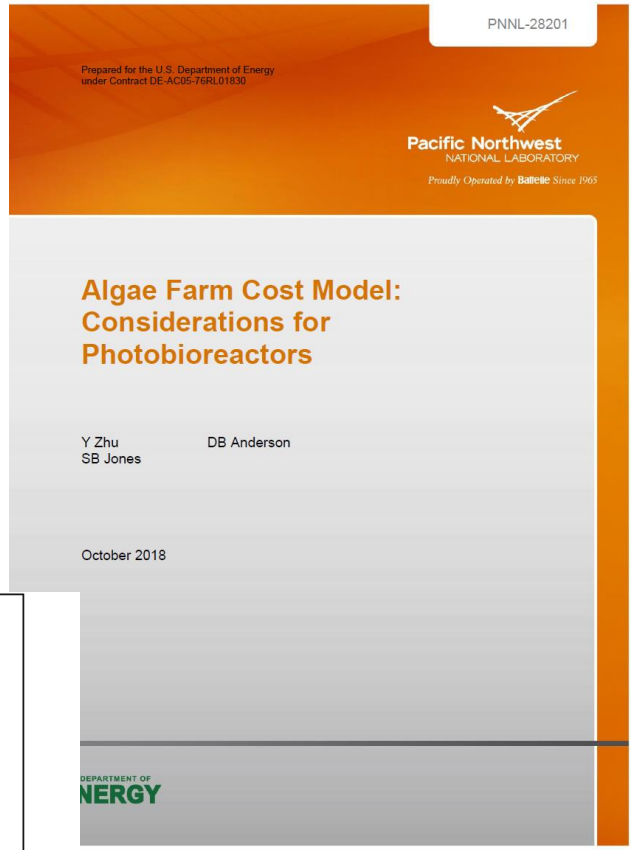

3. Anaerobic digestion, then recycle to ponds:

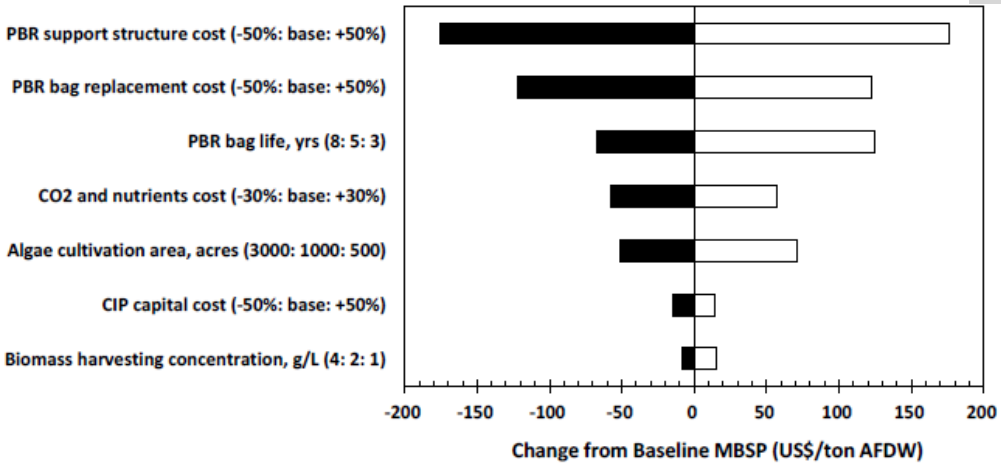



- Direct recycle to algae ponds best option – consumes more natural gas, but overall greatly reduces costs
- **Since the last peer review: additional analysis completed for a manuscript submitted to *Algal Research***

# More Scenarios: Cost Estimation for Photobioreactors – Could they help lower costs?

- Vertical hanging bag type PBR
- Basis: Industrial input and literature for small scale
- Estimated scale-up costs for projected production assumed in NREL open pond model
- Sensitivity to areal productivity considered
- Cultivation and inoculum systems appeared to be the largest cost contributor
- Results published as a PNNL report

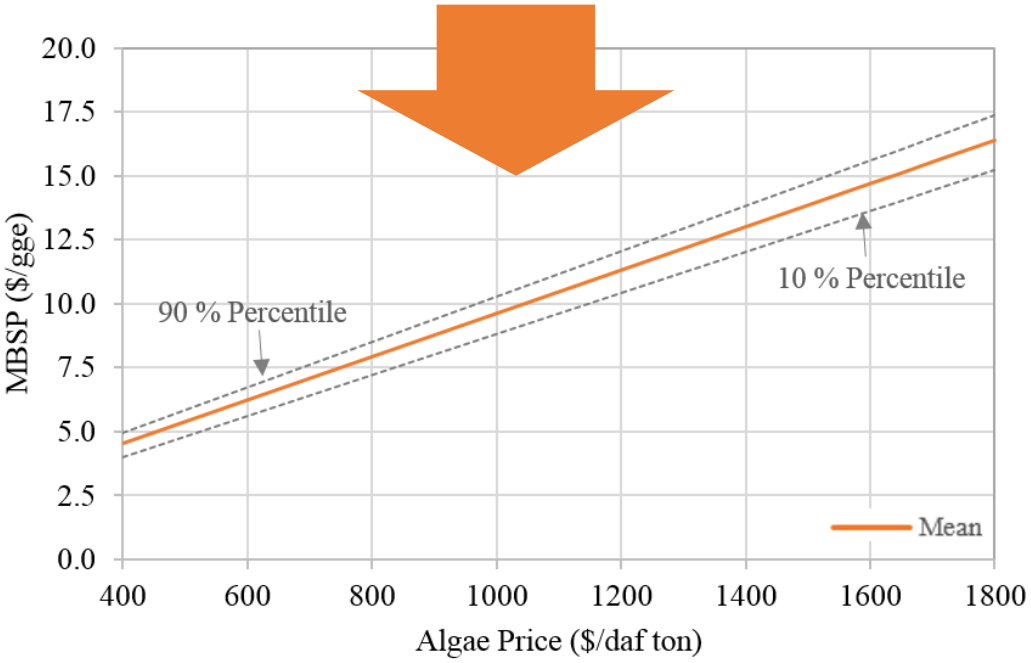


# Robust Models: Predictive HTL Model Development & Uncertainty Analysis

- Developed predictive algae HTL model based on biomass composition and used in a Monte Carlo type uncertainty analysis
- Used data from 13 continuous HTL runs at PNNL to demonstrate method: four types of fresh or salt water algal biomass, *Chlorella, Nannochloropsis, Tetraselmis, and Gaulderia* with a wide range of carbohydrate, lipid and protein contents
- Presented methods at AIChE November Meeting
- **Manuscript submitted to *Algal Research***

**HTL biocrude production cost error bars for a given algal biomass range**




- Recently developed associated correlation for biocrude upgrading

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## 4 – Relevance

# PROJECT GOAL: Develop research-driven process models and perform techno-economic analysis to inform HTL algae conversion research for fuels and chemicals

- **Why project is important**
  - Develops experimentally-based **modeled production costs** indicating high impact research areas for conversion
  - Assists researchers in defining **targeted research**
  - Makes **best use of** limited research **funding**

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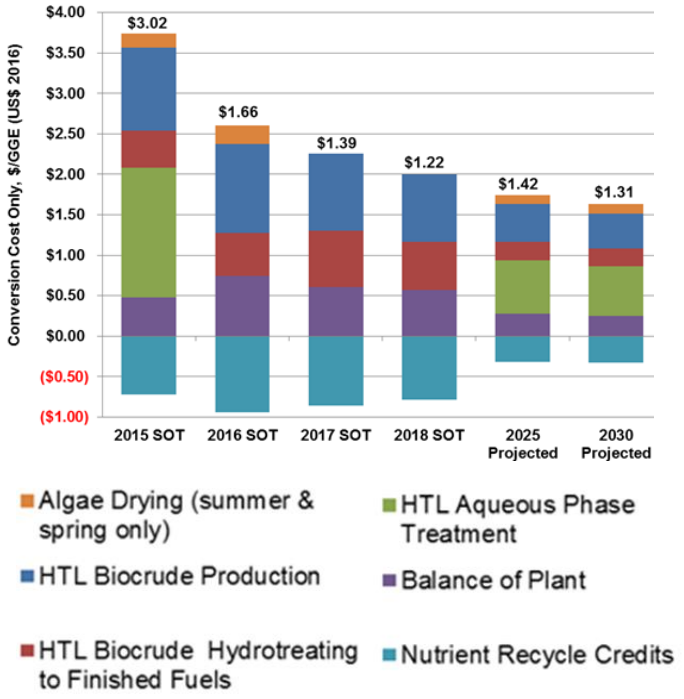
## 4 – Relevance

# Advancing the State of Technology

**Directly supports BETO's performance goal** "By 2030, deliver technologies that can enable the verification of technical performance of algae cultivation, harvesting, and conversion processes at engineering scale capable of converting algal feedstocks to biofuels and bioproducts in support of BETO's goals for mature modeled MFSP of $2.5/GGE for biofuels"

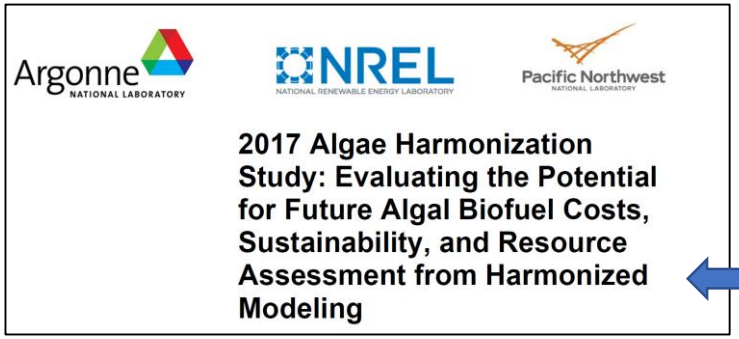
- **Metrics and technical targets are TEA driven**
- **Models are data driven**
- **Enables focused research to reduce costs**
  - Economic use of HTL aqueous
  - Practical solution to algal seasonal variability
  - Improved biocrude conditioning to ensure upgrading catalyst stability
  - Improved biocrude upgrading to increase catalyst life
- **Life cycle inventories sent to ANL for their Supply Chain Sustainability Analysis**



# Informing Stakeholders

Joint lab analysis, termed ***Harmonization***, links farm siting & scale with biomass production and conversion to assess future U.S. potential

PNNL BAT Model for algal farm siting & sizing → NREL Farm Model for algal cost and production rate → **PNNL HTL Model for fuel production cost and quantity** → ANL GREET Model for life cycle analysis




**Multi-lab effort**

- 2030 timeframe
- Externally reviewed
- Published for use by the stakeholder community

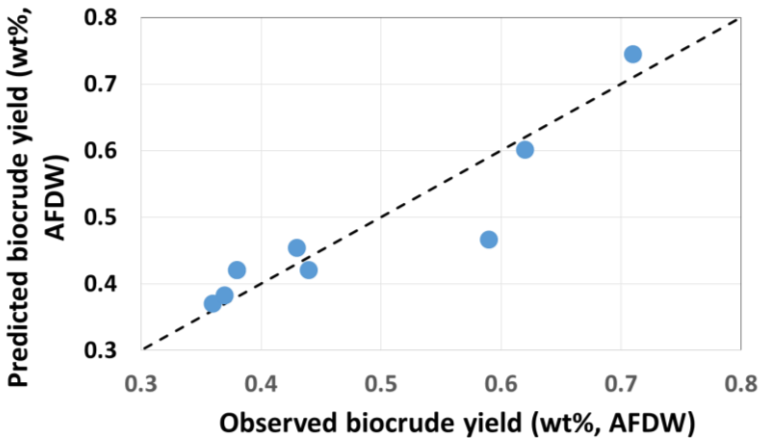
**In addition to the Harmonization Publication:** 2 PNNL publications (plus 3 more submitted to peer review journals); 3 PNNL presentations

# Annual State of Research Technology

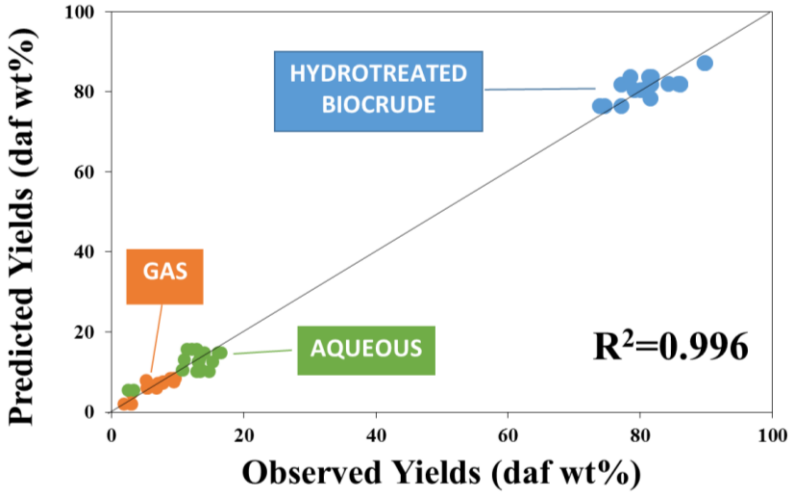
## HTL FY19 SOT

- Incorporate new experimental learnings into the models
- Update models with dewatered algae costs and scale from NREL
- Assess incorporating predictive biocrude yield and upgrading into the Aspen model
- Deliver LCI to ANL for SCSA
- Document experimental basis and TEA results
- **KEY MILESTONE: Deliver summary results to BETO for MYP publication (Q4)**

**Biocrude Yield Correlation Fit**




**Hydrotreated Products Yield Correlation Fit**



# Project Go/No-Go (mid FY20)

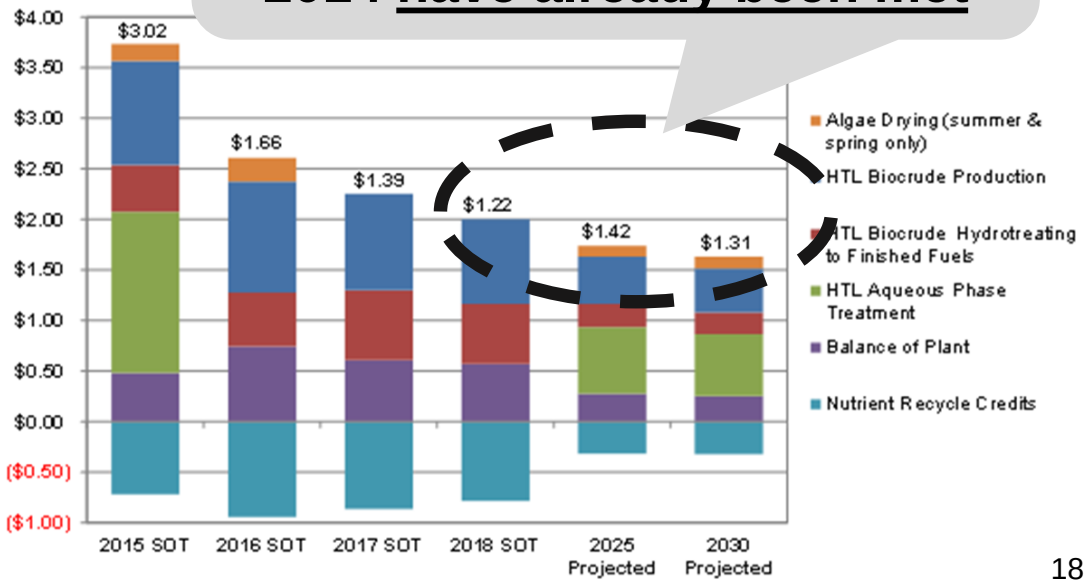
***G/NG:*** The research supported by this analysis project consists of analysis in support of HTL processing of algae. These research areas could possibly contribute to reducing the MFSP to the 2030 target through such means as co-products, optimized heat integration, process intensification and scale.

**Criteria: Develop TEAs for at least one HTL process leading to an MFSP of <$3/gge**

**HTL Research Improvements to Date**

- Raw HTL aqueous recycled to pond eliminating CHG (FY16)
- Mixed feeds eliminate algae dryers and reduce natural gas use (FY17)
- Biocrude conditioning and guard bed improve upgrading reactor performance (FY18)
- HTL plant scale set by summer algae production (FY17 & 18)

**Out-year cost targets from the HTL Design Case published in 2014 have already been met**



# Assess scenarios for future targets

- **Example Scenarios**
  - Multi-step HTL for fuels and products
  - Co-product opportunities from HTL aqueous
  - Improved biocrude conditioning for refinery co-processing
  - Work towards 2030 cost target
- **Apply predictive models and uncertainty analysis methods**
- **Outcome**
  - Meet Go/No-Go cost criteria
  - Publish new target design case in FY20

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# Summary

**Overview:** developing models to guide progress

**Approach:** closely coupled analysis and research

**Technical Accomplishments/Progress/Results:**

- Identifies sustainable cost reduction strategies
- Enables focused, impactful research
- Publishing results for use by stakeholders

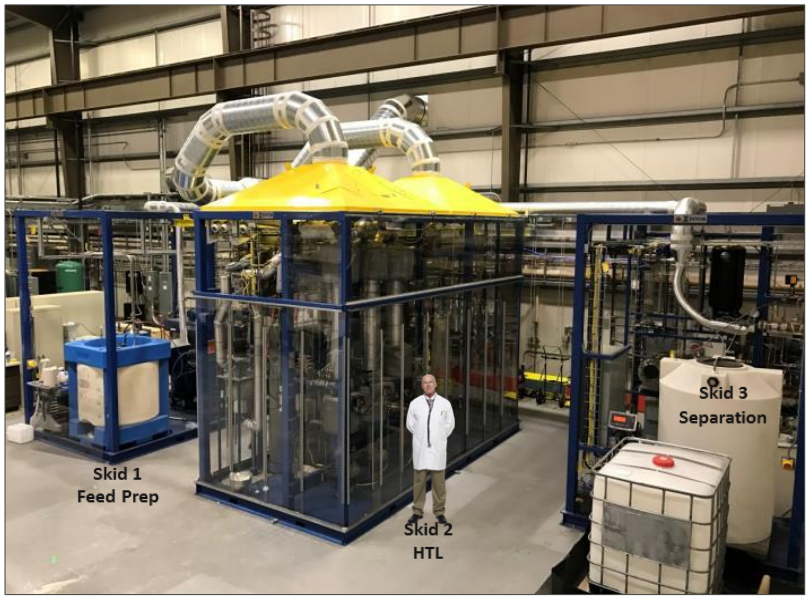
**Relevance:** directly supports meeting BETO's 2022 and 2030 algal fuel cost targets

**Future work:**

- Analysis support for algae HTL and biocrude upgrading
- Annual SOT assessments
- Go/No-Go (mid-FY20)
- Revised target design case aimed at meeting BETO's 2030 cost goals

# Acknowledgements


- Daniel Fishman – BETO Technology Manager
- PNNL HTL Model Development Team
  - Susanne Jones
  - Dr. Yunhua Zhu
  - Dr. Yuan Jiang
  - Dr. Asanga Padmaperuma
- PNNL HTL Experimental Team
  - Daniel Anderson
  - Andrew Schmidt
  - Justin Billing
  - Richard Hallen
  - Heather Job
  - Scott Edmundson
  - Daniel Santosa



- PNNL BAT Team
  - Andre Coleman & Mark Wigmosta
- National Lab Collaborators
  - NREL: Ryan Davis, Jennifer Markham, Chris Kinchin
  - ANL: Jeongwoo Han, Christina Canter, Qianfeng Li, Hao Cai, Thathiana Benavides
  - INL: Damon Hartley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# Additional Slides

- Milestones and Quarterly Progress Measures
- Response to comments from 2017 Review
- Publications
- Presentations
- List of Abbreviations

# Milestones since FY17 Review

| Milestone Name/Description | Criteria | End Date | Type | On time? |
|---|---|---|---|---|
| 1.3.4.101 TC Interface | Deliver to BETO an updated target table for algal processing via HTL showing the FY17 progress towards the performance goals and summarize the supporting experimental information and TEA results in a brief. | 9/30/2017 | Quarterly Progress Measure (Regular) | yes |
| 1.3.1.202 HTL Model Development | Complete draft report of the photobioreactor (PBR) cost model, including sufficient details for use by external stakeholders. The draft will be submitted for BETO review prior to publishing as a PNNL lab report. (Task 1) | 12/31/2017 | Quarterly Progress Measure (Regular) | yes |
| 1.3.1.202 HTL Model Development | Draft outline for a manuscript detailing methodologies for developing a business case for wet waste HTL. This will include siting, scaling, hydrotreating/co-processing considerations, valorization of biocrude, and computation of net present value. The resulting manuscript should serve as a guide for developing strategies for HTL deployment projects. (Task 3) | 3/31/2018 | Quarterly Progress Measure (Regular) | yes |
| 1.3.1.202 HTL Model Development | Joint with Hydrothermal Processing of Biomass (WBS 2.2.2.301) and PNNL HTL Model Development (WBS 1.3.1.202) to issue SOT report for sludge HTL pathway with outyear targets identified towards reduced fuel production costs based on Design Case data package (Task 2) | 6/30/2018 | Quarterly Progress Measure (Regular) | yes |
| 1.3.1.202 HTL Model Development | Joint Milestone with Thermochemical Interface (WBS 1.3.4.101) and PNNL HTL Model Development (WBS 1.3.1.202) to complete updated process models and TEA for Algae HTL and HT process improvements including the MHTLS run data from FY17 , and report the results. (1.3.4.101 - Tasks 1, 2, 3 and 4) (Task 1) | 9/30/2018 | Annual Milestone (Regular) | yes |

**1.3.5.202 HTL Model Development:**

| Milestone Name/Description | Criteria | End Date | Type | On time? |
|---|---|---|---|---|
| Algae HTL Future Scenarios | Work with researchers to identify data needs for the FY19 SOT analysis, and outline research scenarios to investigate towards reducing the costs to produce algal biofuels and for use in updating the 2014 algae HTL design case. | 12/31/2018 | Quarterly Progress Measure (Regular) | yes |
| Algae HTL model enhancement | Improving model fidelity is important towards understanding cost reduction opportunities. Leveraging the learnings from FY18 uncertainty analysis applied to HTL TEA, add a lignin component to the HTL yield prediction model in Aspen, run the model for sensitivity and summarize outcome in a brief to BETO. | 3/31/2019 | Quarterly Progress Measure (Regular) | |
| Algae HTL Future Scenarios Briefing | Review results from the scenario analysis with researchers and complete an outline for a manuscript describing the results and sensitivities. Brief BETO on the outcomes to date. | 6/30/2019 | Quarterly Progress Measure (Regular) | |
| Algae SOT | Joint Milestone with Thermochemical Interface and PNNL HTL Model - Joint Milestone with Thermochemical Interface (WBS 1.3.4.101) and PNNL HTL Model Development (WBS 1.3.1.202 complete the FY19 SOT for algae HTL (using farm input from NREL, and providing LCI to ANL for their SCSA) and describe in a brief that will form the basis for a publication. | 9/30/2019 | Annual Milestone (Regular) | |
| Update Algae HTL Design Report | Using input from external reviewers provided in Q3, revise the updated algae HTL design report and submit final draft to BETO for their final review with intention to publish in the 1st quarter of FY21. | 9/30/2020 | Annual Milestone (Regular) | |
| End of Project Report | Joint Milestone with Thermochemical Interface and PNNL HTL Model - Joint Milestone with Thermochemical Interface (WBS 1.3.4.101) and PNNL HTL Model Development (WBS 1.3.1.202) complete the FY19 SOT for algae HTL (using farm input from NREL, and providing LCI to ANL for their SCSA) and describe in a brief that will form the basis for a publication describing not only the annual SOT, but also the overall outcome of the three year project. | 9/30/2021 | Annual Milestone (Regular) | |

# Response to Previous Reviewers' Comments

- **Previous Comments: Note that the analysis portion was previously reviewed in FY17 when it was a sub-task in the PNNL experimental project**
  - "TEA of this project would greatly benefit greatly by including a reputable member of industry practiced in upgrading oils to make them suitable as a refinery feedstock. The industry partner should advise on the cost of upgrading…to make them acceptable to a refiner and what discount"
- **Response:**
  - This project will be leveraging learnings from the NREL-PNNL refinery integration project which began in FY18 and focuses on understanding the requirements needed for refinery acceptance. The NREL-PNNL project is reviewed by industry experts and learnings from this work will be incorporated into the TEA for algae HTL processing.
  - Biocrude clean-up and upgrading requirements are also being experimentally assessed and those learnings are also being incorporated into the TEA.

# Publications Since FY17 Peer Review

1. Davis R., A. Coleman, M.S. Wigmosta, J. Markham, Y. Zhu, S.B. Jones, and J. Han, et al. 2018. *2017 Algae Harmonization Study: Evaluating the Potential for Future Algal Biofuel Costs, Sustainability, and Resource Assessment from Harmonized Modeling*. PNNL-27547. Richland, WA: Pacific Northwest National Laboratory

2. Zhu Y., S.B. Jones, and D.B. Anderson. 2018. *Algae Farm Cost Model: Considerations for Photobioreactors*. PNNL-28201. Richland, WA: Pacific Northwest National Laboratory.

3. Jiang Y., S.B. Jones, Y. Zhu, L.J. Snowden-Swan, A.J. Schmidt, J.M. Billing, and D.B. Anderson. 2018. "Techno-Economic Uncertainty Quantification of Algal-derived Biocrude via Hydrothermal Liquefaction." *Algal Research*. PNNL-SA-138139. [submitted]

4. Zhu Y., S.B. Jones, A.J. Schmidt, K.O. Albrecht, S.J. Edmundson, and D.B. Anderson. 2018. "Techno-Economic Analysis of Alternative Aqueous Phase Treatment Methods for Microalgae Hydrothermal Liquefaction and Biocrude Upgrading System." *Algal Research*. PNNL-SA-137970. [submitted]

5. Zhu, Y., S. Jones, A. Schmidt, K. Albrecht, D. Anderson. 2019. "*Impacts of Feeding Microalgae/Wood Blended Feedstock to Hydrothermal Liquefaction (HTL) and Upgrading System*". (submitted to *Algal Research)*

6. Cai, Hao, T. Benavides, U. Lee, M. Wang, E. Tan, R. Davis, A. Dutta, M. Biddy, J. Clippinger, N. Grundl, L. Tao., D. Hartley, R. Mohammad, D. Thompson, L. Snowden-Swan, Y. Zhu, S. Jones. 2019 *"Supply Chain Sustainability Analysis of Renewable Hydrocarbon Fuels via Indirect Liquefaction, Ex Situ Catalytic Fast Pyrolysis, Hydrothermal Liquefaction, Combined Algal Processing, and Biochemical Conversion: Update of the 2018 State-of-Technology Cases and Design Cases"* Argonne National Laboratory

# Presentations Since FY17 Peer Review

1. Jiang Y., S.B. Jones, Y. Zhu, L.J. Snowden-Swan, A.J. Schmidt, J.M. Billing, and D.B. Anderson. 10/29/2018. "Techno-Economic Uncertainty Quantification of Algal-derived Biocrude via Hydrothermal Liquefaction." Presented by Yuan Jiang at the AIChE Fall Meeting, Pittsburgh, Pennsylvania. PNNL-SA-139100.

2. Zhu Y., S.B. Jones, A.J. Schmidt, J.M. Billing, K.O. Albrecht, R.T. Hallen, and D.B. Anderson. 06/12/2018. "Co-feeding of algae/wood blend feedstock for hydrothermal liquefaction (HTL) and upgrading – a techno-economic analysis." Presented by Yunhua Zhu at The 8th International Conference on Algal Biomass, Biofuels and Bioproducts, Seattle, Washington. PNNL-SA-135398.

3. Anderson D.B., J.M. Billing, S.J. Edmundson, A.J. Schmidt, and Y. Zhu. 04/29/2019. "Demonstration of the Hydrothermal Liquefaction Pathway for Conversion of Microalgae to Biofuels with Integrated Recycle of Nutrients." Abstract submitted to Biofuels and Bioenergy Conferences, San Francisco, California. PNNL-SA-139499

# Abbreviations and Acronyms

- ANL: Argonne National Laboratory
- AOP: annual operating plan
- BAT: Biomass Assessment Tool
- BETO: Bioenergy Technologies Office
- CHG: catalytic hydrothermal gasification
- GGE: gasoline gallon equivalent
- HTL: hydrothermal liquefaction
- INL: Idaho National Laboratory
- LCA: life-cycle analysis
- MFSP: minimum fuel selling price
- MYP: multi-year plan
- NREL: National Renewable Energy Laboratory
- PNNL: Pacific Northwest National Laboratory
- SCSA: supply chain sustainability analysis
- SOT: state of research technology
- TEA: techno-economic analysis