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Hydrothermal Liquefaction (HTL) Model Development

1.3.5.202

March 24, 2021
Advanced Algal Systems

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PM, PNNL

U.S. DEPARTMENT OF ENERGY BATTELLE

Project Overview

Goal: Develop data-driven process models for performing techno-economic analysis (TEA) of algae hydrothermal liquefaction (HTL) processes to drive research and help advance the state of technology and industry.

- Directly support the Hydrothermal Processing project (WBS# 1.3.4.101)
- Identify barriers and cost reduction strategies
- Assess sustainability impacts
- Inform the setting of technical and cost targets
- Track R&D progress and report it in state of technology (SOT) assessments

History of Algae HTL Pathway Analysis:

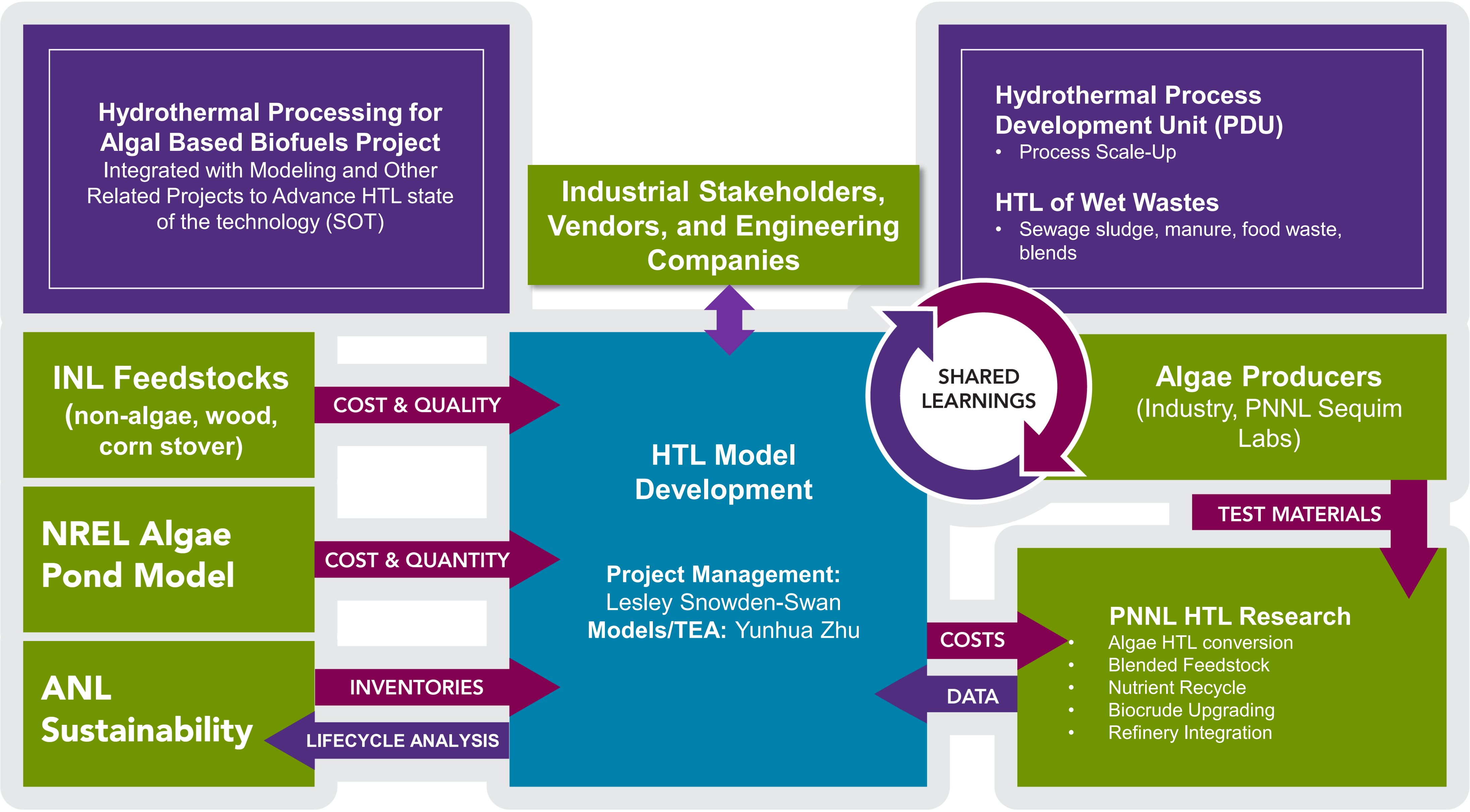
- FY13-16: Algae HTL conversion to fuels conversion testing and system analysis initiated.
- FY17 to FY19: Algae with supplemental wood in non-summer seasons is tested and adapted in the analysis to reduce overall feedstock cost, eliminate algae drying cost and increase plant scale.
- FY20: Sequential hydrothermal liquefaction (SEQHTL) processing is investigated to enable production of co-product and reduce cost.
- FY21: Project pivot to low-cost algae feedstock (e.g., wastewater treatment, macroalgae, nuisance blooms)

Value: Through integrated analysis/experimental projects, we have

- Reduced the modeled conversion cost by $1.55/GGE (from the 2018 to 2020 SOT)
- Have developed a new process configuration (sequential HTL) that allows for generation of marketable co-product that enables the BETO 2030 target MFSP of ≤$2.5/GGE
- **Driven research toward technical and cost targets and helped advance the state of the technology**

1 – Management

Alignment and collaboration provides synergies with BETO project portfolio and industry stakeholders



1 – Management
Quarterly milestones, briefings and risk mitigation through regular communication with experimental/resource teams

Management Controls:

- **Formal project plan** with quarterly milestones and deliverables.
- Quarterly reporting and briefings (presentations) are provided to BETO.
- Project was merit-reviewed in FY18 and will be merit reviewed again in FY21.

Collaboration provides synergistic approach advancing algae-to-fuels:

- **Frequent communication** with Algal Hydrothermal Processing and HTL Process Development Unit projects (WBS# 1.3.4.101 & 3.4.2.301)
- **Collaborate and exchange data/learnings** with many projects at NREL, INL, ANL (e.g., algae pond model, Biomass Scenario Model, Co-Optima, feedstock SOTs, and GREET model)

PNNL's risk management process assigns every project a **risk score** (this one is "**low**").

Risk	Abatement Strategy
Lack of data available to inform models and TEA	• Frequent meetings and communication with experimental team on data needs • Milestones are synced with experimental project's schedule
TEA results have large uncertainty from many assumptions	• Provide sensitivity analysis around key assumptions and variabilities • Developed a quick method for predicting HTL yield and uncertainty for the HTL process.
Models do not reflect real operation at scale	• Frequent discussion with waste generators, vendors, and engineering contractors for reality checks • Industry and academics review our design case reports[1]

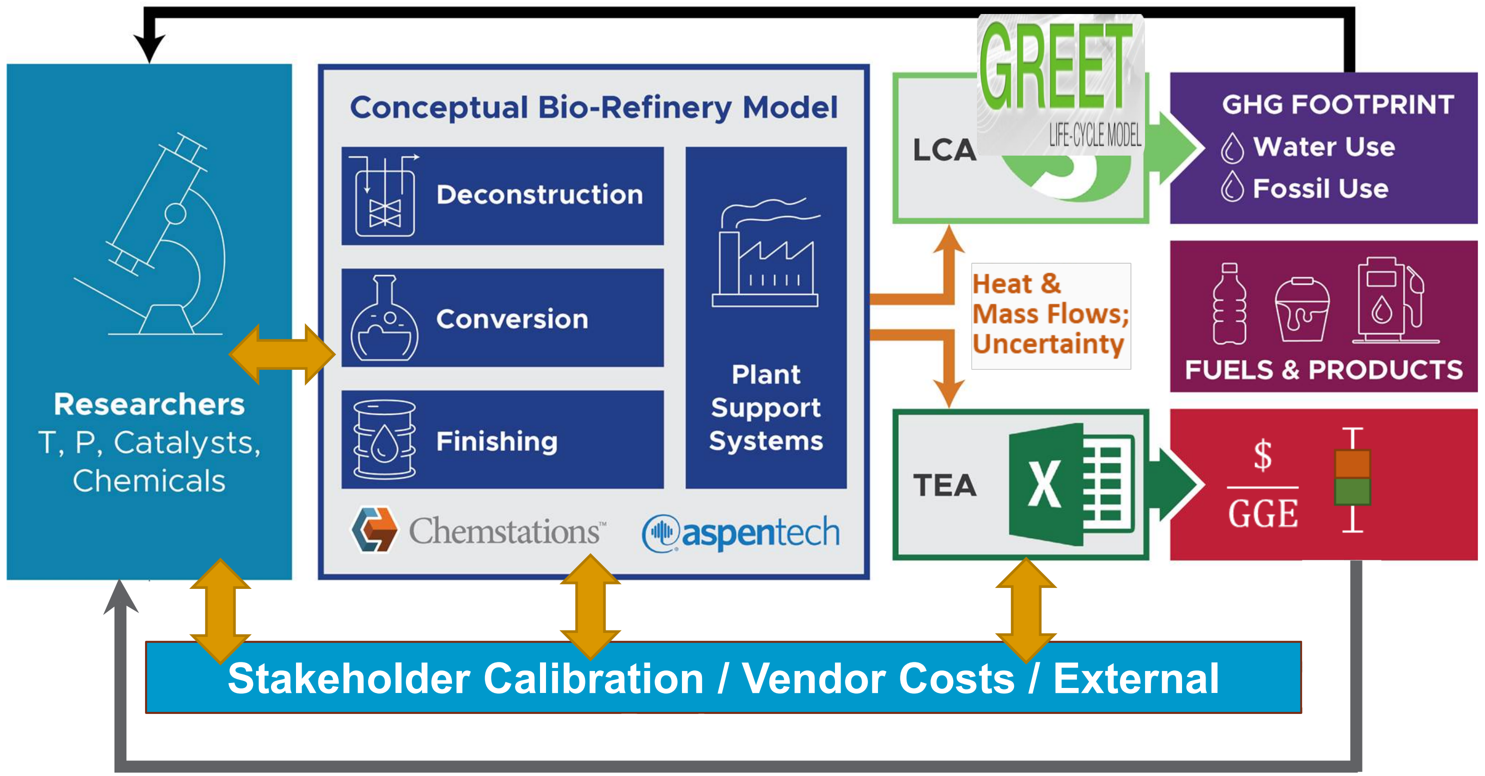
1 BETO's design cases lay out the initial conceptual process configuration and economics of the target case for the pathway.

2 – Approach
Integration with experimental teams and engagement with industry bolsters models and TEA

Technical Approach

- We work closely with the HTL and biocrude upgrading researchers to **identify, interpret, and transform the critical data** needed to develop conceptual process and cost models to simulate commercial-scale plant performance and cost.
- Early in the R&D, we use the initial models to **identify key cost drivers** for the researchers to address and improve moving forward
- We continually **feed back results and questions from the models to the engineering/research team** to hone the TEA to reflect reality as much as possible
- We use a **well-defined basis** for our TEA, as described in the BETO Multi-Year Plan (see slide 21)

Goals: ▪Guide Research ▪Track Progress ▪Reduce Costs ▪ Advance Technology



GGE = gasoline gallon equivalent; GHG = greenhouse gas; TEA = techno-economic analysis;

- We engage with industry (**algae producers, engineering companies, vendors**) to better understand processing and logistical challenges at scale, improve fidelity of our designs, and get realistic equipment costs to inform our models
- We **provide life cycle inventory** for algae HTL and biocrude upgrading to ANL for the LCA and work with them on identifying key drivers and strategies for reducing greenhouse gas emissions
- Developed an **innovative**, data-driven reduced order model for predicting performance and techno-economic uncertainties at scale

2 – Approach
Risk mitigation and go/no-go decision points facilitate progress toward key cost metric targets

Main Challenges and Solutions

- Data acquisition and model fidelity: we have a **continual communication feedback loop** with experimental and resource teams and consult with industry to **improve model relevance**.
- Model uncertainties: we developed a **model for predicting biocrude yield** and estimating **technological and economic uncertainty**.

Go/No-Go Decision Point (FY20): Define sequential HTL configurations that will inform experimental work to allow reducing fuel production costs to $4/GGE for the 2025 goal case at a feedstock cost of $602/ton (AFDW) (milestone to support the FY21 G/N-G for WBS# 1.3.4.101)

  - Showed that sequential HTL can reduce the MFSP for a 2025 goal case to $3.73/GGE (see slide 22).
  - A major **project pivot for FY21** was the realization that there is a need for a more near-term and low-cost algae supply (e.g., macroalgae, turf scrubber, nuisance blooms) to accelerate commercialization and help meet BETO's 2030 goal

Critical Success Metrics

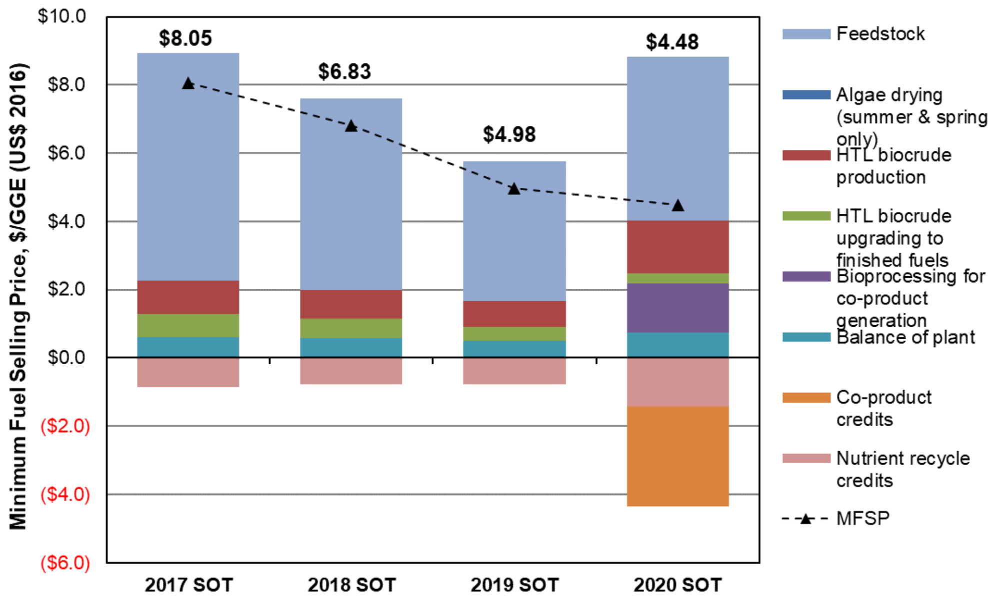
- Achieving **BETO's goal to meet ≤$2.5/GGE by 2030** and greenhouse gas emissions reductions of 60% (cellulosic) compared to petroleum fuels.
- **Publish/present/disseminate** integrated progress of R&D and systems analysis for stakeholder use.

Addressed 2019 Peer Review Comments (see slide 17): 1) Sustainability impacts are determined by ANL with our model output and published in Supply Chain Sustainability Analyses. 2) With the nutrient recycling results from the experimental project with the DISCOVR strain (1.3.4.101), we have validated the TEA assumption for recycle of aqueous to the algae farm.

3 – Impact
Project has driven modeled costs down and provided an industry analog for unproven technology

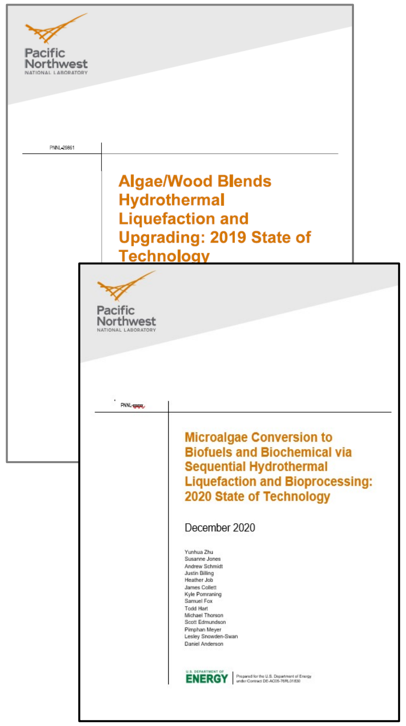
Integrated experimental/analysis projects have:

- **Reduced the conversion costs from $1.39/GGE to -0.33/GGE** with new sequential configuration for generation of valuable co-product and progress made on biocrude upgrading
- **Reduced the MFSP** for the modeled **state of technology** (SOT*) **from $8.05/GGE to $4.48/GGE** (2020 SOT)



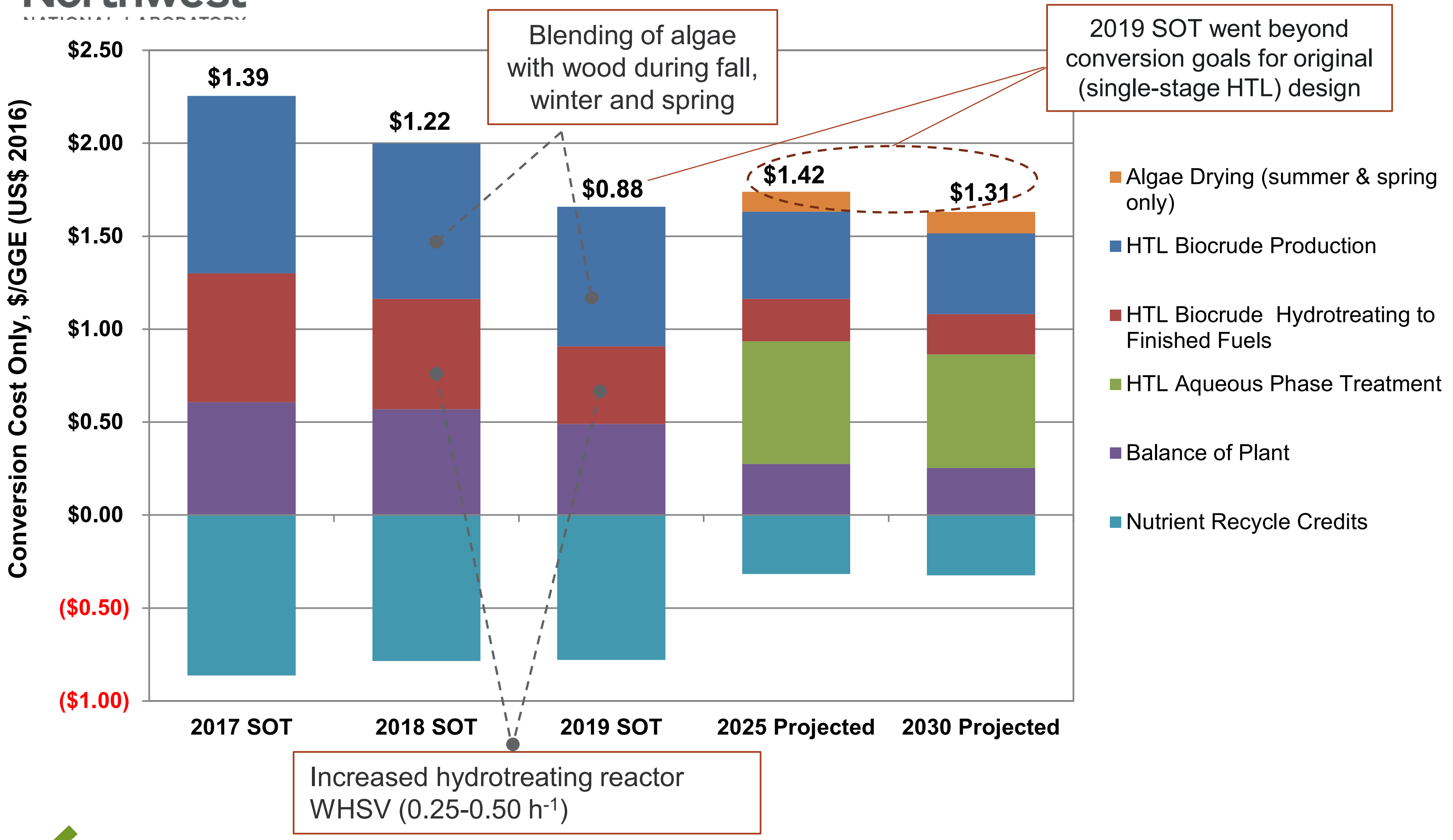
Outreach (since 2019 Peer Review):

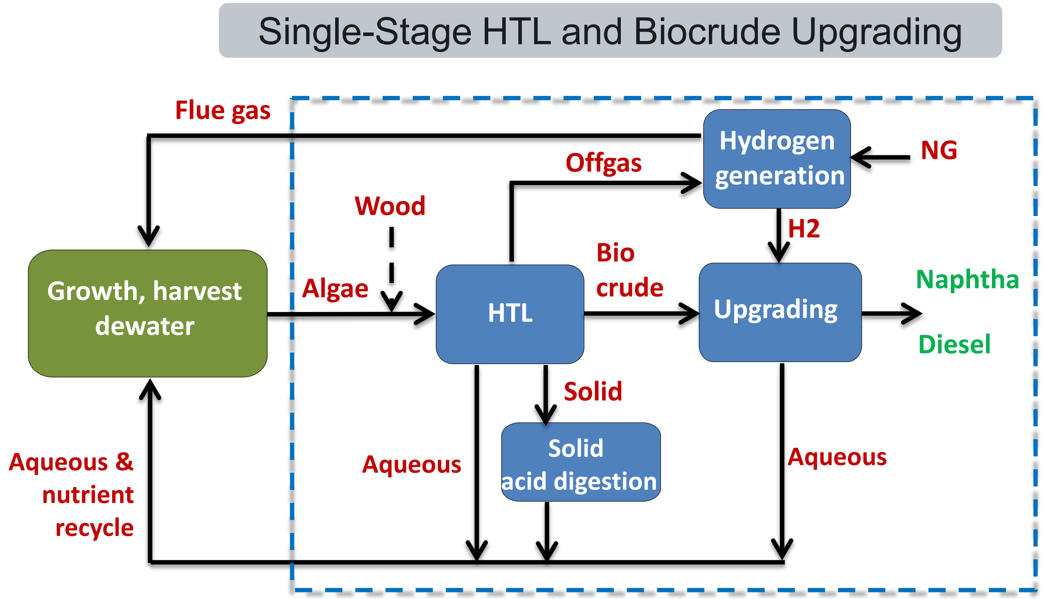
- Published FY19 and FY20 SOT reports which **documented technical and analysis progress** toward cost goals; published 3 papers; presented at 2 conferences
- Models and TEA have **spurred wet waste HTL technology development** for cost-advantaged feedstock, which is the “low-hanging” fruit for near-term commercialization
- Output from this project **provided input to many other projects** including the Biomass Scenario Model, Co-Optima analysis task, US DRIVE project, and GREET model.
- Models informed the **scale-up process** and the detailed heat exchanger design for the Process Development Unit project, **patent application and license**



***The annual SOT analysis is BETO’s primary tool with which the experimental and analysis teams work side-by-side to define the target-enabling research and to drive progress towards that target.**

4 – Progress and Outcomes (FY19)
FY19 SOT Milestone: Reduced cost through blending wood during low-productivity seasons



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Algae/Wood Blends Hydrothermal Liquefaction and Upgrading: ... Technology

April 2020

Yunhua Zhu
Susanne Jones
Andrew Schmidt
Justin Billing
Michael Thorson
Daniel Santosa
Richard Hallen
Daniel Anderson

Algal Research 51 (2020) 102053

Algal Research

Economic impacts of feeding microalgae/wood blends to hydrothermal liquefaction and upgrading systems

Yunhua Zhu, Susanne B. Jones, Andrew J. Schmidt, Justin M. Billing, Daniel M. Santosa, Daniel B. Anderson

Completed **2019 SOT milestone on time** (9/30/2019)

- Blending of wood eliminates algae drying and storage for use in off-seasons, increases plant scale and reduces feedstock cost
- Improved hydrotreater (HT) catalyst performance (doubling of weight-hourly space velocity, or WHSV)

Reduced the conversion cost from $1.22/GGE to $0.88/GGE and the MFSP from $6.83/GGE to $4.98/GGE (see slide 10)

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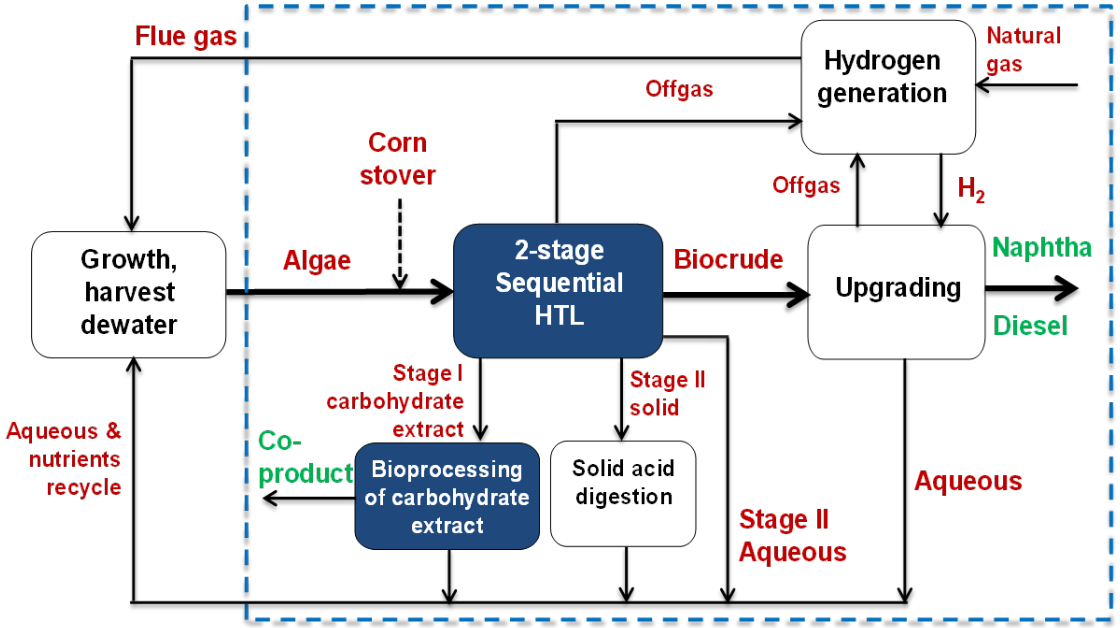
4 – Progress and Outcomes (FY19)
Sequential HTL and co-product generation investigated to reduce cost

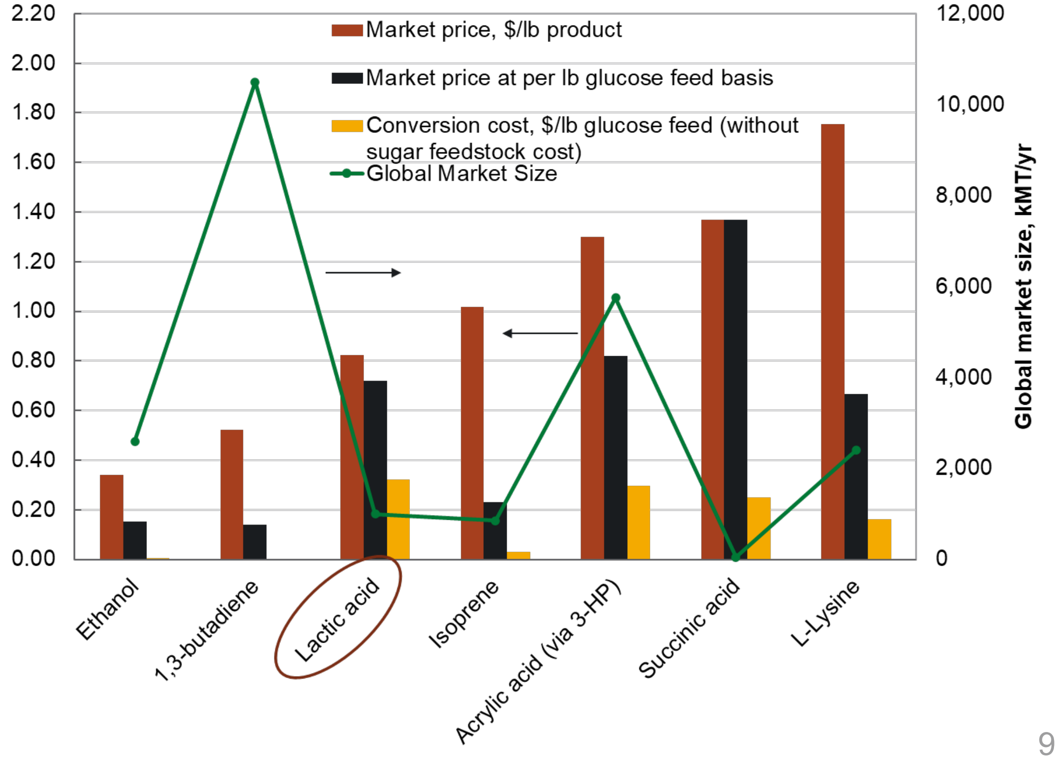
Sequential HTL Modeling

- Changed from single-stage HTL (2019 SOT) to sequential HTL (2020 SOT) to enable **co-product generation from 1st-stage** carbohydrate extract and biocrude production in 2nd stage
- Non-algae feedstock supplement in non-summer seasons: wood (2019 SOT) is changed to corn stover (2020 SOT) as **corn stover demonstrated higher carbohydrate extraction** than wood in prescreening testing
- Leveraged **heat exchanger re-design** from Process Development Unit project

Screening analysis to Select Marketable Co-Product

- **Lactic acid** selected as co-product based on market size, market price, and current technology readiness from carbohydrate conversion
- **Acrylic acid** and **L-lysine** are promising co-product targets from algae sugars bioprocessing **for future work**

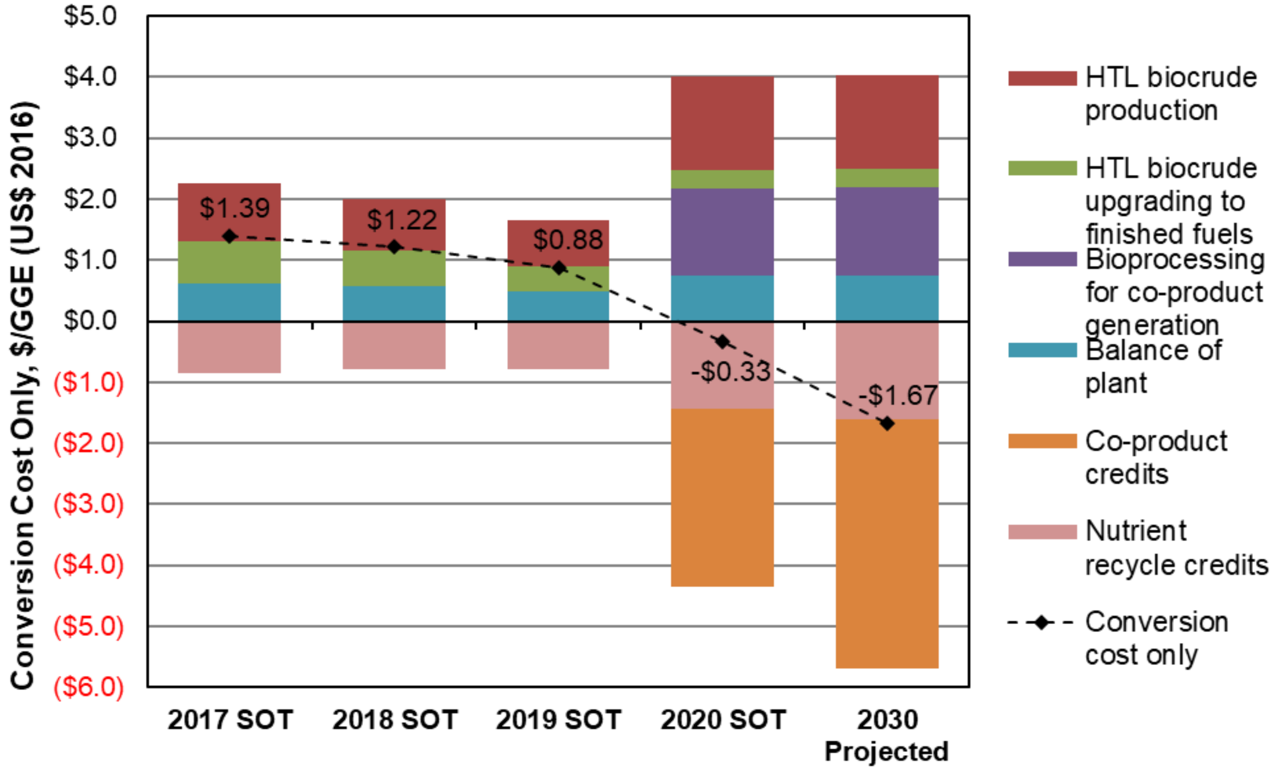


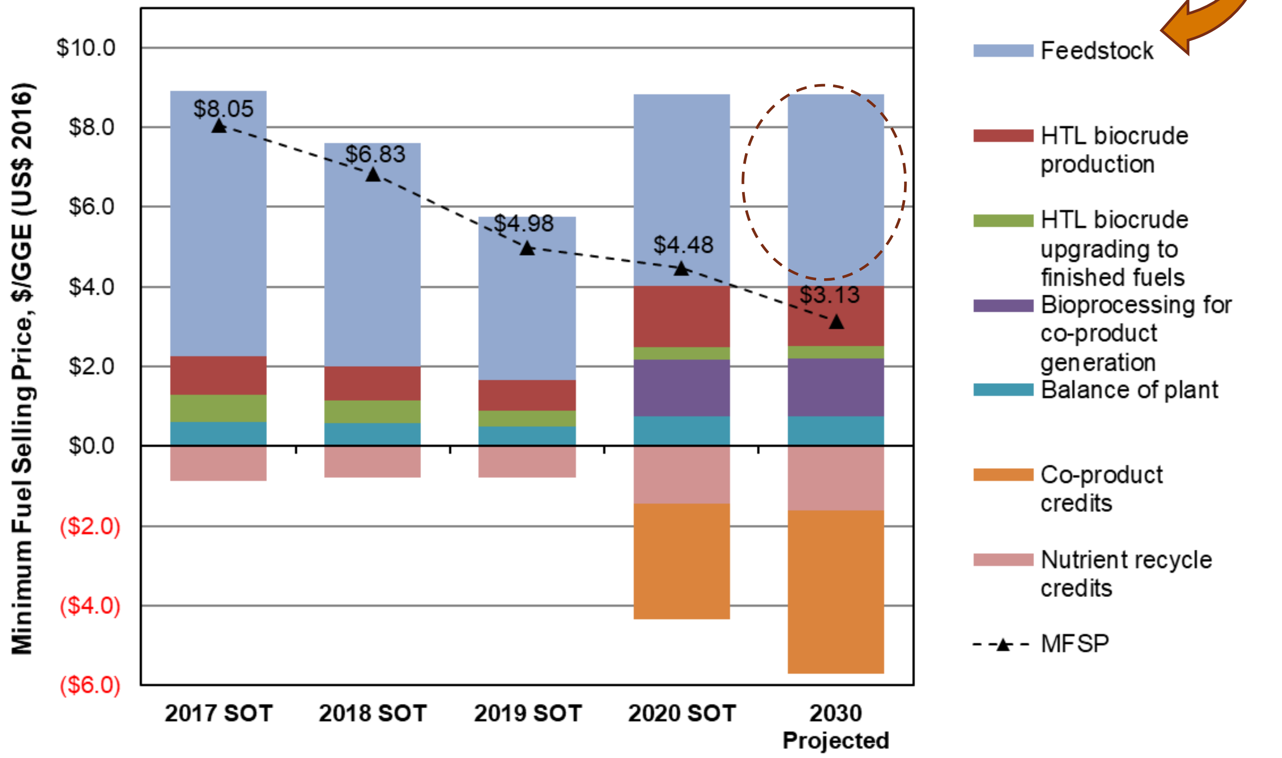


4 – Progress and Outcomes (FY20)

FY20 Milestone: Sequential HTL reduced the SOT MFSP by $0.50/GGE and conversion costs by $1.21/GGE

- Conversion cost (excluding feedstock cost) **reduced from $0.88/GGE in FY19 to $-0.33/GGE in FY20** and production cost **reduced from $4.98/GGE in FY19 to $4.48/GGE in FY20** (see slide 23 for assumptions)
- Even with the progress made to reduce conversion costs, **further reductions in feedstock cost are needed** to meet BETO's 2030 ≤$2.5/GGE goal
- In FY21, we are **pivoting the project** to more near-term, **low-cost algae feedstocks** (e.g., harmful blooms, water remediation algae) to help accelerate deployment opportunities



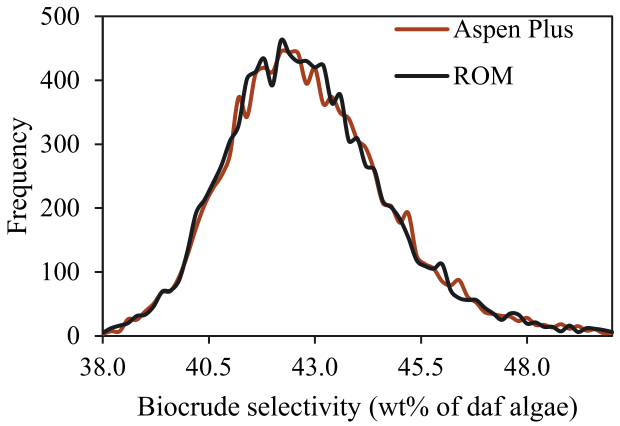


Modeled costs are prepared annually and demonstrate research progress

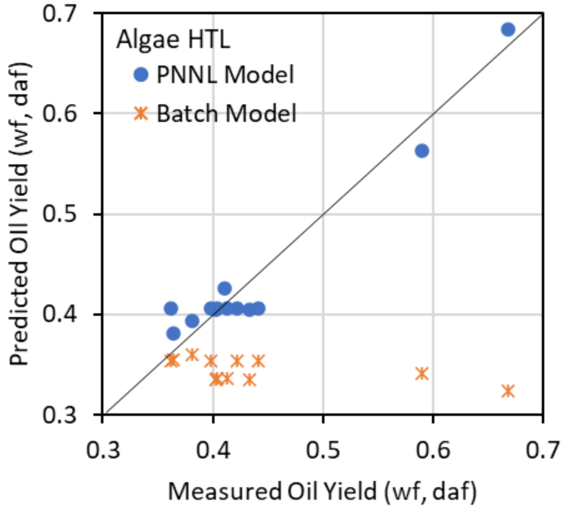
4 – Progress and Outcomes (FY20)

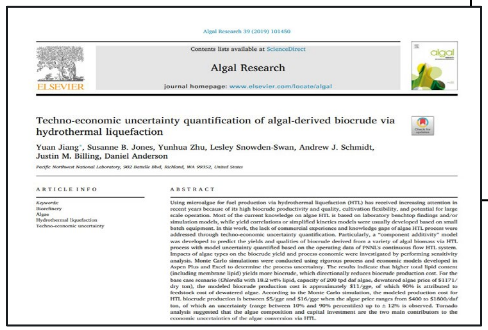
Predictive yield model can quickly estimate HTL performance for variable feedstocks

- Building on prior work[1], a reduced-order model (ROM) for **predicting algae HTL yield** was developed and validated against the rigorous (Aspen Plus) model.



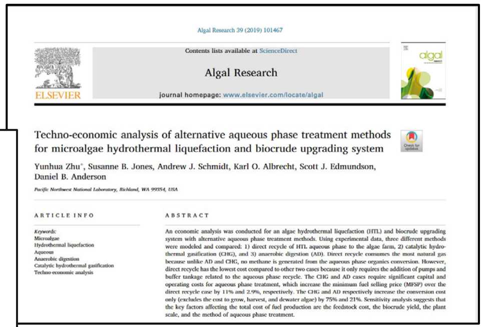
- This is important because:
  - It is the **first in the literature** that is based on continuous system testing (13 runs) and therefore can better predict commercial scale operations than models based on batch data
  - It provides an accurate method for conducting uncertainty quantification that is **2000X faster** than using the rigorous Aspen Plus model
  - The method was **adapted for** building a ROM and uncertainty analysis for **HTL of wet wastes**




Algal Research

Techno-economic uncertainty quantification of algal-derived biocrude via hydrothermal liquefaction

Yuan Jiang, Susanne B. Jones, Yunhua Zhu, Lesley Snowden-Swan, Andrew J. Schmidt, Justin M. Billing, Daniel Anderson


Algal Research

Techno-economic analysis of alternative aqueous phase treatment methods for microalgae hydrothermal liquefaction and biocrude upgrading system

Yunhua Zhu, Susanne B. Jones, Andrew J. Schmidt, Karl O. Albrecht, Scott J. Edmundson, Daniel B. Anderson

1. Jiang et al., 2019. "Techno-Economic Uncertainty Quantification of Algal-derived Biocrude via Hydrothermal Liquefaction." Algal Research 39: 101450

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4 – Progress and Outcomes (FY21 and beyond)

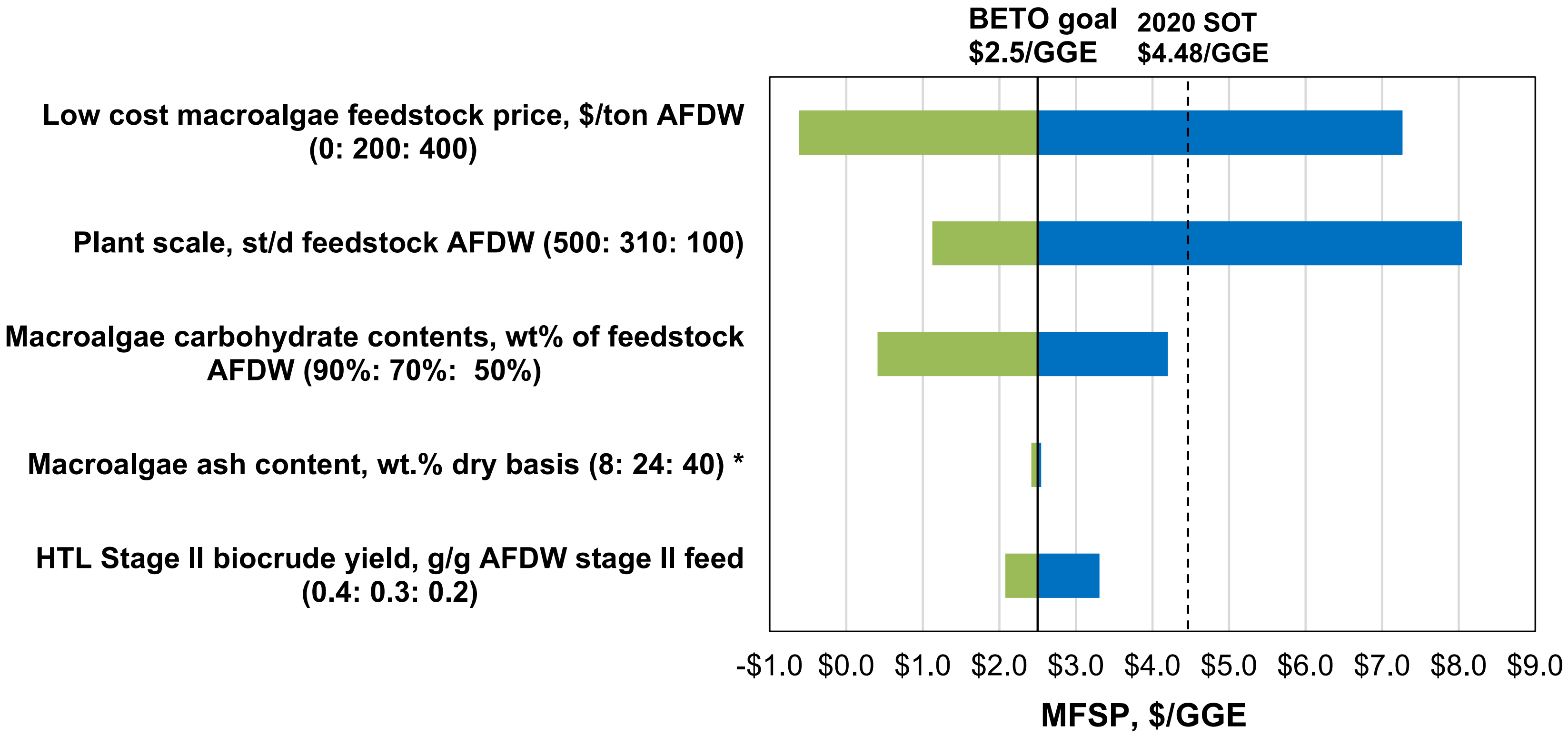
Project pivot in FY21 to low-cost and waste algae to accelerate deployment of HTL

FY21: Project **pivot to** investigate **cost-advantaged algae** and how best to grow and process them

- **Algae blooms** have cost $1billion since 2010. We will leverage learnings from HABITAT project (Army Corps project for lake cleanup in Florida)
- **Turf algae** (wastewater cleanup)
- **Macroalgae (seaweed)**
- Leveraging learnings from the HABITAT project (Army Corps project for cleanup of lake in Florida).

FY22: **New design case** based on down-selected low-cost algae

FY23: **SOT development**



- Preliminary TEA shows sequential HTL of low-cost macroalgae has **high potential to meet the BETO 2030 goal of ≤$2.5/GGE**
- However, there are **challenges** with these feedstocks:
  - High ash/dirt content (plugging, low biocrude yield)
  - High carbo/low lipid
  - Harvesting and transport costs may be significant
  - Slurry prep could be challenging (e.g., macroalgae)

Acknowledgements

- Daniel Fishman – BETO Technology Manager
- PNNL HTL Model Development Team
  - Yunhua Zhu
  - Susanne Jones
  - Lesley Snowden-Swan
  - Pimphan Meyer
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- PNNL HTL Experimental Team
  - Daniel Anderson
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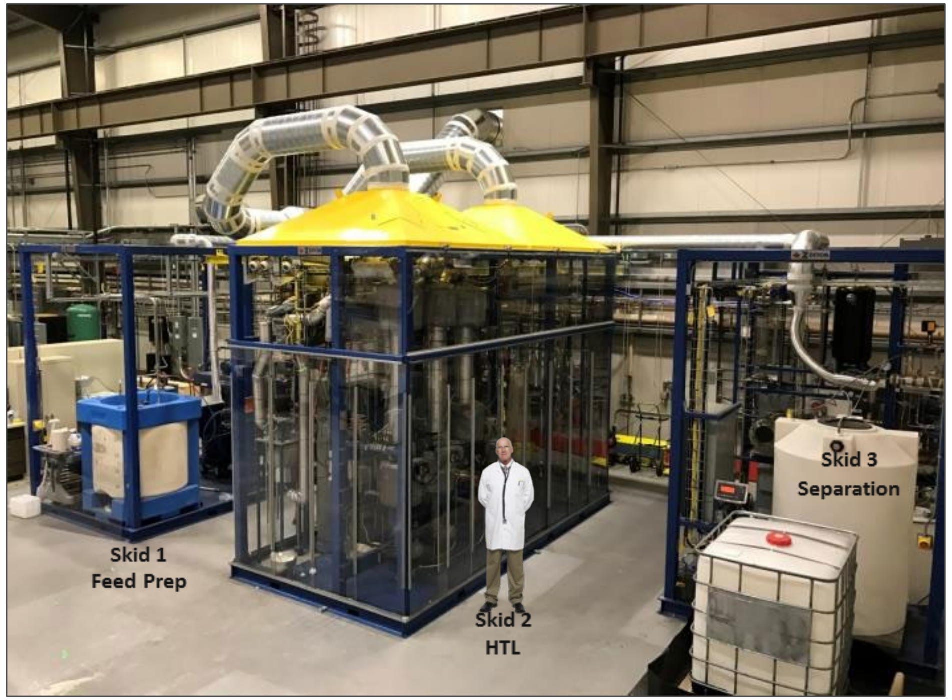
  - Justin Billing
  - Heather Job
  - James Collett
  - Kyle Pomraning
  - Samuel Fox
  - Todd Hart
  - Michael Thorson
  - Scott Edmundson



- PNNL BAT Team
  - Andre Coleman & Mark Wigmosta
- National Lab Collaborators
  - NREL: Ryan Davis
  - ANL: Hao Cai
  - INL: Damon Hartley

Summary

- **Management:** Project plan addresses technical risks and includes clear milestones to meet the integrated experimental/analysis objectives
- **Approach:** Closely coupled modeling, analysis and experimental research that targets cost goals and advances the state of the technology
- **Impact:** Driven down modeled costs, provided the foundational models and TEA for many other projects, and informed a more scalable design for the HTL process
- **Progress and Outcomes:** Guided impactful, focused research that reduced the conversion cost by 127% and MFSP by 34% and will enable the ≤$2.5/GGE target with low-cost algae feedstocks with the sequential HTL process
- **Future work:**
  - FY21: Pivot to low-cost micro- and macro-algae testing and preliminary TEA
  - FY22: Develop SOT and design (goal) case based on sequential HTL testing of cost-advantaged algae

Quad Chart Overview

1.3.5.202 HTL Model Development

Timeline
- Project start date: October 1, 2018
- Project end date: September 30, 2021

	FY20	Active Project
U.S. Department of Energy Funding	(10/01/2020 – 9/30/2021) $200K	(10/01/2018 – 9/30/2021) $600K

Project Partners
- ANL: Life cycle analysis
- INL: Terrestrial feedstock cost and quality
- NREL: Algal feedstock cost and availability
- PNNL: Experimental teams and resource analysis

Barriers Addressed
At-E: Quantification of Economic, Environmental, and other Benefits and Costs
At-A: Analysis to Inform Strategic Direction

Project Goal
Employ TEA coupled with researcher input and feedback to guide and track research towards reducing the costs of renewable fuels and co-products from biomass via HTL; HTL biocrude upgrading to fuels and HTL aqueous carbon valorization.

End of Project Milestone
Using data from the Hydrothermal Processing for Algal-Based Biofuels and Co-Products (WBS 1.3.4.101) and PNNL HTL Model Development (WBS 1.3.1.202) complete a new design case or the FY 2022 SOT for HTL of a down-selected low-cost algal feedstock.

Funding Mechanism
Laboratory Call 2018

Additional Slides

Responses to Previous Reviewers' Comments

1) Feedback: Quantifying sustainability impacts seems lacking and will require more focus.

- **Response:** The life cycle inventory from our conversion models has been provided to ANL for determination of GGEs with the GREET model. Joint laboratory publications contain LCA results and are published for the annual SOTs in the Supply Chain Sustainability Analysis reports on ANL's website.

2) Feedback: Additional work is needed to fully capture all the necessary data regarding nutrient recycling both in open pond and photobioreactor.

- **Response:** Using FY 2020 nutrient recycling testing results from the experimental project strain (1.3.4.101), we have validated the TEA assumption for recycle of aqueous to the algae farm.

3) Feedback: All the conversion related costs are based on one source of research entity. Integrating other collaborators in this area would improve the cost model.

- **Response:** We agree; leveraging the learnings and methods by researchers outside of PNNL is important. Since the 2019 Review, we have designed a new heat exchanger configuration that is more applicable for operation at scale and engaged Fluor, Inc. to provide vendor costs for the new design. The new design and costs have been incorporated into the costing for the process.

Publications, Presentations and Patents Since FY19 Peer Review

- Zhu Y, SB Jones, AJ Schmidt, KO Albrecht, SJ Edmundson, and DB Anderson. 2019. “Techno-economic analysis of alternative aqueous phase treatment methods for microalgae hydrothermal liquefaction and biocrude upgrading system.” Algal Research 39:101467.
- Zhu Y, SB Jones, AJ Schmidt, JM Billing, MR Thorson, DM Santosa, RT Hallen, and DB Anderson. 2020. Algae/Wood Blends Hydrothermal Liquefaction and Upgrading: 2019 State of Technology. PNNL-29861, Pacific Northwest National Laboratory, Richland, WA.
- Zhu Y, SB Jones, AJ Schmidt, JM Billing, DM Santosa, and DB Anderson. 2020. “Economic impacts of feeding microalgae/wood blends to hydrothermal liquefaction and upgrading systems.” Algal Research 51:102053
- Cai, H., O. Longwen, M. Wang, et al. 2020. “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 2019 State-of-Technology Cases”. ANL/ESD-20/2, Argonne National Laboratory, Chicago, IL.
- Jiang Y., S.B. Jones, Y. Zhu, L.J. Snowden-Swan, A.J. Schmidt, J.M. Billing, and D.B. Anderson. 2019. "Techno-Economic Uncertainty Quantification of Algal-derived Biocrude via Hydrothermal Liquefaction." Algal Research 39: 101450
- Zhu Y., S.B. Jones, A.J. Schmidt, H.M. Job, and D.B. Anderson. 2020. "Preliminary Economic Analysis for Sequential Two-Stage Hydrothermal Liquefaction and Upgrading System with Co-product Generation." Abstract submitted to 10th International Conference on Algal Biomass, Biofuels and Bioproducts, Pittsburg, Pennsylvania. PNNL-SA-149327
- Billing J.M., S.J. Edmundson, A.J. Schmidt, Y. Zhu, and D.B. Anderson. 2019. "Demonstration of the Hydrothermal Liquefaction Pathway for Conversion of Microalgae to Biofuels with Integrated Recycle of Nutrients." Presented by J.M. Billing at BBC 2019 - International Conference on Biofuels and Bioenergy, Burlingame, California. PNNL-SA-143036
- Li S., Y. Jiang, L.J. Snowden-Swan, J.A. Askander, A.J. Schmidt, and J.M. Billing. 10/05/2020. "Techno-Economic Uncertainty Analysis of Wet Waste-to-Biocrude via Hydrothermal Liquefaction based on Reduced Order Model." Abstract submitted to 2020 Thermal & Catalytic Sciences Symposium, Richland, Washington. PNNL-SA-152888.
- Patent application: US Pat Appl 16/740,339 (filed January 10, 2020) “Hydrothermal Liquefaction System.” Dan Anderson, Justin Billing, Richard Hallen, Todd Hart, Andrew Schmidt, Lesley Snowden-Swan and Michael Thorson.

Past Publications and Presentations (FY18 to FY19)

- 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
- 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.
- 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
- 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." Presented by Yuan Jiang at the AIChE Fall Meeting, Pittsburgh, Pennsylvania. PNNL-SA-139100.
- Zhu Y., S.B. Jones, A.J. Schmidt, J.M. Billing, K.O. Albrecht, R.T. Hallen, and D.B. Anderson. 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.
- Anderson D.B., J.M. Billing, S.J. Edmundson, A.J. Schmidt, and Y. Zhu. 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

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FY21 Milestones

Milestone Name/Description	Criteria	End Date	Type
FY20 SOT for microalgae sequential HTL and bioprocessing report delivered.	Data analysis package for sequential HTL of microalgae and cellulosic blends with co-product production will be used to develop the annual FY20 SOT case and a report will be prepared.	12/31/2020	Annual Milestone (Regular) (delayed from Q4 FY20)
Initiate process development and analysis for HTL conversion of low-cost algal biomass resources	Perform literature review of low cost algae candidates being considered and work with researchers to develop initial system designs for algae HTL conversion.	3/31/2021	Quarterly Progress Measure (Regular)
Identify data needs for preliminary TEA of low cost algal feedstock	Work with researchers to identify data that will be needed from the Q3 and Q4 HTL testing of macroalgae and turf scrubber algae feedstocks for the preliminary TEA.	6/30/2021	Quarterly Progress Measure (Regular)
Deliver preliminary TEA for down-selected low-cost algal feedstock(s)	Complete a preliminary TEA of HTL of macroalgal and/or turf scrubber algal feedstock based on initial testing data generated from WBS 1.3.4.101 ; summarize the supporting experimental information and TEA results in a brief and deliver to BETO.	9/30/2021	Annual Milestone (Regular)

Analysis Economic Assumptions

Financing Factors for Nth Plant Assumption	
Internal rate of return (IRR)	10%
Plant financing debt/equity	60% / 40% of total capital investment
Plant life	30 years
Income tax rate	35%
Interest rate for debt financing	8.0% annually
Term for debt financing	10 years
Working capital cost	5.0% of fixed capital investment (excluding land)
Depreciation schedule	7-years Modified Accelerated Cost Recovery System schedule
Construction period	3 years (8% 1st yr, 60% 2nd yr, 32% 3rd yr)
Plant salvage value	No value
Start-up time	6 months
Revenue and costs during start-up	Revenue = 50% of normal Variable costs = 75% of normal Fixed costs = 100% of normal
On-stream factor	90% (7,884 operating hours per year)

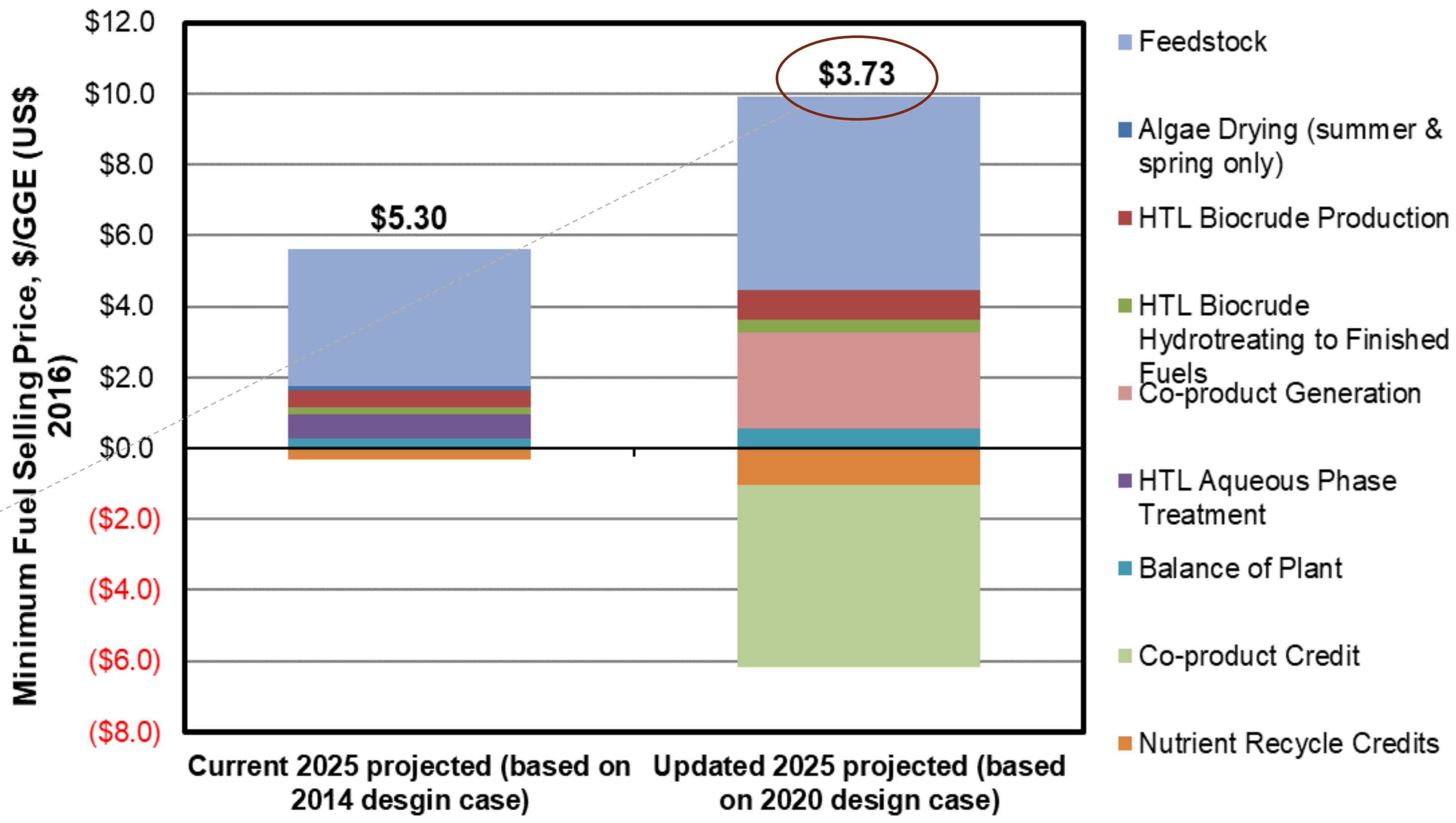
Direct Costs	% of Total Installed Cost
Buildings	1.0%
Site development	9.0%
Additional piping	4.5%
Total Direct Costs (TDC)	15%
Indirect Costs	**% of Total Direct Costs (including installed equip)**
Prorated expenses	10%
Home office & construction fees	20%
Field expenses	10%
Project contingency	10%
Startup and permits	5%
Total Indirect	55%
Working Capital	5% of Fixed Capital Investment

Go/No-Go FY20

- **Description:** "Strategies for sequential HTL enabling reduced fuel costs through co-product development: Define sequential HTL configurations that will inform experimental work needed to allow meeting the FY21 G/NG for 1.3.4.101 (Hydrothermal Processing for Algal Based Biofuels and Bioproducts)."

- **Criteria for "Go":** "Leveraging FY19 and 20 experimental work from 2.2.2.501 for co-products, 1.3.4.101 and 2.2.2.301 for HTL and upgrading, and assuming 65 wt% feed carbohydrate recovery in Stage 1 aqueous, and converting 55wt% (AFDW) Stage 1 solids in Stage 2 into biocrude, identify the co-products and process configurations to allow reducing fuel production costs to $4/gge at a feedstock cost of $602/ton (AFDW)."

"Go" Criteria Met



Key Process Assumptions for FY20 SOT and Low-Cost Macroalga Case Study

	FY20 SOT	Low-cost macroalgae case (ranges of parameters)	Notes
Algae feedstock cost, $/st AFDW	590 (based on 10wt% solid)	200 (0 to 400)	Big uncertainty
Plant scale, st/d AFDW (including both algae and non-algae supplement)	700	310 (100 to 500)	Big uncertainty
Algae/non-algae supplment mass ratio, annual average	58/42	58/42	Seasonal productivity information for macroalgae is needed
Algae carbohydrate contents, wt% of algae feedstock, AFDW	19.8	70 (50 to 90)	High carbohydrate content is beneficial for co-product generation
Algae carbohydrate extraction, wt% of carbohydrates in algae feedstock	98	85	based on cellulose content in macroalgae; need HTL testing data as basis
HTL stage II biocrude yield, g/g stage II solid feed AFDW	0.51	0.3 (0.2 to 0.4)	Estimated based on fat content of macroalgae; need HTL testing data
Algae ash content, wt% of algae feedstock, AFDW	10.5	24 (8 to 40)	Its impacts with plant scale assumed at dry basis needs to be investigated in future work
Co-product yield, g/g total extracted carbohydrates	0.37	0.37	Based on current bioprocessing testing result; expect 50% increase with bioprocessing optimization

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Abbreviations and Acronyms

- AFDW: ash-free dry weight
- 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

24

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Thank you