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Analysis and Sustainability Interface

WBS# 2.1.0.301

March 9, 2021

Data, Modeling, and Analysis

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U.S. DEPARTMENT OF ENERGY BATTELLE

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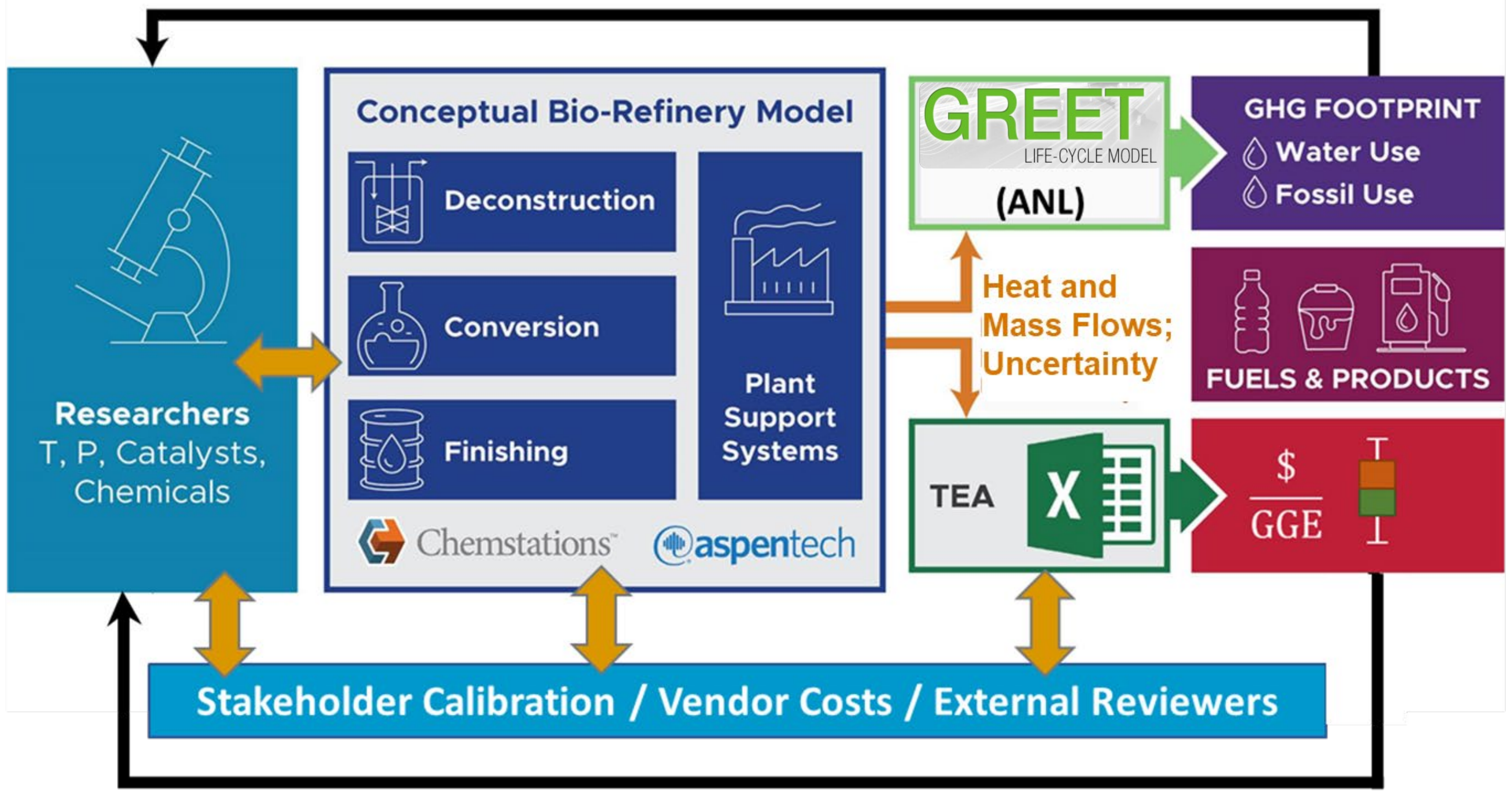
Project Overview

Producing Cost Effective Biofuels is Challenging

GOAL: Develop research-driven process models and perform techno-economic analysis (TEA) to inform biomass conversion research for fuels and chemicals.

- **Work Closely with Researchers**
  - Gather data and establish assumptions to develop data-driven process and cost models.
  - Suggest research directions to reduce costs.
- **Critical Success Factors**
  - Identify gaps and opportunities: where is research needed?
  - Make results available for public use.
- **Challenges and Risks**
  - Data availability
  - Large uncertainties
  - Scalability

Guide Research - Track Progress - Reduce Costs

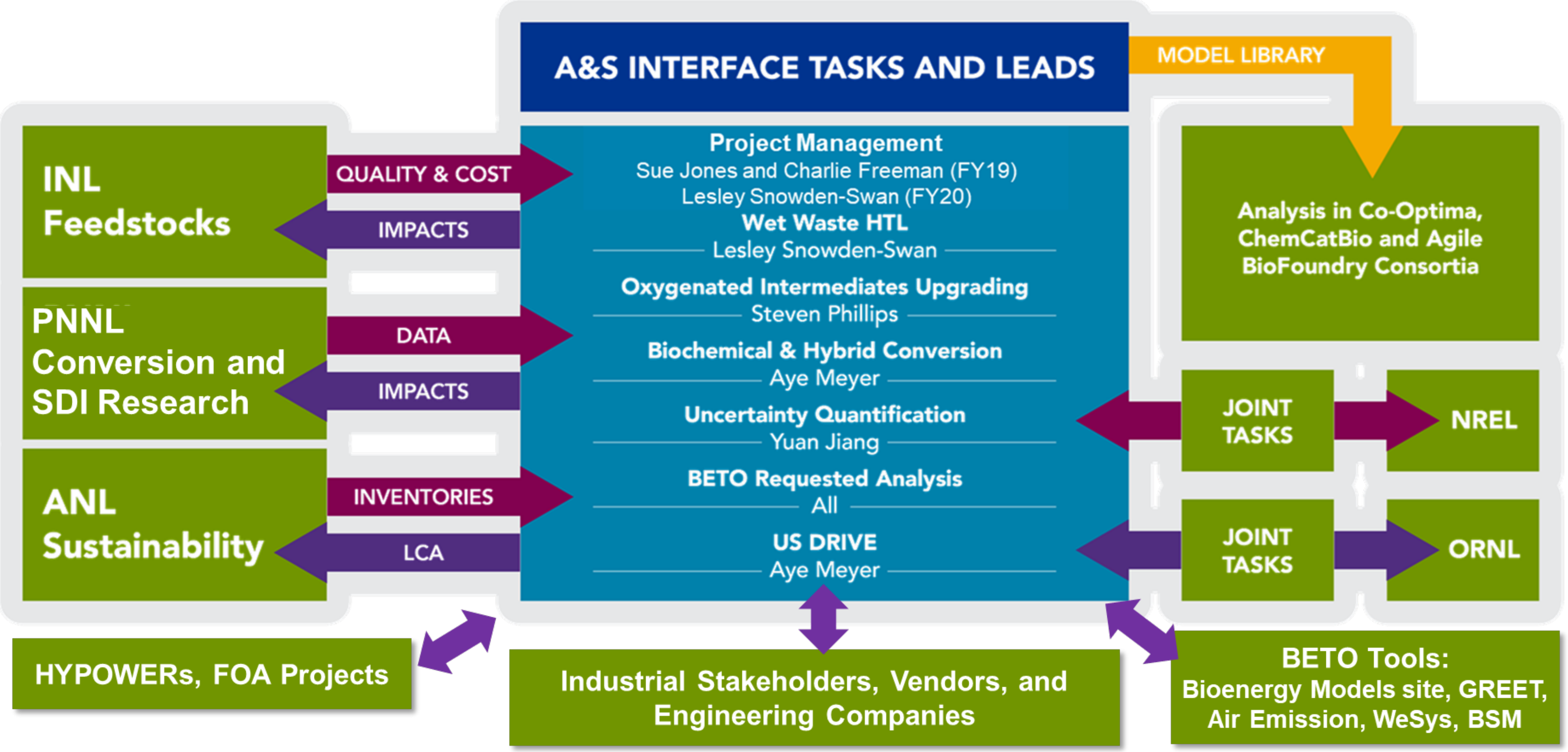


GGE = Gasoline gallon equivalent; GHG = Greenhouse gas emission; TEA = Techno-economic analysis; ANL = Argonne National Laboratory

1 – Management: Project Structure

Management Controls:

- Annual Operating Plans with quarterly progress measures and deliverables
- Quarterly reporting to Bioenergy Technologies Office (BETO)
- Merit reviewed in fiscal year (FY) 2020 with a mid-FY 2021 Go/No-Go decision point
- Planned publications and presentations for use by stakeholders



Synergies with BETO project portfolio and industry stakeholders:

- Continuous discussions and data exchange with experimental teams and BETO consortia.
- Harmonizing assumptions and methods with analysis teams at ANL, NREL, and LLNL.
- Provide information to ANL's GREET Model
- Validate our models by collaborations and exchange of data/learnings with industrial and academic counterparts.

1- Management: Risk Abatement

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

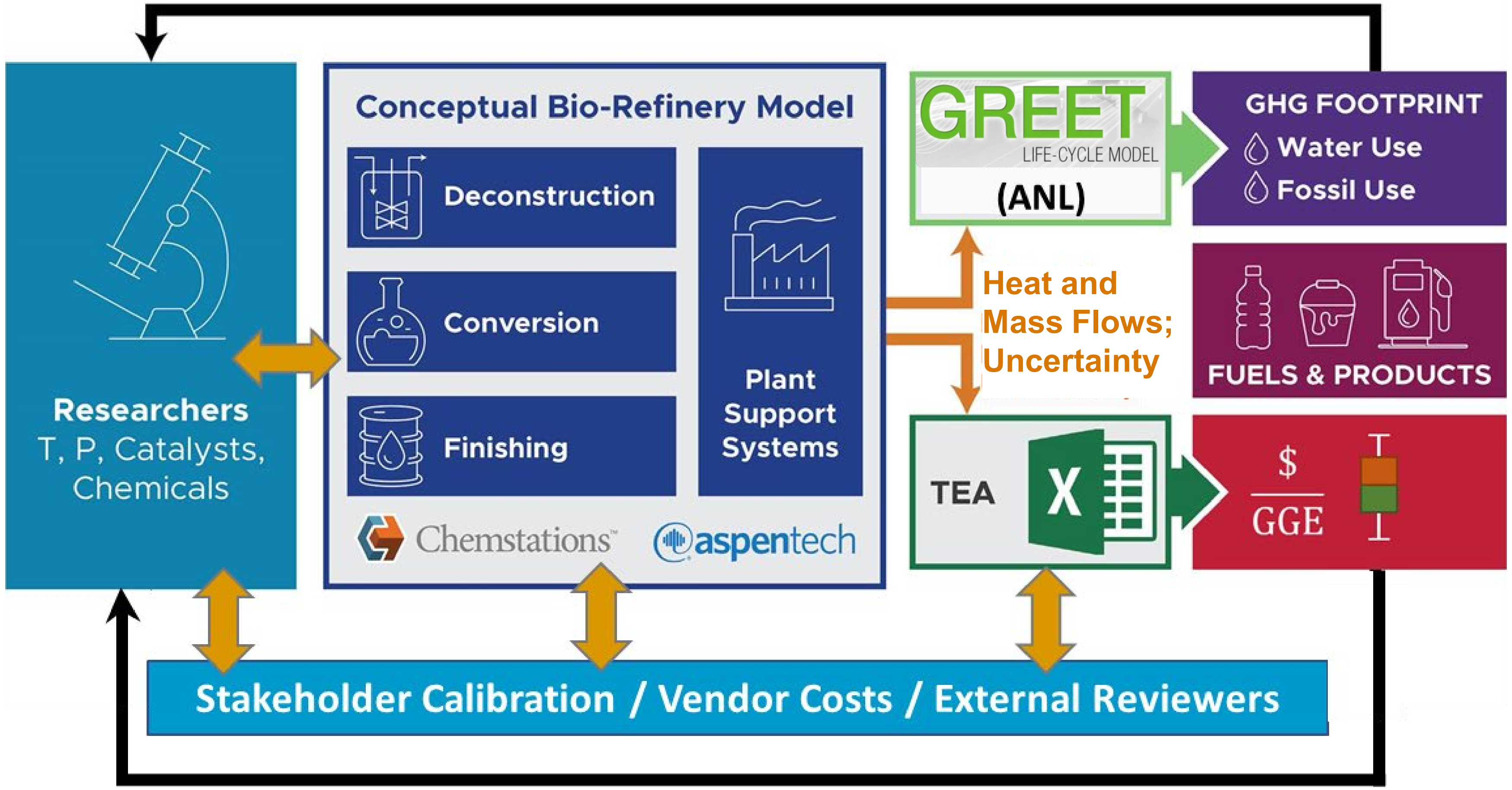
Risk	Abatement Strategy
Lack of data available to inform models and TEA	• Frequent meetings and communication with experimental team on data needs • Synced milestones with experimental project's schedule
TEA results have large uncertainty from many assumptions	• Provide sensitivity analysis around key assumptions and variabilities • Develop flexible models for quick scenario assessments and sensitivity study • Developed quick method for predicting yield and uncertainty (for HTL process)
Models do not reflect real operation at scale	• Frequent discussion with vendors and engineering contractors for reality checks • External review of our design case reports[1] by industry and academics • Experts from fuel, utility and vehicle producers serve as technical team advisors (for USCAR task).

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

2 – Approach : Technical Approach

Technical Approach

- Develop data-driven process models (CHEMCAD and AspenPlus) and cost models (Excel).
- Work closely with researchers to convey impacts and identify data gaps (frequently scheduled meetings).
- Use well-defined basis for economic analysis as described in the BETO Multi-Year Plan (MYP).
- Consider combinations of effects vs. one variable at a time.



GGE = Gasoline gallon equivalent; GHG = Greenhouse gas emission; TEA = Techno-economic analysis; ANL = Argonne National Laboratory

Critical Success Factors

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

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2 – Approach: Go/No-Go Criteria

Go/No-Go Description:

The research supported by analysis from this project consists of biochemical, thermochemical, and hybrid processes. These research areas could possibly contribute to reducing the minimum fuel selling price (MFSP) to below $3/GGE through such means as co-products, novel processing schemes, process intensification, scale, and use of waste feedstocks.

Go/No-Go Criteria:

Develop a TEA for one specific conversion route (biochemical, thermochemical, or hybrid) that reduces the MFSP* to < $2.5/GGE**

*MFSP: minimum fuel selling price

**GGE: gallon gasoline equivalent

Project Go/No-Go memorandum draft[1] *was submitted in Feb. 2021 and will be addressed more in details in the* ***Organic Waste Session*** *at 12:00 to 12:35 ET by Lesley Snowden-Swan, "Techno-Economic Analysis of Wet Waste Hydrothermal Liquefaction Pathway"*

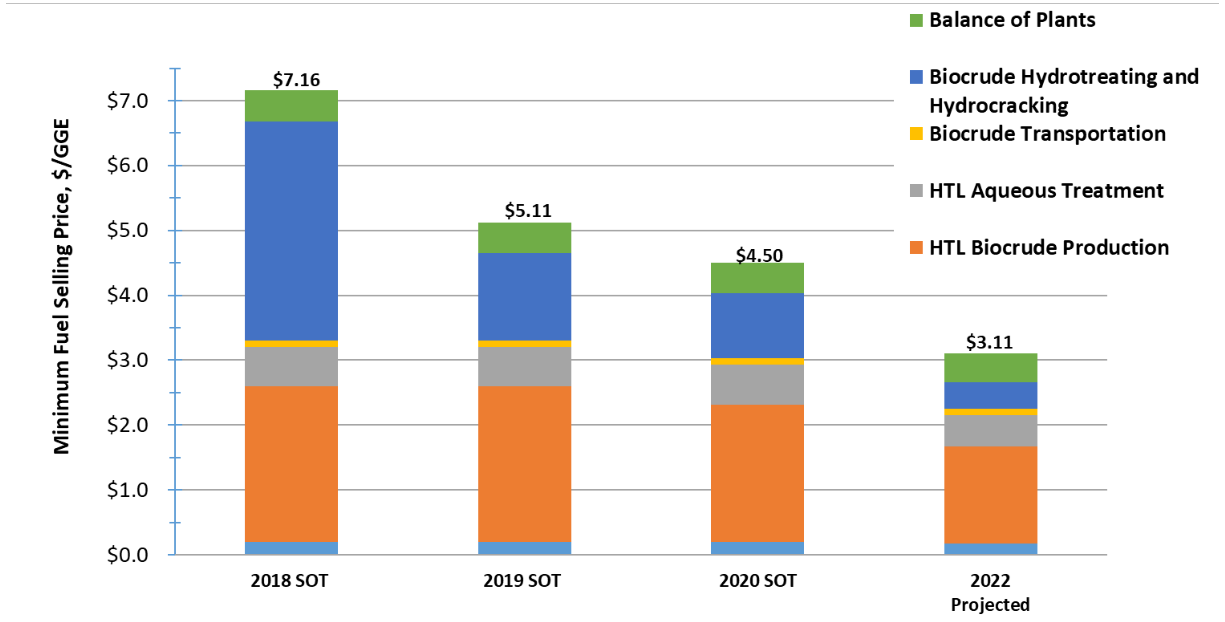
[1] See additional slide 23 for data

3 – Impact: Advancing the State of Research Technology

Wet Waste Hydrothermal Liquefaction (HTL): decreasing biofuel cost through conversion of waste feedstocks

- ➢ Metrics and technical targets are TEA-driven
- ➢ Enables focused HTL and biocrude upgrading research to:

• increase fuel yields • prolong catalyst life • improve process design



- This work directly supports meeting the BETO 2022 milestone

BETO Target: "By 2022, verify integrated systems research for hydrocarbon biofuel technologies that achieve a mature modeled MFSP of $3/GGE with a minimum 60% reduction in emissions relative to currently predominant fuels"

3 – Impact: Enable Meeting BETO Objectives

Supporting BETO Goal Setting

- Contributed to BETO lead multi-laboratory effort to assess potential targets for BETO beyond 2022.

Collaboration with BETO Projects at Other Laboratories

- Input from PNNL process models transferred to ANL for their Supply Chain Sustainability Analysis and GREET model (wet waste HTL)
- NREL's emission analysis (fast pyrolysis and upgrading, wet waste HTL)
- Marine biofuel (fast pyrolysis and upgrading, wet waste HTL)
- Waste-To-Energy project (wet waste HTL)

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3 – Impact : Continual Interactions with Stakeholders

Supporting BETO consortia and other projects by leveraging models for use in:

- wet waste HTL → BIOPROCESSING SEPARATIONS CONSORTIUM
- HTL, FP, indirect liquefaction, biochemical, BDO upgrading, BDO separation → ChemCatBio
- HTL, FP, indirect liquefaction, biochemical, BDO upgrading, BDO separation → CO-OPTIMIZATION OF FUELS & ENGINES
- FP → fcic FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM

Information Dissemination and Use (FY19-FY20)

- 10 peer review articles
- 12 presentations (six analysis only, six supporting experimental work); additional details in backup slides
- Responding to information requests from industry and universities

Supports 6 projects and 4 consortia in 6 National Laboratories

With our breadth and depth, we maintain cognizance over the BETO portfolio and disseminate this knowledge to management and R&D staff

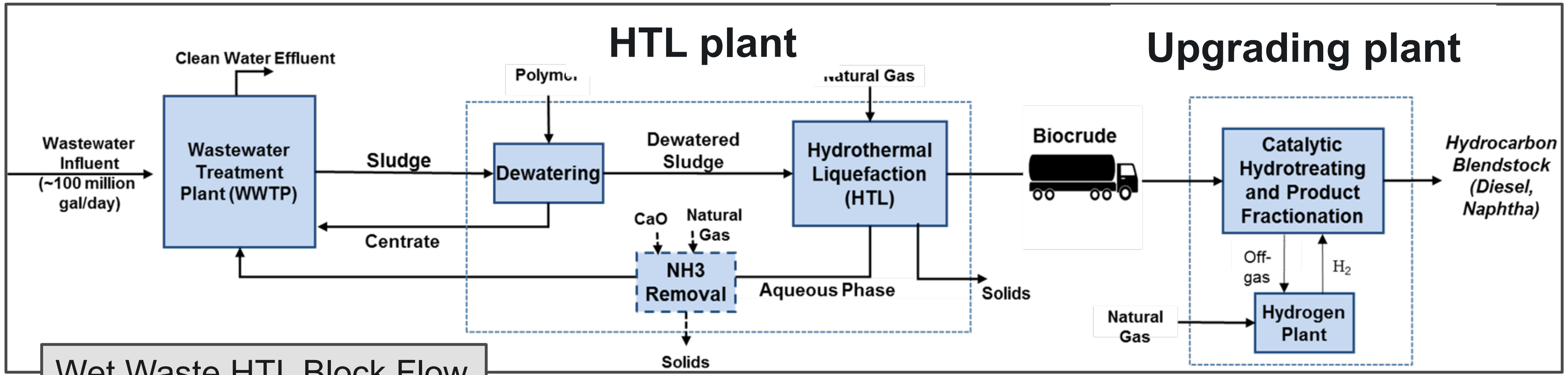
4 – Progress and Outcomes

Overview of Highlights from:

- HTL of Waste Feedstocks
- Enhanced Analysis Methods
- Biochemical and Hybrid Conversion Analysis
- Oxygenated Intermediates Upgrading Analysis
- USCAR Analysis
- Pioneer Plant Cost Estimation

4 – Progress and Outcomes: HTL of Wet Wastes

Objective: Develop data-driven process models for performing TEA and life cycle analysis (LCA) of HTL processes to drive research and help advance waste-to-energy.

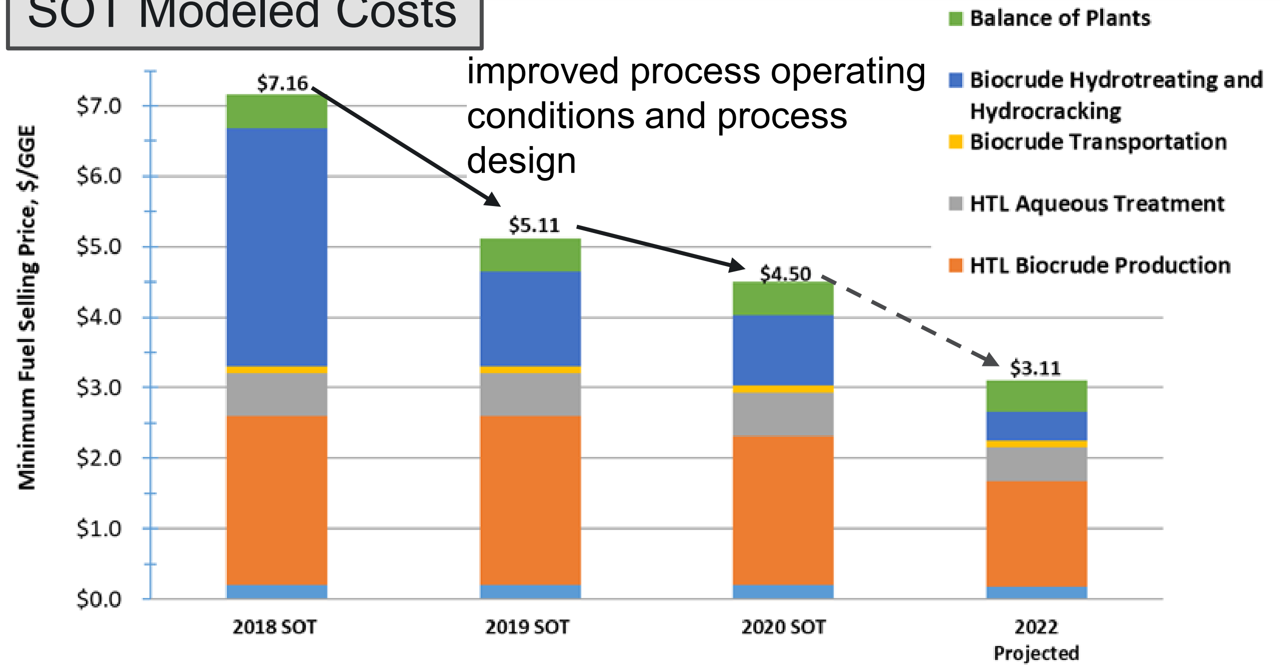


Wet Waste HTL Block Flow

Outcome: generate an actionable plan to meet $3/GGE and report research progress from annual state of technology assessment

This task will be extensively covered by Lesley Snowden-Swan, ***12:00 to 12:35 ET in the Organic waste session***, "Techno-Economic Analysis of Wet Waste Hydrothermal Liquefaction Pathway".

SOT Modeled Costs



4 – Progress and Outcomes: Enhanced Analysis Methods

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Background: Invaluable wet waste HTL flow reactor experimental data in PNNL library and large uncertainty from many assumptions.

Objective: develop a quick yield prediction method and identify ways to reduce process techno-economic uncertainty for wet waste HTL pathway

Outcome: very first predictive yield model and identify parameters reducing uncertainty in TEA for wet waste HTL pathway.

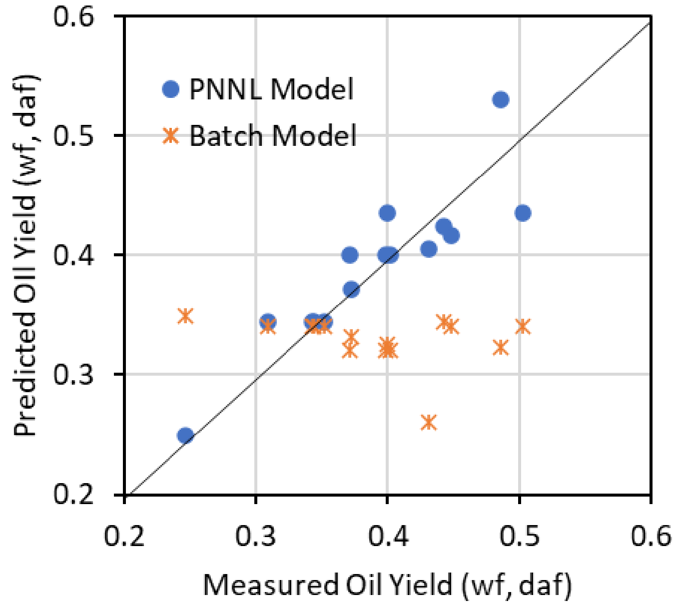
Key takeaway:

Wet waste HTL yields can be quickly predicted from feed compositions

Uncertainty can be reduced by improving controlling feedstock moisture and testing more wastes to expand datasets for reactor model.

Predictive model

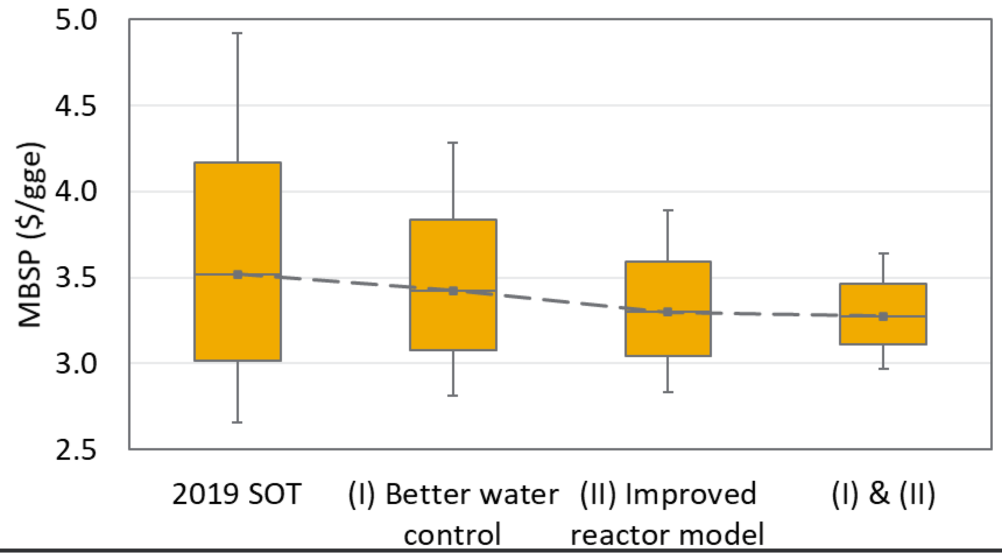
$$y_i = k_{iC}x_C + k_{iL}x_L + k_{iP}x_P + k_{iA}x_A + k_{iS}(1 - x_m)$$



k_{ij}	y_{oil}	y_{aqu}	y_{gas}	y_{char}
x_C	0.3323 (0.0424)[a]	0.3539 (0.0339)	0.3096 (0.0287)	-
x_L	0.4408 (0.1249)	0.6748 (0.0982)	-	-
x_P	-	0.7853 (0.0419)	-	-
x_A	-	-	-	0.3879 (0.0330)
$1 - x_m$	1.0263 (0.1931)	-1.4666 (0.1765)	0.3786 (0.0790)	-

[a] Standard error

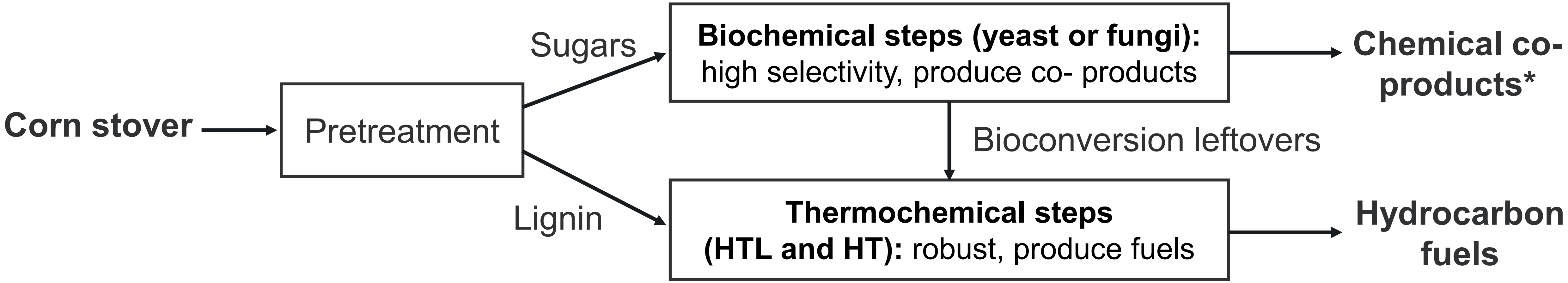
Parameters to reduce in uncertainties



4 – Progress and Outcomes: Biochemical and Hybrid Conversion

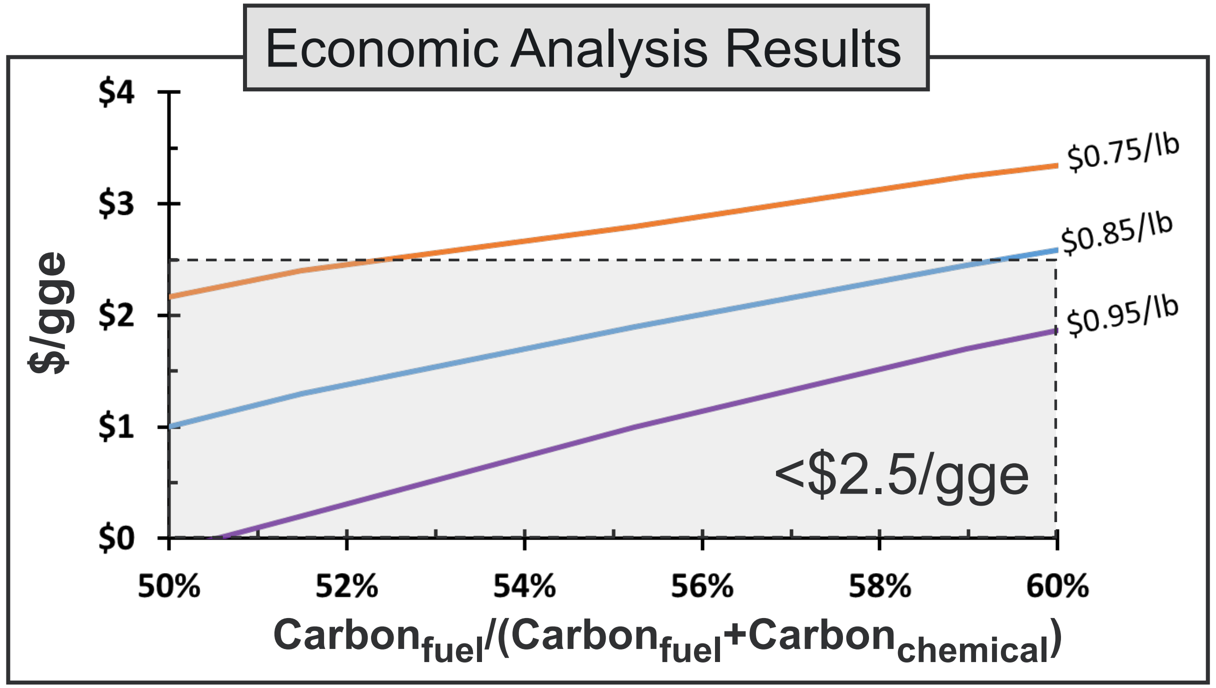
Background: assessment of lignin valorization in biochemical pathway

Objective: assess process economics of the hybrid bioprocessing (biochemistry+ thermochemistry)



Outcome: identify cost drivers and perform their sensitivity analysis

Key Takeaway:
- Carbon splits (fuel vs chemical) and co-product prices are significant cost drivers
- <$2.5/GGE is possible



* Potential chemical co-products have been identified by the seed project (WBS# 2.2.2.501) and Agile BioFoundry (ABF) consortia. The TEA is being summarized.

4 – Progress and Outcomes: Oxygenated Intermediates Upgrading

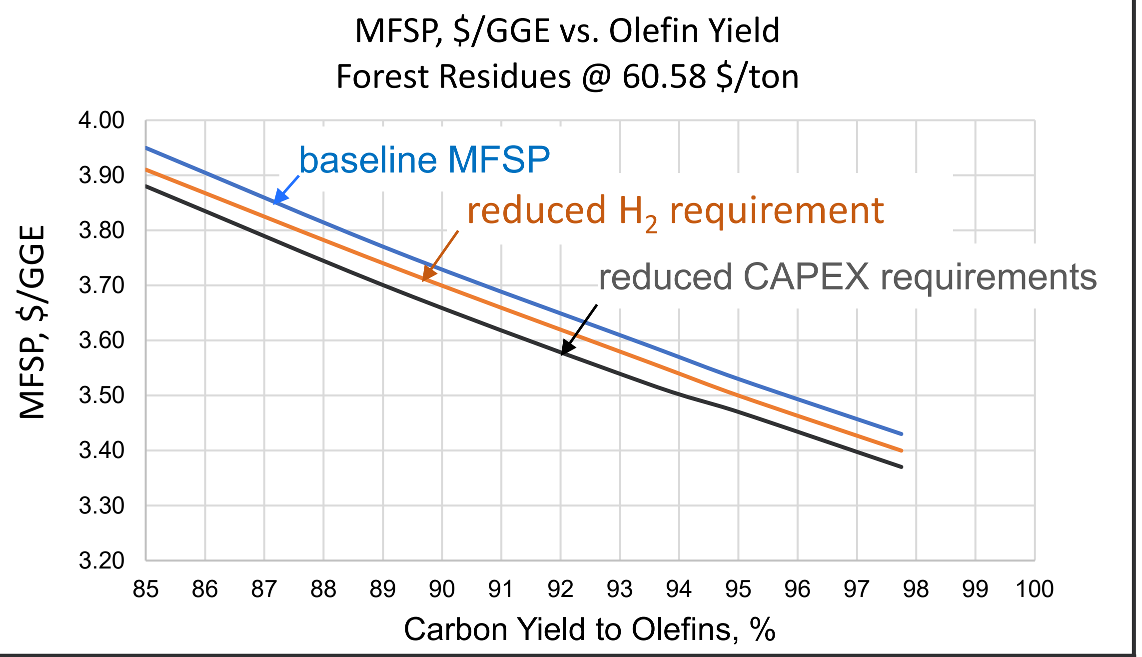
Objective: deliver these findings to experimentalists

- experimental data implications for scale up
- cost drivers
- scenario analysis results for reducing production costs

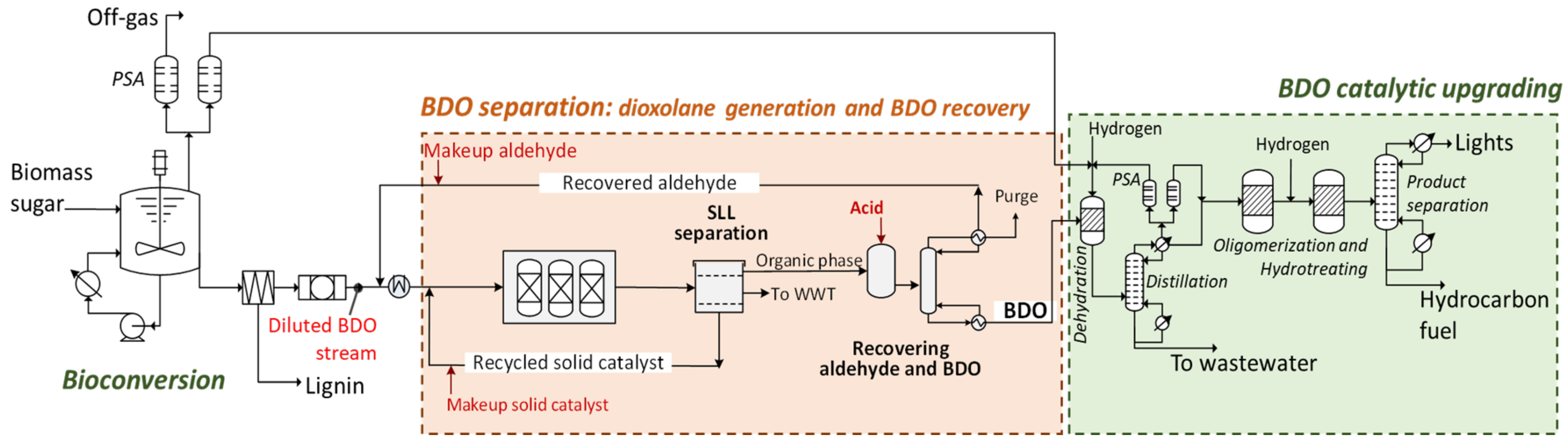
Outcome: suggest approaches to reduce costs

Key takeaway: Optimizing chemical (including catalysts) choices and usages significantly improve the costs.

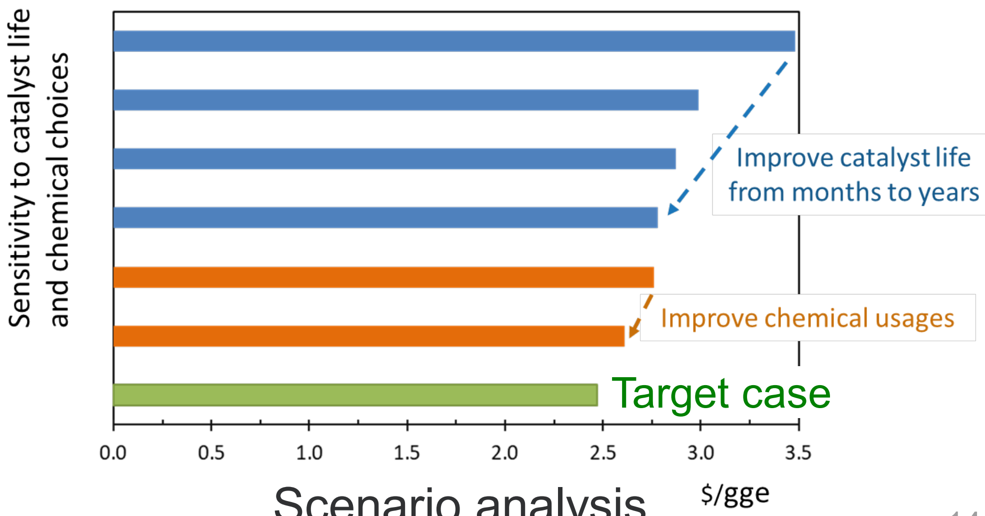
Scenario analysis for Upgrading C2 to distillate



Analysis for 2,3-Butanediol separation via dioxolane generation method (Los Alamos National Laboratory experimental work)



BDO intermediate separation block flow



Scenario analysis

4 – Progress and Outcomes: USCAR (ANL, LLNL, NREL, PNNL)

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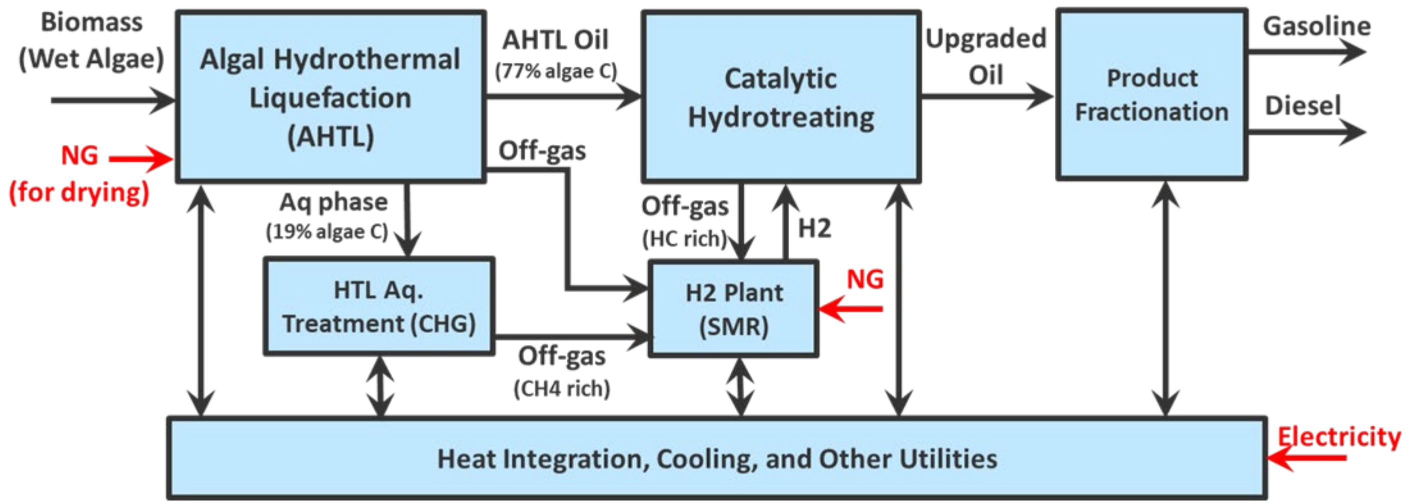
Objective: investigate net zero carbon process scenarios for algae HTL process.

Outcome: show assumptions leading to net zero carbon scenarios for algae HTL process.

Key Takeaway: renewable resource and energy will improve the process life-cycle but they can be challenging in optimizing costs.

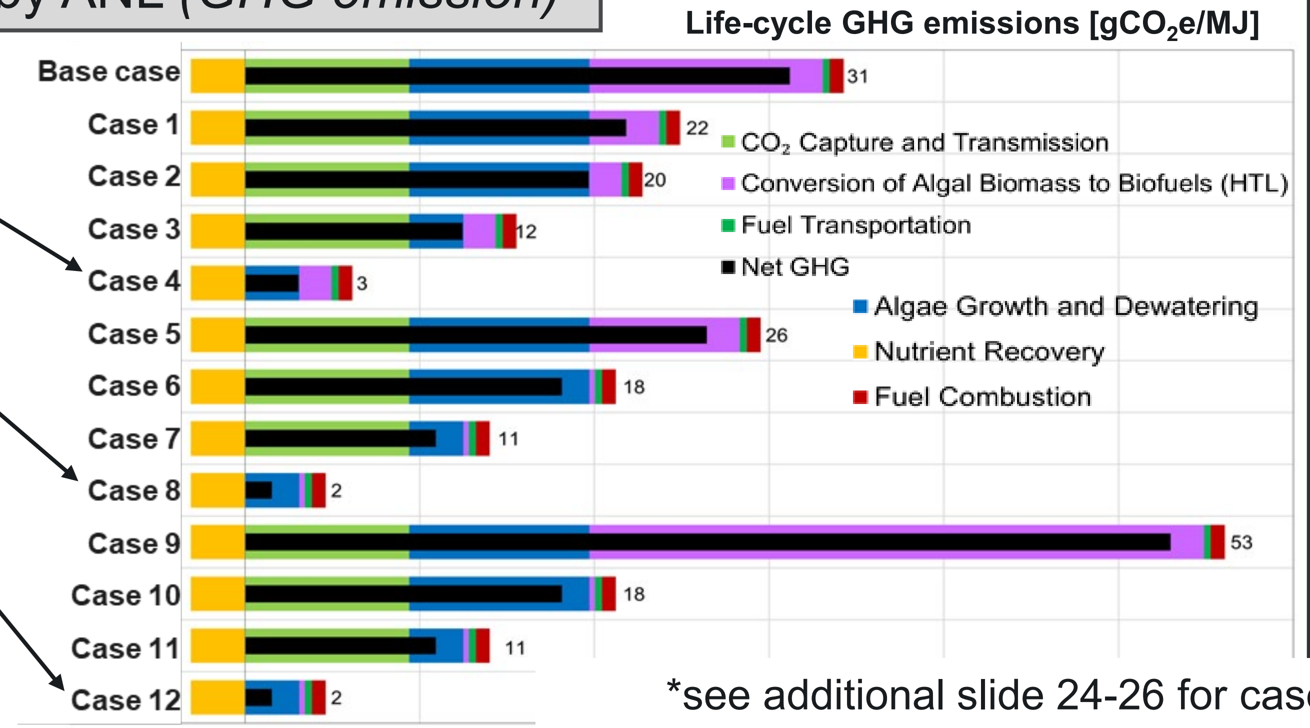
Process flowsheet in *base case* analysis

Using *renewable resource and energy to decarbonize* this process

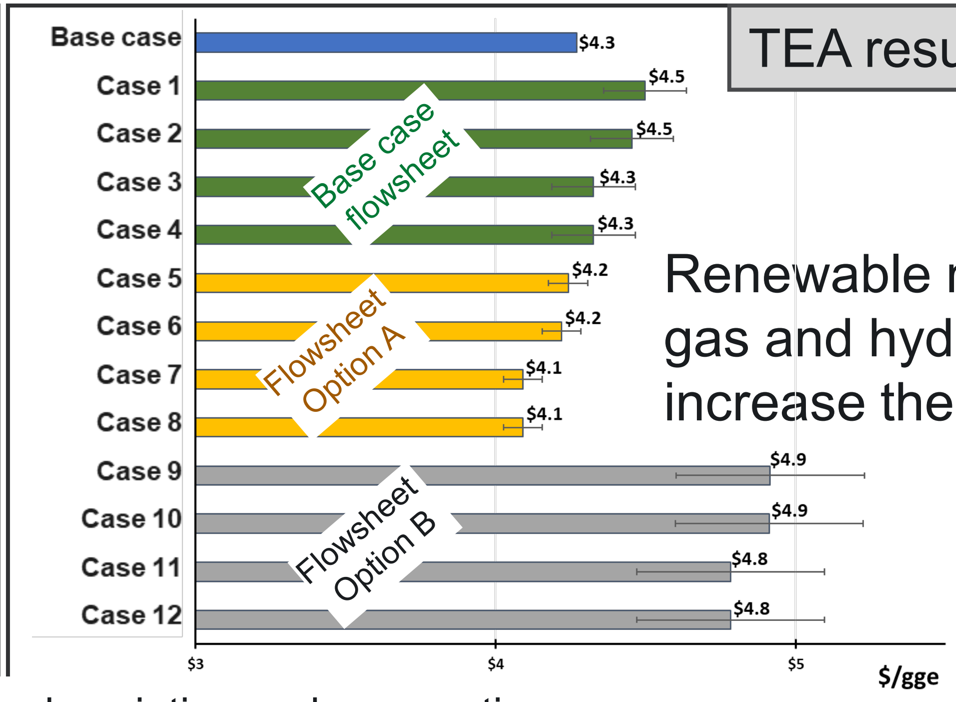


LCA results by ANL *(GHG emission)**

Near net zero carbon scenarios are possible when using renewable resources and energy



TEA results *(cost)**



Renewable natural gas and hydrogen increase the costs

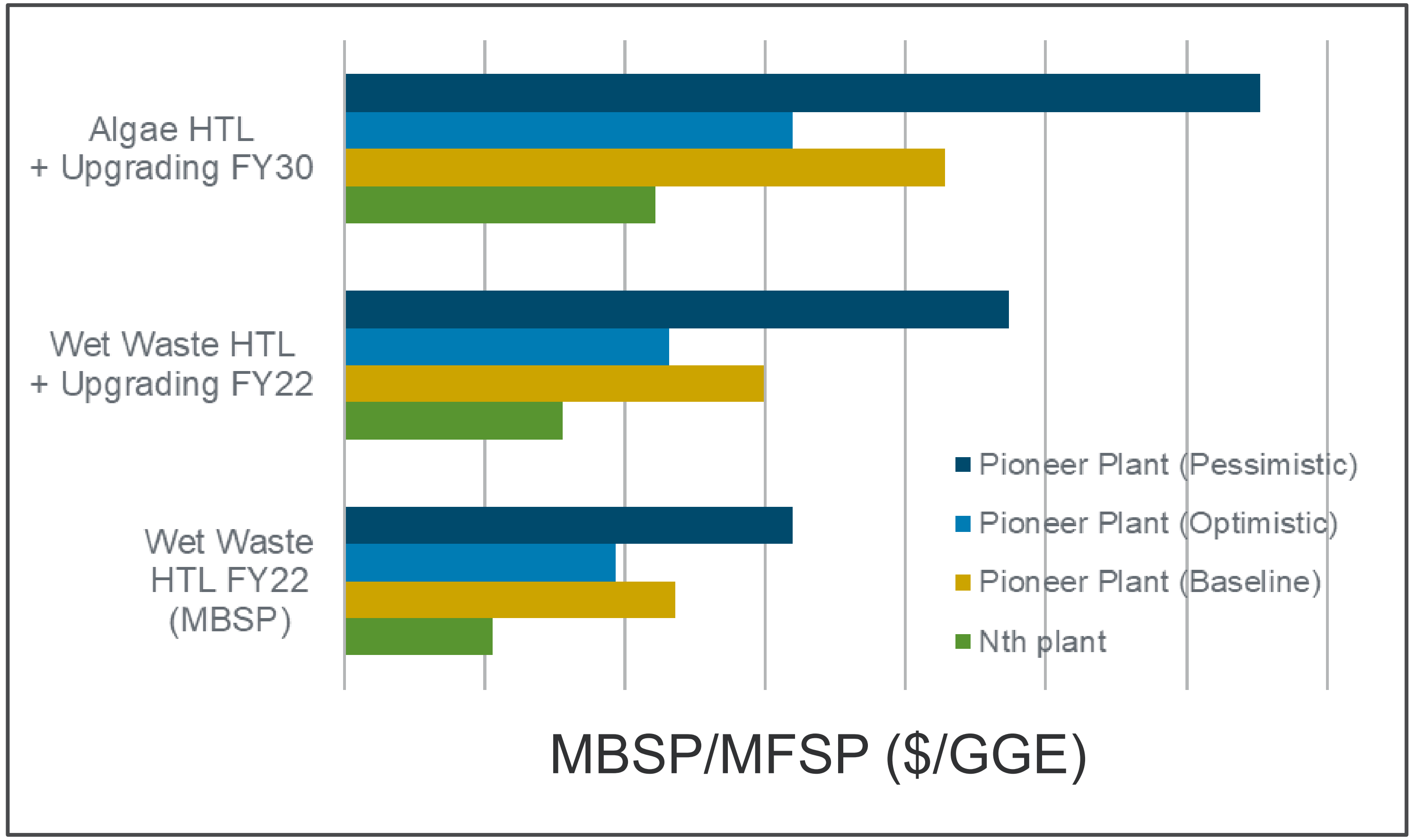
*see additional slide 24-26 for case description and assumptions

4 – Progress and Outcomes: Pioneer Plant Cost Estimation (NREL and PNNL)

Objective: investigate impacts using pioneer plant (1st-of-a-kind process) assumptions

Key Takeaway:

- nth plant assumptions can be optimistic. Capital cost and process performance are often underestimated.
- TEA can be presented in probabilistic distribution including degree of uncertainty at different technology readiness levels (TRLs)



*see additional slide 27 for the analysis assumptions of base, pessimistic and optimistic cases

Thank You

Acknowledgements

- Andrea Bailey – BETO Technology Manager for the A&S Interface Project
- Ian Rowe - BETO Technology Manager for the USDRIVE project
- Alicia Lindauer – BETO Technology Manager for the Analysis and Sustainability Program
- Zia Haq – BETO Senior Analyst
- *PNNL Analysis Team*
  - Lesley Snowden-Swan
  - Susanne Jones (retired)
  - Charlie Freeman
  - Aye Meyer
  - Steven Phillips
  - Yuan Jiang
  - Shuyun Li
  - Jay Askander
  - Jian Liu
- *PNNL Experimentalists*
  - Richard Hallen
  - Justin Billing
  - Daniel Anderson
  - Andrew Schmidt
  - Michael Thorson
  - James Collett
  - Robert Dagle
  - Vanessa Dagle
  - Huamin Wang
  - Karthi Ramasamy
  - Daniel (Miki) Santosa
  - Igor Kutnyakov
- *Waste Resource Team*
  - Tim Seiple
  - Andre Coleman
- *National laboratory collaborators*
  - **ANL:** Uisung Lee, Michael Wong, Hao Cai, Thathiana Benevides, Troy Hawkins, Eunji Woo
  - **NREL:** Ling Tao, Kylee Harris, Eric Tan
  - **LLNL:** A.J. Simon and Hannah Goldstein
  - **LANL:** Andrew Sutton (currently at ORNL), Cameron Moore
  - **INL:** Damon Hartley, David Thompson

Summary

Guide Research - Track Progress - Reduce Costs

- **Overview:** Cost and performance model development to inform economic and sustainable biofuel production
- **Approach:** Closely coupled analysis and research
- **Relevance:** Working towards the 2022 Government Performance and Results Act goal (wet waste HTL)
- **Technical Accomplishments/Progress/Results:**
  - All progress measures and milestones met on time and on budget.
  - Identified sustainable cost reduction strategies.
  - Enabled impactful, focused research.
  - Published results for use by others.
- **Future Work**
  - Analysis to support wet waste HTL SOT.
  - Continued support of BETO’s interest (for de-carbonizing fuel and chemical life-cycles, pathway to achieve 2030 cost targets).
  - Continued support of researchers (to guide their research directions).

Quad Chart Overview

Timeline
- Project start date: 10/01/2019
- Project end date: 09/30/2022

	FY 2020	Active Project
U.S. Department of Energy Funding	10/01/2020 –9/30/2021 $700,000	10/01/2019 – 9/30/2022 $2,125,000

Project Partners
- ANL – LCA Team
- INL – Feedstock Analysis Team
- LLNL – Analysis Team
- NREL – TEA Team
- ORNL – Experimentalists
- PNNL – Experimentalists, Analysis Team
- Industries – HYPOWERs (Martinez, CA), Metro Vancouver (Vancouver, Canada)

Barriers Addressed
At-E: Quantification of Economic, Environmental, and Other Benefits and Costs

At-A: Analysis to Inform Strategic Direction

Project Goal
To employ TEA and LCA methods coupled to researcher input and feedback in order to guide and track research progress towards reducing the costs of renewable fuels and products. This project will maximize the ability of BETO to meet their economic goals through closely coupled and ongoing data exchange and discussion between the experimentalists and the analysts to identify realistic means of achieving that goal.

End of Project Milestone
Waste HTL Business Case will be completed and delivered. Identifying and disseminating data regarding viable routes to economic production of biofuels and chemicals is needed to advance the bioeconomy. We will complete a draft manuscript summarizing the business case for waste HTL and the prospects for producing fuel while also addressing a long-standing waste problem. Publication is targeted for early FY 2023.

Funding Mechanism
Laboratory Call 2019

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Additional Slides

Publications

1. S. Li, Y. Jiang, L.J. Snowden-Swan, J.A. Askander, A.J. Schmidt, Andrew, J.M. Billing. 2021. “Techno-Economic Uncertainty Analysis of Wet Waste-to-Biocrude via Hydrothermal Liquefaction”. Published. *Applied Energy*. 116340. https://www.sciencedirect.com/science/article/abs/pii/S0306261920317220.
2. The Wet Waste HTL pathway 2019 SOT assessment was published as a technical report on the PNNL website at https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-29882.pdf.
3. H. Wang, P.A. Meyer, D.M. Santosa, C. Zhu, M.V. Olarte, S.B. Jones, A.H. Zacher. 2020. "Performance and techno-economic evaluations of co-processing residual heavy fraction in bio-oil hydrotreating." *Catalysis Today*. Status: Published. https://www.sciencedirect.com/science/article/pii/S092058612030660X.
4. E. Tan, T. Hawkins, U. Lee, L. Tao, P.A. Meyer, M. Wang, T. Thompson. “Biofuels for Marine Applications: Techno-Economic Analysis and Life-Cycle Assessment”. *Environmental Science & Technology. Status*: Submitted.
5. Meyer P.A., L.J. Snowden-Swan, S.B. Jones, K.G. Rappe, and D.S. Hartley. 2020. "The Effect of Feedstock Composition on Fast Pyrolysis and Upgrading to Transportation Fuels: Techno-Economic Analysis and Greenhouse Gas Life Cycle Analysis." *Fuel* 259. PNNL-SA-141518. doi:10.1016/j.fuel.2019.116218.
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9. 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. PNNL-SA-138139. doi:10.1016/j.algal.2019.101450.
10. Zacher A.H., D.C. Elliott, M.V. Olarte, H. Wang, S.B. Jones, and P.A. Meyer. 2019. "Technology Advancements in Hydroprocessing of Bio-oils." *Biomass & Bioenergy* 125. PNNL-SA-138596. doi:10.1016/j.biombioe.2019.04.015.

Presentations

1. Snowden-Swan, L. January 23, 2019. “Wet Waste Hydrothermal Liquefaction and Biocrude Upgrading 2018 State of Technology.” Presented at the BETO Quarterly meeting (virtual).
2. S. Phillips, M. Guo, K. Ramasamy. April 1, 2019. “Techno-economics of Catalytic Conversion of Ethanol to Chemical Grade n-Butanol and 1-Hexene” Presented by Steven Phillips at the AIChE Spring meeting, New Orleans.
3. Billing J.M., D.B. Anderson, R.T. Hallen, T.R. Hart, A.J. Schmidt, and L.J. Snowden-Swan. 09/23/2019. "Development of an Integrated Process for the Hydrothermal Conversion of Wastewater Sludge to Recover Energy, Recycle Nutrients, and Destroy Contaminants." Presented by J.M. Billing at WEFTEC 2019, Chicago, Illinois. PNNL-SA-147659.
4. Snowden-Swan L.J., J.M. Billing, A.J. Schmidt, M.R. Thorson, D.M. Santosa, R.T. Hallen, and T.E. Seiple, et al. 10/08/2019. "HTL and Upgrading of Wet Wastes to Renewable Transportation Fuel: Recent Progress and Techno-Economics." Presented by L.J. Snowden-Swan at tcbiomassplus 2019, Rosemont, Illinois. PNNL-SA-148084.
5. Snowden-Swan L.J. 01/23/2019. "2019 State of Technology Meeting." Presented by L.J. Snowden-Swan at BETO January 2019 Quarterly Meeting Webinar, Online Conference, United States. PNNL-SA-140733.
6. Li S., Y. Jiang, L.J. Snowden-Swan, J.A. Askander, A.J. Schmidt, and J.M. Billing. 10/07/2020. "Techno-Economic Uncertainty Analysis of Wet Waste-to-Biocrude via Hydrothermal Liquefaction based on Reduced Order Model." Presented by S. Li at 2020 Thermal & Catalytic Sciences Virtual Symposium, Online, United States. PNNL-SA-155951.
7. Billing J.M., A.J. Schmidt, L.J. Snowden-Swan, T.R. Hart, D.B. Anderson, and R.T. Hallen. 06/17/2019. "Feedstock Blending as a Strategy for Hydrothermal Liquefaction: Lipid-Rich Scum from Primary Sedimentation and Wastewater Sludge." Abstract submitted to Pyroliq 2019: Pyrolysis and Liquefaction of Biomass and Wastes, Cork, Ireland.
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9. Padmaperuma A.B., C. Drennan, and L.J. Snowden-Swan. 12/15/2020. "Distillate fuels from waste." Presented by A.B. Padmaperuma at Pacifichem 2020, Honolulu, Hawaii. PNNL-SA-153208.
10. Thorson M.R., R.T. Hallen, D.M. Santosa, K.O. Albrecht, J.M. Jarvis, T. Schaub, and J.M. Billing, et al. 10/09/2019. "Challenges Upgrading HTL Biocrudes to Fuel." Presented by M.R. Thorson at TC Biomass, Chicago, Illinois. PNNL-SA-148179.
11. Lopez-Ruiz J.A., Y. Qiu, L.J. Snowden-Swan, O.Y. Gutierrez-Tinoco, C.J. Freeman, and J.D. Holladay. 05/31/2021. "Electrocatalytic co-processing of biomass-derived aqueous waste streams and bio-oils at normal temperature and pressure." Abstract submitted to 239th ECS, Chicago, Illinois. PNNL-SA-158489.
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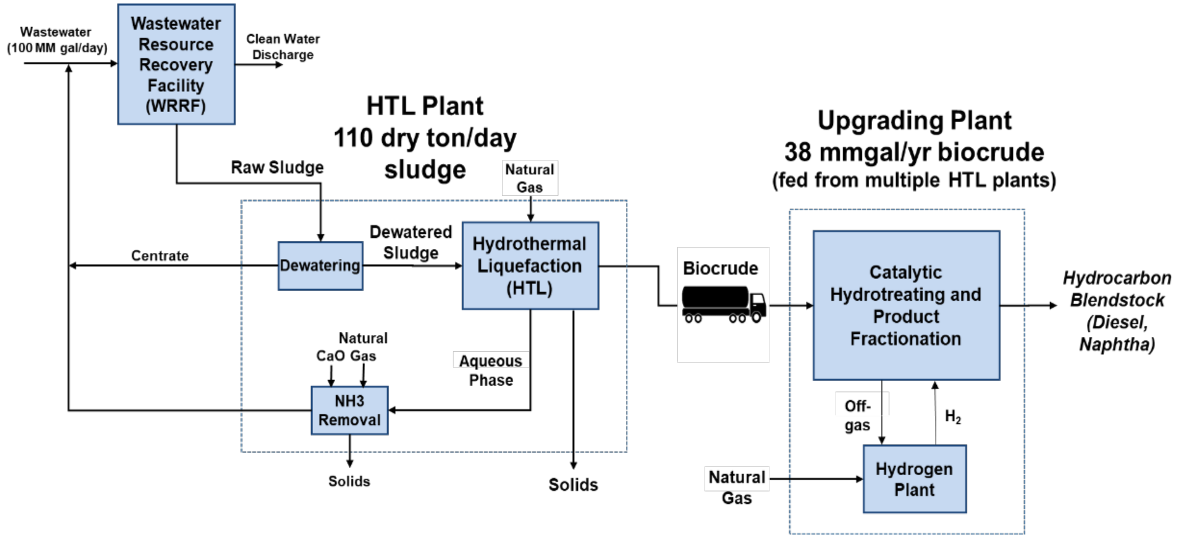
Go/No-Go: Summary From the Memorandum

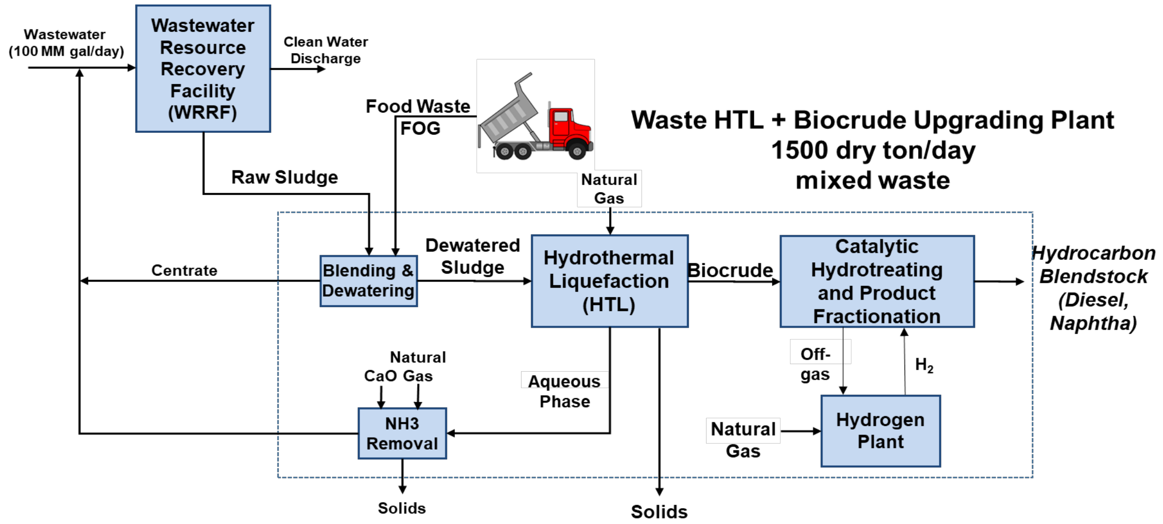
Go/No-Go Criteria

“Develop a TEA for one specific biochemical, thermochemical, or hybrid conversion route that reduces the MFSP to < $2.5/GGE.”

Scenario I

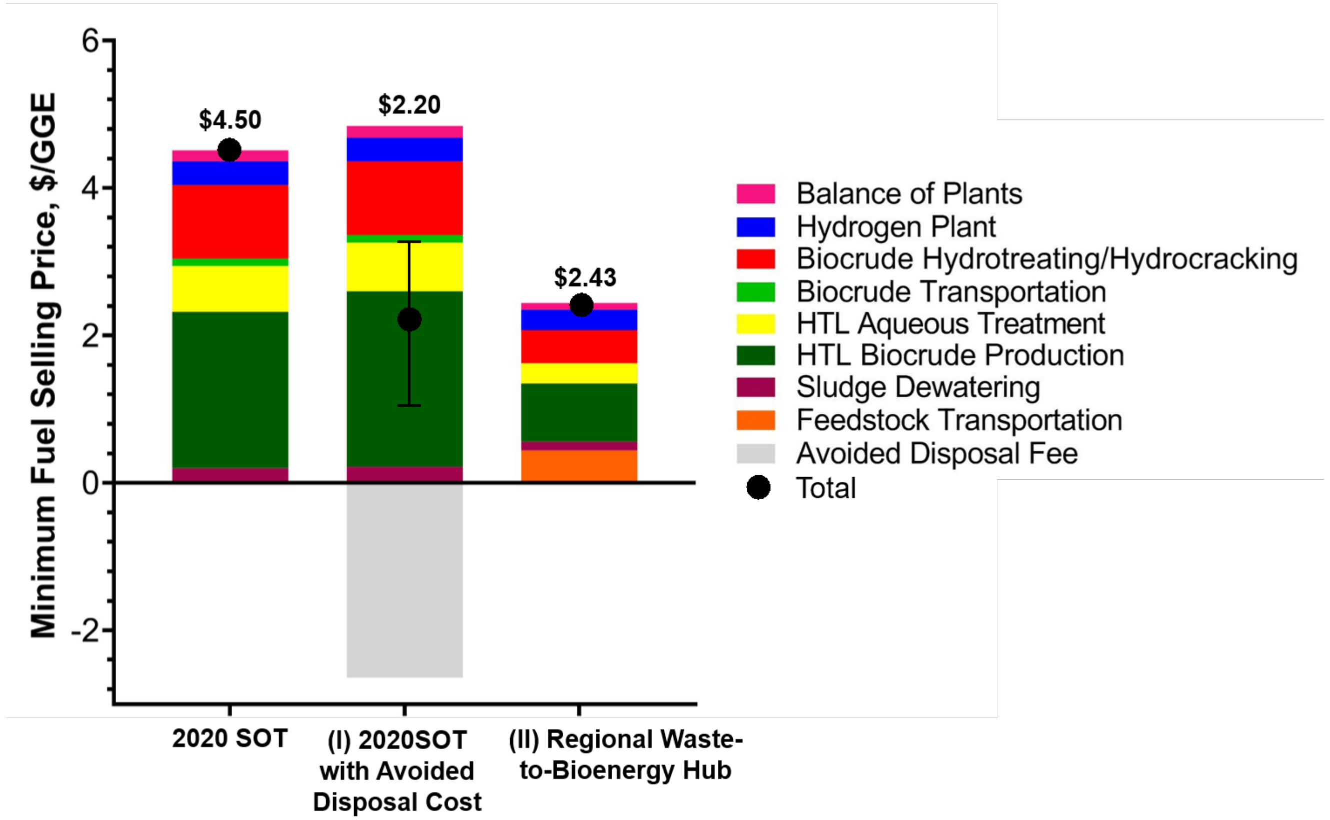


Scenario II

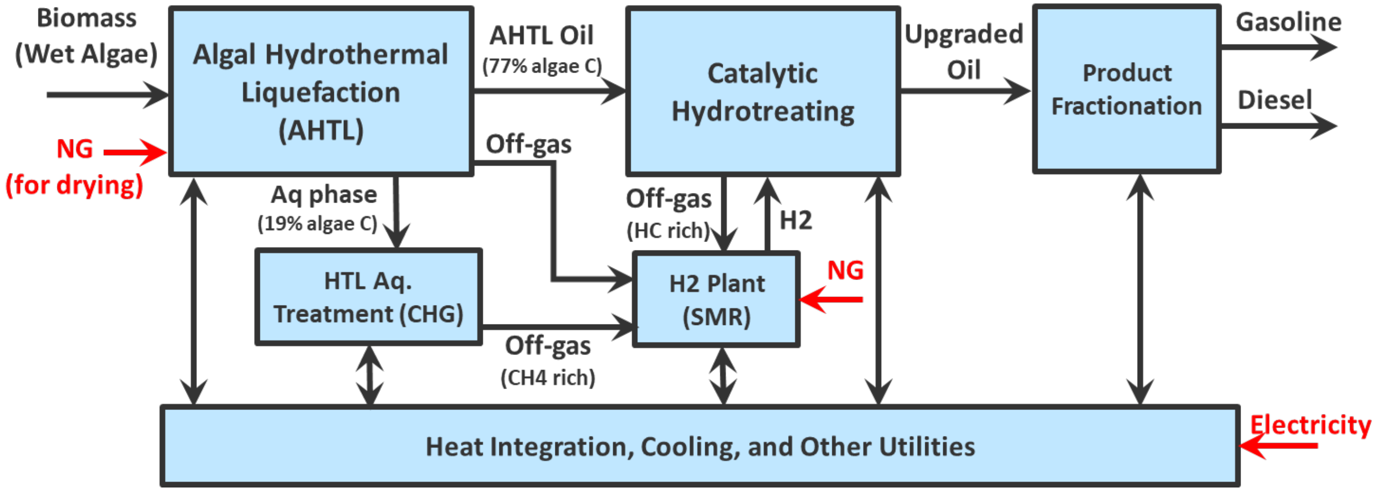


Accomplishment

Successfully completed preliminary analysis of two scenarios for the wet waste HTL and biocrude upgrading pathway to meet an MFSP of <$2.5/GGE.



Assumptions for USDRIVE analysis: Process flowsheets



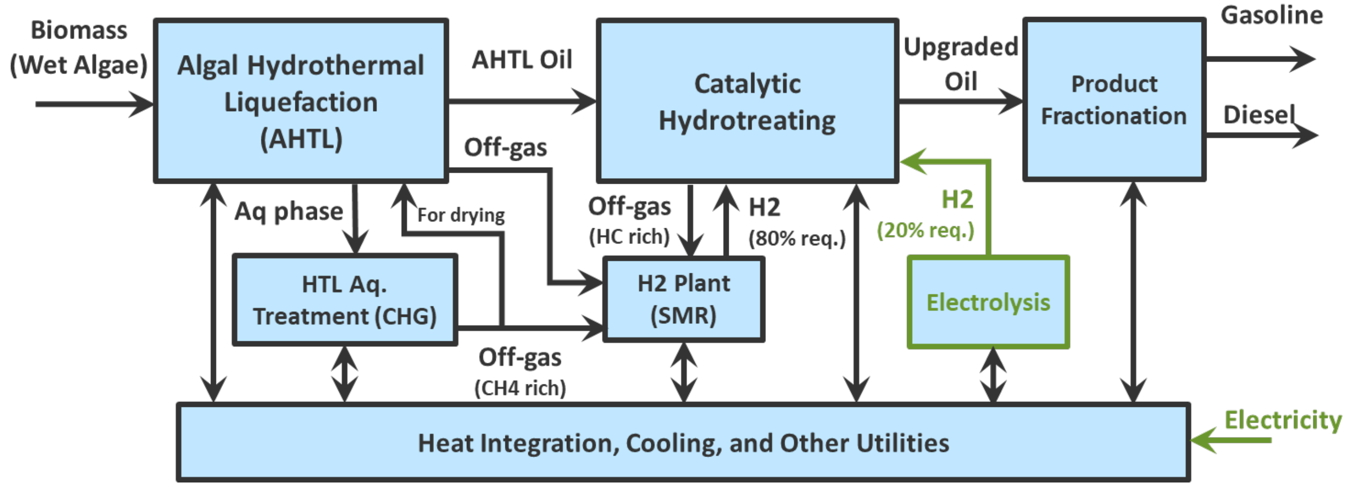
Base case flowsheet*

- Wet algae feedstock
- HTL followed by hydrotreating
- On-site WWT (by CHG) and H2 plant (by SMR)
- Purchased fossil energy includes (1) NG (2) Electricity

*Algae HTL process design case: Jones, S. et al. Process Design and Economics for the Conversion of Algal Biomass to Hydrocarbons: Whole Algae Hydrothermal Liquefaction and Upgrading. Report No. PNNL-23227, (Pacific Northwest National Laboratory, Richland, WA, 2014).

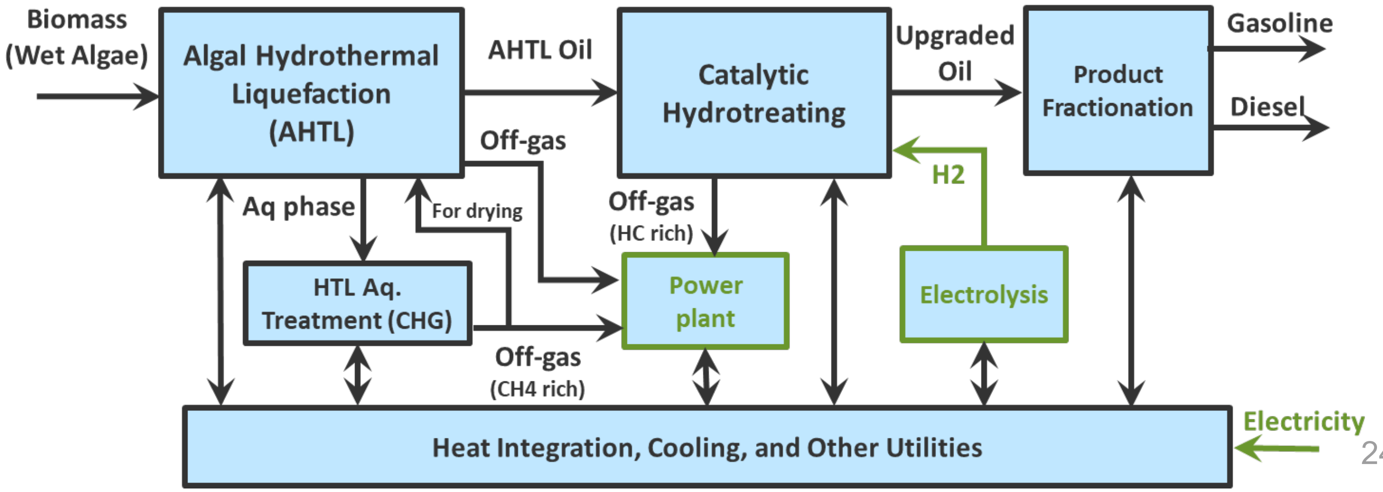
Flowsheet A

- Eliminate NG usage
- Process off-gases used for biomass drying and H2 production by SMR
- Renewable H2 applied and purchase electricity



Flowsheet B

- Eliminate NG usage
- Renewable H2 is from electrolysis
- Process off-gases used for biomass drying and electricity generation



Assumptions for USDRIVE analysis: Analysis case description

Case	Scenario	Conversion area (AHTL to HC production)		Algae farm	CO_2 capture and transmission
		H_2 source	Electricity source	Electricity source	Electricity source
Base case	2030 Target case	SMR using NG and off-gas	U.S. mix	U.S. mix	U.S. mix
Case 1	Replacing fossil NG with RNG	SMR using RNG and off-gas	U.S. mix	U.S. mix	U.S. mix
Case 2	Replacing fossil NG with RNG	SMR using RNG and off-gas	Renew. electricity	U.S. mix	U.S. mix
Case 3	Replacing fossil NG with RNG	SMR using RNG and off-gas	Renew. electricity	Renew. electricity	U.S. mix
Case 4	Replacing fossil NG with RNG	SMR using RNG and off-gas	Renew. electricity	Renew. electricity	Renew. electricity
Case 5	Eliminating NG by using off-gas for drying and electrolysis for H_2 prod.	SMR using off-gas + Electrolysis with U.S. mix	U.S. mix	U.S. mix	U.S. mix
Case 6	Using renewable electricity for conversion process area	SMR using off-gas + Electrolysis with renew. electricity	Renew. electricity	U.S. mix	U.S. mix
Case 7	Using renewable electricity for conversion and algae production	SMR using off-gas + Electrolysis with renew. electricity	Renew. electricity	Renew. electricity	U.S. mix
Case 8	Using renewable elec. from algae to HC production	SMR using off-gas + Electrolysis with renew. electricity	Renew. electricity	Renew. electricity	Renew. electricity
Case 9	Eliminating NG by using off-gas for drying and electrolysis for H_2 prod.	Electrolysis with U.S. mix	U.S. mix	U.S. mix	U.S. mix
Case 10	Using renewable electricity for conversion process area	Electrolysis with renew. electricity	Renew. electricity	U.S. mix	U.S. mix
Case 11	Using renewable electricity for conversion and algae production	Electrolysis with renew. electricity	Renew. electricity	Renew. electricity	U.S. mix
Case 12	Using renewable elec. from algae to HC production	Electrolysis with renew. electricity	Renew. electricity	Renew. electricity	Renew. electricity

AHTL: Algae hydrothermal liquefaction
HC: Hydrocarbon

NG: National gas
RNG: Renewable natural gas

SMR: Steam methane reformer

Assumptions for USDRIVE analysis: Renewable resource cost assumptions

Summary of Renewable Natural Gas Cost Sensitivity Values

	Feedstock	Cost Range ($/MMBTU)		
		min	avg	max
Anaerobic Digestion	Landfill Gas	$ 7.10	$ 13.05	$ 19.00
	Animal Manure	$ 18.40	$ 25.50	$ 32.60
	Wastewater Sludge	$ 7.40	$ 16.75	$ 26.10
	Food Waste	$ 19.40	$ 23.85	$ 28.30

Summary of Renewable Electricity and Renewable H_2 Cost Sensitivity Values

Resource	Baseline	Minimum	Maximum
Renewable Electricity ($/kWh)	$0.02	$0.02	$0.10
Renewable H_2 ($/kg)	$1.38	$1.38	$4.50

Assumptions for Pioneer Plant Cost Estimation

Assumptions for Wet Waste HTL 2022 Pathways

		HTL			Biocrude Upgrader		
	Range	Baseline	Optimistic	Pessimistic	Baseline	Optimistic	Pessimistic
PCTNEW	0–100%	42%	40%	48%	14%	0%	23%
IMPURITIES	0–5	3	2	4	2	1	3
COMPLEXITY	0–n	4	3	5	6	6	6
INCLUSIVENESS	0–100%	33%	33%	33%	33%	33%	33%
PROJECT DEFINITION	2-8	8	8	8	7	6	8
Cost Growth		0.42	0.45	0.37	0.56	0.69	0.45
Capital as % of nth Plant		241%	220%	274%	178%	145%	223%

Assumptions for Algae HTL Pathway

	Range	Baseline	Optimistic	Pessimistic
PCTNEW	0–100%	15%	8%	23%
IMPURITIES	0–5	2.5	1.5	3.5
COMPLEXITY	0–n	10	9	11
INCLUSIVENESS	0–100%	33%	33%	33%
PROJECT DEFINITION	2-8	7	6	8
Cost Growth		0.50	0.62	0.38
Capital as % of nth Plant		200%	162%	262%

Abbreviations and Acronyms

- ABF: Agile BioFoundry
- ANL: Argonne National Laboratory
- BDO: butanediol
- BETO: Bioenergy Technologies Office
- BSM: Biomass Scenario Model
- EPC: engineering, procurement, and construction
- FOA: funding opportunity announcement
- FP: fast pyrolysis
- FY: fiscal year
- GGE: gasoline gallon equivalent
- HTL: hydrothermal liquefaction
- LANL: Los Alamos National Laboratory
- LCA: life cycle analysis
- LLNL: Lawrence Livermore National Laboratory
- MFSP: minimum fuel selling price
- NREL: National Renewable Energy Laboratory
- ORNL: Oak Ridge National Laboratory
- PNNL: Pacific Northwest National Laboratory
- SOT: state of technology
- TEA: techno-economic analysis
- TRL: technology readiness level
- WeSys: Waste to Energy System Simulation

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