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Techno-Economic Analysis for the Wet Waste Hydrothermal Liquefaction Pathway

Project WBS 2.1.0.301
(Focusing on Task 1)

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Organic Waste Technology Area

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U.S. DEPARTMENT OF ENERGY BATTELLE

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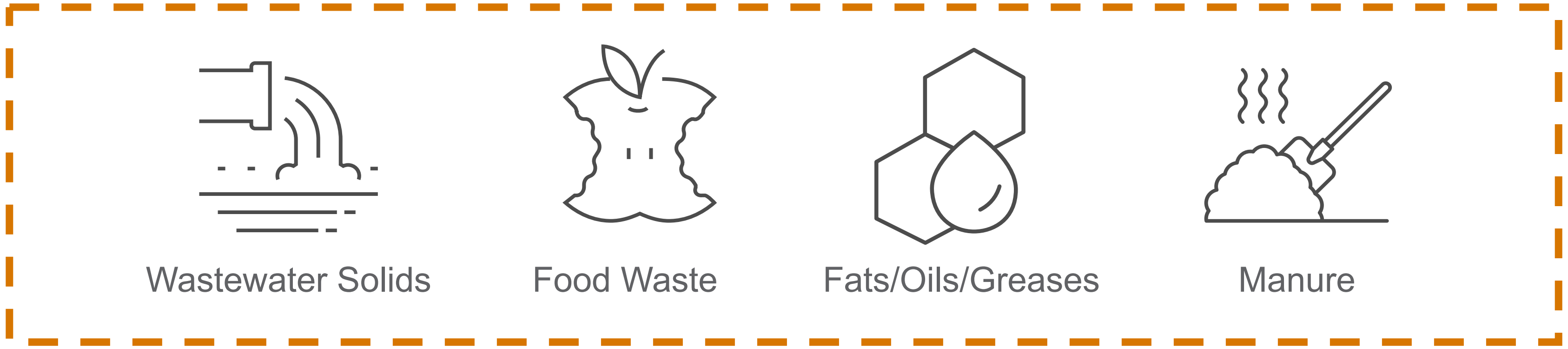
Project Overview

Advancing waste-to-energy through highly integrated analysis and R&D

- **Problem:** ~77 million dry tons of wet waste are generated annually, much of which is landfilled or incinerated, and could be converted to ~5.5 billion gallons of fuel per year (which is ~12% of the 2021 petroleum distillate demand).

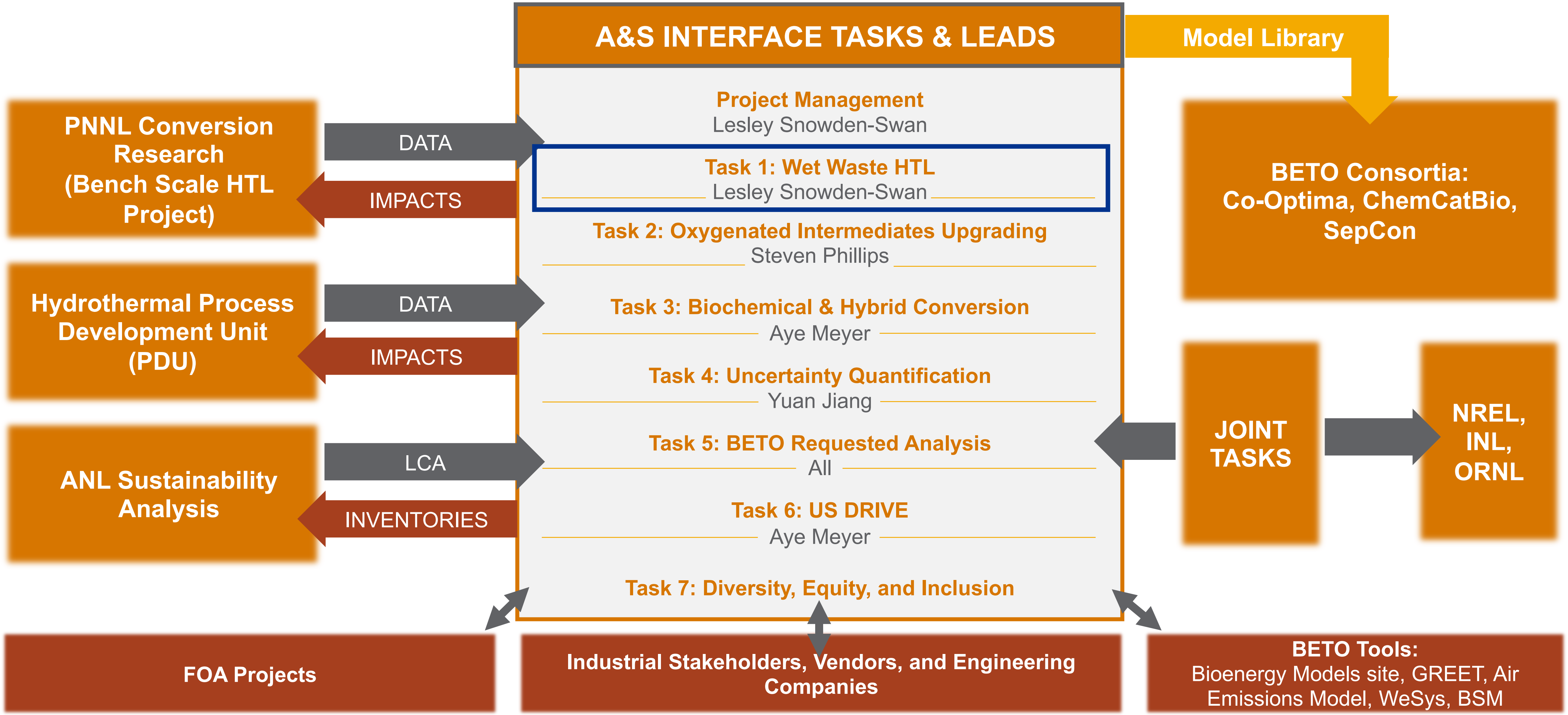


- **Goal:** Advance waste-to-energy through development of data-grounded waste hydrothermal liquefaction (HTL) process models, techno-economic analysis (TEA) and life cycle analysis (LCA) that guides the R&D toward BETO's GHG emissions reduction target of ≥70% (relative to petroleum) and reduced conversion costs.

- **Value:** We have reduced the modeled minimum fuel selling price (MFSP) by $0.67/GGE and reduced modeled GHG emissions to 21 g CO_2-e/MJ (77% lower than petroleum baseline), evaluated initial feasibility of sustainable aviation fuel (SAF) from this pathway, and are developing a business case study to provide added relevance for stakeholders.

GGE=gasoline gallon equivalent

1 – Approach
Communication and collaboration provides synergies with BETO project portfolio and industry stakeholders



Note: This project supports several Conversion areas. Regarding Organic Waste, this talk will focus on Task 1 work. Other tasks are covered in Catalytic Upgrading (2.3.1.304; 2.6.3.500), Biochem (2.1.0.100), and DMA sessions (US DRIVE).

ANL=Argonne National Lab; NREL=National Renewable Energy Lab; LCA=life cycle analysis; FOA=funding opportunity announcement; GREET=Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies model; WeSys=Waste to Energy System Simulation model; BSM=Biomass Scenario Model

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1 – Approach
Risks are mitigated by clear project plan, milestones, and frequent communication with experimental team and industry

➢ Management Controls:

- **Formal project plan** with quarterly milestones and deliverables.
- **Go/No-Go Milestone**:(3/31/24) Develop Case Study for SAF that can meet ≥70% GHG reduction at a competitive price and significantly contribute to BETO's volumetric goals.
- **Quarterly reporting** and briefings (presentations) are provided to BETO.
- Project went through BETO's **Merit Review** process in FY22.

➢ Collaboration provides synergistic approach to waste-to-energy solution:

- **Frequent communication** with PNNL Bench Scale HTL, Waste-to-Energy, and PDU projects (WBS# 1.3.5.202, 2.0.1.113, & 3.4.2.301)
- **Collaborate and exchange data/learnings** with industry (GLWA, Gibby Group, CCCSD)

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] • Industry partners on Business Case (FY23)

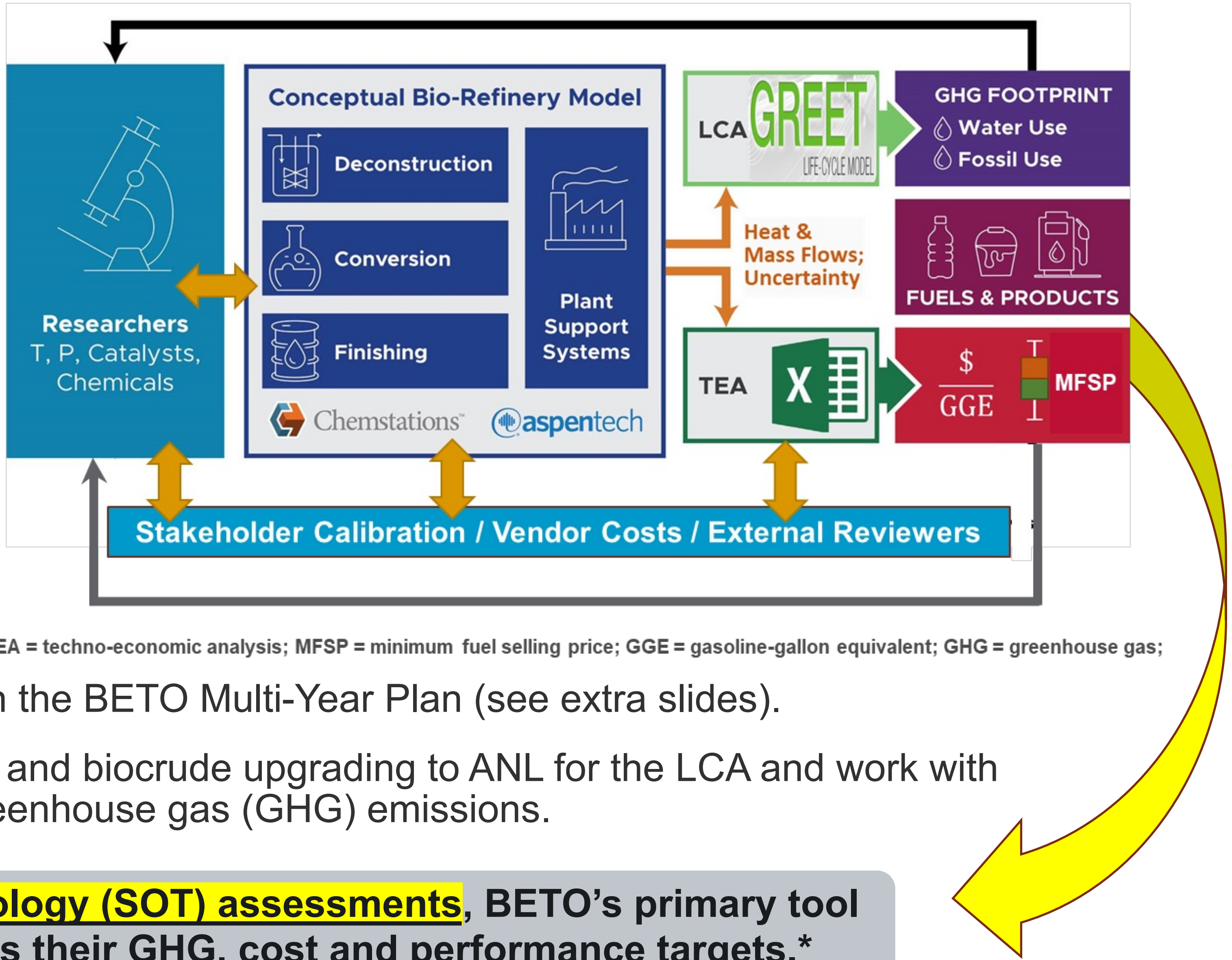
1 BETO's design cases lay out the initial conceptual process configuration and economics of the target case for the pathway.

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

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

➢ Technical Approach

- We work closely with the HTL and biocrude upgrading researchers to **identify, interpret, and transform the critical data** to develop the conceptual process and cost models to simulate commercial-scale plant performance and cost.
- Early in the R&D, we **identify key cost drivers** for the researchers to improve moving forward.
- We **continually feed back results and questions from the analysis** to the engineering/research **team** to better inform and hone the models to **reflect reality as much as possible.**
- We engage with industry (**waste generators, engineering contractors, vendors**) to better understand challenges at scale and improve models.



TEA = techno-economic analysis; MFSP = minimum fuel selling price; GGE = gasoline-gallon equivalent; GHG = greenhouse gas;

- We use a **well-defined basis** for our TEA, as described in the BETO Multi-Year Plan (see extra slides).
- We **provide the life cycle inventory (LCI)** for waste HTL and biocrude upgrading to ANL for the LCA and work with them to identify key drivers and strategies for reducing greenhouse gas (GHG) emissions.

ALL of this feeds into the annual State of Technology (SOT) assessments, BETO's primary tool for advancing and tracking R&D progress towards their GHG, cost and performance targets.

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1 – Approach
Diversity, Equity, and Inclusion (DEI) Plan

➢ **PNNL has a Robust DEI Strategy:**

- **National labs** are **uniquely positioned** to prepare the future diverse **STEM workforce** and build **STEM pathways for students** to **contribute to mission needs**.
- Attracting diverse, qualified talent enables PNNL to achieve the highest levels of **innovation, creativity, and problem solving**.
- PNNL offers a **wide range of paid, flexible internships in STEM** for underrepresented students to pursue rewarding careers at DOE, PNNL, and other Labs.
- In FY 2021, **61% of interns were women and/or from historically underrepresented groups**, a nearly 10% increase from FY 2020.

➢ **Project DEI Task:**

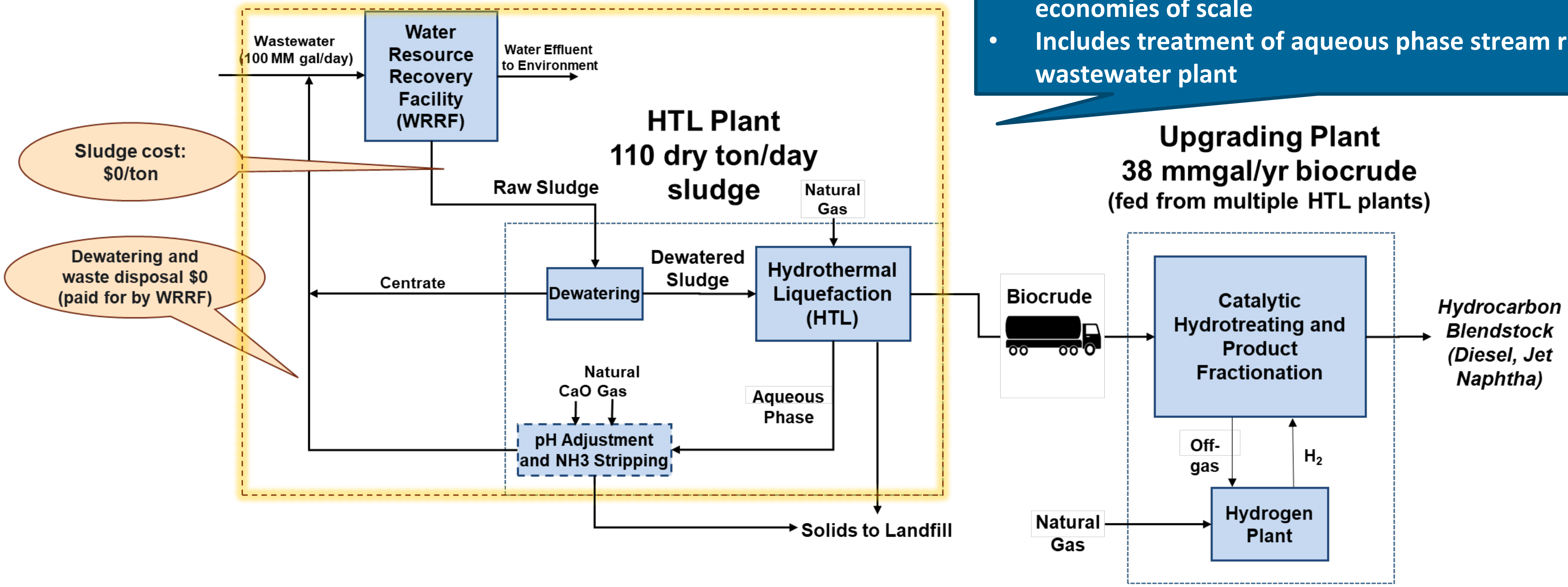
- We will contribute to the enhancement of DEI in the workforce by hiring a student intern from groups underrepresented in STEM and/or disadvantaged communities.

➢ **DEI Milestone:**

- **Milestone (3/31/24):** Hire at least one **student intern from groups underrepresented in STEM** and/or disadvantaged communities.

2 – Progress and Accomplishments
Process model for waste-to-biofuel (original system boundary)

- Focused on wastewater sludge but works for other wet wastes
- Decoupled upgrading plant reduces capital cost through economies of scale
- Includes treatment of aqueous phase stream recycle to wastewater plant



- Original assumption was that the HTL plant would be owned by the WRRF/municipality and therefore:
  - Feedstock assumed to be available at no cost ($0/dry ton)
  - Disposal costs for HTL aqueous phase and solids assumed to be paid for by the municipality (not included)
  - Dewatering cost was excluded, as it is already part of the WRRF's operations
- After years of experience working with the industry, we now know that the HTL project will almost certainly be taken on by a separate owner/operator, given the nature of the operations.

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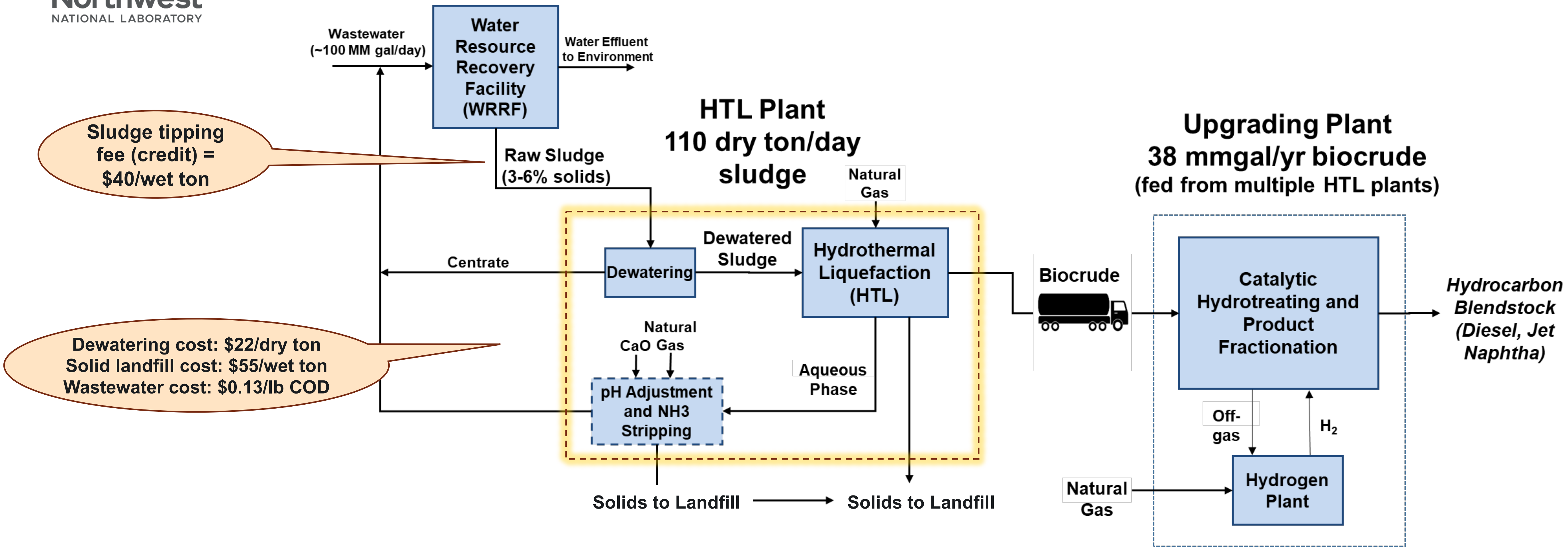
2 – Progress and Accomplishments

FY21: New system boundary (separate HTL owner/operator)

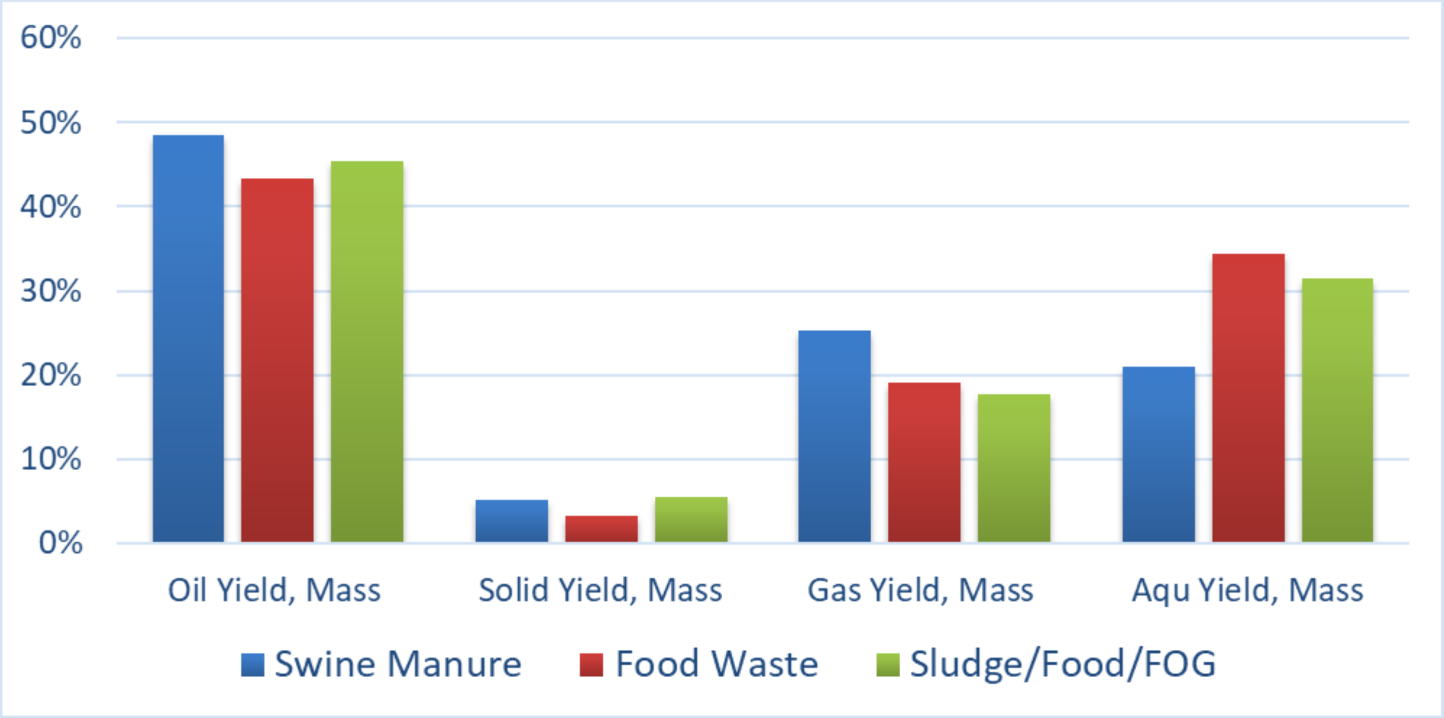


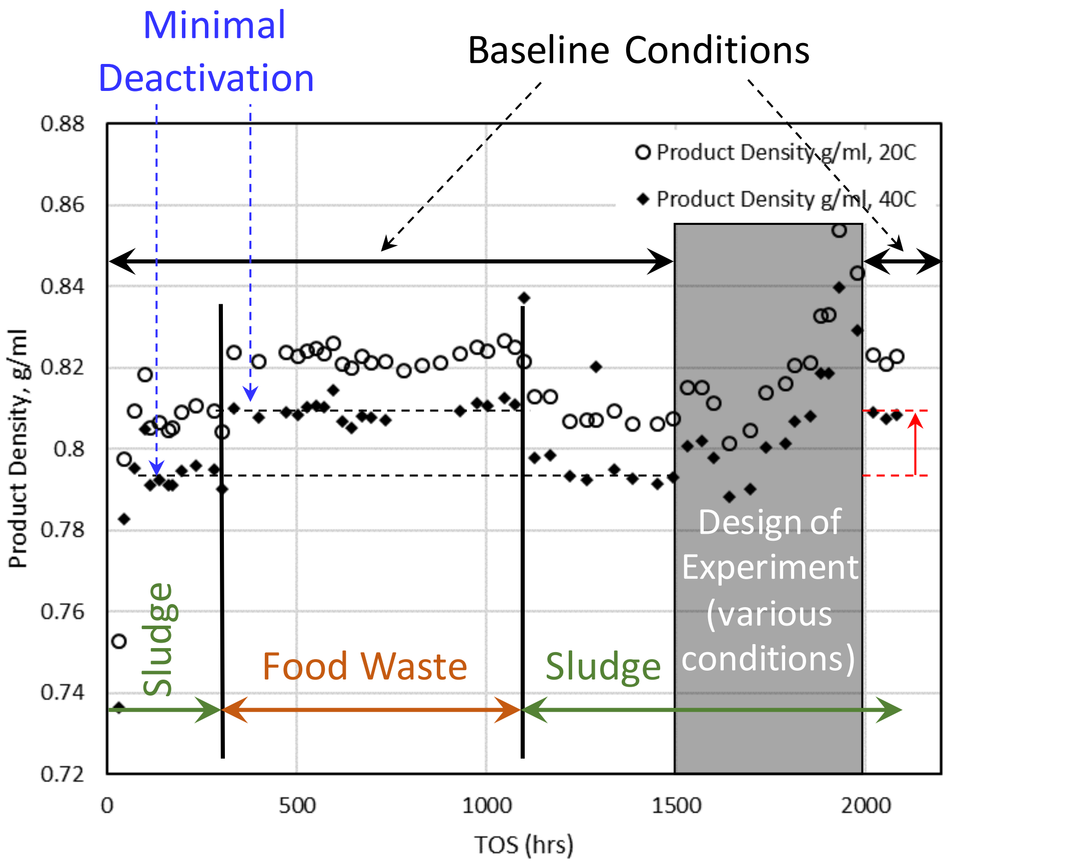
- Sludge is pumped down the street and **HTL plant pays to dewater to 25%** (polymer and electricity)
- **Waste disposal costs included:** Solids are landfilled ($51/ton) and HTL aqueous phase is discharged ($0.13/lb excess COD and $0.56/lb excess ammonia fees)
- **WRRF pays HTL plant owner ("tipping fee")** to take their sludge waste (credit of $40/wet ton[1]; $171/dry ton, 2016$)
- **System boundaries are more realistic** and cleaner for investigating impacts of aqueous and solids treatment

1 Badgett, Newes, and Milbrandt. 2019. "Economic analysis of wet waste-to-energy resources in the United States." *Energy,* and personal communication w/ A. Badgett.

2 – Progress and Accomplishments
FY21: Testing of higher feed solids and longer time-on-stream for hydrotreater catalyst

Experimental Team Successfully ran 25% solids feed for 3 feeds





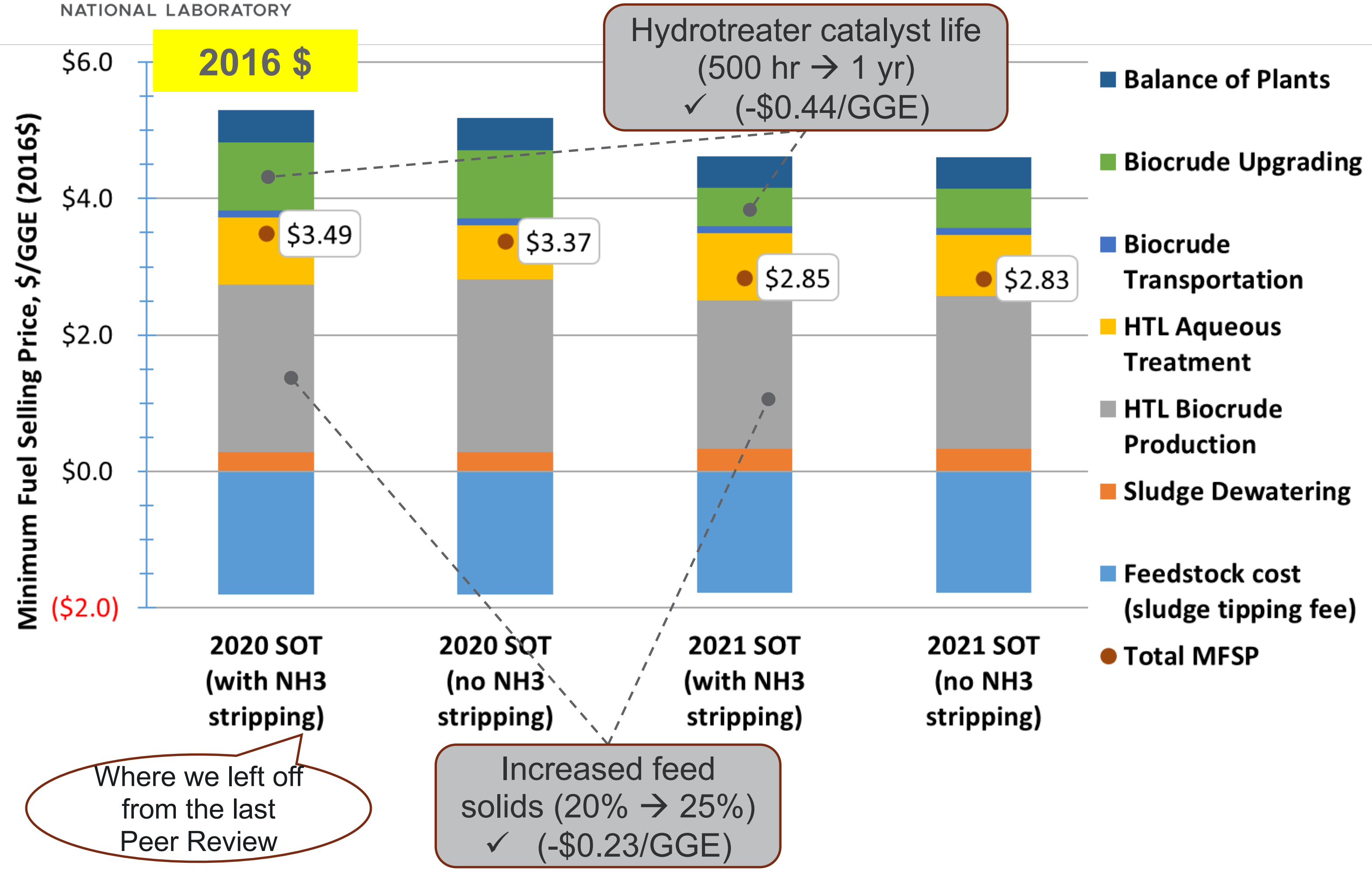
Experimental Team's 2000+ Hour Hydrotreating Run[1]

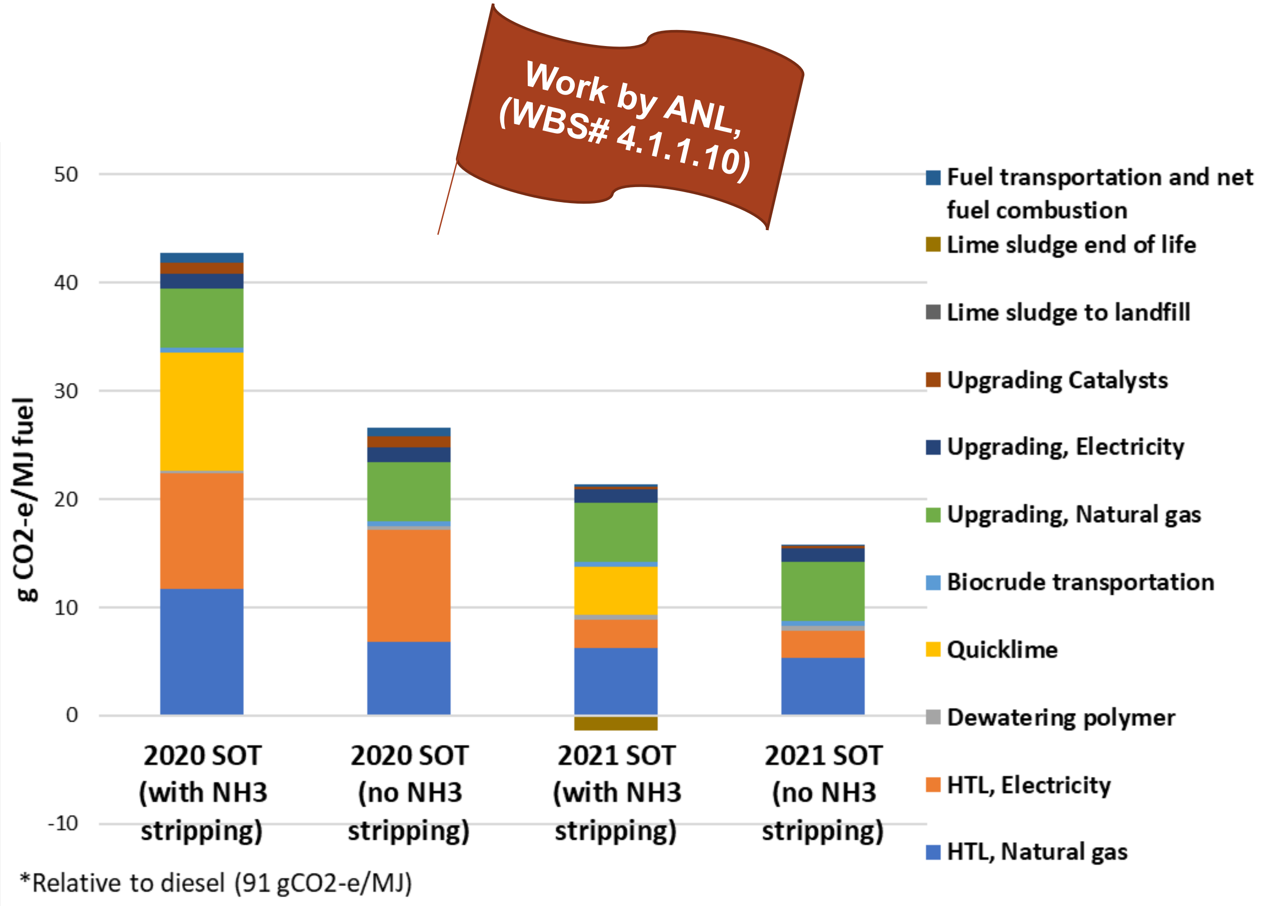
- Maximizing HTL feed solids and hydrotreater catalyst life were previously identified as key cost drivers:
  - Increased feed solids reduces capital and operating costs and GHGs for HTL plant.
  - Hydrotreater catalyst ran for 2000+ hours time-on-stream (TOS), giving us confidence to assume a 1-year lifetime, resulting in ~18% lower operating cost for the upgrading plant.

1 Subramaniam et al. 2021. *ACS Sustainable Chemistry & Engineering* 9, no. 38:12825-12832. doi:10.1021/acssuschemeng.1c02743

2 – Progress and Accomplishments

FY21: HTL Pathway SOT (new system boundary)



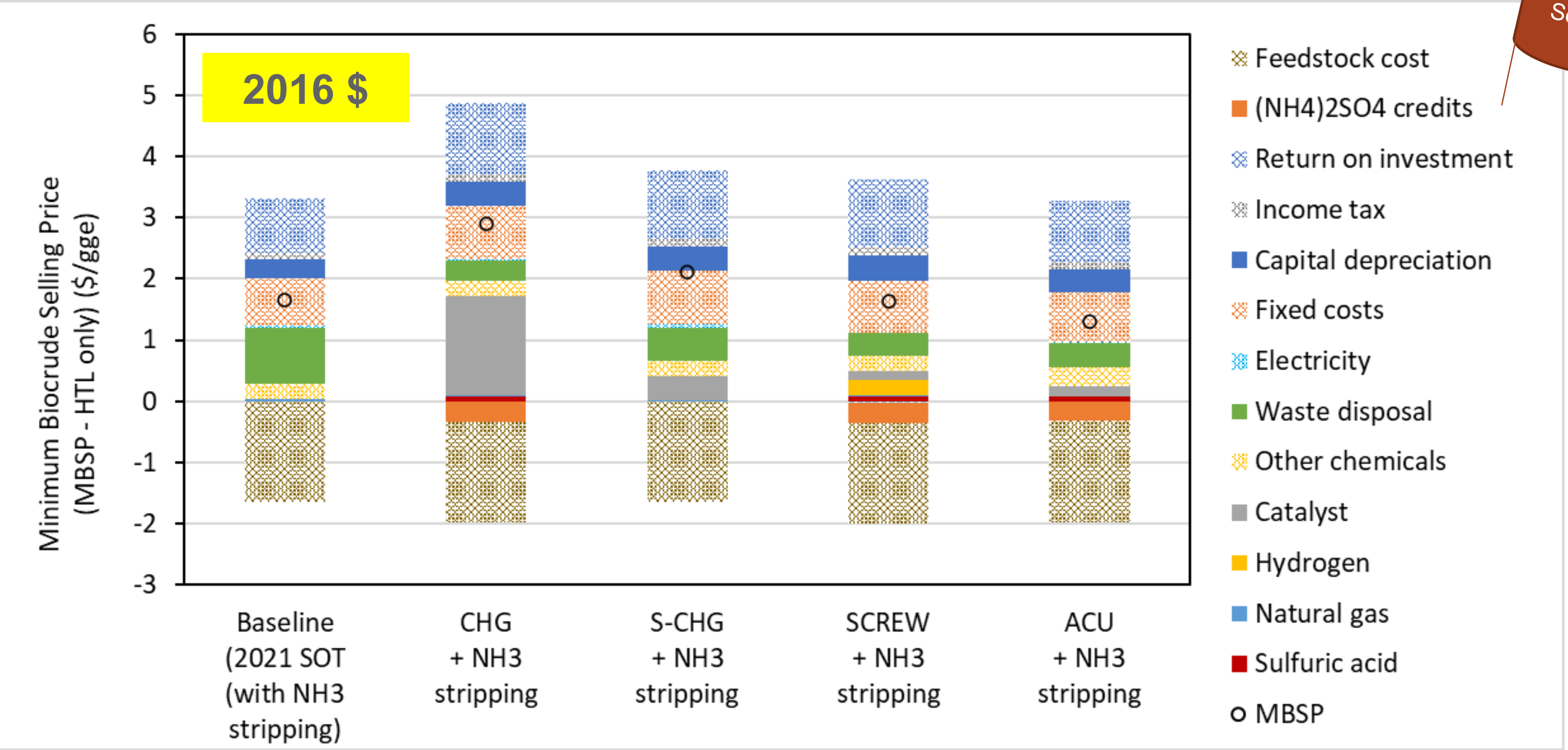


- Improvements in modeled 2021 SOT performance resulted in **reduced MFSP (**$0.67/GGE) and **reduced GHG emissions**
- New insight gained from better definition of system boundary: minimal cost difference between treating the aqueous onsite ("with NH3 stripping" case) or paying to discharge raw aqueous back to the WRRF ("no NH3 stripping" case) when you include nutrient fees

2 – Progress and Accomplishments

FY21/22: Integrated TEA/LCA of HTL aqueous phase treatment options

Using Data from Hydrothermal PDU (3.4.2.301) and SoCalGas CRADA



	CHG	S-tolerant CHG	SCREW	ACU
Catalyst	Ru/C	*	NiMo/C	ZnZr Oxide
Catalyst life (year)	0.25	1	1	1
Regeneration / guard bed	Acetone wash, H_2 reduction	Acid wash	Guard bed (C)	Guard bed (C)
Temperature (°C)	350	350	400	400
Pressure (bar)	211	211	36	1
LHSV (h^{-1})	0.54	0.54	0.5	0.27
COD reduction (%)	99	65	97.7	92

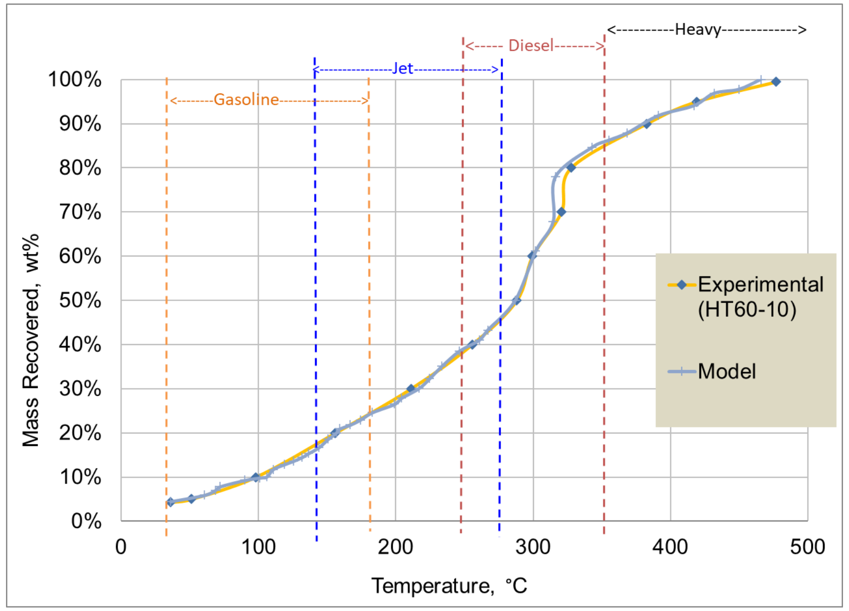
CHG = Catalytic Hydrothermal Gasification; ACU = Aqueous-phase Catalytic Upgrading;
SCREW = Steam-phase Catalytic Reduction of Wastewater

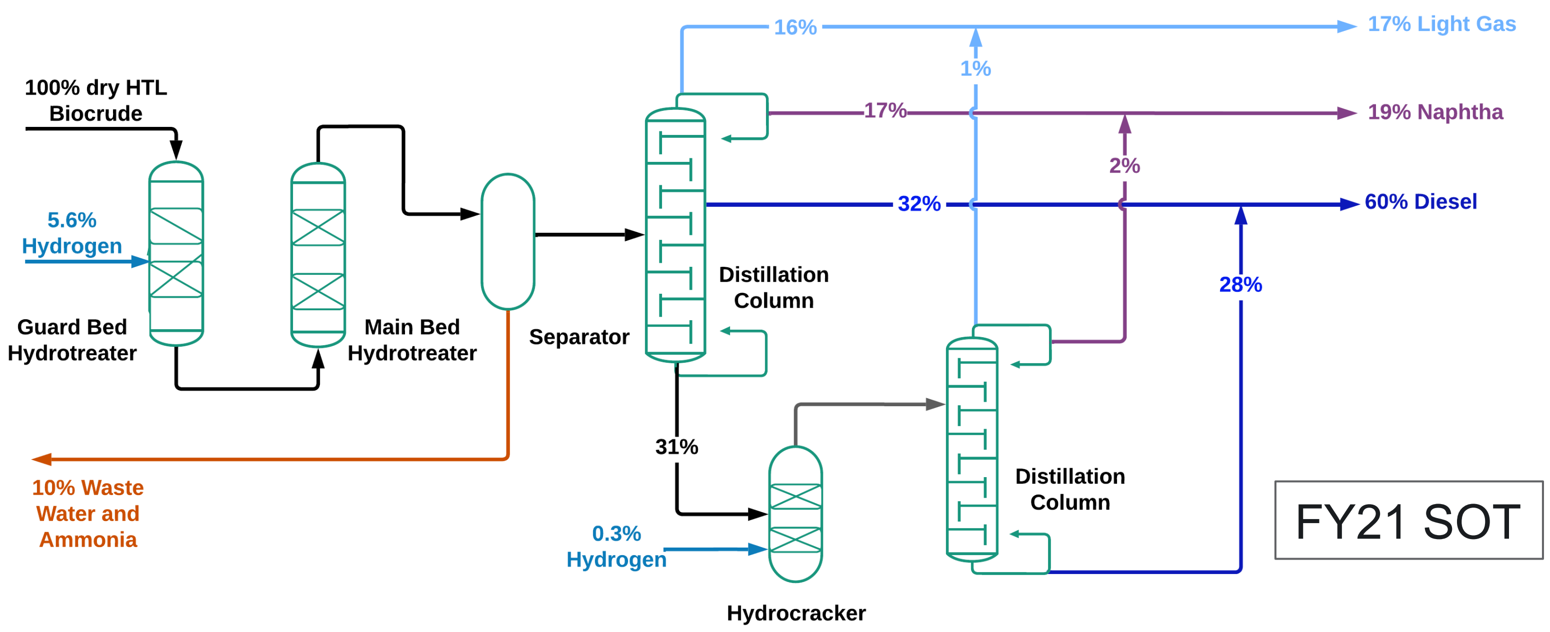
* Confidential – SoCalGas PNNL CRADA Protected Information

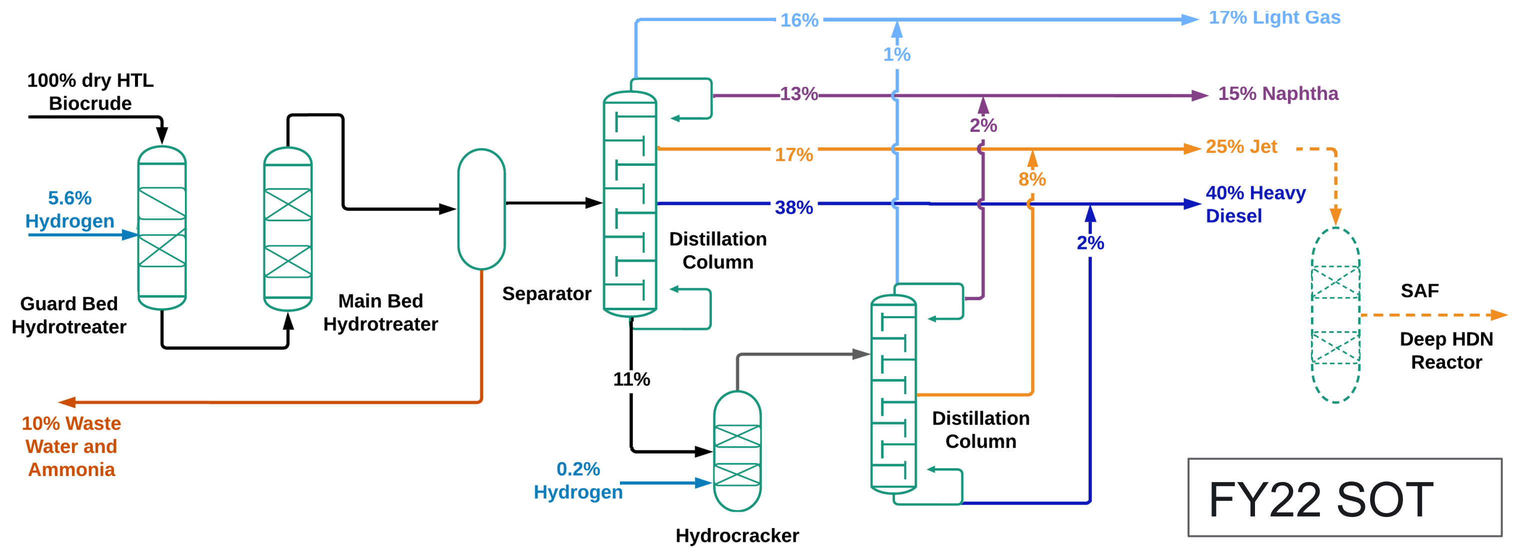
- Important because COD load in aqueous phase could be problematic for a WRRF.
- All options reduce wastewater disposal cost (green bars) relative to the SOT.
- The cost of CHG is reduced by using a sulfur-tolerant catalyst to improve catalyst life.
- The SCREW pathway cost is equal to the SOT baseline, where savings in wastewater disposal cost and by-product credits offsets the cost of H_2 and additional capex.
- The ACU pathway is promising as it can achieve high COD reduction (enabling $(NH_4)_2SO_4$ production) with low pressure, cheaper catalyst.
- LCA is being added to the analysis (by ANL's GREET team).

2 – Progress and Accomplishments
FY22: Initial assessment of sustainable aviation fuel (SAF)

- With BETO's recent focus on "hard-to-electrify" fuels, we took a first look at the feasibility of SAF
- Tier α and Tier β testing of sludge-derived jet cut performed by University of Dayton[1] shows positive fuel props (see extra slides and next talk)
- Deep hydrodenitrogenation (HDN) was also performed on the jet cut to further reduce N
- Model was updated to match simulated distillation of hydrotreated biocrude product and include a final "deep HDN" step.







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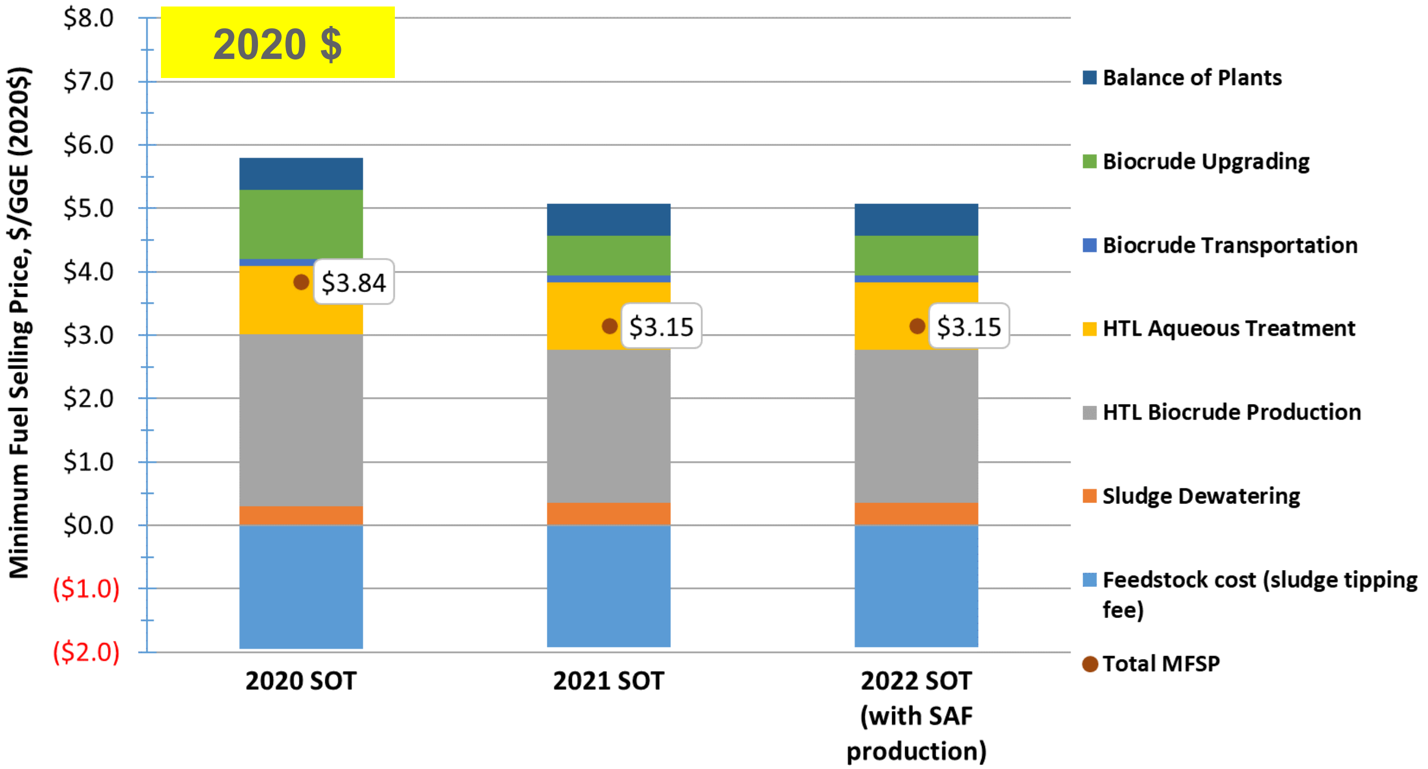
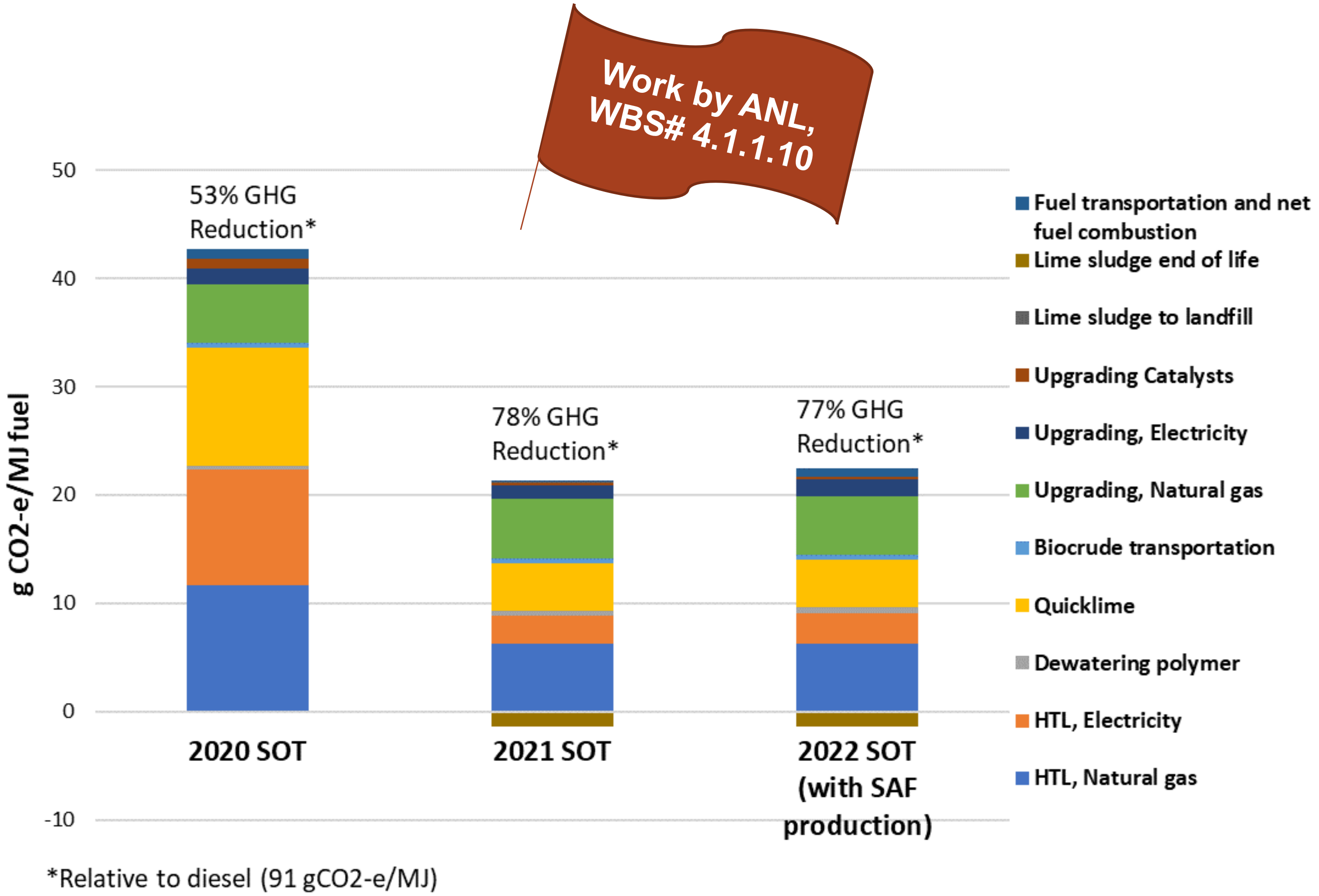
2 – Progress and Accomplishments

FY22 SOT: Initial assessment of SAF from HTL





- Initial evaluation shows it is **possible to produce SAF** with **77% reduced GHGs** and **no impact to MFSP**
- **More work is needed to validate the feasibility of SAF from this pathway** (PNNL work in progress, via "Denitrogenation of wet waste-derived biocrude to meet SAF specifications " WBS 2.3.3.301)
- Moving forward, we are **pivoting toward further decarbonization** (via the use of renewable power, heat, and H_2 and recovery of waste streams) while enabling reasonably priced process for renewable fuel

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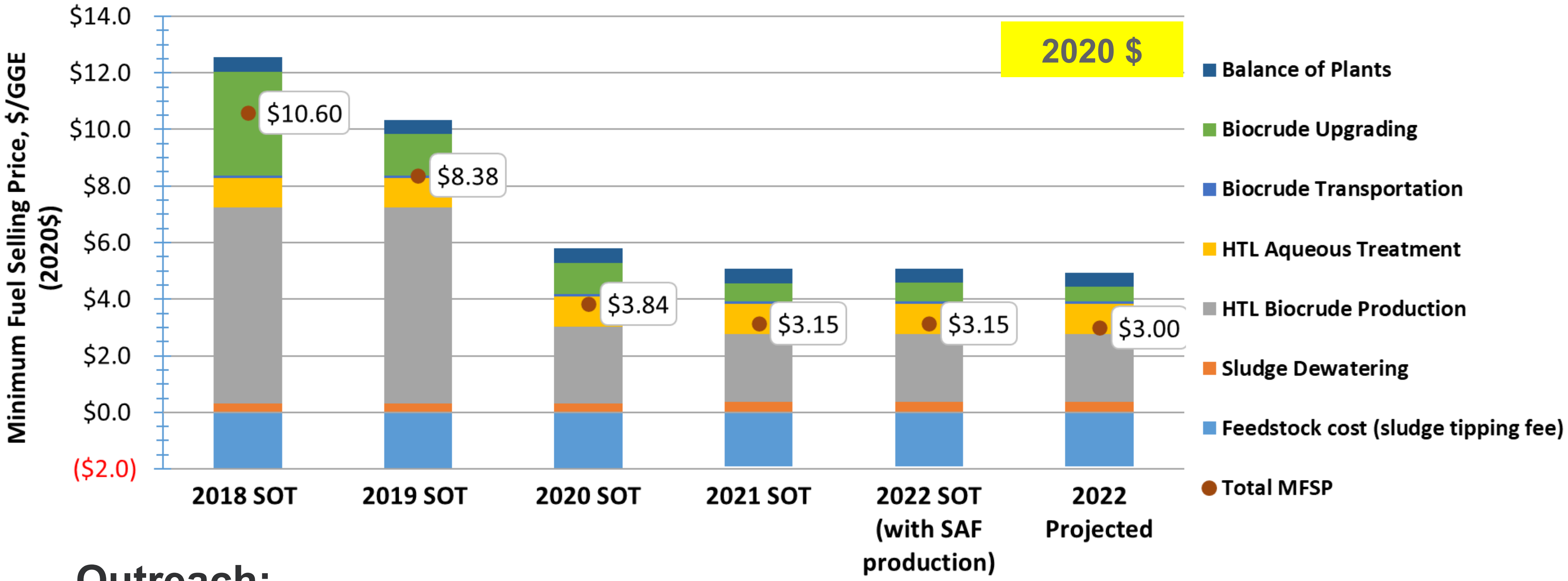
3 – Impact
Combined R&D/analysis has driven down modeled costs



Outreach:

- ➢ Published FY 2021 and FY 2022 **SOT reports** which **document technical progress** toward cost goals; published 5 related articles based on our modeling (with 3 more submitted)
- ➢ Contributed to BETO's **Multi-Year Program pathway update** ("R&D State of Technology" report)

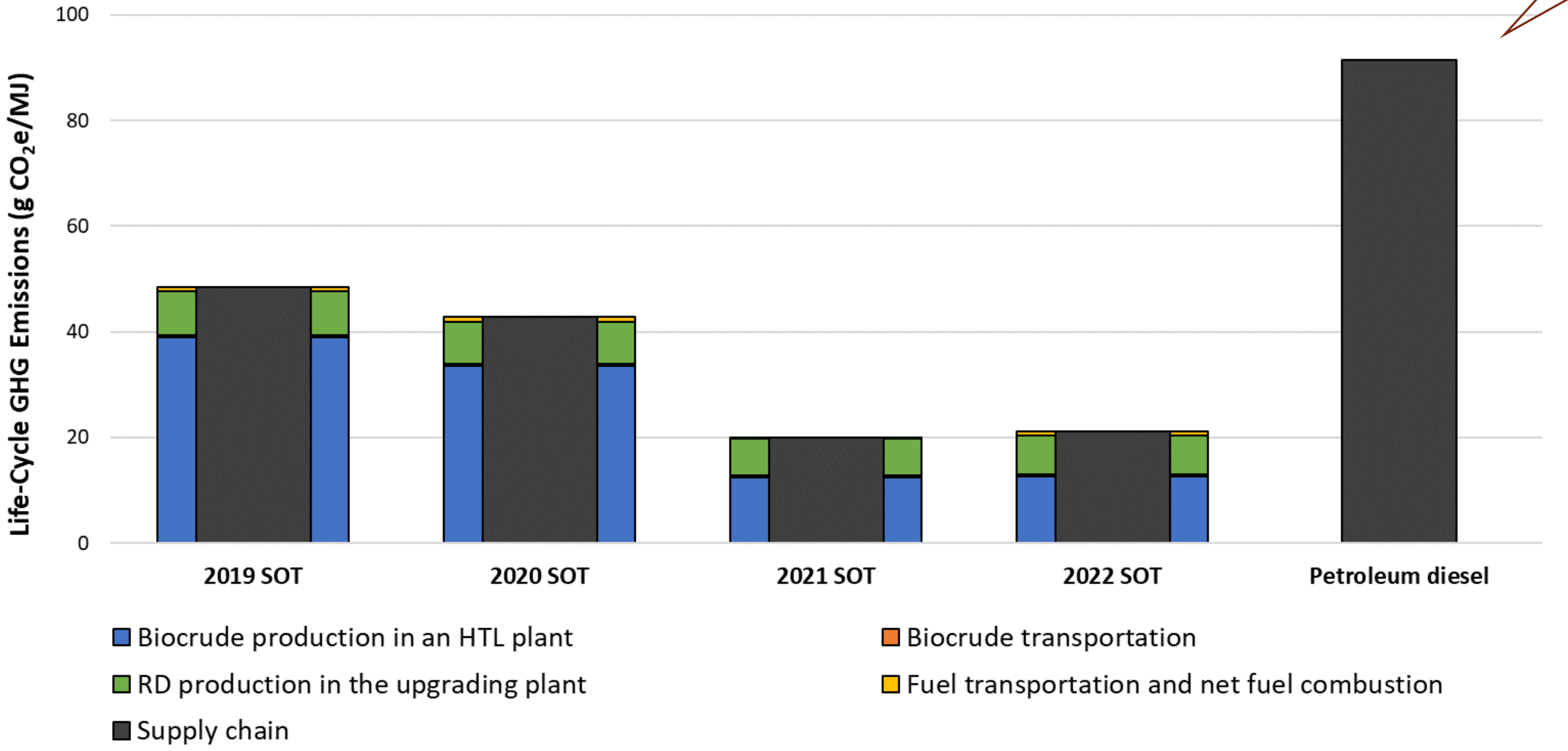
***The annual SOT assessment is BETO's primary tool with which the experimental and analysis teams work side-by-side to define the target-enabling research and to drive progress towards that target.**

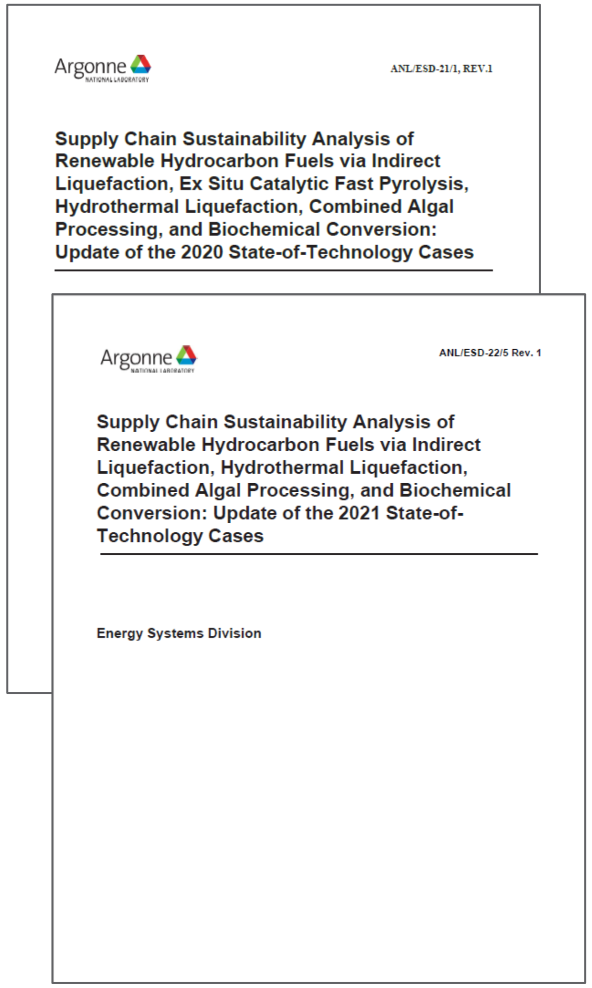
3 – Impact

Combined R&D/analysis has driven down modeled carbon intensity

- This work supplies life cycle inventory (LCI) to ANL's GREET analysis team to estimate GHG emissions relative to **BETO's target of ≥70% reductions**
- This work contributed to FY 2020 and 2021 **Supply Chain Sustainability Analysis** (SCSA) reports (collaboration between ANL, INL, NREL, PNNL)

*Work by Hao Cai, Longwen Ou (ANL) (4.1.1.10 DMA Session)



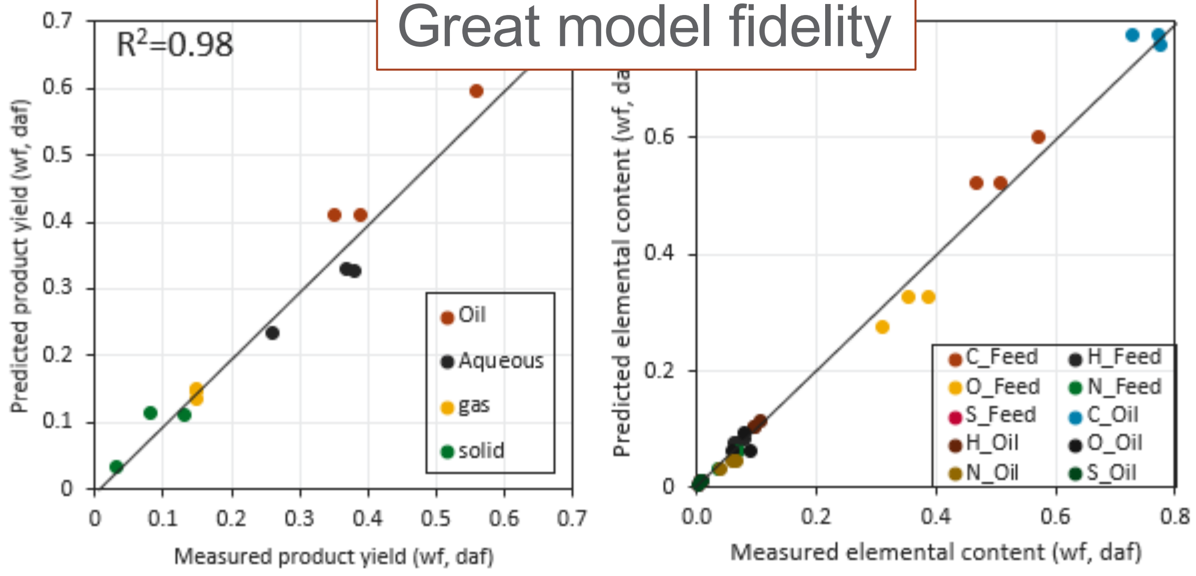


3 – Impact

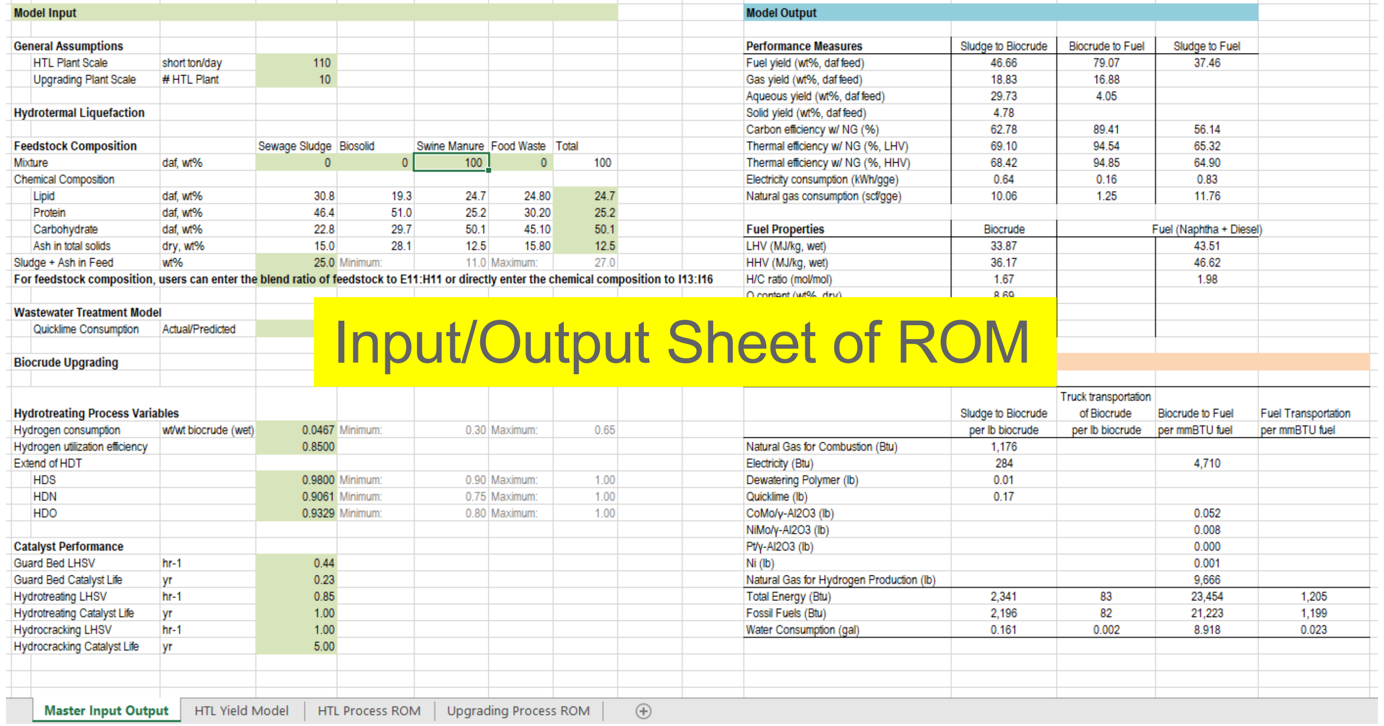
Releasing publicly available tool for predicting HTL yields and GHG performance

- ➢ Building on prior work[1,2], we have produced **one of the only** and by far most comprehensive **reduced-order model (ROM)** for predicting continuous system HTL yield based on **29 data sets** from PNNL and validated the model with 3 additional data sets
- ➢ This is important because the ROM provides a **simple but accurate tool** for estimating HTL performance and a **highly efficient method** for integrated TEA/LCA **uncertainty quantification**
- ➢ The ROM was also built out to **include biocrude upgrading, LCI and environmental results** using the GREET model
- ➢ The **ROM will be published** with the new manuscript (in review) and will **assist stakeholders** with generating **process metrics** needed for economic assessments and **LCI** for conducting LCA

Great model fidelity



Input/Output Sheet of ROM



Model Input						
General Assumptions						
HTL Plant Scale	short ton/day	110				
Upgrading Plant Scale	# HTL Plant	10				
Hydrotermal Liquefaction						
Feedstock Composition		Sewage Sludge	Biosolid	Swine Manure	Food Waste	Total
Mixture	daf, wt%	0	0	100	0	100
Chemical Composition						
Lipid	daf, wt%	30.8	19.3	24.7	24.80	24.7
Protein	daf, wt%	46.4	51.0	25.2	30.20	25.2
Carbohydrate	daf, wt%	22.8	29.7	50.1	45.10	50.1
Ash in total solids	dry, wt%	15.0	28.1	12.5	15.80	12.5
Sludge + Ash in Feed	wt%	25.0	Minimum:	11.0	Maximum:	27.0
For feedstock composition, users can enter the blend ratio of feedstock to E11:H11 or directly enter the chemical composition to I13:I16						
Wastewater Treatment Model						
Quicklime Consumption	Actual/Predicted					
Biocrude Upgrading						
Hydrotreating Process Variables						
Hydrogen consumption	wt/wt biocrude (wet)	0.0467	Minimum:	0.30	Maximum:	0.65
Hydrogen utilization efficiency		0.8500				
Extend of HDT						
HDS		0.9800	Minimum:	0.90	Maximum:	1.00
HDN		0.9061	Minimum:	0.75	Maximum:	1.00
HDO		0.9329	Minimum:	0.80	Maximum:	1.00
Catalyst Performance						
Guard Bed LHSV	hr-1	0.44				
Guard Bed Catalyst Life	yr	0.23				
Hydrotreating LHSV	hr-1	0.85				
Hydrotreating Catalyst Life	yr	1.00				
Hydrocracking LHSV	hr-1	1.00				
Hydrocracking Catalyst Life	yr	5.00				

Model Output			
Performance Measures	Sludge to Biocrude	Biocrude to Fuel	Sludge to Fuel
Fuel yield (wt%, daf feed)	46.66	79.07	37.46
Gas yield (wt%, daf feed)	18.83	16.88	
Aqueous yield (wt%, daf feed)	29.73	4.05	
Solid yield (wt%, daf feed)	4.78		
Carbon efficiency w/ NG (%)	62.78	89.41	56.14
Thermal efficiency w/ NG (%, LHV)	69.10	94.54	65.32
Thermal efficiency w/ NG (%, HHV)	68.42	94.85	64.90
Electricity consumption (kWh/gge)	0.64	0.16	0.83
Natural gas consumption (scf/gge)	10.06	1.25	11.76
Fuel Properties	Biocrude		Fuel (Naphtha + Diesel)
LHV (MJ/kg, wet)	33.87		43.51
HHV (MJ/kg, wet)	36.17		46.62
H/C ratio (mol/mol)	1.67		1.98
O content (wt%, dry)	8.69		

	Sludge to Biocrude per lb biocrude	Truck transportation of Biocrude per lb biocrude	Biocrude to Fuel per mmBTU fuel	Fuel Transportation per mmBTU fuel
Natural Gas for Combustion (Btu)	1,176			
Electricity (Btu)	284		4,710	
Dewatering Polymer (lb)	0.01			
Quicklime (lb)	0.17			
CoMo/γ-Al2O3 (lb)			0.052	
NiMo/γ-Al2O3 (lb)			0.008	
Pt/γ-Al2O3 (lb)			0.000	
Ni (lb)			0.001	
Natural Gas for Hydrogen Production (lb)			9,666	
Total Energy (Btu)	2,341	83	23,454	1,205
Fossil Fuels (Btu)	2,196	82	21,223	1,199
Water Consumption (gal)	0.161	0.002	8.918	0.023

Master Input Output | HTL Yield Model | HTL Process ROM | Upgrading Process ROM

1 Jiang et al., 2019. "Techno-Economic Uncertainty Quantification of Algal-derived Biocrude via Hydrothermal Liquefaction." Algal Research 39: 101450
2 Li et al. 2022. "Techno-Economic Uncertainty Analysis of Wet Waste-to-Biocrude via Hydrothermal Liquefaction." Applied Energy 283.

3 – Impact
Working with and informing stakeholders/partners

- Modeling/analysis is leveraged for many other BETO projects:
  - Marine Fuels Analysis (multi-Lab)
  - Algae HTL Modeling (PNNL)
  - Co-Optima (multi-Lab)
  - Aloviam pilot project (PNNL)
  - Biofuels Air Emissions Analysis (NREL)
  - Waste-to-Energy (NREL and PNNL)
  - Bioeconomy Scenario Model (NREL)

- Modeling/analysis also leveraged for industry and university collaborations:
  - US DRIVE to maximize decarbonization of HTL pathways with renewables. Regular engagement with industrial advisory board consisting of numerous auto and energy companies (multi-Lab and industry) interested net-zero carbon fuels
  - FOA project with Princeton/UIUC/PNNL to develop treatment/recovery system for aqueous phase (T-MEC process, presented later in the session)
  - FOA project (new) with Great Lakes Water Authority (Detroit) to assess community impacts of an HTL plant
  - Provided HTL costing and guidance for WPI’s undergraduate student project

Summary

- **Overview:** Evaluated viability of waste-to-energy through integrated analysis/R&D
- **Approach:**
  - ✓ **Technical:** Coupled modeling, analysis and experimental R&D targeting GHG and cost goals
  - ✓ **Management:** Project plan addresses risks and includes clear milestones to meet the HTL team's objectives
  - ✓ **DEI:** Hire student intern from groups underrepresented in STEM
- **Progress and Outcomes:** Guided impactful research that reduced modeled costs and GHGs to 81% lower than petroleum fuels
- **Impact:** Driven design toward BETO's ≥70% GHG emissions reduction goal, driven modeled MFSP down, and shown initial feasibility of wet waste to SAF from this pathway
- **Future work:** FY23 Design/Business Case for Added Value to Stakeholders
  - ✓ Written for a broader audience than SOT reports
  - ✓ Site-specific w/ industry partners
  - ✓ Site analysis of waste resource, infrastructure
  - ✓ First of a kind plant costs
  - ✓ Credits/incentives (RFS, LCFS, BTC)
  - ✓ Sustainability analysis (joint w ANL)
  - ✓ Results presented as a range of values (sensitivity/uncertainty analysis)
  - ✓ Technology maturity level (TRL)

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Quad Chart Overview

Timeline
- Project start date: October 1, 2022
- Project end date: September 30, 2025

	FY22 Costed	Total Award
DOE Funding	10/01/2021 –9/30/2022 $600,000 (Project) $270,000 (HTL Task)	10/01/2022 – 9/30/2025 $ 1,800,000(Project) $ ~470,000 (WTE Task)

Project Cost Share
N/A

TRL at Project Start: 7
TRL at Project End: 5

Project Goal
FY20-22: Provide TEA and LCA in support of accelerating EERE and BETO thermochemical and biochemical conversion research, focused on assessing the state of research technology (SOT) and the potential for cost reductions and sustainability impacts.

FY23-25: Bridge gap between traditional SOTs and the needs of key external stakeholders by developing design Case Studies with relevant business case components.

End of Project Milestone
Complete Design Case Study for SAF via an oxygenated intermediate (e.g., ethanol, methanol, 2,3-BDO) specific to a relevant site/region's feedstock availability and other critical factors such as access to infrastructure, utilities, and petroleum refining (for co-processing of intermediates). Includes range of values for profitability metrics, GHGs and other sustainability metrics that shows the potential of the pathway to meet 70% GHG reduction at a competitive price (e.g., $2.5/GGE with credits/incentives) and significantly contribute to volumetric fuel goals.

Funding Mechanism: Lab Call

Project Partners
ANL: Life cycle analysis
INL: Feedstocks
NREL: Techno-economics & waste resource analysis
PNNL: Experimentalists & waste resource analysis

Acknowledgements

- Andrea Bailey, BETO Technology Manager
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Argonne National Lab (GHG Analysis)
- Longwen Ou
- Hao Cai
- Uisung Lee
- Troy Hawkins

PNNL Experimental Team
- Mike Thorson
- Andy Schmidt
- Todd Hart
- Miki Santosa
- Uriah Kilgore
- Sam Fox

PNNL Wet Waste HTL Analysis
- Shuyun Li
- Yuan Jiang
- Aye Meyer
- Yunhua Zhu
- Ben Spry

PNNL Waste Resource Team
- Tim Seiple
- Andre Coleman

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Additional Slides

Responses to Previous Reviewers' Comments

Feedback: The HTL aqueous waste stream is included in the TEA/LCA, but it seems to be in early stages and the assumptions made regarding treatment needs were not clear. This is a very important part of the scale up and delivery of the technology and I encourage the team and BETO to focus on this area.

- **Response:** The baseline assumption is that the HTL aqueous phase is treated by ammonia stripping and then recycled back to the WRRF. Indeed, effective treatment of the aqueous phase is critical to the successful scale up of the HTL technology and we continue to work on testing of industrially available and novel treatment/valorization methods in our Process Development Unit (PDU) project to drive towards the most economical and environmentally beneficial solution. Update: we have carried out TEA of 4 technical options for aqueous phase treatment in the current analysis.

Feedback: Material costs have dramatically escalated in 2020, is the sensitivity to this capture in the analysis in any way?

- **Response:** The analysis was updated to 2020 dollars for the 2022 SOT assessment and reflects higher capital and operating costs. (Chemical prices increased by 8%, labor increased by 15%, equipment cost increased by 10%).

Feedback: Although feedstock price variation is now explored in the sensitivity analysis, the continued use of zero feedstock cost as the base case still appears unrealistic. A more representative cost should be determined and used for the base case and then sensitivity performed on that.

- **Response:** The zero-feedstock cost assumed for the base case is considered to be conservative given that it is likely there will be some sort of "tipping fee" that a WRRF would pay an HTL plant owner/operator. However, we are modeling a future time where it is entirely possible that waste for renewables production could become a commodity due to increased demand (e.g., recent shift in FOG demand for HEFA production). Update: We have incorporated waste tipping fee into our base case analysis.

Publications, Presentations, and Patents (since FY21 Review)

- Li S., Y. Jiang, L.J. Snowden-Swan, J.A. Askander, A.J. Schmidt, and J.M. Billing. 2021. "Techno-Economic Uncertainty Analysis of Wet Waste-to-Biocrude via Hydrothermal Liquefaction." Applied Energy 283. PNNL-SA-156267. doi:10.1016/j.apenergy.2020.116340
- Snowden-Swan L.J., J.M. Billing, M.R. Thorson, A.J. Schmidt, Y. Jiang, D.M. Santosa, and T.E. Seiple, et al. 2021. Wet Waste Hydrothermal Liquefaction and Biocrude Upgrading to Hydrocarbon Fuels: 2020 State of Technology. PNNL-30982. Richland, WA: Pacific Northwest National Laboratory.
- Snowden-Swan L.J., S. Li, M.R. Thorson, A.J. Schmidt, D.J. Cronin, Y. Zhu, and T.R. Hart, et al. 2022. Wet Waste Hydrothermal Liquefaction and Biocrude Upgrading to Hydrocarbon Fuels: 2022 State of Technology. PNNL-33622. Richland, WA: Pacific Northwest National Laboratory. Wet Waste Hydrothermal Liquefaction and Biocrude Upgrading to Hydrocarbon Fuels: 2022 State of Technology
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- Li S., E. Tan, A. Dutta, L.J. Snowden-Swan, M.R. Thorson, K. Kallupalayam Ramasamy, and A. Bartling, et al. 2022. "Techno-economic Analysis of Sustainable Biofuels for Marine Transportation." Environment Science and Technology 56, no. 23:17206-17214. PNNL-SA-173450. doi:10.1021/acs.est.2c03960
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- Ou L., S. Li, L. Tao, S.D. Phillips, T.R. Hawkins, A. Singh, and L.J. Snowden-Swan, et al. 2022. "Techno-economic Analysis and Life-Cycle Analysis of Renewable Diesel Fuels Produced with Waste Feedstocks." ACS Sustainable Chemistry & Engineering 10, no. 1:382-393. PNNL-SA-164877. doi:10.1021/acssuschemeng.1c06561
- Bartling A., P.T. Benavides, S.D. Phillips, T.R. Hawkins, A. Singh, M. Wiatrowski, and E. Tan, et al. 2022. "Environmental, Economic, and Scalability Considerations of Selected Bio-Derived Blendstocks for Mixing-Controlled Compression Ignition Engines." ACS Sustainable Chemistry & Engineering 10, no. 20:6699-6712. PNNL-SA-170232. doi:10.1021/acssuschemeng.2c00781
- “Bioenergy Technologies Office 2020 R&D State of Technology.” 2022. https://www.energy.gov/eere/bioenergy/articles/beto-2020-rd-state-technology
- Tan E., T.R. Hawkins, U. Lee, L. Tao, P.A. Meyer, M.Q. Wang, and T. Thompson. 2021. "Biofuel Options for Marine Applications: Technoeconomic and Life-Cycle Analyses." Environmental Science & Technology 55, no. 11:7561-7570. PNNL-SA-152627. doi:10.1021/acs.est.0c06141
- Phillips S.D., S.B. Jones, P.A. Meyer, and L.J. Snowden-Swan. 2022. "Techno-economic Analysis of Cellulosic Ethanol Conversion to Fuel and Chemicals." Biofuels, Bioproducts & Biorefining 16, no. 3:640-652. PNNL-SA-165430. doi:10.1002/bbb.2346
- Cai, H., et al. 2021. “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 2020 State-of-Technology Cases.” https://www.osti.gov/biblio/1807565

Publications, Presentations, and Patents (continued)

- Cai, H., et al. 2022. “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 2021 State-of-Technology Cases.” https://www.osti.gov/biblio/1862925
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- Meyer P.A., L.J. Snowden-Swan, U. Lee, and E. Yoo. 04/19/2022."Decarbonization of Hydrothermal Liquefaction of Wet Waste to Transportation Fuels and Its Techno-Economic Analysis and Life Cycle Analysis." TC Biomass Conference. Denver, Colorado.
- Pierobon F., Y. Jiang, P.A. Meyer, and L.J. Snowden-Swan. 11/08/2022. "Life Cycle Assessment Research at Pacific Northwest National Laboratory: System Analysis Team." Online Conference, United States.
- Pomraning K.R., Z. Dai, S. Deng, N. Munoz Munoz, Y. Kim, B.A. Hofstad, and Y. Gao, et al. 08/10/2022. "Bioconversion of lignocellulosic feedstocks to 3-hydroxypropionic acid using acidophilic fungi." Presented by K.R. Pomraning at Society for Industrial Microbiology and Biotechnology, San Francisco, California.
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- Mevawala C.R., M.F. Guo, C.O. Brady, L.J. Snowden-Swan, and K. Kallupalayam Ramasamy. 11/19/2021. "Municipal Solid Waste (MSW) to Sustainable Aviation Fuel (SAF): Process Modeling and Economic Analysis." Presented by C.R. Mevawala at 2021 AIChE Annual Meeting, Online Conferenece, United States.
- Guo M.F., U. Sanyal, C.O. Brady, S. Subramaniam, C.R. Mevawala, L.J. Snowden-Swan, and K. Kallupalayam Ramasamy. 04/07/2021. "Waste Streams to Sustainable Aviation Fuel: Cycloalkanes Rich Fuel from Ethanol over Mixed Oxide Catalysts." ACS Conference, Richland, Washington.
- Lopez-Ruiz J.A., N.W. Riedel, S. Li, Y. Qiu, and L.J. Snowden-Swan. 04/21/2022. "Renewable Fuel Production via Electrocatalytic Co-processing of Biomass-Derived Aqueous Waste and Bio-oils at Normal Temperature and Pressure." Presented by J.A. Lopez-Ruiz at TCBiomass 2022, Denver, Colorado.

- U.S. Patent No. 11,279,882, March 22, 2022, “Hydrothermal Liquefaction System”. Dan Anderson, Justin Billing, Richard Hallen, Todd Hart, Andrew Schmidt, Lesley Snowden-Swan and Michael Thorson.

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BETO Analysis Projects

Analysis & Sustainability Interface: PNNL 2.1.0.301 (Multi-criteria)
Strategic Analysis Support: NREL 4.1.1.30 (Multi-criteria)
GREET Development: ANL 4.1.1.10 (LCA)
Algae LCA: ANL 1.3.5.204 (LCA)

Supply Chain Strategic/Sustainability Analysis

Biomass Sourcing → **Biomass Transport + Pre-Processing Logistics** → **Biorefinery Conversion** → **Jet/Vehicle End-Use**

Supply Scenario Analysis: ORNL 1.1.1.3 (Resource Assessment)
Microalgae Analysis: PNNL 1.3.5.203 (Resource Assessment)

Feedstock Supply Chain Analysis: INL 1.1.1.2 (TEA)

BC Analysis: NREL 2.1.0.100 (TEA)
TC Analysis: NREL 2.1.0.302 (TEA)
Wet Waste HTL: PNNL 2.1.0.301 (TEA)
Algae HTL: PNNL 1.3.5.202 (TEA)
Algae system TEA: NREL 1.3.5.200 (TEA)

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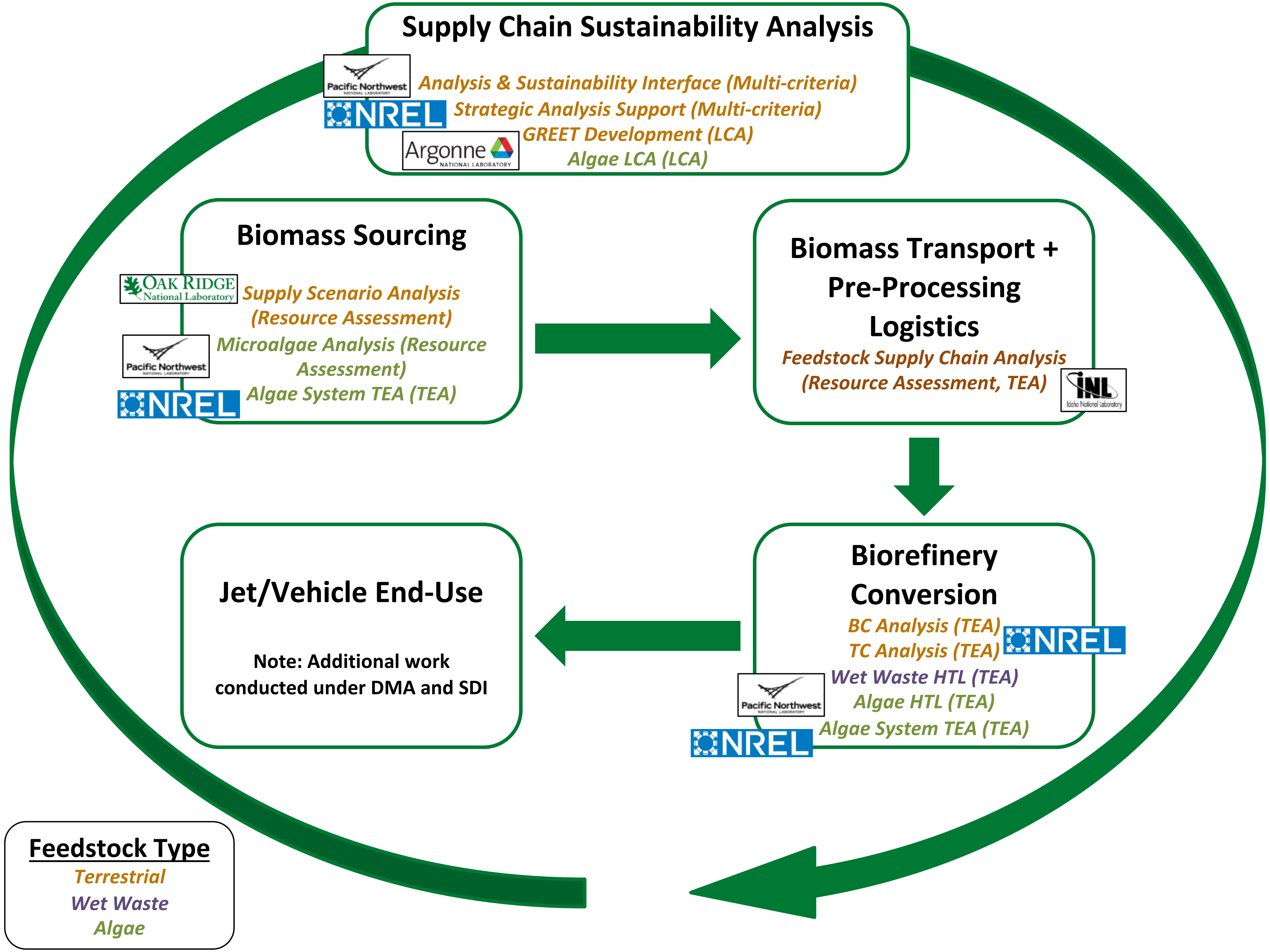
BETO Analysis Projects



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 MACRS 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

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2 – Progress and Accomplishments

All milestones met and driving toward BETO's targets

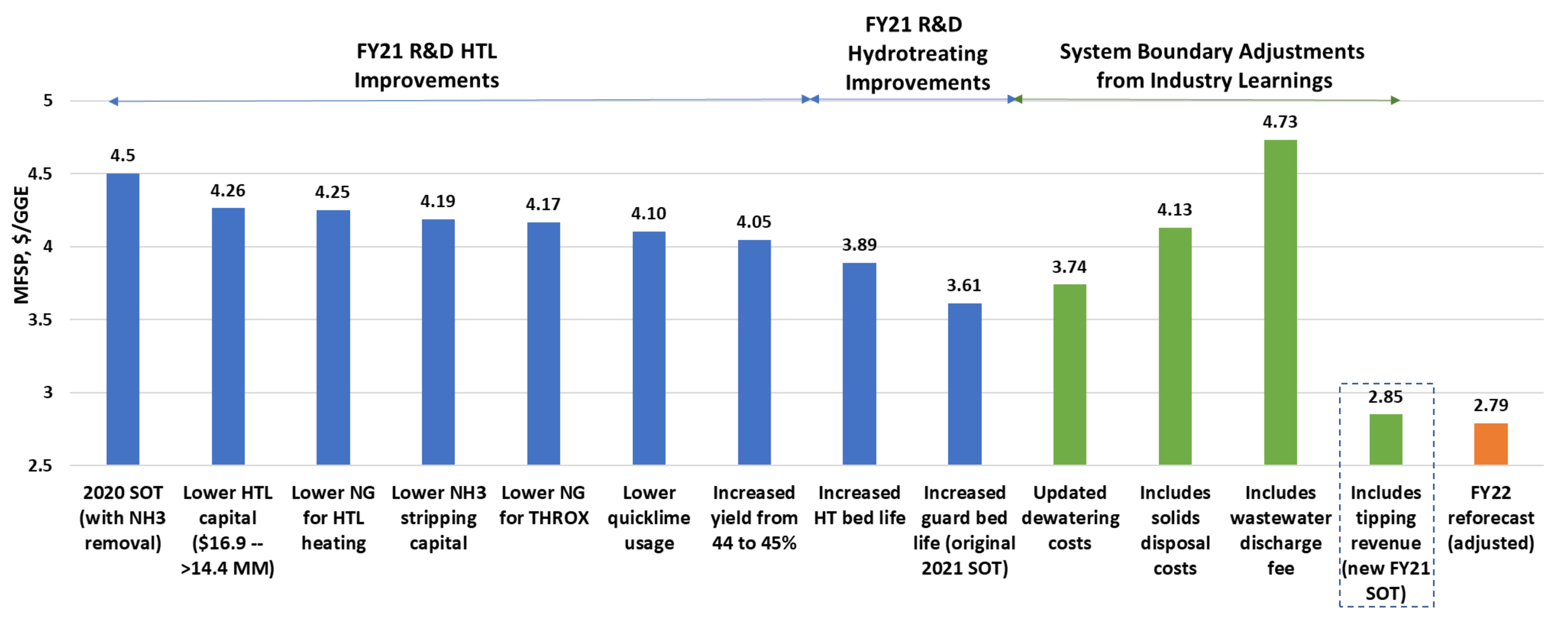
Key Milestones	Description/Criteria	Status
✓ FY21 Annual Project Milestone (6/30/21)	Complete annual SOT update for the HTL pathway, provide LCI for LCA, send technical tables to BETO for MYP update.	Completed. SOT report published at http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-30982.pdf. This fed into BETO's R&D State of Technology report published at https://www.energy.gov/eere/bioenergy/articles/beto-2020-rd-state-technology
✓ FY22 Annual Project Milestone (6/30/22)	Complete annual SOT update for the HTL pathway, provide LCI for LCA, send technical tables to BETO for MYP update.	Completed. Report is published at https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-33622.pdf.
✓ FY22 Project Merit Review (every 3 yrs)	Full proposal submitted for BETO Merit Review process.	Completed and approved for FY23-26 funding.
FY23 Annual Project Milestone (9/30/23)	Complete design case study for Wet Waste HTL that provides business case information and enhanced stakeholder value regarding cost and other impacts of the technology.	In progress and on schedule.

Progress Toward Project Goals: We have met the key milestones in the project management plan and are working toward enabling BETO's goals and advancing waste-to-energy by:

1) Guiding research and driving GHGs toward **BETO's 70% GHG reduction** and modeled cost goals
2) Investigating technical and economical viability of SAF

2- Progress and Accomplishments

FY21: Cost impacts of R&D advancements and adjustments from learnings (cumulative)



➢ Note: we also re-forecasted the 2022 case to incorporate our R&D learnings into the performance targets

2 – Progress and Accomplishments
FY21: Analysis of wet waste HTL regional waste-to-energy hub

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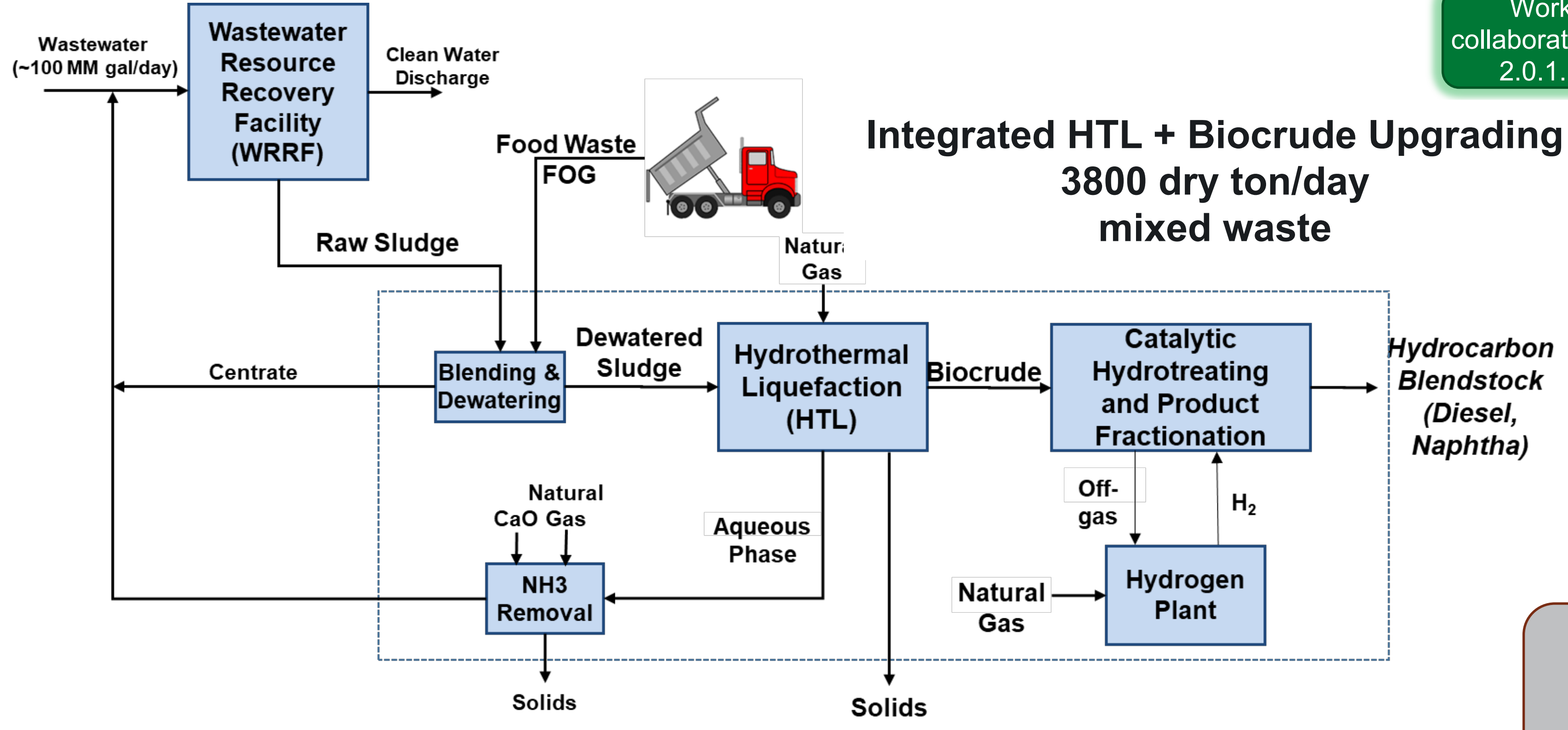
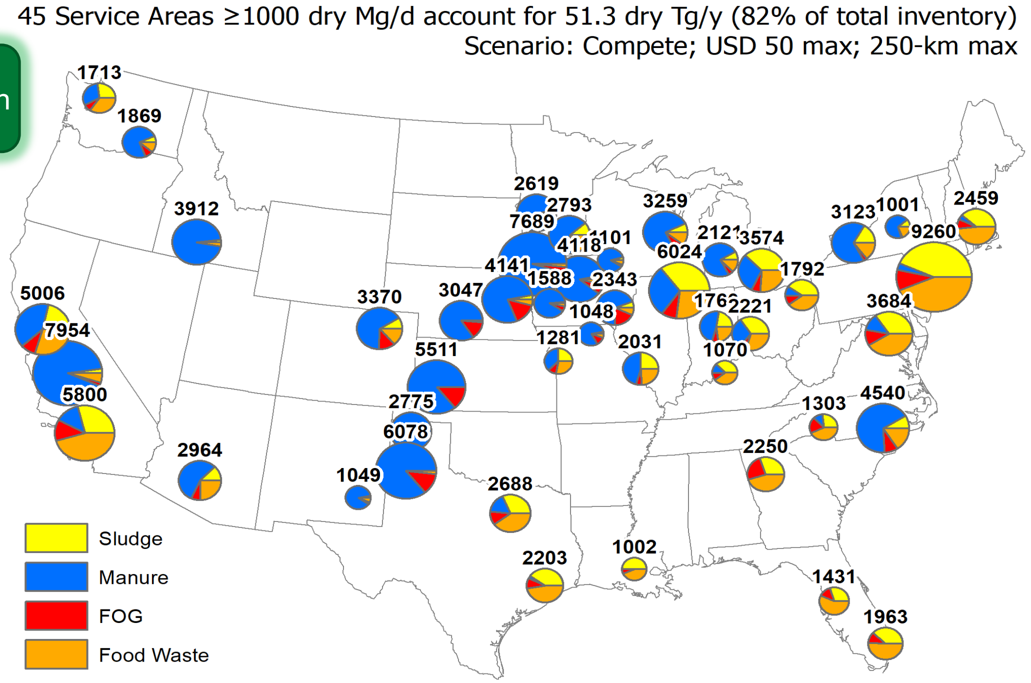


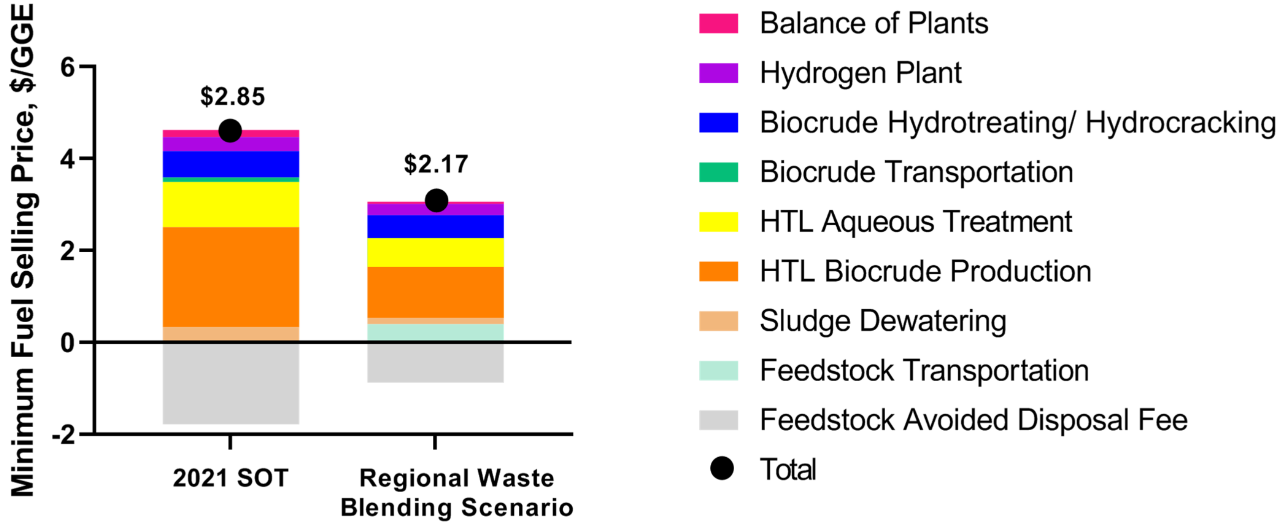
Work in collaboration with 2.0.1.113



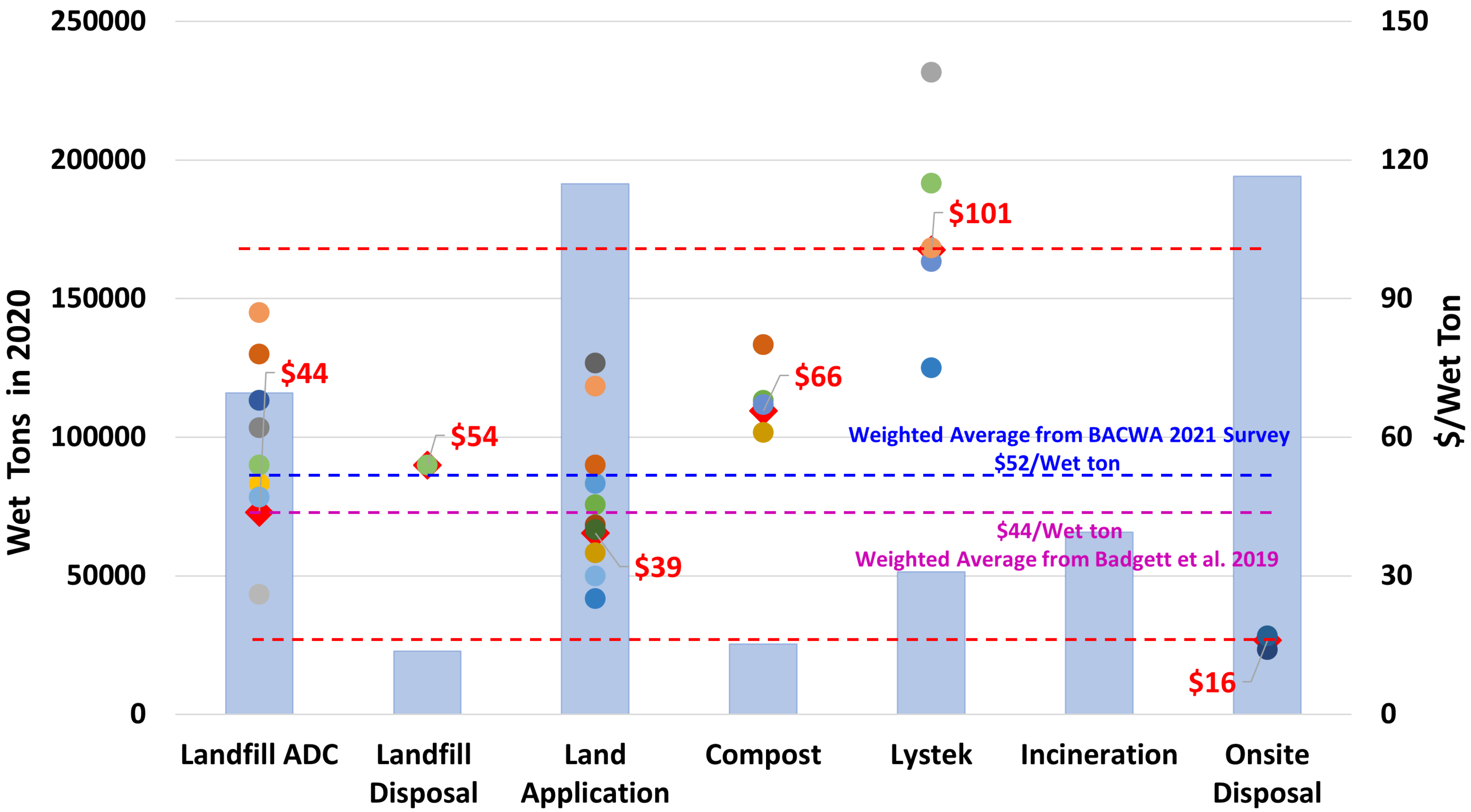
This work helped BETO meet their Government Performance Results Act (GPRA) Milestone

Key Assumptions:

- Large scale (3800 TPD) plant possible in metropolitan area
- **Grounded in experimental data** for HTL and upgrading; testing team ran an actual blend of sludge/food/FOG
- Estimated feedstock cost (tipping fee) is -$111/dry ton
- Estimated feedstock transportation cost is $50/dry ton
- Will be leveraged for FY23 Business Case



2 – Progress and Accomplishments
FY21: Updated price of sludge feedstock

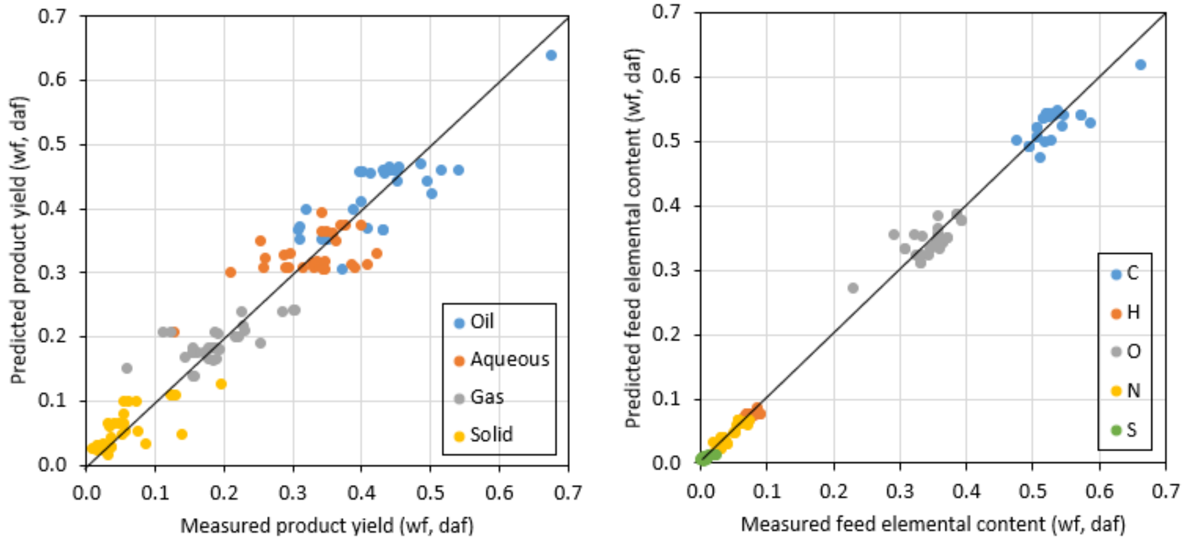


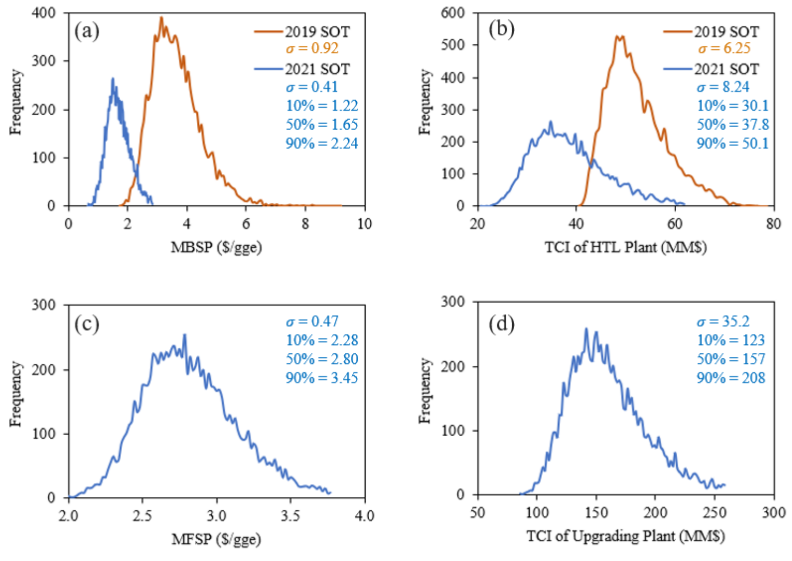
- Surveyed literature for incurred costs for sludge management by WRRFs
- Represents more realistic impact of based on industry’s experience

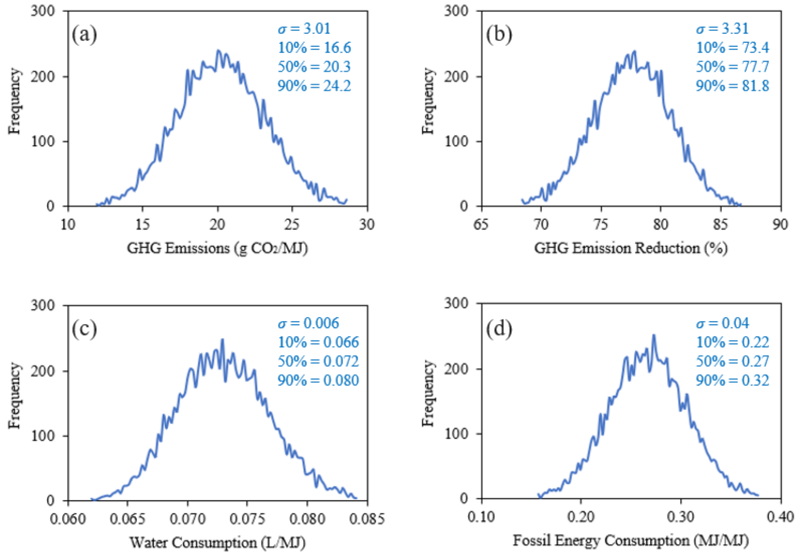
2 – Progress and Accomplishments

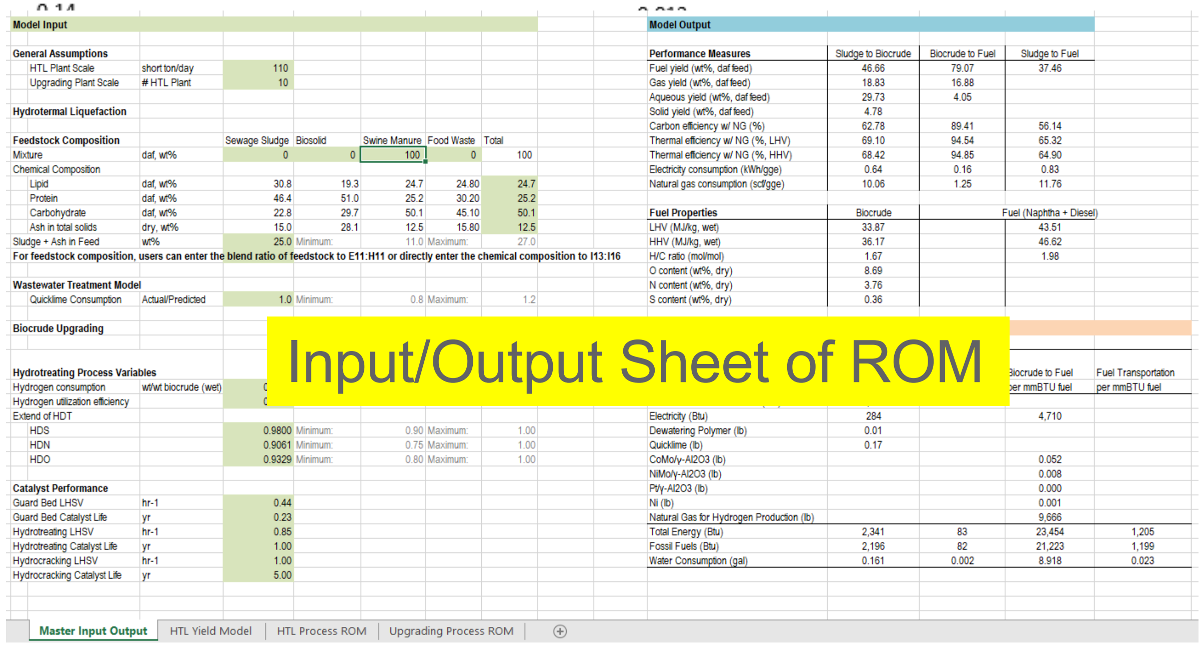
FY22: Updated wet waste HTL predictive yield model

- The **ROM** facilitates **less time-intensive** integrated TEA/LCA **uncertainty quantification**
- Building on prior work[1,2], we enhanced our **reduced-order model (ROM)** for predicting HTL yield with 14 newly **collected data sets (29 total)** from PNNL's continuous system
- The ROM was also built out to **include downstream upgrading unit** and **LCI and environmental results** using the GREET model
- The **ROM will be published** with the new manuscript (in review) and will assist stakeholders with generating process metrics including **M&EB** for TEA and **LCI** for conducting LCA









1 Jiang et al., 2019. "Techno-Economic Uncertainty Quantification of Algal-derived Biocrude via Hydrothermal Liquefaction." Algal Research 39: 101450
2 Li et al. 2022. "Techno-Economic Uncertainty Analysis of Wet Waste-to-Biocrude via Hydrothermal Liquefaction." Applied Energy 283.

2 – Progress and Accomplishments

Performance of pre-WRRF HTL aqueous-phase COD reduction technologies

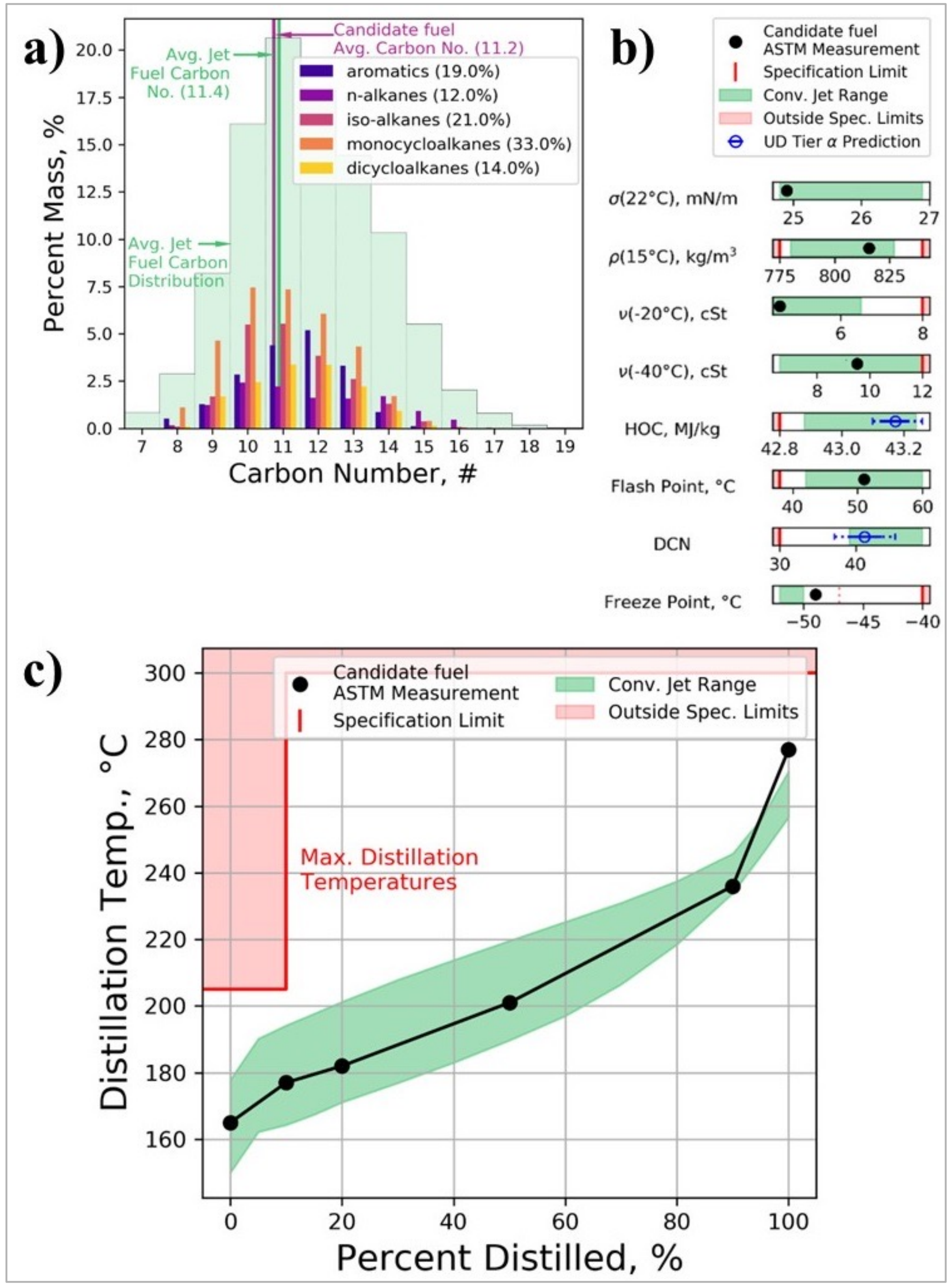
Technology	S-CHG	CHG	SCREW	ACU
Operating condition				
Temperature (°C)	350	350	400	400
Pressure (bar)	211	211	36	1
Liquid hourly space velocity (h^{-1})	0.54	0.54	0.5	0.27
Catalyst				
Type	Sulfided RuTe/C	Reduced Ru/C	NiMo/C	ZnZr Oxide
Catalyst life (year)	1	0.25		
Regeneration [Frequency]	Acid wash [0.25 year]	Acetone wash, hydrogen reduction [5 days]	Not needed	Not needed
Guard bed [Replace frequency]	Not needed	Not needed	C [10 days]	C [10 days]
Reactor performance				
H_2 consumption (g/100g feed)			0.39 *	
COD reduction (%)	65	>99	97.7	92
C removal (%)	63	100	85	78
N (organic) removal (%)		100	18	
S removal (%)	18	100	93	
Off gas composition (mol%, exclude NH_3 and H_2S)				
CH_4	72	28	24	12
CO_2	21	27	27	76
H_2	2	17		
C_{2+}		28	49	12

2 – Progress and Accomplishments

FY22: Initial testing for sustainable aviation fuel (SAF)

- A jet fuel boiling range cut was generated from distillation of hydrotreated biocrude
- Tier α and Tier β testing of jet cut carried out by University of Dayton[1]
- Deep hydrodenitrogenation (HDN) testing performed on the jet cut to further reduce N

HDN Reactor Data	Value
Catalyst	NiMo/Al2O3
WHSV, hr^{-1}	0.5
Temperature, °C (°F)	400 (752)
Pressure, MPa (psi)	10.8 (1,566)
N before HDN, ppm	5100
N after HDN, ppm	53



1 Cronin et al. 2022. "Sustainable Aviation Fuel from Hydrothermal Liquefaction of Wet Wastes." *Energies*: 15, 1306. https://doi.org/10.3390/en15041306

Abbreviations and Acronyms

- ANL: Argonne National Laboratory
- AOP: annual operating plan
- BETO: Bioenergy Technologies Office
- BSM: Biomass Scenario Model
- BTC: blenders tax credit
- CCCSD: Contra Costa County Sanitary District
- CHG: catalytic hydrothermal gasification
- COD: chemical oxygen demand
- DAF: dry, ash-free
- DEI: Diversity, Equity, and Inclusion
- DMA: Data, Modeling, and Analysis
- FOA: funding opportunity announcement
- FOG: fats, oils, and greases
- FY: fiscal year
- GGE: gasoline gallon equivalent
- GHG: greenhouse gas
- GLWA: Great Lakes Water Authority
- GPRA: Government Performance Results Act
- GREET: Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model
- HDN: hydrodenitrogenation
- HTL: hydrothermal liquefaction
- INL: Idaho National Laboratory
- LCA: life cycle analysis
- LCFS: low carbon fuel standard
- LCI: life cycle inventory
- M&EB: mass and energy balance
- MBSP: minimum biocrude selling price
- MFSP: minimum fuel selling price
- MYP: multi-year plan
- NREL: National Renewable Energy Laboratory
- PDU: process development unit
- PNNL: Pacific Northwest National Laboratory
- RFS: Renewable Fuel Standard
- ROM: reduced order model
- SAF: sustainable aviation fuel
- SCSA: supply chain sustainability analysis
- SOT: state of research technology
- TEA: techno-economic analysis
- T-MEC: thermo-microbial electrochemical
- TOS: time-on-stream
- TRL: technology readiness level
- WBS: work breakdown structure
- WeSys: Waste to Energy System Simulation
- WRRF: water resource recovery facility

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Thank you