Techno-Economic Analysis for Wet Waste Hydrothermal Liquefaction Pathway

2.1.0.301
(Task # 1 of Analysis & Sustainability Interface)

March 9, 2021
Organic Waste Program

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PI, PNNL

Project Overview

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

Problem: The U.S. generates 77 million dry tons of wet waste that could be converted to ~5.5 billion gallons of fuel per year (~12% of the 2019 petroleum diesel demand).

Goal: Advance waste-to-energy through development of data-driven waste hydrothermal liquefaction (HTL) process models and techno-economic analysis (TEA) that guides the R&D toward improved performance and reduced conversion costs.

Value: We have reduced the modeled pathway minimum fuel selling price (MFSP) by \$2.66/GGE (from \$7.16 to \$4.50/GGE) for a small-scale HTL plant with a 110 ton/day feed rate and developed an actionable plan to enable reaching BETO’s 2022 and 2030 cost goals.

GGE=gasoline gallon equivalent

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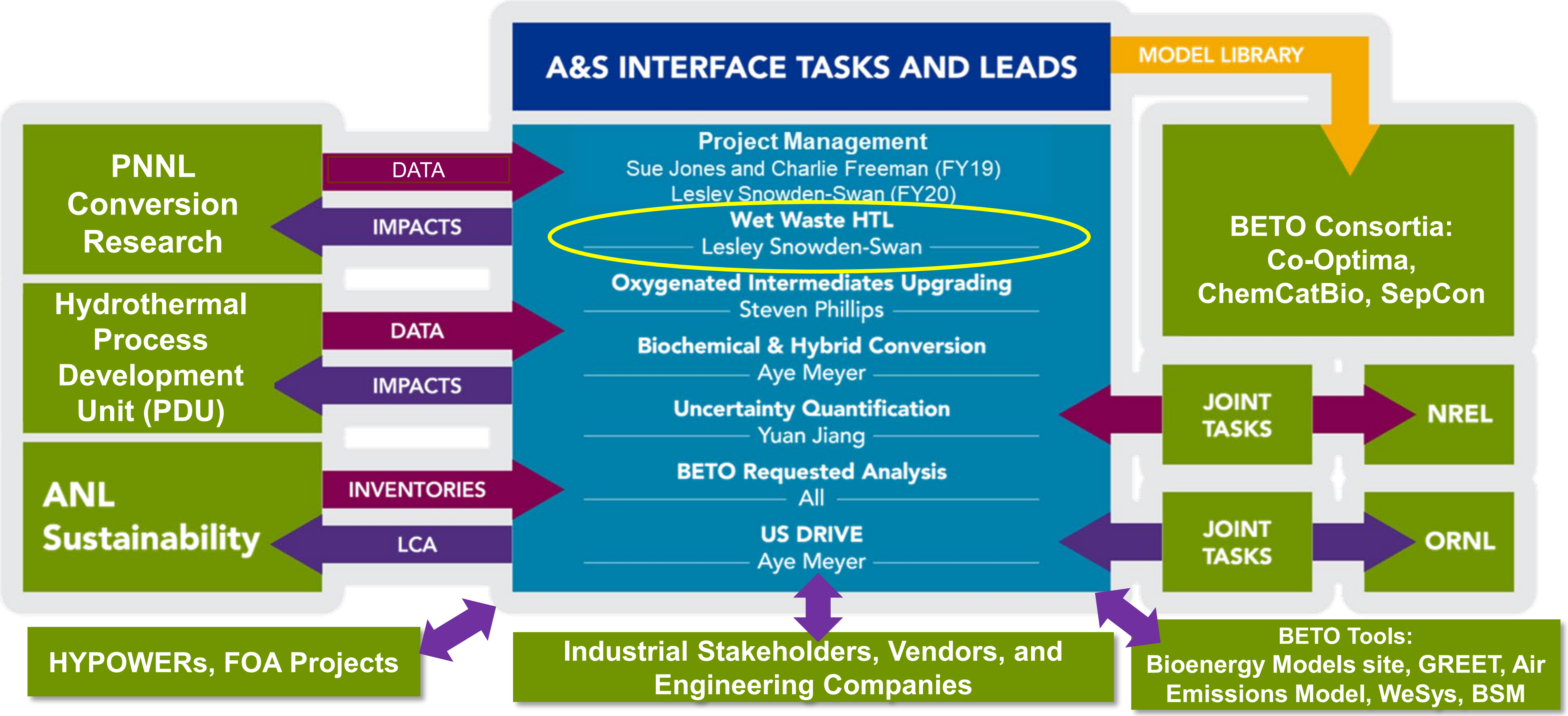
1 – Management
Alignment and collaboration provides synergies with BETO project portfolio and industry stakeholders



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

This project supports research activities in several Conversion areas including WTE. In the context of BETO's Organic Waste R&D, this presentation will focus primarily on the WET WASTE HTL task.

1 – Management
Risks are mitigated by communicating often with experimental team and collaborating with industry

Management Controls:

- **Formal project plan** with quarterly milestones and deliverables.
- Quarterly reporting and briefings (presentations) are provided to BETO.
- Project was merit-reviewed in FY19 and will be merit reviewed again 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, CCCSD, Austin Water) and NREL and ANL projects (e.g., staff serve on advisory board of WeSys model)

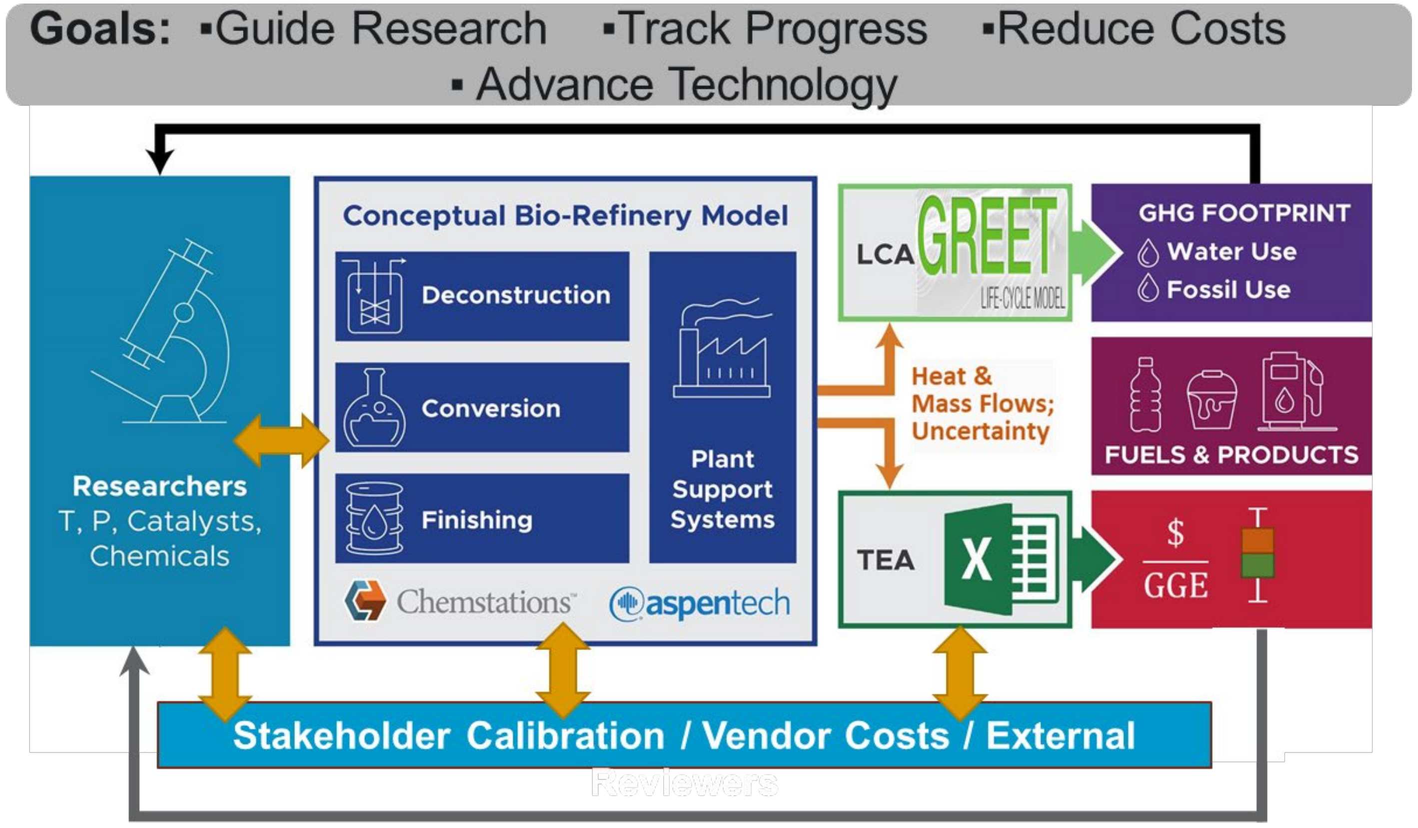
PNNL's risk management process assigns every project a **risk score** (this one is "**low**").

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.

PDU: Process Development Unit
GLWA: Great Lakes Water Authority
CCCSD: Contra Costa County Sanitary District

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



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

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 processing and logistical challenges at scale, improve fidelity of our designs, and get realistic equipment costs to inform our models.
- We use a **well-defined basis** for our TEA, as described in the BETO Multi-Year Plan (see slide 25).
- We **provide the life cycle inventory** 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.
- Developed an **innovative**, data-driven reduced order model for predicting performance and techno-economic uncertainty 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

- FY21 (2/15): "Develop a TEA for one specific biochemical, thermochemical, or hybrid conversion route that reduces the MFSP to ≤$2.5/GGE (gasoline-gallon equivalent)."
  - ✓ The HTL pathway can enable ≤$2.5/GGE via regional-scale wet waste blending and HTL processing hubs (see slide 26)

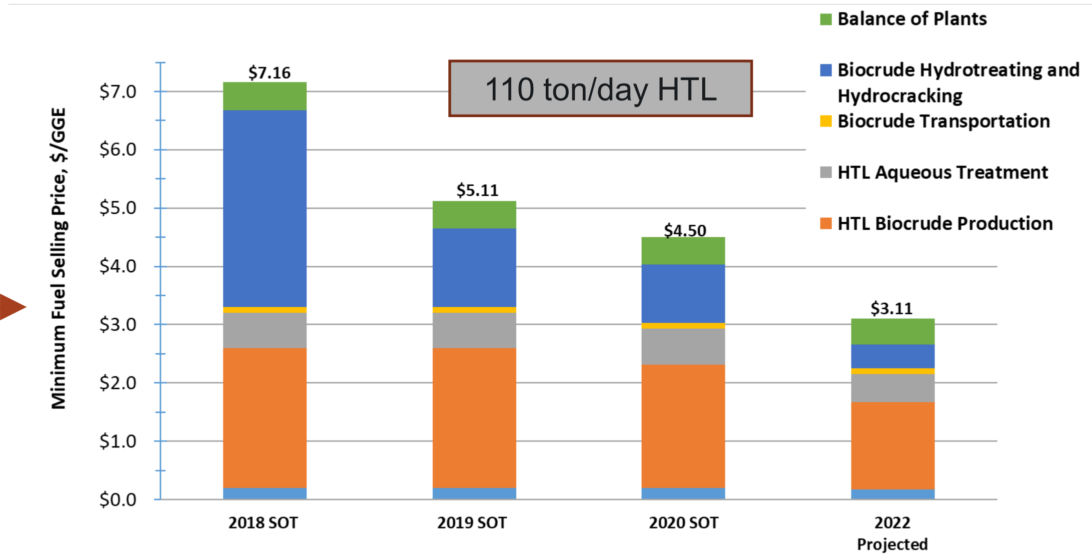
Critical Success Metrics

- Achieving **BETO's $3/GGE cost goal** (for 2022) and **≤$2.5/GGE goal** (for 2030) and **GHG emissions reductions** of **60%** compared to petroleum fuels.
- **Publish/present/disseminate** integrated progress of R&D and analysis for stakeholder use and help increase industry awareness of advanced waste-to-energy technology.

Changes as a result of 2019 Peer Review: Incorporated avoided disposal cost for wet waste (in sensitivity analysis, Slide 10); increased outreach via Circular Economy Technical Assistance project (see slide 7);

3 – Impact

Driven modeled costs down and provided an industry analog for unproven technology

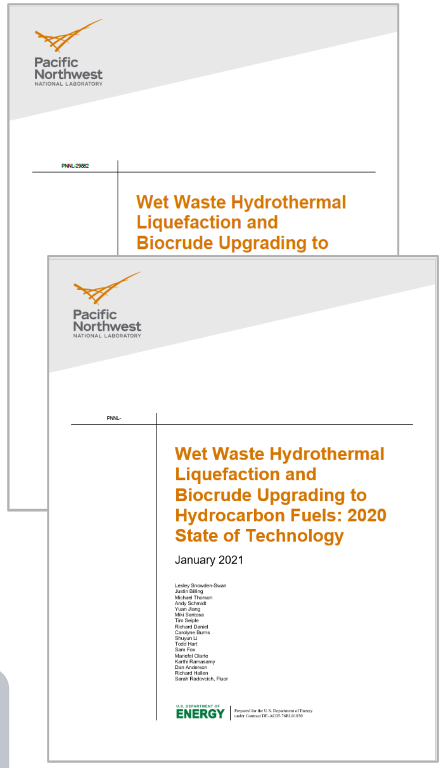


Integrated experimental/analysis projects have:

- **Reduced the MFSP** for the modeled state of technology (SOT*) from $7.16/GGE to $4.50/GGE (2020 SOT)
- Helping BETO validate a **Government Performance Results Act (GPRA) milestone** (to provide an FY 2021 SOT of ≤$3.03/GGE) for large-scale regional plant[2]

Outreach:

- Published FY 2019 and FY 2020 SOT reports which **document technical and analysis progress** toward cost goals; presented at nine conferences; published eight related articles
- **Helping educate state and local policymakers** via a **waste-to-energy** database and report (joint w/NREL through Circular Economy Technical Assistance project, U.S. Department of Energy (DOE) Weatherization and Intergovernmental Programs.
- Models and TEA have produced **foundational scaled cost information** utilized in a wide range of analyses (resource analysis at PNNL, NREL, WeSys, Biomass Scenario Model, and GREET)
- Models helped **inform industrial scale-up** (detailed heat exchanger design in Hydrothermal PDU)



***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.**

4 – Progress and Outcomes

All milestones met and driving toward BETO's targets

Key Milestones	Description/Criteria	Status
FY19 Annual Project Milestone (6/30/19)	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 (https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-29882.pdf). MYP support report at: https://www.energy.gov/sites/prod/files/2020/07/f76/beto-2019-state-of-technology-july-2020-r1.pdf
FY20 Annual Project Milestone (6/30/20)	Complete annual SOT update for the HTL pathway, provide LCI for LCA, send technical tables to BETO for MYP update.	Completed. Report is in review by BETO and will be published in Q2.
FY21 Project Go/No-Go (2/15/21)	Develop a TEA for one specific conversion route that reduces the MFSP to ≤$2.5/gge	Completed. Analysis framework will be leveraged for the FY21 SOT and BETO's GPRA goal.
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.	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 the research and **driving modeled costs toward BETO's $3/GGE and ≤ $2.5/GGE goals**
2) Providing modeling and analysis to **inform commercial scale design** (heat exchanger re-design)

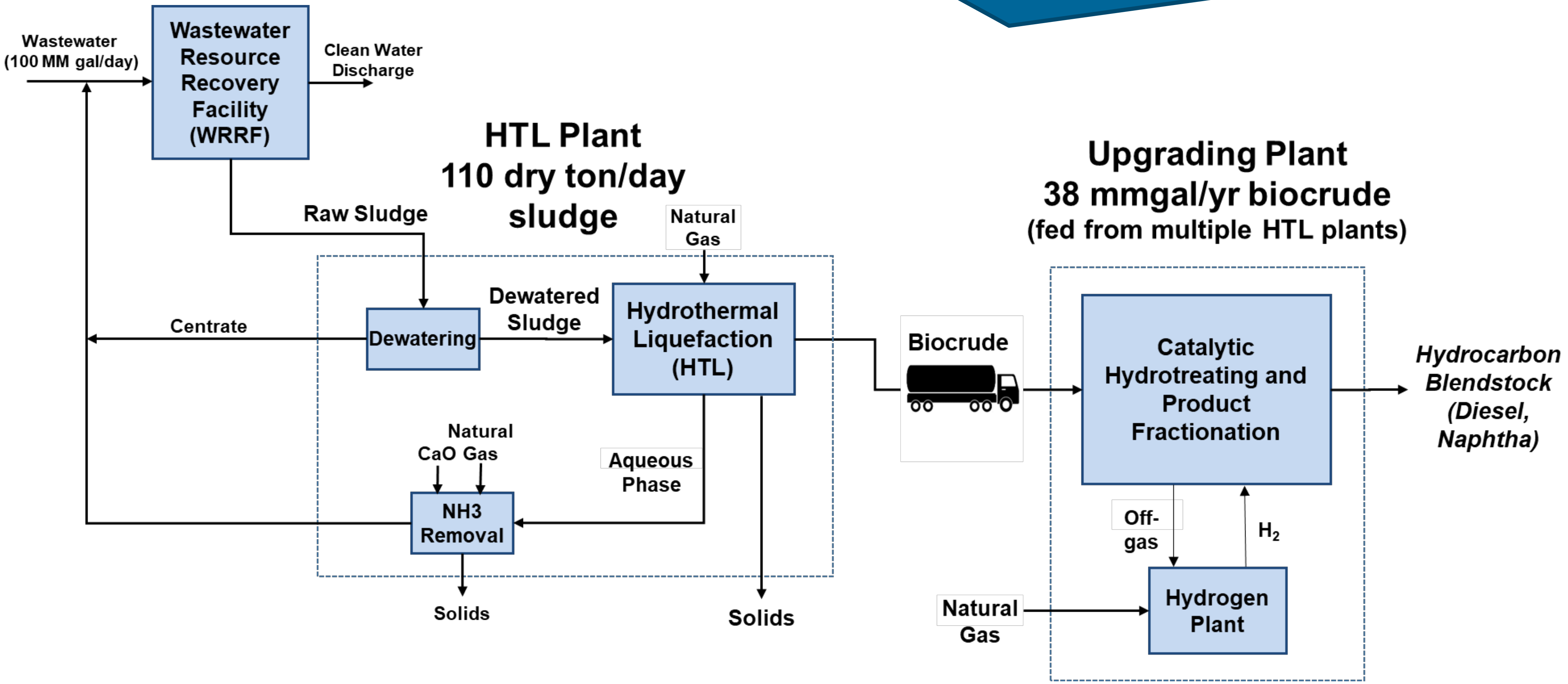
4 – Progress and Outcomes

Wet waste HTL conceptual process model assumptions

Key Assumptions:

- Mature Nth plant assumptions (see slide 25 for full list)
  - Future time when several plants are up and running
  - Ignores redundancies, longer start-up, special financing
  - Internal Rate of Return = 10%
- **Grounded on experimental data** for HTL and upgrading
- Biocrude transported 100 miles (round-trip) at \$0.10/GGE to a larger scale upgrading plant that processes 10X the biocrude
- Excludes renewable fuel credits (reflects a future time)
- **Zero feedstock cost** (feedstock price is included in sensitivity analysis, slide 10)

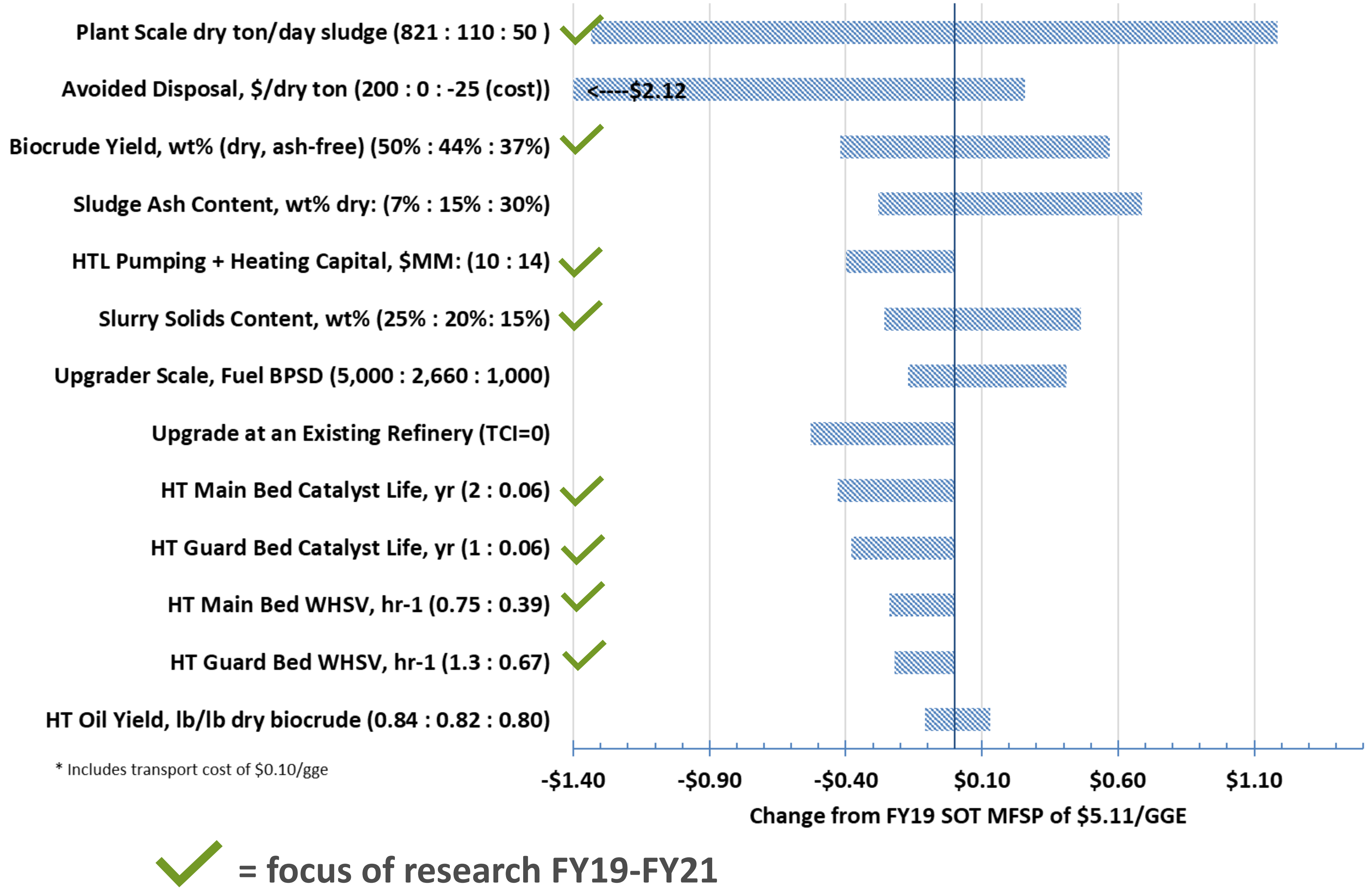
- **Focused on wastewater sludge but works for other wet waste (& blends)**
- **Decoupled upgrading plant reduces capital cost through economies of scale**
- **Includes treatment of aqueous phase stream recycle to wastewater plant**



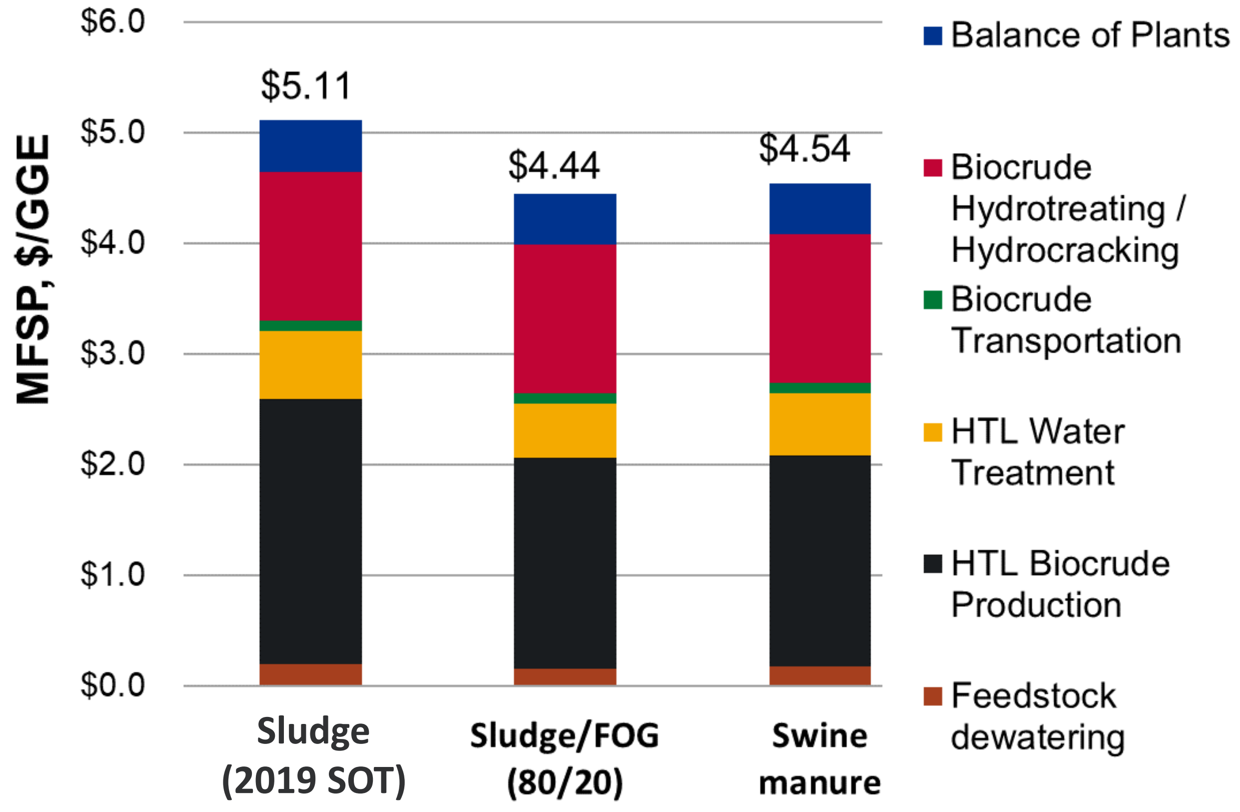
4 – Progress and Outcomes (FY19)

Sensitivity analysis targets important cost drivers for research focus

- Scenario/sensitivity analysis is conducted and **communicated to the experimental team** to target **key cost drivers** and associated research to advance technology
- Focus has been on **areas of greatest impact** that can be improved with R&D
- Progress in these areas have **paved the way to meet the $3/GGE goal** by 2022
- **Avoided disposal cost** could have a significant impact on MFSP (addresses 2019 Peer Review comment)

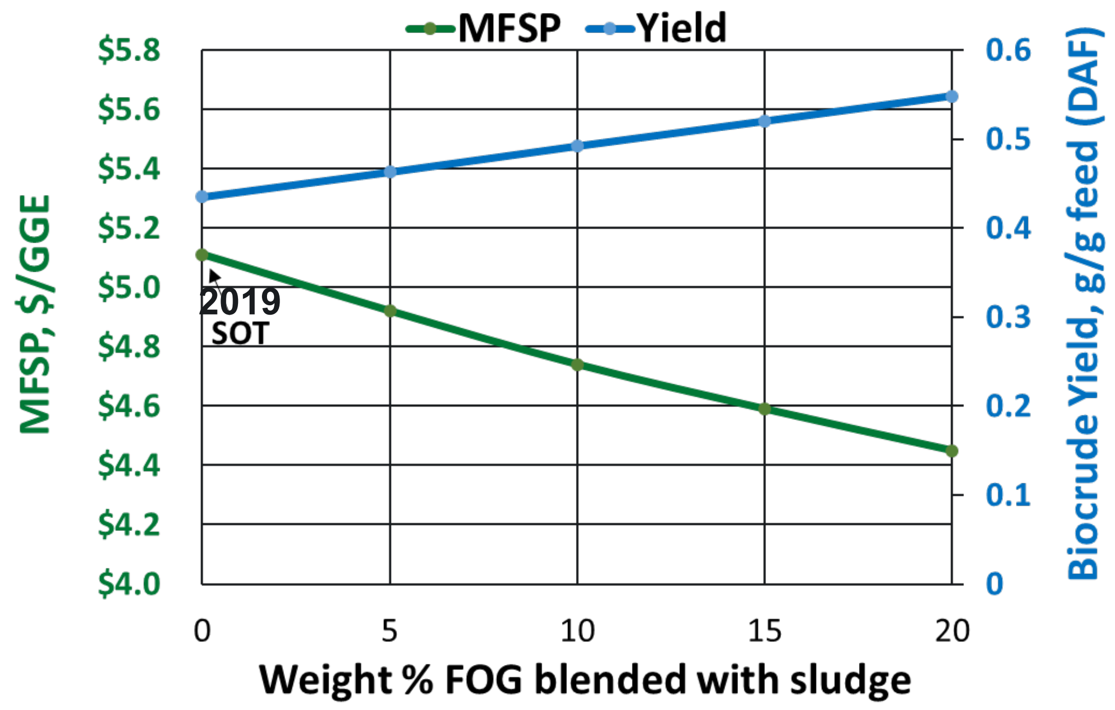


4 – Progress and Outcomes (FY19)
Fat/oil/grease (FOG) and manure have higher yields and can improve economics of wastewater sludge



- Higher biocrude yields for manure and FOG reduce MFSP by ~ $0.60-70/GGE

- Addition of FOG, even at low levels, improves yield and economics



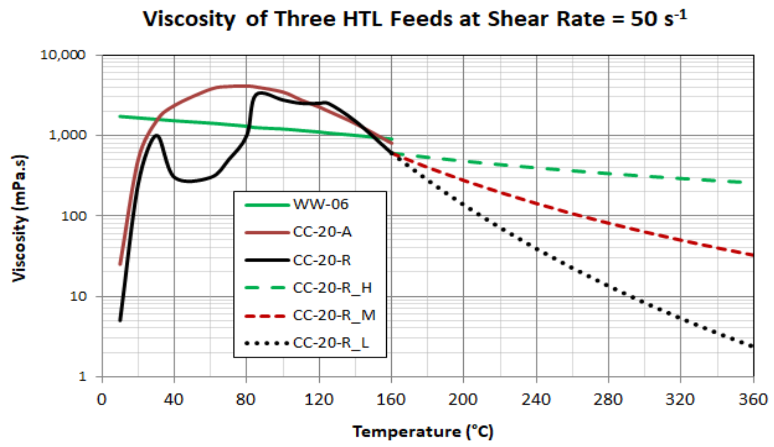
This analysis laid the groundwork for expanding the research/analysis into **regional waste HTL hubs** processing blends of sludge, FOG, manure, and food waste.

4- Progress and Outcomes (FY20)

Redesign of HTL heating & pumping configuration reduced capital cost by 13%

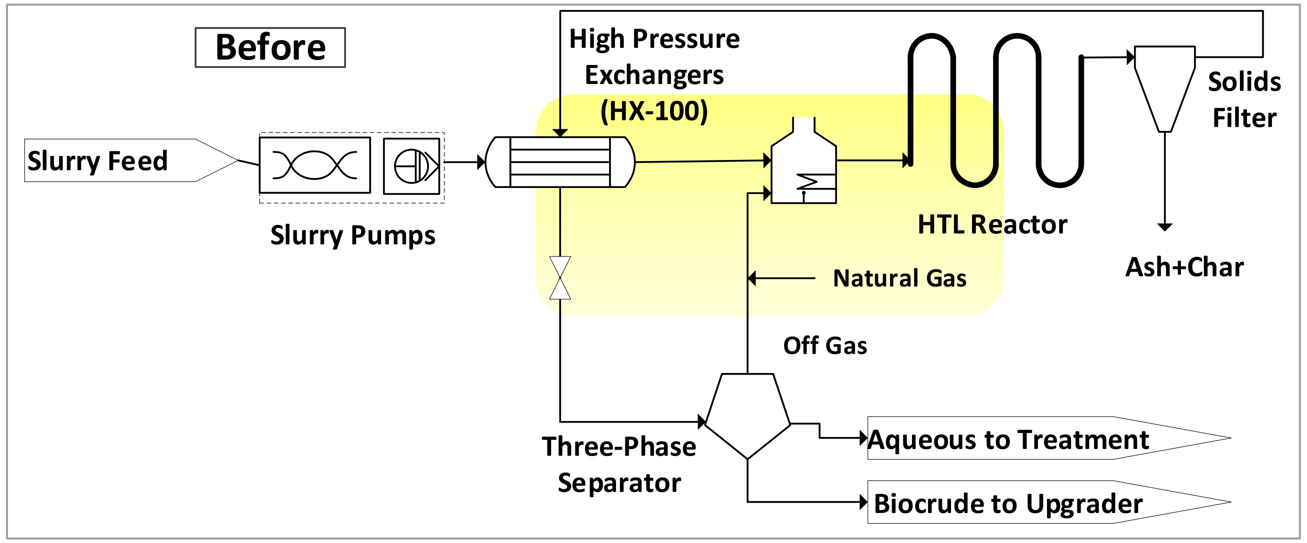
Models built in this project provided the key design parameters for re-design of heating/pumping scheme

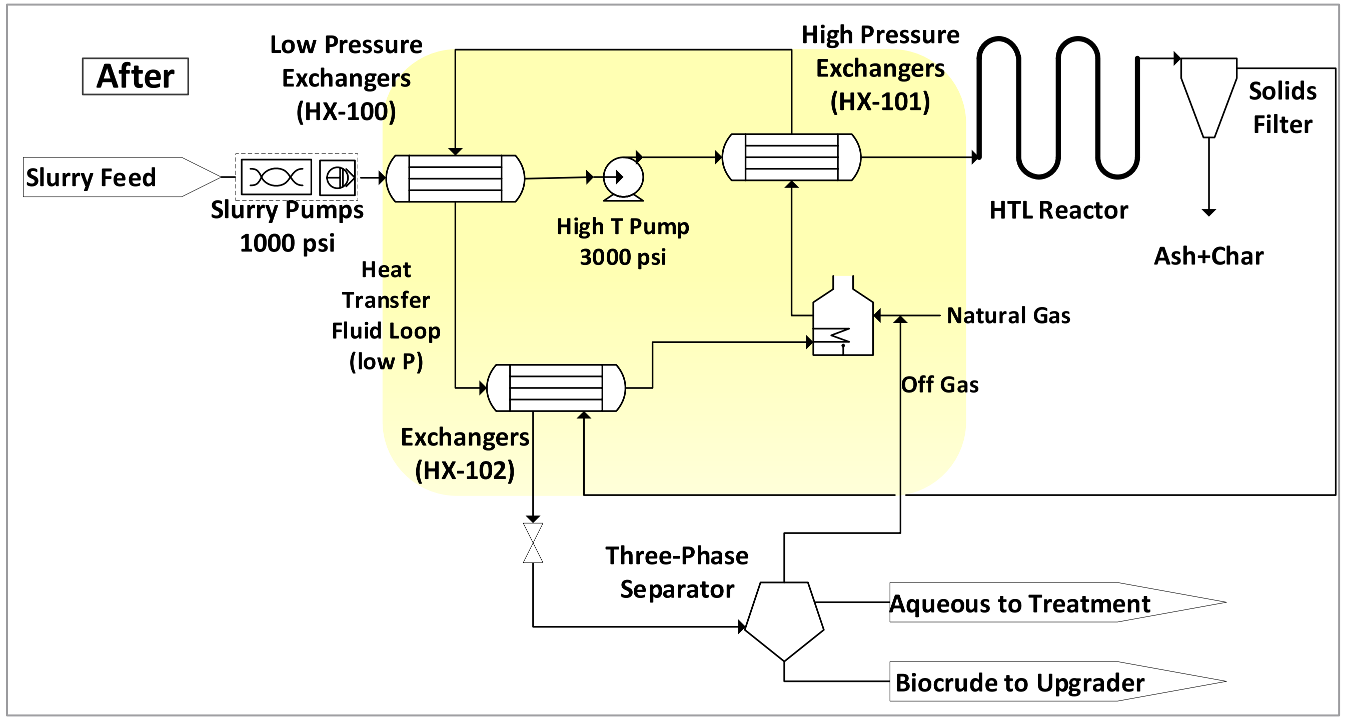
- Under subcontract on the Hydrothermal PDU project, **Fluor rigorously modeled and sized exchangers using standard industry design software** (Heat Transfer Research Institute) and obtained costing (Snowden-Swan was point of contact).
- New design **reduces the installed capital cost by 13%** and the modeled 2020 SOT MFSP for the wet waste HTL pathway by $0.26/GGE and improves the robustness of the model.



PDU-generated sludge viscosity data improved exchanger design fidelity

Innovation:
New design is more scalable and is the basis of a patent application and license.

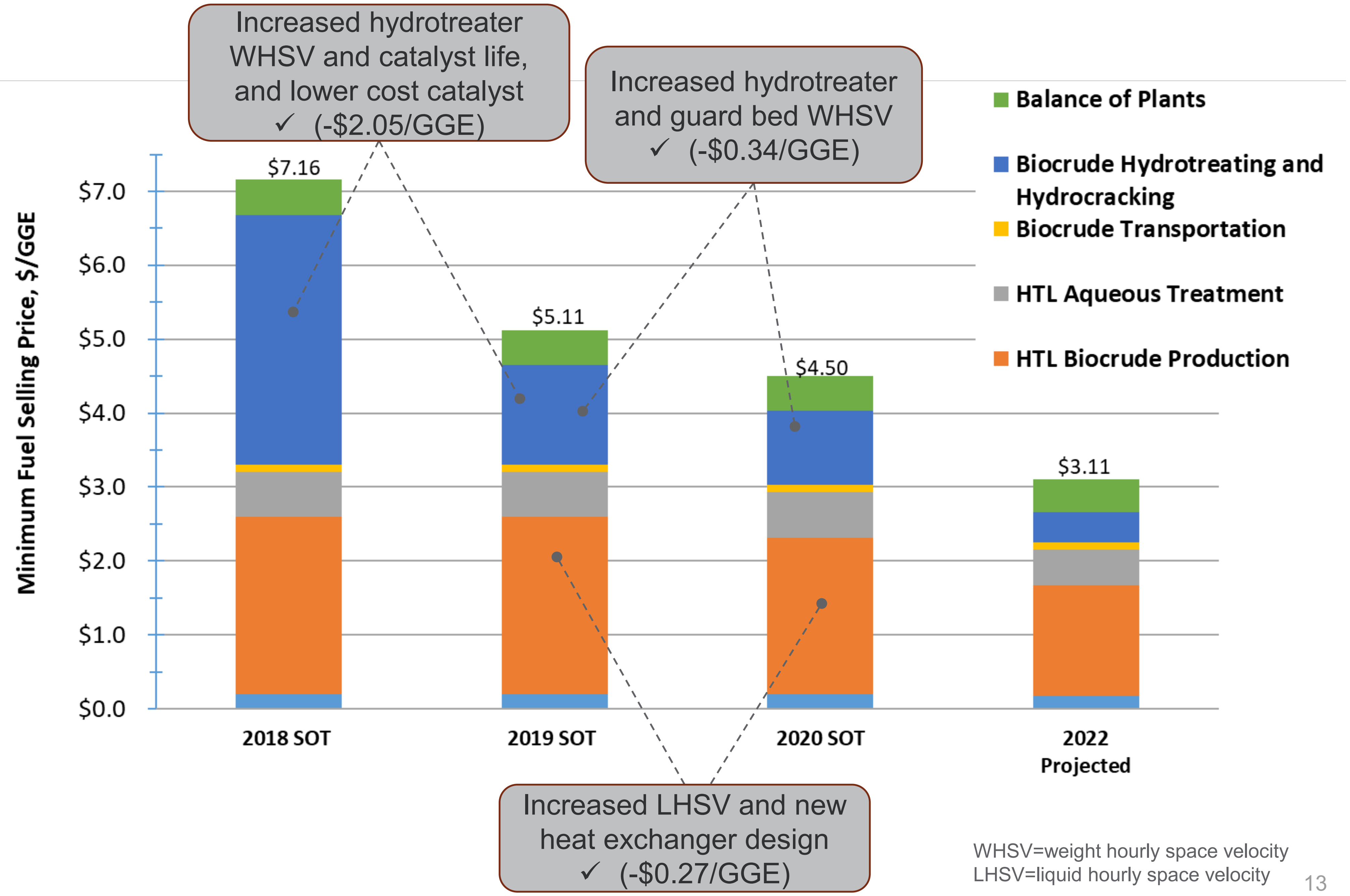




4 – Progress and Outcomes (FY19-20)
SOT assessment is guiding R&D and driving down cost

Impact:

- Models informed new heat exchanger design, which reduced cost by 26 cents per GGE
- Worked with researchers early on to identify hydrotreating (HT) catalyst performance as a key cost driver: pushing performance has reduced MFSP by $2.39/GGE
- GREET analysis by ANL estimated GHG emissions are 53% reduced from petroleum baseline for the 2020 SOT (see slide 27)

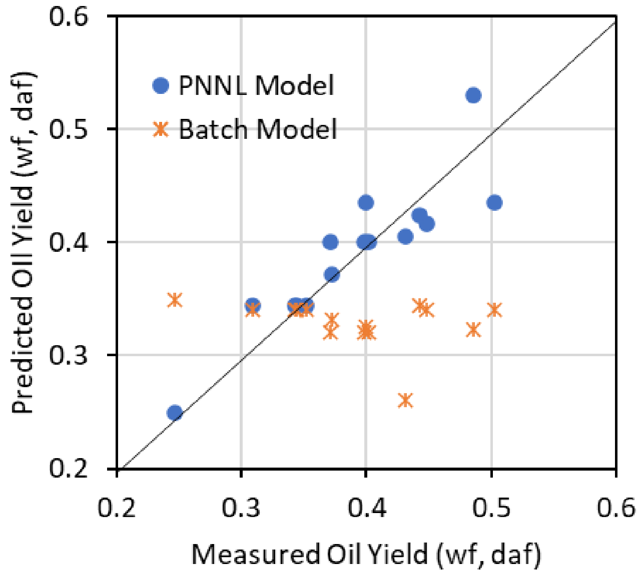


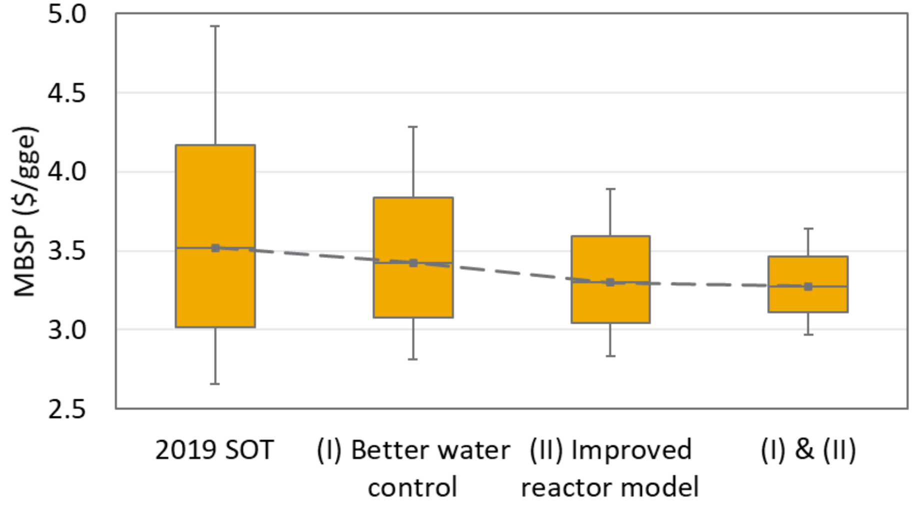
WHSV=weight hourly space velocity
LHSV=liquid hourly space velocity

4 – Progress and Outcomes (FY20)

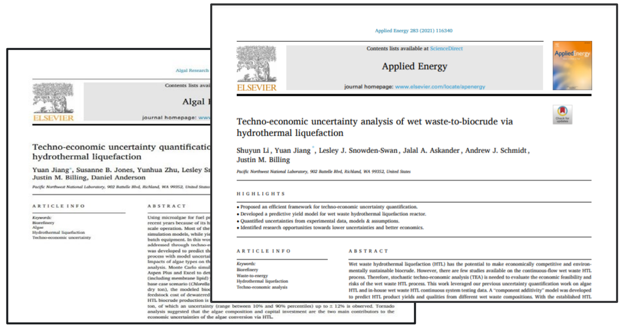
Predictive yield model can quickly estimate HTL performance for variable feedstocks

- Building on prior algae work[1], a reduced-order model (ROM) for predicting HTL yield was developed.
- This is important because:
  - It is the **first predictive model** based on continuous system testing (13 runs) and can better predict scaled-up operations than batch-based models
  - We used it to develop an uncertainty quantification method that is **2000X faster** than using the rigorous Aspen Plus model (see slide 28)
  - The analysis identified ways to **reduce process techno-economic uncertainty** (feedstock moisture control and expanding the waste testing database)





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



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

4 – Progress and Outcomes (FY21 and beyond)

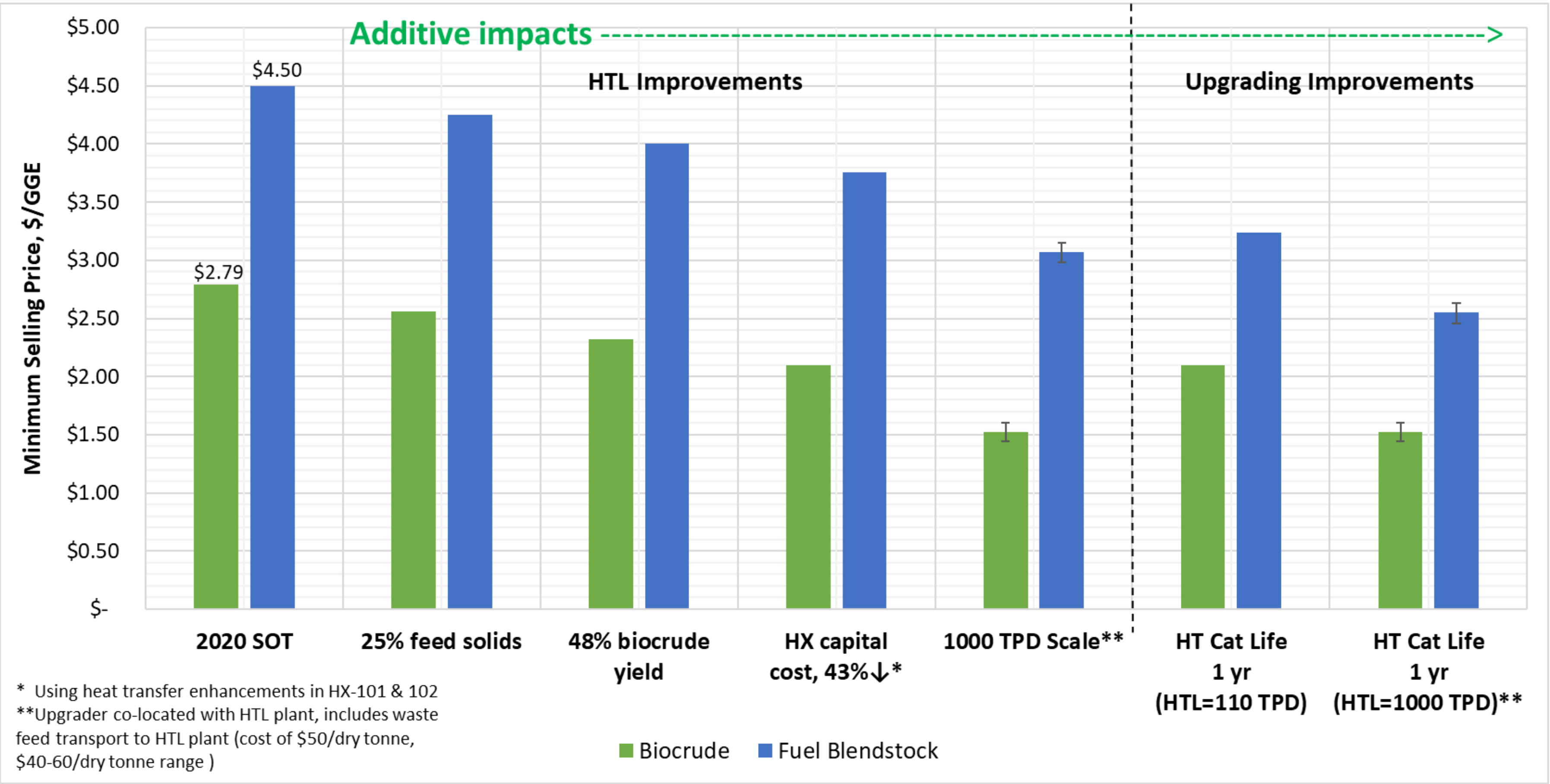
Retiring assumptions and reducing technological uncertainty for the HTL pathway

Assumption	Current SOT	Target	Estimated Cost Reduction*	Planned Campaign
HTL Feed Solids	20%	25%	$0.25/GGE	Q4 milestone, 2021 (HTL Bench/PDU)
HTL Biocrude Yield	44%	48% (stretch goal)	$0.25/GGE	Q4 milestone, 2021 / 2022 (HTL Bench/PDU)
Hydrotreater Catalyst Life	552 hours	1 year	$0.52/GGE	2021 (PDU)
HTL Scale & Feedstock	110 TPD / WRRF Sludge	≥1000 TPD / Blended Waste	$0.56/GGE	Q2 2021 milestone (HTL Bench and waste-to-energy teams)
HTL Aqueous Treatment	NH_3 Stripping	Effective and lower cost 50% C and N removal for recycle	TBD	2021-22 (PDU)
Heat exchanger design	Shell/Tube	Shell/Tube with core inserts	$0.24/GGE	2021-22 (PDU)

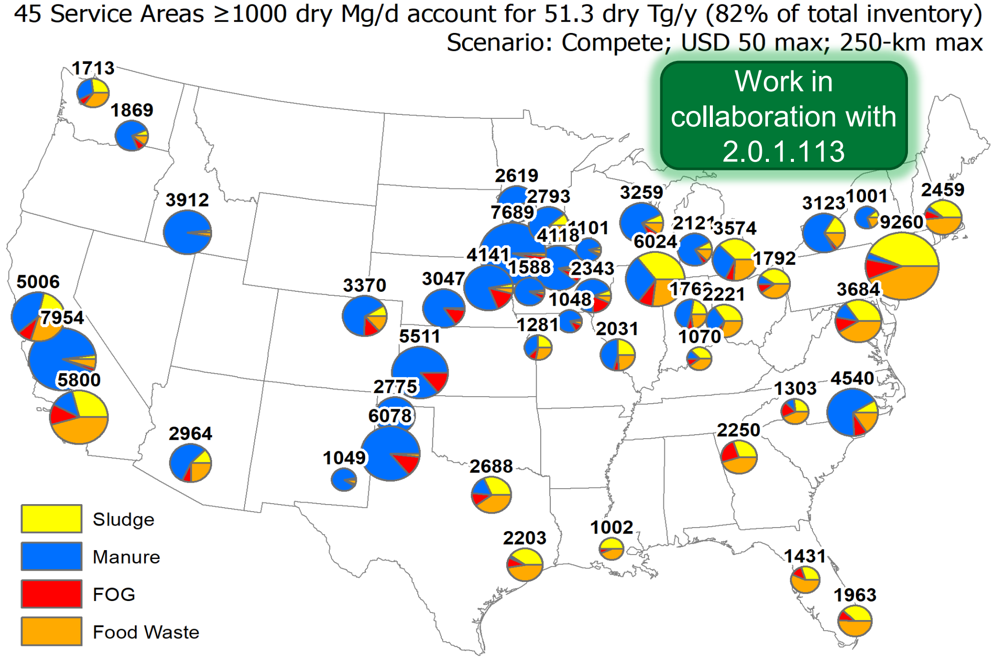
Preliminary Projections

4 – Progress and Outcomes (FY21 and beyond)

Integrated analysis, R&D, and resource assessment is creating a vision for regional waste-to-energy hubs



(Improved cases are preliminary projections. Do not cite.)



Regional collection and blending enables economies of scale

- Planned improvements **lead to $3/GGE 2022 and ≤ $2.5/GGE 2030** program goals
- The testing and TEA of a regional waste blend (Detroit area) at 25% solids **enabled a "Go"** for the project **Go/No-Go of ≤ $2.5/GGE** (see slide 26)

Acknowledgements

- Andrea Bailey, BETO Technology Manager

Systems Analysis Team

- **Analysis and Sustainability Project Team**

Yuan Jiang	Steve Phillips
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Waste Resource Team
- Tim Seiple
- Andre Coleman

Experimental Team
- Andy Schmidt
- Justin Billing
- Mike Thorson
- Dan Anderson
- Todd Hart
- Sam Fox

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- Michael Wang

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Summary

- **Overview:** Accelerating viability of waste-to-energy through integrated analysis/R&D
- **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 and have informed industrial scale-up of the process through our heat exchanger re-design
- **Progress and Outcomes:** Guided impactful, focused research that reduced cost by 37% and informed a more scalable design for the HTL process
- **Future work:**
  - Deliver FY21 SOT, reflecting research progress and waste processing hub scenario
  - Deliver the TEA for the GPRA milestone (FY21)
  - Conduct business case in 2022 (annual milestone) including the impact of regional waste conversion plants/bioenergy hubs to enable ≤ $2.5/GGE

Quad Chart Overview

Timeline
- Project start date: October 1, 2019
- Project end date: September 30, 2022

	FY21	Active Project
DOE Funding	10/01/2020 –9/30/2021 $700,000 (Project) $300,000 (WTE Task)	10/01/2019 – 9/30/2022 $2,125,000 (Project) $670,000 (WTE Task)

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

Barriers Addressed

At-A: Analysis to Inform Strategic Direction

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

Project Goal
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.

End of Project Milestone
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 FY23.[Task 1]

Funding Mechanism
Lab Call 2019

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Additional Slides

Responses to Previous Reviewers' Comments

Feedback: Information was not presented on emissions reduction, either from an environmental or regulatory perspective.

- **Response:** The life cycle inventory from our conversion models is provided to Argonne National Laboratory for determination of greenhouse gas emissions with the GREET model. Joint Lab publications containing the resulting of the LCA are published for the annual SOTs in Supply Chain Sustainability Analysis reports on ANL's website. The GHG emissions results for the HTL pathway is provided on slide 27.

Feedback: The model appears to be missing a category for feedstock cost, which for wastewater sludge would be negative. While one might argue that not including this is a more conservative approach, one could also argue this is unrealistic and denying the primary reason to consider use of wastes as a feedstock at all. Waste disposal is a legitimate cost and its elimination through use of HTL deserves to be counted.

- **Response:** The average range of waste tipping fee for the US has been determined by the resource assessment team and included in the TEA sensitivity analysis, shown in the tornado chart (slide 10).

Feedback: including outreach to build awareness of HTL technology status and cost with WWT and POTW municipal government host sites.

- **Response:** Our collective team (experimental, resource analysis and TEA) has built strong relationships with several POTWs around the country and continues to present at wastewater industry trade and research organization conferences, such as WEFTEC (Water Environment Federation) and Pacific Northwest Clean Water Association workshop. We are also helping to develop a state and local policymakers guide that includes information and publications on wet waste HTL through the DOE's Circular Economy Technical Assistance project.

Publications, Presentations and Patents (since FY19 Review)

- Snowden-Swan, L.J. et al. 2021. Wet Waste Hydrothermal Liquefaction and Biocrude Upgrading to Hydrocarbon Fuels: 2020 State of Technology. In draft.
- H. Wang, P.A. Meyer, D.M. Santosa, C. Zhu, M.V. Olarte, S.B. Jones, A.H. Zacher. " 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
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- 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
- “Bioenergy Technologies Office 2019 R&D State of Technology.” 2020 https://www.energy.gov/sites/prod/files/2020/07/f76/beto-2019-state-of-technology-july-2020-r1.pdf
- “Integrated Strategies to Enable Lower-Cost Biofuels.” July 2020. Department of Energy EERE. https://www.energy.gov/sites/prod/files/2020/07/f76/beto-integrated-strategies-to-enable-low-cost-biofuels-july-2020.pdf
- 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.

Presentations (since FY19 Review)

- 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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Project History

History of HTL Analysis Task:

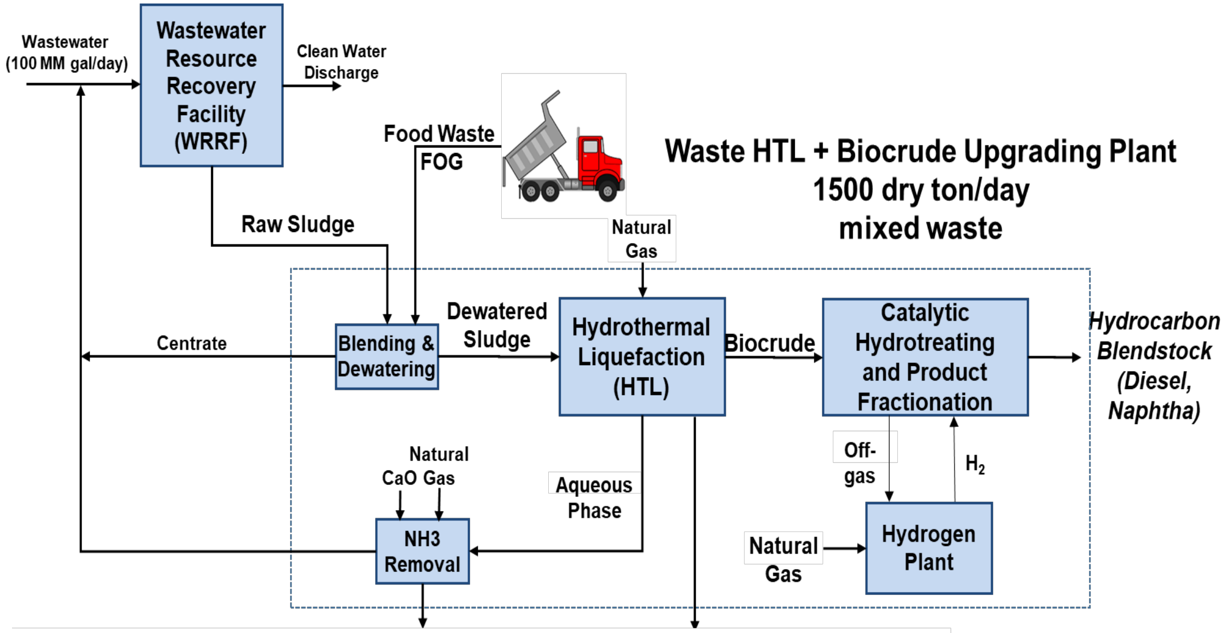
- Began in FY16 on algae and wood HTL work, initial testing of wastewater sludge and TEA were performed for a collaborative project with Water Environment & Reuse Foundation and industry showed feasibility at wastewater resource recovery facility (WRRF) scale.
- Design (goal) case developed in FY17, set technical and cost targets to reach by 2022.
- Performed annual State of Technology (SOT) assessments in FY18, 19, and 20, which have guided the research and tracked progress toward the 2022 goal of $3/GGE.

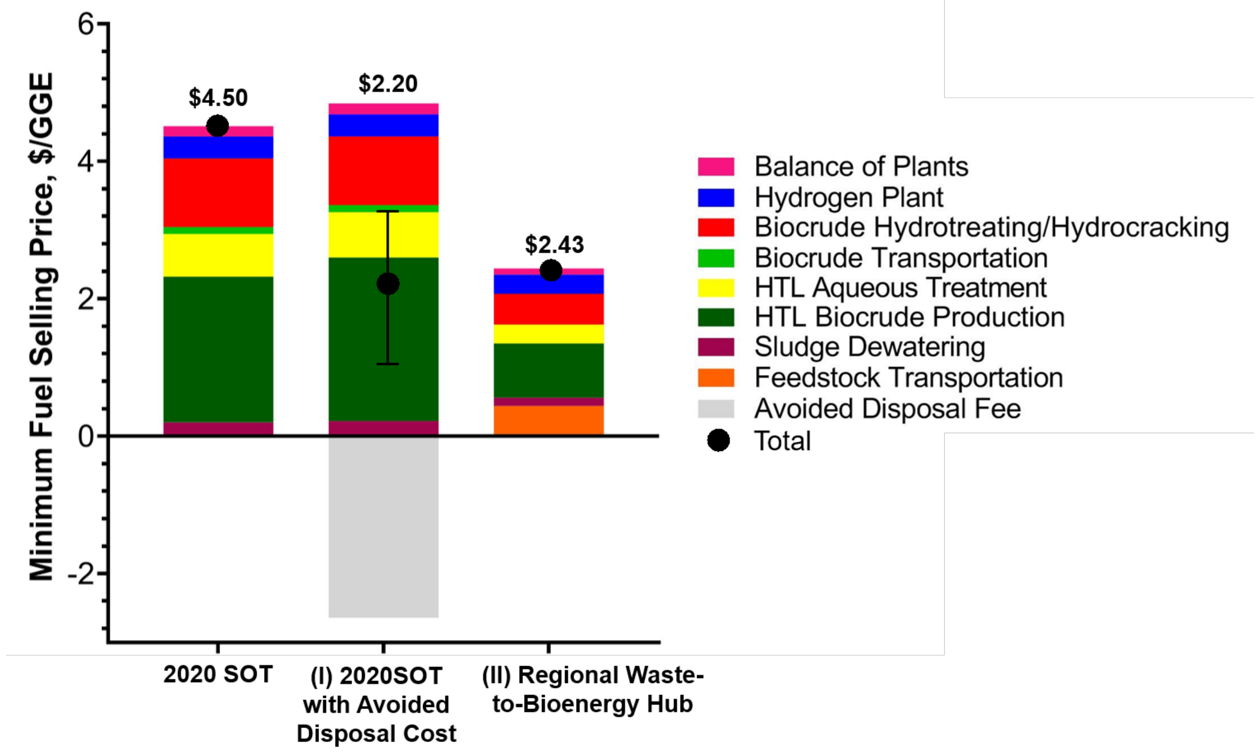
Analysis Economic Assumptions

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

4-Progress and Outcomes
FY21 Go/No-Go (delivered 2/15/21)





	2020 SOT	Scenario 1: SOT with Avoided Waste Disposal Cost	Scenario 2: Regional Waste-to-Bioenergy Hub
HTL scale, dry short ton/day	110	110	1500[1]
Upgrader scale, mmgal/y biocrude	38	38	51
Region	Generic WRRF	Generic WRRF	Detroit and surrounding region (100-mile radius)
Feedstock composition	GLWA Sludge	GLWA Sludge	Sludge / food waste / FOG
Feed solid, wt%	20%	20%	25%
Ash free solid, wt%	15%	15%	21.3%
Biocrude yield (from testing)	44%	44%	46%
Avoided disposal credits, $/ton waste	0	55.36[2]	0
HTL solid waste disposal, $/ton waste	0	55.36[2]	0
Transportation cost of waste feedstock to HTL, $/dry ton waste	0	0	45.36 (155-mile maximum collection radius)
Transportation cost of biocrude, $/GGE	0.1	0.1	0 (co-located with HTL)
Hydrotreating Catalyst Life, year	0.06	0.06	1.0

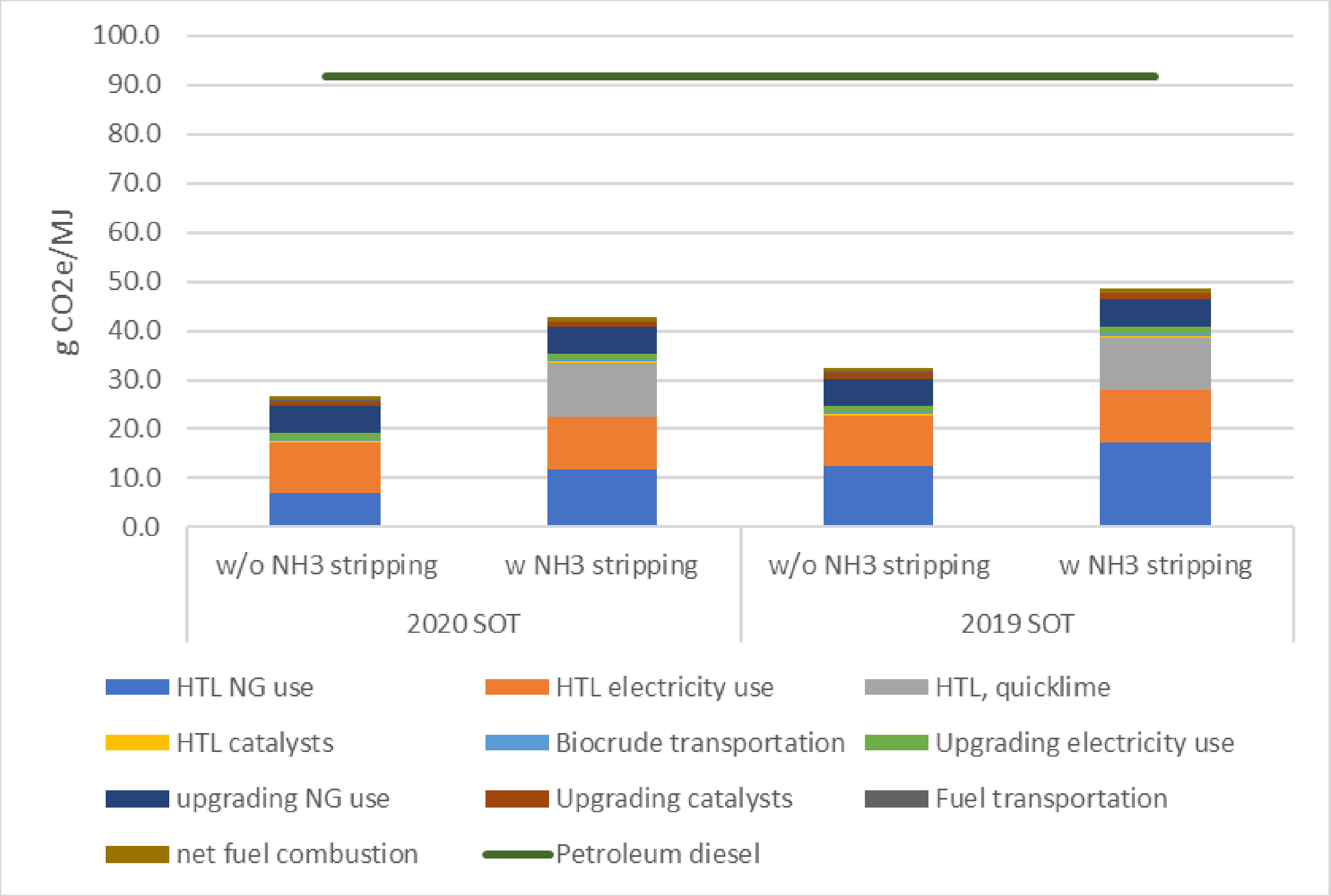
1 That the full scale of the Detroit hot spot is actually 2,486 TPD (excluding manure).
2 Average waste landfilling tip fee in 2019 dollars for wet waste per short ton based on EREF report (https://erefdn.org/product/analysis-msw-landfill-tipping-fees-2)

4 – Progress and Outcomes

GREET analysis shows blendstock fuel GHGs are 53-71% reduced from petroleum (analysis by ANL*)

- Material and energy balance for the HTL and biocrude conversion modeled plants are provided to ANL for LCA

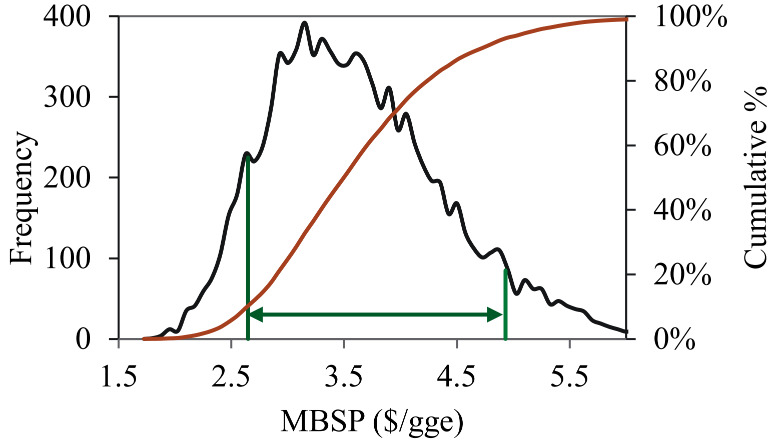
- Analysis shows GHG emissions for the 2020 SOT are reduced 53-71% from petroleum (both with and without NH_3 stripping of the aqueous phase are included in the analysis)

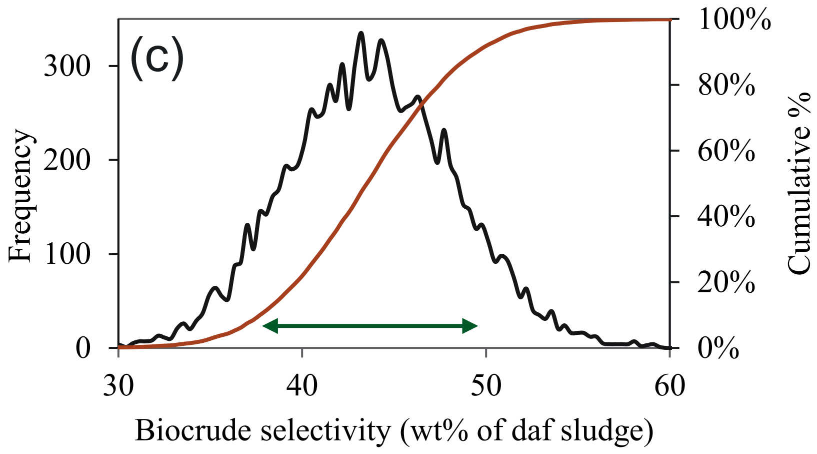


*Analysis conducted by Hao Cai, Argonne National Laboratory

4-Progress and Outcomes

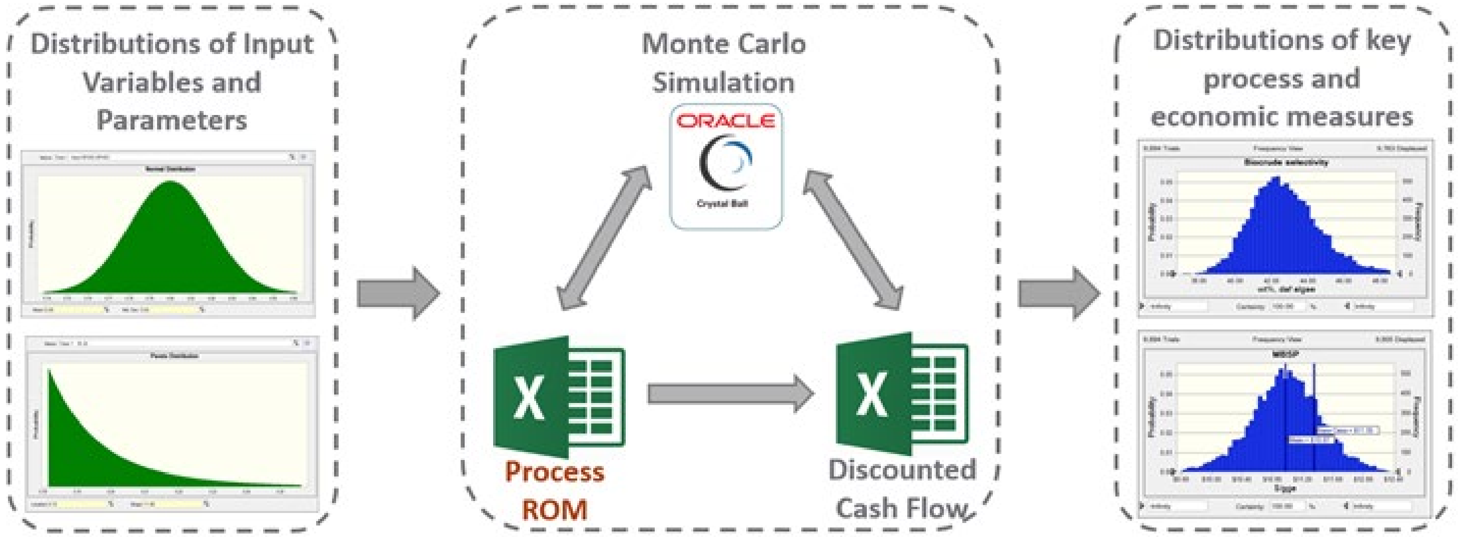
Uncertainty Quantification Methodology





S. Li, Y. Jiang, L.J. Snowden-Swan, J.A. Askander, A.J. Schmidt, Andrew, J.M. Billing. "Techno-Economic Uncertainty Analysis of Wet Waste-to-Biocrude via Hydrothermal Liquefaction." Applied Energy.

Framework for techno-economic uncertainty quantification



Predictive model – use feedstock compositions (carbohydrate, lipid, protein, ash, moisture) to estimate the yield (oil, gas, aq, char)

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

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)	-

4 – Progress and Outcomes Summary (FY19-21)
SOT assessment is guiding R&D and driving down cost

- ***FY19 SOT Major Developments --- Reduced MFSP by $2.05/GGE***
  - Demonstrated extended hydrotreating (HT) catalyst lifetime by 83%
  - Increased HT reactor throughput by 34% (weight-hourly space velocity, WHSV)
  - Demonstrated a less expensive, equally effective HT catalyst
  - Demonstrated viability of multiple high-impact wastes (sludge, FOG, manure)
- ***FY20 SOT Major Developments --- Reduced MFSP by $0.61/GGE***
  - Models provided basis of heat exchanger re-design, which resulted in $0.26/GGE reduction and more scalable design for commercial operation
  - Increased hydrotreating throughput resulted in reduction of $0.34/GGE
  - Developed first predictive HTL yield model based on continuous system operation and estimated uncertainty in biocrude selling price
  - Models helped enable heat exchanger re-design (on PDU project)
  - With 2.0.1.113, laid groundwork for regional waste HTL modeling in FY21
- **FY21 Progress to date –**
  - **Go/No-Go delivered** and met with HTL regional blending scenario (≤$2.5/GGE)
  - On schedule to deliver **FY21 SOT** and help BETO meet **GPRA milestone**

HTL and Upgrading Plant Carbon and Energy Efficiencies

HTL Plant	2018/2019 SOT with NH_3 Removal	2020 SOT with NH_3 Removal	2022 Projected with NH_3 Removal
Carbon Efficiency			
Biocrude C / Feed C	65.4%	65.3%	72.1%
Biocrude C / (Feed + NG) C	59.2%	60.7%	65.5%
Energy Efficiency (LHV)[(a)]	60.5%	63.5%	68.8%
Energy Efficiency (LHV)[(b)]	62.5%	65.7%	70.6%
Upgrading Plant			
Carbon Efficiency			
Fuel C / Biocrude C	87.0%	87.0%	88.9%
Fuel C / (Biocrude + NG) C	82.5%	82.5%	83.2%
Energy Efficiency (LHV)[(a)]	85.5%	85.5%	85.9%

(a) Including extra electricity at WRRF for chemical oxygen demand (and including biomass energy)
(b) Excluding extra electricity at WRRF for chemical oxygen demand (and including biomass energy)
SOT = state of technology
WRRF= wastewater treatment and water resource recovery facility
NG = natural gas

Pacific Northwest
NATIONAL LABORATORY

Abbreviations and Acronyms

- ANL: Argonne National Laboratory
- AOP: annual operating plan
- BETO: Bioenergy Technologies Office
- BSM: Biomass Scenario Model
- CCCSD: Contra Costa County Sanitary District
- CHG: catalytic hydrothermal gasification
- DAF: dry, ash-free
- 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
- HTL: hydrothermal liquefaction
- INL: Idaho National Laboratory
- LCA: life cycle analysis
- LCI: life cycle inventory
- LHSV: liquid hourly space velocity
- 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
- SCSA: supply chain sustainability analysis
- SOT: state of research technology
- TEA: techno-economic analysis
- WeSys: Waste to Energy System Simulation
- WHSV: seight hourly space velocity
- WIP: Weatherization and Intergovernmental Programs
- WRRF: water resource recovery facility

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Thank you