# Bench Scale Hydrothermal Liquification of Wet-Wastes 2.2.2.302

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Organic Wastes Review Panel

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77 million dry tons of wet-waste per year

# Hydrothermal Liquefaction (HTL): A sustainable solution for wet-wastes

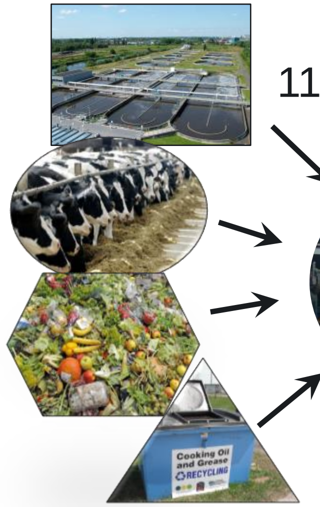
**Value of HTL**

1. HTL solves a wet-waste problem by eliminating wet-wastes (convert wet-wastes to fuel)
2. There is potential for 5.5 billion gallon/year of fuel in the U.S. (diesel $gallon_{eq}$).

**Robustness of HTL**

- Tolerates high solid content
- Accepts tremendous feedstock diversity (no drying!)
- Consistent biocrude product

# **Project Overview:** HTL is the most promising pathway for wet-wastes.



HTL Plant
110 dry tons/day/plant sludge

**HTL Conditions**
330-350°C / 2900 psig / 10-30 min
“Accelerating what the earth does”

HTL Biocrude

**Stable biocrude**
60% C-yield
Gravity-separable
Thermally stable

Hydrotreater

**Hydrotreater**
400°C / 1500 psig
“Standard refinery unit-op”

Hydrocarbon blendstock
(Diesel, Jet, Naptha)

**Fuel Blendstocks**
(95%+ C-yield)
Predominantly high cetane diesel (70%)

**Primary Challenge:** Reduce commercialization barriers

- Reducing uncertainty by retiring process assumptions (e.g., 500-hour catalyst life)
- Developing technology to reduce capital intensity of HTL (capital is the primary cost)

**Approach:** Targeted research based on shared learnings from PDU (3.4.2.301), Analysis (2.1.0.301) and Waste to Energy (2.1.0.113)

- Reduce cost of capital for HTL
- Improve hydrotreater catalyst activity and catalyst life

PDU= Process Development Unit

# **1 - Management:** Project interfaces proactively with related projects to leverage learnings/maximize value.

**BIOPROCESSING SEPARATIONS CONSORITUM**

**STRATEGIES FOR CO-PROCESSING IN REFINERIES**

CHALLENGES

SAMPLES

DATA

DATA AND SAMPLES

WET WASTE

Feedstocks, process viability, and process feedback

**Industrial PARTNERS and advisory boards**

Water Resource Recovery Facilities (e.g., Great Lakes Water Authority [GLWA])

Refineries

Universities (US and abroad)

International Energy Agency and consortiums

HTL Workshop (host)

**BENCH SCALE HTL *of Wet Waste Feedstocks***

Wet waste HTL donversion

Feedstock testing biocrude

Upgrading assessment-driven R&D

DATA

**HYDROTHERMAL PDU**

HTL process scale-up (pumping, heat exchangers, separations)

Upgrading catalyst evaluation and process development

Aqueous process development

Industrial engagement

Majority of HTL process development done here

DATA

COSTS

Experimental DATA

RESOURCE

Availability and compositions

**HTL MODEL DEVELOPMENT**

Assessment tools drive research

Techno-economic analysis

State of research

Technology life-cycle analysis

**RESOURCE ASSESSMENT**

Feedstock availability

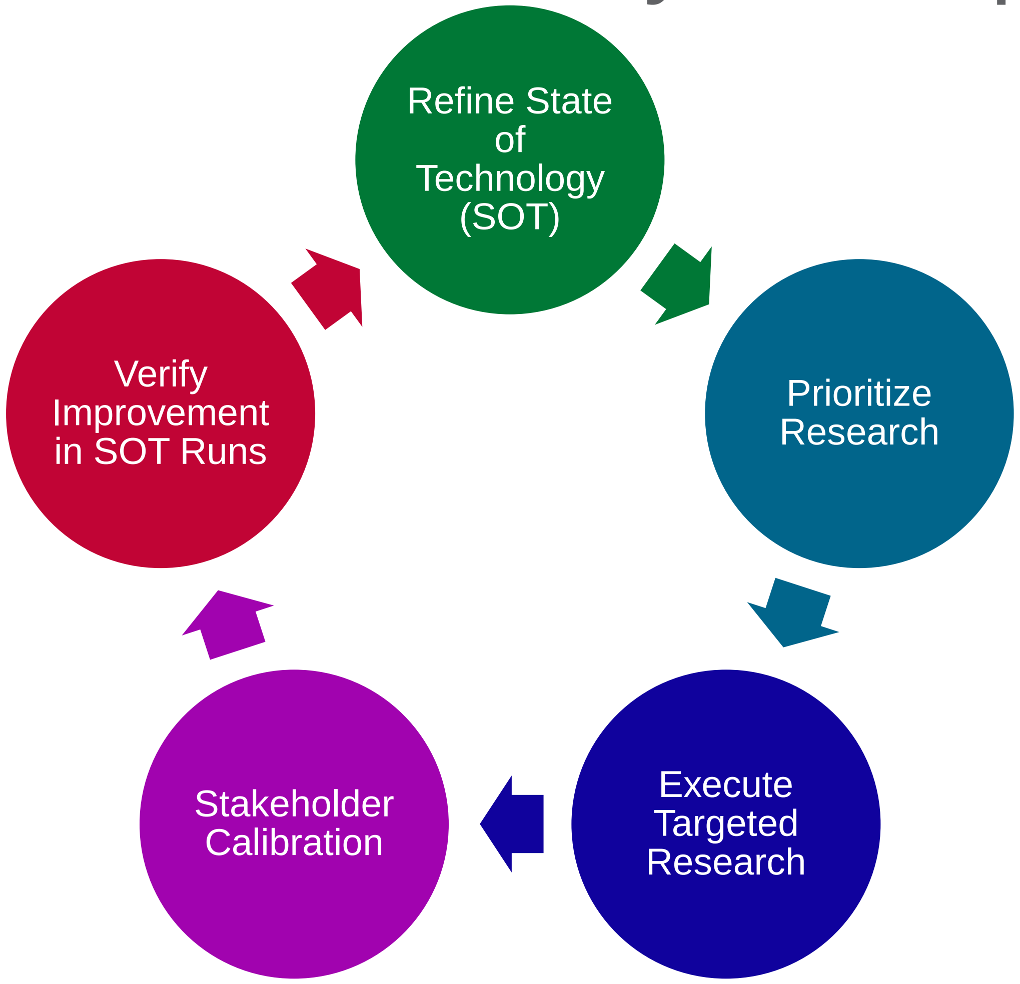
Feedstock performance

Realistic plant size

Transportation costs

PDU= Process Development Unit

# 1 - Management: Continuous iteration with economic analysis keeps focus on impactful research.

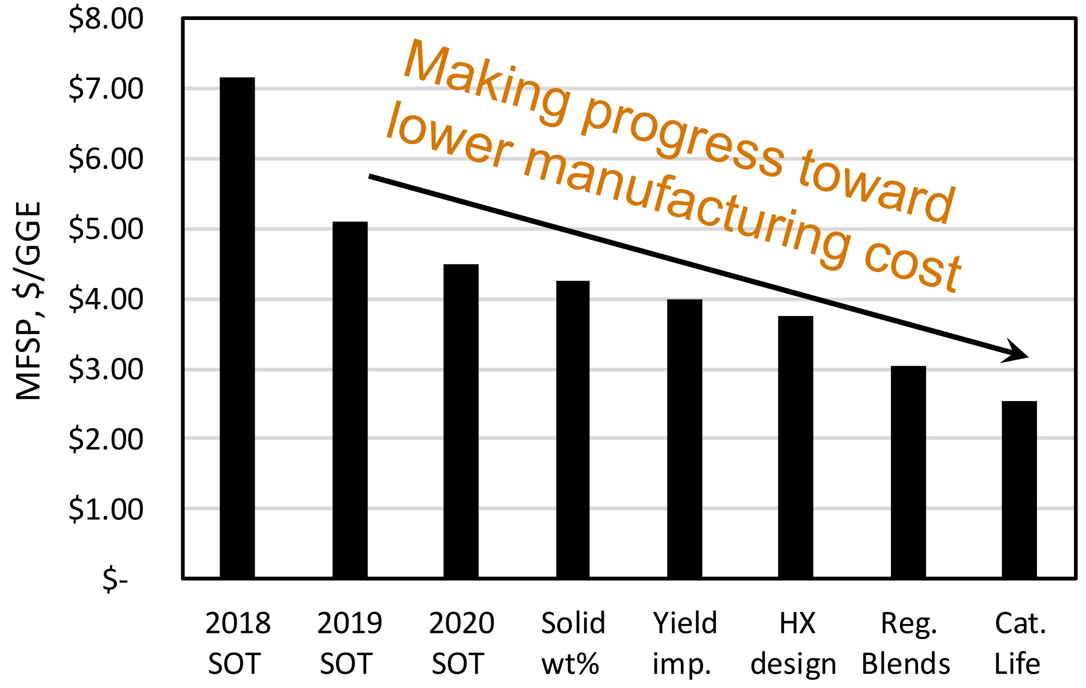



## Regular Communications

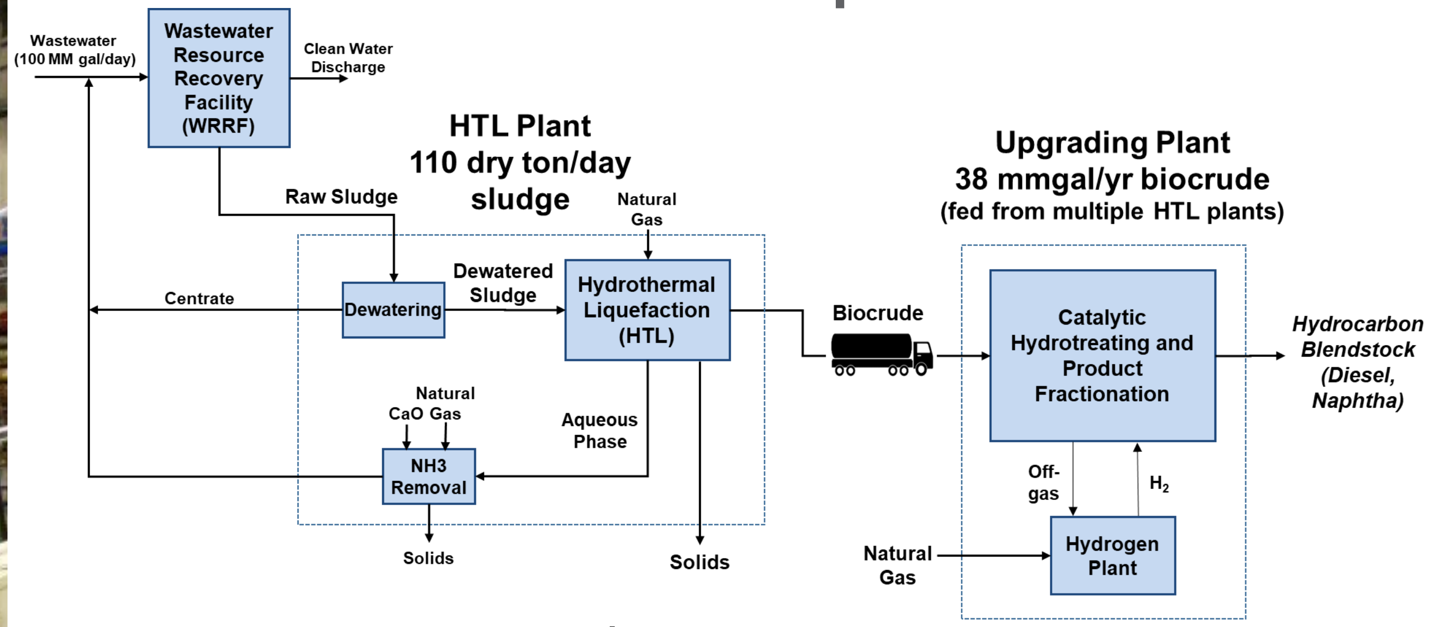
- Monthly cross-team meetings, including process research updates and economic implications
- Quarterly updates with Bioenergy Technologies Office (BETO) (video and written)
- Frequent vetting of alternative process ideas PDU (3.4.2.301), Analysis (2.1.0.301), Waste to Energy (2.1.0.113), and industrial collaborators

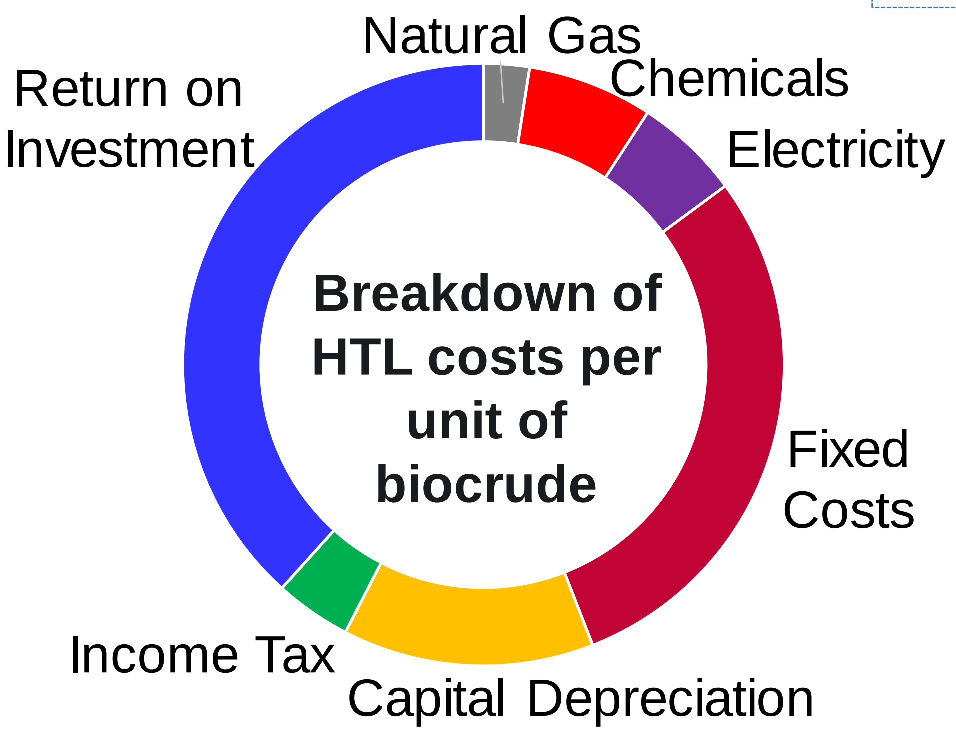
## Key Research Areas

- Regional wet-waste blending to increase plant size
- Process high wt% solids feedstock to reduce capital and increase process yield
- Increase hydrotreating catalyst activity and lifetime



# 2 - Approach: Example of leveraging techno-economic analysis (TEA) and resource assessment to drive process research



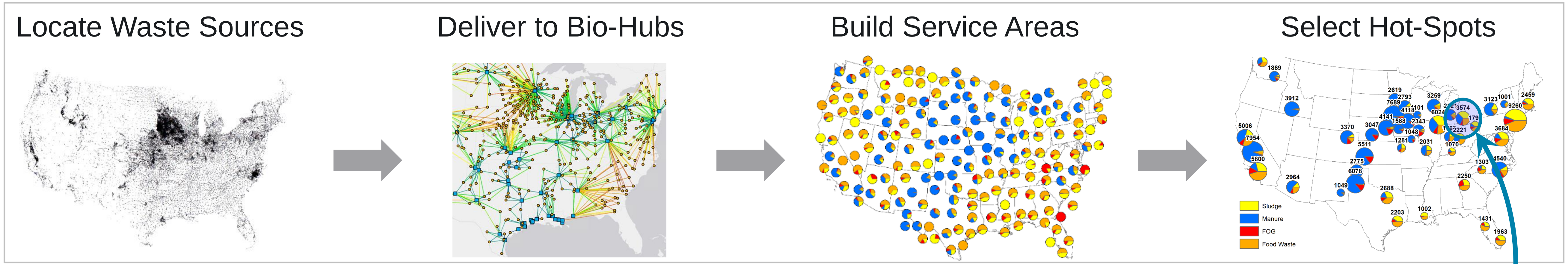

**Collaboration:** Analysis team (WBS 2.1.0.301) identified the majority of HTL costs lie in capital costs.

- Drives brainstorming on ways to reduce capital
  - Example: Increasing plant size to 1,000 dry tons/day (from 100 dry tons/day) decreases minimum fuel selling price (MFSP) by $0.69/ gas gallon equivalent (GGE) (WBS 2.1.0.301).

**Outcomes:**

- Motivates realistic transportation costs, plant sizes, and wet-waste compositions for regional HTL plants (WBS 2.1.0.113).
- Evaluate impact of regional wet-waste blends on HTL and upgrading process performance and yields.

# 2 - Approach: Example of leveraging techno-economic analysis and resource assessment to drive process research

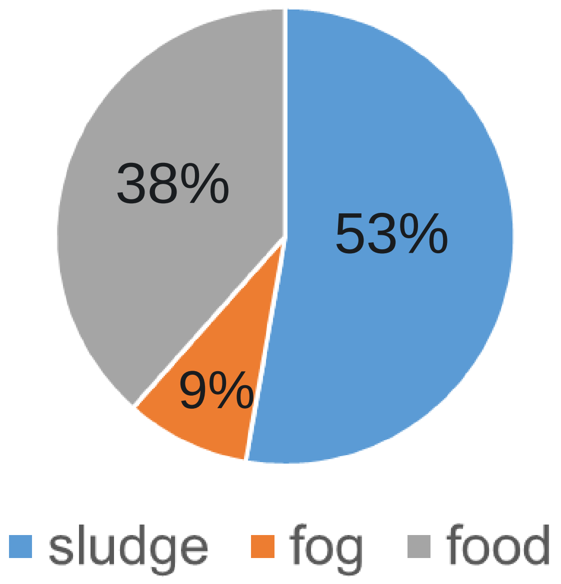



**Collaboration:** The "Waste to Energy" Team (WBS 2.1.0.113) modelled feedstock supply to determine realistic blending ratios.

- 82% of total wet organic feedstocks in the U.S. can be processed at HTL conversion hot spots (≥1000 dry metric t/d) with transportation costs of $50 per dry metric ton.
- Detroit, MI, selected as a representative blending profile at a ratio of 53:38:9 sludge-food-FOG.

**Outcome:** Experimental plans to characterize HTL conversion efficiency for a "typical" metro area with potential for significant reduction in modelled HTL fuel price.

*Detroit, MI wet-waste profile (observed):*




*(exclude manure)*

FOG= Fats Oils and Grease

# 2- Approach: Regional wet-waste blends

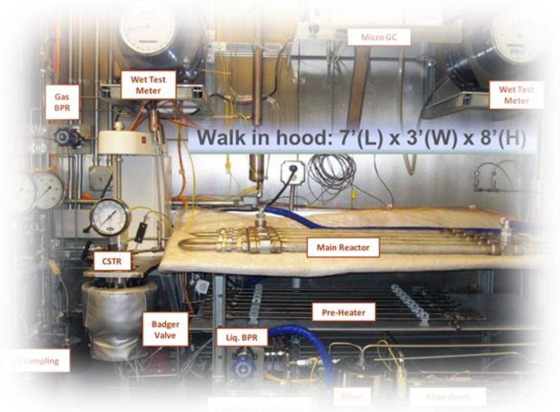
**Objective:** Use realistic regional wet-waste blends to increased HTL plant size

- Increasing plant size to 1,000 dry tons/day (from 100 dry tons/day) decreases MFSP by $0.69/GGE.

**Approach:** Test representative wet-waste blends for regional hot spots as compared to stand-alone wet-wastes.

- Real and representative feedstocks sourced from partners and collaborators.
    - Addressing real-world formatting challenges
    - No model or simulated feeds
- Use continuous flow tubular reactors which scale directly from bench to engineering reactors.

**Bench-Scale**




**Engineering-Scale**

**Risks to experimental approach:**

- **Feedstock Availability:** Foster relationships with real-world waste generators [e.g., GLWA). Coordinate early with resource assessment team and real waste generators to define realistic regional blend "hot spots".
- **Negative Impacts of Blended Wastes:** Evaluate HTL of individual wet-waste streams (e.g., sludge, food) to biocrude and upgrading to fuel blendstocks.

**2021 Milestones**

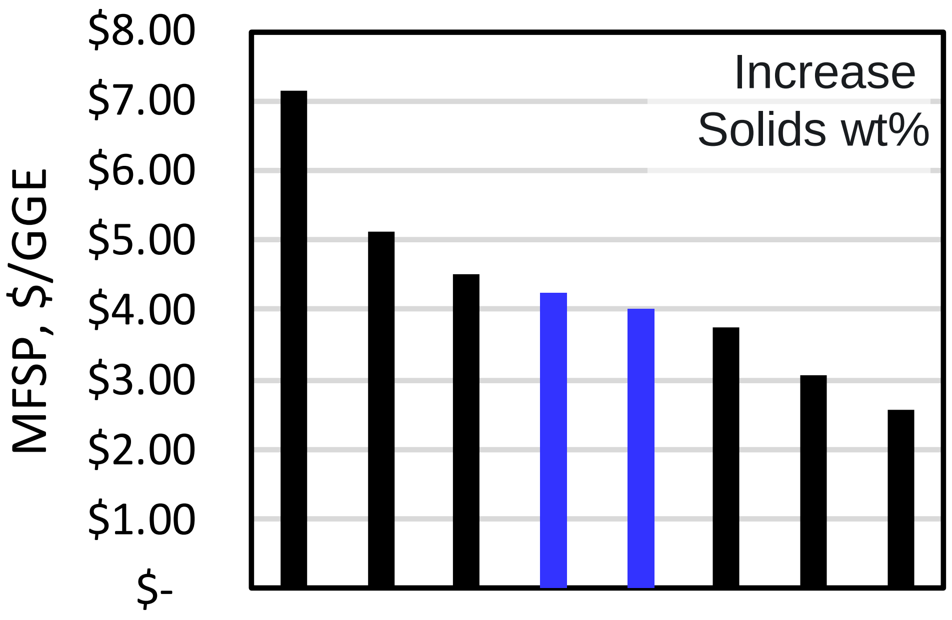
- Test at least one blend to support a 9x increase in the scale of HTL plant size compared to the design case (110 dry tons/day) while maintaining the design case biocrude yield of 44%.
- Quantify and report the yield of plastic to fuel when blended and co-processed with a wet-waste stream

GLWA = Great Lakes Water Authority

# 2 - Approach: Process wet-wastes with high solids content to reduce capital costs and improve yields

**Objective:** Increase HTL process yield and reduce HTL capital costs by processing wet-waste feedstocks with elevated solids content.

- TEA shows solids content significantly impacts HTL conversion costs.
- 25 wt% is a realistic solids feedstock conc.




**Approach:** Modify process equipment to handle high solid wt%.

- Demonstrate pumpability with multiple 25 wt% feeds.
- Commercial pumps can pump 25 wt% wet-waste streams.

Process a wet-waste stream at solids contents between 20 to 25wt% to make clear correlations.

- Use continuous, scalable HTL system and real waste streams.

**Risks to Experimental Approach:**

*Pumpability*: Laboratory equipment can't pump high solids feed.

- Modify equipment and replace pumps, if necessary.

*Improved Yield*: No yield improvement from increased solids wt%.

- HTL wood data indicates yield correlated to solids content.

**2021 Milestone:** Modify experimental equipment and demonstrate pumping of feedstocks with solids content of 25% at a rate of 4L/hr for four hours.

**2021 Go/No-Go (Q1):** Determine the impact of increased solids content (25%) on HTL and upgrading to fuels.

# 2- Approach: Improve hydrotreater catalyst activity and lifetime.

**Objective:** Reduce upgrading costs by increasing hydrotreater catalyst activity (catalyst development) and extending hydrotreating life.

**Approach:** Leverage catalyst development and learnings from PDU (3.4.3.201) to improve hydrotreating catalyst activity and life.

- All testing done on whole pill extrudates to ensure scale-able data
  - Satisfy criteria necessary to ensure data quality (Mear's criteria, Gierman criteria, etc.)
- >20x scale-up from bench to engineering hydrotreater demonstrates scaleability performance

**Risks to Experimental Approach:** *Catalyst Activity:* Upgraded fuel does not meet fuel blendstock specifications at elevated flow rates.

- Partner with industrial catalyst suppliers
- Evaluate multiple catalyst types (NiMo, CoMo) and extrudate sizes on partnership project (PDU, 3.4.3.201)

*Catalyst Life:* Catalyst deactivation limits life.

- Develop guard bed reactors to pre-treat biocrude (slurry and fixed-bed reactors) to on PDU (3.4.3.201)

**2020 Milestone:** Increase catalyst weight hour space velocity (WHSV), a measure of reaction rate or catalyst activity, from 0.3hr$^{-1}$ to 0.5 hr$^{-1}$

**2022 Milestone:** Achieve 2,000 hours of stable hydrotreating performance at a WHSV of 0.75 hr$^{-1}$ (2022)

WHSV = Weight Hour Space Velocity, a measure of reaction rate or catalyst activity, PDU= Process Development Unit

# **3 - Impact:** Clear path to improving economic viability of HTL

## Aligned with BETO Conversion Goals:

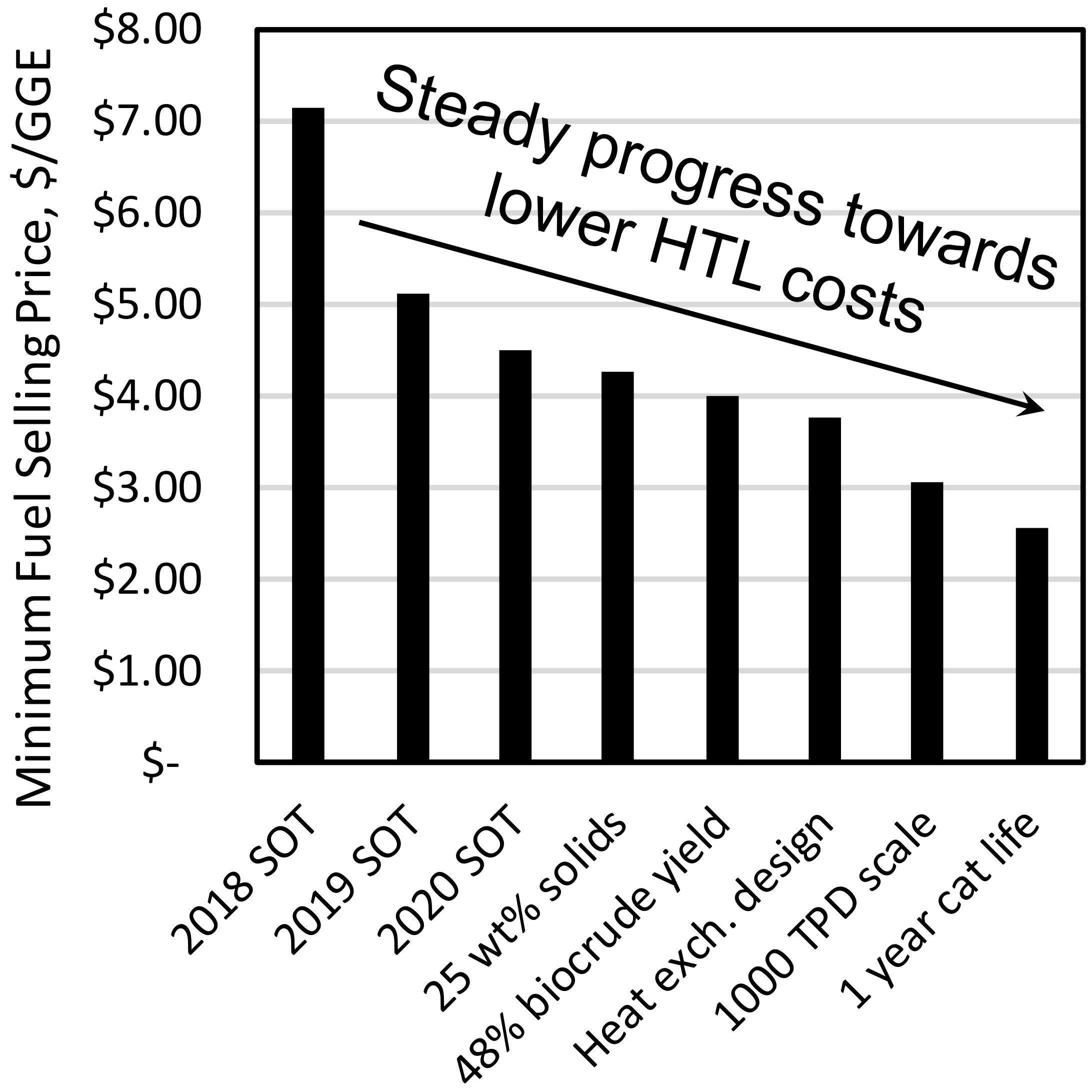
*Planned improvements provide clear path to $3/GGE in 2022 and $2.5/GGE in 2030.*

## 2021 GPRA Goal Aligned to this Project:

*Provide final SOT achieving a modeled cost of $3.03/GGE.*

## Impactful Improvements:

- Reduced the cost of NiMo hydrotreater catalyst and increased catalyst activity, including:
  - Extended hydrotreater catalyst life beyond 500 hours; and
  - Increased catalyst activity over 3x.
- Increase solids loading for process intensification.
  - Improvement in process yield via increased solids loading.
- Demonstrated viability of multiple high-impact wet-wastes
  - Regional wet-waste blending to increase plant size to 1000 TPD.

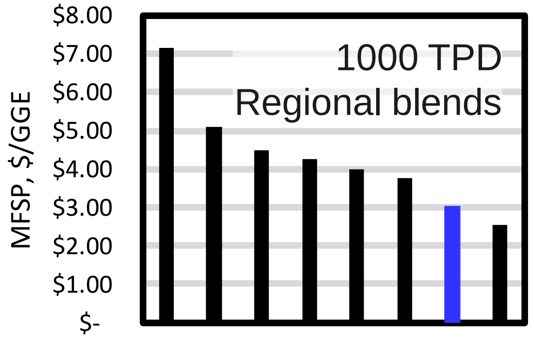


# 3 - Impact: Providing impact towards HTL commercialization

- Advancing HTL technology to reduce technology uncertainty
  - Providing a sustainable means of **converting wet-waste streams** to fuels
  - Advanced **HTL and upgrading process technology** for **wet-wastes**
  - Providing **scale-able**, commercially relevant HTL and upgrading data
  - **Retiring process assumptions** to reduce modelled HTL conversion costs
- Advancing HTL knowledge sharing and collaboration
  - Project is supporting **collaborative annual operating plan and competitive projects** with the U.S. Department of Energy (DOE).
  - Hosted internationally attended **HTL workshop** focused on jet fuel.
  - **Invited as advisor for international projects,** including International Energy Agency Bioenergy Task 34: Direct Thermochemical Liquefaction, HyFlexFuel: HTL Consortium.
- Advancing the prospects for HTL commercialization
  - Project has led to several **industrial collaborations** and projects
  - Supporting **pilot plant project opportunities**

***Project provides impact for DOE, the research community, and opportunities for technology commercialization.***

# 4 - Progress and Outcomes: *HTL of food waste, a wet-waste blendstock*



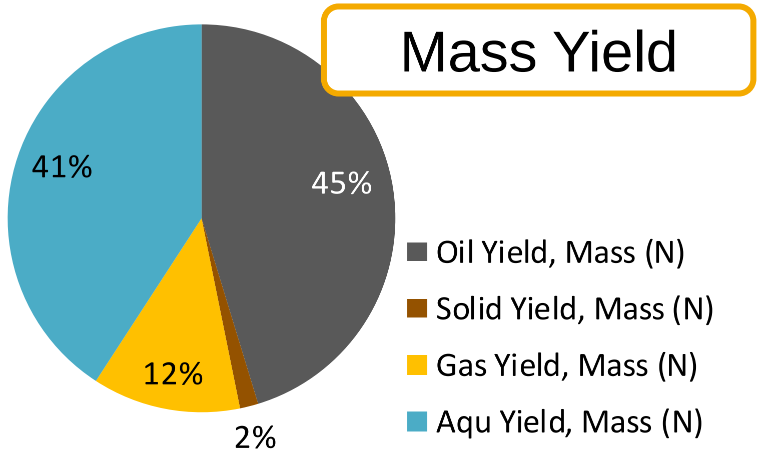

**Objective:** Test a regional wet-waste blend to support a 9x increase in HTL plant size while maintaining a biocrude yield of 44% (2021 milestone)

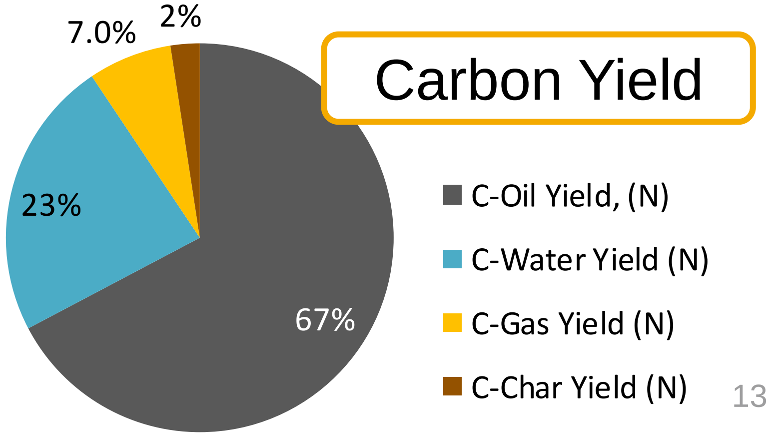
**Progress:** Tested individual components of regional wet-waste blend

- Testing HTL of food waste from a regional prison cafeteria in a continuous, plug-flow HTL reactor gives similar performance to HTL of sewage sludge.
  - *Quality Feedstock Attributes*: High solids without concentration (23%), low ash (<5 %), and high fat (18%)
  - *Good Process Performance*: Improved HTL yields (45%), carbon yields (67%), and above average biocrude
- Promising hydrotreating results of the HTL biocrude
  - Low density (0.81g/ml) of upgraded product
  - Similar upgraded oil oxygen content (0.23% vs 0.18% for sewage sludge)

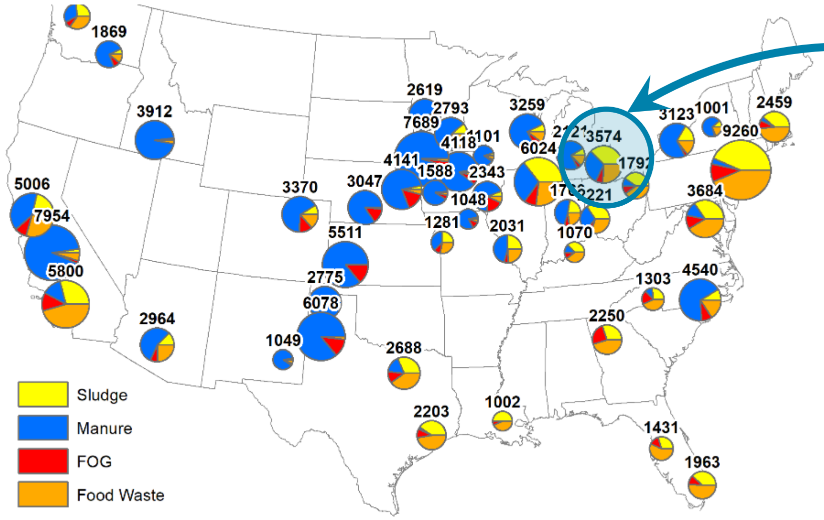
**Key Learning:**

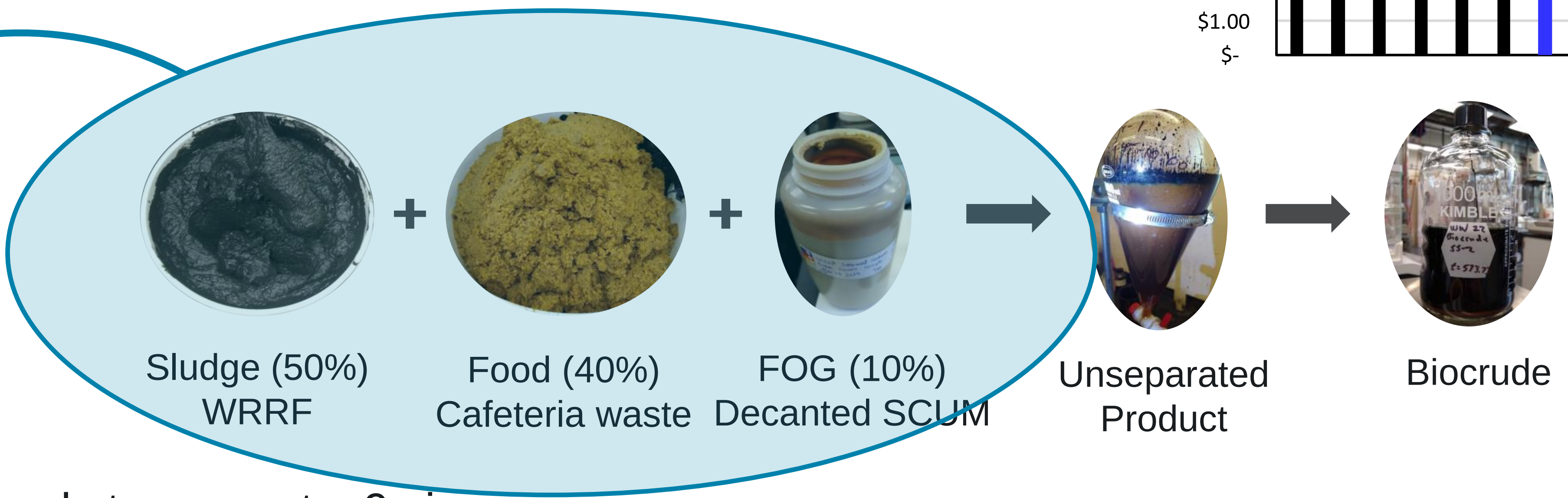
***Food waste makes an excellent HTL feedstock.***

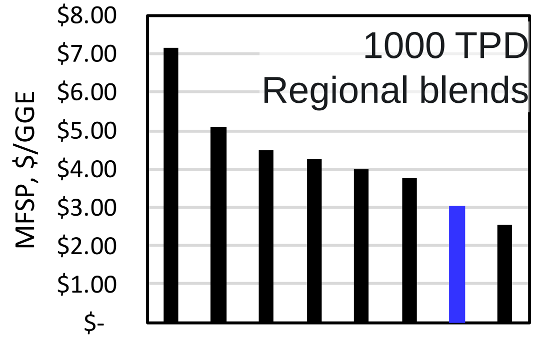



# 4 - Progress and Outcomes:
## Representative real-world regional blend




**Objective:** Test regional wet-waste blends to support a 9x increase in HTL plant size while maintaining a 44% yield (2021 milestone).

**Progress:** Tested representative, real-world regional blend using real-world wet-waste streams (food waste, sludge, FOG).

- Resource-informed HTL feedstock composition

*HTL Performance*:

- Consistent biocrude yield / properties
- Pending hydrotreating results

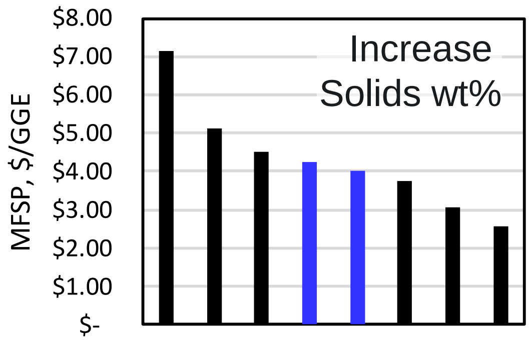
**Impact:** Blended wet-wastes = excellent HTL feedstock

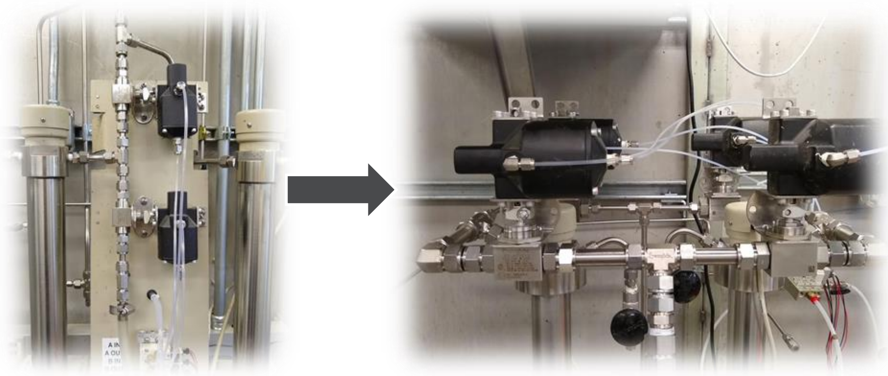
Bonus: HTL of PET has promising results as a blendstock

| Biocrude Properties | | Food Waste | Regional Blend (Consistent) | Sewage Sludge |
|---|---|---|---|---|
| Carbon | wt% | 75.9% | 74.8% | 78.0% |
| Hydrogen | wt% | 11.2% | 11.5% | 10.6% |
| dry calc HHV | MJ/kg | 38.7 | 38.8 | 39.1 |
| Oxygen | wt% | 8.6% | 8.0% | 5.3% |
| Nitrogen | wt% | 4.3% | 4.8% | 5.0% |
| Sulfur | wt% | 0.0% | 0.7% | 1.0% |
| TAN | mgKOH/goil | 110 | 98 | 52 |
| Density | g/ml | 1.00 | 0.96 | 0.98 |
| Filterable Solids | wt% | 0.08% | 0.14% | 0.15% |

WRRF = Water Resource Recovery Facility, PET = Polyethylene Terapthalate

# 4 - Progress and Outcomes: Increase solids content in HTL wet-waste blends




**Pumping is only a challenge at the laboratory scale.** Existing pumps exists at commercial scale.

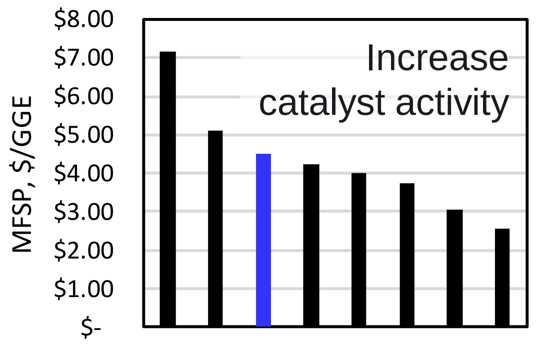
**Impact:** Increased solids content improves yield and reduces HTL capital costs.

**Objective:**

- **2021 Milestone:** Modify experimental equipment and demonstrate pumping of feedstocks with solids content of 25% at a rate of 4L/hr for four hours.
- **2021 Go/No-Go (Q1):** Determine the impact of increased solids content (25%) on HTL and upgrading to fuels.

**Progress**:

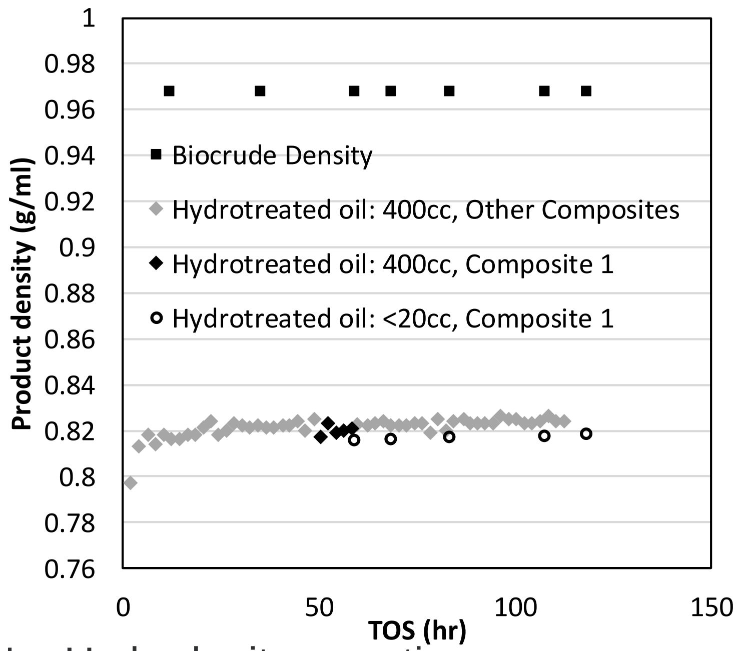
- Modified process equipment to enable pumping higher solids content using laboratory equipment
- Demonstrated pumping 25 wt% solids feedstocks and tested pump modifications with for >4 hours at >4L/hr (2 feedstocks)
- Processed regional “hot-spot” blend with real-world wet-waste streams at 20 and 25 wt% solids
  - Increase in biocrude yield (>2%) from high solid content
    - $46^{+}$% yield at 25 wt% (vs 44% in design case)
  - >60% carbon yield to biocrude
- Consistent biocrude quality
  - Low viscosity, density
  - Consistent ash, oxygen, sulfur, and nitrogen %
- Concurrent efforts under way to scale-up process with higher solids systems in the scaled-up system (PDU, 3.4.2.301)

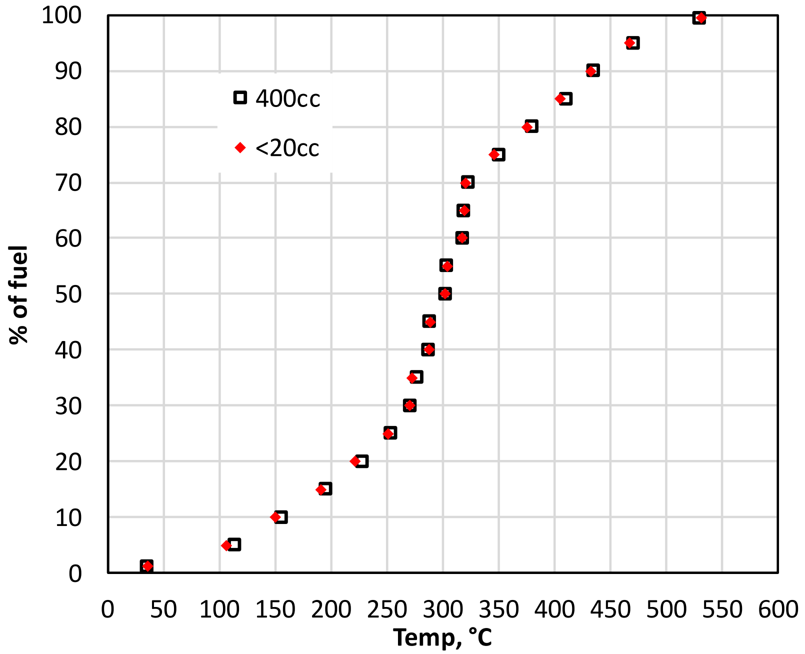


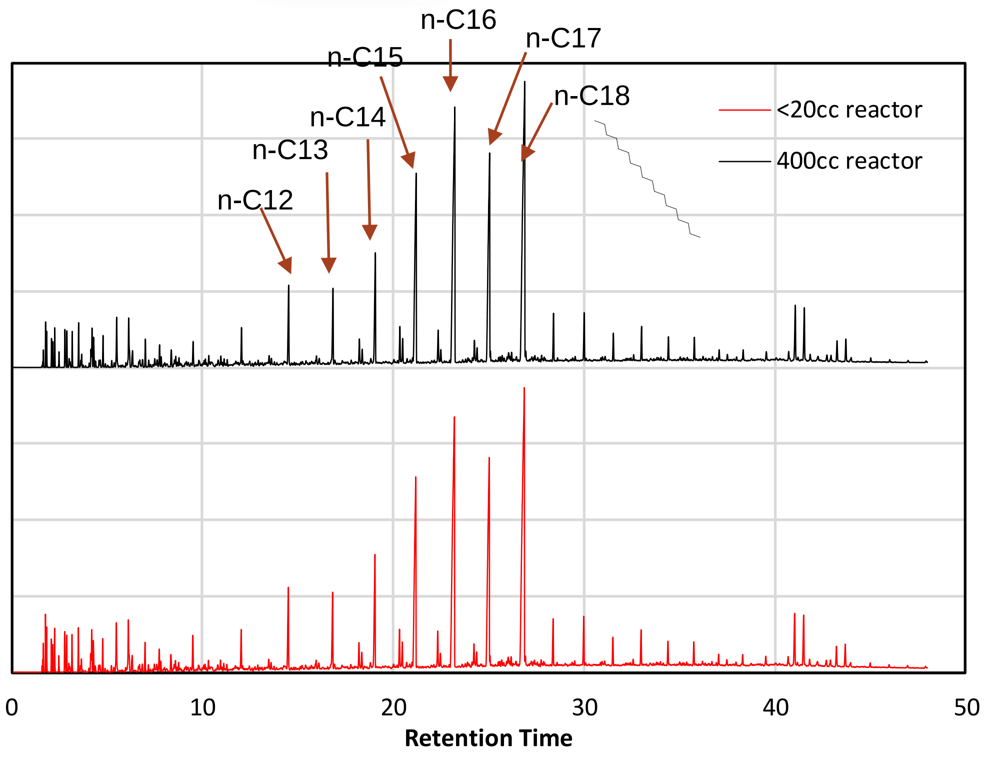

# 4 - Progress and Outcomes: Increased reactor WHSV with scale-able data

**Objective:** Increase catalyst WHSV from 0.3 $hr^{-1}$ to 0.5 $hr^{-1}$ (2020 milestone).

- 3x increase in hydrotreater catalyst activity (WHSV: 0.3→1.0 $hr^{-1}$)
  - Improved HDN catalyst (NiMo); lower cost catalyst
  - High cetane diesel product; diesel cut: 72%
- Scalable results
  - Leveraged industrial practices of co-packing with inert material
  - Matched scale-up performance (HTL PDU, 204.4.301)
  - Good agreement in density, GCMS, and SIMDIS

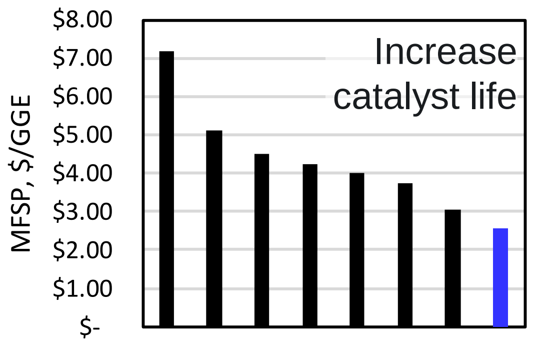




HDN = Hydrodenitrogenation

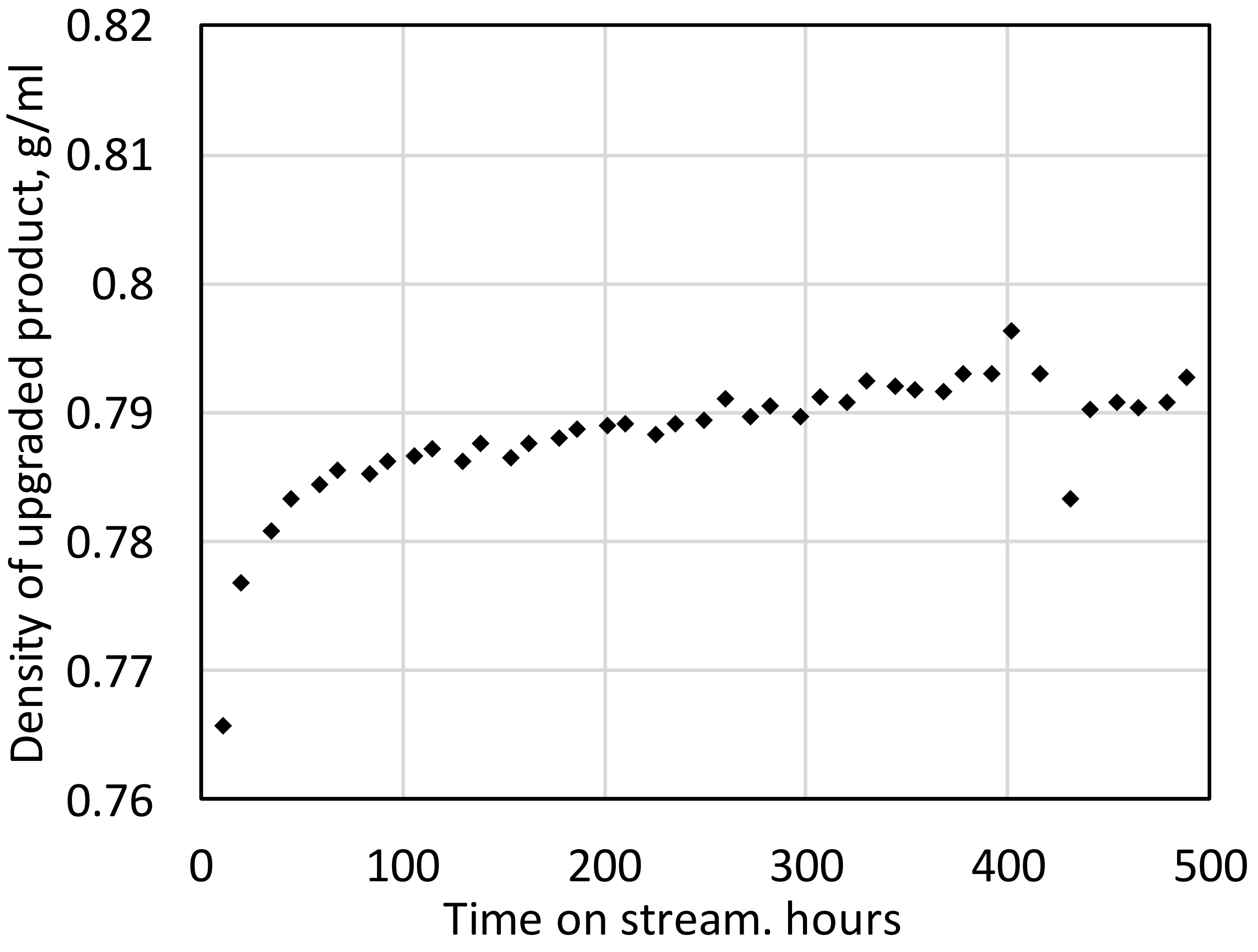
# 4 - Progress and Outcomes: Increase hydrotreater catalyst lifetime




**Objective:** Achieve 2,000 hours of stable hydrotreating performance at a WHSV of 0.75 $hr^{-1}$ (2021 milestone).

**Progress:**

- **>500 hours on stream** with on-spec product at a WHSV of 0.75 $hr^{-1}$
- **4.2 L** of biocrude from a sludge + FOG feedstock were upgraded catalytically in a trickle-bed bench-scale hydrotreater
- Low product density (<0.80g/ml)
  - FOG decreases the upgraded fuel density
- High diesel yield (70%)
- 2022 Plans: 2000-hour hydrotreater run
  - 2000-hr run completed to understand catalyst deactivation (via PDU, 3.4.2.301)




Impact: Significant progress extending hydrotreater catalyst lifetime

# Summary

- **Overview:** Executing on strategy to meet SOT target of $3/GGE in 2022
- **Approach:** Carry out targeted research prioritized based on TEA
- **Impact:** De-risk commercialization of HTL by advancing the technology to enable an economically viable pathway to fuel for <$2.50/GGE by 2030
- **Progress and Outcomes:**
  - ✓ Reduced hydrotreating costs via improved catalyst with increased WHSV
  - ✓ Intensified HTL process and improved process yield via increase solids loading
  - ✓ Demonstrated viability regional HTL processing by converting high-impact, regional wet-wastes to quality HTL biocrudes. This will enable increased plant size.
- **Forward Looking Plans:**
  - ✓ Upgrade biocrudes derived from regional “hot-spot” blend and high solid content to determine the impact of the entire HTL waste to fuel process (2021)
  - ✓ Evaluate regional waste “hot-spot” blend high in manure (2021)
  - ✓ Achieve modelled hydrotreater catalyst lifetime of one year through long TOS (2,000 hours$^{+}$) testing and effective guard bed utilization (2022)

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# Acknowledgements

- Beau Hoffman, BETO Technology Manager
- Mark Philbrick, BETO Waste-to-Energy Coordinator

**Experimental Team:**

- Andy Schmidt
- Justin Billing
- Mike Thorson
- Dan Anderson
- Rich Hallen
- Todd Hart
- Sam Fox
- Miki Santosa
- Senthil Subramanian
- Igor Kutnyakov
- Matt Flake

**PDU Team**

**Analysis Team:**

- Yuan Jiang
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- Yunhua Zhu
- Aye Meyer
- Lesley Snowden-Swan

**Waste Resource Team:**

- Tim Seiple
- Andre Coleman

PDU= Process Development Unit

# Quad Chart Overview

## Timeline
- Project start date: 10-01-2019
- Project end date: 9-30-2022

| | FY20 | Active Project |
|---|---|---|
| **DOE Funding** | $360K | $1,080K |

## Project Partners: NMSU, Genifuel, WRF, MetroVancouver, Central Contra Costa Sanitary District, GLWA - City of Detroit, Aloviam

Collaborators: National Renewable Energy Laboratory/PNNL – Waste To Energy Resource Assessment, Bioprocessing Separations Consortium, Oak Ridge National Laboratory – Materials of Construction, Strategies for Co-Processing in Refineries, HYPOWERS team

## Barriers Addressed
Ct-I. Development of Processes Capable of Processing High-Moisture Feedstocks in Addition to Conventional Anaerobic Digestion

Ct-E. Improving Catalyst Lifetime

## Project Goal
Improve impact and cost performance of the HTL technology through targeted research and development. Using TEA and resource assessment tools to prioritize research; tasks for the current fiscal year include:
- Hydrotreating catalyst life and activity
- Biocrude yield improvement through increased solids content, feedstock blending, and liquid phase separations
- Improved ammonia removal from HTL aqueous

## End of Project Milestone
Exceed the 2022 goal case for upgrading wet-waste derived HTL biocrude. Demonstrate catalytic upgrading of wet-waste derived HTL biocrude with improved scalable reactor design, higher activity catalyst, and biocrude pretreatment.

Achieve a WHSV of 0.75 $h^{-1}$ and an extended TOS of 1,000 hours.

## Funding Mechanism
Laboratory Call Annual Operating Plan 2019

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# Additional Slides

# Responses to Previous Reviewers' Comments

Weakness: The project did not yet quantify progress to improve cost performance from hydrotreating catalyst life, increased solids content, feedstock blending and liquid phase separations or ammonia removal.

- The reviewers were correct to identify the need to improve the hydrotreating performance which have a significant impact on the modelled minimum fuel selling price (MFSP)
- Significant strides were made in increasing the hydrotreating catalyst life and activity since the last peer review. Much of the cost reduction from the 2018 SOT ($7.16/GGE) through the 2020 SOT ($4.50/GGE) was due to hydrotreater improvements in both activity and life of the catalyst (both main hydrotreater and the guard-bed).
  - Collaborations were made to test commercial hydrotreater catalysts
  - Hydrotreater activity of was increased more than 3x
  - Catalyst life was demonstrated beyond 500 hours
    - ✓ Data from the process development unit (3.4.2.301) shows stable catalyst performance in a 2000 hour run

SOT = State of Technology

# Publications, Patents, Presentations, Awards, and Commercialization

- Publications and Patent Applications
  - JM Jarvis, KO Albrecht, JM Billing, AJ Schmidt, RT Hallen, TM Schaub. “Assessment of hydrotreatment for hydrothermal liquefaction biocrudes from sewage sludge, microalgae, and pine feedstocks.” *Energy & Fuels* 32 (8), 8483-8493.
  - JR Collett, JM Billing, PA Meyer, AJ Schmidt, AB Remington, ER Hawley, et al. “Renewable diesel via hydrothermal liquefaction of oleaginous yeast and residual lignin from bioconversion of corn stover.” *Applied Energy* 233, 840-853.
  - LJ Snowden-Swan, JM Billing, MR Thorson, AJ Schmidt, DM Santosa, et al. “Wet-Waste Hydrothermal Liquefaction and Biocrude Upgrading to Hydrocarbon Fuels: 2019 State of Technology.” PNNL. Richland, WA.
  - Dan Anderson, Justin Billing, Richard Hallen, Todd Hart, Andrew Schmidt, Lesley Snowden-Swan and Michael Thorson. Filed January 10, 2020. “Hydrothermal Liquefaction System.” US Pat Appl 16/740,339.
  - 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, 151-168.

# Publications, Patents, Presentations, Awards, and Commercialization

- Presentations
  - Santosa D.M., A.J. Schmidt, J.M. Billing, D.B. Anderson, and Y. Zhu. 10/07/2019. "Evaluating effect of silaging of Pine/Chlorella Blend via Hydrothermal Liquefaction (HTL) and hydrotreating (HT) pathway." TC Biomass 2019, Chicago, Illinois.
  - Santosa D.M., and M.R. Thorson. 10/07/2020. "Improving Scalability Of Hydrotreating Reactor: Upgrading Of Biocrude To Fuel Blendstocks." TCS 2020, Richland, Washington.
  - Thorson M.R., R.T. Hallen, K.O. Albrecht, J.M. Jarvis, T. Schaub, T.L. Lemmon, and J.M. Billing, et al. 10/07/2019. "Challenges Upgrading HTL Biocrudes." TC Biomass 2019, Rosemont, Il, Illinois.
  - 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.
  - 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.
  - Billing J.M., L.J. Snowden-Swan, A.J. Schmidt, M.R. Thorson, R.T. Hallen, and D.B. Anderson. 06/16/2020. "Successful scale-up of continuous hydrothermal liquefaction (HTL) systems to enable resource recovery from wet organic wastes." Presented by J.M. Billing at ACS Green Chemistry & Engineering Conference, Online, United States.
  - Billing J.M., A.J. Schmidt, L.J. Snowden-Swan, T.R. Hart, D.B. Anderson, and R.T. Hallen. 09/08/2019. "Hydrothermal Liquefaction of Wastewater Sludge: Process Overview." Presented by J.M. Billing at Pacific Northwest Clean Water Association Pre-Conference Workshop, Portland, Oregon.

# Abbreviations and Acronyms

- BETO: Bioenergy Technologies Office
- DOE: U.S. Department of Energy
- FOG: Fats, Oils, and Grease
- GGE: gasoline gallons equivalent
- GLWA: Great Lakes Water Authority
- HTL: hydrothermal liquification
- MFSP: PDU: process development unit
- PFR: Plug Flow Reactor
- PNNL: Pacific Northwest National Laboratory
- SOT: State of Technology
- TEA: techno-economic analysis
- TPD: Dry Tons per Day
- WHSV: Weight Hour Space Velocity


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# Thank you