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DOE Bioenergy Technologies Office (BETO) 2017 Project Peer Review

Hydrothermal Processing of Biomass

March 7, 2017
Waste to Energy

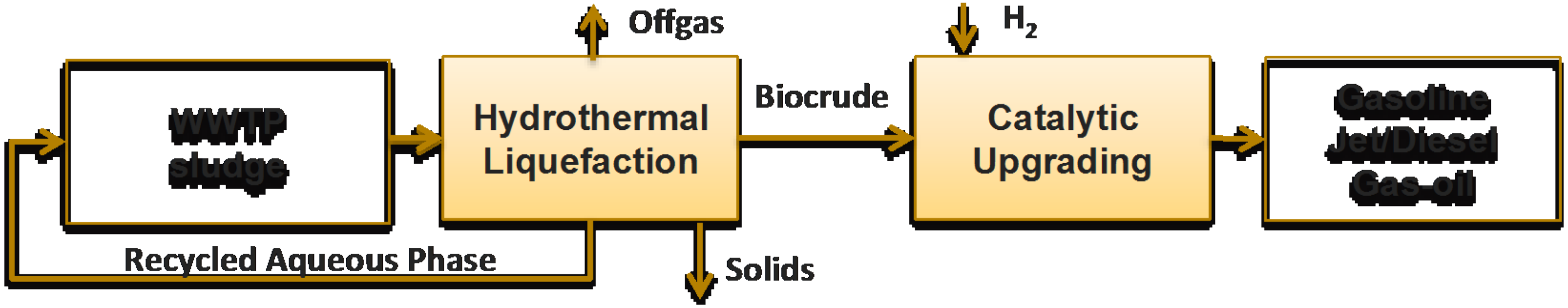
Justin Billing, Rich Hallen, Andy Schmidt,
Lesley Snowden-Swan

Pacific Northwest National Laboratory

Goal Statement

Provide scientific and engineering data for the successful commercialization of hydrothermal liquefaction (HTL) technology

- Demonstrate high process and carbon efficiencies for HTL with a broad range of feedstocks and assess value of biocrude for fuels and chemicals
- Improve overall process performance and economics to meet the Conversion Program goal of $3/gge.
- Determine the value and best pathway to market for the products
- Enable sustainable technology that reduces greenhouse gas emissions relative to petroleum-derived fuels, and displaces petroleum-derived products to enhance U.S. energy security
- Provide an additional pathway for utilizing wet and waste feedstocks important to meeting energy and sustainability challenges (MYPP goal)



Quad Chart Overview

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Timeline

- New project started by combining Improved HTL and Hydrothermal Processing of Wet Waste for FY 15
- FY15 milestone demonstrated viable business case for HTL of wet sludge
- FY 16 a new US WWTP partner for design case identified
- Current HTL effort 50% complete to meet FY18 Q4 Go/No-Go HTL performs at scale

Budget

	FY 15 Costs	FY 16 Costs	FY 17 Budget
DOE Funded	$1.35M	$1.8M	$2.05M

Barriers Addressed

- Ct-F. Efficient High-Temperature Deconstruction to Intermediates: Current SOT is 40-70% C efficiency
- Ct-H. Efficient Catalytic Upgrading of Intermediates to Fuels and Chemicals: Single stage HT at >95% C efficiency

Partners

- NMSU, biocrude characterization
- CSU, fuel evaluation
- Great Lakes Water Authority, Metro Vancouver and WE&RF, wastes
- Genifuel, licensee/commercialization
- Various other feedstock suppliers
- Other interactions/collaborations
  - NREL/PNNL – Waste to Energy Assessment
  - PNNL – TC Interface and Algae HTL Model Devel.
  - INL - Feedstock
  - ORNL – Corrosion
  - PNNL/NREL – Charac. & Valor. of Aq. Phases

1 – Project Overview

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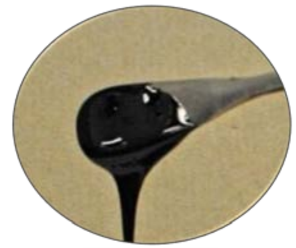
Hydrothermal Liquefaction (HTL)

Conversion of a biomass slurry (e.g., wet waste, wood, sludge) to biocrude and aqueous product

- 300–350°C
- 2800–3000 psig
- 10–30 min res. time

Slurry Feedstock



Biocrude Product

+

Aqueous Product (contains organics)

Hydrotreated Biocrude

Develop, demonstrate, and assess HTL technology for sustainable biofuels production.

- Team with others national labs, universities, commercial and industrial organizations
- Obtain currently available feedstocks
- Conduct experimental evaluation in continuous, bench-scale systems
- Generate data packages and conduct assessments

WATER ENVIRONMENT & REUSE FOUNDATION WE&RF

GLWA Great Lakes Water Authority

CITY OF DETROIT — DETROIT Water & Sewerage Department

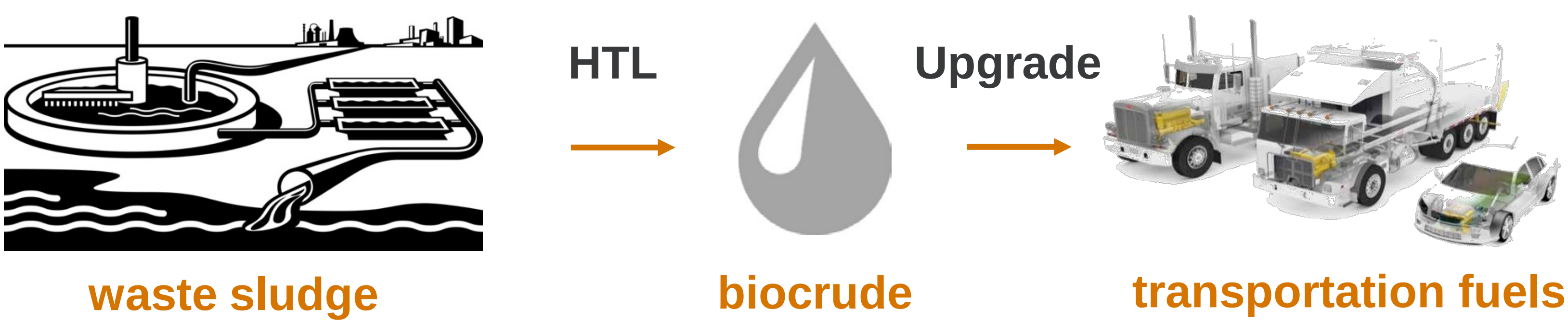
leidos

Genifuel

metrovancouver SERVICES AND SOLUTIONS FOR A LIVABLE REGION

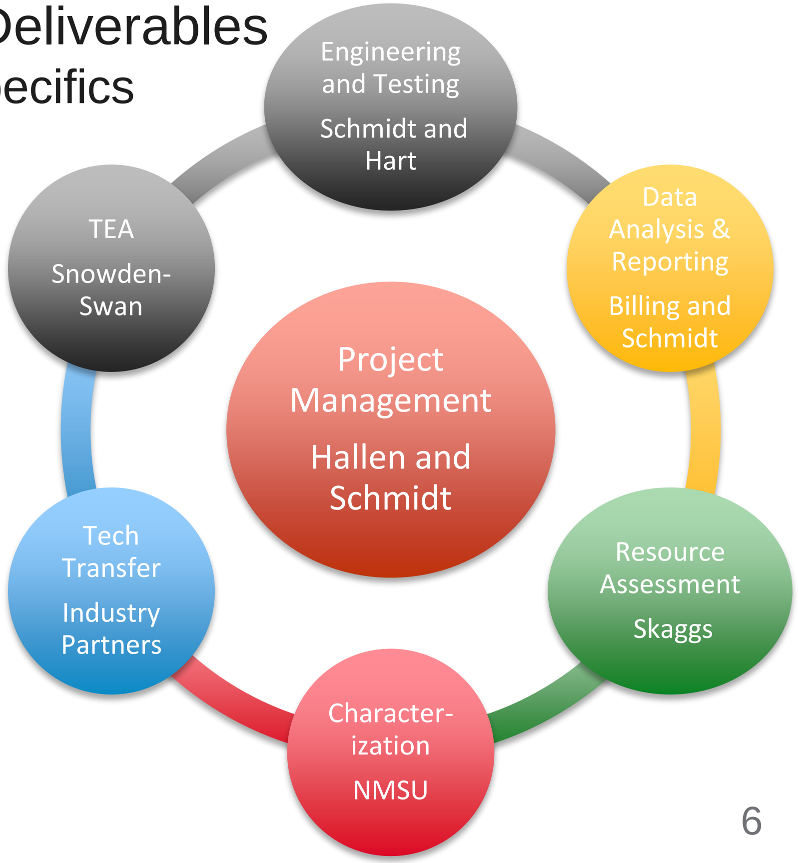
Overview - Why Invest in HTL?

- Robust and can be applied to wide range of feedstocks at similar processing conditions
- Conceptually simple (feed preparation, pump, heated pipe, gravity separate biocrude)
- Wet feedstocks (ag resid, sludge, manure) exploit HTL attributes and minimize deployment challenges associated with pumping
- HTL biocrude is thermally stable and can be readily upgraded
- High carbon efficiency to product; greater than 50% to HC product
- Economics compare favorably with other biomass conversion technologies
- HTL has not been commercially deployed. Issues are pumping to high pressures, scalable reactor configurations, and capital costs



2 – Approach (Management)

- Management Approach – Two Approved Project Management Plans
  - One for PNNL, one for BETO
- Marketability and Tech Transfer—Genifuel, WE&RF, municipalities, university analysts
  - Dissemination through publications, presentations, press releases
- AOP with scheduled Milestones and Deliverables
  - See Additional Slides for Milestone Specifics
- Weekly project meetings
- Coordination with assessment teams
  - Techno-economic analysis
  - Resource Assessment
- Regular updates to BETO
  - Quarterly Reports
  - Deep Dives
  - Highlights Conversion Call



2 – Approach (Technical)

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Advancement of HTL → move towards \$3/GGE at >50% reduced GHG

- Testing with continuous flow reactor designs → Scalable reactor designs and higher volumetric efficiencies reduce \$/GGE and commercial barriers
- Feedstock testing → HTL is feed flexible, but specific yields of diverse feeds must be determined to unravel chemistry and assess economics.
- Detailed characterization of biocrudes → understand impacts of feedstock and process conditions on biocrude quality
- Characterize upgraded product for evaluation as blendstock and/or for refinery insertion

Technical Feasibility & Process Economics of HTL of Wet Waste

- Resource inventory and feedstock characteristics (WTE, agriculture residuals, WWT sludges, other industrial byproducts and wastes)
- Working with industrial partners (municipal WWTPs, WE&RF and licensee)
- Experimentally conduct HTL tests to determine biocrude yields
- Determine yield and quality of upgraded product

3 – Technical Accomplishments/ Progress/Results

DOE Consortia

- **2011-2014** NABC - Wood
- **2010-2013** NAABB - Algae

2015-2016 WE&RF WWTP Project

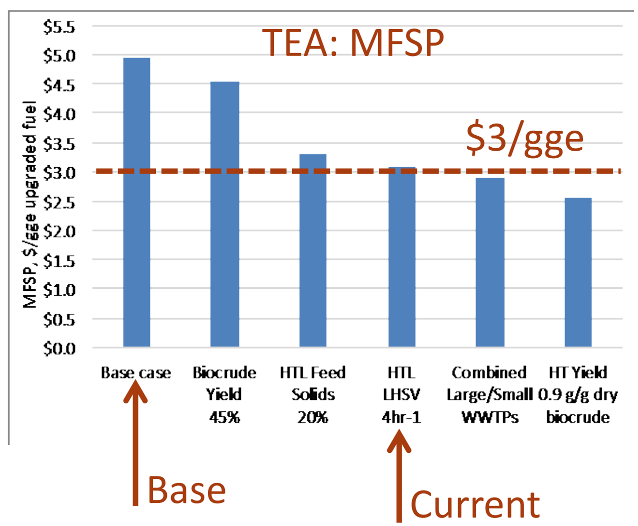
- Demonstration
- Report/Validation
- TEA and LCA
- **Recommendations and Goal Case**

12 of 14 recommendations were addressed or implemented. The other two applied to CHG.

Assessment-driven research and development

2015 Wet Wastes

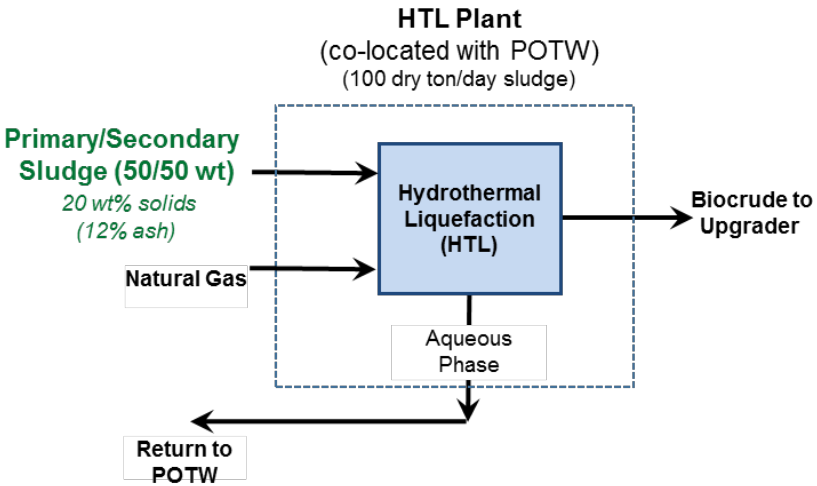
- Grape Pomace, Spent Grain
- Oleaginous Yeast + Lignin
- **WWTP Sludge**



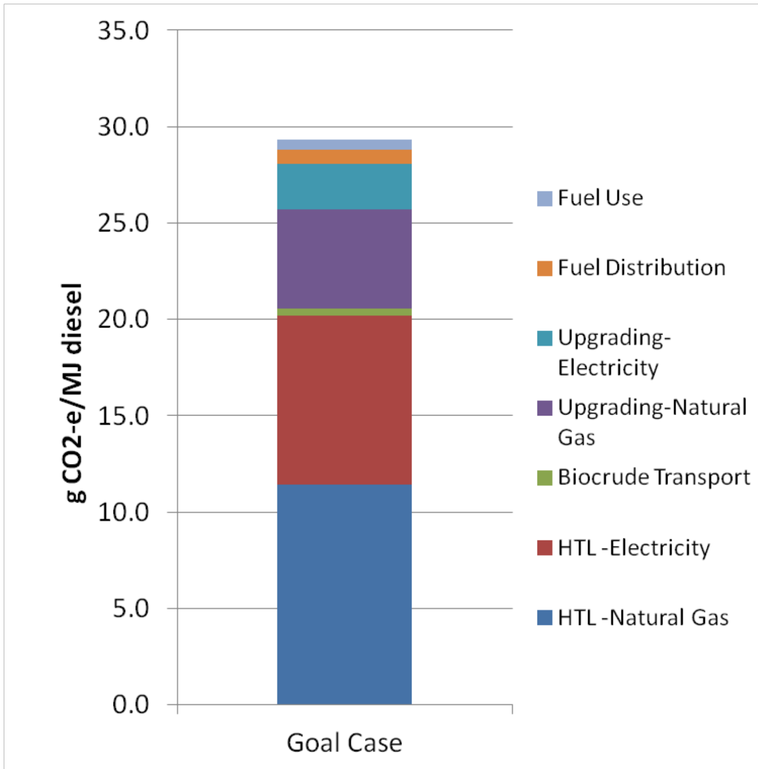
2016 Implemented Recommendations

- Detroit WWTP Sludge
- 20 wt% solids
- LHSV = 4 h^{-1}
- **Met TEA yield goal of 45%**

TEA and LCA is conducted to guide research: Preliminary TEA and LCA for Goal Case



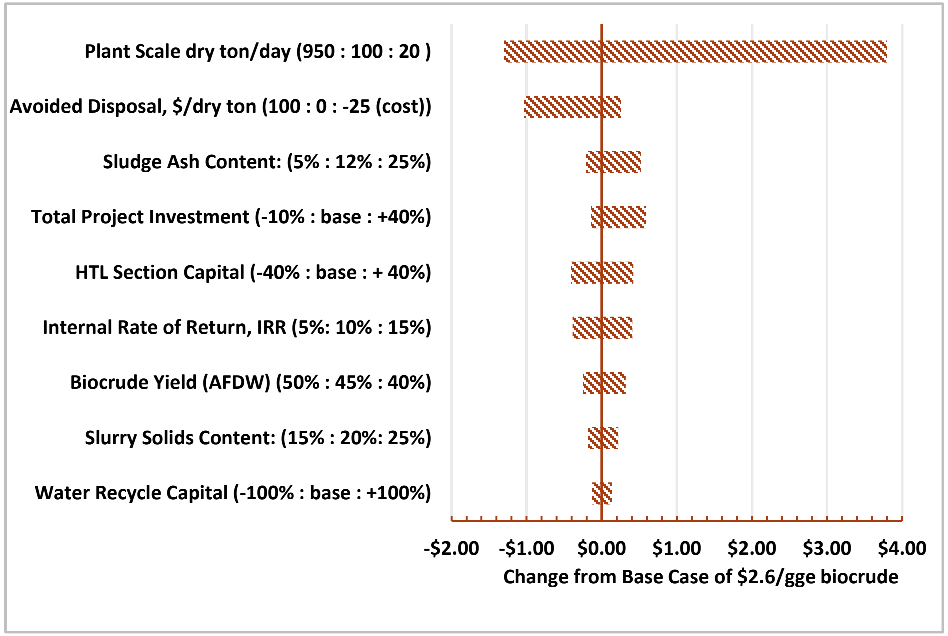
HTL Plant		Upgrading Plant	
Sludge feed rate: Feed solids: Solids ash content:	100 dtpd 20% 12%	Biocrude feed rate:	37,000 lb/hr (34 MM GGE/yr)
Biocrude Yield: g dry oil/g dry ash-free sludge MM GGE/yr	 0.45 3.4	Upgraded Fuel Yield: Total, g oil/g biocrude Diesel, MM GGE/yr Naphtha, MM GGE/yr	 0.90 27.6 10.1
Total Capital Investment	$27.7	Total Capital Investment	$110.1
MFSP Biocrude	**$2.6/gge**	**MFSP - Final Fuel**	**$3.2/gge**
MFSP Biocrude (with $50/ton avoided disposal cost)	**$2.0/gge**	**MFSP - Final Fuel (with $50/ton avoided disposal cost)**	**$2.7/gge**



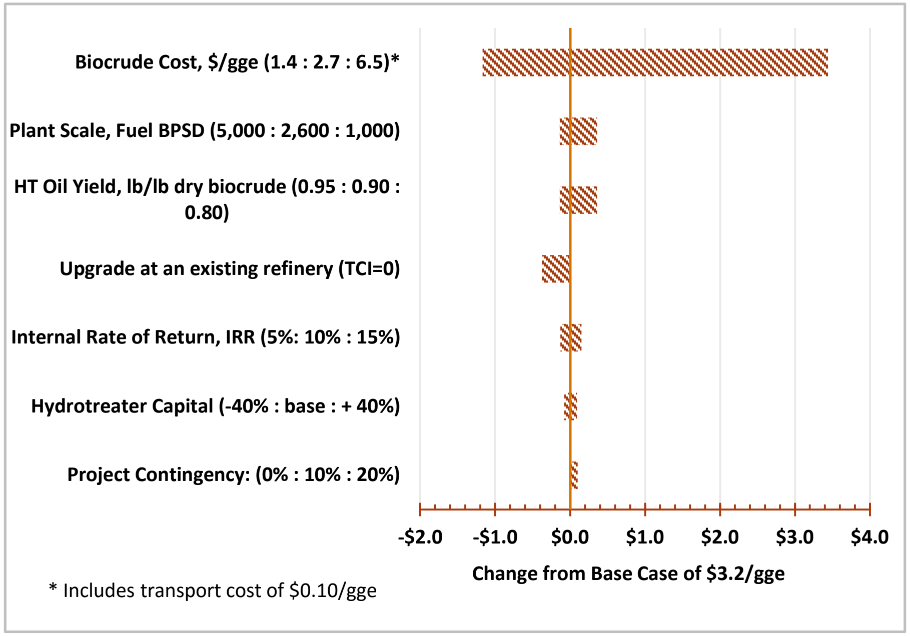
- **Fuel price is in the feasible range of $3/gge**
- **GHG emissions are >60% reduced from petroleum diesel (92 g CO_2-e/MJ)**

Sensitivity analysis identifies cost drivers and areas of improvement: Preliminary analysis for Goal Case

HTL Plant



Upgrading Plant



- **Plant scale** and **avoided sludge disposal cost** are highly variable and are major **cost drivers** for the HTL plant
- TEA and sensitivity analysis feeds into the **design case** (2017), which will **define** the **future testing** required to enable the Goal Case
- Annual **State of Technology assessments** will **track progress** toward the Goal Case

3 – HTL of additional feedstocks

- Range of feedstock tests completed in FY15-16 to assess HTL technology applicability and chemistry
  - WWTP sludges
    - Primary
    - Secondary
    - Biosolids
  - Spent grain, grape pomace
  - Waste paper pulp
  - Feedstock mixtures

- No issues feeding or pumping at pressure for feedstocks
- No issues with system plugging or fouling
- All feedstocks produced phase separable biocrude
- Other feedstocks obtained and considered
  - Cafeteria waste, potato processing waste

Processing Experience
Feedstocks comprised of simple starches or sugars have half the biocrude yield of more biochemically complex feedstocks with lipids and protein

3 – Development of the MHTLS

- New modular HTL system (MHTLS) commissioned and used to demonstrate scalable reactor design, tubular plug flow reactor with heat integration
- Plug flow reactor design tested utilizing improved bench-scale unit
  - Demonstrated 4× increase in throughput with continuous pumping and pressure letdown, linear velocity significantly increased to prevent plugging
- MHTLS Skid 1 utilized for sample preparation of 50:50 primary:secondary sludge from Detroit WWTP
- Skid 2 and 3 testing continuing

3 – Detailed Characterization of HTL Biocrude Samples

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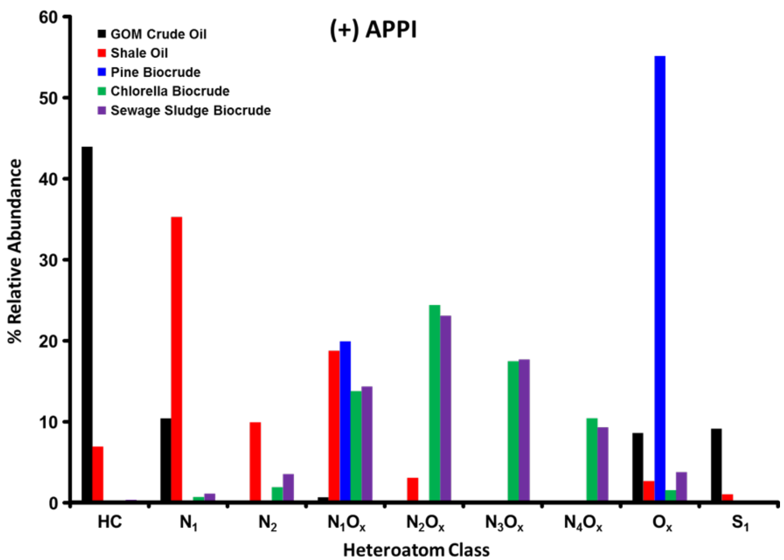
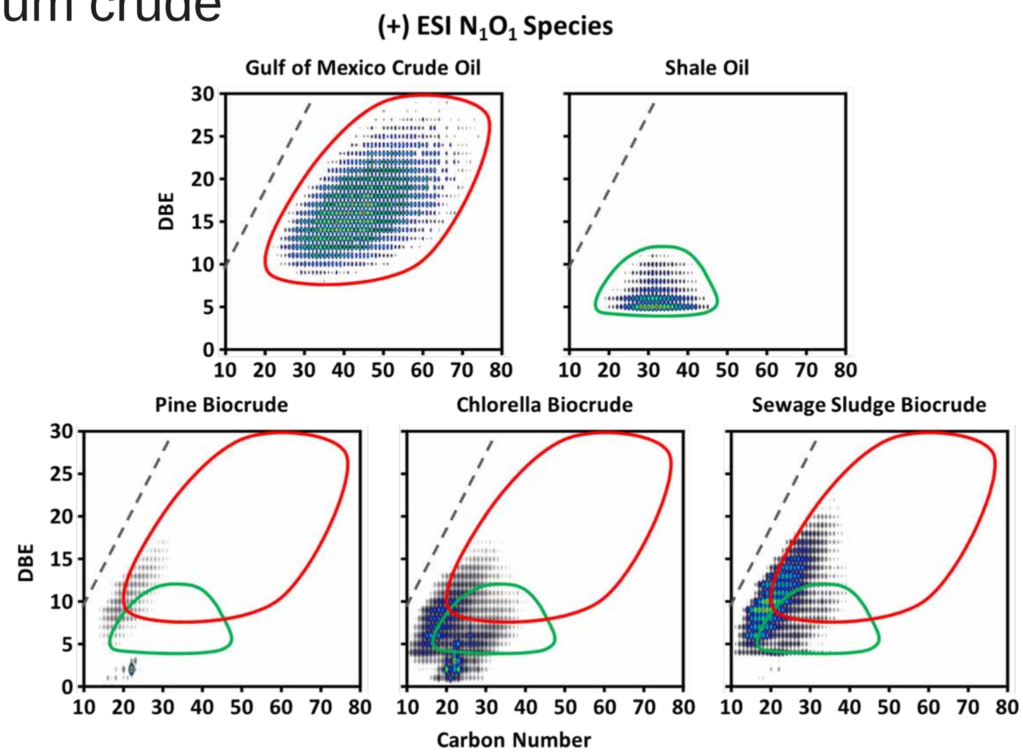
- In collaboration with NMSU and FSU MagLab user facility, FT-ICR-MS high mass resolution, elemental composition and degree of unsaturation assigned for biocrude samples for comparisons
- Detailed characterization of HTL biocrude publications completed, including comparison to petroleum crude

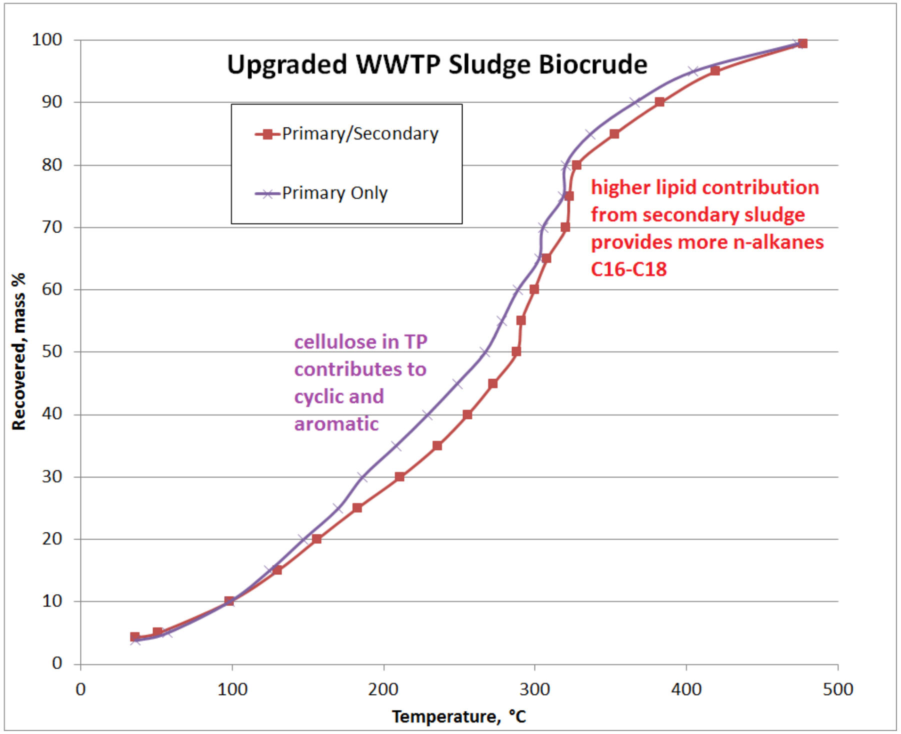




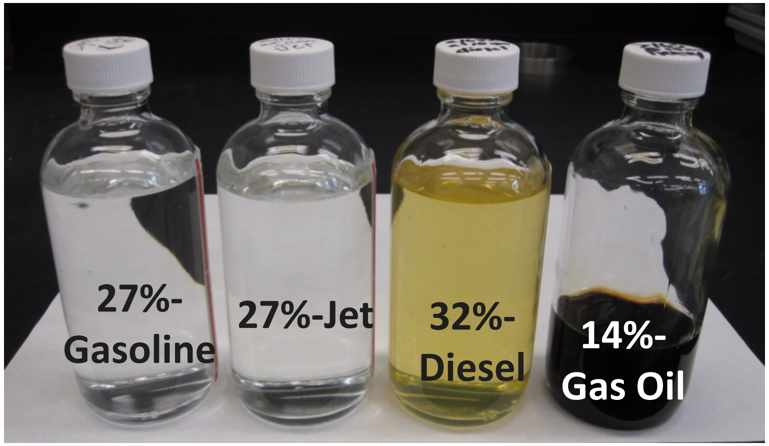
Jarvis JM, JM Billing, RT Hallen, AJ Schmidt, T Schaub. 2017. "Hydrothermal Liquefaction Biocrude Compositions Compared to Petroleum Crude and Shale Oil." Energy & Fuels, in press. doi: 10.1021/acs.energyfuels.6b03022

3 – Upgrading, Fractionation and Characterization

- Detailed characterization data package assembled for blendstock and refinery integration evaluation by PNNL/NREL team
- Chemical and physical property characterization
- Fractionation and characterization of fuel properties (CSU engine test)



Simulated Distillation
Boiling Point Distribution



- Single stage hydrotreater with baseline Co/MoS catalyst
  - Biocrude: Detroit Sludge at two LHSV, 2 and 4 h^{-1}
  - Pressure: 1540 psi; Temperature: 400°C
- Upgrading run >300 hours, ~2L biocrude upgraded to hydrocarbons
- No catalyst deactivation

4 – Relevance

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HTP Project alignment with Bioenergy Technologies Office goals:

"Enable sustainable, nationwide production of biofuels that are compatible with today's transportation infrastructure, can reduce greenhouse gas emissions relative to petroleum-derived fuels, and can displace a share of petroleum-derived fuels to reduce U.S. dependence on foreign oil"

MYPP Barriers addressed:

- Ct-F: 40-70% C efficiency, Ct-H: Single-stage HT with >95% C efficiency

Support MYPP Technology Development Timeline:

- **Overall**: By 2022, validate hydrocarbon biofuel production from at least two additional pathways at pilot or demonstration scale (<1 ton/day).
- **Conversion:** By 2022, validate an nth plant modeled MFSP of $3/GGE for two additional conversion pathways to hydrocarbon biofuel with GHG emissions reductions of 50% or more compared to petroleum-derived fuel.

Applications of the expected outputs from this project:

- New data to support HTL Design Case with goal of $3.00/GGE and >50% GHG
- Validating additional feedstock blends and innovative processes that can meet long-term cost goals and maximize the volume of U.S. biomass resources that can be accessed for biofuels production.
- Provide data for environmental sustainability assessments
- Provide data for assessing upgraded HTL biocrude quality and assign value as fuel blendstock and/or for refinery insertion.

4 – Relevance: Partnerships

2015 WE&RF LIFT HTL PROJECT REVIEW
Hosted by PNNL with HTL Lab tours

- Characterization and assessment from feedstock to finished fuel
- Working with licensee (Genifuel) to identify opportunities, speed commercialization and investment/scale-up by others.

- Partnership with Water Environment & Reuse Foundation (WE&RF) to assess WWTP stream opportunities and HTL test materials
- Independent technology validation conducted by Leidos
- WE&RF-led HYPOWERS Proposal selected for PD2B3 funding
- Work for others and Technology Assistance Program (TAP)
  - Strategic relationships with large and small businesses for technology maturation and deployment

5 – Future Work

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- Upgrade select biocrude samples and evaluate hydrocarbon products as blendstock or for refinery integration.
- Expand bench-scale HTL capabilities to allow processing at longer time-on-stream utilizing improved solids and liquid separations.
- Characterize feedstocks, biocrude, aqueous product, and ash streams and publish data
- Extended time-on-stream HTL campaign with wet waste feedstock.
- Apply hydrothermal processing to lignocellulosic biorefinery waste streams.
- Support engineering scale testing utilizing the Modular HTL System
- Go/No Go decision point FY18 Q4: HTL performs at scale

PNNL Scaled HTL System

5 – Future Work

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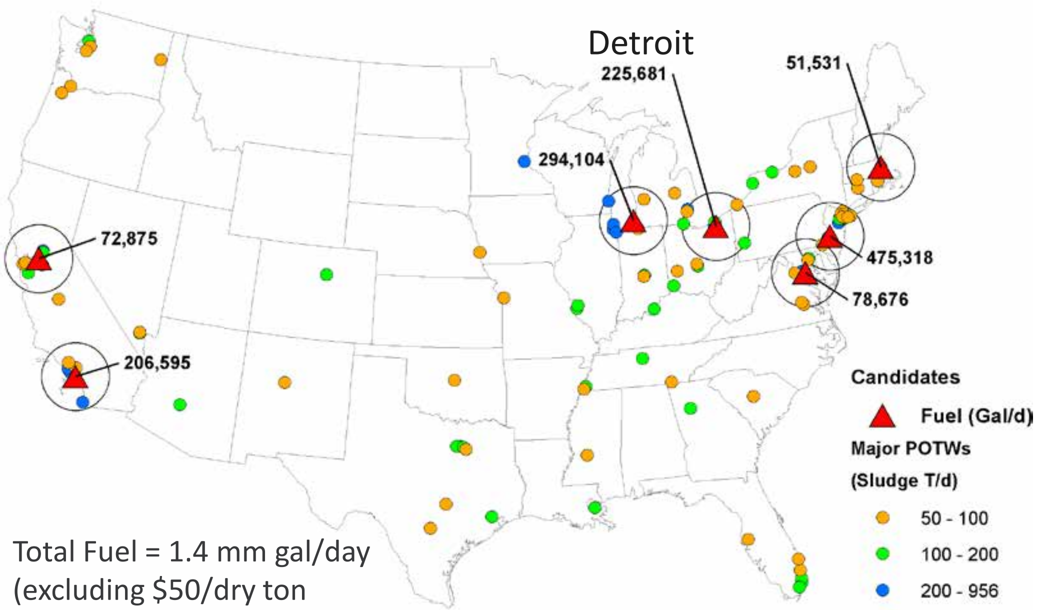
- Complete Design Case for wet waste HTL utilizing WWTP sludge.
- Conduct HTL processing of additional wet waste feedstocks identified by WTE resource assessment team (e.g. food/industrial wastes, animal manure)
- Utilize process models, TEA, and LCA for implementing improved HTL conversion process and feedstocks.
- Head-to-head assessment of HTL and anaerobic digestion in collaboration with our partners at Great Lakes Water Authority and the University of Michigan



Total Fuel = 1.4 mm gal/day (excluding $50/dry ton avoided cost)

Example: Hydrotreater Siting Analysis

- ~30-40% of the total sludge in the U.S. can be used to produce fuel under \$3/gge.
- These upgrader sites collect biocrude from HTL plants of all sizes within 100 miles radius.
- Aggregation potential is very sensitive to scale and disposal cost.
- MFSP <\$3/gge regions identified: Philadelphia/NY, Chicago, Detroit, L.A., D.C., San Francisco, Boston

Summary

Advance HTL Technology for Alternate Pathway to Hydrocarbon Fuels

1) Advance reactor designs and separation improvements
2) Upgrading biocrude to blendstock or for refinery insertion
3) Determine path to $3/GGE and >50% GHG reduction

Address Technical Barriers: Critical Success Factors

1) Used assessment tools to identify and develop WWTP sludge as a feedstock
2) Produced biocrude from wide range of feedstocks
3) Developed modular HTL system for data generation and process validation
4) Demonstrated ease of HTL biocrude upgrading and provided critical data

Future Work

1) FY17 Complete Design Case for Wet Waste HTL of WWTP sludge
2) FY18 Establish SOT for Wet Waste Design Case
3) FY18 Q4 Go/No-Go: Demonstrate that HTL performs at scale
4) Based on Design Case and resource assessments, convert additional feedstocks to biocrude samples, upgrade biocrude samples, and provide engineering data.
5) Extended time-on-stream HTL campaign with wet waste feedstock.
6) Expand hydrothermal processing to lignocellulosic biorefinery waste streams.

Additional Slides

Responses to 2015 Peer Reviewers' Comments

Comments Related to Technical Progress and Accomplishments

- Need to see a yield structure or material balance in comparison to other pathways, e.g. FP or CFP
  - Response: Completed.
  - Go/No-Go decision completed for HTL and CAT-HTL versus fast pyrolysis.
  - HTL is a Go.
- Catalyst stability over 200 hours is a good indicator that catalyst may be viable.
  - Response: PNNL has completed multiple runs over 300 hours of time-on-stream without catalyst degradation with biocrude from non-algae containing feedstocks.
  - Upgrading HTL biocrude from mixed feedstocks containing algae requires a guard bed for hydrodemetalization of soluble iron caused by porphyrin complexation. Results published in collaboration with TC Interface project.
- Early results are promising pending results of TEA. TEA should identify critical success factors to be addressed.
  - Response: Completed major milestone in FY15 Q4 demonstrating the path to \$3/GGE fuel from WWTP primary sludge waste.

Go/No-Go and Major Milestones

Go/No-Go Completed

- Compare HTL and CAT-HTL to pyrolysis FY15 SOT
- HTL compares favorably to fast pyrolysis.
- HTL and CAT-HTL costs basically the same as improvements by CAT are offset by additional CapEx for catalytic reactor and catalyst costs.
- **Decision: Go**

Major Milestone Completed

- Demonstrate by TEA, viable business case and potential renewable energy impact for HTL/CHG processing of wet wastes to meet $3/GGE.
- Preliminary TEA and LCA were published for the HTL sludge data from the WE&RF LIFT evaluation.
- **Outcome: HTL Design Case proceeding for WWTP sludge**

Go/No-Go and Major Milestones

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Due Date	Status	Milestones and Deliverables
12/31/15	Complete	Demonstrate by TEA, viable business case and potential renewable energy impact for HTL/CHG processing of wet wastes to meet $3/GGE
3/15/16	Complete	Go/No-Go Memorandum delivered showing that conventional HTL and CAT-HTL were a GO with similar economics that would meet or exceed the 2015 cost target for fast pyrolysis and upgrading.
12/31/16	Complete	Complete experimental testing and assemble data package for the wet waste sludge design case.
9/30/17	On Schedule	Deliver a design case for municipal wastewater sludge conversion to fuels that defines the pathway's target process parameters necessary and achievable to enable a final fuel product cost of $3/gge in the year 2022.

Publications, Patents, Presentations, Awards, and Commercialization

Awards

- 2015 FLC Excellence in Technology Transfer Award
- EERE "Recognition of Innovation" for HTL technology transfer toGenifuel Corporation, presented to the team by DOE Assistant Secretary David Danielson. March 2015.
- 2015 R&D 100 Award "Hydrothermal Processing to Convert Wet Biomass into Biofuels"

Patents

- Schmidt AJ, TR Hart, JM Billing, GD Maupin, RT Hallen, DB Anderson. "Liquefaction processes and systems and liquefaction intermediate compositions." US Patent No. 9,388,364. Issued on July 12, 2016.
- Elliott DC, TR Hart, GG Neuenschwander, JR Oyler, LJ Rotness, AJ Schmidt, AH Zacher. "System and process for efficient separation of biocrudes and water in a hydrothermal liquefaction system." US Patent No. 9,404,063. Issued on August 2, 2016.

Publications

- Billing JM. 2016. "Hydrothermal Liquefaction of Wastewater Treatment Plant Solids." IEA Bioenergy Task 34 Pyrolysis October 2016(39):17-22.
- Jarvis JM, JM Billing, RT Hallen, AJ Schmidt, T Schaub. 2017. "Hydrothermal Liquefaction Biocrude Compositions Compared to Petroleum Crude and Shale Oil." Energy & Fuels (in press). doi: 10.1021/acs.eneryfuels.6b03022
- Jarvis JM, N Sudasinghe, KO Albrecht, AJ Schmidt, RT Hallen, DB Anderson, JM Billing, and T Schaub. 2016. "Impact of Iron Porphyrin Complexes when Hydroprocessing Algal HTL Biocrude." Fuel 182:411-418. doi:10.1016/j.fuel.2016.05.107
- Marrone, P. 2016. "Genifuel Hydrothermal Processing Bench-Scale Technology Evaluation Project." Water Environment & Reuse Foundation. https://www.werf.org/i/a/ka/Search/ResearchProfile.aspx?ReportId=LIFT6T14, accessed 03 February 2017.
- Snowden-Swan LJ, Y Zhu, SB Jones, DC Elliott, AJ Schmidt, RT Hallen, JM Billing, TR Hart, SP Fox, and GD Maupin. 2016. Hydrothermal Liquefaction and Upgrading of Municipal Wastewater Treatment Plant Sludge: A Preliminary Techno-Economic Analysis Rev. 1. PNNL-25464 Rev. 1, Pacific Northwest National Laboratory, Richland, WA.

Publications, Patents, Presentations, Awards, and Commercialization (continued)

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Publications (continued)

- He Y, X Li, X Xue, MS Swita, AJ Schmidt, and B Yang. 2017. "Biological Conversion of the Aqueous Wastes from Hydrothermal Liquefaction of Algae and Pine Wood by Rhodococci." Bioresource Technology 224:457-464. doi:10.1016/j.biortech.2016.10.059
- Maddi B, EA Panisko, TW Wietsma, TL Lemmon, MS Swita, KO Albrecht, and DT Howe. 2017. "Quantitative Characterization of Aqueous Byproducts from Hydrothermal Liquefaction of Municipal Wastes, Food Industry Wastes, and Biomass Grown on Waste, ACS Sustainable Chemistry & Engineering." Accepted, in press. doi: 10.1021/acssuschemeng.6b02367
- Panisko EA, TW Wietsma, TL Lemmon, KO Albrecht, and DT Howe. 2015. "Characterization of the Aqueous Fractions from Hydrotreatment and Hydrothermal Liquefaction of Lignocellulosic Feedstocks." Biomass & Bioenergy 74:162-171. doi:10.1016/j.biombioe.2015.01.011

Key Presentations

- Albrecht KO, RT Hallen, AJ Schmidt, JM Billing, MA Lilga, AR Cooper, JE Holladay, and DB Anderson. 2016. "Waste Streams as Economic Feedstocks for the Production of Sustainable Liquid Fuels." Presented by Karl O Albrecht at 2nd CRC Advanced Fuel and Engine Efficiency Workshop, Livermore, CA on November 2, 2016.
- Billing JM, AJ Schmidt, TR Hart, GD Maupin, RT Hallen, and DC Elliott. 2015. "Continuous Hydrothermal Liquefaction of Cellulosic and Lignocellulosic Biomass." Presented by Justin M. Billing at ACS 249th National Meeting, Denver, CO on March 25, 2015.
- Billing JM, AJ Schmidt, TR Hart, GD Maupin, KO Albrecht, H Wang, DB Anderson, RT Hallen, and DC Elliott. 2015. "Continuous Flow Hydrothermal Liquefaction of Biomass Feedstock." Presented by Justin Billing at tcbiomass 2015, Chicago, IL on November 4, 2015.
- Billing JM, DB Anderson, RT Hallen, TR Hart, GD Maupin, AJ Schmidt, and DC Elliott. 2016. "Design, Fabrication, and Testing of the Modular Hydrothermal Liquefaction System (MHTLS)." Presented by Justin M Billing at TCS 2016, Chapel Hill, NC on November 3, 2016.

Publications, Patents, Presentations, Awards, and Commercialization (continued)

Key Presentations (continued)

- Billing JM, DC Elliott, RT Hallen, TR Hart, AJ Schmidt, PA Marrone, JC Moeller, and P Kadota. 2017. "Bench-Scale Evaluation of the Genifuel Hydrothermal Processing Technology for Wastewater Solids." Presented by Philip A Marrone at WEFTEC 17 Conference, Chicago, IL on September 30, 2017.
- Drennan C. 2016. "Hydrothermal Liquefaction - a new paradigm for sustainable bioenergy." Presented by Corinne Drennan at Bioenery Australia 2016, Brisbane, Australia on November 14, 2016.
- Elliott DC, DB Anderson, RT Hallen, AJ Schmidt, and JM Billing. 2016. "Recent Developments in Hydrothermal Processing of Wet Biomass." Presented by Douglas C. Elliott (Invited Speaker) at South Dakota School of Mines and Technology, Rapid City, SD on March 22, 2016.
- Holladay JE, and C Drennan. 2015. "Waste to Energy." Presented by John Holladay at Mass Production of Biomass Refineries Workshop, Broomsfield, CO on May 11, 2015.
- Maddi B, EA Panisko, TW Wietsma, TL Lemmon, MS Swita, KO Albrecht, and DT Howe. 2016. "Quantitative Characterization of Aqueous Byproducts from Hydrothermal Liquefaction of Municipal Wastes, Food Industry Wastes, and Biomass Grown on Waste." Presented by Balakrishna Maddi at TCS 2016, Chapel Hill, NC on November 1, 2016.

Press Release and Social Media

- Reddit Ask Me Anything (AMA) live event with Justin Billing. “Human Waste to Biofuels” in r/Science category. Archived questions and responses at The Winnower. doi: 10.15200/winn.148060.00259. Stats: Most popular biofuels AMA, 10,031 user click-throughs, 7,576 up-votes, estimated 16.2M people who saw the link on Reddit or other social media.
- “From the Toilet to the Tank,” YouTube video. 2016. https://youtu.be/ER4C6EapZQ4, accessed 03 February 2017. Currently 97K views.
- “Fuel from sewage is the future – and it's closer than you think.” PNNL News Center. November 2, 2016. Story adapted by dozens of national and international media outlets including Popular Science and the Huffington Post UK. http://www.pnnl.gov/news/release.aspx?id=4317, accessed 03 February 2017.

HYPOWERS Project Summary Slide

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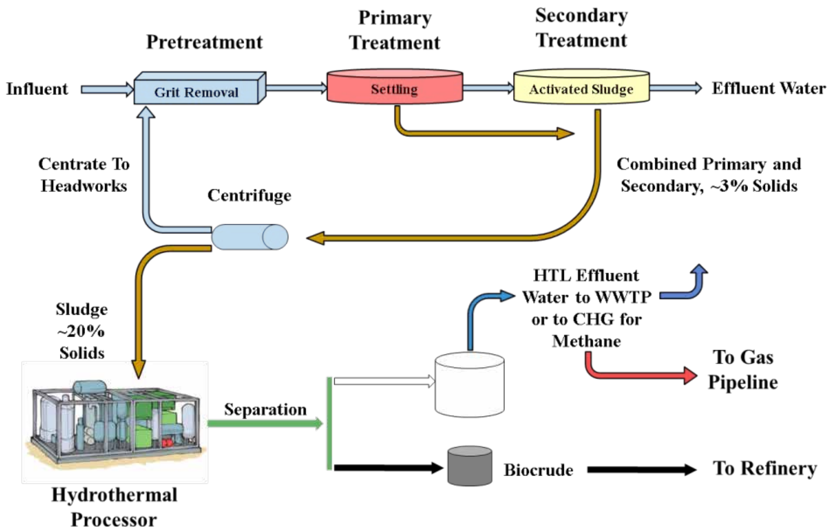
Area of Interest: Quickly and efficiently converts wastewater solids to hydrocarbon fuels while sharply reducing greenhouse gas emissions.
Applicant : Water Environment & Reuse Foundation (WE&RF)
Project Title: HYPOWERS: Hydrothermal Processing of Wastewater Solids
Principal Investigator: Jeff Moeller, M.S., P.E.
Key Partners: Genifuel Corporation, Pacific Northwest National Laboratory, Merrick & Company, Central Contra Costa County Sanitary District, Tesoro Corporation, Southern California Gas Company, MicroBio Engineering, MetroVancouver, Brown and Caldwell, plus 12 contributing utilities.
Proposed Total Project Cost: Phase 1 = $2,457,299
- Applicant funds: $1,228,666 = 50.0% of total
- DOE funds: $1,228,633 = 50.0% of total

Proposed Phase 1 Project Duration: 24 months inc. validation

Hydrothermal Processing of Wastewater Solids



Technology Summary: The HYPOWERS project will tap into a new source of energy—wet waste—to profitably produce biocrude oil and natural gas, replacing fossil fuels while using existing infrastructure. Hydrothermal Processing (HTP) uses water, temperature and pressure to convert wastewater solids to biofuels in less than one hour with automated equipment.
Description of the Technology's Impact: Wastewater treatment produces over 12 million metric tons (dry weight) of solids in the US annually. Converting these solids with HTP will produce the equivalent of 41 million barrels of oil per year and save $2.2 billion in solids disposal costs.

Proposed Project Objectives/Goals:
1. Demonstrate Hydrothermal Processing as an integral and reliable step in wastewater treatment at an operating utility.
2. Eliminate the need for management and removal of wastewater solids and their associated costs.
3. Convert more than 40% of the dry mass of wastewater solids to biocrude oil and the remainder to renewable gas.

Project's Key Idea/Takeaway: Transform wastewater treatment to eliminate wastewater solids while profitably producing renewable hydrocarbon fuels using existing infrastructure, offsetting fossil fuels, and reducing greenhouse gas emissions.

WE&RF Recommendations

Rec #	Recommendations from WERF LIFT6T14 Rpt 8-2016	Status under WERF Project	PNNL Progress in FY2016/2017
1	Determine the optimal sludge feed concentration thought HTL	9.7% to 16.3% total solids processed	20.3% total solids demonstrated
2	Perform long term HTL/CHG Test with single representative feed	4 tests with 3 feeds; 26 L total processed	1 Feed, 33 Liters processed in single long duration HTL test.
3	Repeat HTL test with Secondary Sludge	Marginal results with Secondary Sludge	Feed was 50:50 ratio of primary + secondary sludge
4	Determine representative mix of primary and secondary sludge and perform HTL	Not investigated	Waste to Energy AOP conducted surveyed of CONUS → 50:50 blend
5	Demonstrate better temp control and monitoring over the HTL	Significant fluctuation	Improved plug flow and higher line velocities gave better control
6	Demonstrate effective SO4 removal to enable CHG	Ion exchange removed SO4, but also much of organic	No progress in CHG. Direct aqueous recycle to headworks being pursued.
7	Determine CHG catalysis life with SO4 removal	Not tested.	No longer a priority, no progress
8	Perform energy balance during long term test (in Recommendation 2).	Not appropriate for bench unit	Determined from modeling. Engineering scale unit constructed with integrated heating capability

WE&RF Recommendations

Rec #	Recommendations from WERF LIFT6T14 Rpt 8-2016	Status under WERF Project	PNNL Progress in FY2016/2017
9	Produce enough biocrude for burner test	Several hundred ml produced	Produced sufficient biocrude (> 1000 ml) for 300 h hydrotreating test
10	Perform TCLP test on HTL solids stream	Not part of scope	Conducted for 50:50 primary:secondary mix. TCLP passed for As, Ba, Cd, Cr, Cu, Pb, Hg, Ni, Se, Ag, Zn.
11	ID trace organic contaminates of concern in sludge and determine their fate in HTL/CHG	Not part of scope	Initial testing conducted, results published. Additional characterization underway.
12	Characterize filtrate from dewatering sludge (prior to HTL) to ensure filtrate compatibility during recycle to headworks	Not part of scope	Plant current dewater sludges to ~30% solids with filtrate back to headworks.
13	ID interested WWTP facilities and perform site specific TEA	10 paying member sites, workshop included 30 industrial participants.	SOT/Goal case focused on Detroit. Other WWTPS have joined HYPOWER project
14	Perform full LCA including value of carbon offsets from scaled up HTL-CHG	Not part of scope	Underway as part of flowsheet development.

Engine Testing of HTL Fuel Fractions at Colorado State University

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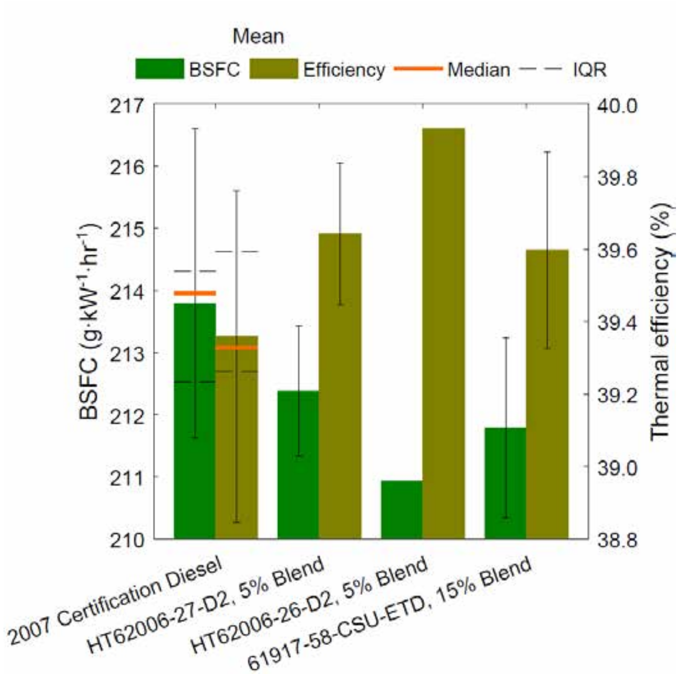
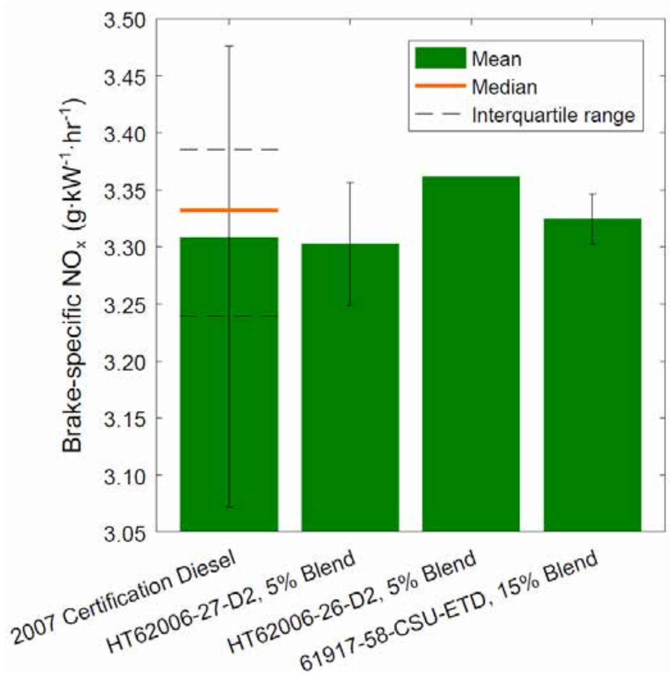
Fuel consumption and thermal efficiency



NO_x Emissions



LEGEND

- **HT62006-27-D2**
  50:50 Wood:Algae
- **HT62006-26-D2**
  Wood
- **61917-58-CSU-ETD**
  Ethanol to Diesel

Colorado State University

Conclusion from draft report: "When compared to the baseline case of the engine running on pure certification diesel, no substantial change in engine performance was observed when fuels derived from hydrothermal liquefaction of wood and algae were blended with certification diesel at 5% by volume. Future testing should examine HTL fuels blended at a higher rate (15-20%), depending on fuel availability."

HTL Bench-Scale Reactor System

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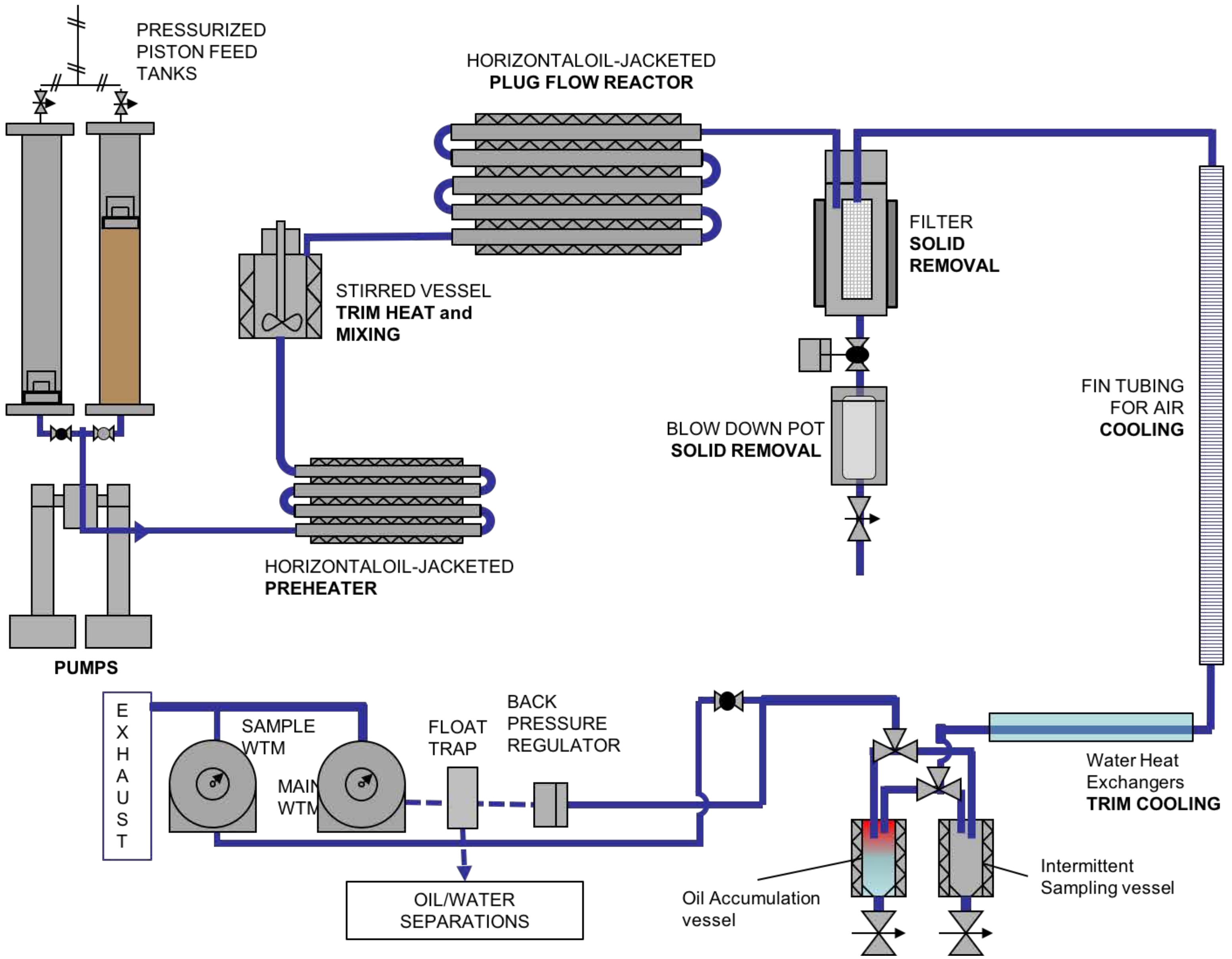
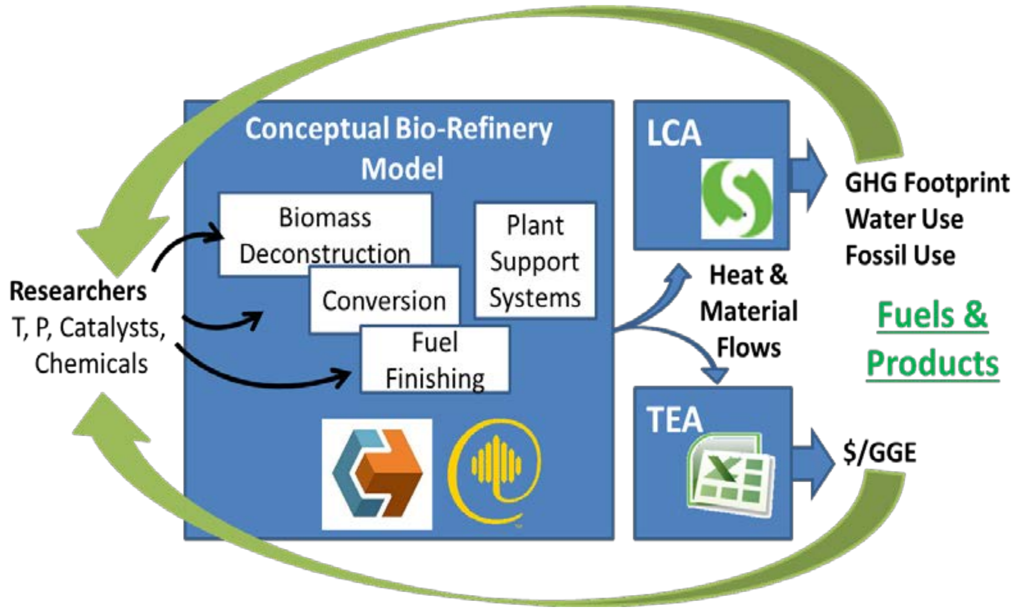


TEA Methodology

- Develop detailed heat and material balance biorefinery models
- Develop detailed capital and operating costs for ISBL and OSBL
- Perform discounted cash flow analysis
- Determine sustainability metrics
- Perform sensitivity analysis



GOALS: Guide Research
Track Progress
Reduce Costs

ISBL= Inside Battery Limits; OSBL = Outside Battery Limits; TEA = Techno-economics; LCA = Life Cycle Analysis

TEA Assumptions

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Financing Factors for Nth Plant Assumption	
Internal rate of return	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

Integrated POTW / HTL Plant for Sludge-to-Biocrude

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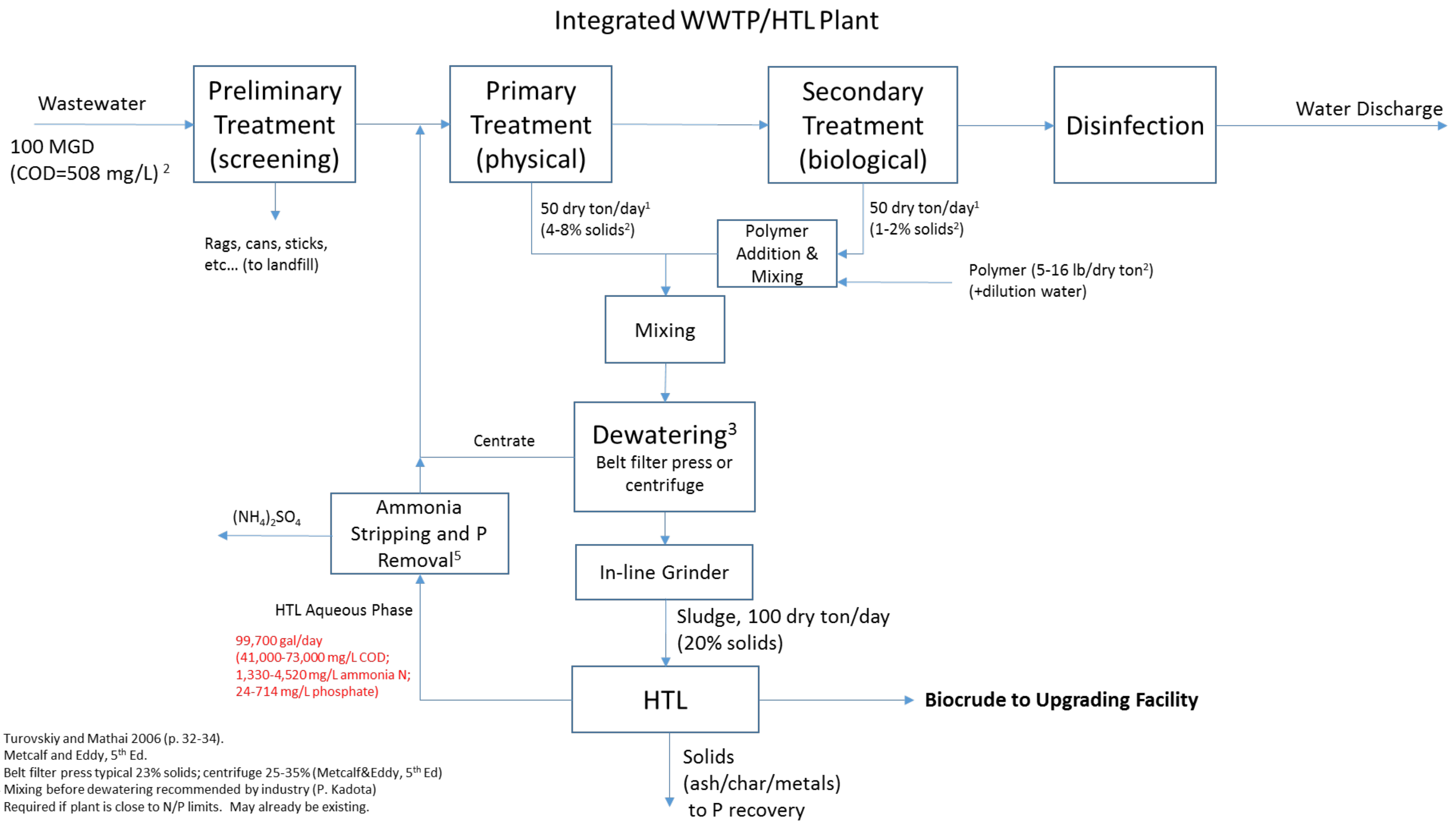

1 Turovskiy and Mathai 2006 (p. 32-34).
2 Metcalf and Eddy, 5th Ed.
3 Belt filter press typical 23% solids; centrifuge 25-35% (Metcalf&Eddy, 5th Ed)
4 Mixing before dewatering recommended by industry (P. Kadota)
5 Required if plant is close to N/P limits. May already be existing.

Preliminary TEA Results for Target Case

HTL Plant		Upgrading Plant	
Sludge feed rate: Feed solids content: Sludge solids ash content:	100 dry ton/day 20% 12%	Biocrude feed rate:	37,000 lb/hr (34 MM GGE/yr)
Biocrude Yield: g dry oil/g dry daf sludge MM GGE/yr	 0.45 3.4	Upgraded Fuel Yield: Total, g oil/g biocrude Diesel, MM GGE/yr Naphtha, MM GGE/yr	 0.90 27.6 10.1
Capital Costs, $million		Capital Costs, $million	
HTL	$11.3	Hydrotreating & Hydrocracking	$33.3
Aqueous Treatment	$1.5	Hydrogen Plant	$20.2
Steam Cycle	$0.4	Steam Cycle	$1.3
Balance of Plant	$1.2	Balance of Plant	$4.2
Total Installed Capital	$14.4	Total Installed Capital	$59.0
Total Capital Investment	$27.7	Total Capital Investment	$110.1
MFSP Biocrude	**$2.6/gge**	**MFSP - Final Fuel**	**$3.2/gge**
MFSP Biocrude (with $50/ton avoided disposal cost)	**$2.0/gge**	**MFSP - Final Fuel (with $50/ton avoided disposal cost)**	**$2.7/gge**

Key Assumptions:

- Biocrude transportation cost: $0.10/gge (200 mile round-trip)
- Algae HTL models employed; adjusted with <u>primary</u> sludge data
- Nth plant assumptions; $2014 USD

Summary of POTW size distribution and U.S. population served (from Seiple et al., in review).

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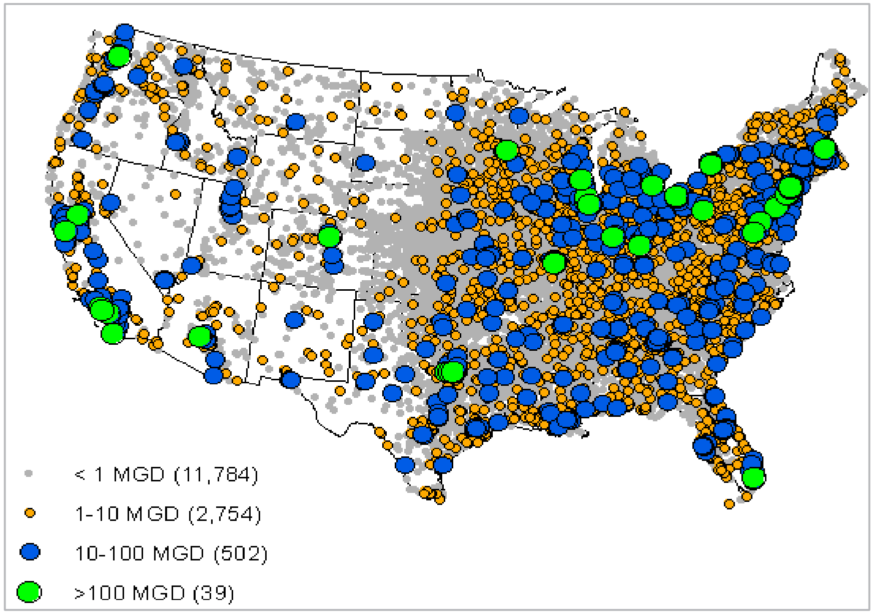

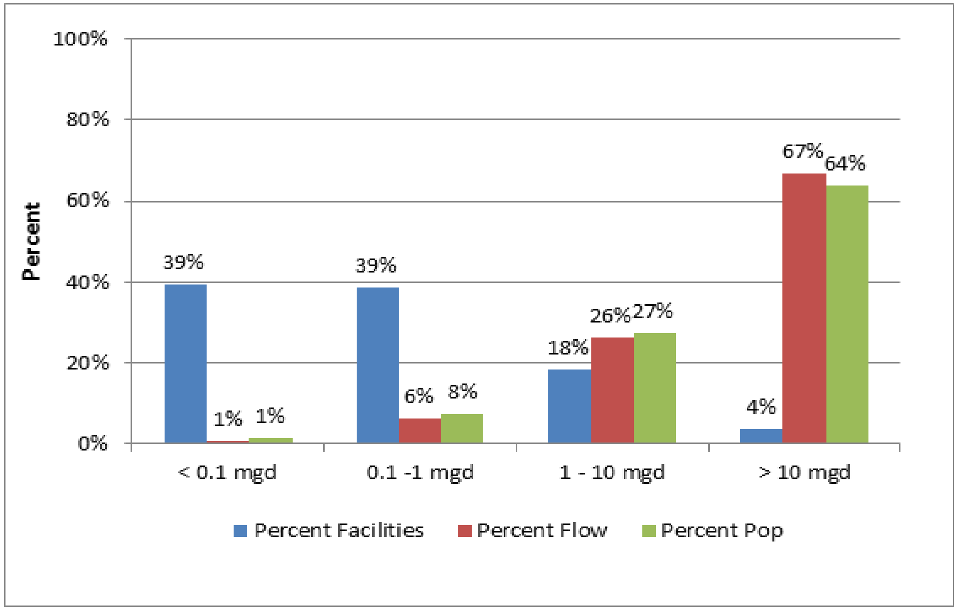

- From Clean Water Needs Survey database (EPA) of 11,000 WWTPs