DOE Bioenergy Technologies Office (BETO) 2019 Project Peer Review

Pacific Northwest NATIONAL LABORATORY

Waste-to-Energy: Feedstock Evaluation & Biofuels Production Potential – PNNL

March 4th, 2019

Waste to Energy

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Goal Statement

Transform underutilized waste into sustainable feedstocks for biofuels production

Challenge: Wet Waste-to-Energy (WtE)

Identify economic opportunities to leverage existing waste infrastructure to increase energy recovery, reduce waste, and reduce costs to both waste and energy operators.

Project Goal: Initial focus on Wastewater Sector

Help achieve BETO's MYP 2024 target for *waste feedstock resource assessment* by identifying economically feasible biofuels conversion opportunities at US municipal wastewater treatment plants (WWTP).

Quad Chart Overview

Timeline

Project start: 2015 (Q4. seed project); 2016 (full project)
Project end: 2021
Status: 50% complete

	Pre FY 17 Costs	FY 17 Costs	FY 18 Costs	Total Planned Funding (FY19 - End Date)
DOE Funded	$371K	$287.9K	$337.9K	$1,075K
Project Cost Share	N/A			

Partners:

NREL, WERF (now WRF), Genifuel, PNNL HTLTeam

Barriers Addressed

- Ft-A. - Feedstock Availability and Cost
- Ft-I. - Feedstock Supply System Integration & Infrastructure
- Ot-A. - Availability of Quality Feedstock

Objective

Provide foundational data, modeling and analyses to enable WtE industry to capitalize on existing infrastructure and waste aggregation potential, to convert underutilized organic wastes into biofuels.

End of Project Goal

Identify priority starting points to achieve BETO feedstock and biofuel production targets, and contribute to triple bottom line sustainability (environmental, financial, and social) for waste operators.

1 – Project Overview

Leverage existing infrastructure; aggregate and blend wastes

Building on previous project outcomes

- 76 million dry tons per year (MDT/y) of wet waste, including sludge; manure; food; fats, oils, and grease (FOG) at 56,000+ sites nationwide, could yield 5.6 Bgal/y diesel equivalent[1,2,3]

Current Goals: Economics and Blending

1. Assess national waste aggregation and blending total potential
2. Identify economic sludge feedstocks at WWTPs
   a) Compare anaerobic digestion (AD) for renewable natural gas (RNG) versus hydrothermal liquefaction (HTL) for renewable diesel production
   b) Quantify cost-effective sludge feedstocks
3. Prioritize feedstock blend combinations and proportions for PNNL HTL Team

U.S. Wastewater Sector

160 TBtu/y of influent chemical energy (as COD)

Most energy lost to 7.1 MT/y disposed biosolids, effluent, and methane flaring

80% of non-sludge wet feedstock mass is within 25 miles of a WWTP ≥1 mgd

- 73% of manure (26 MT)
- 96% of food (15 MT)
- 92% of fog (5 MT)

See "Additional Slides" for bibliography

2 – Management Approach

Collaborative planning with independent task management

PNNL Team

- Rick Skaggs – Advisor / PM
- Tim Seiple – Assessment / CBA
- André Coleman – Blending

Regular Partner Interactions

Annual

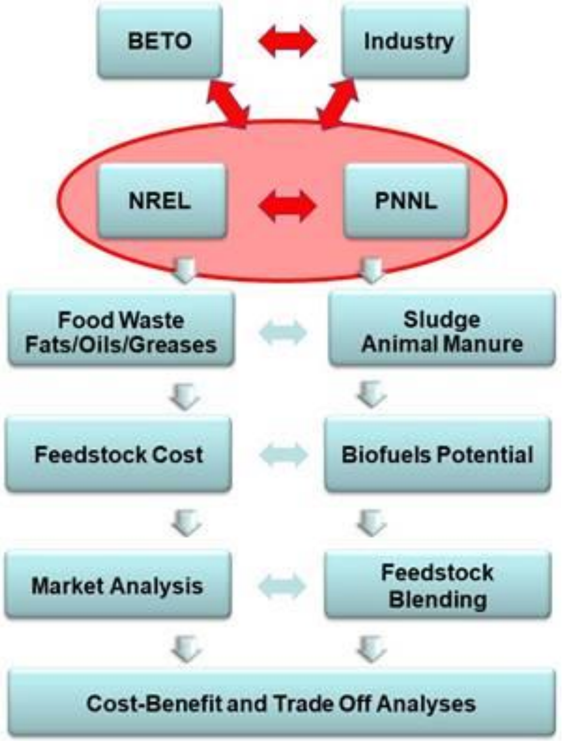
- AOP and PMP submittals
- Go/no-go decision point
- Workshops, Conferences, Publish

Quarterly

- Progress reporting to BETO

Monthly

- Monitor budget and schedule
- BETO Multi-lab WTE Team calls
- PNNL-NREL joint team calls (as needed)
- PNNL-Industry calls
- PNNL HTL/TEA Team calls



2 – Technical Approach Roadmap

Two principle research elements since last Peer Review

FY2017 - Waste aggregation and feedstock blending

- Modeled waste aggregation service areas
- Assessed impacts of feedstock profiles and blending strategy on biocrude yield (maximize feedstock utilization vs. conversion efficiency)
- Blending economics not yet considered

FY2018 - Economic opportunities to leverage WWTP

- Developed modeled energy, solids, financial budgets for current and future WWTP configurations
- Performed Cost-benefit analysis (CBA) to compare economics of long-term energy recovery strategies (AD for RNG vs. HTL for diesel)
- Quantified economic sludge sources and magnitudes (Go/No-Go: >10 MDT/y)

Key Challenges

- Lack of site-specific liquid/solids process, energy/solids, biogas, disposal cost data
- Scaling costs for HTL

Critical Success Factors

- Industry input to model realistic configurations and technology insertion points
- Resource assessment directly informs TEA, and HTL experimental design

2 – Technical Approach: FY2017 Blending

Regional waste aggregation & optimized feedstock blending

Service Areas → Feedstock Profiles → Blending Model[7] → HTL Yield Curves

Blending Basics: Feedstock bio-composition determines biocrude yield. Therefore we can optimize blending of different wastes with preference for Lipids > Proteins > Carbohydrates

Hypothesis: Biochemical optimization to maximize conversion rate will outperform simply mixing 100% of waste to maximize feedstock utilization

Method: Develop 100-mile radius service areas and assess impacts of blending strategies on “local” feedstock utilization and biocrude yield

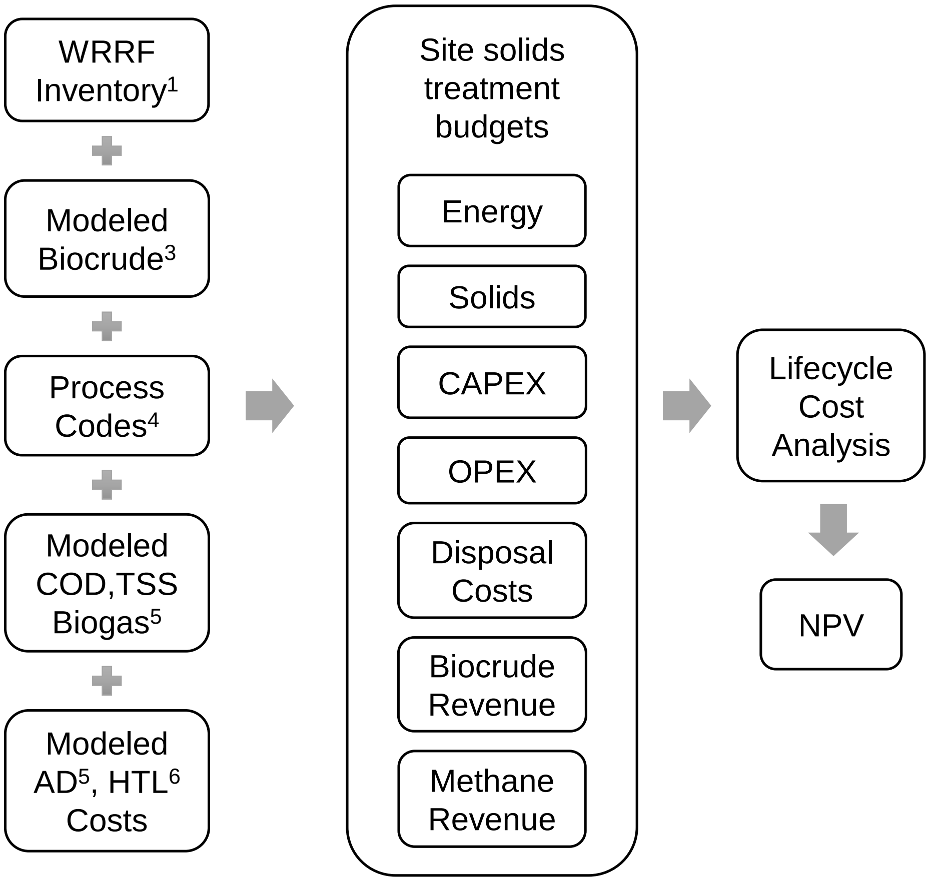
Blending Scenarios (service area level)

1. “100% Blend” – All available feedstock is blended before conversion
2. “Optimal Blend” - Biochemically optimized batches are converted

See “Additional Slides” for bibliography

2 – Technical Approach: FY2018 CBA

Site-specific economic analysis of solids treatment alternatives



CBA Basis: Modeled 30-year profitability of current and future liquid/solids treatment configurations (capex, opex, disposal costs, biofuels revenue, and avoided disposal).

Metric: *Cost-effective* if net present value ≥0

WWTP Upgrades focus on maximizing energy recovery for biofuels production (AD vs. HTL).

Recoverable COD/TSS in **total and dewatered** primary/secondary sludge for *WWTP* ***≥1 mgd***

	COD (PJ/y)	TSS (MDT/y)
Baseline	(Total / Dewatered Sludge)	
Current	1.57 / 1.37	11.5 / 10.0
Future	1.84 / 1.60	12.7 / 11.1

* Future COD/TSS availability differs from current due to new liquid processes to enhance solids capture

CBA Scenarios

1. "Current" – Verified ≥10 mgd
2. "100% HTL" – all new HTL units
3. "100% AD" – add AD where missing
4. "100% New AD" – all new AD units

See "Additional Slides" for bibliography

3 – Technical Accomplishments Roadmap

PNNL is following the PMP and producing meaningful results

PNNL completed all FY17 and FY18 milestones in the PMP

National blending potential	Complete	*Manuscript in-process*
Develop WWTP database	Complete	
Develop cost-benefit analysis	Complete	
Apply CBA nationally for sludge	Complete	*Manuscript in-process*

Major Accomplishments

A1: Demonstrated WWTP can economically supply >10 MDT/y of feedstock to produce 1 Bgal/y DGE, addressing a Go/No-Go decision

A2: Demonstrated HTL is more cost-effective than AD at similar scales, when considering disposal costs

A3: Developed regional feedstock profiles to serve as the basis for future economic blending modeling

A4: Experimented with economically informed blending (economic sludge + 20% FOG)

New data and tools

- WWTP engineering database
- Reusable CBA, waste aggregation, and blending models
- Prioritized list of sludge sources and magnitudes
- Feedstock hotspots
- Service area feedstock profiles and optimized biocrude yield curves

3 – Technical Accomplishments

A1: Economic analysis of sludge feedstocks

<u>Go/No-Go decision</u>: Yes, WWTPs can sustainably supply >10 MDT/y of sludge feedstock facilities ≥4 mgd using HTL

HTL is economically feasible at facilities ≥4 mgd

- Sustainably produce 1 Bgal/y DGE, about 2.5% of 2017 highway use of special fuels[9]
- Economically recover 1.12 PJ/y (70%) of COD in dewatered sludge at WWTP ≥1 mgd
- Economically utilize 11 MDT/y (86%) of total sludge generated at WWTP ≥1 mgd
- Cost reduction: Save additional $1.5 B/y in disposal costs

Leveraging WWTP Infrastructure is "low hanging fruit" for WTE

- WWTPs are well engineered, spatially distributed waste collection systems with natural WTE technology insertion points
- Dewatered sludge can be diverted directly into HTL units

3 – Technical Accomplishments

A2: Economic comparison of AD and HTL

HTL Pros vs. AD

- Better energy recovery efficiency
- Better solids reduction efficiency
- Higher biofuels output on DGE basis
- Lower disposal costs
- Higher avoided disposal savings
- Larger economic feedstock supply
- Economic at smaller scales

HTL Cons vs. AD

- Not market ready, but on the horizon (5 mgd pilot in progress and lots of experimental data)
- Uncertainty regarding scaled and modular costs

Bottom Line: A key element to making HTL economically feasible at smaller scales than AD is considering solids disposal costs and avoided disposal savings

Cost-effective feedstock supply, and biofuel, and plant scale

Scenario	Min Plant Scale with NPV ≥0 (MGD)	Economic Feedstock (MDT/y)	Approx. DGE (Bgal/y)
100% HTL	4	11.1	1.06
100% AD	19	3.6	0.16
100% New AD	95	0.4	0.02

Future AD vs HTL Potential Performance ≥5 MGD (comparison not limited by economics)

Metric	Scenario		
	Current Practice*	100% AD**	100% HTL
Energy Recovery Eff. (%COD)	40	51	80
Solid Reduction Eff. (%TSS)	41	55	77
Residuals (MDT/y)	5.5	4.9	2.2
Disposal Costs ($B/y)	2.2	2.0	0.9
Disposal Avoidance ($B/y)***	1.1	1.8	2.9

* Current practice COD/TSS baselines are lower than future scenarios

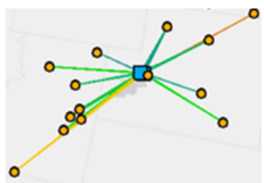
** Both future AD scenarios have same performance, but different CAPEX

*** Avoided disposal cost equals total solids generated minus converted solids, multiplied by average disposal fee.

3 – Technical Accomplishments

A3: Modeled regional waste aggregation profiles in the U.S.

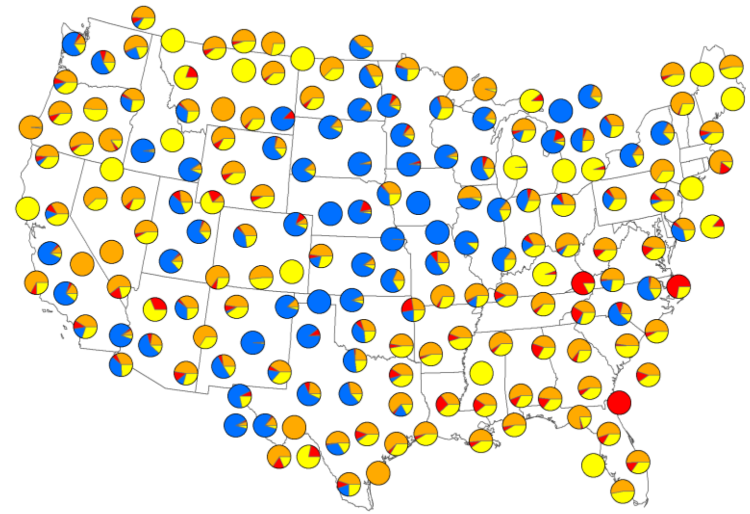
Spatially modeled 213 waste aggregation "service areas" in the U.S. (100 mile search radius around WWTP)



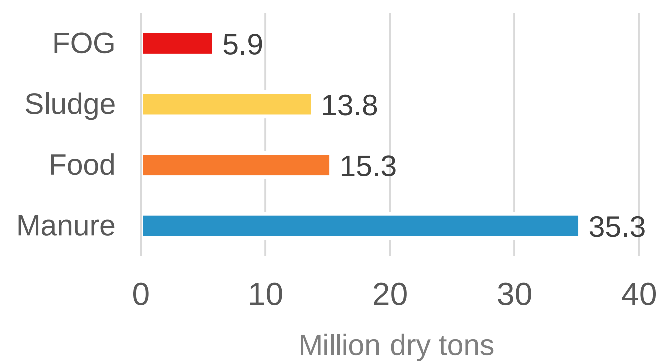
Service area feedstock profiles describe the total and proportional feedstock mass, and dominant type(s)

Service areas are the basis for blending scenarios

213 Service Area Profiles



National Profile



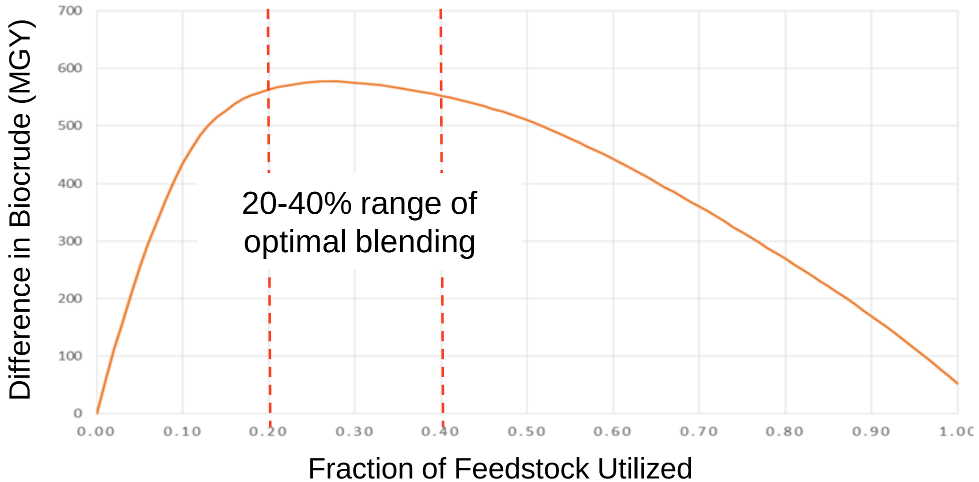
3 – Technical Accomplishments

A3: Biochemically optimized blending improves biocrude yield

Service Area Based Blending Results

- "Optimal" blending improves yield an average 52 MGY nationally, over simply mixing 100% of available blendstocks
- Curve reflects tradeoff between maximizing conversion efficiency ("Optimal") vs maximizing feedstock utilization ("100% blend")
- Highest average increase in biocrude yield occurred between 20-40% blendstock utilization; priority use of Lipid>Protein>Carb
- These tools help prioritize investment, especially if blendstock utilization is limited by market, seasonal, or operational constraints (e.g. capacity, availability, etc.)
- In FY19, we address economic blending
- Many different blending strategies can now be tested.

Difference in biocrude yield between "Optimal" and "100% Blend"



Comparison of biocrude yield by blending scenario

Feedstock Fraction (%)	No Blend (BGY)*	100% Blend (BGY)	Optimal Blend (BGY)	[Optimal] – [100% Blend] (BGY)
10	0.44	0.59	1.02	0.435
25	1.10	1.47	2.05	0.576
50	2.21	2.94	3.46	0.510
75	3.32	4.42	4.73	0.315
100	4.42	5.89	5.94	0.052

* Individual feedstocks converted separately; not a blending scenario

3 – Technical Accomplishments

A4: Economic sludge + FOG is "low hanging fruit" for blending

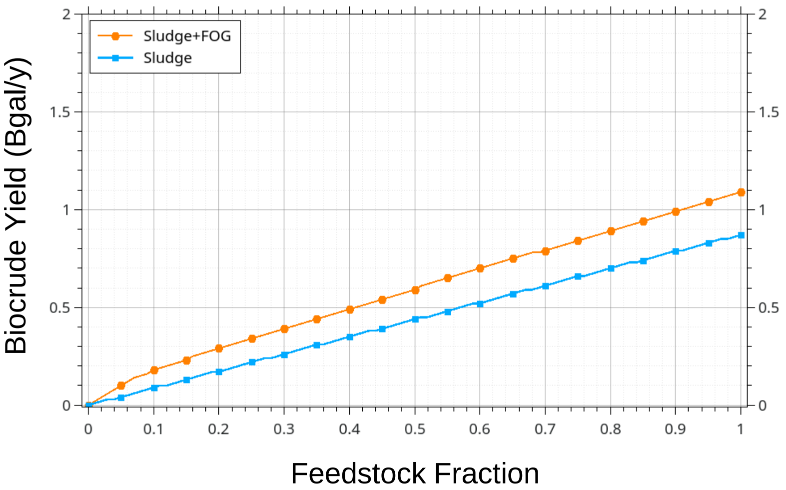
Hypothetical Blending Scenario

- CBA results limit service areas and sludge feedstock availability
- FOG is a high lipid, low carb blendstock
- ~20% of FOG is brown grease (low reuse)
- 99% of FOG is within 100 miles of economic sludge sources

Important Results

- Blending can increase biocrude yield by 200 MGY over economic sludge alone
- Blending likely also has a positive feedback on economic viability of sludge by increasing onsite yield and revenue
- PNNL HTL Team is now in the process of analyzing sludge + FOG samples

Biocrude Yield Curve:
Economic Sludge + 20% FOG



Feedstock	Supply (MDT/y)	Biocrude Yield (BGal/y)
Economic Sludge	10.7	0.9
Economic Sludge + 20% FOG	11.9	1.1

4 – Relevance

Assess feedstock aggregation and blending potential and quantify economic feedstock sources and magnitudes

Study of wet WTE feedstock and logistics directly supports BETO's mission

- BETO MYP 2024 target for waste feedstock resource assessment
- BETO's 2016 MYPP categorizes wet WTE as an "Emerging Area… that may contribute significantly to bioenergy goals"
- Building block of BETO's 2017 "Biofuels and Bioproducts from Wet and Gaseous Waste Streams: Challenges and Opportunities" Report
- BETO's strategic plan lists wet WTE as element of a strong bioeconomy; WTE technologies are among the sub strategies to reduce cost, improve performance and incorporate sustainability as a market enabler

Study Impact

- Demonstrated WWTP can supply >10 MDT/y of feedstock while reducing treatment and disposal costs
- Strategic Analysis/Communication through peer reviewed publishing
- Foundational data, models, and analyses help prioritize investment by identifying and prioritizing cost-effective opportunities to utilize 76 MDT/y of wet wastes (sludge, manure, food, fat/grease) for biofuels production
- Prioritize HTL experimental work on blend performance
- Design bio-chemically optimized blends based on local economic feedstock supply

5 – Future Work in FY2019

Identify economic portion of 35 MDT/y manure from confined beef, dairy and swine

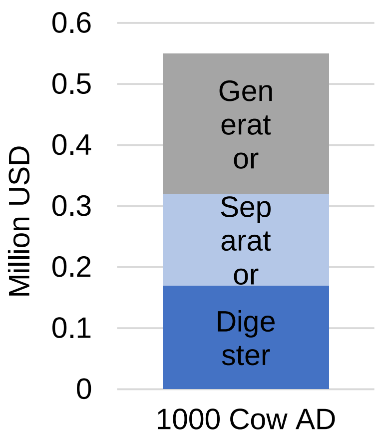
FY2019 Objectives

- Characterize manure systems (energy/solids/costs)
- Configure CBA framework to model manure infrastructure, with comparison of AD to HTL
- (9/30/19) Milestone: Apply CBA to identify economic manure supplies and biofuels production potential
- Inform PNNL HTL Team on manure blend design
- Stretch Goal: Initiate blending economics modeling

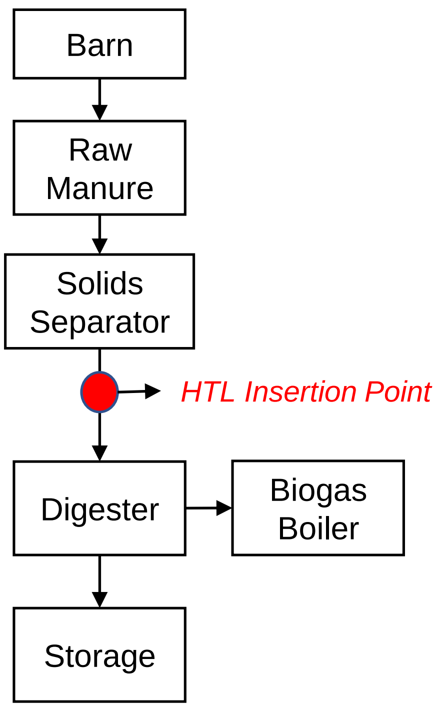
Farms by number of animals

x1000 Head	Beef	Dairy	Swine
< 1	6,690	3,482	4,879
1-5	1,025	1,756	13,131
5-10	245	124	1,582
10-25	213	22	306
25-50	63	0	39
50-100	10	0	21
100-500	2	0	5
> 500	0	0	1
	8,248	5,384	19,964

Ex. On-farm AD Capex ($100k/y O&M)



Typical On-farm AD System



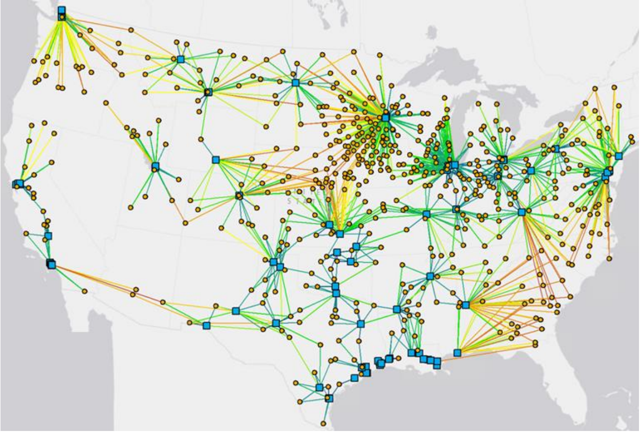
5 – Future Work in FY2020

Bring it all together: Combine CBA and blending to identify economic blending opportunities for biorefinery integration

Initiate regional scale economics based, optimized blending analyses for all wet feedstocks, utilizing PNNL next generation conversion yield model[8] and joint PNNL-NREL feedstock cost-supply curves.

- Update blending with next-gen PNNL HTL conversion model
- Apply CBA to identify cost-effective conversion and refining opportunities with exiting (or proposed) biorefineries
- Apply blending model to prioritize co-liquefaction opportunities and propose comprehensive blend designs (wet WTE + MSW)
- Stretch Goal: Economic mining HTL waste for metals/nutrients

Conceptualized integrated CBA based blending and refining model



Summary

It is possible to make significant quantities of renewable fuel and eliminate waste at the same time.

Project outcomes that contribute to BETO MYP 2024 target for waste feedstock resource assessment

1. Demonstrated biochemically optimized blending (maximizing conversion rate) improves yield over simple blending (maximizing feedstock utilization)
2. WWTP can economically supply 11 MDT/y (86% of sludge) to produce 1Bgal/y DGE, about 2.5% of 2017 highway use of special fuels[9]
3. A key element in making HTL economically feasible at smaller scales than AD is considering solids disposal costs and avoided disposal savings
4. Blending FOG with economic sludge is “low hanging fruit” for WTE
5. WWTPs are highly engineered, spatially distributed systems co-located with most other wet wastes

Future Work: 1) Economic manure conversion, 2) CBA informed optimized blending of all feedstocks with biorefinery integration

New data and tools

- Comprehensive WTTP engineering database
- Reusable cost-benefit, waste aggregation, and blending models
- Prioritized list of sludge sources and magnitude
- Feedstock hotspots
- Regional feedstock profiles and optimal biocrude yield curves

Thank you

Pacific Northwest
NATIONAL LABORATORY

Additional Slides

- Presentation References
- Responses to 2017 Reviewers’ Comments
- Publications and Presentations

Presentation References

1. Seiple T, Coleman A, Skaggs R. 2017. "Municipal Wastewater Sludge as a Sustainable Bioresource in the United States" Journal of Environmental Management 197:673–680. 10.1016/j.jenvman.2017.04.032
2. Milbrandt A, Seiple T E, Heimiller D, Skaggs R, Coleman A 2018. "Wet waste-to-energy resources in the United States" Resource, Conservation and Recycling, vol. 137:32-47. doi.org/10.1016/j.resconrec.2018.05.023
3. Skaggs R, Coleman A, Seiple T, Milbrandt A. 2017. "Waste-to-Energy Biofuel Production Potential for Selected Feedstocks in the Conterminous United States" Renewable & Sustainable Energy Reviews doi.org/10.1016/j.rser.2017.09.107
4. WERF, 2015, "A Guide to Net-Zero Energy Solutions for Water Resource Recovery Facilities – Final Report", No. ENER1C12
5. WERF, 2014. "Utilities of the Future Energy Findings", Report No. ENER6C13
6. Snowden-Swan, Lesley, et al. Conceptual Biorefinery Design and Research Targeted for 2022: Hydrothermal Liquefaction Processing of Wet Waste to Fuels. United States: N. p., 2017. doi:10.2172/1415710.
7. Z. Wang, "Reaction mechanisms of hydrothermal liquefaction of model compounds and biowaste feedstocks" [dissertation], Engineering Administration, University of Illinois at Urbana-Champaign, Champaign, Illinois, USA (2011)
8. Jiang Y, Jones S, Zhu Y, Snowden-Swan L, Schmidt A, Billing J, Anderson D, "Techno-Economic Uncertainty Quantification of Algal-derived Biocrude via Hydrothermal Liquefaction" 2018. (in progress)
9. U.S. DOT FHA Monthly Motor Fuel Report - https://www.fhwa.dot.gov/policyinformation/motorfuel/dec17/dec17.pdf

Responses to 2017 Reviewers' Comments

Reviewer Comments

"Anaerobic digestion should also be considered as a baseline scenario."

"A less positive comment, however, is on the use of HTL as a reference for the bioenergy potential of the feedstock of interest. While HTL is a promising technology, it is not yet proven at any significant scale, let alone commercially, and is not well known. I think that using a different reference would be preferable as it would provide a more immediate and reliable reference points for practitioners in the field."

2017 Response : "Though we used HTL for our initial baseline, we plan to directly compare HTL with anaerobic digestion (AD) as part of our future work.

2019 Update:

We directly compared HTL for biocrude with anaerobic digestion (AD) for renewable natural gas (RNG) production as part of our FY18 cost benefit and tradeoff analyses. We also considered both AD upgrade and full AD replacement scenarios, to account for the fact that most large AD systems in the US are near of past their design lifecycle.

We selected HTL as a representative thermochemical technology because of the broad base of HTL experimental work presented in the literature and because PNNL is participating in multiple programs to deploy HTL at increasing scale including: PNNL Modular HTL System (500L/d), Metro Vancouver Pilot System (10,000L/d), and HYPOWERS installation in Contra Costa (15,000 L/d).

Publications, Patents, Presentations, Awards, and Commercialization

Publications

- Seiple T, Coleman A, Skaggs R. 2017. "Municipal Wastewater Sludge as a Sustainable Bioresource in the United States" *Journal of Environmental Management* 197:673–680. 10.1016/j.jenvman.2017.04.032
- Milbrandt A, Seiple T E, Heimiller D, Skaggs R, Coleman A 2018. "Wet waste-to-energy resources in the United States" *Resource, Conservation and Recycling,* vol. 137:32-47. doi.org/10.1016/j.resconrec.2018.05.023
- Skaggs R, Coleman A, Seiple T, Milbrandt A. 2017. "Waste-to-Energy Biofuel Production Potential for Selected Feedstocks in the Conterminous United States" *Renewable & Sustainable Energy Reviews doi.org/10.1016/j.rser.2017.09.107*
- *Snowden-Swan, Lesley, et al. Conceptual Biorefinery Design and Research Targeted for 2022: Hydrothermal Liquefaction Processing of Wet Waste to Fuels. United States: N. p., 2017. doi:10.2172/1415710.*

Publications In-Progress

- Seiple T, Coleman A, Skaggs R. "Leveraging U.S. Wastewater Recovery Infrastructure for Enhanced Energy Recovery"
- Coleman A, Skaggs R, Seiple, T. "Feedstock Blending – Maximize U.S. Wet Waste Reduction vs. Biocrude Production."

Conference Presentations

- Seiple TE, A Coleman, and R Skaggs. 2017. "National Assessment of Wastewater Solids as an Energy Feedstock." Presented by Timothy E Seiple at 2017 Residuals and Biosolids Conference, SEATTLE, WA on April 11, 2017. PNNL-SA-124894.
- Skaggs R, A Coleman, and TE Seiple. 2017. "Waste-to-Energy (WTE): Feedstock Evaluation and Biofuels Production Potential." Presented by Richard Skaggs at WEF Residuals & Biosolids Conference, SEATTLE, WA on April 4, 2017. PNNL-SA-125090.
- Snowden-Swan LJ, JM Billing, AJ Schmidt, RT Hallen, KO Albrecht, TE Seiple, MD Bearden, and Y Zhu. 2017. "Techno-Economic Analysis of Renewable Hydrocarbon Fuel from Municipal Sludge." Presented by Lesley J Snowden-Swan at Residuals and Biosolids: The Future of Biosolids and Bioenergy, SEATTLE, WA on April 11, 2017. PNNL-SA-125239.