Waste-to-Energy: Optimized Feedstock Blending at Scale PNNL

WBS 2.1.0.113

March 9, 2021
Organic Wastes Review Panel

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Previous AOP Project Title "Feedstock Evaluation and Biofuels Production Potential"

PNNL is operated by Battelle for the U.S. Department of Energy

What if… we could build a biorefinery in every state and divert all 76 million dry T/y of organic wastes into transportation biofuels…forever?

Project Overview

Accelerate the adoption of promising conversion technologies

What we do (End of 3rd Year Goal)

Deliver and exercise a reusable, data-driven geo-economic framework to **find practical, real-world opportunities** to convert underutilized wet organic wastes (sludges, manures, food waste, fats, oils, and grease) into low-cost biofuels.

How we do it

- Model Real-World Supply & Infrastructure (routing, cost, quantity, and quality)
- Optimize Regional Plant Scales (what is likely, realistic, practical)
- Propose Feasible Starting Points (pilot-to-commercial scales)

Why it matters

We provide credible analysis to

- Help the waste management community find realistic strategies to reduce treatment and disposal costs and improve energy recovery
- Ground-truth economic models and lab experiments with real-world cost, scale and waste composition data

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1 – Management

Cross-project integration to collectively achieve an MFSP[1] of $2.50/gge[2] by 2030

Our W2E[3] Team (Blue Dot)

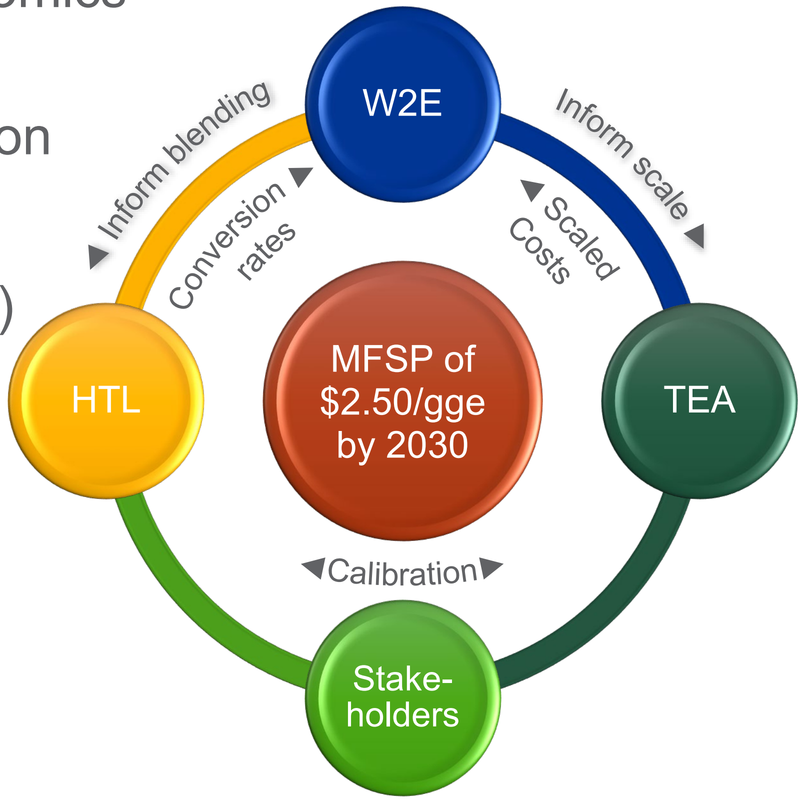
- Tim Seiple (PM) – Geo-economics
- André Coleman – Blending
- Robert Brigantic – Optimization

Project Controls

- Annual Operating Plan (AOP) with quarterly milestones and Go/No-Go checkpoint
- Risk register
- Merit reviewed in 2020
- Peer-reviewed in 2019

Regular Communications

- Monthly multi-lab calls with sponsor
- Quarterly reporting to sponsor
- As-needed calls with regulators/industry
- Publications, conferences, and workshops



Project Links

Continuous integration with TEA[4] (WBS 2.1.0.301) and HTL teams (Bench-scale 2.2.2.302 & PDU 3.4.2.301) maximizes impact

Project Risks: Overall risk level: "Low"

1. Imperfect engineering/spatial data: mitigated by calibrating with coarser regulatory and industry reporting
2. Projecting markets: mitigated through sensitivity analysis and external review
3. True feedstock price unknown: mitigate by modeling expected cost components

Stakeholder Engagement

Calibrate assumptions and share results with Water Research Foundation, NEBRA[5], Biosolids Coordinators, Waste generators and haulers, and soon with DOE Clean Cities

1 – (MFSP) Minimum fuel selling price based on nth plant costs
2 – (GGE) gasoline gallon equivalent
3 – (W2E) Waste-to-energy
4 – (TEA) Techno-economic Analysis
5 – (NEBRA) North East Biosolids & Residuals Association

2 – Approach: FY2021 Realistic Supply Modeling

Building a business case for any transformational conversion technology requires an understanding of realistic feedstock travel costs and total price

FY2021 Objective: Use real-world waste and infrastructure data to identify the likely location, cost, scale and composition of blended waste hot-spots

Approach: Develop and apply a geo-economic supply model to simulate competition among candidate "bio-hubs" for a finite set of waste resources to maximize scale at or below a fixed feedstock price

- **Data-driven**: simply change the price or re-configure underlying resource data and instantly get new results
- **Metric:** Mass-weighted avg. cost per dry metric ton

Hot-spot: ≥1000 dry t/d cost-effective feedstock

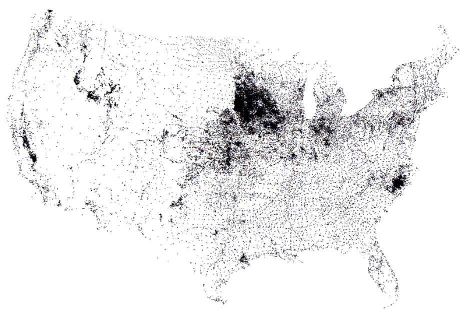
Challenges: True feedstock prices are unknown; computationally intensive problem; requires optimization

Current Model Capability	By End-of-FY2021
Fixed truck size, load time, % solids	**Waste and scale dependent** pump rate, % solids, truck size, frequency, ownership
Trucking only with map distances	National Freight Analysis Framework v.4 **multi-modal** network with linear optimization
Wet Organic Resources	Add **industrial HSW** (high-strength waste) sources to our National Wet Waste Inventory
Feedstock price = delivery cost	**Total feedstock price** (add formatting, storage, fees, credits; could be negative)

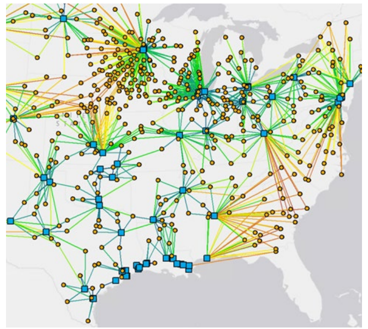
Project Links: Inform FY2022 State of Technology (SOT) report on feasible supply scales and costs to help reduce MFSP (WBS 2.1.0.301). Develop real-world regional blend profiles to inform Bench-scale experiments (WBS 2.2.2.302)

Generalized geo-economic model workflow

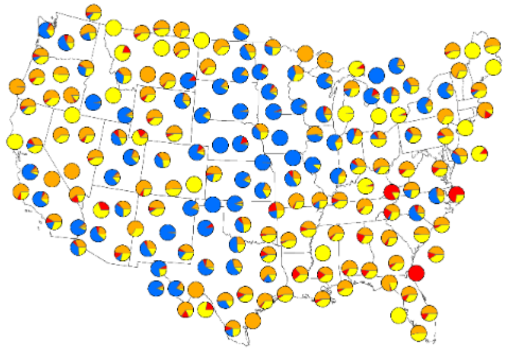
Define waste sources



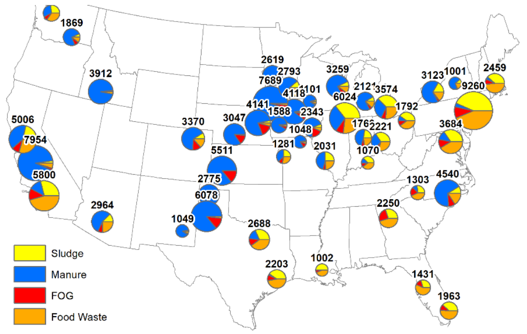
Model travel costs



Build Service Areas



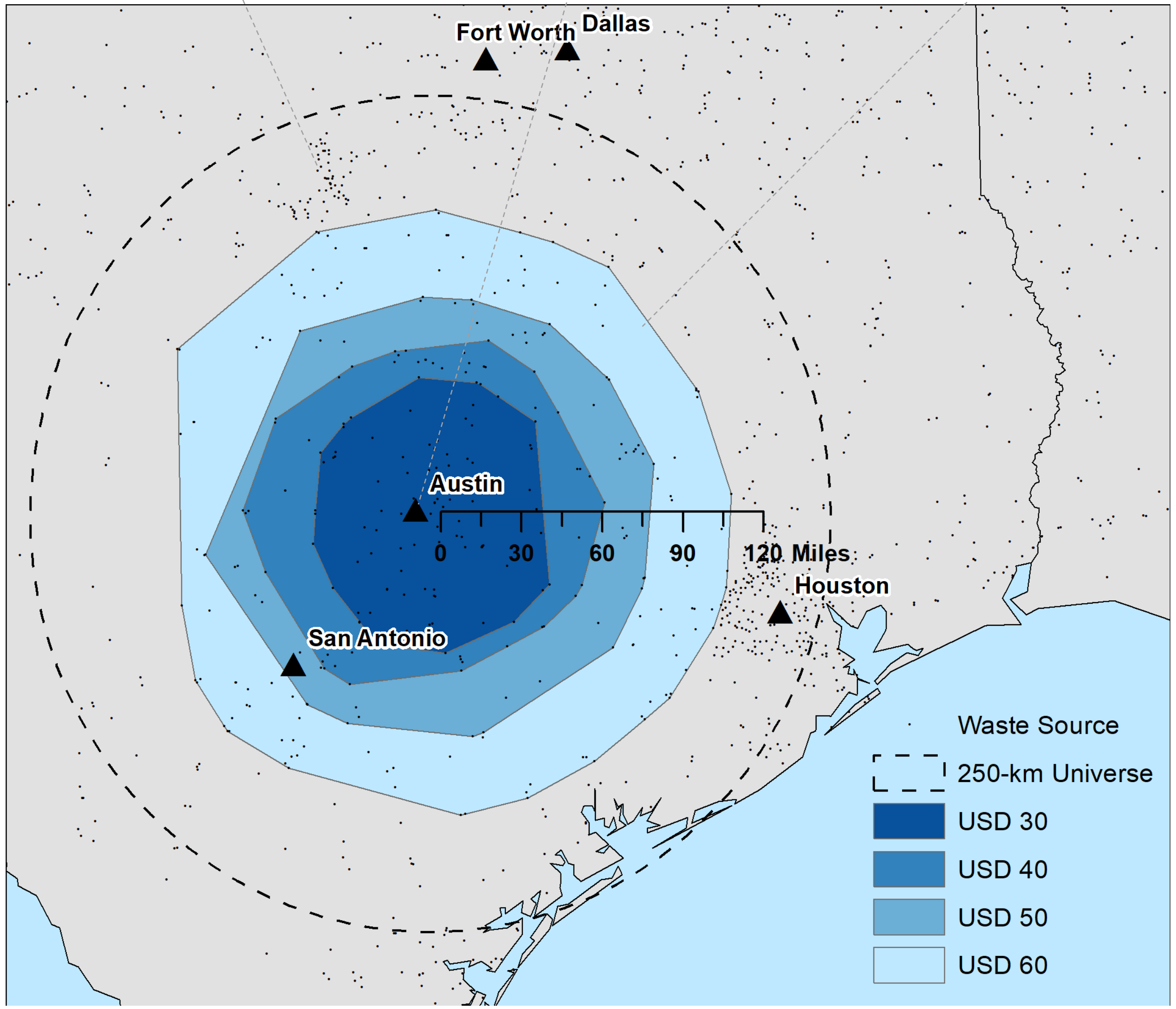
Select Hot-Spots



2 – Approach: FY2021 (Analysis example)

Metro Case Study (Austin, TX): Trade-offs between feedstock cost and scale

Waste Source (**w**) (black dots) Bio-hub (**B**) Service Areas (**S**) (blue polygons)



250-km universe sets the computational bounds of the scenario

This example illustrates what comes out of our geospatial cost model

Recap: A service area (**S**) is defined by a set of waste sources (**w**) capable of delivering waste to a proposed Bio-hub (**B**), such that the delivery price (mass-weighted average cost per dry metric ton) for the overall service area remains at or below a specified value

- The weighted average price changes as each source is considered
- Resource competition from adjacent Bio-hubs is disabled for this example case study but is enabled for national service area modeling
- Assumptions and constraints are highly configurable

e.g., Austin, TX: Increasing the feedstock price from $30 to $60 per dry metric ton increases supply from 482 to 3300 dry metric tons per day.

2 – Approach: FY2022 Optimized Regional Blending

Find the practical conversion plant scale for each region by balancing capital savings with feedstock costs

FY2022 Objective: Evaluate different regional waste collection and blending options to better understand key cost and scale drivers

Approach:, Apply the FY2021 enhanced geo-economic supply model and existing blending model to perform trade-off and sensitivity analysis to assess the impacts of key assumptions and various waste collection and blending strategies on conversion performance (scale, efficiency, yield) by comparing

- Cost-effective supply price and scale (hot-spots)
- Bio-chemical blending profiles
- Biocrude conversion rate (kg biocrude/kg biomass) and yield (liter/y) curves

Example analysis questions include

- What is the opportunity cost of mixed waste collection to reduce cost vs. separate collection to maximize conversion efficiency (biochemical optimized blending)
- How does limiting or prioritizing certain wastes impact conversion rate and total yield
- How and where does rail access improve supply?
- How does limiting municipal cooperation impact scale?

Challenge: Regional solutions are unknown and unique

Go/No-Go (Q1): Increasing HTL plant scale to 1000 dry t/d is key to achieving an MFSP of $2.50/gge. We will illustrate at least one cost-effective hot-spot based on end-of-FY2021 modeled feedstock prices.

Generalized blending analysis workflow (by scenario)

Run cost model

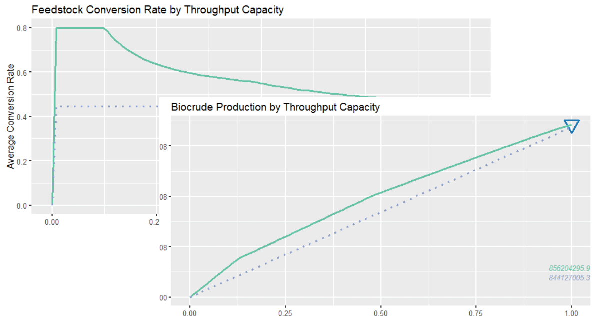
Scenario-specific cost-effective supply

Create blending profiles

Run blending model

Batch feedstock into 1% increments and select conversion formula based on ratio of lipids, protein, and carbohydrates.

Compare Performance



2 – Approach: FY2023 Propose Feasible Sites

Integrate lessons learned with latest TEA/Bench-scale data to make final recommendations on where to start planning pilot-to-commercial scale conversion

FY2023 Objective: Provide credible and practical guidance to the U.S. waste management community regarding cost-effective, regionally-optimized, large-scale conversion and biorefinery opportunities

Approach: Finalize our supply model assumptions and integrate the latest conversion factors and scaled plant costs to produce final hot-spot reports that summarize

1. Proposed plant location
2. Regional supply scale and composition ("conversion diet") as a function of price
3. Cost break-down (collection, conversion, upgrading) and detailed incremental cost of adding each waste site

Challenge: Markets and regional partnerships may develop in ways that diverge from our hypothesis, but the waste sector is already experiencing rapid consolidation.

Project Links: Final results will be shared with TEA and Bench-scale teams to refine the SOT and experimental design

Getting the word out: Hot-spot case study reports will be disseminated to municipalities and industry through partner organizations (e.g., WRF, DOE Clean Cities, AgSTAR, etc.), conferences (e.g., WEFTEC), and peer-reviewed publications.

3 – Impact Summary (How our results are used)

Our results have an immediate impact – and we're just getting started

Major impacts

1. Illustrated that regional blending could increase modeled HTL plant scale by a factor of 10 and reduce MFSP by $0.69/gge
2. Rapid "conversion diet" assessment to guide HTL blend design

Honorable Mentions

- Our methods, data, and tools have been adopted by other projects to perform economic assessments for sustainable aviation fuels (SAF) and marine biofuels.
- NEBRA is using our sludge estimates as a basis for a new national biosolids report
- Harmonized with "System Modeling of the Waste to Energy Industry" (WBS 2.1.0.104)
- Peer reviewed publications and conference papers (see publications slide)

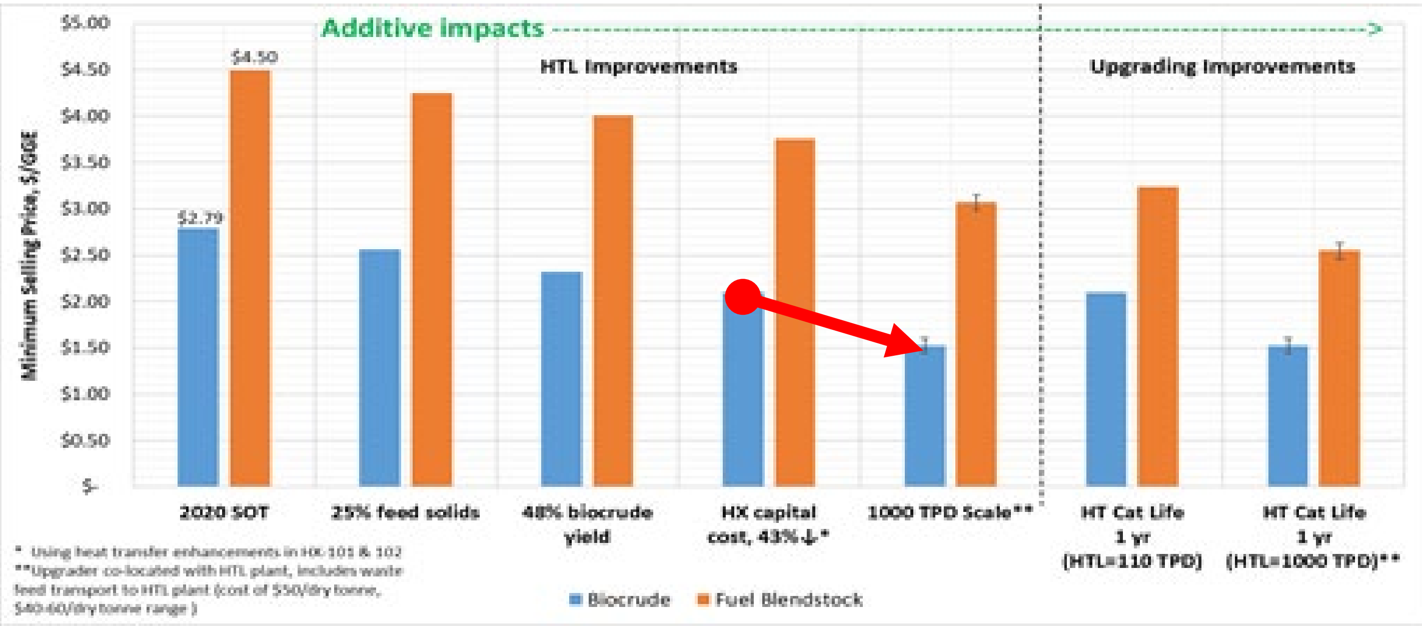
3 – Major Impact #1: Increase HTL Plant Scale

Illustrated regional blending can achieve 10x increase in HTL plant scale, thereby reducing MFSP by $0.69/gge

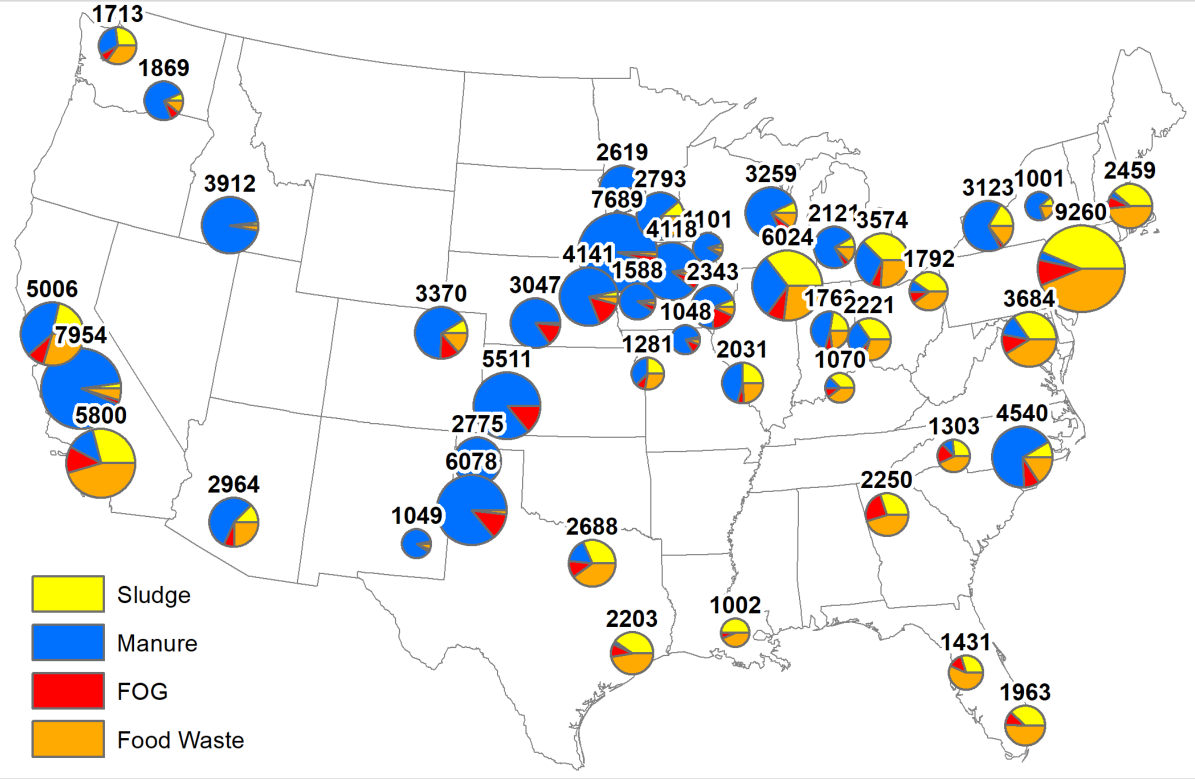
Finding: 45 HTL conversion hot-spots (≥1000 dry metric t/d) can access 82% of total wet organic feedstocks at USD $50 per dry metric ton

Impact: The Analysis and Sustainability Interface Team (WBS 2.1.0.301) was able to increase modeled HTL plant scale by a factor of 10 in the FY2020 SOT (sensitivity case) compared to the 100 dry metric t/d baseline and reduce MFSP by $0.69/gge

Increasing HTL plant scale is a major step toward achieving $2.50/gge MFSP by 2030



45 Conversion Hot-spots can access 82% of supply at $50/t dry



Go/No-Go Practice Run: We were able to produce these early results by simplifying key assumptions (to be refined in FY2021)

- Feedstock price = delivery price
- $85/h trucking chargeout rate (inc. labor)
- Straight-line travel distances

3 – Major Impact #2: "Conversion Diet" Analysis

Using real-world data to quickly inform conversion experiments that feed into TEA

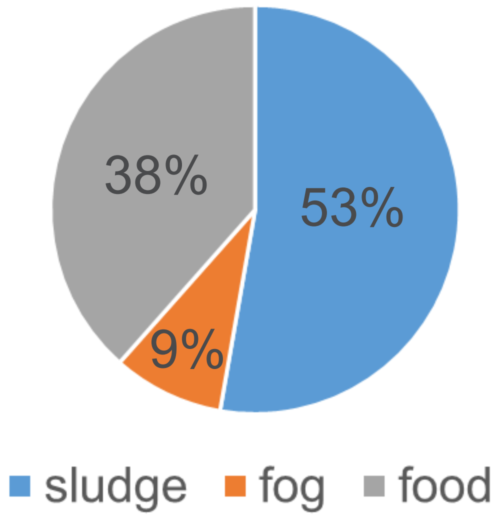
Need: The "Bench Scale" Team (WBS 2.2.2.302) needed to design a realistic blending experiment to characterize HTL conversion efficiency for a "typical" Metro area as a primary input to TEA (WBS 2.1.0.301) to determine scaled plant costs.

Finding: We were able to quickly model feedstock supply to illustrate cost-effective scale and bio-composition ratios

- Detroit, MI selected as a representative blending profile with 1,660 dry t/d of feedstock at a ratio of 53:38:9 sludge-food-fog
- Minor manure fraction was excluded from this experiment

Impact: Quickly adapt to needs of other projects and provide data-drive scenario design consistency across projects

Detroit, MI blending profile (observed)



Resource-informed HTL experimental blend design

Sludge (50%) + Food (40%) + FOG (10%) = Easily Separated Product → Biocrude

4 – Progress and Outcomes Summary

Following our AOP and on target to hit our Go/No-Go in March 2022

Status: In our first year of a three-year project; following the AOP/PMP and finishing up the Q2 milestone.

Major outcomes in current project cycle (FY2021 to FY2023)

1. Completed our Q1 milestone (transport network integration)
2. **Bonus!** Performed preliminary national economic feedstock assessment to inform the FY2020 SOT Team regarding feasible plant scales in the U.S. for a range of feedstock prices
3. Actively working on Q2 milestone (characterize industrial HSW sources)

Major outcomes since 2019 Peer Review (FY2018 to FY2020)

- Illustrated HTL integration at wastewater treatment plants is cost-effective ≥5 Mgal/d (influent flow), which could save $1B/y in biosolids disposal costs
- Assessed national biocrude potential from blended wastes based on max travel distance (prior to having our cost model)
- Developed an initial transportation cost model as the basis for estimating cost-effective blending and feedstock price modeling

4 – Major Outcome #1: Retire $0 Cost Assumption

Moving toward realistic transport costs and comprehensive feedstock price

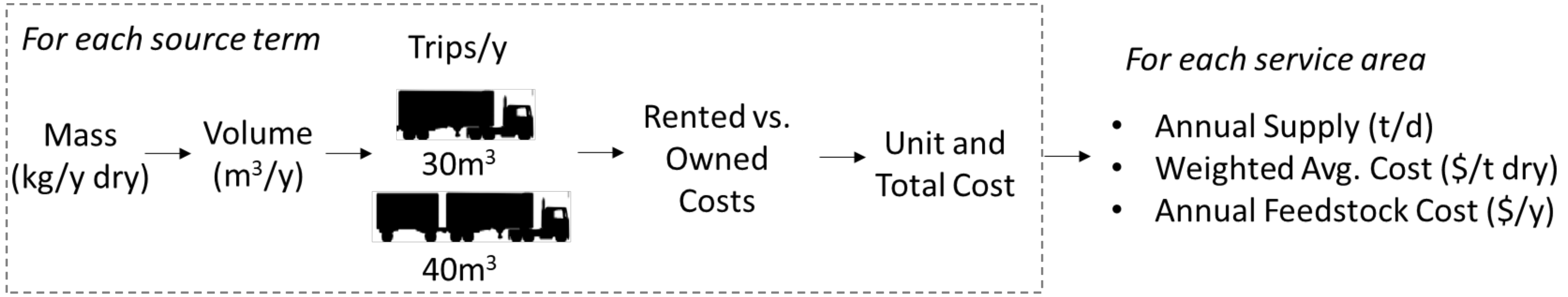
Old: In the past, all W2E economic analyses assumed a feedstock price of $0 per dry ton. There was no way to quantify feedstock costs or estimate supply scale at a given price.

New! We developed a geospatial supply model that estimates cost-effective scale based on realistic hauling and transaction practices.

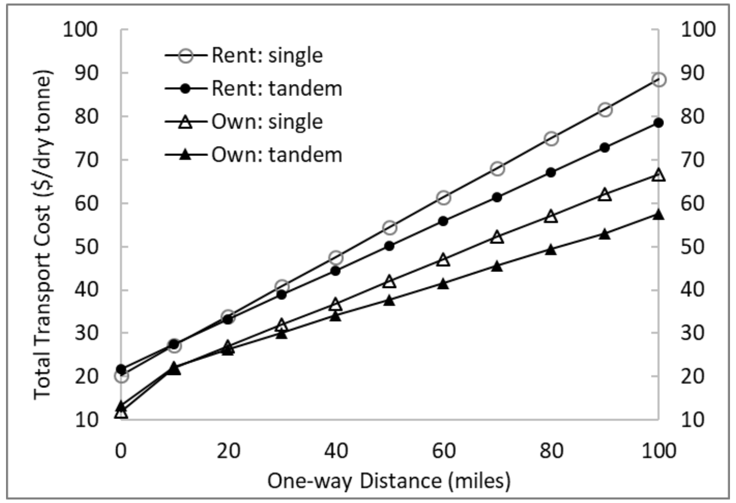
- Variable pump rates (load times), % solids (waste volume), truck type, shipping frequency, owned vs rented equipment, and expense rates based on waste type/size
- Multi-modal network with linear optimization

Gradual refinement: Initially we model trucking only and assume feedstock price = delivery price (always ≥0), then refine in FY2021 Q3 to include storage, formatting, service/tipping fees, and possibly credits (prices could be <0)

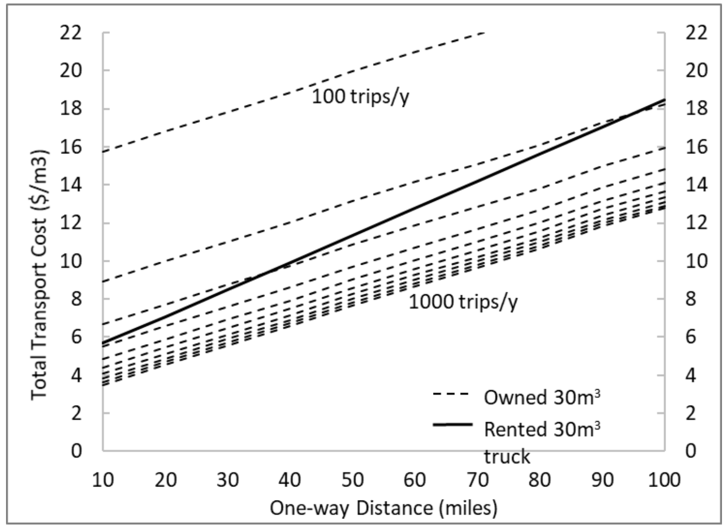
Generalized transport cost model workflow



Total transport cost ($/t dry) to haul 3,440 t/y dry solids (16,500 m^3/y at 20% solids) from 0-100 miles. Requires 550 trips/y (~1.5 trips/d) for a 30m^3 truck and 412 trips/y for a 40m^3 tandem.



The supply model automatically selects the cheapest ownership model (rent vs. own) based on expected annual truck utilization



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4 – Major Outcome #2: Regional Supply by Price

Geographic view of cost-effective feedstock hot-spots in the U.S.

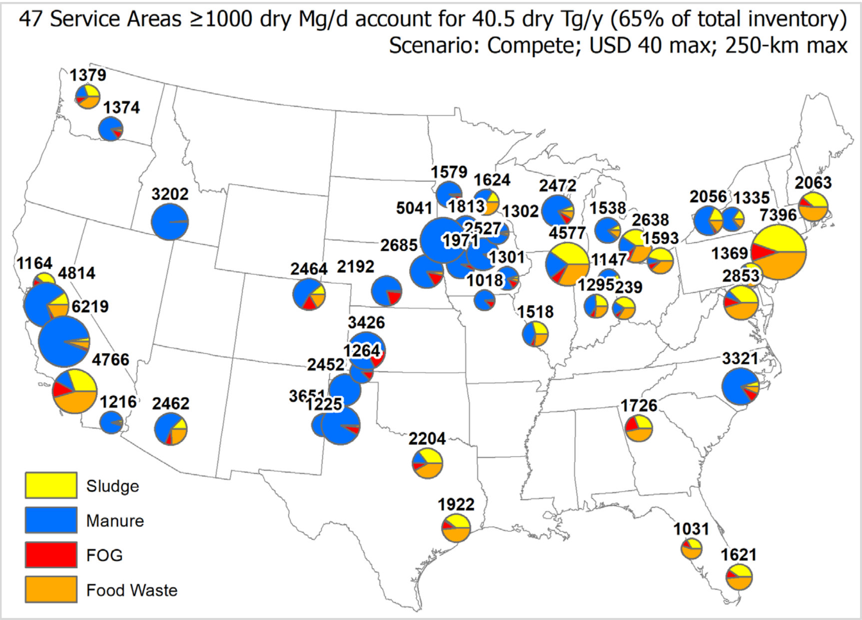
We are still in a period of model development and iterative learning. But the TEA team asked us to propose a resource-informed HTL plant scale for FY2020 SOT sensitivity analysis

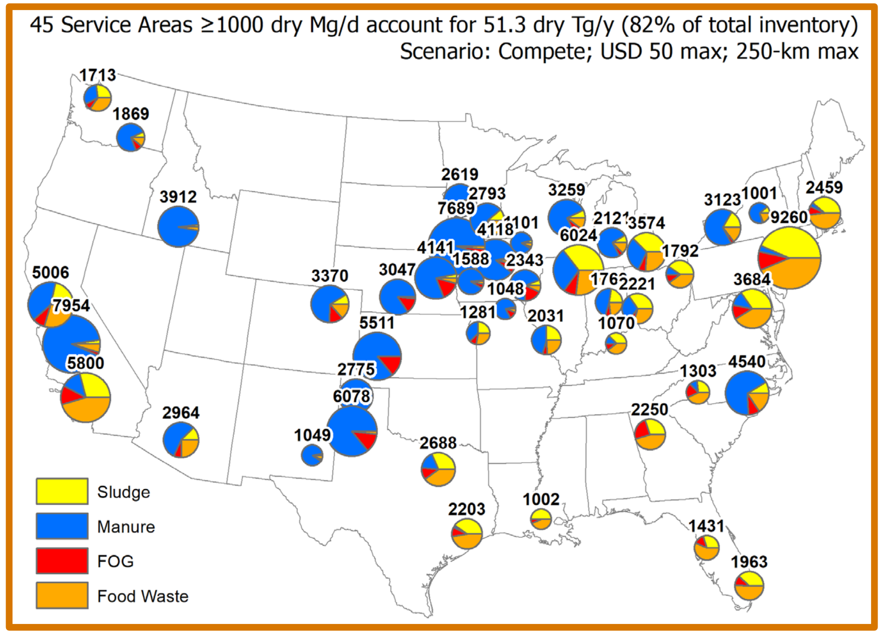
New! We completed a preliminary assessment of regional supply scale by price ($30-$60/t dry). Based on this, the TEA team chose a scale of 1000 t/d dry and a feedstock price of $50/t dry.

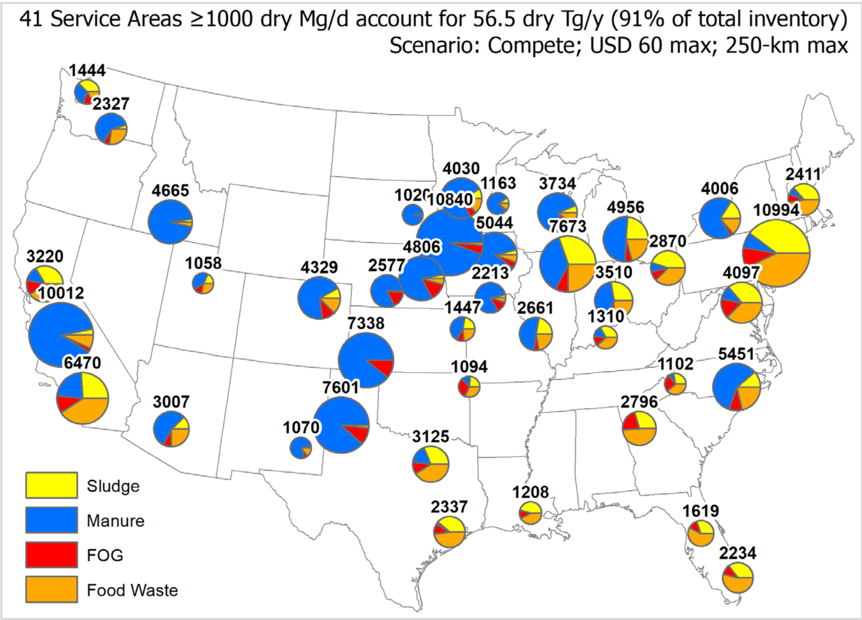
FY2022 Go/No-go Practice Run! - We are excited we can already illustrate there are likely places in the U.S. with ≥1000 dry t/y of cost-effective feedstock, but we still need to

- Complete network optimization
- Refine feedstock price beyond travel cost
- Perform sensitivity analysis to finalize assumptions

Supply Hot-spots (≥1000 t/d dry) at USD $40, $50, and $60 per dry metric ton







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Summary

Now is the time to think big about transforming waste management in the U.S.

Overview	**Transform underutilized wet organic wastes** into sustainable feedstocks for biofuels production by assessing distribution and scale of cost-constrained supply and identifying real-world opportunities for pilot-to-commercial scale conversion and biorefining
Management	**Continuous cross-project integration** with TEA and Bench-scale teams to align assumptions and methods and share knowledge/data to maximize impact. Calibration with regulators and industry experts
Approach	Overcome risks from imperfect engineering and market data to develop and apply **geo-economic models** to assess impacts of feedstock aggregation and blending strategies on conversion/biorefinery location, scale, and performance
Impact	**Accelerate adoption of transformational conversion technologies** by providing evidence to justify TEA scaling assumptions to reduce MFSP in the SOT and inform HTL blending experiment design. Provide credible guidance to the waste management community for regional deployment planning
Progress & Outcomes	**Following our AOP plus bonus analysis**: Enhanced feedstock model with network routing; performed an initial cost-effective feedstock analysis to quickly inform the FY2020 SOT about the relationship between delivery price and feasible plant scale
Future work	**Complete our remaining tasks** in the current project cycle (FY2021-2023) • Task 2: Characterize industrial high-strength waste sources (FY2021 Q2) • Task 3: Model feedstock prices; update feedstock estimates (FY2021 Q3-Q4) • Task 4: Economic optimized blending (FY2022) • Go/No-Go: Illustrate feasibility of large-scale conversion (FY2022 - Q1) • Task 5: Conversion and biorefinery siting analysis (FY2023) **The next natural step for us** is to partner with key municipalities to perform triple-bottom-line geo-economic analysis using “hyper-local” data to jointly develop a waste conversion roadmap to guide local infrastructure investment and waste management

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Quad Chart Overview

Timeline
- Project start: 10-01-2021
- Project end: 09-30-2023

	FY20	Active Project
DOE Funding	$300k	$900k

Project Partners

TEA/SOT (PNNL, 2.1.0.301), Bench Scale HTL (PNNL, 2.2.2.302), GREET Analysis (ANL, 2.1.0.104)

Barriers Addressed
- **Ft-A. Feedstock Availability and Cost**

Project Goal

Perform geospatially explicit economic modeling to (1) reduce uncertainty regarding wet organic feedstock supply magnitudes, distribution, and costs; (2) assess the impacts of waste aggregation and blending strategies on plant scale and final fuel price; (3) and identify regions in the U.S. capable of supporting large-scale conversion and biorefining.

End of Project Milestone

Deliver and apply an enhanced, data-driven, regional scale, blended feedstock analysis framework to quantify the impacts that real-world feedstock distribution and aggregation, formatting, and blending strategies have on conversion and biorefinery location, scale, profitability, and final fuel price.

Funding Mechanism
- **Lab Call AOP**

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Additional Slides

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Responses to Previous Reviewers' Comments

Key 2019 Peer Reviewer Comments

1. *"There are so many directions in which one can go with the feedstock data developed in this project that there needs to be a clear, agreed-upon path forward."*
2. *"Internal economics (e.g., transportation) are not fully developed"*
3. *"identify possible externalities that may impact the system…examples of ecological or environmental services include odor control, nutrient management, water management, and solid recycling, with energy recovery being a desirable cost offset but not in most cases the primary"*

Our new project (FY2021-2023) was developed to specifically address these key reviewer comments

1. **Clear direction:** We worked closely with BETO to carefully align our project outcomes and milestones with the TEA (PNNL, 2.1.0.301) and Bench Scale HTL (PNNL, 2.2.2.302) projects. These three projects are now tightly coupled and focused on a common BETO goal - Enable commercialization of promising conversion technologies by illustrating economically viable pathways to biofuels for ≤$2.50/gge by 2030.
2. **Economics:** During our previous period of performance (FY2018 – 2020) we were trying to understand total feedstock and biofuels potential of wet organic wastes. Having completed that work, our new project is focused on quantifying cost-effective supply and blending performance. As a result, we plan to fully address the "internal economics" of feedstock formatting, transport, blending, and conversion.
3. **Externalities:** We have been able to estimate the monetary value of the solids converted to biofuels, as well as the potential savings from avoided solids disposal and reduced OPEX and primary energy by switching technologies. As our models mature and we focus on specific case studies, we will propose or contribute to a more comprehensive triple bottom line accounting of specific technologies like HTL.

Go/No-Go Highlight: Illustrated that wastewater treatment plants >4.6 Mgal/d can economically utilize 10.7 million dry t/y (80%) of sludge feedstock to produce 1 Bgal/y of biocrude intermediate. We were able to meet the minimum goal for feedstock utilization (10 million t/y) using a single waste stream.

Publications, Patents, Presentations, Awards, and Commercialization

Publications

- Coleman A.M, Bynuum L.E., Seiple T.E., Oster M.R., Skaggs R.L. **2020**. “Evaluation of Waste-to-Energy Feedstock Blending to Maximize Efficiency of Biofuel Production and Organic Waste Reduction” Applied Energy (in-progress) (Impact factor: 8.848, CiteScore: 16.4)
- Seiple T.E., R.L. Skaggs, and A. Coleman. **2020**. "Municipal wastewater sludge as a renewable, cost-effective feedstock for transportation biofuels using hydrothermal liquefaction." *Journal of Environmental Management* vol. 270. doi:10.1016/j.jenvman.2020.110852
- Seiple, Timothy **2020.** “Data for: Municipal wastewater sludge as a renewable, cost-effective feedstock for transportation biofuels using hydrothermal liquefaction”, Mendeley Data, v2 doi:10.17632/wf64vzcg58.2
- Seiple, Timothy; Milbrandt, Anelia **2020**. “National Wet Waste Inventory (NWWI)”, Mendeley Data, v1 http://dx.doi.org/10.17632/f4dxm3mb94.1
- 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:10.1016/j.resconrec.2018.05.023.
- Skaggs, R, Coleman, A, Seiple, T, Milbrandt, A, **2018**. Waste-to-energy biofuel production potential for selected feedstocks in the conterminous United States. Renew. Sustain. Energy Rev. 82 (3), 2640–2651. doi:10.1016/j.rser.2017.09.107.
- Seiple T, Coleman A, Skaggs R. **2017**. "Municipal Wastewater Sludge as a Sustainable Bioresource in the United States" *Journal of Environmental Management* vol. 197:673–680. doi:10.1016/j.jenvman.2017.04.032.

Conference Papers

- Seiple T.E. "Leveraging U.S. Wastewater Infrastructure for Energy Recovery." Presented by T.E. Seiple at **WEFTEC 2019**, Chicago, Illinois. PNNL-SA-147585.
- Seiple, T. “Regional blending of wet organic wastes for conversion to biofuels”. Accepted for **WEFTEC 2021**

Milestone Summary

Principle research elements since 2019 Peer Review

New project cycle (FY2021 to FY2023) Integrates resource assessment, TEA scaled costs, and bench-scale conversion results into a data-driven, geo-economic analysis framework to help reduce feedstock cost and scale uncertainty for various conversion pathways in a real-world context.

Period	Objective	Technical Approach	Milestone
FY2020 (last cycle)	Leverage existing infrastructure; Assess total blending potential in U.S.	WRRFs[1] >4.6 Mgal/d can economically use 10.7 million dry t/y (80%) of sludge feedstock to produce 1 Bgal/y of biocrude with HTL[2]. Blending all wet wastes could yield 6 Bgal/y of biocrude.	Annual - Complete ✓
FY2021	Quantify supply cost and scale	Geo-economic model to estimate cost-constrained supply	Annual
Q1	Quantify transport costs	Integrate network transport into supply model (Task 1)	Q1 Complete ✓
Q2	Add more wastes sources	Include industrial high strength waste (HSW) sources (Task 2)	Q2 Ongoing
Q3	Quantify feedstock prices	Full feedstock price considers waste formatting, transport, service/tipping fees, competitive uses, etc. (Task 3)	Q3
Q4	Cost-informed feedstock supply	Deliver updated economic supply estimates (Task 3)	Q4
FY2022	Assess regional blending strategies	Produce regional blending profiles and conversion efficiency and yield curves for different blending strategies (Task 4)	Annual
Q1	Prove large-scale conversion is feasible	Criteria: Identifying ≥1 region in the U.S. with ≥1000 dry metric tons per day of cost-effective feedstock supply	Go-No/Go
FY2023	Illustrate real-world deployment opportunities	Perform initial siting analysis for pilot-to-commercial scale conversion and biorefinery facilities (Task 5)	Annual

1 – (WRRF) Water resource recovery facility, a modern term for wastewater treatment plant
2 – (HTL) Hydrothermal Liquefaction

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Thank you