Waste-to-Energy: Optimized feedstock aggregation and blending at scale

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Organic Waste Conversion Technology Area Panel

Principle Investigator

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Identify cost-effective opportunities to deploy transformational clean energy technologies in the U.S. to treat organic wastes

Project Overview

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Why our project matters

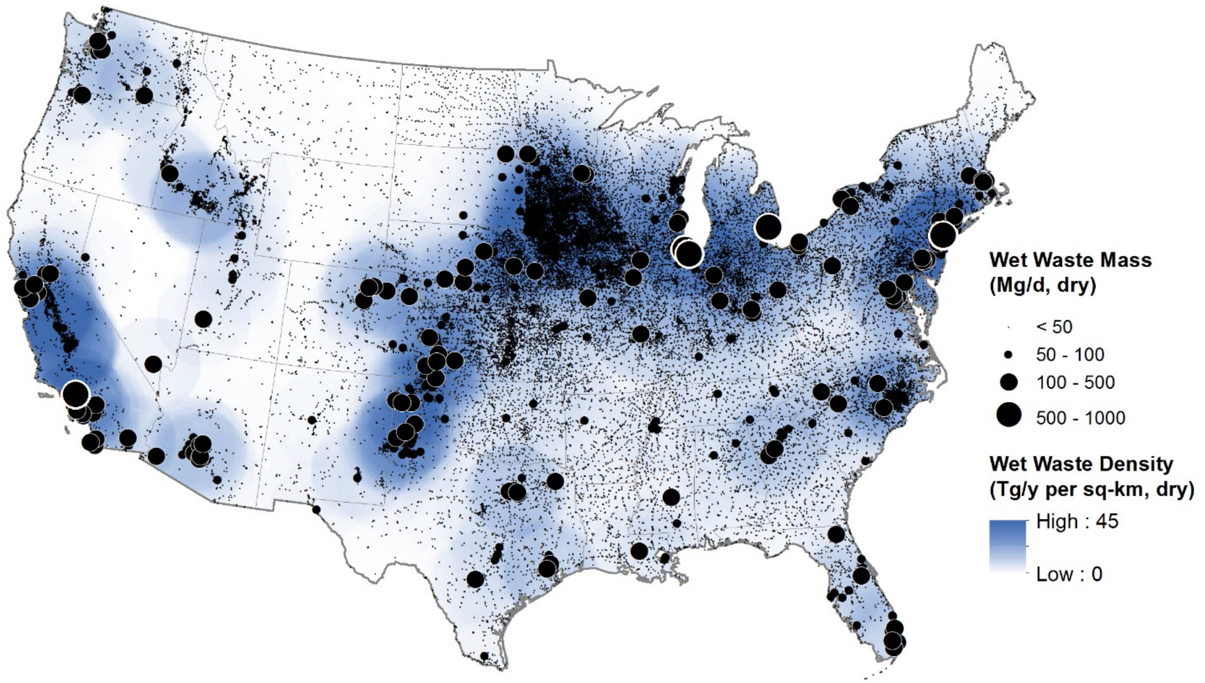
- Waste-to-energy (WtE) solutions can reduce waste treatment and disposal costs and environmental harm
- Our project integrates the latest WtE experimental performance data with real-world resource data to find feasible WtE deployment opportunities (from pilot-to-commercial scales)

Scope History (evolving since 2016)

- National wet waste resource assessment
- National biocrude potential estimates
- Identify cost-effective feedstock "hot-spots"
- Biorefinery siting and waste supply chain modeling

Current Research Objectives

- Optimized conversion and biorefinery siting analysis
- Characterizing the impacts of key assumptions on feedstock "gate" prices



Wet organic waste distribution and density (PNNL, 2022)

What are wet organic wastes?

- >76 million dry T/y of sludges, manures, food waste, and fats, oils, and grease
- 5.6 Bgal/y of biocrude potential
- 56,000 locations nationwide

Cross-project integration maximizes impact for BETO and the public

Approach (Management & Communication)

Project Controls

- Annual Operating Plan
- Go/No-Go review
- Peer-review
- Risk register

Regular Communications

- Monthly program calls
- Quarterly/Annual reporting
- Publications & conferences

Stakeholder Communication

Waste Regulators: EPA, USDA, Biosolid Coordinators

Waste Researchers: Water Research Foundation (WRF), Northeast Biosolids & Residuals Association (NEBRA)

City Leaders: Waste Handlers; Waste Treatment Plant Operators

Key BETO Project Collaborations

- *Experimental*: Bench-scale (2.2.2.302) and PDU (3.4.2.301)
  - They give us conversion rates, in exchange we recommend precise regional blends that make the experimental work representative of the real world.
- *Techno-economics*: Analysis & Sustainability Interface (ASI) (2.1.0.301)
  - TEA work benefits immensely from our waste logistics modeling. They give us scaled plant costs, in exchange we provide feedstock prices and feasible plant scales to make TEA scenarios more realistic.

Approach (Management & Communication) continued…

Go/No-Go (completed 31-MAR 22)

- *Criteria:* Screening analysis should identify at least one region capable of economically converting ≥1000 t/d dry solids to fuel at \$2.50/GGE.
- *Result*: Applying a preliminary version of our model, we identified >20 sites capable of using ≥1000 t/d of waste to make biofuels at \$2.50/GGE, which accounts for 61% of total national waste feedstocks

Diversity, Equity & Inclusion (DEI) Goals

- There are no DEI hiring goals defined for this project
- Our goal is to reduce waste-related social, economic, and environmental harm to at-risk communities

Key Risk	Strategy
Imperfect resource data	(Mitigate) We use the best publicly available national data
Feedstock price uncertainty	(Mitigate) Use sensitivity analysis to model a range of feedstock properties that impact gate prices
Plant cost and performance uncertainty	(Accept) We are subject to the accuracy of upstream technology performance and cost data

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Testing technology deployment strategies using realistic supply chain logistics and siting analysis

Approach (Overview)

Technical Approach Summary

- Geospatially explicit, micro-economic optimized siting analysis
- Couples experimental technology cost and performance data with real-world bioresource data and transport logistics

Leaps forward since 2021 Peer Review NEW

- Any feedstock, any WtE technology
- Geospatially optimized siting
- Dynamic feedstock prices
- Network-based routing

Key Benefits

- Continuous “on-the-ground” technology testing
- Reusable supply chain and siting models
- Open-source, standards-based implementation
- Data-driven model with many configurable parameters supports flexible scenario definition

Final Scenario (Planned for end of FY2023)

Siting of integrated HTL Biorefineries (integrated conversion and upgrading) for a range of build-out options (many small plants vs. fewer large plants)

- Limit waste sources to ≥1 dry t/d
- Direct supply of waste by producers to WtE plant
- Perform sensitivity for key drivers of minimum fuel selling price (MFSP) and feedstock price (track the shift from liability to commodity)

Future Scenarios (If project is renewed)

- *Non-integrated* HTL conversion and biorefining (2-stage optimized siting)
- *Indirect Supply,* where “Middle-man” delivers blended waste under long-term contract
- *HTL Conversion-only,* where biocrude is delivered to the nearest existing refinery

Geospatially optimized WtE siting workflow

Approach (Model Workflow)

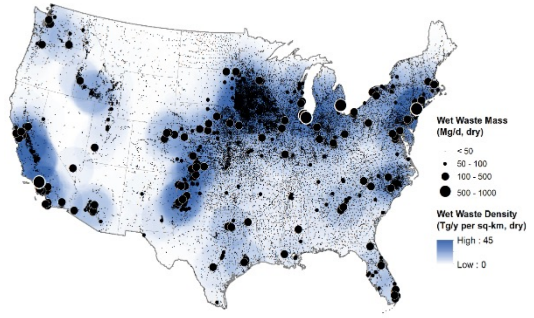
Model Inputs

- Realistic waste sources data {mass, type, location, properties}
- Realistic cost factors (transport, disposal, energy, etc.)
- Realistic modeled travel costs
- Experimental conversion (yield) factors
- Experimental conversion & upgrade scaled plant cost curves

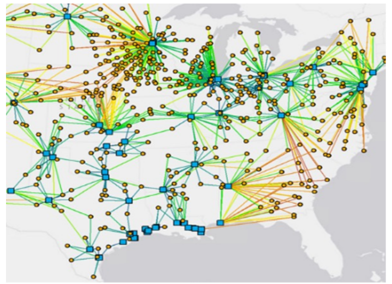
Procedure

1. Compute travel time between all 56,000 waste sources
2. Perform regression analysis to predict travel time from distance
   - Improves computation (query a function; not a huge table)
   - Preserves geographic variability (drive faster in MT than D.C.)
3. Run optimization (siting) model
   - Determines locations, scales, cost, and profit
   - Run model several times and check for solution consistency
4. Generate graphics and summary statistics

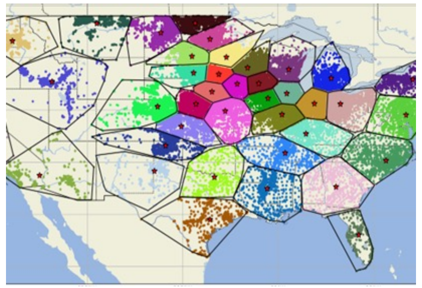
Waste Resources



Routing Model



Optimized Siting



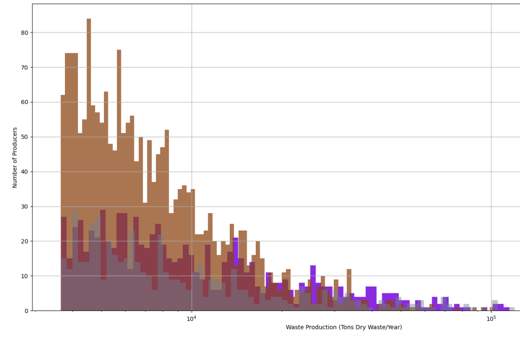
All the complexity is reduced to intuitive metrics and actionable information

Approach (Model Outputs)

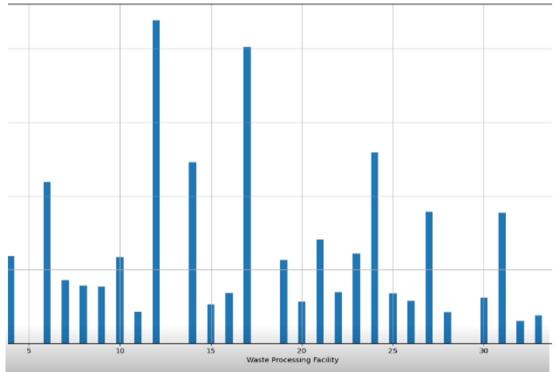
Standard Model Outputs

(Summarized by WtE site and system averages)

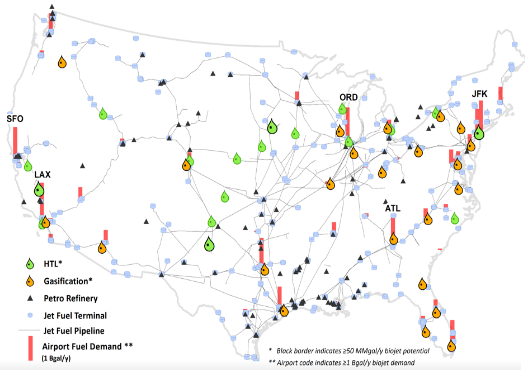
- Number of feasible sites, locations, and scales
- Net Profit
- Total waste disposal savings
- Total fuel production
- Total feedstock utilization by type
- Feedstock “gate” prices (by type)
- Total travel costs and ton-miles
- Waste related truck traffic compared to National Freight Analysis Framework



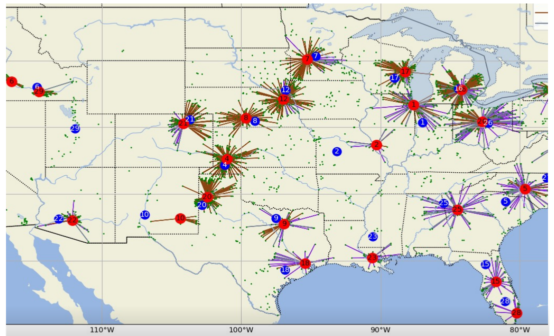
Histogram: Sources by size



Histogram: Facility scales



Map: Facility locations



Map: Index of sources

Examples of graphical outputs

Progress and Outcomes (Overview)

Significantly enhanced model capability; New data, results, and knowledge forthcoming!

Project Status: Final year of a 3-year analysis project

Milestones: Step-wise progress on straightforward milestones

Description	Due Date	Status
Finalize methods and assumptions	12/31/2022	100% Complete
Model and data verification	3/31/2023	100% Complete
Final biorefinery siting analysis	6/30/2023	In-Progress
Deliver and publish model, data, results	9/30/2023	Planned

Task Update: One task remains; finish, test, apply, and deliver model

Progress toward project goal

- We have enough time/funding to deliver our model and results
- Excited to publish and share results (planned articles)
  - Seiple T.E., Bakker, C., 2022. "**Cost-effective opportunities to convert low-cost wet organic wastes into biofuels in the US**." Applied Energy (manuscript in-progress; Impact factor: 11.446, CiteScore: 20.4)
  - Bakker, C., Seiple T.E., 2022. "**Profitability and Scalability for Waste-to-Energy Supply Chains" Applied Energy** (manuscript in-progress; Impact factor: 11.446, CiteScore: 20.4)

State-of-the-art realism for waste supply chain modeling and WtE siting analysis

Progress and Outcomes (Highlights)

We are proud of our progress since the 2021 Peer Review

- ✓ Geospatially optimized siting at any scale for any feedstock using any WtE technology (**Highlight #1**)
  - Previously, siting was limited to conversion of wet waste by HTL at existing waste sites
- ✓ Dynamic feedstock prices (**Highlight #1**)
  - Previously, we modeled feedstock supply at fixed gate cost limits (e.g., what can we collect at $50/t?), which arbitrarily constrained plant scales and ignored profit impacts on feedstock value
- ✓ Realistic supply logistics using network-based routing (**Highlight #2**)
  - Previously, we used straight-line map distances
- ✓ Feedstock-specific properties that impact cost and performance
  - Previously, we used a single set of values for "blended feedstock"
- ✓ Fully configurable energy, price, and technology parameters
- ✓ Automated workflow using open-source data and software libraries

Geospatial Micro-economic optimization is a 2-for-1; (Determines siting locations and feedstock prices)

Progress and Outcomes (Highlight #1)

State-of-the-art Siting Analysis

- Fully dynamic geospatial siting
- Optimizer maximizes system-wide profitability
  - Model objectives can be modified
- Technology and feedstock agnostic
- Open-source optimization library (IPOPT)
- Speed-ups
  - Replace 70M travel times with regression f(x)
  - Machine Learning (ML) algorithm selects siting candidates each iteration
  - "Pruning" techniques reduce run-times 10x
- Flexible scenario configuration
  - Build-out options (many small vs. few large)
  - Integrated vs. distributed deployments
  - Policy constraints (e.g., limit feedstocks, add fuel credits, moratoriums, etc.)

And.. Dynamic feedstock "gate" prices

- Micro-economic optimizer calculates gate prices endogenously as a function of willingness-to-pay to maximize system-wide profits
- Feedstocks can have individual scalable prices
- Configurable parameters that influence gate prices
  - Waste Property {Type, %Solids, %Ash, Yield}
  - Transport and disposal cost factors
  - Max plant scale (proxy for max. disposal fee)
  - Biofuels price (proxy for min. disposal fee)

Key Challenge

- Optimization does not give a single "right" answer; so we run scenarios multiple times and test for model consistency
  - Objective function values should be within 1%
  - High RAND index indicates results are robust

Detailed road network and realistic speed limits enable accurate waste routing and travel time estimation

Network Dataset Source

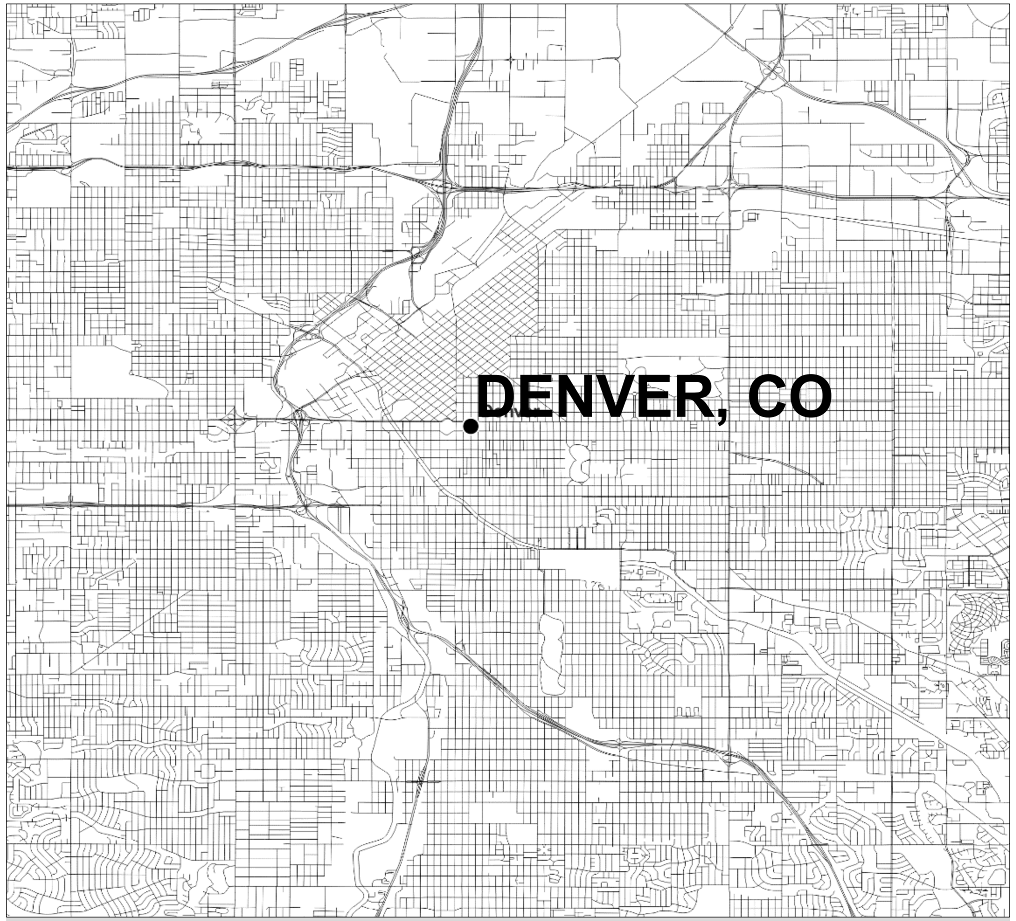
- U.S. Census Bureau's 2021 MAF/TIGER state level edges dataset (42,326,968 road edges)
- Attributes: {road length, road type}

Key Benefits

- Very low average on- and off-network connection cost of 0.5 mins for all waste points (**low error**)
- Accurate routing around natural features
- Custom speed limits favor travel on main roads
- Automated network re-builds (for updates)
- Open-source data enables publishing
- Supports imposing a maximum search radius
- Capable of multi-modal transport modeling

Model Output

- Origin-Destination Matrix table containing least cost paths between all waste sources



Network detail for Denver, CO.

Even as we develop the model, our data, tools, and analysis capabilities are being applied across a wide array of clean energy projects

Impact (Summary)

Foundational data and knowledge to the public

- Our *National Wet Waste Inventory* database is the standard resource dataset for projects performing TEA to evaluate wet waste conversion technologies
- Feedstock visualizations offer baseline facts for everyone (**Highlights 1 & 2**)
- We fulfill data/info requests from public institutions (i.e., Universities, NREL, ORNL)

Support for many WtE research projects (biofuels, biojet, marine, RNG)

- <u>Regional "diet" analysis</u> **(Highlight #3)** for HTL Bench-scale Team (WBS 2.2.2.302), HTL PDU Team (WBS 3.4.2.301); Detroit, MI; and Austin, TX
- <u>Feedstock supply and cost estimates</u> (**Highlight #4**) for Analysis & Sustainability Interface Team (WBS 2.1.0.301) and Marine Biofuels (PNNL); Advanced Pretreatment/Anaerobic Digestion (WSU)
- <u>Independent Testing</u> (**Highlight #5**) to evaluate impacts of modeled assumptions
- <u>Biorefinery siting analysis</u> (**Highlight #6**) for Sustainable Aviation Fuels (PNNL) and Great Lakes Water Authority HTL Business Case (PNNL); Sustainability Tracking for Waste Supply Chains (PNNL, 1.1.1.6)

By the end of FY23

- Publish a definitive set of the best places to start deploying WtE in the U.S., along with detailed economic and performance summaries

Dispelling myths about waste distribution and creating a new vision for what is possible

Impact (Highlight #1)

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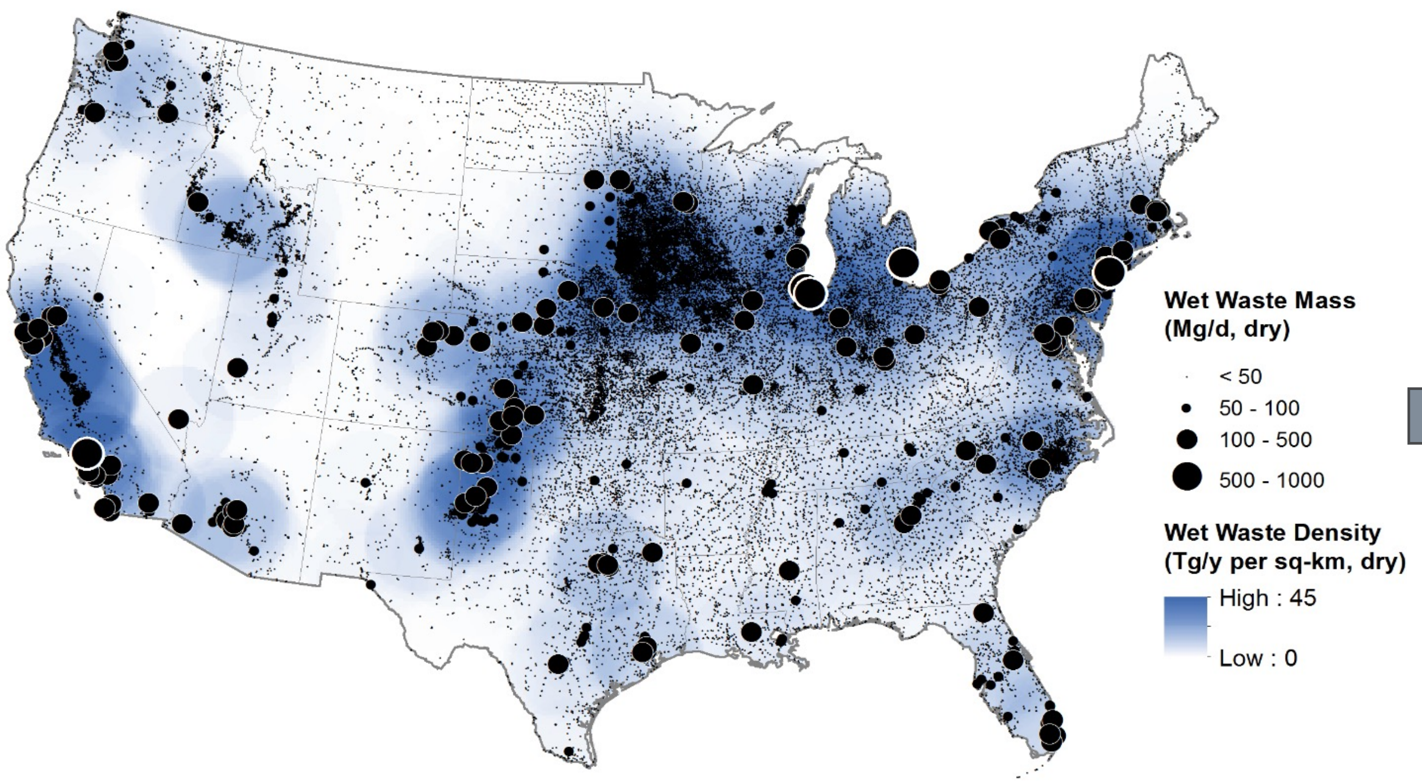
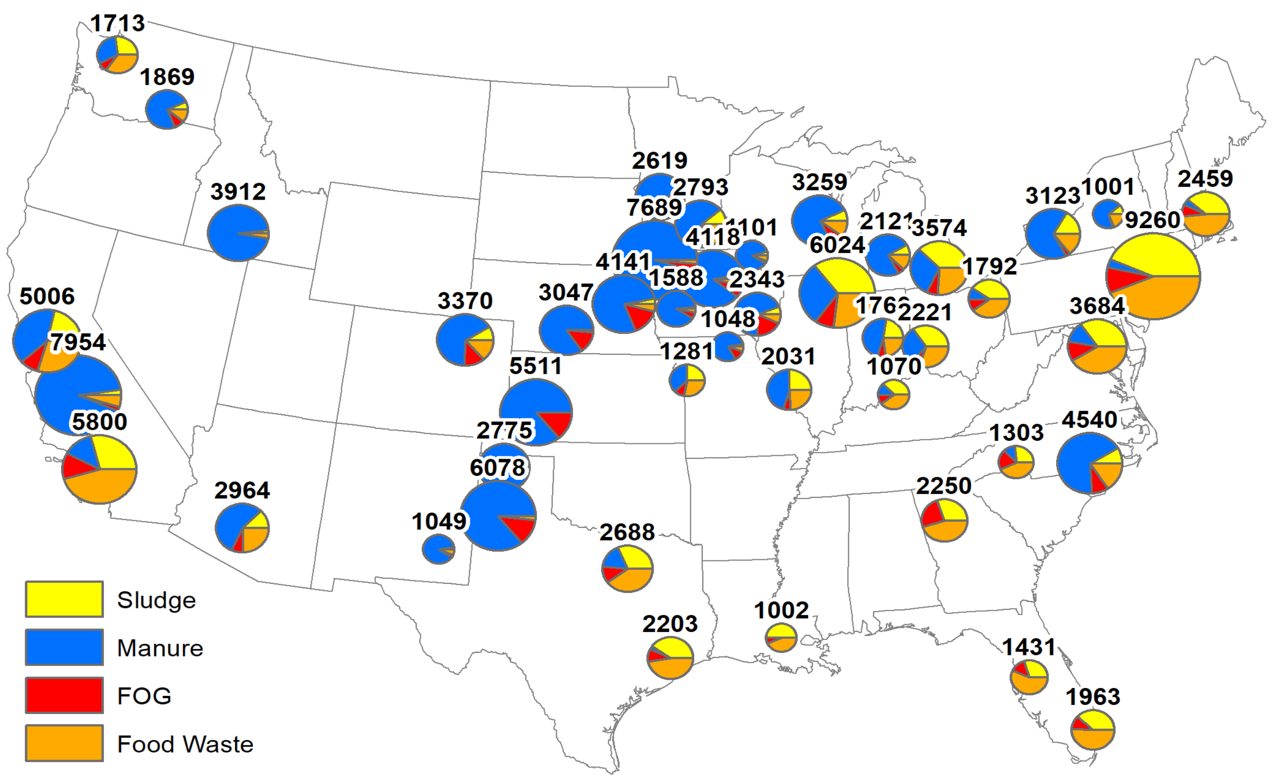
Data contradict the notion that wastes must be handled in a distributed manner. In reality, communities can work together achieve common WtE goals

Aggregation exercises indicate 82% of wet organic wastes could be moved to sites ≥1,000 t/d for ≤$50 per dry tonne. These places are “low hanging fruit” for WtE.



Wet organic waste spatial distribution and density



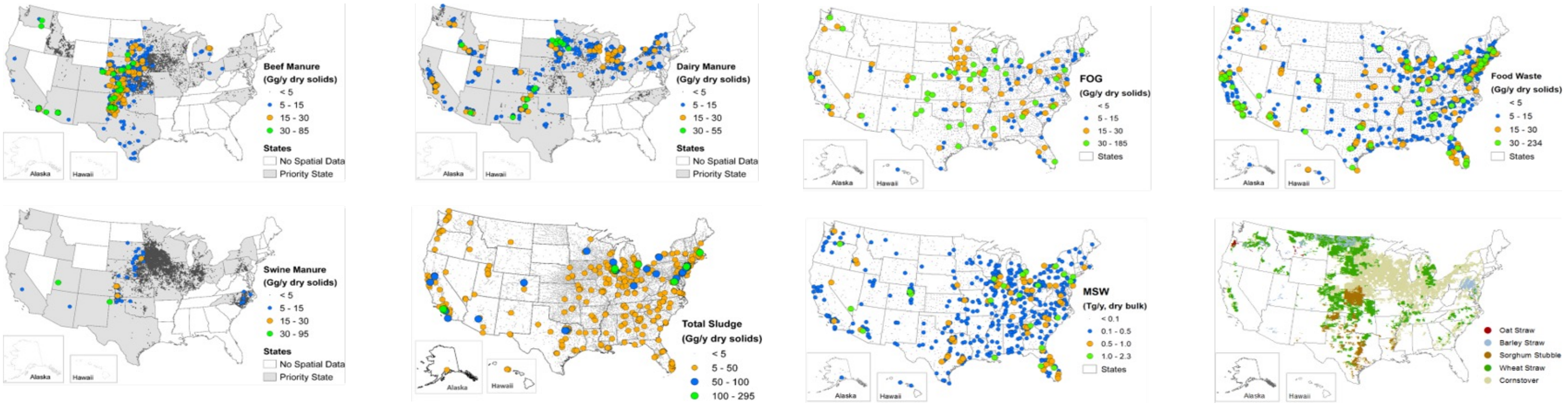
Potential for large scale wet waste aggregation

Simplifying complex data for easy interpretation

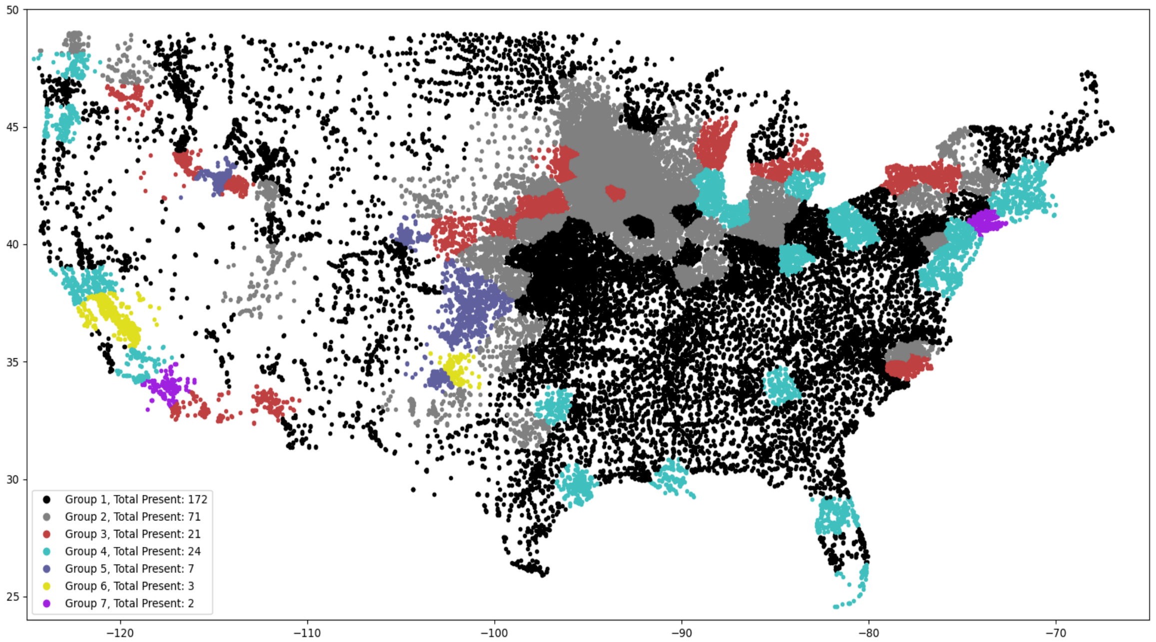
Impact (Highlight #2)

Mapping generalized feedstock "zones" will make it easy for Industry to find targets for their WtE technology

(inspiration – kid's puzzle)



Example map of generalized feedstock zones



- Challenging ML clustering problem; work in-progress ☺
- Maps will help focus research and pilot-to-commercial scale deployments
- Which map to share? Results are sensitive to number, type, and scale of waste sites and the number of classes

Zone Descriptions

1. Very small waste sites
2. Small/medium manure
3. Medium manure
4. Medium food, sludge
5. Medium/large manure
6. Large manure
7. Large food, sludge

Precision design of blended waste conversion experiments (Detroit, MI)

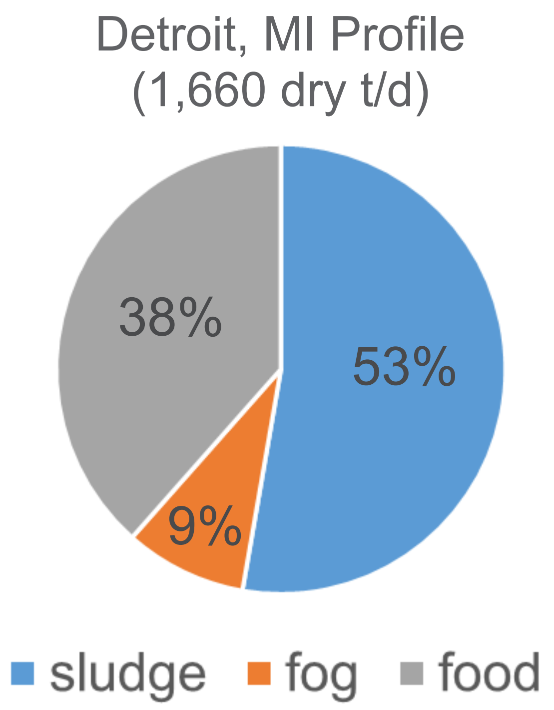
Impact (Highlight #3)

Regional feedstock composition ("diet") analysis

- We receive many requests for custom feedstock reports
- Users set the geographic boundary, waste type, and scale

HTL example

- The "Bench Scale" Team (2.2.2.302) wanted to characterize HTL conversion efficiency for a "typical" metro area
- **Impact:** Analysis indicated the waste profile for Detroit is composed of 53% sludge, 38% food, and 9% FOG, which resulted in a representative blend with a 50:40:10 ratio



Representative experimental blend design

Real-world feedstock supply modeling to inform TEA plant scale selection

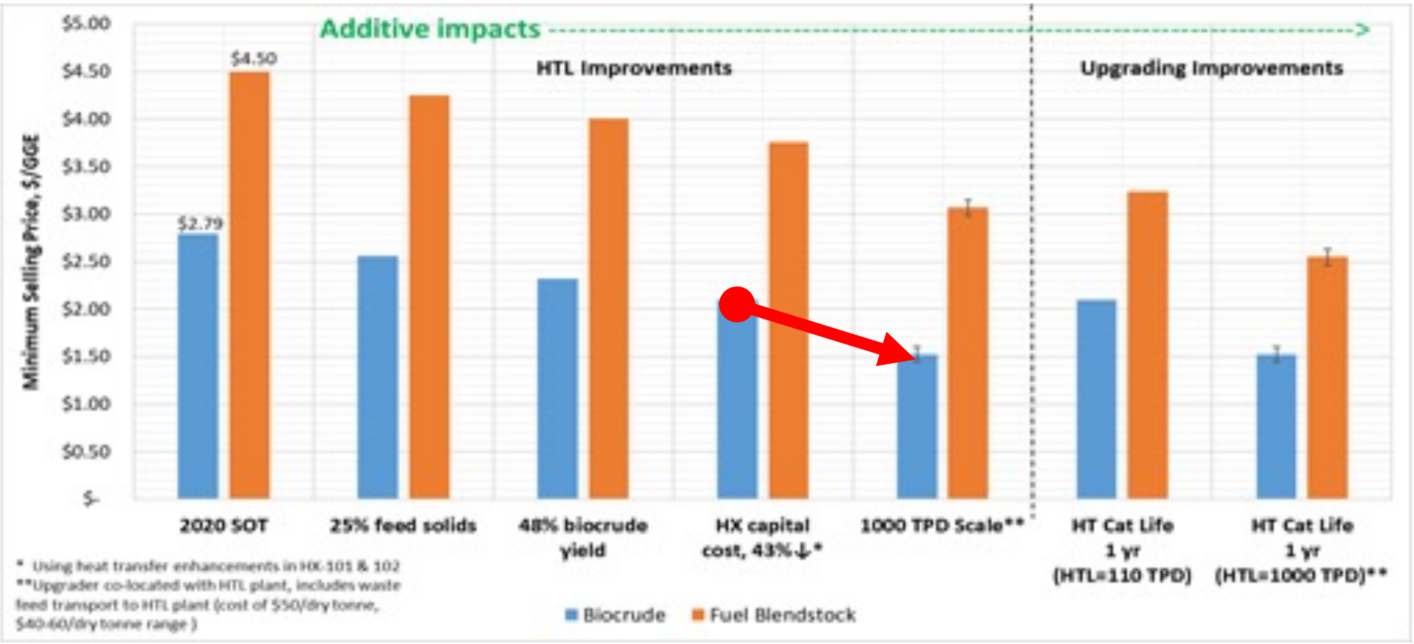
Impact (Highlight #4)

Feedstock supply analysis

- We receive many requests to estimate feedstock supply at fixed delivery cost limits
- Users select maximum delivery price(s), minimum scale (dry t/d), and waste type(s)

HTL example

- The Analysis and Sustainability Interface Team (PNNL, 2.1.0.301) wanted to select a representative large plant scale for TEA sensitivity analysis
- **Impact:** We determined there were ~45 areas in the U.S. able to access ≥1000 dry metric t/d of feedstock at USD $50/t. The ASI Team was comfortable increasing HTL scale by a factor of 10x over the baseline in a sensitivity analysis, which reduced *modeled* MFSP by $0.69 per gasoline gallon equivalent (GGE)



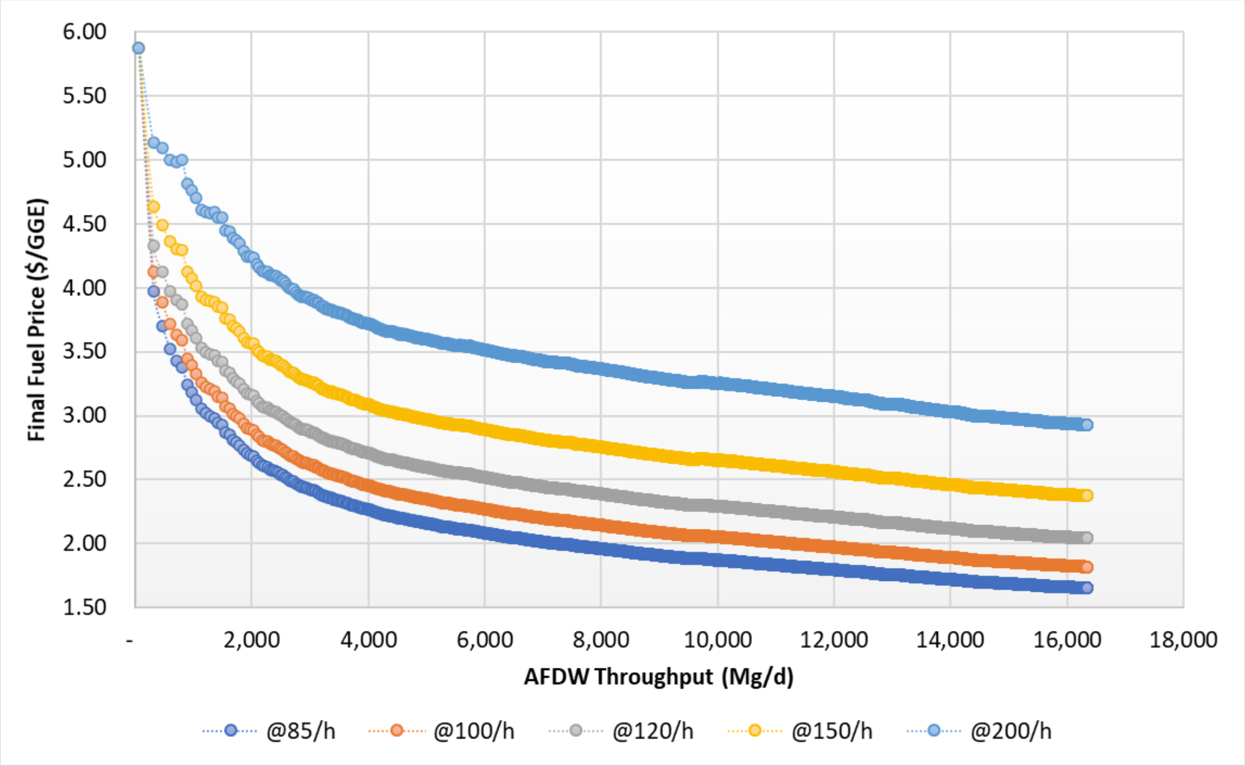
Increasing HTL plant scale is a major driver for achieving $2.50/gge MFSP by 2030

Testing modeled technology cost and performance assumptions against real-world data

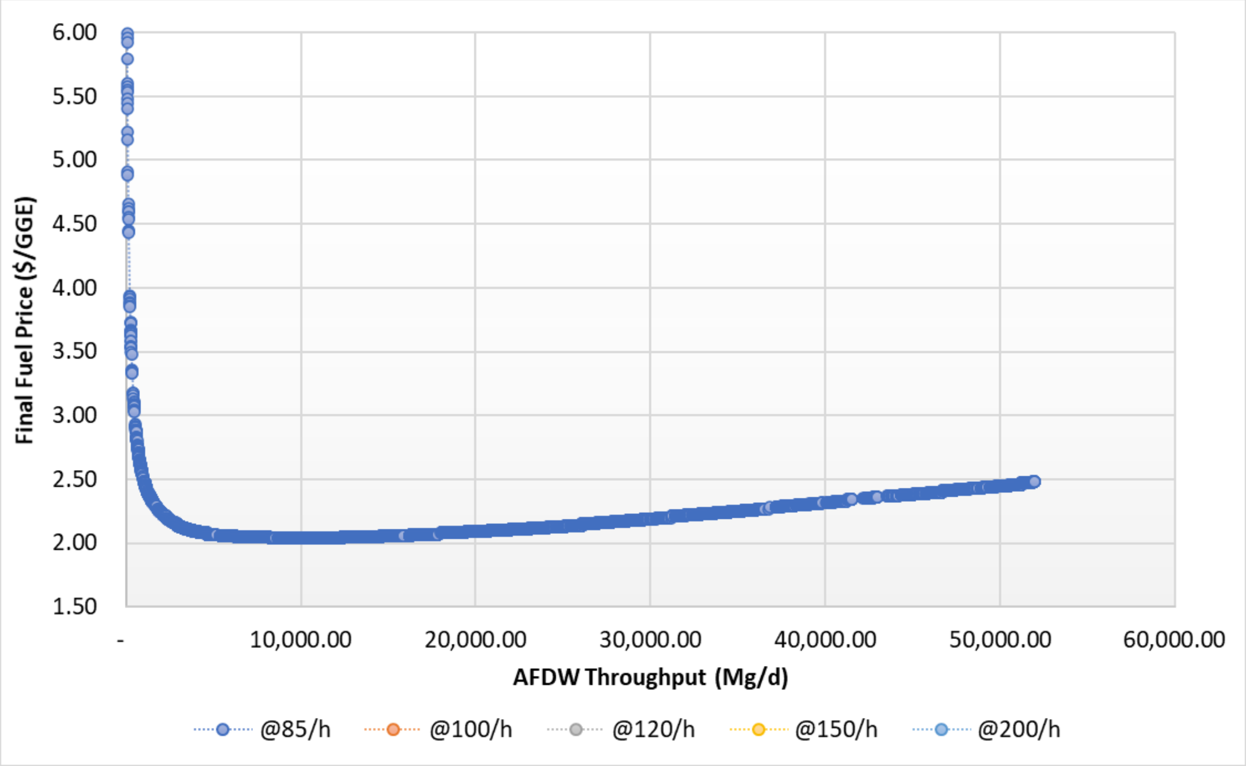
Impact (Highlight #5)

The observed imbalance between economies-of-scale and transportation costs demonstrates the value of testing technology assumptions using real-world data!

As part of a sensitivity analysis to test our siting model, we noticed final fuel prices did not rebound, as expected. This suggested economies-of-scale impacts on fuel price were outpacing travel costs, regardless of travel distance and truck charge-out rates



After extending the model from 200–500 miles, an inflection point is finally observed at very large (unrealistic) plant scales, which suggests the scaled plant cost function should be adjusted or capped. **For now we limit maximum plant scale**



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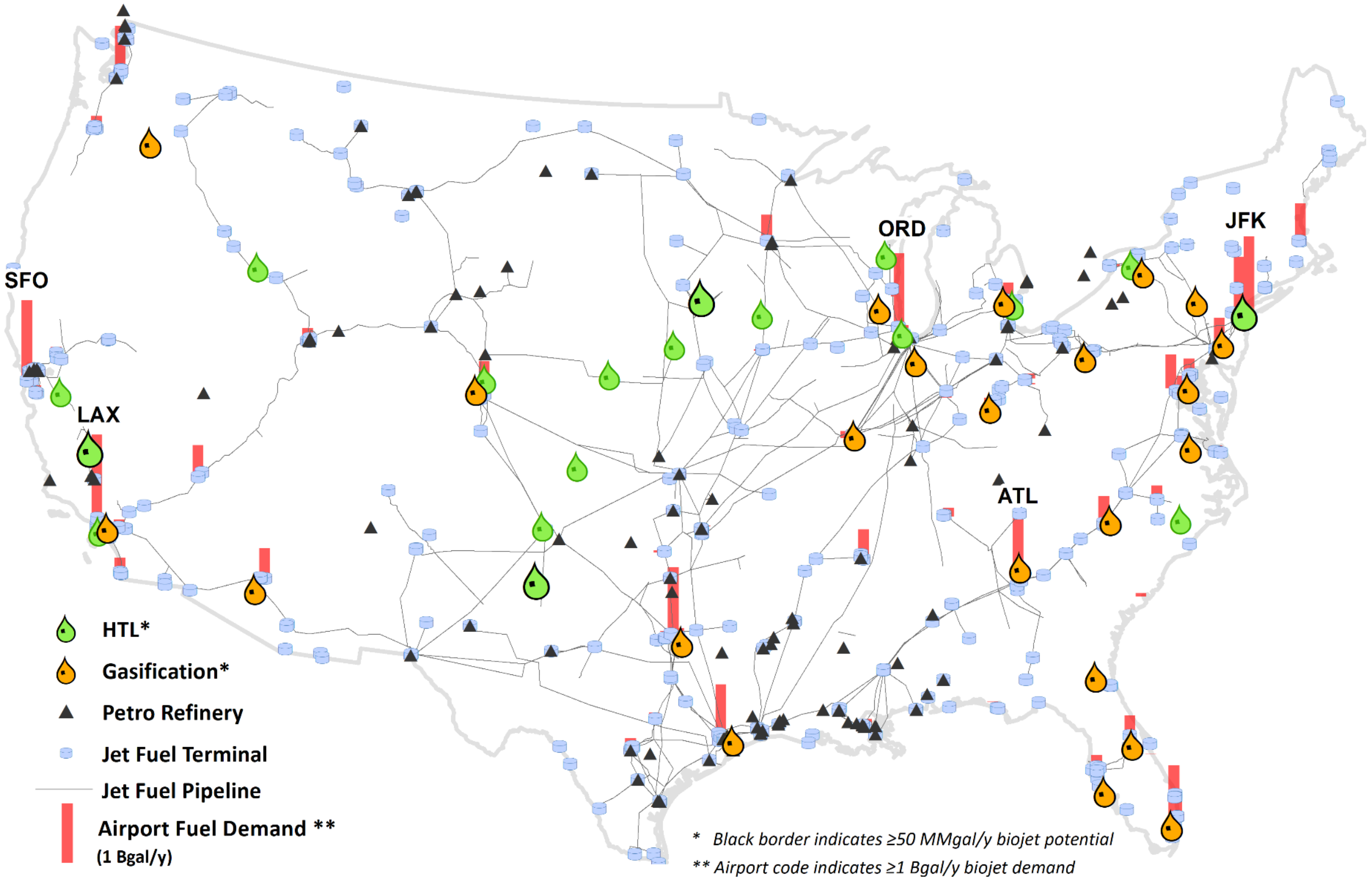
An early version of our model was used to estimate Sustainable Aviation Fuel (SAF) potential of mixed wet/dry wastes

Impact (Highlight #6)

- First-in-kind biorefinery siting analysis for SAF using low-cost waste conversion
- Our first attempt to model multiple feedstocks (wet organic waste and MSW) and multiple technologies (HTL and gasification) in the same scenario
- Exercise led to innovations in our approach
  - Coupled RA-TEA for rapid analysis
  - TEA wrapper for siting model to simulate WtE competition



Proximity of feasible WtE sites to jet fuel storage and major airports

*This work is currently being submitted for publication as follows: Seiple T.E., Jiang Y., et al., 2023. "Opportunities for Sustainable Aviation Fuel from Low-Cost Wastes in the US." ACS Sustainable Chemistry & Engineering (**in-progress**; Impact Factor: 9.224, CiteScore 2021: 14.5)*

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Moving Forward – Leverage learnings from this model to convince communities to collaborate on common WtE goals

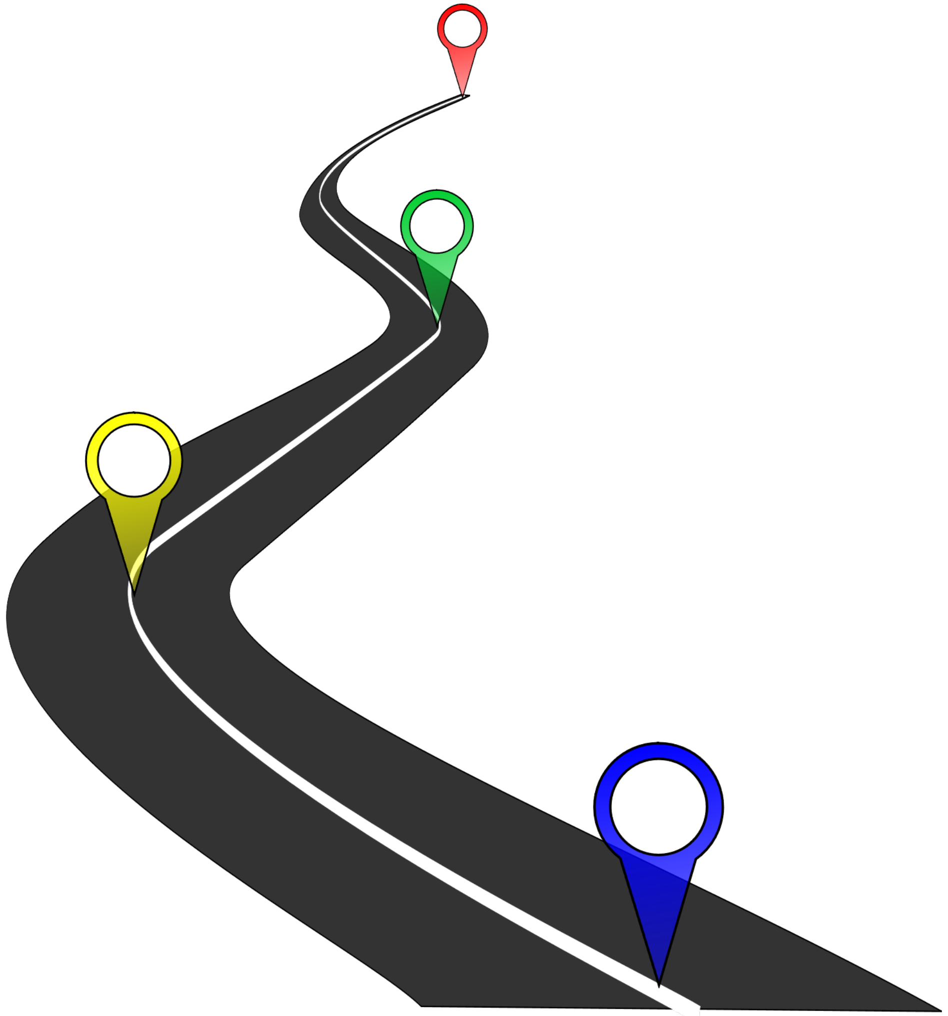
Impact (Future)

We enjoy this project and think it provides a lot of value to the public

- To date, our support for the public was limited to preliminary investigative work, because the model wasn't completed and verified

Now we are ready to hit the road! (FY24–FY27)

- Shift focus from national assessment to local analysis
- Work with key cities to develop WtE strategies/plans
- Design a standard reporting package for city leaders
  - Potentially build dashboards, if budget permits
- Refresh national resource database (>5 yrs. old) and add new waste types (scum, livestock mortalities)
- Further model enhancements
  - Integrate Yield and Scaled Cost calculations into our optimization model for more accurate yield and plant cost estimation for blended wastes
  - Add support for distributed conversion and upgrading (two-step optimized siting)



Courtesy: https://publicdomainvectors.org

Summary

Leverage national capability to promote regional-to-local WtE collaboration

Overview	**Transform underutilized wet organic wastes** into sustainable feedstocks for biofuels by assessing supply distribution, scale, and cost and by identifying real-world opportunities for **pilot-to-commercial** scale conversion and biorefining
Management	**Continuous cross-project integration** to harmonize assumptions and share knowledge/data to maximize impact. Calibrate with regulators, industry, and cities
Approach	Couple **realistic supply chain and optimized siting** models to identify candidate conversion facility locations, scales, and performance
Progress & Outcomes	Following our AOP and on track to deliver our model and results by end of project. **Lots of new capability** including 1) network-based transport modeling; 2) geospatially optimized siting; and 3) dynamic feedstock price modeling
Impact	**Providing credible evidence** to guide clean energy research and waste-to-energy deployment planning
Future work	Focus on direct outreach; Model alternative deployment scenarios; Refresh national resource database (>5 years old)

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Quad Chart Overview

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

	$300,000	$900,000 (FY 2021-2023)

TRL at Project Start: n/a, Analysis project
TRL at Project End: n/a, Analysis project

Project Goal
Perform geospatial economic modeling to (1) reduce uncertainty regarding wet organic feedstock supply magnitudes, distribution, and delivery cost; (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 model to quantify the impacts that real-world feedstock distribution, aggregation, formatting, and blending strategies have on conversion location, scale, profitability, and fuel price.

Funding Mechanism: Lab Call AOP

Project Partners
ASI (PNNL, 2.1.0.301)
HTL Bench-scale (PNNL, 2.2.2.302)
PDU (PNNL, 3.4.2.301)
TBL (PNNL,1.1.1.6)

Responses to Previous Reviewers' Comments

Lack of greenhouse gas (GHG) tracking

Modeling GHGs is not within our scope. We are modeling feedstock supply economics. Other BETO projects are modeling GHGs. For example, Argonne National Laboratory's (ANL) Supply Chain Sustainability Analysis (SCSA) project applies the GREET model (https://greet.es.anl.gov/net) to PNNL-developed conversion lifecycle process models. The resulting GHG accounting is published in the SCSA report, which includes analyses for all BETO technology pathways and coincides with State of Technology (SOT) reports, including PNNL's HTL SOT.

Lack of clarity on long-term feedstock prices, especially in relation to quality

We tackled this challenge head-on. Our enhanced siting model is based on micro-economic principles and is capable of modeling scalable feedstock prices by waste type as a function of an HTL plant's willingness-to-pay while maximizing system-wide profitability. We can also use sensitivity analysis to investigate the impacts of direct versus indirect waste collection options.

Publications, Patents, Presentations, Awards, and Commercialization

Publications

- Seiple T.E., Bakker, C., 2022. “Cost-effective opportunities to convert low-cost wet organic wastes into biofuels in the US.” Applied Energy (**in-progress**; Impact factor: 11.446, CiteScore: 20.4)
- Bakker, C., Seiple T.E., 2022. “Profitability and Scalability for Waste-to-Energy Supply Chains” Applied Energy (**in-progress**; Impact factor: 11.446, CiteScore: 20.4)
- 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. “Regional blending of wet organic wastes for conversion to biofuels”. Accepted for **WEFTEC 2021**
- Seiple T.E. "Leveraging U.S. Wastewater Infrastructure for Energy Recovery." Presented by T.E. Seiple at **WEFTEC 2019**, Chicago, Illinois. PNNL-SA-147585.

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Thank you