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Triple bottom line sustainability indicators for waste-to-energy supply chains

April 3, 2023

Technology Area Panel Feedstock Technologies

Principal Investigators

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Pacific Northwest National Laboratory

Earth Systems Predictability and Resiliency Group

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Project Overview

Period of Performance: FY22-FY24

History: New project building on the success of several BETO-funded waste-to-energy projects including WTE (2.1.0.113); TEA/SOT (2.1.0.301); PDU (3.4.2.301)

Project Goal

- Development a triple-bottom line sustainability (social, environment, economic) assessment tool for local government to evaluate trade-offs of different organic waste streams and energy conversion strategies that help achieve local/regional policy objectives over the current and long-term

Why it Matters

- There is intrinsic opportunity in carbon recovery/minimizing carbon intensity in underutilized organic waste feedstocks (334-411 Tg/yr)
- Local government lack the data and tools required to evaluate sustainability trade-offs for various technology pathways → barriers in the development of waste-to-energy plans
- Incorporating equity and justice indicators directly into the model with input from NGOs and disadvantaged community leadership
- Contributes to BETO goal of 3 Bgal/yr of multi-modal transportation biofuels at $2.50/GGE & 50% GHG reduction by 2030 & Sustainable Aviation Fuel (SAF) goals through a dynamic systems sustainability approach

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1 – Approach (Summary)

Apply state-of-the-art science to build standardized tools for public entities

Problem Statement

- Numerous *barriers* exist for local governments to optimally utilize organic waste resources, including **1)** limited knowledge on modern waste-to-energy technologies, **2)** standard definitions of sustainability measures, and **3)** effective planning and trade-off tools to realize what is possible.

Project Tasks

- *Sustainability Framework* – Clear guidance on how to define, measure, and track sustainability impacts of waste-to-energy systems over time
- *Pathway Analysis Model* – Assess the long-term TBL sustainability trade-offs of using waste feedstocks, conversion technologies, and spatial configurations
- *Stakeholder Engagement* – Help communities understand their local feedstock supply and identify relevant technology options

When used together, these capabilities will help communities choose sustainable waste-to-energy investments to serve *their* needs and objectives

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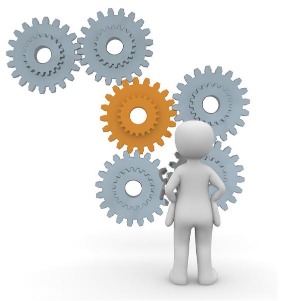


1 – Approach (Management)

Our Team

- Dr. André Coleman, Tim Seiple (PM/PI) – **Spatial Modeling**
- Dr. Craig Bakker – **Multi-Objective Optimization**
- Dr. Chrissi Antonopoulos – **Economist**
- Dr. Saurabh Biswas **- Sustainability**
- Dr. Michael Walsh, Dallase Scott – **Stakeholder Engagement**
- Dr. Bethel Tarekegne – **Project Reviewer**

Diversity, Equity & Inclusion – Workforce Development

- Post-Master's through PNNL Diversity Internship Program

Project Controls

- Annual Operating Plan with regular milestones
- Monthly budget and risk review

Regular Communications

- Weekly team meetings
- Quarterly presentation to sponsor
- Calls with stakeholders, regulators, industry
- Publications, conferences, and workshops

Project Linkages

Builds upon BETO success: WTE (2.1.0.113); SOT (2.1.0.301); PDU (3.4.2.301)

Top Project Risks

1. Insufficient data to support model
2. Low stakeholder interest
3. Difficulty quantifying core TBL indicators

Stakeholder Engagement

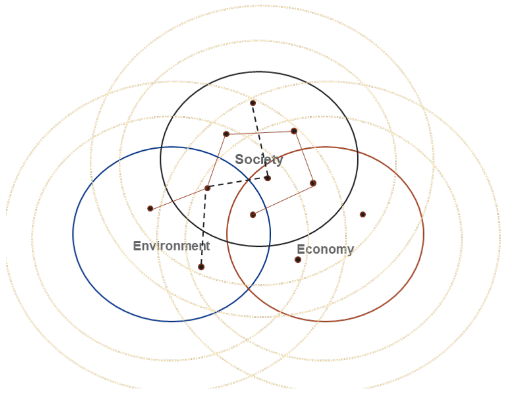
Explicit stakeholder engagement task supported by a subcontractor with expertise in elicitation and facilitation

Go/No-Go (Completion FY23-Q2)

Formal endorsement of our approach by a major municipal partner (Metro-Boston). We plan to on-board more partners as we progress (e.g., Great Lakes Water Authority; linkage to PR100)

1 – Approach (Sustainability Framework)

Foundation of this project – determine what the solution should look like

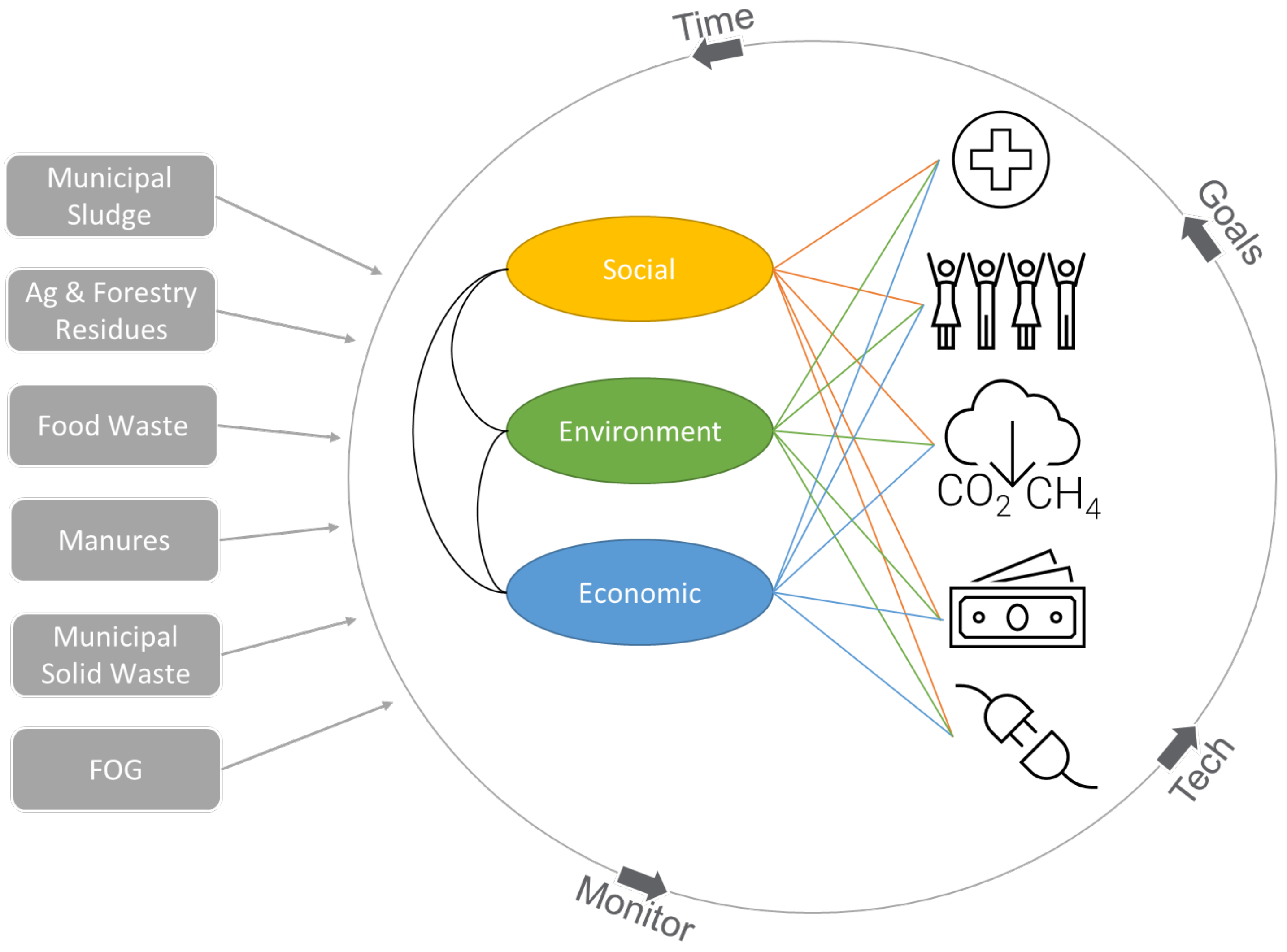


Key Challenges

- Sustainability is an outcome of complex interactions between interdependent systems (social, economic, and environmental)
- A single indicator of a static state is insufficient
- Current methods trade one impact for another (weak sustainability)

Objective

Define and measure strong sustainability (interdependence) for waste resource energy conversion that can represent current and long-term conditions across sustainability classes and evolving objectives through dynamic systems approach.



1 – Approach (Pathway Analysis)

Measure trade-offs of multiple feedstock and technology options

Key Challenges

- Developing scalable cost data for every conversion technology we want to represent
- Benchmarking existing and emerging technologies in a consistent manner
- Reducing enormous volumes of data and assumptions to meaningful information

Technical Approach

- Define technology pathways (feedstock + technology + product + energy end use)
- Inventory real-world waste supply and infrastructure data
- Classification of regionally blended wastes to understand supply "diet" archetypes
- Geospatially-informed TEA model to test performance of existing pathways with local data

Analysis Scope

- Support conventional and emerging technologies (e.g., anaerobic digestion, hydrothermal liquefaction, gasification)
- Feedstocks include wet organic wastes, organic MSW, agricultural and forest residues

Feedstocks being considered in this project (CONUS)

Value	Units	Feedstock
77	Tg/y, dry	Wet organic wastes: Confined animal manure, wastewater solids, fats, oils, and grease (FOG), and food waste
52	Tg/y, dry	Organic fraction municipal solid waste
150-207	Tg/y, dry	Recoverable Ag. residues: corn stover (75%), wheat straw (20%), and other grain straw (barley, oat, sorghum)
55-75	Tg/y, dry	Recoverable forest residues
334-411	**Tg/y**	**TOTAL**

1 – Approach (Stakeholder Engagement)

Key Challenges

- Diverse perspectives (waste producers, regulators, city managers, industry)
- Lack of awareness of emerging technologies
- Getting people's time and interest (changing business models is a low priority)
- Bridge the gap between national waste-to-energy research and municipal operational environment

Engagement Strategy

A deliberate mix of national dialogue, formal on-boarding, and education)

- *Host a National Dialogue* among waste conversion thought leaders (DOE, EPA, NGOs) to elicit feedback on the project approach and findings
- *Conduct a Survey* of waste community to understand barriers, generate interest, define key stakeholders, and identify potential future partners
- *Host "Local Implementers" Workshops* to engage with municipal waste managers and local cognate entities via 1:1 conversations, workshops, and pathway case study design
- *Develop Educational Materials* such as technical bulletins, interactive trade-off game (e.g., Climate Interactive), and pathways analysis exercises

2 – Progress and Outcomes

Following our AOP/PMP; On target meet project annual milestone

Project Status: Quarterly milestones have been met; the Go/No-Go is complete, and the team is on-track to meet our annual milestone in accordance with our AOP/PM

Description	Due Date	Status
Methods and Materials Formulation	12/31/2022	100% Complete
Model Dev & Stakeholder Engagement	3/31/2023	100% Complete
Case Study Definition	6/30/2023	In-Progress
Initial Case Study Analysis & Review	9/30/2023	Early Start

Task Updates: Making equal progress on three tasks (sustainability framework, pathway analysis, and stakeholder engagement)

Progress Toward Project Goal

- We are on schedule to meet our FY23 annual milestone to create physical implementations of the major pieces of the proposed system (indicators and pathways model), to demonstrate our concept.
- Metro-Boston region setup as an initial case study

2 – Progress and Outcomes

Highlight #1: Composite Indicators for Waste-to-Energy

- Deconstructed waste-to-energy related processes to guide sustainability indicator review and organization (table below)
- Mapping and classification of qualitative and quantitative indicators potentially relevant to waste supply and conversion (table to right)
- Identified gaps in available data and/or measurement methods

Deconstructing Bioenergy/Waste Conversion by Process Typology

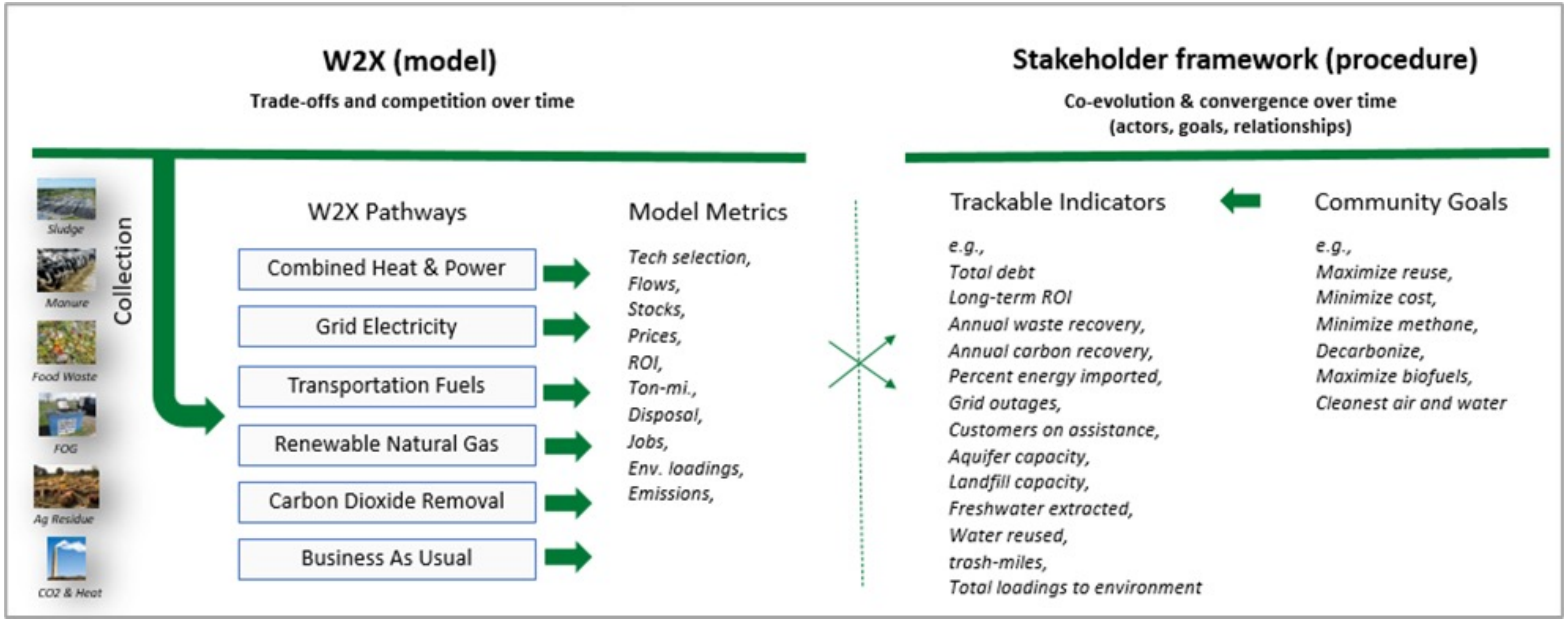
Scale(s) of Phenomena	Processes and their Spatial-Temporal Typology
Planetary, Climatic & Biodiversity zones	Bio-physical cycles with ecological boundaries
Planetary, Climatic & Biodiversity zones, Economic regions, International, National, Project scale	Intra & inter-boundary material impacts on sub-systems (social-ecological-economic-technological)
Economic regions, International, National, Municipal scale	Social negotiations; of policy, regulatory and financial goals & frameworks by institutional actors
Ecological/Economic Zones	Cascading or spillover effects; for adjacent economic activities and ecology/environment
Local (community, project site, social groups, individuals etc.)	Socio-Cultural mediation and norms
	Place specific fundamentals of justice, equity and wellbeing
	Manifested shocks & risks of climate change, pollution & resource use
Project geography	Risks, Fallouts and Safeguards at the project-society interface

TBL Component	Subcategory	Proposed Indicator
Economy/Environment	Resilience	Reduced energy imports
		Flexible end uses of energy
		Primary energy inputs
		Energy supply risk
	Reliability	Capacity factor
		Peak demand
		Energy Storage
Economy	Import/Export	Import potential
		Export potential
	Profitability	Profit with Trade
		Green credits
		Economies of scale
		Disposal costs
	Growth	Jobs
		Producer Price Index
		Consumer Price Index
		Agricultural production
Environment	Recovery	Avoided waste disposal
		Avoided carbon
		Avoided nutrient extraction
		Avoided fossil fuels
		Avoided metal extraction
	Water	Species biodiversity
		Water Use
		Wastewater discharge
		PFAS/PFOA
	Soil/Land Cover	Forest and/or urban canopy
		Land cover
	Air	Direct Emissions (Ozone, CO, PM, VOCs/SVOCs, Odor, Methane)
Society	Policy	Clean energy policy
	Security	Food availability
	Exposure	Particulate matter PM2.5
		Air toxics cancer risk
		Traffic proximity and volume
		Superfund proximity
		Hazardous waste proximity

2 – Progress and Outcomes

Highlight #2: Sustainability Framework

- Designed TBL Sustainability Framework, published in IEEE International Symposium On Technology and Society 2022 (ISTAS22)
- Proposed workflow synthesizes traditional TEA Pathway Analysis (*left*) with stakeholder-informed Sustainability Monitoring (*right*)
- Developed and coded the conceptual model to enable procedural implementation



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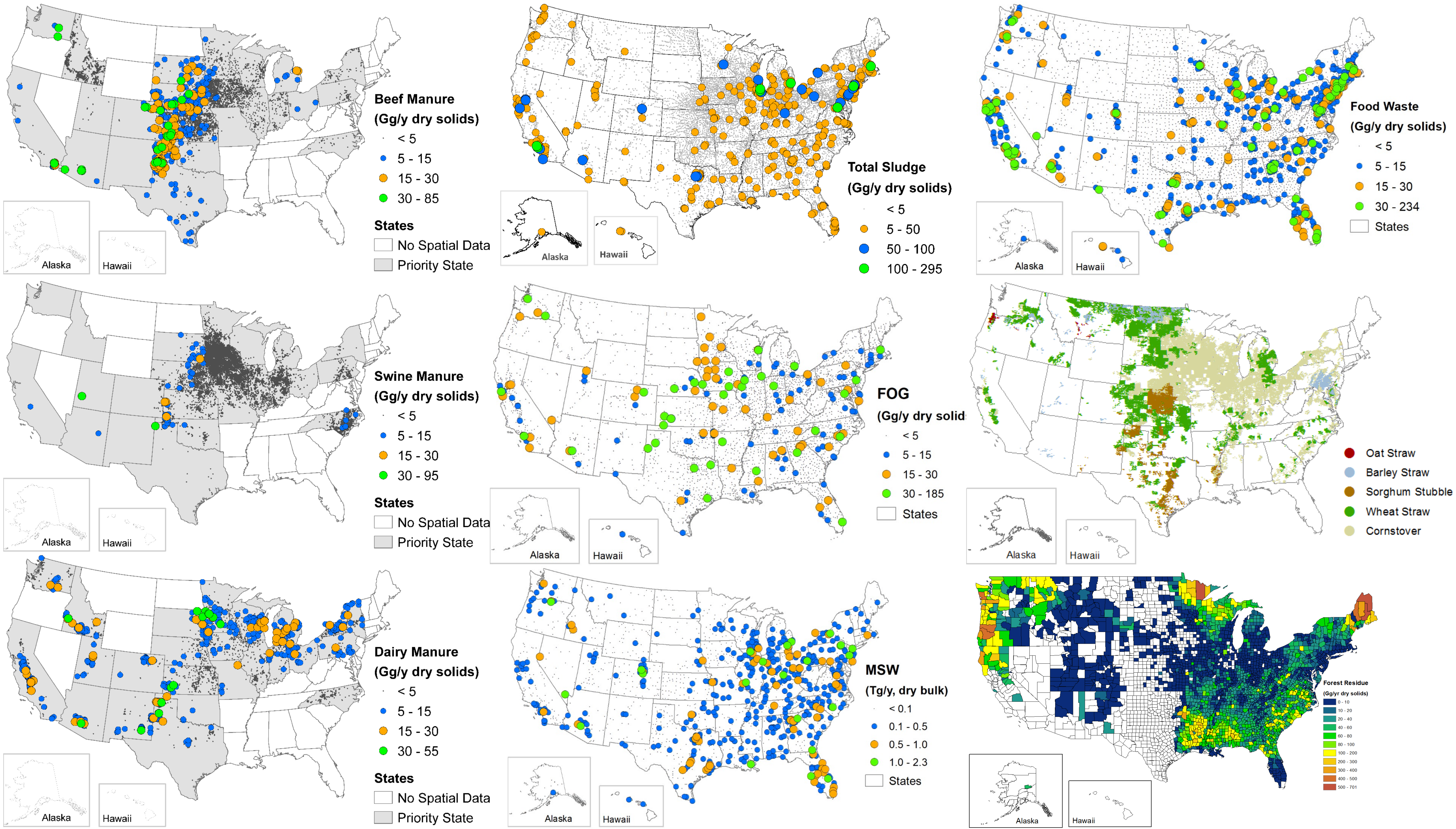
2 – Progress and Outcomes

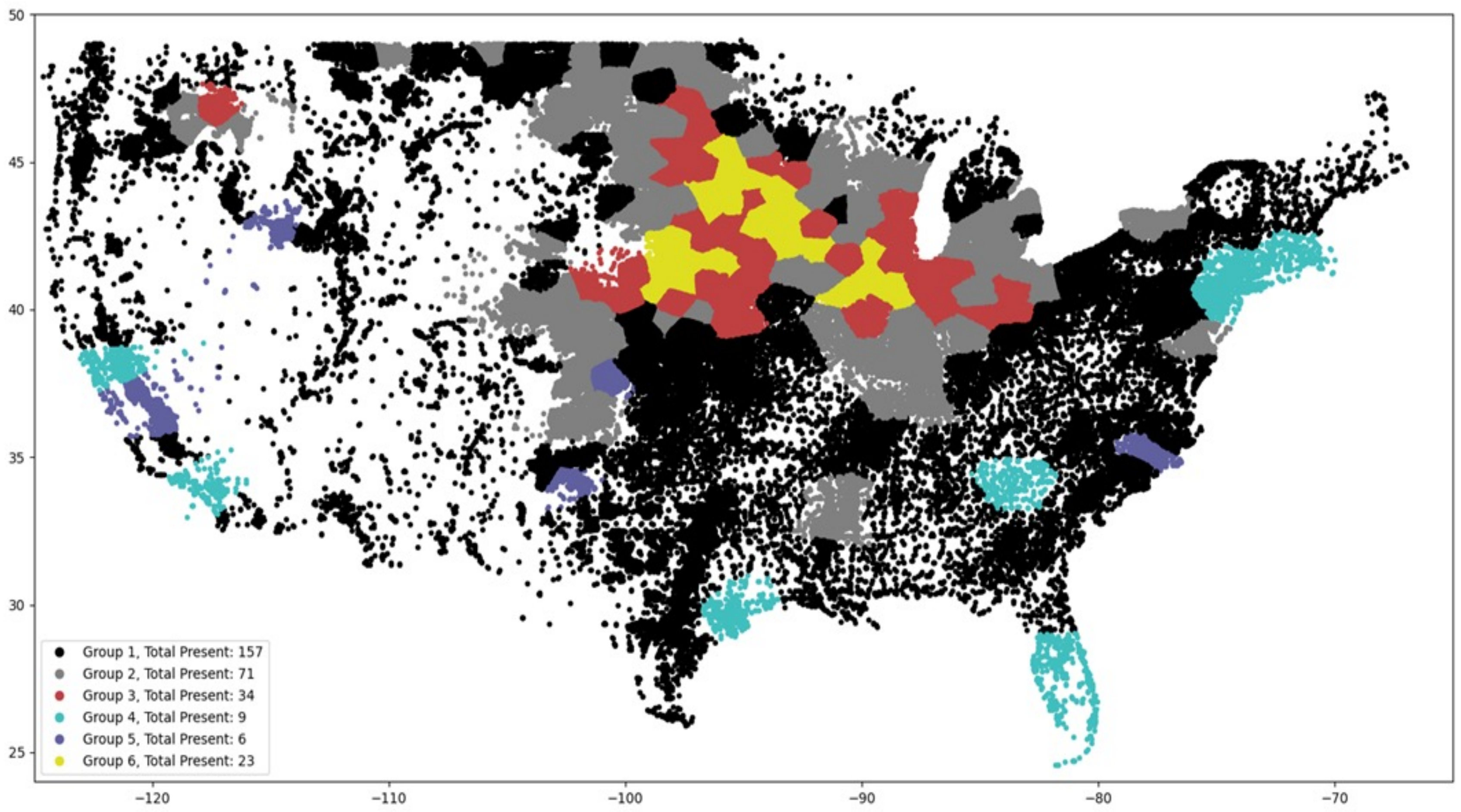
Highlight #3a: Cluster-based classification of regional blended wastes to understand supply "diet" archetypes – six types of waste region



2 – Progress and Outcomes

Highlight #3b: Cluster-based classification of regional blended wastes to understand supply "diet" archetypes – six types of waste region

- Generalizing regional feedstock character
- Sensitivity to number, type, and size of feedstocks



1. Small waste producers
2. Small/medium manure producers
3. Medium manure producers
4. Medium food/sludge producers
5. Large manure producers
6. Large food/sludge producers

2 – Progress and Outcomes

Highlight #4: Stakeholder Engagement

- Endorsement from Metro Boston Area Planning Council and Boston Green Ribbon Commission
- Conducted >20 stakeholder interviews representing 8 organization types
- Disseminated stakeholder survey to ~120 waste management entities
- Participated in U.S. Conf. of Mayor's Municipal Waste Manager's Association 2022 Summit (CA)
- Hosted Waste-to-Energy Summit for 30 Metro-Boston regional planners, NGOs, city, and state government

3 – Impact

- Stakeholder Learning
  - Cost is a priority
  - Lack of familiarity with emerging conversion technologies/strategies
  - Waste managers hear about many options but don't have what they need to inform change
  - Need for more trustworthy, transparent, and objective support in this space
- Ongoing development of sustainability tools that are adaptive to entity objectives and policies
- Addressing technical and educational barriers to accelerate technology deployment
- Contributes to BETO goal of 3 BGY multi-modal transportation biofuels @ $2.50/GGE & 50% GHG reduction by 2030 & Sustainable Aviation Fuel (SAF) goals
- Social equity and environmental justice are a centerpiece of the model implementation

Conference Presentation - **Developing a Sustainability Tracking Framework and Proposing Indicators for Modeling Sustainable Bioenergy Projects.** Biswas S., C.A. Antonopoulos, T.E. Seiple, C. Bakker, M.J. Walsh, and A. Coleman. In *IEEE International Symposium On Technology And Society* 2022 (ISTAS22, Nov 10-12, Hong Kong/Virtual).

Article - Biswas S., C.A. Antonopoulos, T.E. Seiple, C. Bakker, M.J. Walsh, and A. Coleman. 2022 **Developing a Roadmap for Tracking Sustainability in Bioenergy Transitions.** *IEEE Technology and Society (Accepted)*

Summary

Overview	Develop a unified sustainability assessment method to evaluate the long-term trade-offs of waste conversion strategies to guide policy objectives and local investment
Management	Cross-domain SME collaboration with direct input from regulators, industry experts, and key cities
Approach	Couple geospatial-focused resource and TEA modeling with stakeholder-informed sustainability monitoring
Progress & Outcomes	Following our AOP; Steadily advancing all major tasks; Met Go/NoGo (endorsement); On track to complete prototype by end of FY23
Impact	Leverage state-of-the-art science methods to develop new standardized data and tools for the *local government*; Provide credible evidence and guidance to the waste management community to support regional deployment planning and prioritization
Future work	Continue case studies in diverse locations and situations to mature framework and models; work towards published standards of sustainability tracking for waste-to-energy and bioenergy; advance collaborative development and adoption of proposed standard methods

Quad Chart Overview

Timeline
- Project start date: 10-01-2021 (FY22)
- Project end date: 09-30-2024 (FY24)

	$375,000	$1,125,000 (FY 2022-2024)
	$0	$0

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

Project Goal
Develop new methods for defining, measuring, and tracking sustainability goals for waste resource supply chains, which consider local waste “diet”, community sustainability and energy goals, and non-traditional benefits (e.g., health, environment, equity).

End of Project Milestone
Deliver: (1) final model specification documentation; (2) final report summarizing national and regional impacts of bioenergy investments on the economic welfare of partner cities; (3) peer-reviewed manuscripts focused on pathway analysis methodology, case studies, and respective analysis and findings; (4) and stakeholder-oriented communications summarizing region-specific key findings and recommendations.

Funding Mechanism: Lab Call AOP

Project Partners
WTE (PNNL, 2.1.0.113)

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Thank you

Additional Slides

Triple bottom line sustainability indicators for WtE supply chains

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Project Objectives

- Develop and apply a set of standardized triple-bottom line (TBL; social, environment, economic) indicators to measure and model analyses for multi-sector stakeholders to assess and compare the sustainability gains and losses of proposed locally-optimized, multi-feedstock, multi-technology WtE deployment strategies in the context of regional socio-enviro-economic operating conditions and policy goals.

Technical Approach

- A spatially-explicit data-driven framework and pathways analysis model (scenario/tradeoff analysis) will be built and implemented with stakeholder input and review for several local/regional case study sites. The model implements multi-objective optimization techniques that consider wet, dry, gaseous waste feedstock supply, distributed to centralized conversion using conventional and emerging technology waste utilization pathways to reveal potential solutions with associated TBL benefit scoring and tradeoffs.

Project Attributes

Project Start/End	10/1/2021 – 9/30/2024
FY22 Budget	Total: $375k
Collaborations	Michael Walsh
DOE TM Lead	Chenlin Li Chenlin.Li@ee.doe.gov

Project Milestones and Outcomes

End of Project Goal: Deliver and make openly available, a scenario planning model, including documentation, case studies, and peer-reviewed manuscript, that optimizes multi-stakeholder social, environmental, and economic sustainability benefits and is of direct use to local/state/regional and industry partners to enable the informed development of next generation waste-to-energy solutions.

Go/No-Go: Formal endorsement of TBL-enabled Pathway Analysis approach by at least one priority municipal partner in the form of letter of endorsement and/or jointly developed, municipal-specific, draft TBL Pathway Analysis plan to serve as a template for subsequent case study specification. (9/30/2023)

Decarbonization Pillars and EERE Emphasis Areas

Identifying regionally optimized sustainable carbon recovery pathways that minimize carbon intensity will help decarbonize energy-intensive industries & transportation across all modes pillars for EERE, and target BETO's goal of producing 3 Bgal/y of multi-modal transportation biofuels at $2.50/GGE with a 50% GHG reduction by 2030. Additional energy justice and public outreach benefits are expected by

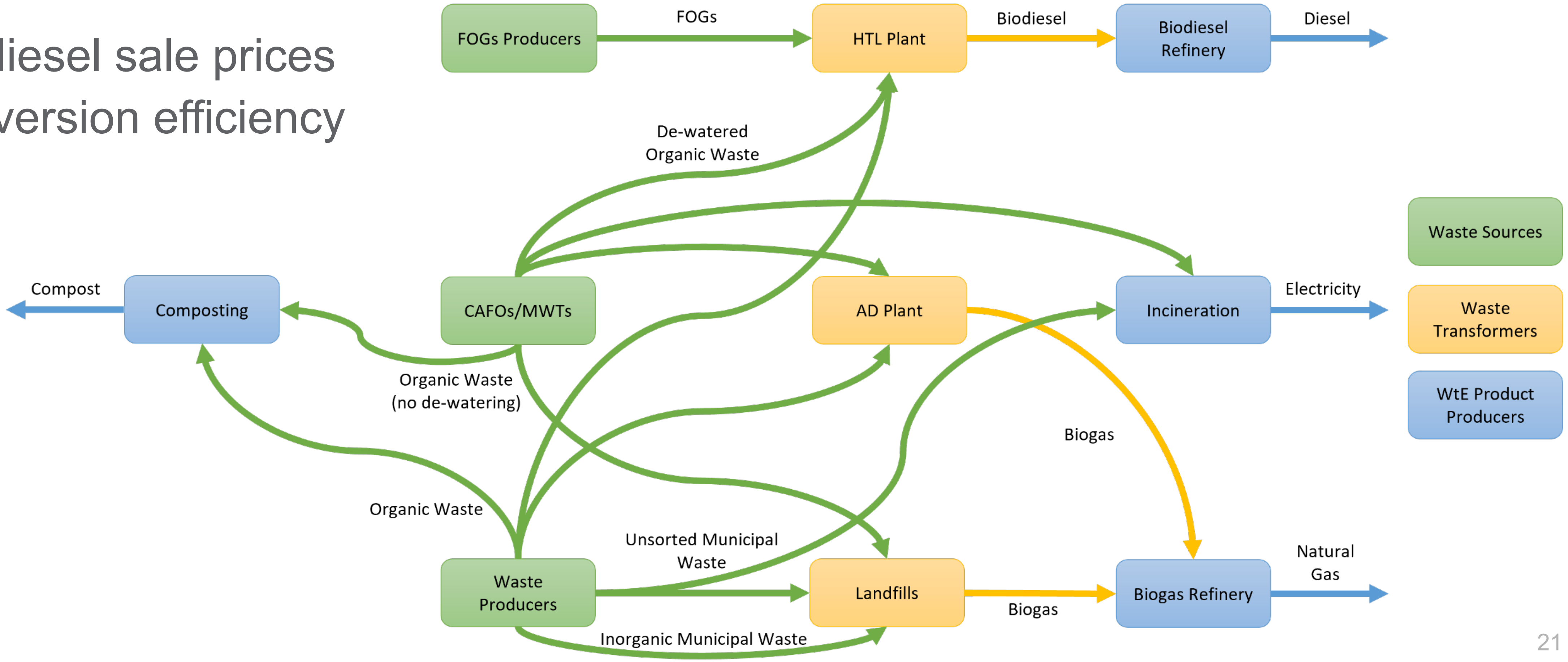
(1) Incorporating equity and justice indicators directly into the model;
(2) Eliciting review from non-traditional sources such as NGOs and disadvantaged community leadership; and
(3) Providing state/local leaders with actionable data necessary to develop cooperative environmentally, socially, and financially sustainable WtE deployment strategies that equitably create clean energy jobs.

Micro-Economic Model Description

- Players
  - Make decisions to pursue their goals
  - Have physical and economic constraints
- Market Clearing
  - Treat waste as a commodity
  - Market prices produced endogenously by the model
- Scenario Parameters
  - Travel and processing costs
  - Process efficiencies
  - Facility locations and capacities
- Primary Outputs
  - Stocks and Flows
  - Market Prices
  - Shadow Prices – values, prices, or costs of constraints
- Secondary Outputs
  - Combine primary outputs with external data
- Numerical Solution with Analytical Insights

Techno-Economic Model Construction

- Model Structure
- Key Primary Outputs
  - Production capacities (e.g., biodiesel)
  - Waste flows
  - Gate fees
  - Biogas and biodiesel sale prices
  - Waste-to-X conversion efficiency shadow prices
- Key Secondary Outputs
  - Emissions (e.g., PFAS, GHGs)
  - Economic Productivity (e.g., Jobs, Revenue, ROI)

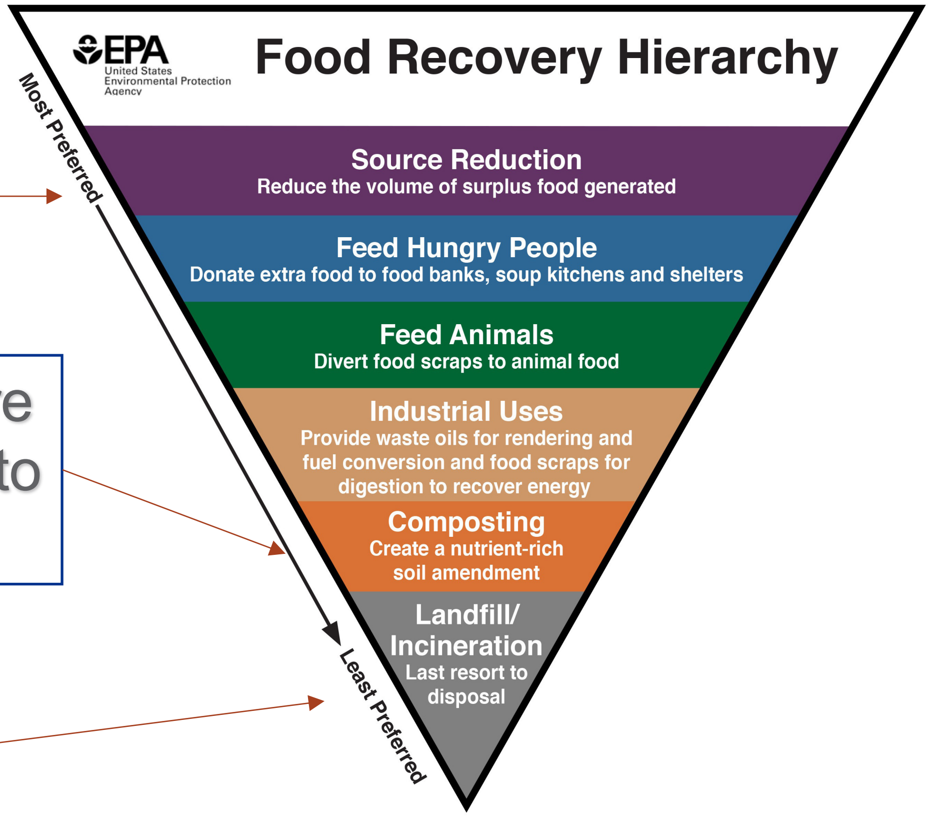


Waste Management Ground Rules

Source reduction is an energy strategy

EPA has struggled with where to place composting relative to energy recovery

What we do with most of our waste today



A central goal of this project is to better understand options in the *middle of the pyramid* using **data** and **community priorities**

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Decision Making Is Becoming More Complex

Municipalities, businesses, institutions, and regulators are all challenged by the need to make decisions over multiple and increasingly complex criteria.

Historical Decision-Making Criteria

Safety
Air & Water Quality

Cost

Practicality
(Reliability, Convenience)

Sustainable Decision-Making Criteria

Cost, Safety, Practicality plus:

Climate Goals

Land Use

Resiliency

Natural Resources
(Land, biomass, water)

Equity

Employment

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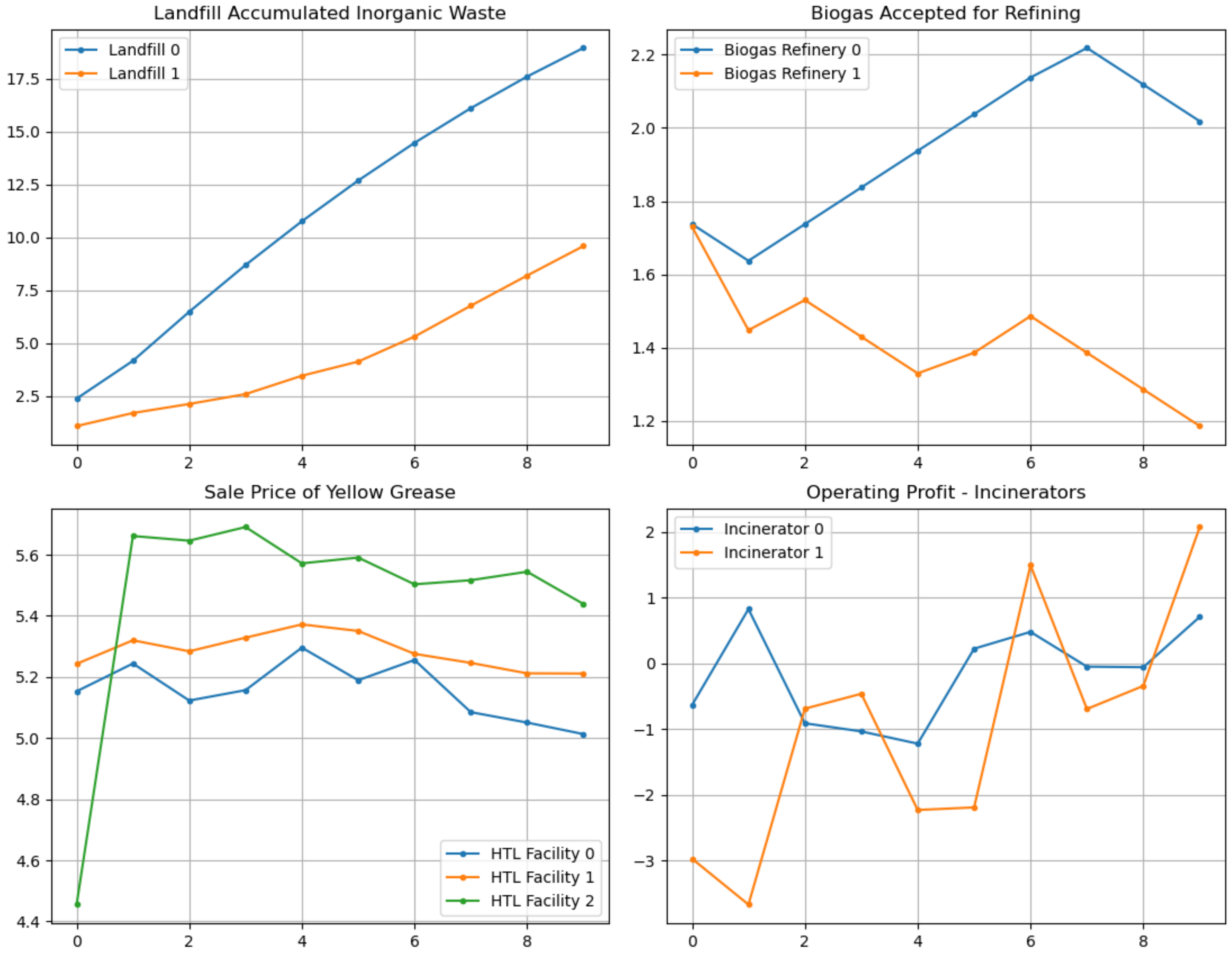
Sample Model Outputs

- 10-Step Time Horizon
- Stocks – Landfill Inorganic Waste
- Flows – Biogas Sent for Refining
- Prices – Sale Price of Yellow Grease at HTL Plants
- Profit – Incinerator Operating Profit



2 – Progress and Outcomes (Sustainability)

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Project geography	Risks, Fallouts and Safeguards at the project-society interface

2 – Progress and Outcomes (Pathway Analysis)

Defined technology pathways (feedstock + technology + product + end use)

Feedstock(s)	Technology	Final Use
MSW	Gasification	Syngas to heat and power
MSW	Gasification	biofuels
MSW	Mixed Incineration + Fermentation	Methane/steam to power
Wet wastes; MSW-Organics; Ag. Residue	Hydrothermal Liquefaction	Biocrude to biofuels
Wet wastes; MSW-Organics; Ag. Residue	Hydrothermal Liquefaction	Biocrude to heat and power
Wet wastes; MSW-Organics; Ag. Residue	Anaerobic Digestion	Biogas to CNG or PNG
Wet wastes; MSW-Organics; Ag. Residue	Anaerobic Digestion	Biogas to heat and power

3 – Impact

Stakeholder Participants (Listening Sessions)

Stakeholder Organization	*Stakeholder Position*	*Organizational Role*
DOE Office of Economic Impact and Justice	AAAS Fellow	Federal DOE EJ Office
Northeast Waste Management Officials' Association	Executive Director	Multi-state waste regulator network, currently developing WtE programs focused on engaging with environmental justice communities.
Conservation Law Foundation	State VP, Waste Program Director, Staff Attorneys	Environmental advocacy with a focus on legal action, rapidly developing environmental justice, and bioenergy capacity.
Environmental League of Massachusetts	Executive Director	Environmental advocacy with a particular focus on legislative and political action
City of Cambridge (MA)	Recycling Director	Early municipal adopter of organics collection. Significant environmental justice population
National Resources Defense Council	Senior Resource Specialist, Food Waste Initiatives	Food justice and food waste management in urban areas
EPA	Anaerobic Digestion Staff	Ongoing focus on AD, LFG, food waste, and technical assistance
Boston (formerly NYC)	Zero Waste Director	Major city with organic waste collection and AD infrastructure. Significant environmental justice population.
Academic Researcher	Professor	Author of multiple studies on emissions and emissions accounting and related policy associated with WtE/anaerobic digestion
Union of Concerned Scientists	Director of Fuels Policy	Environmental advocacy with a historical bioenergy policy focus
Boston Globe	Climate Reporter	Perspectives and knowledge of the press
Waste Dive	Waste Reporter	Perspectives and knowledge of the press