DOE Bioenergy Technologies Office (BETO) 2023 Project Peer Review

Multi-Input, Multi-Output Biorefineries to Reduce Greenhouse Gas and Air Pollutant Emissions

April 5, 2023
Data, Modeling, and Analysis
Corinne Scown (PI)
University of California, Berkeley

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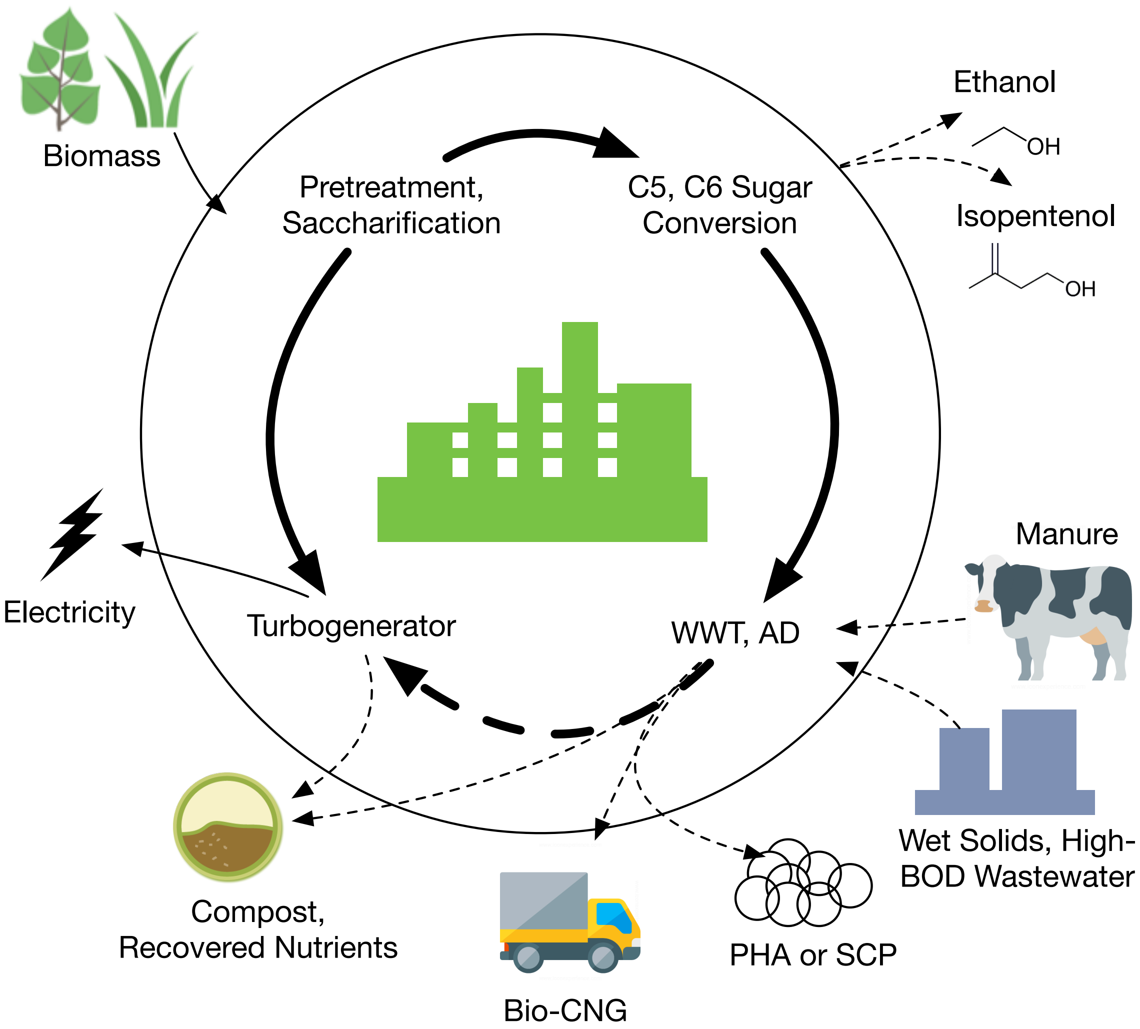
Project Overview

Research Question: Can lignocellulosic biorefineries co-process organic waste in rural communities at comparable or lower costs and environmental impacts relative to a conventional standalone design?

Objective: Conceptualize, design and assess the economic and environmental performance of multi-input, multi-output biorefineries

Goals:

- Design a set of cost-competitive biorefineries capable of taking in lignocellulosic biomass and organic waste, producing multiple value-added products
- Build and demonstrate integrated siting, TEA, and LCA models to simulate these designs and explore tradeoffs



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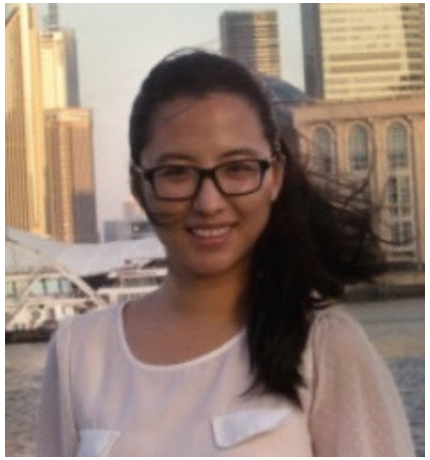
1 – Approach

Corinne Scown (PI)
TEA/LCA Expert



Yan Wang
(Former Postdoc)
TEA/LCA

Melissa Moore
(New Postdoc)
TEA/LCA

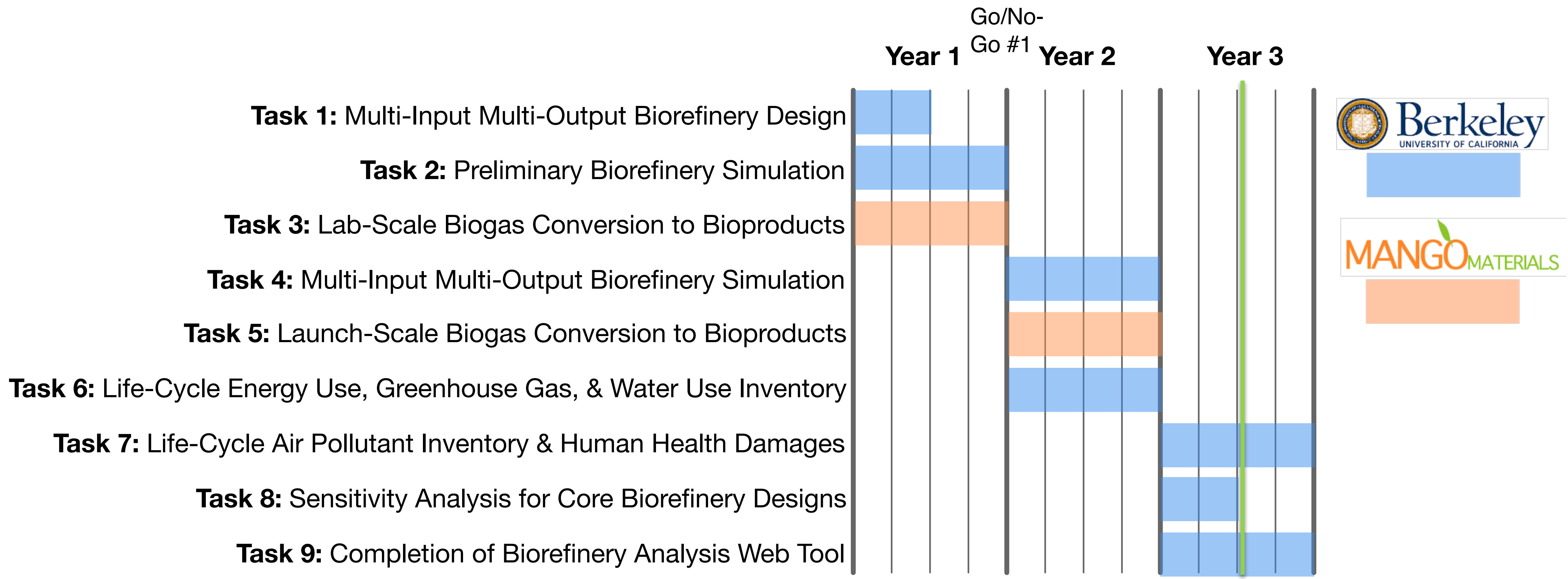
Allison Pieja (Co-PI)
CTO, Mango Materials

Molly Morse (Co-PI)
CEO, Mango Materials

Additional partners:

- EBMUD (data, advisory board)
- JBEI (modeling resources)

1 – Approach


Go/No-Go #1
Year 1
Year 2
Year 3
Task 1: Multi-Input Multi-Output Biorefinery Design
Task 2: Preliminary Biorefinery Simulation
Task 3: Lab-Scale Biogas Conversion to Bioproducts
Task 4: Multi-Input Multi-Output Biorefinery Simulation
Task 5: Launch-Scale Biogas Conversion to Bioproducts
Task 6: Life-Cycle Energy Use, Greenhouse Gas, & Water Use Inventory
Task 7: Life-Cycle Air Pollutant Inventory & Human Health Damages
Task 8: Sensitivity Analysis for Core Biorefinery Designs
Task 9: Completion of Biorefinery Analysis Web Tool
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MANGO MATERIALS

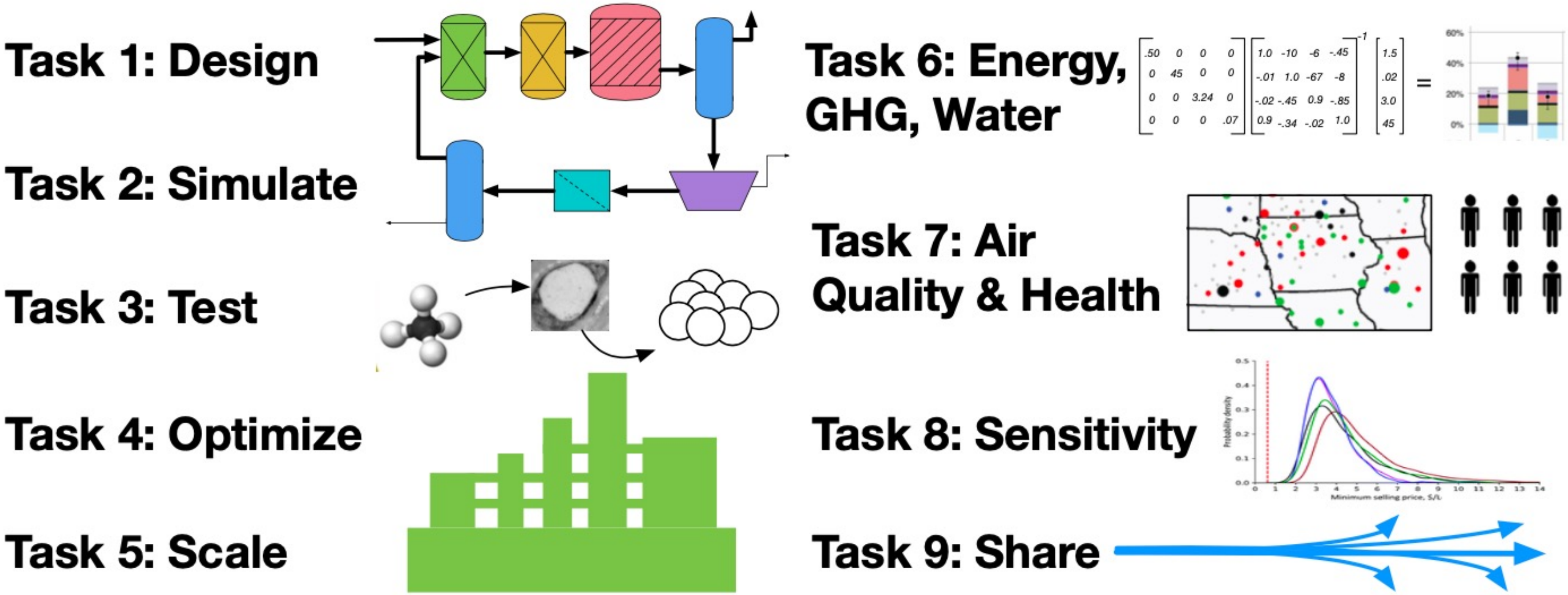
1 – Approach

Challenges

- Determining tipping fees/costs & local availability for organic waste inputs
- Quantifying air quality impacts of our scenarios & business-as-usual baseline
- Deploying results in web tool that is usable

BP 1 Go/No-Go: Complete biorefinery designs for 4 configurations including ethanol, isopentenol, bio-CNG, & PHA

BP 2: Report bioproduct yields on key nutrients at launch scale in biogas & estimate minimum yield required for profitability



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2 – Progress and Outcomes

Budget Period 1 Milestones

Quarter	Milestone	Description
1	1.1.1	Identify ≥3 key feedstock contaminants, report concentrations in >10 feedstock types.
2	3.1.1	Report bench-scale PHA yields on key nutrients (nitrogen).
3	3.2.1	Report bench-scale SCP yields on key nutrients (nitrogen).

Budget Period 2 Milestones

Quarter	Milestone	Description
5	4.1.1	Develop MSP, mass/energy balances for ≥3 AD feedstock blends.
6	5.2.1	Report launch-scale bioproduct yields on key nutrients (nitrogen).
7	6.1.1	Estimate fossil energy demand for ≥5 designs.

Budget Period 3 Milestones

Quarter	Milestone	Description
9	7.1.1	Life-cycle air pollutant inventory for ≥5 designs.
10	8.2.1	Uncertainty analysis for cost, GHG, and air pollutants.
11	9.1.1	Demonstrate web tool for at least 2 biorefinery designs.

Metrics

Optimized biorefinery designs will produce a suite of fuels and products that, compared to an identical portfolio of conventional alternatives, will:

- Reduce GHG emissions by > 70%
- Reduce fossil energy use by > 50%
- Reduce air pollutant emissions (on monetized local human health damage basis) by > 20%

Complete

On schedule

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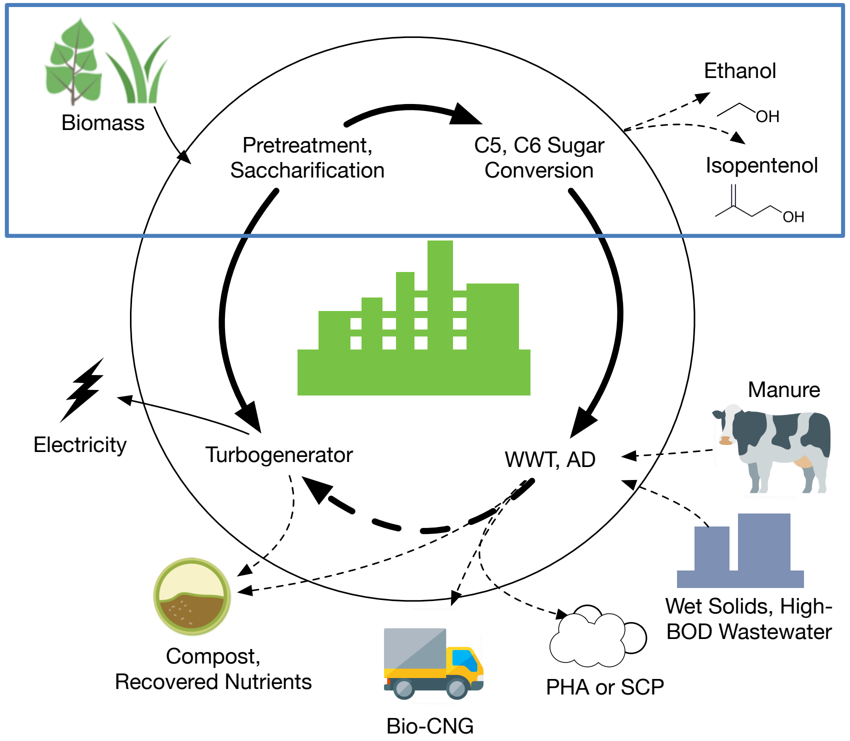
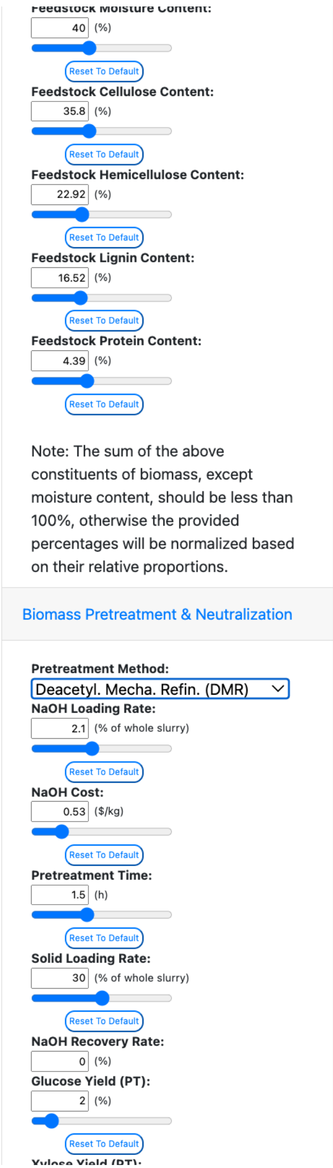
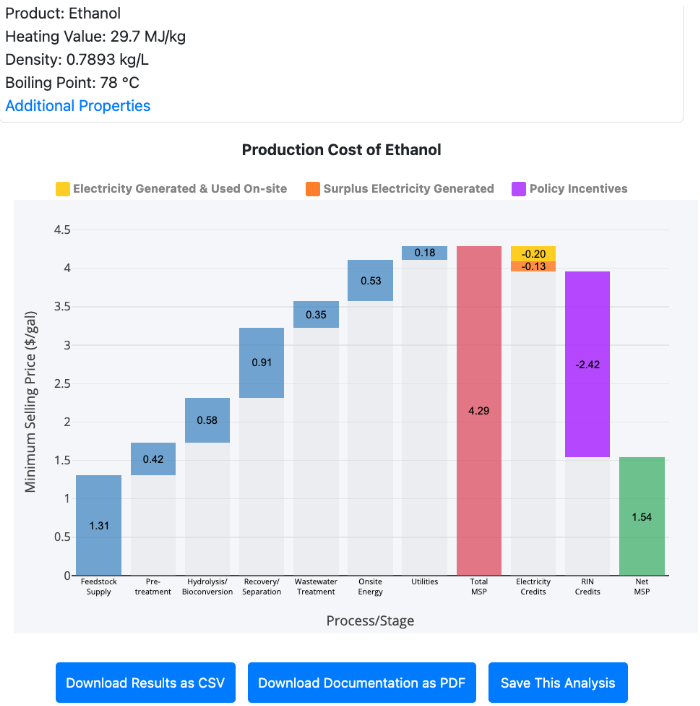
2 – Progress and Outcomes

Discussed in 2021 review







- Multiple biomass feedstocks
- Pretreatment: Dilute Acid, AFEX, DMR, IL
- Products modeled: ethanol, isopentenol
- i.org/tea_lca_tool/

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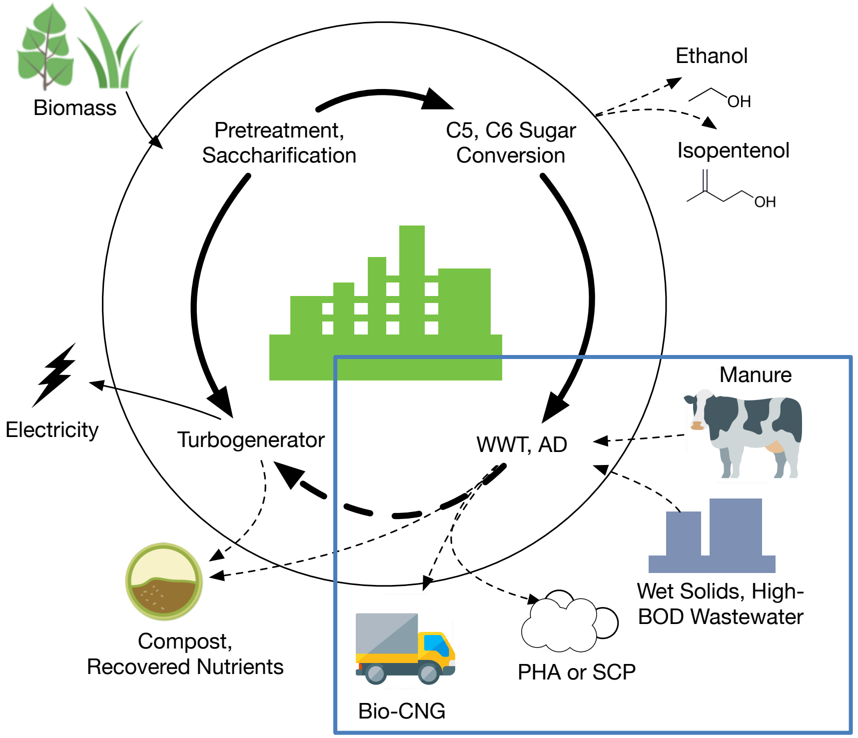
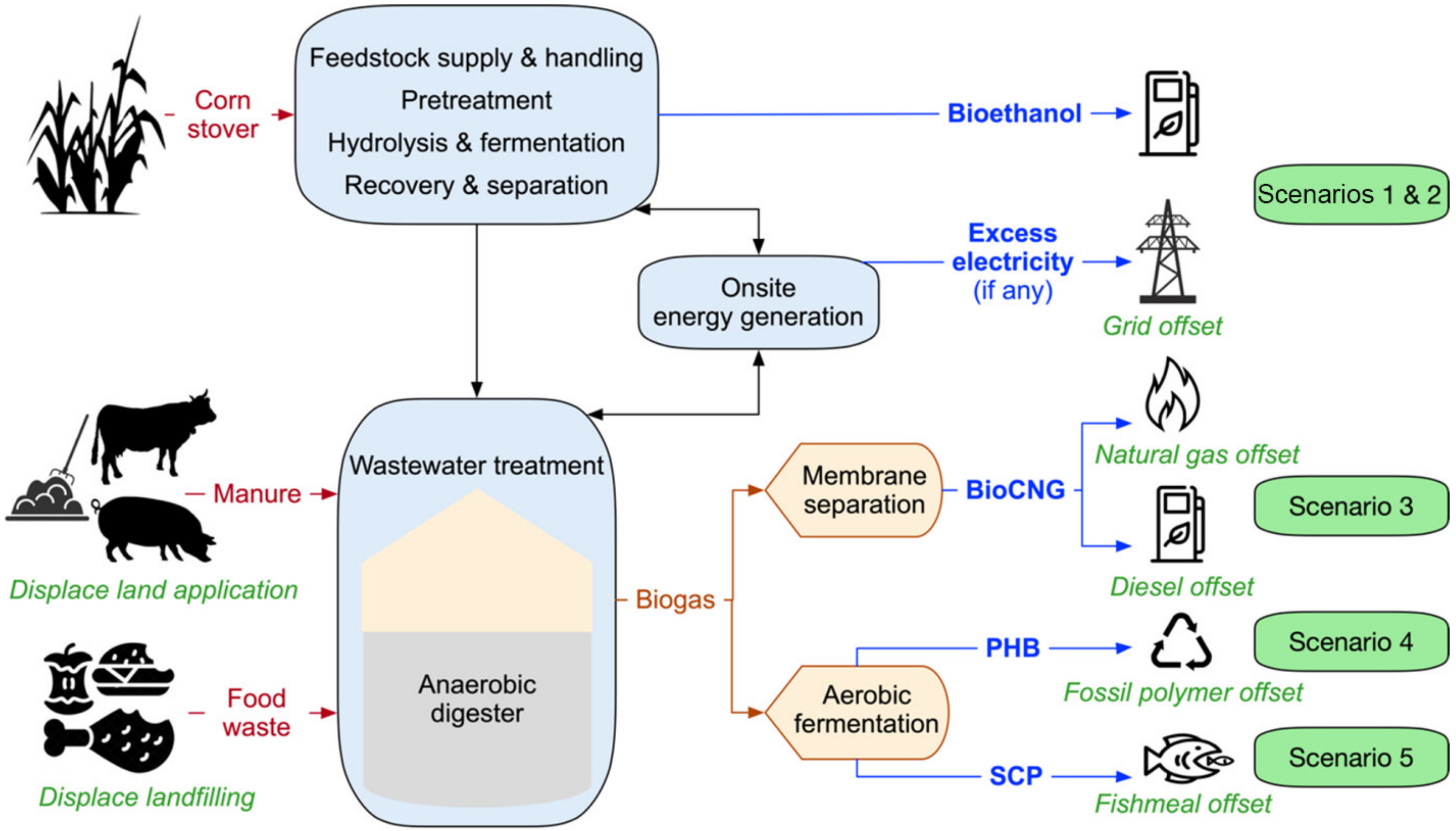
2 – Progress and Outcomes





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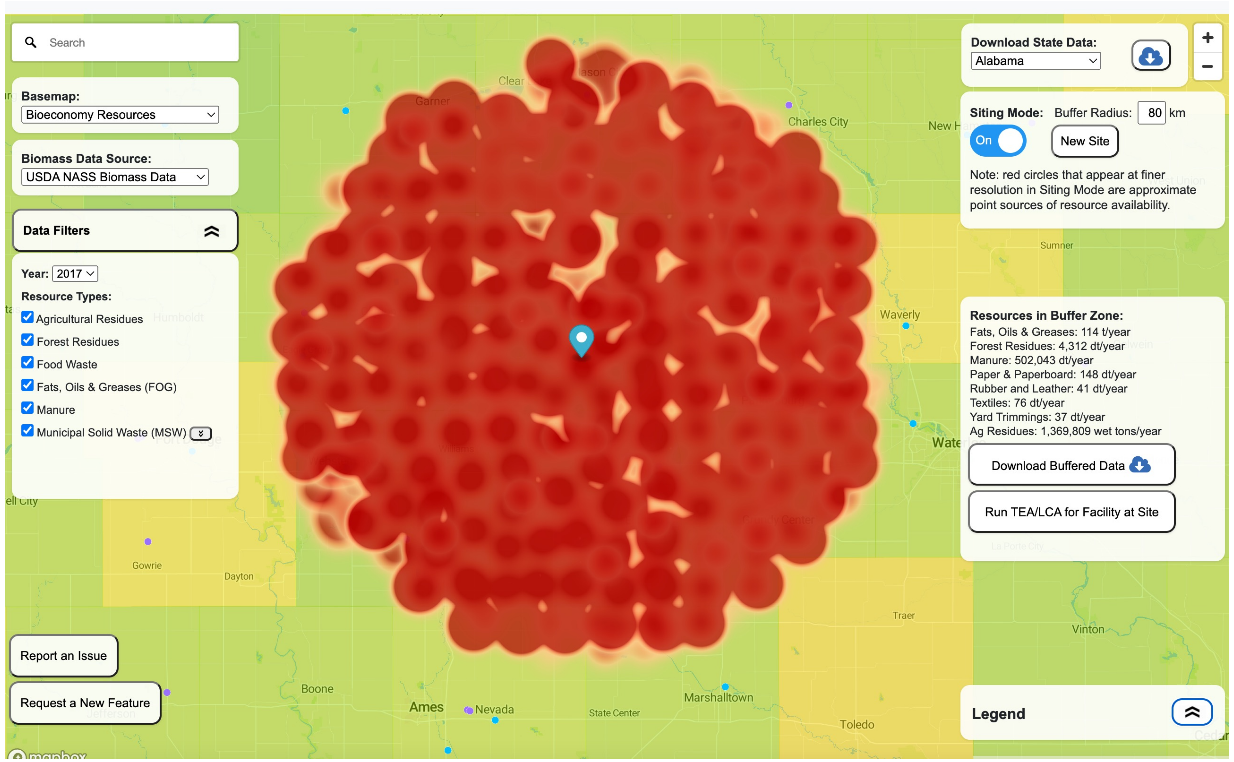
Source: Wang et al. 2023 *Environmental Science & Technology*

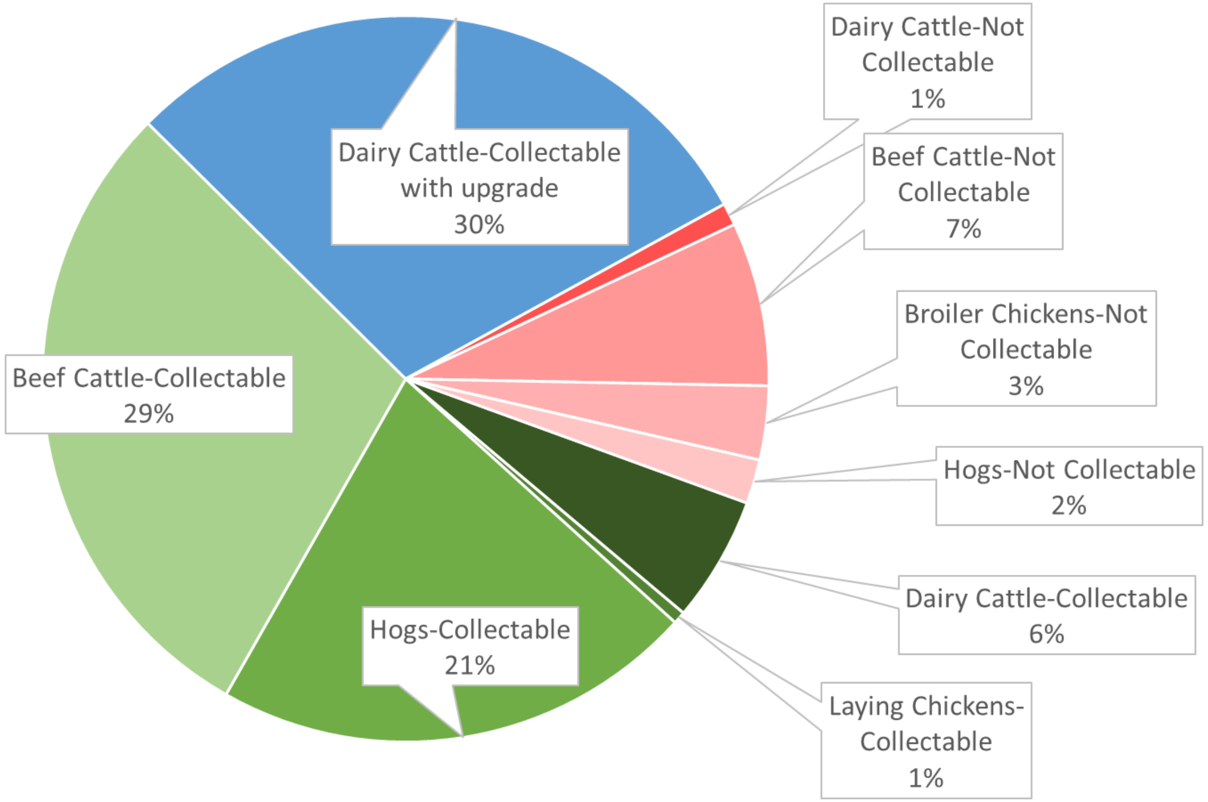
2 – Progress and Outcomes

Representative availability around biorefinery in U.S. corn belt:
Hog manure: 4,600 wet metric ton/day
Cattle manure: 1,100 wet metric ton/day
Food waste: 400 wet metric ton/day

Manure availability is a major source of uncertainty. A fraction is collectable, and some is beneficially used as fertilizer.



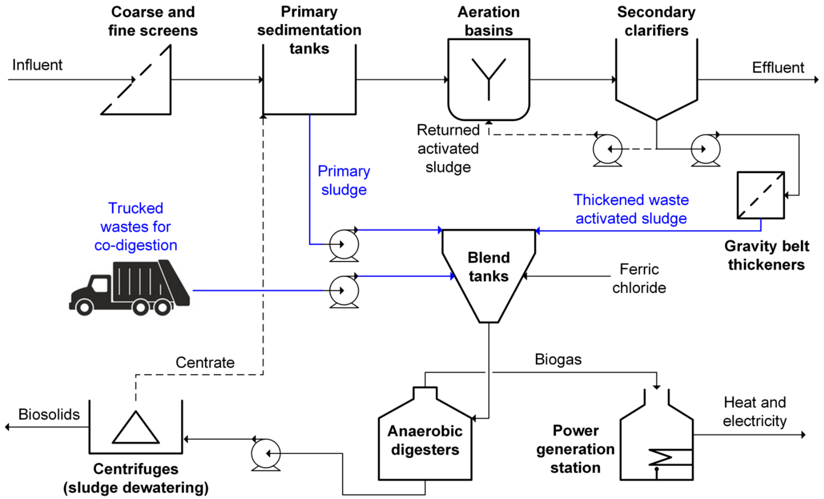
Screenshot: https://biositing.jbei.org/national

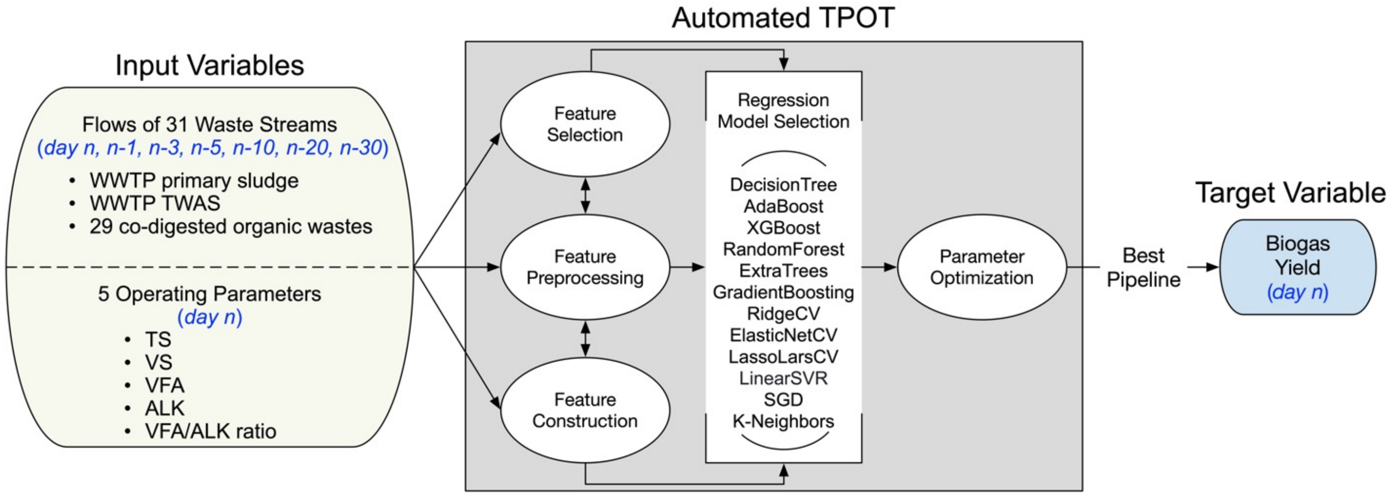


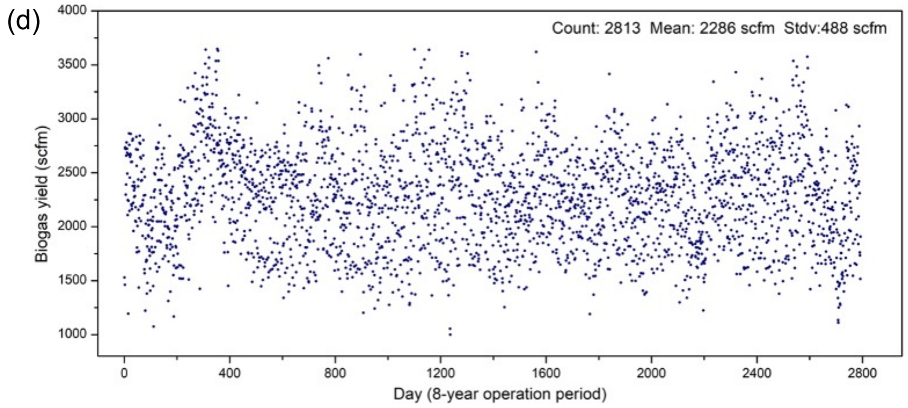
Source: Moore et al. *In Preparation*

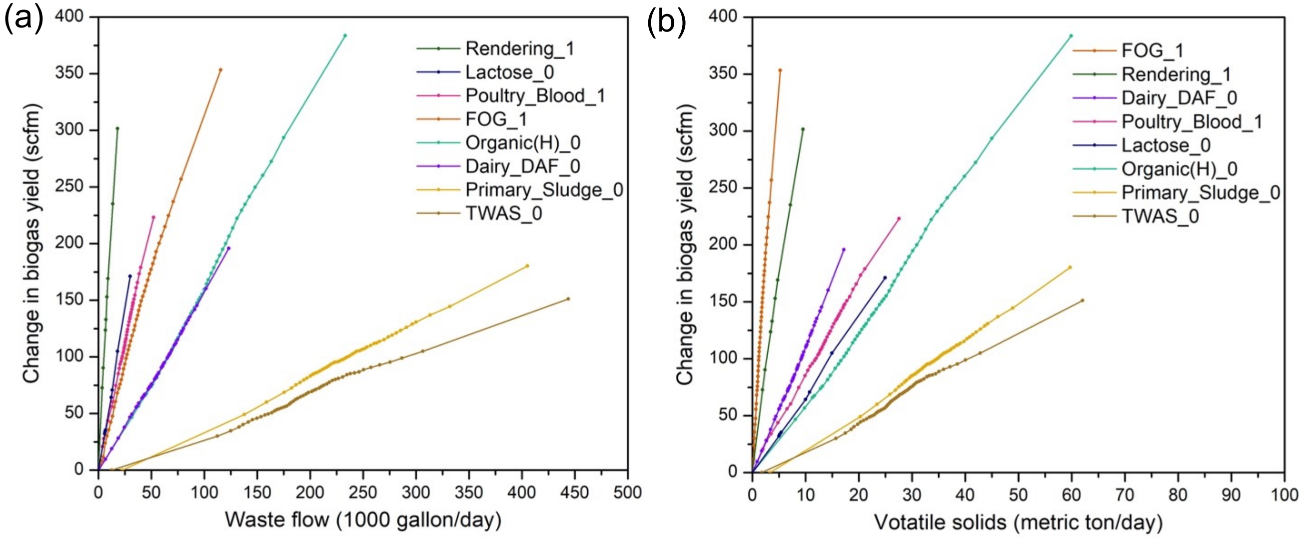
2 – Progress and Outcomes

- Explored practicality of co-digesting mixed waste by partnering with EBMUD (8 years, 31 waste streams)



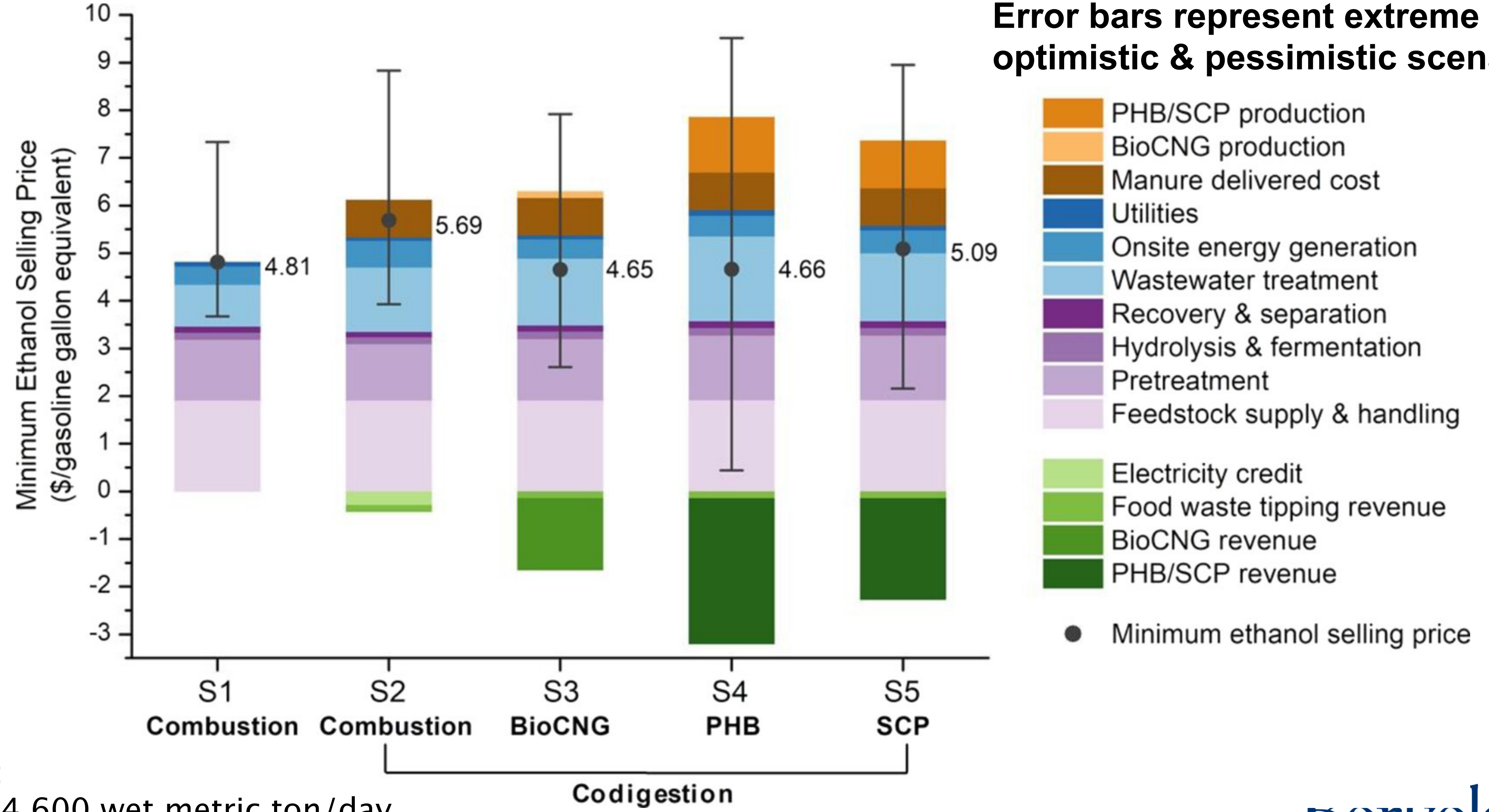






Source: Wang et al. *ACS Sustainable Chemistry & Engineering*

2 – Progress and Outcomes

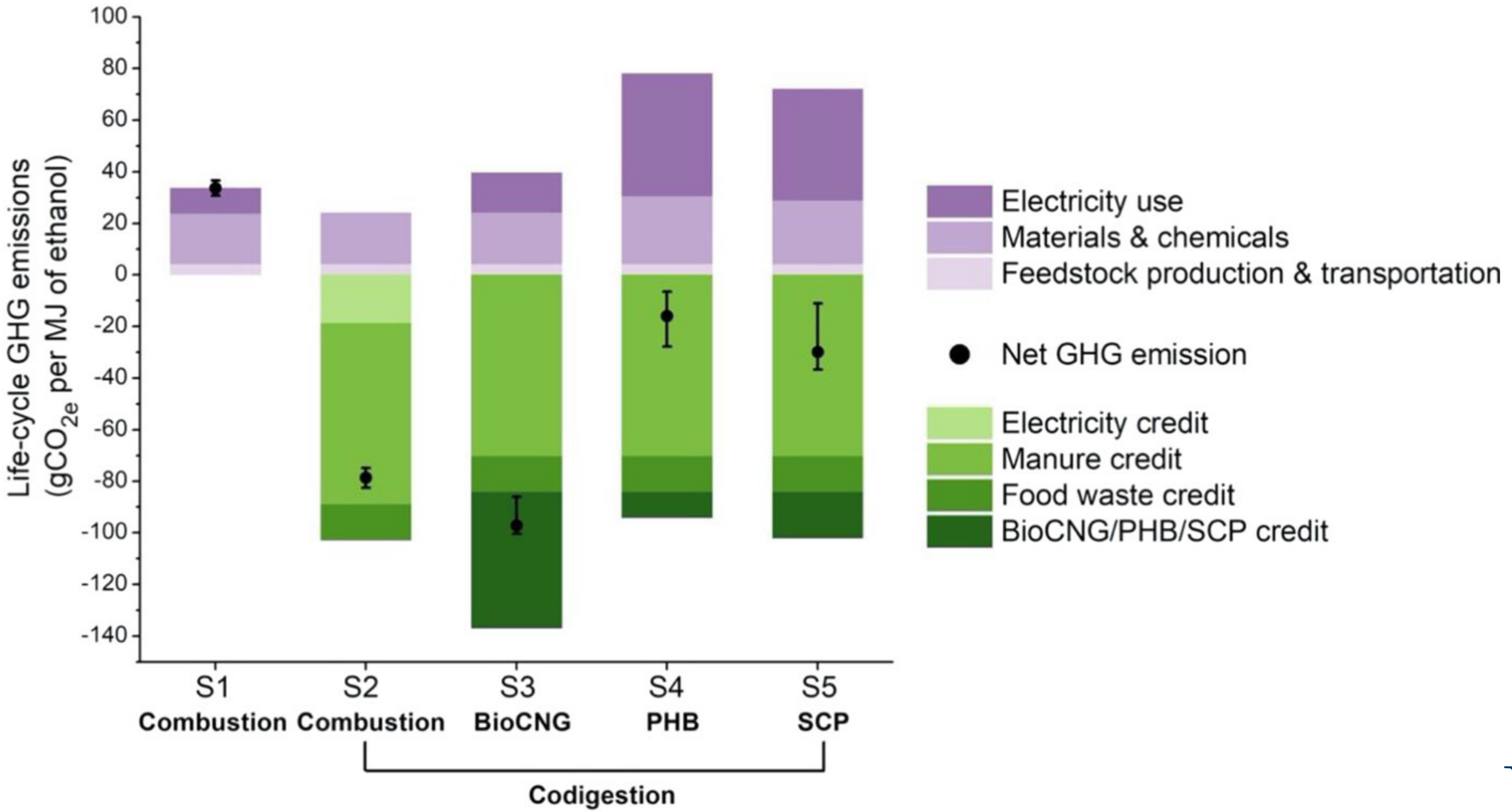


Error bars represent extreme optimistic & pessimistic scenarios

Co-digestion:
Hog manure: 4,600 wet metric ton/day
Cattle manure: 1,100 wet metric ton/day
Food waste: 400 wet metric ton/day

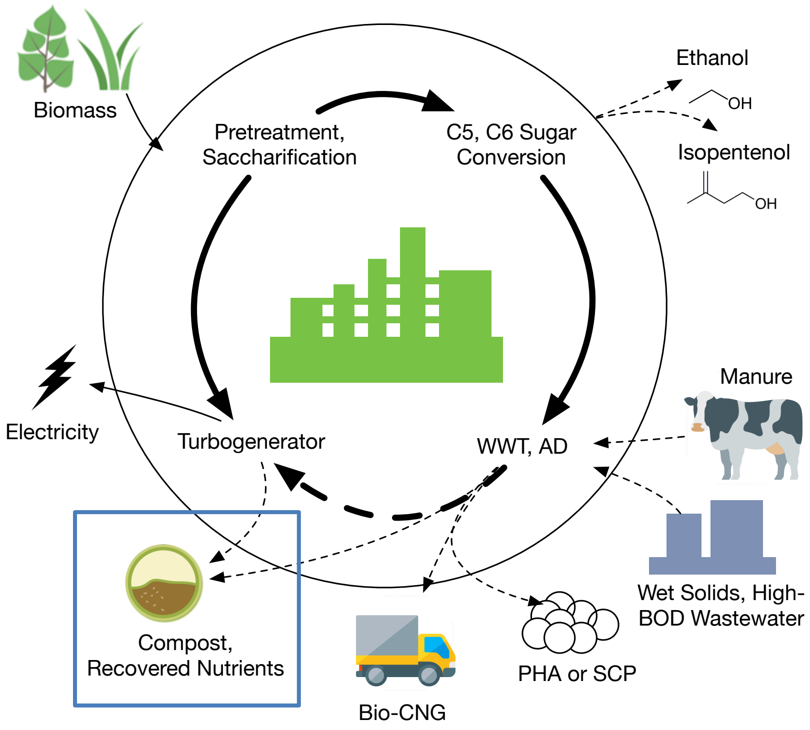
Source: Wang et al. 2023 *Environmental Science & Technology*

2 – Progress and Outcomes

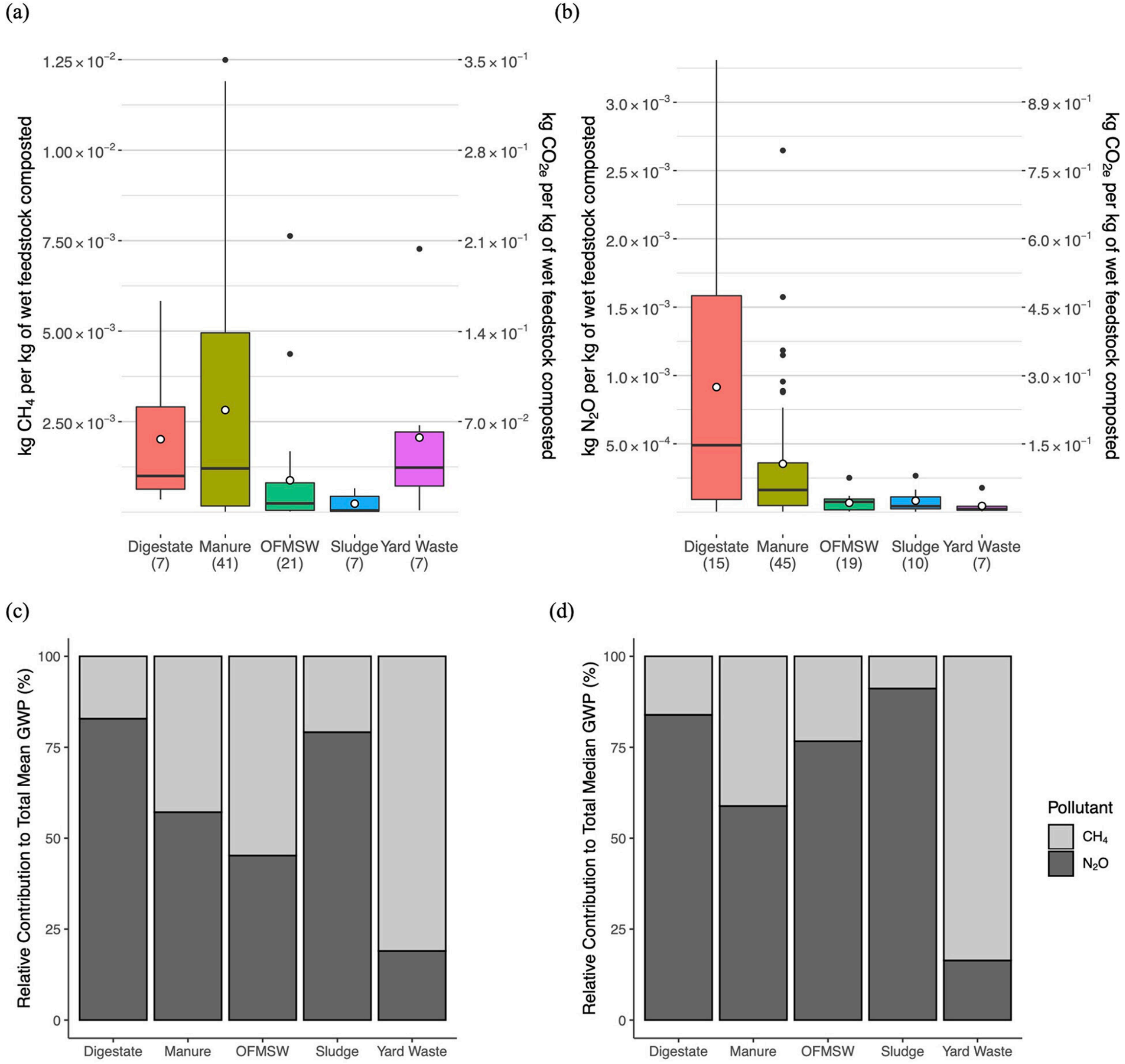


Source: Wang et al. 2023 *Environmental Science & Technology*

2 – Progress and Outcomes

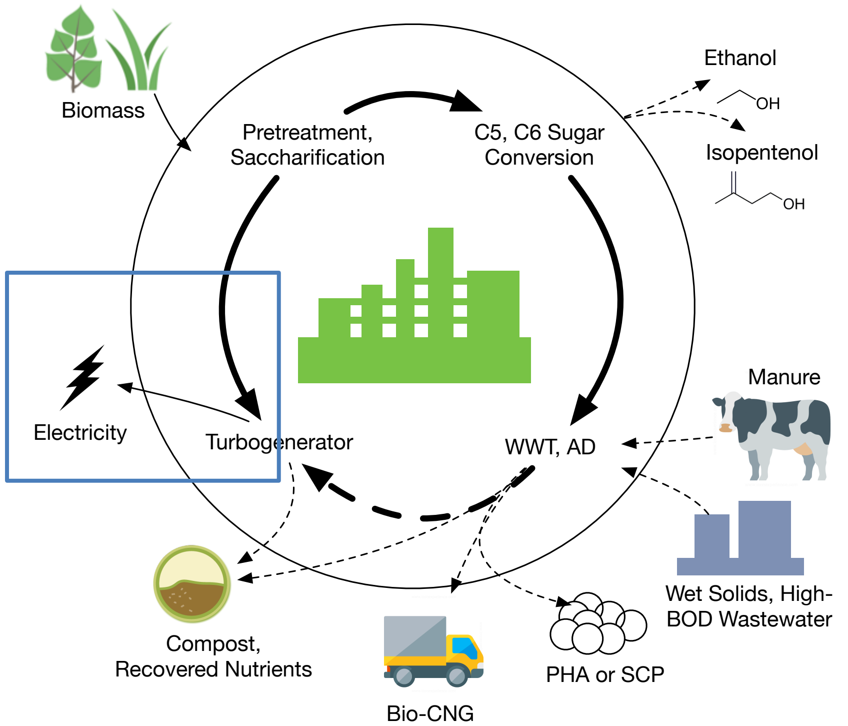


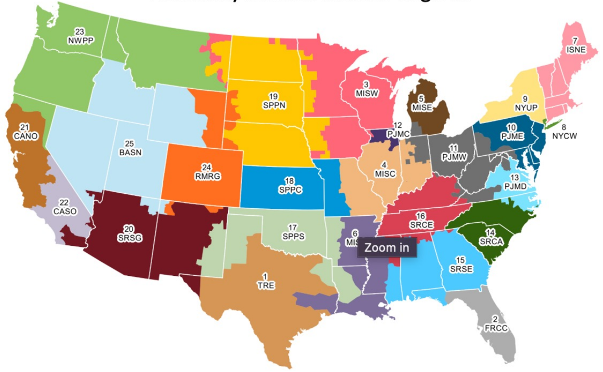
Diverting manure and other organic waste to co-digestion rather than composting untreated material appears to offer GHG (N_2O and CH_4) and air quality (NH_3) advantages



Source: Nordahl et al. 2023 *Environmental Science & Technology*

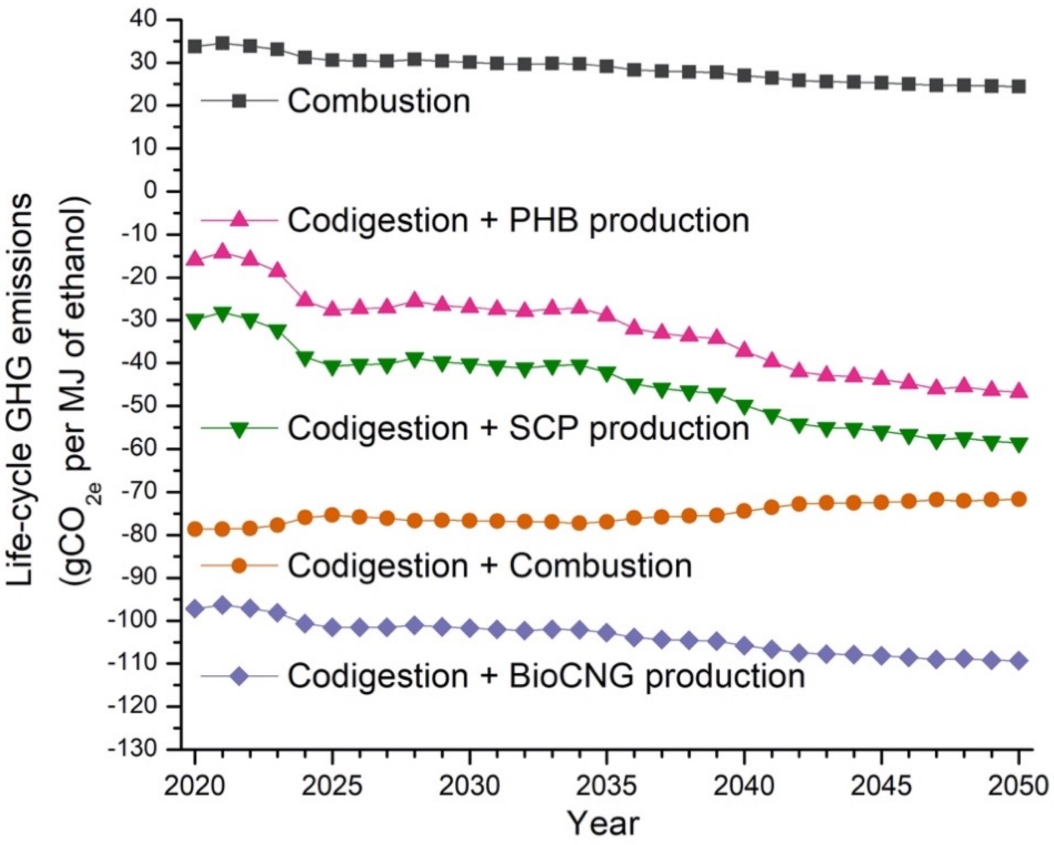
2 – Progress and Outcomes





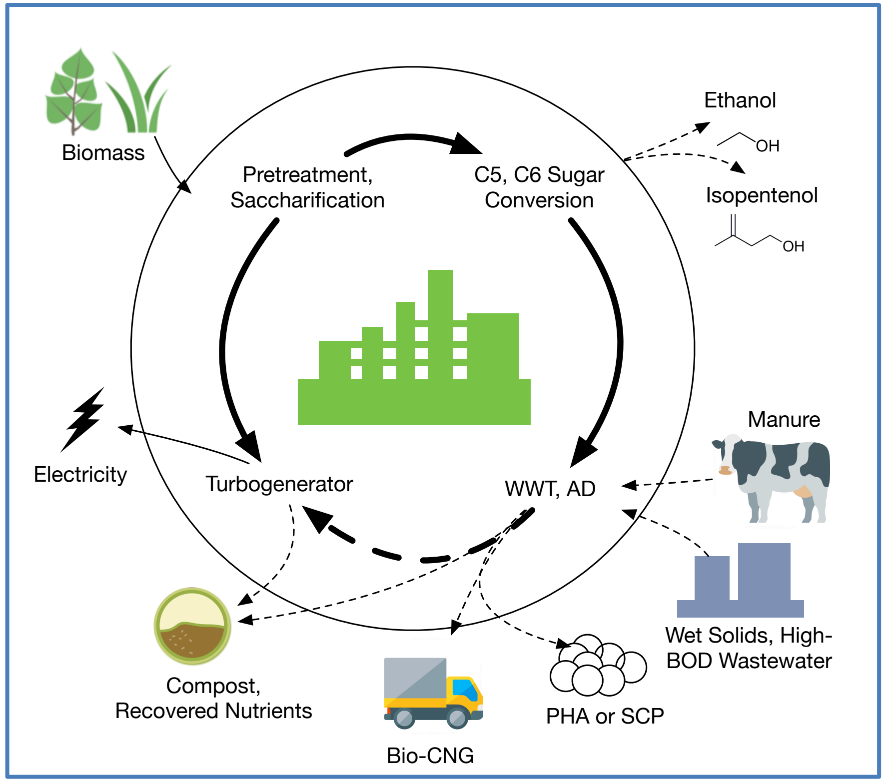
Annual Energy Outlook Low Renewable Cost case for MISW & MISC

Grid decarbonization impacts PHB and SCP scenarios more dramatically



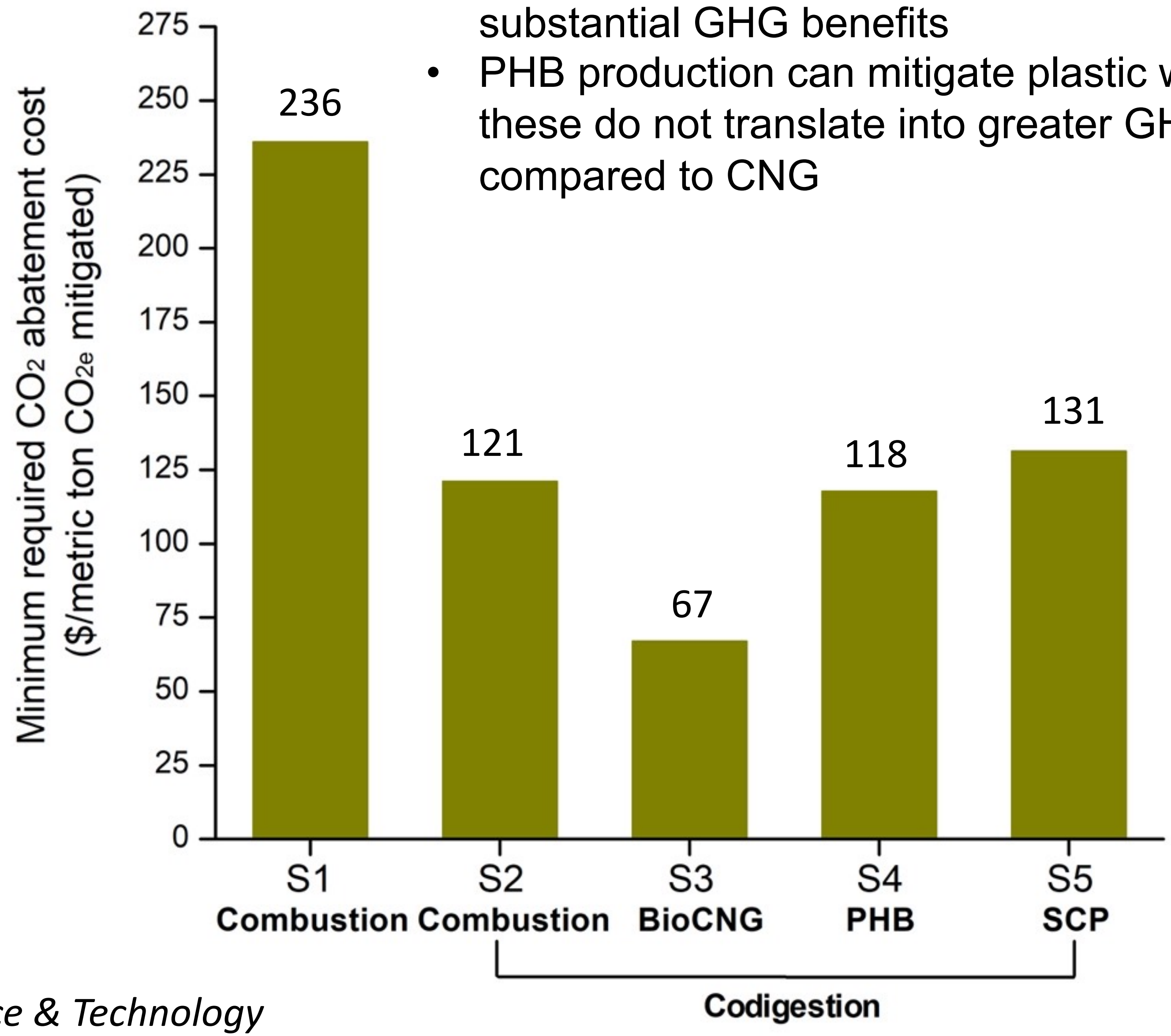
Source: Wang et al. 2023 *Environmental Science & Technology*

2 – Progress and Outcomes



Key takeaways:

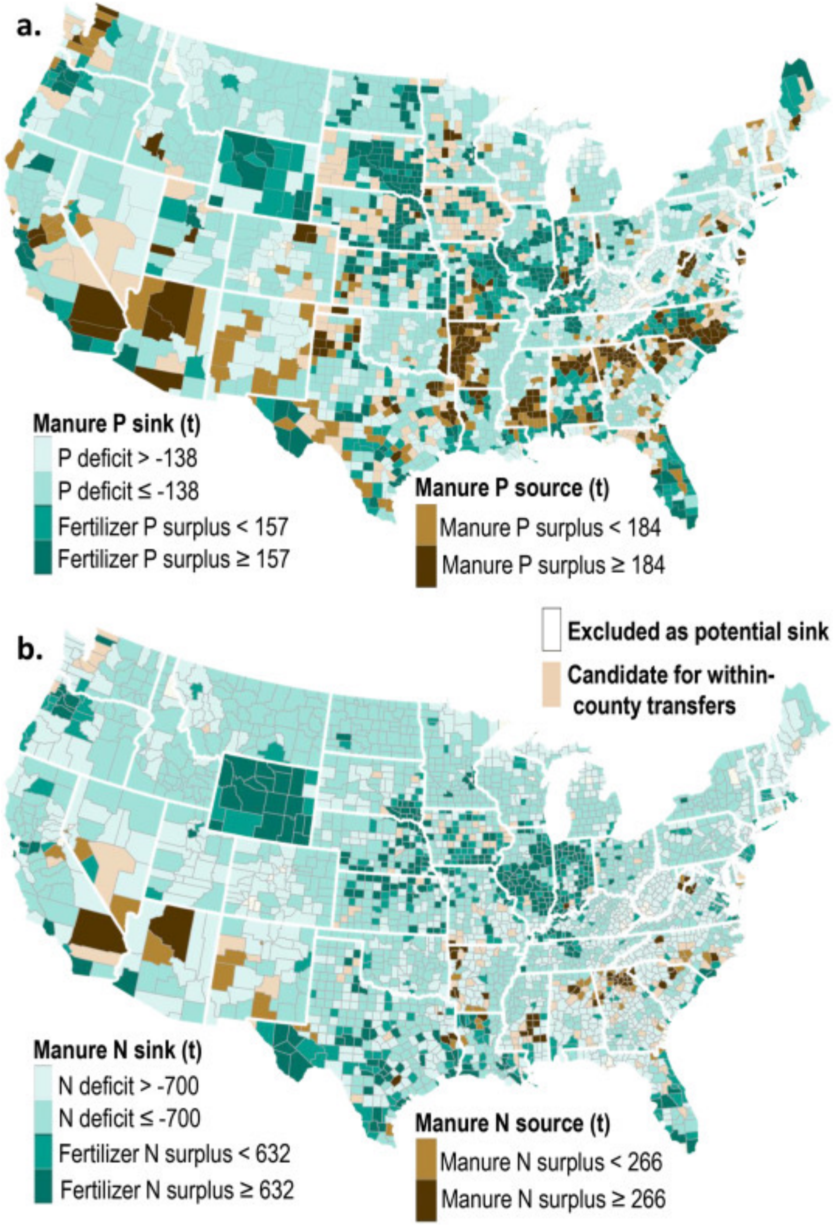
- Co-digesting manure and food waste yields substantial GHG benefits
- PHB production can mitigate plastic waste, but these do not translate into greater GHG benefits compared to CNG



Source: Wang et al. 2023 *Environmental Science & Technology*

3 – Impact

- Co-digesting organic waste and upgrading biogas offers potential for
  - Local water quality benefits
  - Diversion from landfills and manure lagoons
  - Production of compostable plastics or aquaculture feed
  - Concentrated CO_2 capture & sequestration opportunities
- Potential for targeted investments to divert manure in areas w/ overabundance of nutrients
- Web-based tools offers ability to explore economics & environmental impacts for non-experts



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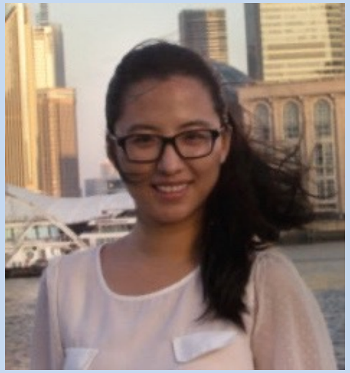
Source: Spiegal et al. 2020

3 – Impact

Long-term analysis informed by data & practical experience from deployment

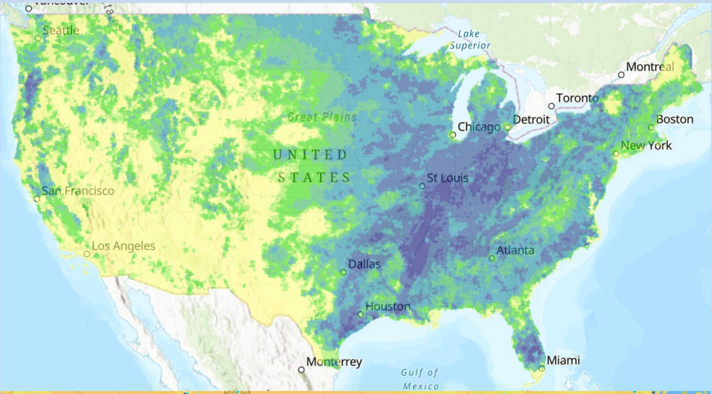
Training next TEA/LCA leaders

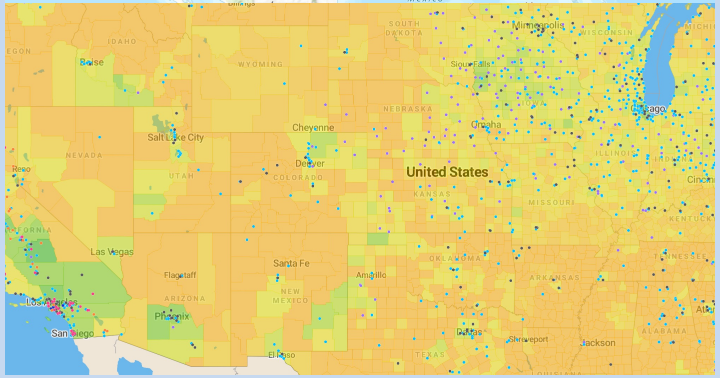


Yan became TEA expert @ Shell Hydrogen

Melissa was waste-to-energy engineer before PhD, passion for TEA/LCA

Biorefineries to alleviate nutrient pollution & methane emissions





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Summary

- **Goal:** Conceptualize, design, and asses the economic and environmental performance of multi-input, multi-output biorefineries that can convert locally-produced lignocellulosic biomass, manure, and other wet organic waste into liquid fuels, platform chemicals, and high-value products.
- **Approach:** Use an LCA and TEA framework to design and evaluate multi- input, multi-output biorefineries. Integrate empirical data on the production of polyhydroxyalkanoate (PHA) and single cell protein (SCP) from raw biogas, in addition to empirical data on pretreatment and bioconversion from previous work.
- **Progress:** Final biorefinery designs completed, cost, GHG, and energy results published for PHA and SCP production with varying co-digestion configurations. Water and air pollutant results generated. Web tool operational.
- **Potential Impact:** Improved environmental quality and jobs in rural communities, > 70% GHG reduction, > 50% fossil energy reduction, and > 20% air pollution health damage reduction relative to base case.
- **Future Work:** Publish water and GHG results, post PHA and SCP scenarios on web tool.

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Quad Chart Overview

Timeline
- Start date: July 1, 2020
- End date: June 30, 2023

	FY20 Costed	Total Award
DOE Funding		
Project Cost Share		

Project Partners
- Mango Materials

Project Goal
Conceptualize, design, and asses the economic and environmental performance of multi-input, multi-output biorefineries that can convert locally-produced lignocellulosic biomass, manure, and other wet organic waste into liquid fuels, platform chemicals, and high-value products.

End of Project Milestone
Provide a set of optimized biorefinery designs that take in biomass and wet organic waste to produce a suite of fuels and products, valuable results on the economic and environmental impacts of these multi-input multi-output biorefineries, as well as a set of important modeling tools for researchers and stakeholders interested in evaluating their own technologies in in the context of their communities.

Funding Mechanism
BETO FY19 Multi-Topic FOA, AOI 10: Reducing Water, Energy, and Emissions in Bioenergy

DE-FOA-0002029

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*Only fill out if applicable.

Additional Slides

Response to Reviewer Comments

- Recommendation to address potential overlap with other projects in BETO portfolio
  - Update: Engaged with labs across the BETO portfolio to share findings and coordinate on parameters through Roads to Removal report. Offering findings as potential resource for Billion Ton Update
- Question regarding usability of web tools
  - Update: Engaged in regular user trainings. Main users appear to be: investors conducting due diligence, researchers doing preliminary TEA/LCA

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Publications, Patents, Presentations, Awards, and Commercialization

Invited Talks

"Biomanufacturing to Address Near-Term Climate Goals", Invited Panel Discussion, National Academies Biomanufacturing Workshop, Washington, DC, March 3, 2023. [virtual]

"Challenges in Biomanufacturing Contributing to a Circular Bioeconomy", Invited Panel Discussion, National Academies Biomanufacturing Workshop, Washington, DC, October 24, 2022. [virtual]

"Waste-Based Materials for Carbon Sequestration & a Circular Economy", Invited Talk, EBI-Shell Net Zero Emission Materials Workshop, University of California, Berkeley, October 13, 2022.

“Designing the bioeconomy for deep decarbonization", Keynote Talk, Annual Green Chemistry & Engineering Conference, June 3, 2022. [virtual]

“Overcoming the Engineering and Environmental Challenges of Achieving a More Circular Economy”, Invited Talk, CUWP Seminar Series, University of Wisconsin-Madison, April 14, 2022. [virtual visit]

“Overcoming the Engineering and Environmental Challenges of Achieving a More Circular Economy”, Invited Talk, Ezra's Systems Roundtable Seminar, Cornell University, February 4, 2022. [virtual due to COVID]

“Weighing Life-Cycle Climate and Health Tradeoffs in the Push Toward Zero Waste”, Invited Talk, EEE Research Seminar, Purdue University, January 18, 2022. [virtual]

“Converting Wet, Stinky Waste into Usable Energy”, Guest Lecture for UC Berkeley E93, October 29, 2021.

“Circular Plastics and the Environment”, Invited Talk, IEEE Silicon Valley/Bay Area Sustainability (SVS) Webinar, October 13, 2021. [virtual due to COVID]

“Designing the Bioeconomy for Deep Decarbonization: Opportunities and impacts for the agricultural sector”, Invited Conference Presentation, Society for Industrial Microbiology and Biotechnology Annual Meeting, Austin, TX, August 9, 2021. [virtual]

“Opportunities and impacts for the agricultural sector”, Invited Plenary Talk, Designing the Bioeconomy for Deep Decarbonization, DOE Multi-Lab Workshop, April 30, 2021.

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Publications, Patents, Presentations, Awards, and Commercialization

Publications

Wang, Y., Baral, N.R., Yang, M. and Scown, C.D., 2023. Co-Processing Agricultural Residues and Wet Organic Waste Can Produce Lower-Cost Carbon-Negative Fuels and Bioplastics. *Environmental Science & Technology*. DOI: 10.1021/acs.est.2c06674

Nordahl, S.L., Preble, C.V., Kirchstetter, T.W. and Scown, C.D., 2023. Greenhouse Gas and Air Pollutant Emissions from Composting. *Environmental Science & Technology*. DOI: 10.1021/acs.est.2c05846

Scown, C.D., 2022. Prospects for carbon-negative biomanufacturing. *Trends in Biotechnology*. DOI: 10.1016/j.tibtech.2022.09.004

Wang, Y., Huntington, T. and Scown, C.D., 2021. Tree-based automated machine learning to predict biogas production for anaerobic co-digestion of organic waste. *ACS Sustainable Chemistry & Engineering*, 9(38), pp.12990-13000. DOI: 10.1021/acssuschemeng.1c04612

Orner, K.D., Smith, S., Nordahl, S., Chakrabarti, A., Breunig, H., Scown, C.D., Leverenz, H., Nelson, K.L. and Horvath, A., 2022. Environmental and Economic Impacts of Managing Nutrients in Digestate Derived from Sewage Sludge and High-Strength Organic Waste. *Environmental Science & Technology*, 56(23), pp.17256-17265. DOI: 10.1021/acs.est.2c04020

National Academies of Sciences, Engineering, and Medicine, 2022. Current Methods for Life Cycle Analyses of Low-Carbon Transportation Fuels in the United States.

Awards

ACS Sustainable Chemistry & Engineering Lectureship, 2022

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EXTRA SLIDES

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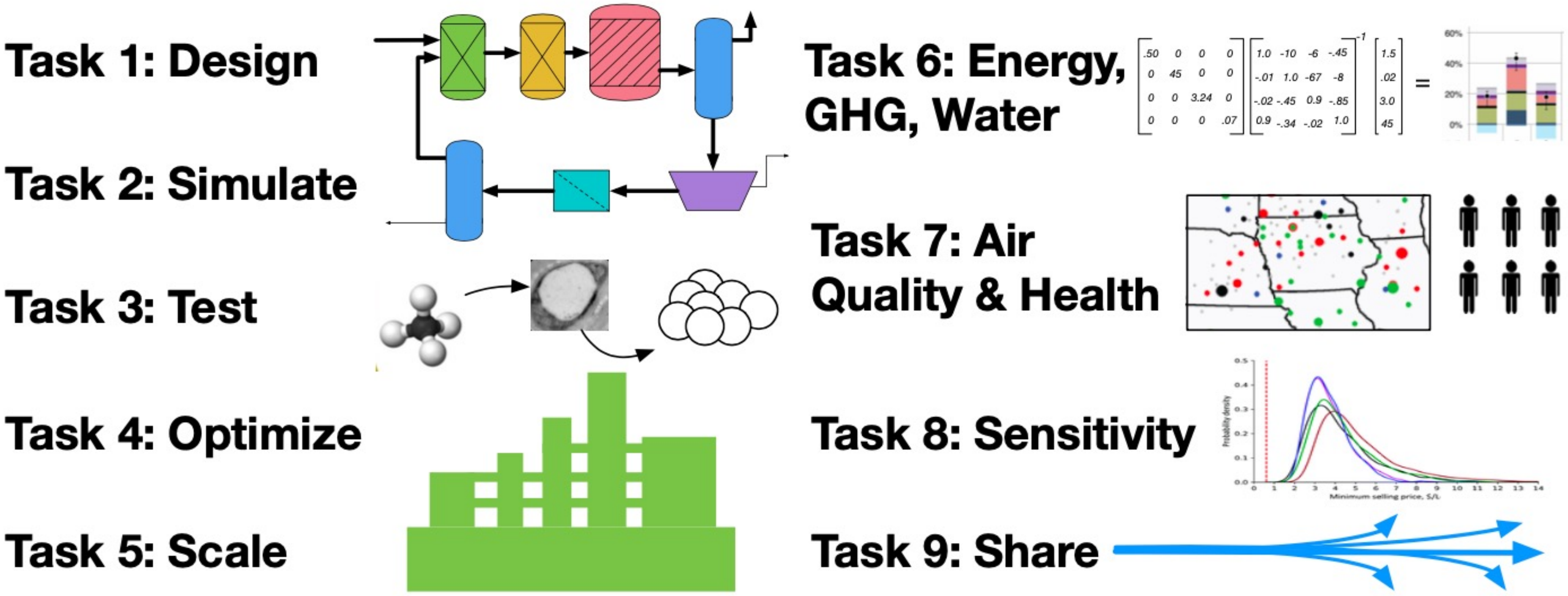
1 – Approach

1. Biorefinery scenarios designed & simulated in SuperPro Designer to generate mass/energy balances & estimate costs
2. Biogas yield & composition simulated using promising feedstock types & real-world AD data from EBMUD
3. PHA & SCP yields @ bench scale tested
4. Biorefinery designs optimized based on early modeled & empirical results
5. Gas fermentation scaled up at launch facility, data collected at larger scale
6. Life-cycle assessment developed for optimized biorefinery designs for energy, GHG, water
7. Sensitivity analysis to explore technical & market risks
8. Air pollutant & health damages estimated using integrated assessment model
9. Web-based modeling tools deployed for use in broader research & industry community



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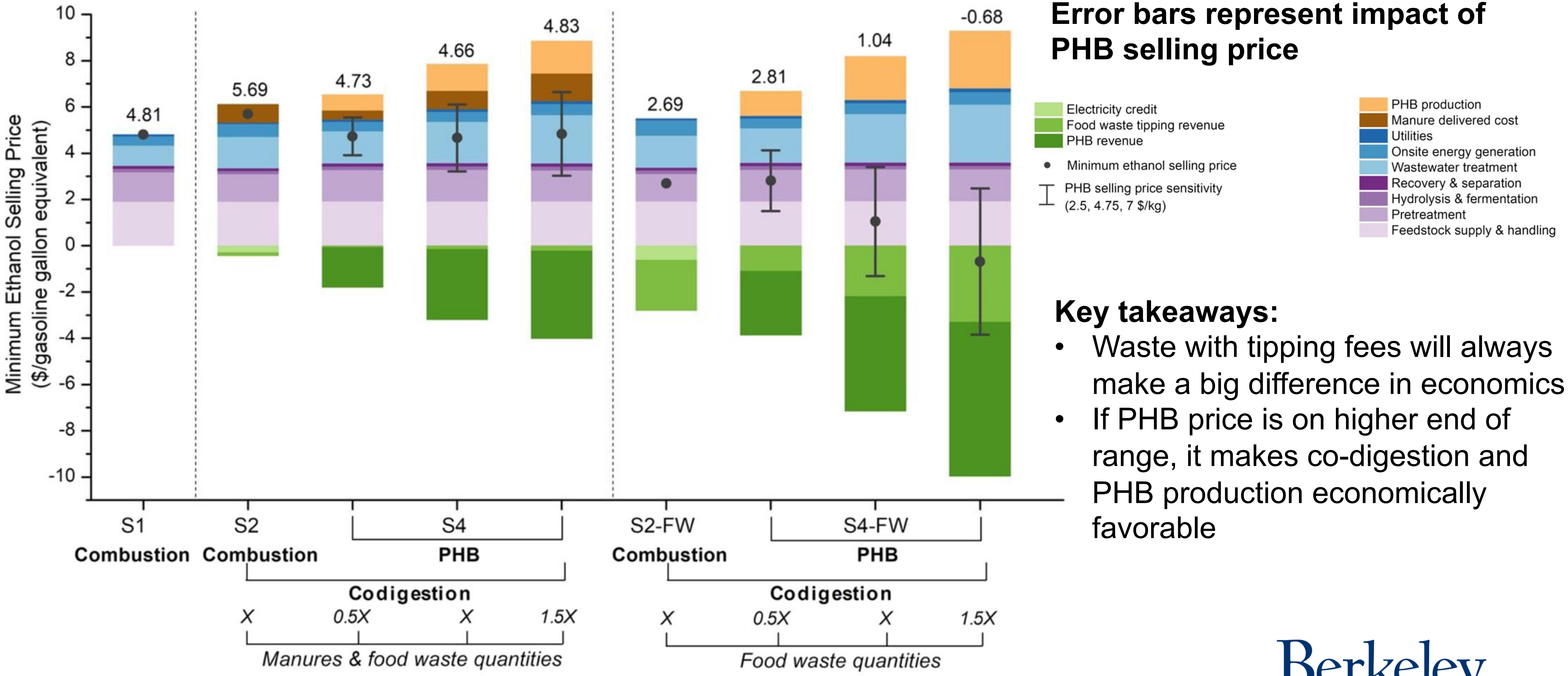
2 – Progress and Outcomes



Error bars represent impact of PHB selling price

Key takeaways:

- Waste with tipping fees will always make a big difference in economics
- If PHB price is on higher end of range, it makes co-digestion and PHB production economically favorable

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Source: Wang et al. 2023 *Environmental Science & Technology*