# DOE Bioenergy Technologies Office 2019 Project Peer Review: The Waste-to-Energy System Simulation Model (WBS# 2.1.0.104)

Daniel Inman, PhD
March 5th, 2019
NREL

# Project Goals

- **Goal:** to use systems thinking and analyses to generate non-trivial system insights around the development of the industry and to use these insights to inform the R&D opportunities.
- **Outcomes:**
  1) A state-of-the art computational model of the waste-to-energy (WTE) industry in the U.S.
  2) Analyses that uncover non-intuitive system insights and endogenous behaviors
  3) Dissemination of our findings to stakeholders
- **Relevance:** This project is relevant to BETO and the broader stakeholder community because we develop and disseminate actionable insights about the nascent WTE industry (e.g., identifying bottlenecks, synergies, impacts of R&D decisions, local/regional implications, and areas of leverage) and the long-term potential of WTE technologies. Outcomes from this project inform R&D opportunities.

# Quad Chart Overview

## Timeline

**Project Start**: 10/1/2017
**AOP Cycle End**: 9/30/2020
**Amount Complete**: ~50%

| | FY 18 Costs | FY 19 Costs | FY 20 Costs | Total Planned Funding |
|---|---|---|---|---|
| DOE Funded | $300K | $300K | $300K | $900K |

**Partners**: Pacific Northwest National Laboratory, Lexidyne LLC, Environmental Protection Agency

## Barriers addressed

**At-A**: Comparable, Transparent, and Reproducible Analyses . The WESyS model is transparent, reproducible, and trackable.

**At-B**: Analytical Tools and Capabilities for System-Level Analysis. WESyS is a systems modeling tool built using established approaches and data.

**At-C**: Data availability across the Supply Chain

**Objective:** to build and exercise a system dynamics (SD) model of the waste-to-energy (WTE) industry in the United States and to develop and analyze scenarios that explore the evolution of the WTE industry and how it may be deployed in a way makes a substantial contribution to the country's transportation energy. We want to understand how novel technologies develop in the context of multiple mature technologies.

**End of Project Goal:** to directly addresses specific Bioenergy Technologies Office questions, we will expand the model to include a range of developing technologies and novel sources of waste feedstocks.

# 1 – Project Overview

# Simulating Industrial Trajectories

- Our model, the waste-to-energy system simulation (WESyS) model, tracks technological investments and energy production from landfills, publicly-owned treatment works (POTWs), and concentrated animal feeding operations (CAFOs) in two U.S. regions – California (CA) and the rest of the U.S. (ROTUS).
- We have collaborated extensively with scientists from the U.S. Environmental Protection Agency as well as with other national labs.
- The model is built using peer-reviewed data for resource potential and process techno-economics.
- Investment and buildout of the industry is tracked throughout a simulation.
- Results are a snapshot of the industry at a point in time or the development trajectory over time.

# 2 – Approach

# Personnel and Responsibilities

- Team members and responsibilities
  - Daniel Inman, PhD – Project task lead and analyst
  - Annika Eberle, PhD – Lead analyst
  - Laura Vimmerstedt, MS – Senior Analyst
  - Ling Tao, PhD – Analyst/process design liaison
  - Arpit Bhatt, MS - Analyst/process engineer
  - Dylan Hettinger – Programmer
  - Steve Peterson (Consultant) – Lead model architect

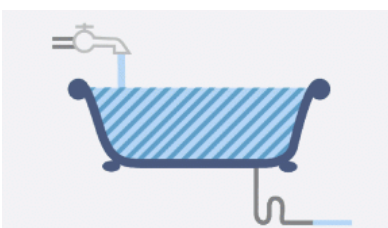
# Management Workflow

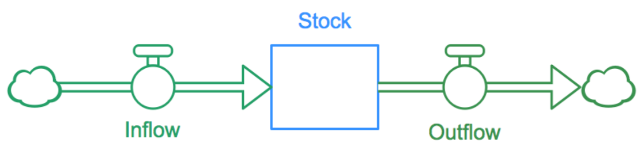
- Regularly interface with partners and subcontractors (PNNL, Lexidyne, BETO)
- Monthly team meetings
- Regularly scheduled calls with BETO
- Experiential modeling sessions with stakeholders
- Quarterly AOP milestones
- Database management best practices
- State-of-the-art workflow
- Study versioning – reproducibility
- Quantitative QA/QC on models

NREL’s HPC System

# System Dynamics Modeling

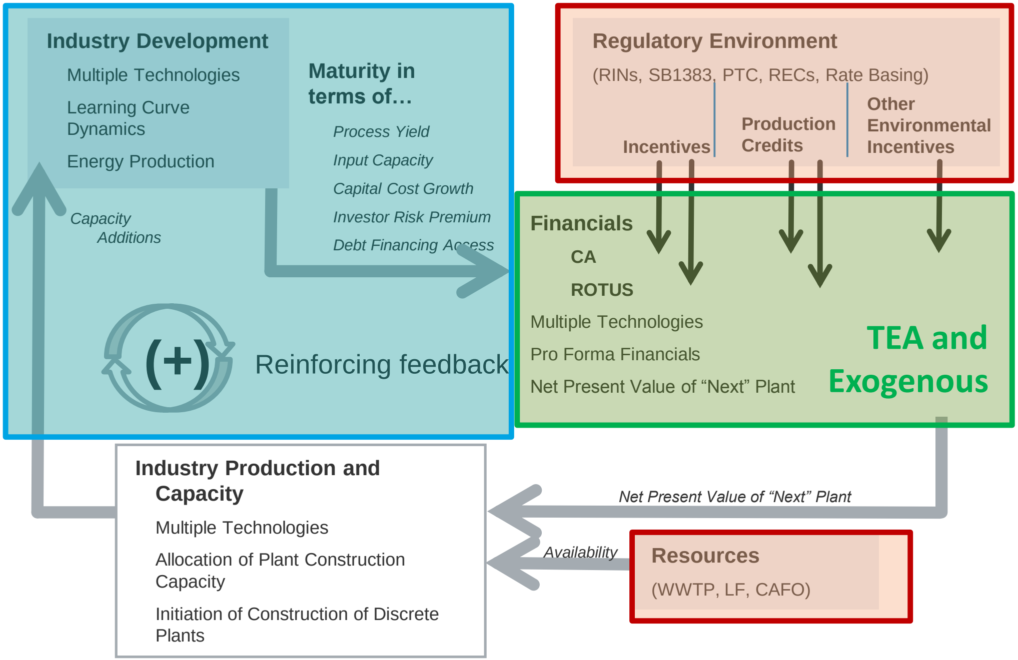
- We use system dynamics to model the waste-to-energy (WTE) system in the U.S.
- System dynamics is a modeling approach that uses coupled ordinary differential equations to represent complex (non-linear) systems.
- SD was developed at MIT in the 1940s by Jay Forrester and has been applied to a variety of problems at several large organizations (e.g., GE, GM, U.S. Navy, U.S. DOE).
- SD practitioners use systems thinking, management insights, and computation to hypothesize, test, and refine endogenous explanations of system change.






$$Stock(t) = \int_{t_0}^{t} [Inflow(s) - Outflow(s)]\, ds + Stock(t_0)$$

# WESyS is Focused on Endogenous Behavior




We use exogenous parameters such as technoeconomics and existing policies as model inputs.

# Success Factors

**Success factors**

- Ground truth technical and economic model assumptions
- Balance detail complexity with computational efficiency
- Stakeholder buy-in on vetting and calibration
- Accurately represent the complex decision process around investment in WTE
- Understand the nuanced market for energy products from WTE systems

**Challenges**

- Consistent and verified data
- Anticipating analyses that are relevant to the industry.

# 3 – Technical Accomplishments and Results

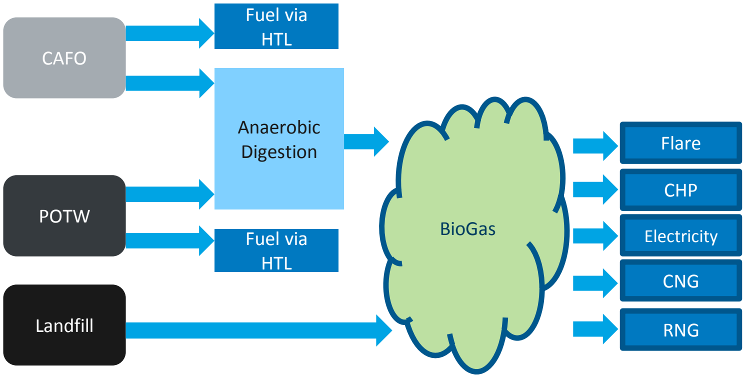
Large Sensitivity Study of WESyS
Q3 & Q4 FY 2018

# Accomplishments: Milestones

- All planned milestones have been met and delivered on schedule
- We built and tested a system dynamics model of the waste-to-energy system in the U.S.
- We developed a state-of-the-art workflow for executing large studies, cataloging results, and analyzing data.
- We analyzed the energy fates of biogas and sludge in California and the Rest of the U.S. (ROTUS) were assessed.
- We have conducted several state of the art interactive analysis and visualization workshops for our BETO clients.
- We have developed a suite of real-time statistical analysis tools for use with WESyS and other similar models.
- Completed a large sensitivity study of the model
  - The next several slides will present results from our recent sensitivity study.

# Results: Sensitivity Study of WESyS

- Our objective is to understand the technical, economic, and local conditions that lead to specific end fates of biogas and biosolids.
- Plant configurations considered:
  - No waste-to-energy (WTE)
  - Flaring
  - Combined heat and power (CHP)
  - Electricity (Elec)
  - Compressed natural gas (CNG)
  - Renewable natural gas (RNG)
  - Hydrothermal liquefaction (HTL)



# Results: Factors Varied in Study

**Learning**

- Commercial progress ratio for HTL
- Exogenous production of HTL
- Initial commercial maturity of HTL
- Commercial experience for learning

**Policy**

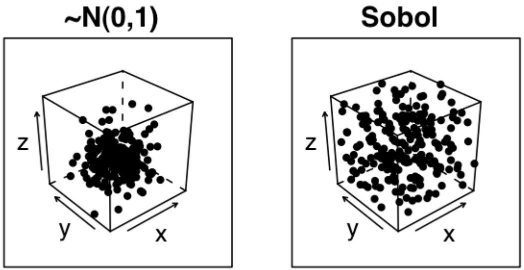
- Production tax credits
- RIN price
- Rate based investment for electricity
- Grant for PNG interconnect
- Diversion of organics via SB1383

**TEA and Exogenous**

- Expected operating cost
- Expected fixed capital investment
- Conversion efficiencies
- Coproduct sales revenue
- Debt interest rate
- Depreciation period
- Expected equity fraction
- Pipeline length
- Required rate of return
- Tipping fee
- Dwell time
- Fuel prices

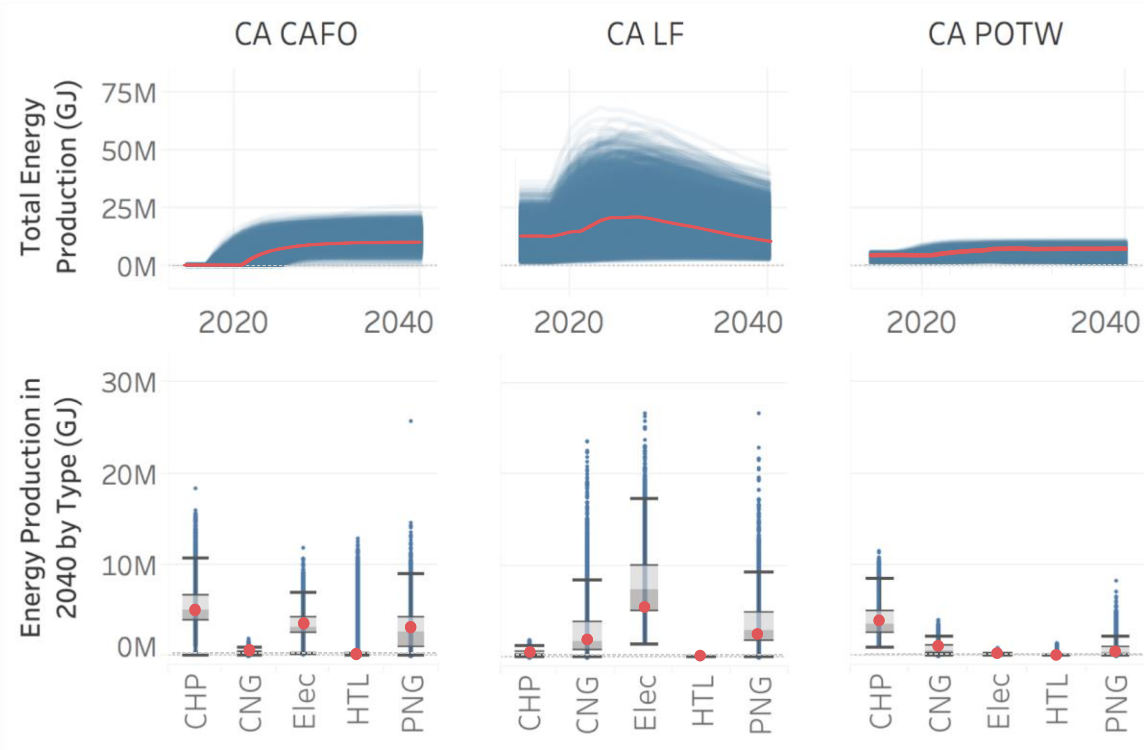
# Results: Study Design and Analysis

1. We used Sobol's quasi-random sequences to design two studies (CA and ROTUS) with ~65 factors and 7,500 replications each (~1 million runs per study).
2. Global Sensitivity Analysis: We determined the total, first, and second-order sensitivity indices using variance-based decomposition.
3. Local sensitivity analysis: We performed Mood's Median test on specific regions of interest.




Comparison of a Gaussian sampling distribution to Sobol's Quasi Random Sequence.

# Results: Summary of CA Energy Trends




Blue = all sensitivity results

Red = model default results

# Results Among Biogas Sources: CA

| Biogas Source | Model Factor | $S_{ti}$ |
|---|---|---|
| **POTW** | CHP Efficiency | 0.15 d |
| | **HTL Technology Demo.** | **0.30 a** |
| | HTL Comm. Maturity | 0.23 b |
| | HTL Pre-Comm Maturity | 0.27 ab |
| | Anaerobic Digester Yield | 0.23 b |
| **CAFO** | Rate of Return | 0.20 b |
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| | **HTL Pre-Comm Maturity** | **0.29 a** |
| | HTL Learning Rate | 0.22 b |
| **Landfill** | **$CH_4$ Recovery** | **0.73 a** |

- HTL is attractive for manure and sludge once sufficient demoing has been done.
- Maturity is very important for HTL to be attractive in the WTE space b/c the incumbent technologies are proven and mature.
- These results are not directional – competitive interactions are present
- In terms of non-intuitive insights, we found that the tipping fee, and certain incentives are not among the top influential factors.

# 4 – Project Relevance

# Relevance to Stakeholders

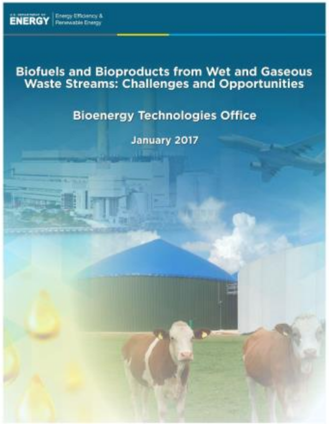
**Relevance to BETO**

- *"to develop industrially relevant, transformative, and revolutionary bioenergy technologies to enable **sustainable, domestically produced** biofuels, bioproducts, and biopower for a prosperous nation. "*
  - *In order to meet the above goal, decision makers and technologists need to understand where to focus their efforts, what hurdles exist, and how to minimize them.*
- *"generates scientific knowledge that **proactively addresses issues affecting the scale-up potential, public acceptance, and long-term viability** of advanced bioenergy systems. "*
  - *For novel, revolutionary technologies to thrive, we need to provide them with knowledge gained through experiential learning without the exposing them to the potentially catastrophic risks.*
  - *WESyS does just that – it acts as a flight simulator that allows researchers to experiment, fail, succeed, and gain industrial knowledge about the WTE industry in the process. They can then leverage this knowledge to make better and more informed decisions.*

# Relevance to Stakeholders

**WTE Community**

- Provide outreach and analysis to key stakeholders
  - We have provided briefings to agencies such as the California Air Resources Board on our results, contributed key analysis to BETO's challenges and opportunities report, participated in DOE-led industry workshops (Golden, CO & Berkeley, CA)
- We have utilized advanced visualization and computation to conduct experiential modeling and analysis sessions with BETO and the broader WTE community (e.g., Waste Management Inc.).




WESyS being run in 3-D mode in NREL's advanced visualization center.

# Looking Forward

To increase our relevance and provide the most impactful project outputs, we have focused the remaining 18 months on increasing the detail complexity represented in the model and understand the system-wide implications. Additionally, we will be working with process engineers/developers to include additional novel technologies.

Specifically we will perform the following activities:

- Fundamentally change the technology investment decision framework in the model to allow for:
  - technological investments that are less than the maximum throughput
  - multiple, sequential technology investments
- This will allow us to better represent the current status of the industry where projects may invest in a given technology and at a later date, expand the existing investment, or invest in a different technology.

Key milestones:

- Q4 FY19 - Understand the system-wide implications of multiple-technology investments at individual facilities. This will exercise the additional WESyS model structure and logic to that was added in Q2 and Q3 (allowing facilities to invest in more than one WTE technology) by performing an analysis to explore how this affects the buildout of the WTE industry over time.

Go/No-Go milestones:

- Q1 FY20 - Critical model review. Are the analyses and model relevant for BETO and the stakeholder community at large?

# Summary

**Overview:** WESyS dynamically evaluates potential waste-to-energy feedstocks, technologies, and end uses using a scenario-based approach. Results from this project enable the development of insights into potential industry growth and market penetration, particularly with respect to policies, incentives, technological advances (R&D, industrial learning), related and/or competing energy markets, demand for petroleum-based fuels, and competing uses of feedstock.

**Approach:** WESyS uses a system dynamics modeling framework. The model is built from vetted and/or published resource, market, and techno-economic data. A flexible, modular, and transparent architecture is used.

**Accomplishments:** All milestones completed. Developed a state-of-the-art approach modeling approach, impactful analyses on biogas and sludge, large-scale sensitivity studies completed.

**Relevance:** WESyS is a flight simulator that allows researchers to experiment, fail, succeed, and gain industrial knowledge about the WTE industry in the process. They can then leverage this knowledge to make better and more informed decisions.

**Future Work:** Increasing relevance by adding real-world detail complexity and understanding the impacts of multiple investments at facilities and assessment of food wastes and emerging technologies.

# Thank you

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# Additional Slides

# Peer Review 2017 Comments and Responses

**Comments regarding lack of rationality and inadequate stakeholder engagement:**

Based on feedback from the reviewers we have decided to modify our work plan for the remainder of FY17, going into FY18. Our focus for Q3 and Q4 has changed and will now be to: 1) regionalize the WESyS model, and 2) perform a preliminary scenario analysis that is informed by input from the July 2017 WTE Workshop. Specifics of our new approach are as follows. In order to develop a regionalized WESyS model that is relevant for application to the WTE industry, we would will include four stages of stakeholder engagement in our model development. The first stage will involve presenting the model at the July 2017 WTE Workshop in California. During this presentation, we will provide an overview of the structure and capabilities of WESyS and answer questions about the model. In the second stage, we would like to have several breakout sessions with stakeholders at the workshop in order to solicit feedback regarding emerging issues surrounding WTE policy and technology. These sessions would ideally be hosted by BETO with members of the WESyS team there to facilitate the discussion. Topics could include how stakeholders might use the WESyS model, the relevance of the model's technology types, current and future policy and regulatory frameworks, and other important frameworks that could be incorporated into WESyS in the future. Stage three would involve using the stakeholder feedback to develop the research questions and analysis scenarios for Q4. This stage would involve working with BETO to 1) synthesize stakeholder input from the workshop into actionable scenarios, 2) rank the scenarios based on BETO priorities, 3) down-select to a maximum of four scenarios for analysis in Q4, and 4) identify future directions and scenarios that could potentially be explored in FY18. The outcomes of stage three would include a refined scenario design and the identification of a baseline set of conditions (examples below; final selection will be based on feedback from CA Workshop).

**Regional differences in technologies, capex, opex:** While we strive to have the most representative data, the model is a high-level systems model and will not represent all potential differences between technologies and regions. That said, because of the architecture, it is flexible enough to perform case study or sub-regional analyses in which such variance could be assessed.

**Transition dynamics vs prediction:** SD is designed to understand system feedbacks. The WESyS model is geared towards understanding how the system may respond to specific scenarios or sets of scenarios. Output from the model should be viewed as directional and order-of-magnitude as opposed to precise point predictions because we do not necessarily represent statistical relationships (i.e. there are no error bars associated with our output).

**Sufficient redundancy:** Although the lead model architect is one person, our team has decades of combined experience in system dynamics modeling and analysis. There are at least three other individuals on the team that could serve as lead architect if needed.

# Sensitivity Study – Additional Detail

# Milestone Information

- **WBS #**: 2.1.0.104
- **Milestone title**: A briefing, in the form of a presentation, on the technoeconomics, policy drivers, and market conditions that lead to specific end fates of biogas. This briefing will discuss key drivers that lead to direct conversion to fuels/products, anaerobic digestion followed by: flaring, combined heat and power, pipeline injected renewable natural gas, compressed natural gas, and biofuels/products.
- **Due date**: 9/30/2018
- **Completion date**: 9/25/2018
- **Details:**

# Producing Energy from Biogas in the U.S.: System Levers and Bottlenecks

Daniel Inman, Annika Eberle,
Laura Vimmerstedt, and Dylan Hettinger

09.25.2018

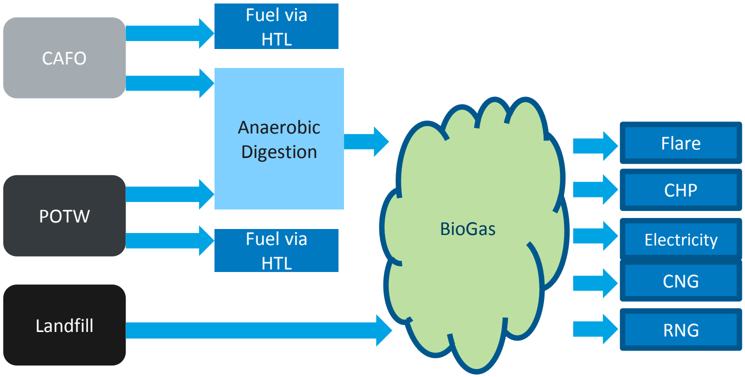
# Overview

- Study introduction
- Approach
- Global sensitivity results for specific cases
- Local sensitivity results for select regions
- Discussion and summary
- Next steps and future work

# Introduction

- This study focuses on the energy fate of biogas collected from publicly owned treatment works (POTWs), landfills, and confined animal feeding operations (CAFOs) in California (CA) and the rest of the U.S. (ROTUS). We also include results for fuel produced via HTL.

- Plant configurations considered:
  - No waste-to-energy (WTE)
  - Flaring
  - Combined heat and power (CHP)
  - Electricity (Elec)
  - Compressed natural gas (CNG)
  - Renewable natural gas (RNG)
  - Hydrothermal liquefaction (HTL)



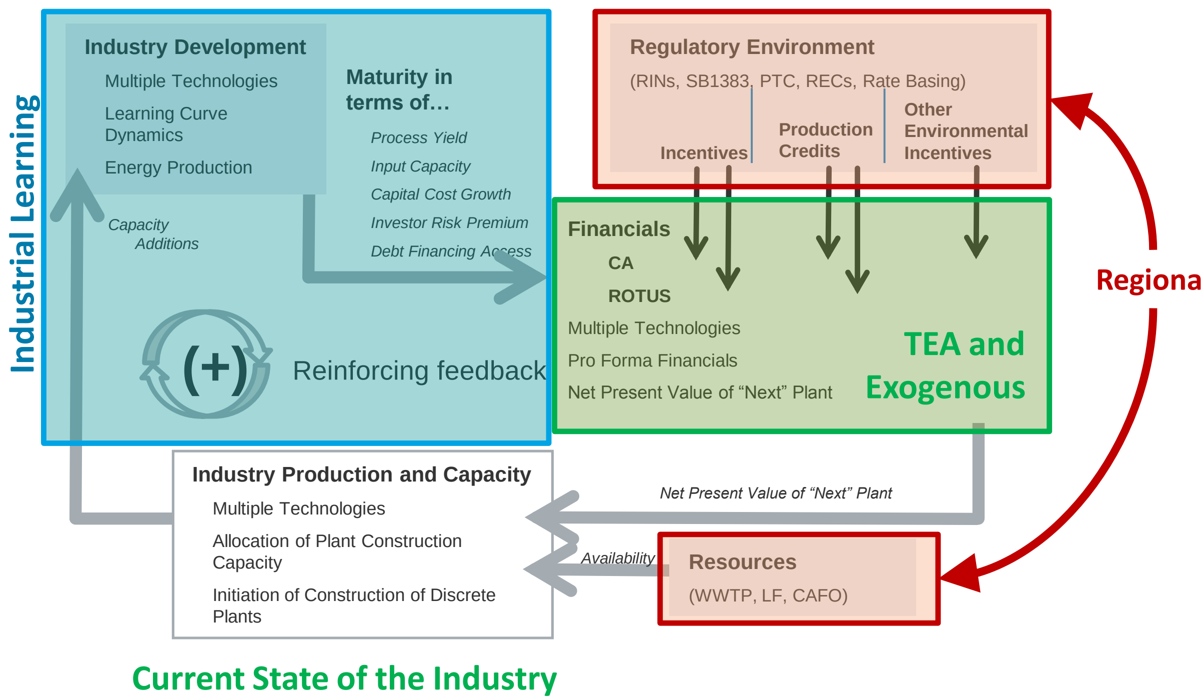
# Objective

- Our objective is to understand the technoeconomics, policy, and regulatory conditions that lead to specific end fates of biogas.
- To explore these issues, we performed global and local sensitivity analyses on NREL's Waste to Energy System Simulation (WESyS) model.

Source: East Bay Municipal Utility District

# Approach

# Influence Diagram for WESyS



# Factors Varied in Study

### Learning

- Commercial progress ratio for HTL
- Exogenous production of HTL
- Initial commercial maturity of HTL
- Commercial experience for learning

### Policy

- Production tax credits
- RIN price
- Rate based investment for electricity
- Grant for PNG interconnect
- Diversion of organics via SB1383

### TEA and Exogenous

- Expected operating cost
- Expected fixed capital investment
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- Coproduct sales revenue
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- Depreciation period
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- Pipeline length
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# Study Design and Analysis

1. We used Sobol's quasi-random sequences to design two studies (CA and ROTUS) with ~65 factors and 7,500 replications each (~1 million runs per study).
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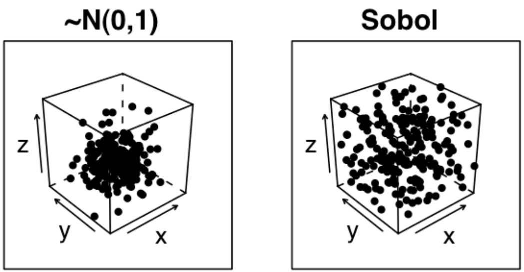



Comparison of a Gaussian sampling distribution to Sobol's Quasi Random Sequence.

# Variance Decomposition

- We calculated first-order, second-order, and total effects indices using Sobol's variance decomposition approach.
- This presentation focuses on the Total Effects ($S_{ti}$) index (first- and second-order indices are included in the back up slides).
- In sensitivity analysis, the total effects index is an indicator of how important a particular factor is – alone and in combination with all other factors.

Expected value of the conditional variance = the average conditional variance for $X_{i\ (1,\ N)}$

Conditional variance in model output for measure A; factor $X_i$ is fixed at a constant value.

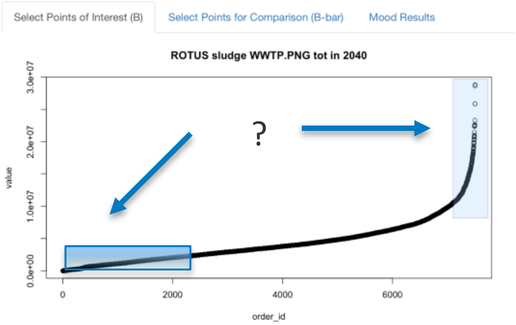
$$S_{Ti} = 1 - \frac{V[E(Y|X_{\sim i})]}{Var\ (Y)}$$

Variance in model output for measure A; all factors varied.

# Local Sensitivity

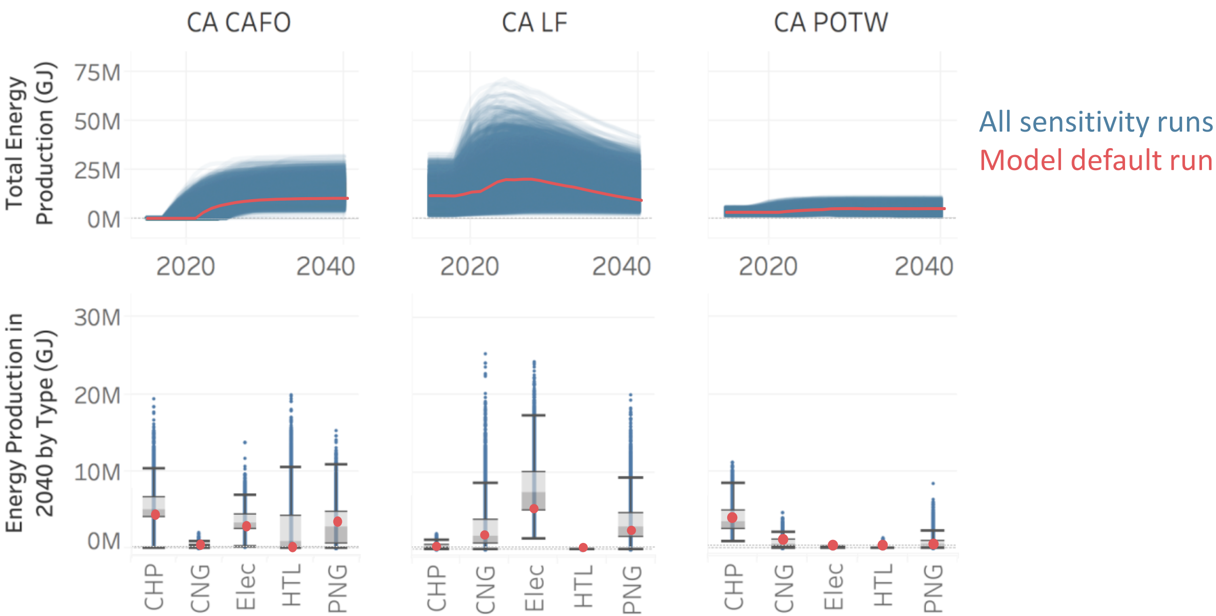
- Local sensitivity analysis (LSA) is a collection of techniques that answer the question "*what model settings led to this interesting result?*"
- Often referred to as Monte-Carlo filtering, a region of interest is selected (filtered) from a large number of runs and then compared to another region within the results-space.
- To perform LSA, we used ***Mood's Median*** test (modified Pearson's chi-square test): a two-way non-parametric test where

$$H_o = \text{Md } B = \text{Md } \bar{B};\ H_1 = \text{Md } B \neq \text{Md } \bar{B}.$$

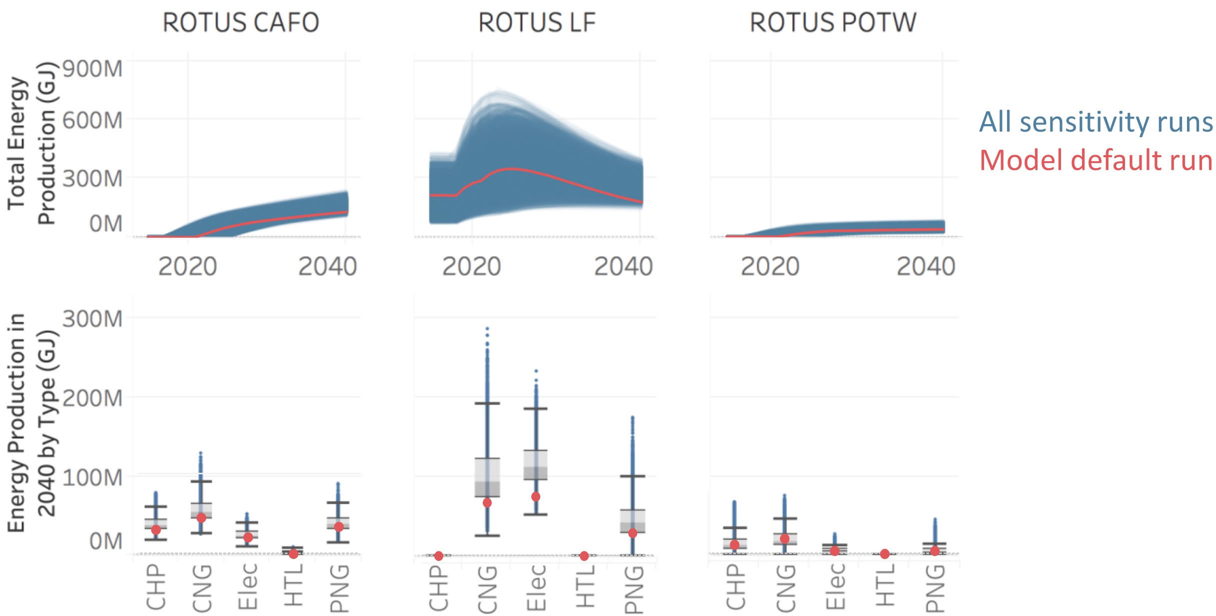


# High-Level Summary of Results

# Summary of CA Biogas Trends



# Summary of ROTUS Biogas Trends



# Summary of Impactful System Factors

Learning

- Demo-scale learning for HTL
- Commercial maturity for HTL
- Learning rate for HTL

Policy

- Project delays
- Production credits
- Energy prices (elec, NG, oil)

TEA

- Amount of recovered $CH_4$ from landfills
- CNG efficiency and yield
- Digester yield
- Rate of return

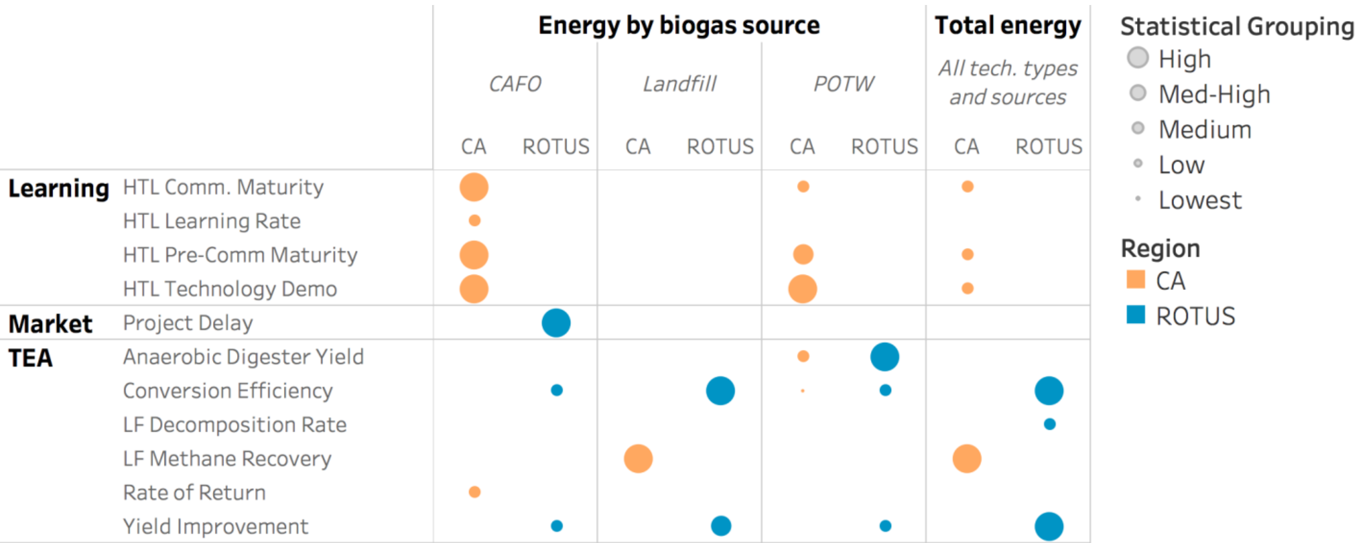
# Results

Global sensitivity analysis

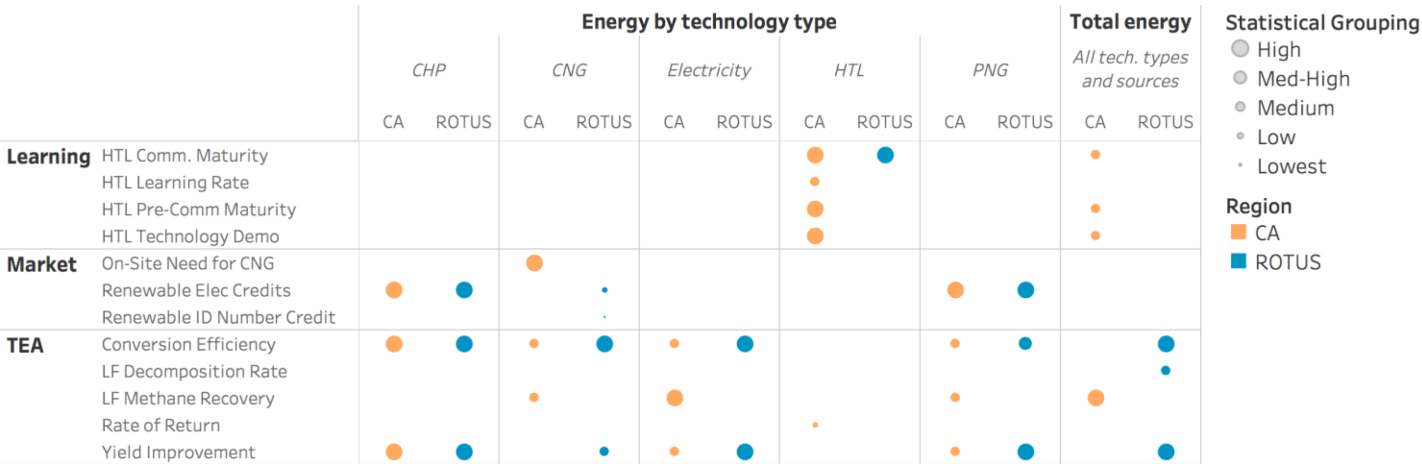
# Orientation and Caveats

- On the following slides we will present results in the following order:
  - Insights among technologies within regions
  - Comparisons among technologies between regions
- General caveats include:
  - Fixed capital will be installed on-site
  - Facilities that invest in technology other than flare can not invest again except for POTWs in which the capital is retired/expired
  - There is no mechanism to move waste offsite – i.e. consolidate waste from multiple outlets
  - RINs, RECs, and LCFS credits do not expire
  - HTL nth plant design case is based on PNNL (2016/PNNL-25464): biocrude from sludge case (Table 6)
  - We do not have the full range of CA policies that may impact WTE
  - We vary the commercial maturity for HTL from 0 to 1 even though it is not commercially mature (at present, it is arguably non-zero).

# Results by Biogas Source

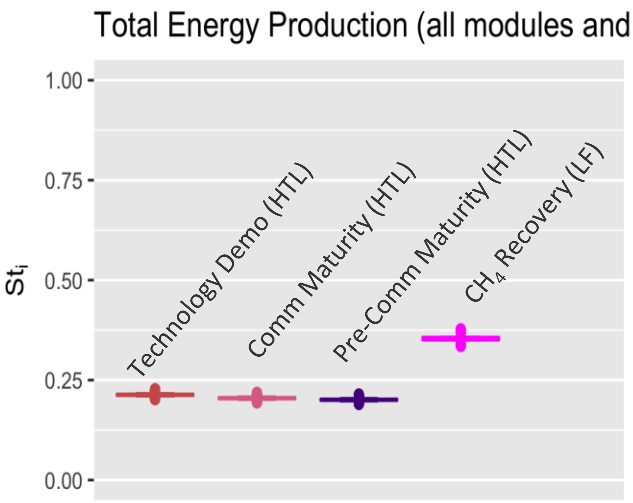


# Results by Technology



# CA Results

# Total Effects Results for CA




- Across all sources of biogas and energy conversion options assessed, the amount of biogas captured from landfills is the single most important factor when is comes to maximizing long-term energy production from biogas in CA.
- We used industry average recovery rates and oxidation factors in the model and varied these conservatively.
- Older landfills tend to be much less efficient at containing and capturing biogas. Efficiency values range from 0 to 95%, depending on the phase of the project (Lee et al., 2017)
- Newer landfills have higher rates of oxidative loss of LFG. The IPCC suggests the loss of LFG though oxidation is 10%, studies have found this number to be between 30 and 44% (Chanton et al., 2009).

# Results Among Biogas Sources: CA

| Biogas Source | Model Factor | $S_{ti}$ |
|---|---|---|
| **POTW** | CHP Efficiency | 0.15 d |
| | **HTL Technology Demo.** | **0.30 a** |
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| | HTL Learning Rate | 0.22 b |
| **Landfill** | **$CH_4$ Recovery** | **0.73 a** |

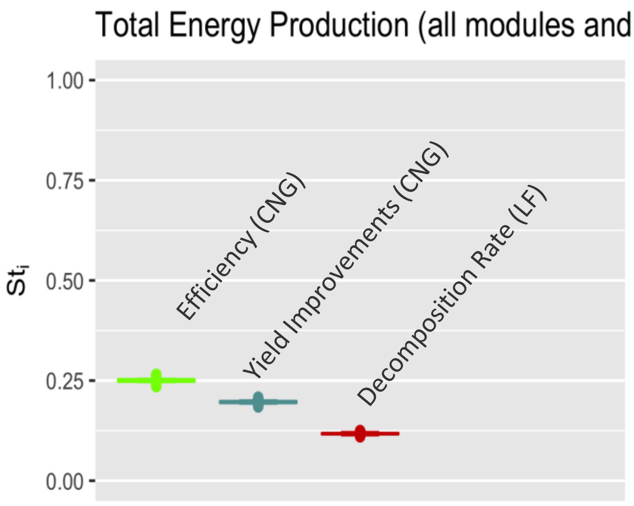
- HTL is attractive for manure and sludge once sufficient demoing has been done
- Maturity is very important for HTL to be attractive in the WTE space b/c the incumbent technologies are proven and mature
- These results are not directional – competitive interactions are present

# Results Among Technologies: CA

| Technology | Model Factor | $S_{ti}$ |
|---|---|---|
| **CHP** | **Conversion Efficiency** | **0.23 a** |
| | **Renewable Elec Credits** | **0.25 a** |
| | **Yield Improvement** | **0.22 a** |
| **CNG** | Conversion Efficiency | 0.15 b |
| | $CH_4$ Recovery | 0.20 b |
| | **On-Site Use** | **0.60 a** |
| **PNG** | Conversion Efficiency | **0.20 b** |
| | **Renewable Elec Credits** | **0.40 a** |
| | Yield Improvement | 0.158 b |
| | $CH_4$ Recovery | 0.15 b |
| **HTL** | Rate of Return | 0.2 c |
| | **Technology Demo.** | 0.80 a |
| | **Comm. Maturity** | **0.68 a** |
| | **Pre-Comm Maturity** | 0.74 a |
| | Learning Rate | 0.45 b |
| **Electricity** | Conversion Efficiency | 0.20 b |
| | **$CH_4$ Recovery** | **0.45 a** |
| | Yield Improvement | 0.18 b |

# ROTUS Results

# Total Effects Results for ROTUS




- CNG is generally the most attractive technology across biogas sources.
  - We assume CNG is only used on-site
  - We assume wholesale NG prices for CNG
  - CNG is eligible for D3 RINS
- In terms of total energy production, process efficiency and yield improvements for CNG are the most influential factors for total energy production from biogas in ROTUS.

# Results Among Biogas Sources: ROTUS

| Biogas Source | Model Factor | $S_{ti}$ |
|---|---|---|
| **POTW** | CNG Conversion Efficiency | 0.12 b |
| | CNG Yield Improvement | 0.08 b |
| | **AD Yield** | **0.60 a** |
| **CAFO** | **Project Delay** | **0.40 a** |
| | CNG Conversion Efficiency | 0.20 b |
| | CNG Yield Improvement | 0.15 b |
| **Landfill** | **CNG Conversion Efficiency** | **0.20 a** |
| | Elec Conversion Efficiency | 0.12 b |
| | CNG Yield Improvement | 0.15 ab |
| | Elec Yield Improvement | 0.10 b |

- Technoeconomic parameters tend to be the most influential determinants of total energy production across biogas sources.
- Our default assumptions for efficiency are conservative and based on current installed capital – not state of the art.
- Likewise, our assumptions for yields are conservative.
    - AD yield ~ 280 $M^3$ $Mg^{-1}$

# Results Among Technologies: ROTUS

| Technology | Model Factor | $S_{ti}$ |
|---|---|---|
| **CHP** | **Conversion Efficiency** | **0.30 a** |
| | **Renewable Elec Credits** | **0.25 a** |
| | **Yield Improvement** | **0.30 a** |
| **CNG** | **Conversion Efficiency** | **0.40 a** |
| | Renewable ID Number Credit | 0.08 d |
| | Yield Improvement | 0.30 b |
| | Renewable Elec Credits | 0.20 c |
| **PNG** | Conversion Efficiency | 0.27 ab |
| | **Renewable Elec Credits** | **0.30 a** |
| | Yield Improvement | 0.23 b |
| **HTL** | Comm. Maturity | 0.85 a |
| **Electricity** | **Conversion Efficiency** | 0.45 a |
| | **Yield Improvement** | 0.40 a |

- Across most technologies, efficiency and process yields are among the most impactful factors.
- For low TRL technologies, the commercial maturity is the single most important factor with regard to maximizing adoption.
- Existing renewable energy policies (RINs and RECs) are also statistically influential.

# Discussion

# Landfills are the Largest Source of Biogas

- Landfills have potential to provide more than 600 $10^6$ MJ of energy from biogas. Electricity is the most promising option, followed by CNG.
- Because the potential energy in landfills is already in the form of biogas, and many of them already have capital installed for biogas capture, very little is needed for low cost, mature technologies to gain broad deployment.
- For landfills, energy production potential between electricity generation and CNG are similar.
- Because electricity and CNG from landfill biogas displace two different fossil fuels (diesel vs natural gas/coal) in two different energy sectors (heavy duty transportation vs electricity for transmission), they respond to very different levers.

# Low TRL Technologies Need Increased Maturity to Become Competitive

- HTL has potential for modest levels of adoption under certain conditions.
- Based on the PNNL design report, the *Nth* plant commercial scale HTL facility can be cost-competitive and reduces the amount of sludge (disposal burden) by more than 90%.
- This study illustrates the importance of industrial learning from demonstration-scale facilities.
- In cases where HTL has modest levels of adoption, the rate of learning, pre-commercial, and commercial maturity is higher than what is in the default model.

# Research and Development Efforts Drive Energy Production from Biogas

- Technical process improvement – process efficiency and yield were important levers in nearly all technologies and across sources of biogas.
- Similarly, anaerobic digester yield is a high-leverage factor for AD-based technologies.
- In addition to R&D, existing policies are influential
  - In this study we did include existing local and federal policies.
  - Credits for renewable energy (RECs, RINs, and LCFS) are high-leverage factors for those pathways that are eligible.

# Conclusions

- The WTE industry has several mature technology options to choose from for conversion of biogas to energy, however the most attractive technology varies by the source of biogas.
- Landfills offer the greatest biogas-to-energy potential. Because most landfills are required to install capture and flare equipment to comply with RCRA (1976) and CAA (1963), the most attractive options are those that require the least amount of additional capital (CNG and Electricity).
  - Also, landfills have an on-site need for CNG as a fuel for their vehicle fleet. This need is expected to expand, which will likely favor more investment in CNG technologies by landfills.
- CAFOs and POTWs are similar because they both have a waste problem, which influences their investment decisions. Anaerobic digestion-based conversion technologies are currently mature and have experienced moderate levels of adoption at both POTWs and CAFOs.
- Although for both CAFOs and POTWs, CNG has the highest maximum production, there are no clear statistical differences among the AD-based technologies assessed (CHP, CNG, PNG, and Elec) in terms of their relative strength of influence on the model's output.

# Conclusions cont.

- Near and mid-term development of commercially mature technologies will result in the greatest energy production, but will not overcome the maturity gap for low TRL technologies.
- Conversely, if large-scale development is delayed long enough that low-TRL technologies have a chance to mature, they could become much more competitive.
  – Their relative yield and efficiency enable them to become attractive investments once their risk and costs decline.