Analysis of Counterfactual Scenario Greenhouse Gas Emissions of Waster Streams for Renewable Natural Gas Production

FWP-155-NJB-1034

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U.S. Department of Energy
National Energy Technology Laboratory
Resource Sustainability Project Review Meeting
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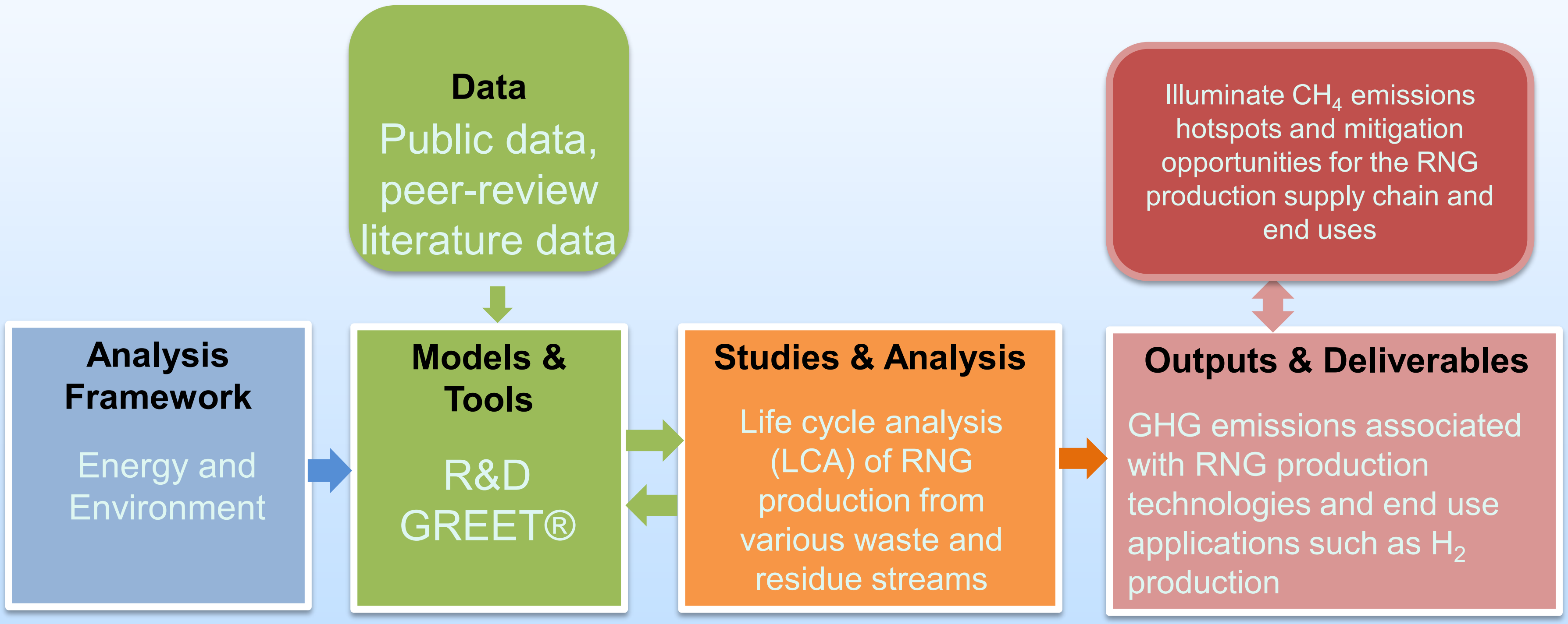
Project Overview

Budget	Barriers Addressed
• FECM Funding for FY24: $150K • Co-funding from HFTO for FY24: $150K	• Inconsistent data, assumptions, and guidelines • Siloed analytical capability and suite of models and tools for evaluating sustainability

Timeline	Partners
• **Start**: March, 2023 • **End**: March, 2025 • **% complete (FY24)**: 50%	• **Project Lead**: Argonne National Laboratory • **Partners**: Industry and university experts

Overall Project Objectives: Evaluate GHG emission implications of RNG production from waste and residue streams

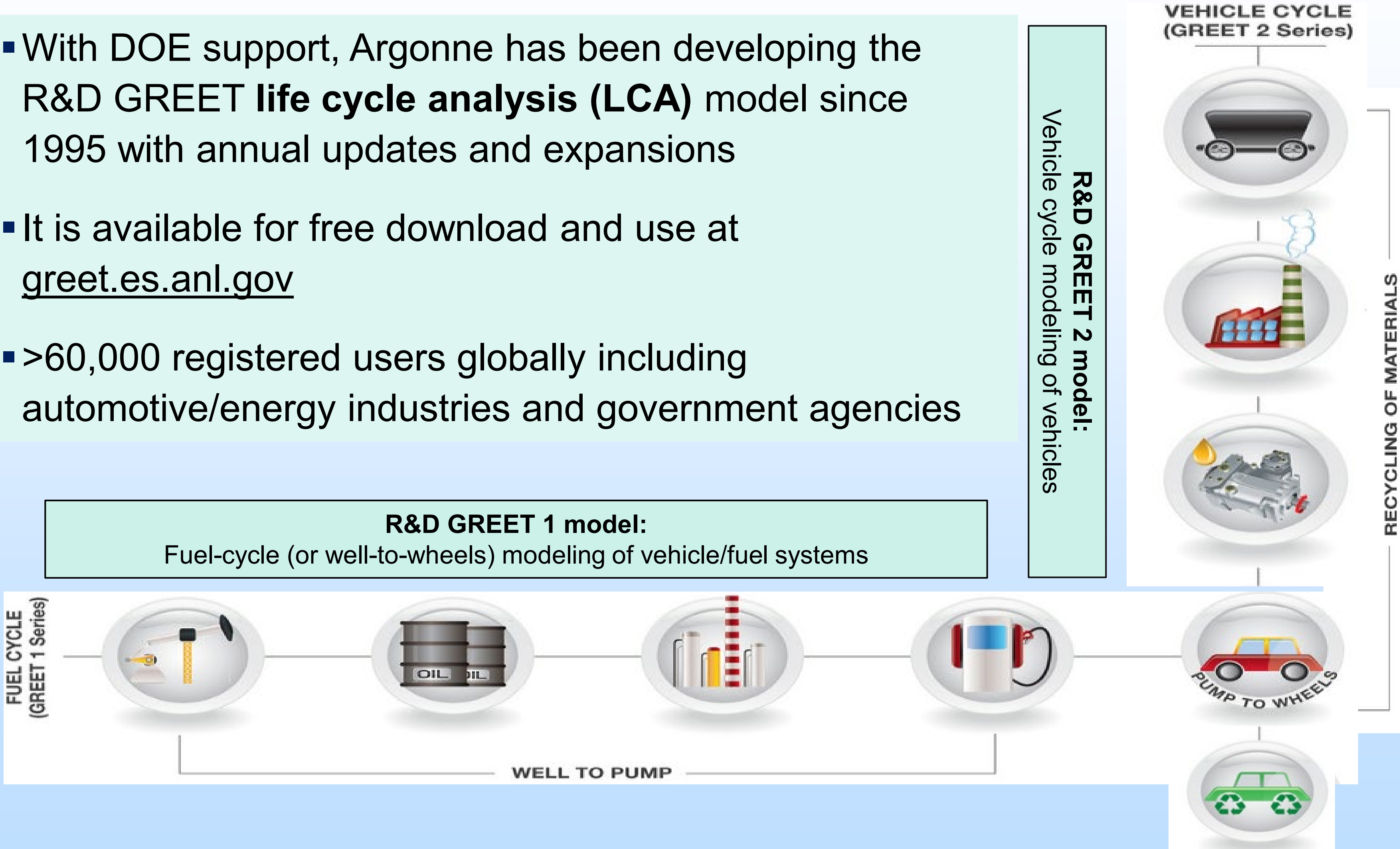


The R&D GREET® (Greenhouse gases, Regulated Emissions, and Energy use in Technologies) model

- With DOE support, Argonne has been developing the R&D GREET **life cycle analysis (LCA)** model since 1995 with annual updates and expansions
- It is available for free download and use at greet.es.anl.gov
- >60,000 registered users globally including automotive/energy industries and government agencies

R&D GREET 1 model:
Fuel-cycle (or well-to-wheels) modeling of vehicle/fuel systems

R&D GREET 2 model:
Vehicle cycle modeling of vehicles



R&D GREET sustainability metrics include energy use, criteria air pollutants, **GHG**, and water consumption

Energy use	Air pollutants	Greenhouse gases	Water consumption
• Total energy: fossil energy and renewable energy • Fossil energy: petroleum, natural gas, and coal • Non-fossil energy: biomass, nuclear energy, hydro-power, wind power, and solar energy	• VOC, CO, NOx, PM_{10}, $PM_{2.5}$, and SOx • Estimated separately for total and urban (a subset of the total) emissions	• CO_2, CH_4, N_2O, black carbon, and albedo • CO_{2e} of the five (with their global warming potentials)	• Addressing water supply and demand (energy-water nexus)
Resource availability and energy security	*Human health and environmental justice*	*Global warming impacts*	*Regional/seasonal water stress impacts*

R&D GREET includes a suite of models and tools

- R&D GREET coverage
  - ✓ R&D GREET1: fuel cycle (or WTW) model of energy systems
  - ✓ R&D GREET2: vehicle manufacturing cycle and material embodied emissions
- Modeling platform
  - ✓ Excel
  - ✓ .net
  - ✓ New Generation of GREET (under development)
- Other GREET derivatives
  - ✓ 45VH2-GREET by IRS based on GREET1
  - ✓ CA-GREET by CARB, based on GREET1
  - ✓ ICAO-GREET by ANL, based on GREET1
  - ✓ China-GREET and MENA-GREET by ANL, with support of Aramco
  - ✓ AFLEET by ANL: alternative-fuel vehicles energy, emissions, and cost estimation

GREET use by agency

United States Government	Production tax credits and clean hydrogen standard under IRA and BIL
California Environmental Protection Agency Air Resources Board	CA-GREET3.0 built based on and uses data from ANL GREET
DEQ State of Oregon Department of Environmental Quality	Oregon Dept of Environ. Quality Clean Fuel Program
EPA	EPA RFS2 used GREET and other sources for LCA of fuel pathways; GHG regulations
NHTSA	National Highway Traffic Safety Administration (NHTSA) fuel economy regulation
ICAO / Federal Aviation Administration	FAA and ICAO AFTF using GREET to evaluate aviation fuel pathways
USDRIVE	GREET was used for the US DRIVE Fuels Working Group Well-to-Wheels Report
MARAD Maritime Administration	LCA of renewable marine fuel options to meet IMO 2020 sulfur regulations for the DOT MARAD
USDA	US Dept of Agriculture: ARS for carbon intensity of farming practices and management; ERS for food environmental footprints; Office of Chief Economist for bioenergy LCA
Government of Canada	Environment and Climate Change Canada for its Clean Fuel Standard

Project Scope

- **Landfill gas**
  - Flaring
  - Active gas collection and controls

- **Municipal solid waste**, including food waste, yard trimmings, corrugated containers, office paper, textiles, etc.
  - Landfill
  - Incineration
  - Composting
  - Anaerobic digestion

- **Animal manure**, including dairy manure, swine manure, cattle manure, etc.
  - Deep pit
  - Anaerobic lagoon
  - Liquid/slurry storage
  - Solid storage
  - Drylot

- **Wastewater sludge**
  - Anaerobic digestion with energy and nutrient recovery
  - Anaerobic digestion without energy or nutrient recovery
  - Landfill
  - Incineration
  - Land application

- **Crop residues** such as corn stover and rice straw
  - Natural decay
  - Prescribed burning
  - Sustainable removal

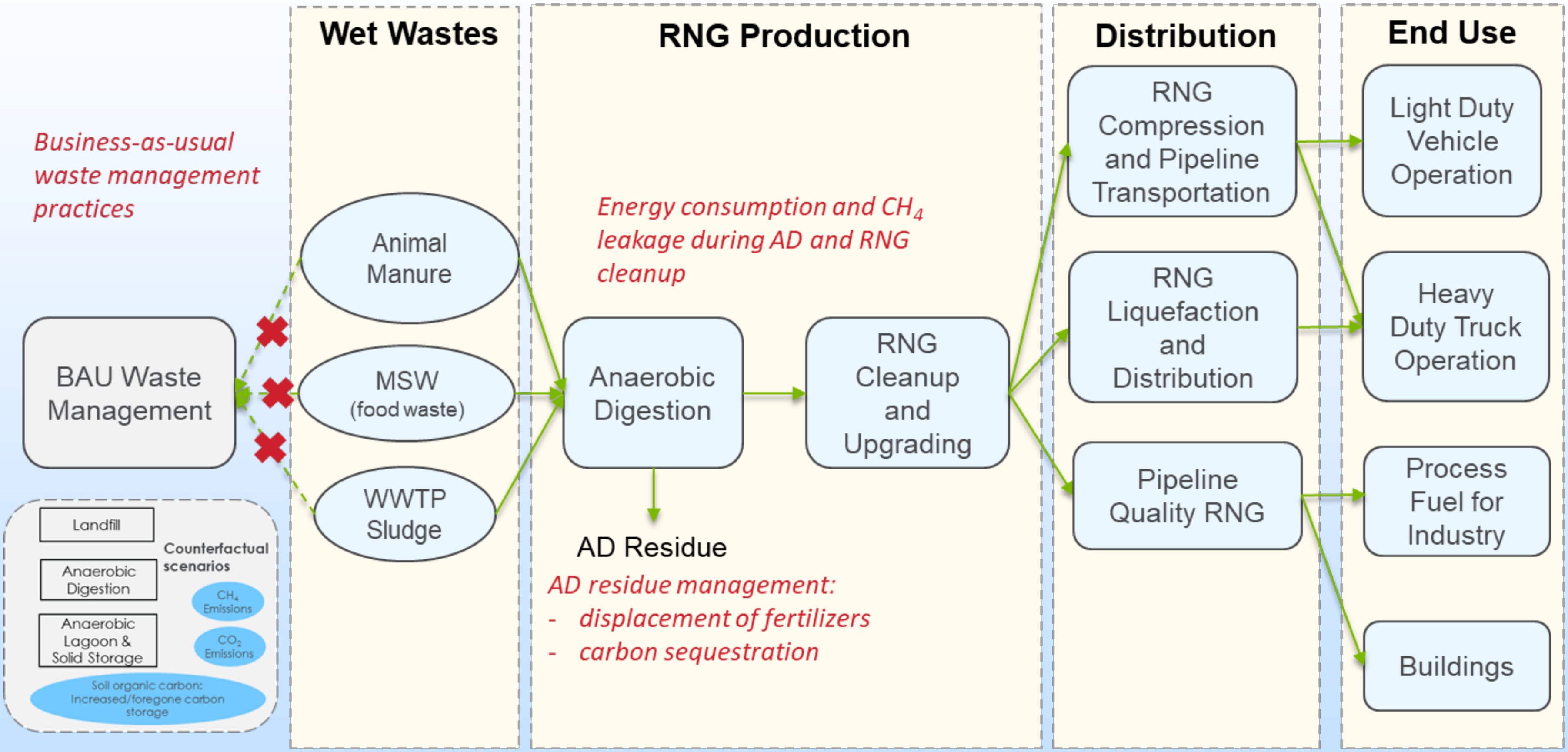
- **Forest residues** including forest thinning
  - Natural decay
  - Prescribed burning
  - Sustainable removal
  - Wildfires

Project Schedule and Milestones

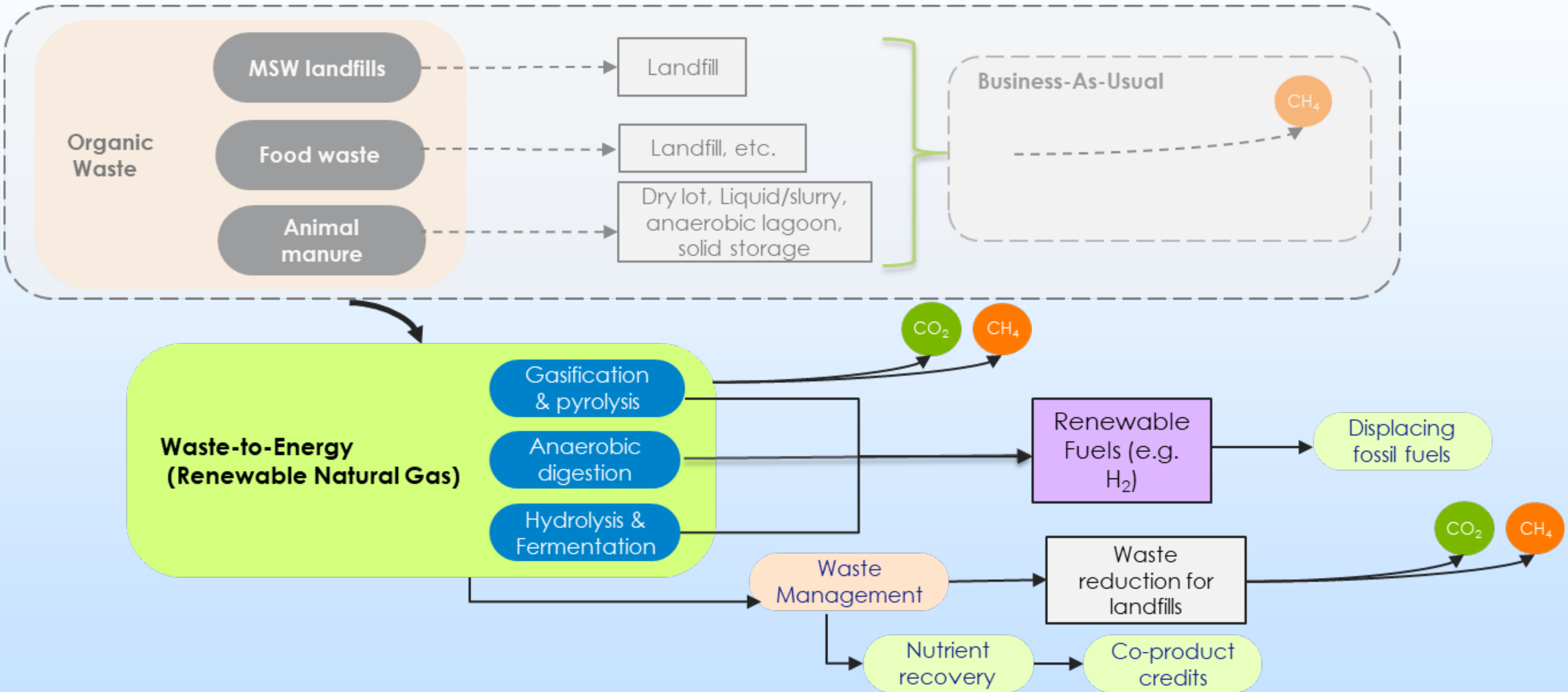
Project Task Structure	FY23			FY24				FY25		Deliverable
	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	
Task 1. Landfill gas counterfactual scenario analysis.										
Milestone 1.1										Type A
Milestone 1.2										Type B
Task 2. Municipal solid waste counterfactual scenario analysis										
Milestone 2.1										Type A
Milestone 2.2										Type B
Annual milestone										Type C
Task 3. Animal manure counterfactual scenario analysis										
Milestone 3.1										Type A
Milestone 3.2										Type B
Task 4. Wastewater sludge counterfactual scenario analysis										
Milestone 4.1										Type A
Milestone 4.2										Type B
Task 5. Crop residues and forest residues										
Milestone 5.1										Type A
Milestone 5.2										Type B
Task 6. GREET Development and Implementation										
Annual milestone										Type C

Deliverable Type A: A quantitative, statistical dataset that summarizes the BAU waste management practices with regional fidelity;
Deliverable Type B: A quantitative analysis of GHG emissions and carbon sequestration effects associated with landfill gas counterfactual scenarios;
Deliverable Type C: A new R&D GREET model that is expanded to include analysis details and results of counterfactual scenarios. Journal submission.

GREET RNG Module



LCA of RNG and Downstream Uses Need to Address Emissions Associated with Business-As-Usual (i.e., Counterfactual Scenarios)

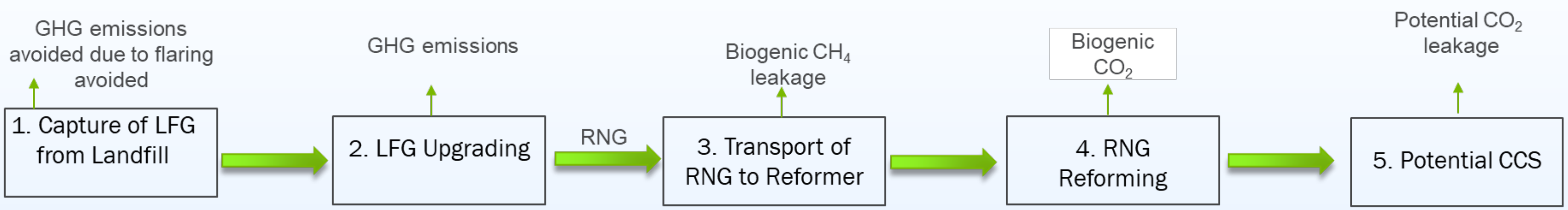


Seq. CO_2: Avoided CO_2 emissions from sequestered carbon; AD: Anaerobic digestion;

Landfill gas-to-RNG & H_2 in R&D GREET

Progress

Key Steps in Landfill Gas (LFG) to H_2 Pathway

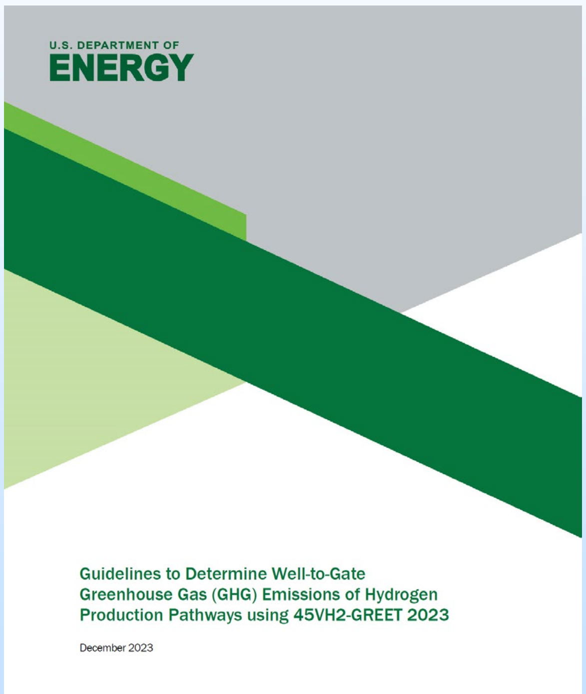


Key Assumptions of LFG Reforming in R&D GREET 2023

Step	Value	Notes
1. Capture of LFG	-0.17 $kgCO_2e/kg\text{-}H_2$	Assumes that all LFG used would otherwise have been flared, but that ~0.2% of LFG is leaked during the flaring process. This results in -1,068 g CO_2e/mmBtu of flared LFG that are considered avoided GHG emissions.
2. LFG Upgrading	3.02 $kgCO_2e/kg\text{-}H_2$	Represents emissions associated with the U.S. average electricity consumption during upgrading of LFG, resulting in a carbon intensity of 19,055 g CO_2e/mmBtu of RNG.
3. Transport of RNG	0.71 $kgCO_2e/kg\text{-}H_2$	Emissions associated with leakage of RNG and RNG compression for transport.
4. RNG reforming	-2.15 : 0.06 $kgCO_2e/kg\text{-}H_2$	Range depends on whether or not steam is co-produced and valorized. Emissions from this step do not include CO_2 emissions onsite, which are comparable to CO_2 emissions that would have been generated by flaring of LFG in Step 1.

- Captured LFG that is currently flared presents an opportunity for being diverted to RNG & H_2 production.
- When captured LFG is diverted to RNG & H_2 production from being flared, it results in a small amount of avoided CH_4 emissions.

Technical Guideline for Landfill Gas-Derived H_2 for 45V Clean Hydrogen Provision Under the IRA


U.S. DEPARTMENT OF
ENERGY

Guidelines to Determine Well-to-Gate Greenhouse Gas (GHG) Emissions of Hydrogen Production Pathways using 45VH2-GREET 2023

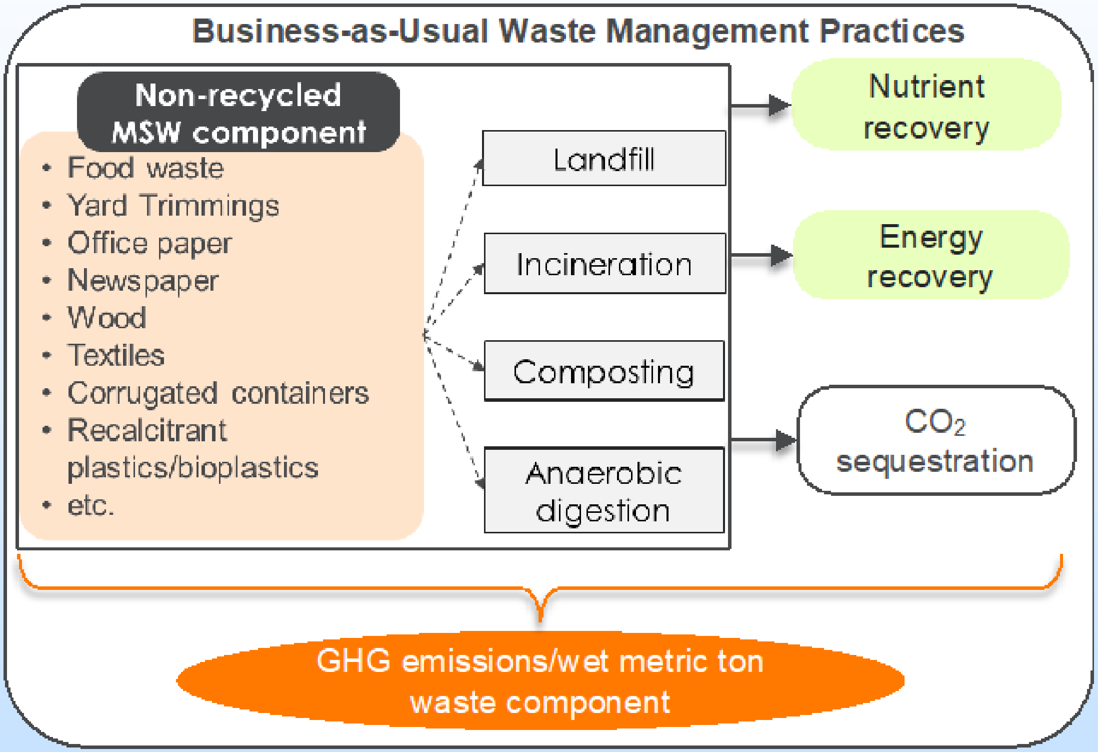
December 2023

2.4.3 Landfill Gas

45VH2-GREET 2023 allows users to simulate reforming of RNG derived from LFG. Background data associated with this pathway includes: (1) avoided emissions associated with the counterfactual scenario, (2) emissions associated with LFG upgrading to produce pipeline-quality gas, and (3) the amount of leakage of RNG during pipeline transport.

45VH2-GREET 2023 assumes that the counterfactual scenario for LFG gas is that the gas being consumed by a reformer would otherwise have been flared. This counterfactual scenario includes estimates of: (a) methane emissions associated with incomplete combustion of LFG during flaring, (b) N_2O emissions associated with LFG flaring, and (c) any other non-CO_2 emissions that result from combustion (e.g., CO). The avoided emissions associated with assumptions (a), (b), and (c) of the counterfactual are estimated at 1,065 g CO_2e/MMBtu of LFG. The CO_2 emissions generated from reforming of LFG are treated as 0, assuming they represent CO_2 emissions that would otherwise have been generated via flaring in the counterfactual. RNG is assumed to be transported to SMR or ATR plants via 680 miles of pipeline transportation.[27]

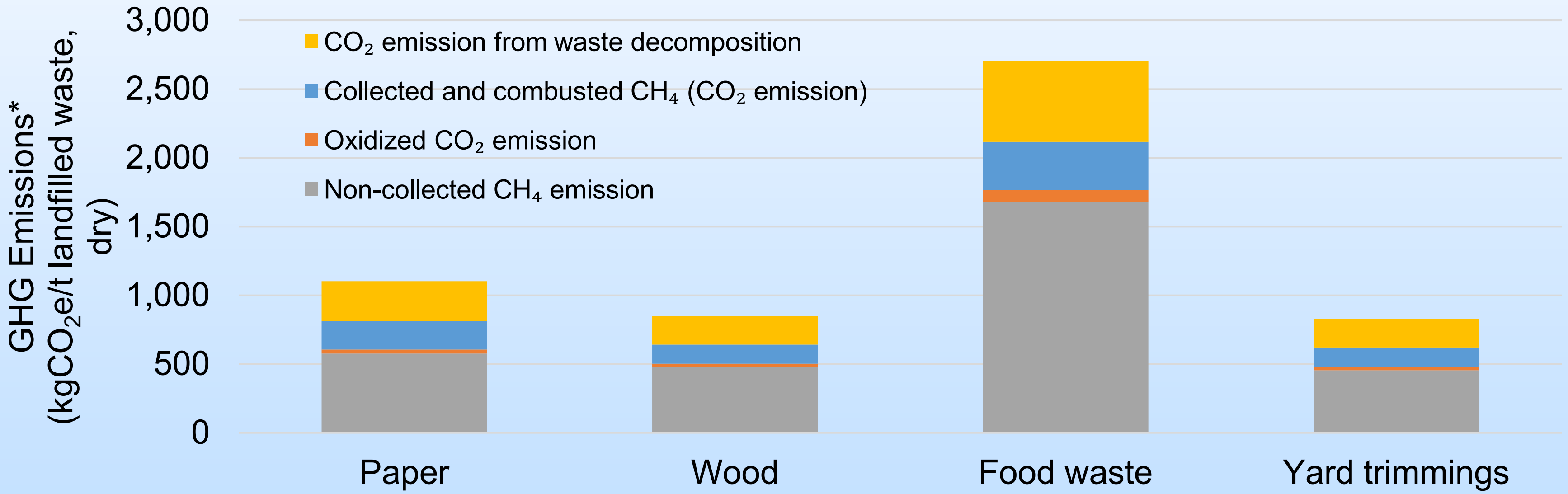
MSW: BAU Management Practices



Waste Type	Waste Material (*i*)	Composition in NRMSW (*%NRMSW$_i$*)	Component-specific % Shares of Waste Management System (*%WMS$_{i,WM}$*)			
			Landfill	Incineration	Composting	AD
Paper and paperboard	Corrugated Containers	0.51%	80%	20%	0%	0%
	Magazines/Third-Class Mail	1.30%	100%	0%	0%	0%
	Newspaper	0.78%	80%	20%	0%	0%
	Office Paper	1.11%	100%	0%	0%	0%
	Phonebooks	0.19%	100%	0%	0%	0%
	Other paper and paperboard	5.51%	71%	29%	0%	0%
Organic waste	Food Waste	27.70%	56%	12%	4%	28%
	Yard Trimmings	15.53%	30%	7%	63%	0%
	Mixed MSW	0.00%	65%	15%	11%	8%
	Wood	6.58%	81%	19%	0%	0%
	Textiles	6.37%	78%	22%	0%	0%
	Rubber/Leather	3.29%	67%	33%	0%	0%
Plastics	Bioplastics, high biodegradable	-	-	-	-	-
	Bioplastics, low biodegradable	-	-	-	-	-
	Fossil-based plastics, recalcitrant					
	HDPE	2.52%	83%	17%	0%	0%
	LDPE	3.61%	83%	17%	0%	0%
	PET	1.89%	83%	17%	0%	0%
	LLDPE	3.61%	83%	17%	0%	0%
	PP	3.55%	83%	17%	0%	0%
	PS	0.98%	83%	17%	0%	0%
	PVC	0.37%	83%	17%	0%	0%
	PLA	0.04%	-	-	-	-
	Other plastics	1.34%	83%	17%	0%	0%
Glass	Glass, beer and soft drink bottles	1.23%	80%	20%	0%	0%
	Glass, wine and liquor bottles	0.48%	81%	19%	0%	0%
	Glass, other bottles and jars	1.24%	81%	19%	0%	0%
	Glass, other durable goods	1.08%	87%	13%	0%	0%
	Miscellaneous Inorganic	1.79%	80%	20%	0%	0%
Metal	Steel	5.63%	82%	18%	0%	0%
	Aluminum	1.41%	83%	17%	0%	0%
	Non-ferrous	0.36%	90%	10%	0%	0%

Landfill Specific Parameters Are Developed to Estimate Avoided LFG Emissions for Specific MSW Components

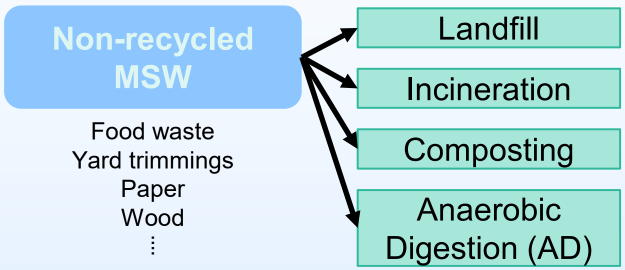
- Due to significant variations in landfill conditions and operations, setting an appropriate BAU which diverts waste from is critically important.

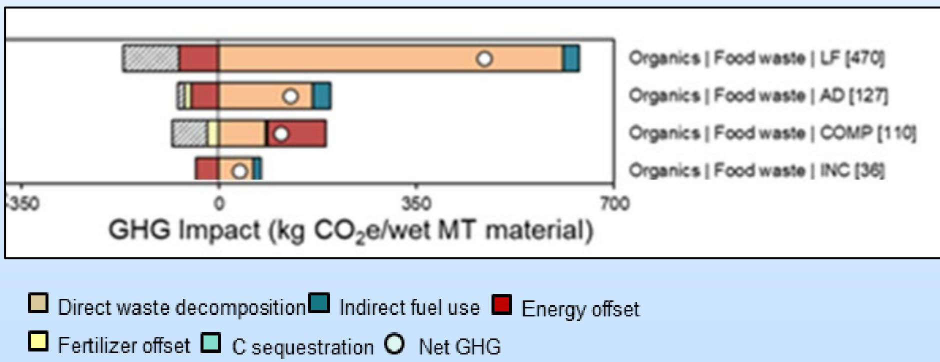


* This figure does not present biogenic carbon uptake, but only shows LFG emissions

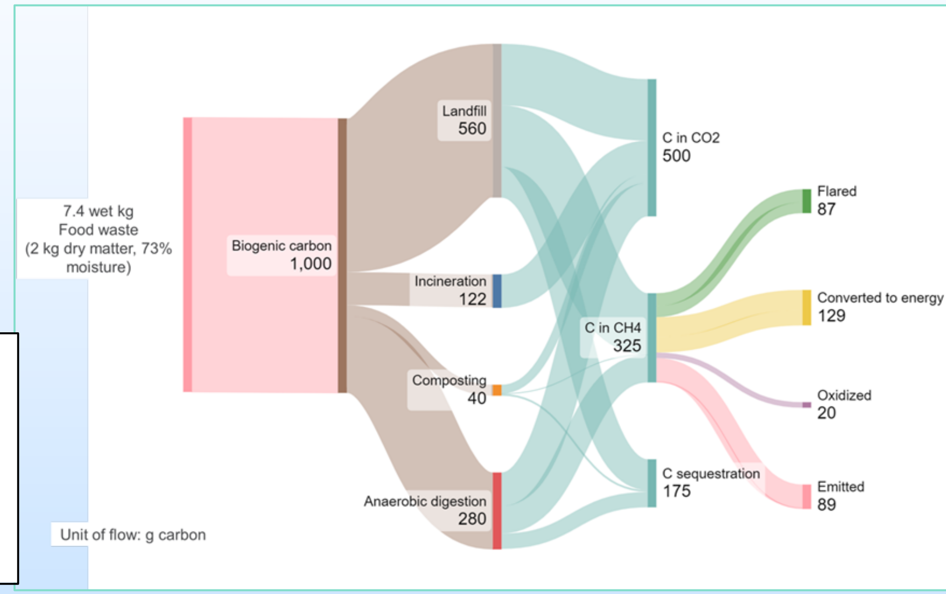
GHG emissions of food waste management

Evaluated the impact of four major BAU MSW management practices at the component level





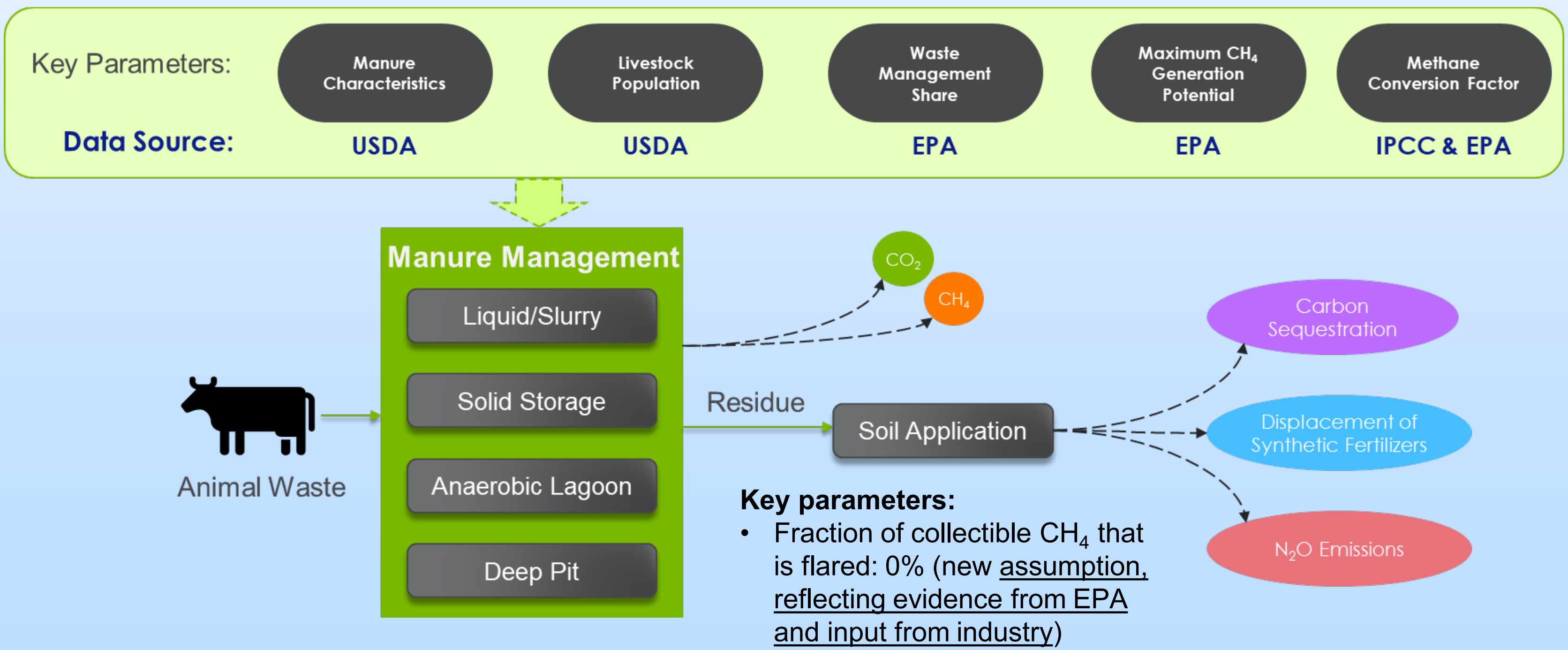
Carbon balance for average U.S. food waste management



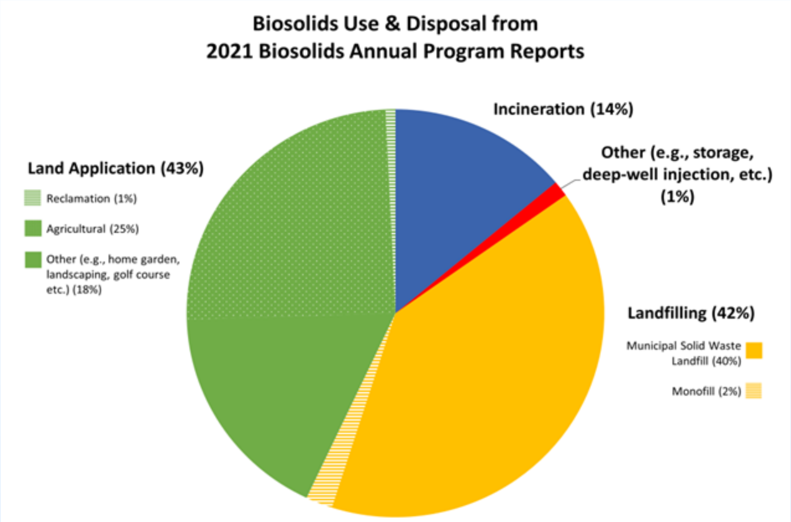
Operational conditions, regional parameters, and waste feedstock characteristics contribute to variation in GHG emissions from managing food waste via landfilling, anaerobic digestion, composting, or incineration.

Methane Emissions from Animal Manure Management in R&D GREET

- R&D GREET models the emissions from business-as-usual (BAU) management of animal manure
  - Beef, dairy cow, dairy heifer, swine, layer, and broiler and turkey
- R&D GREET utilizes multiple data sources to estimate the emissions from animal waste management
- The BAU emissions are avoided when animal manure is diverted to bioenergy production, thus generating GHG credits for the bioenergy products (e.g., hydrogen)



Wastewater Sludge: BAU Management Practices



Wastewater flow and technology share by plant size

(Data from EPA Clean Watersheds Needs Survey)

WWTP Size (MGD)	Number of plants	Total Flow (MGD)	Technology share (Landfill / AD / Incineration / Others)
<1	11,264	2,256	100%
1~5	2,612	5,792	89% / 11%
5~10	556	3,785	59% / 38% / 3%
10~20	294	4,062	41% / 52% / 7%
20~50	180	5,262	19% / 60% / 20%
50~75	29	1,755	14% / 83% / 3%
75~100	33	2,837	9% / 81% / 10%
100~200	26	3,863	10% / 61% / 29%
>200	14	4,756	12% / 84% / 4%

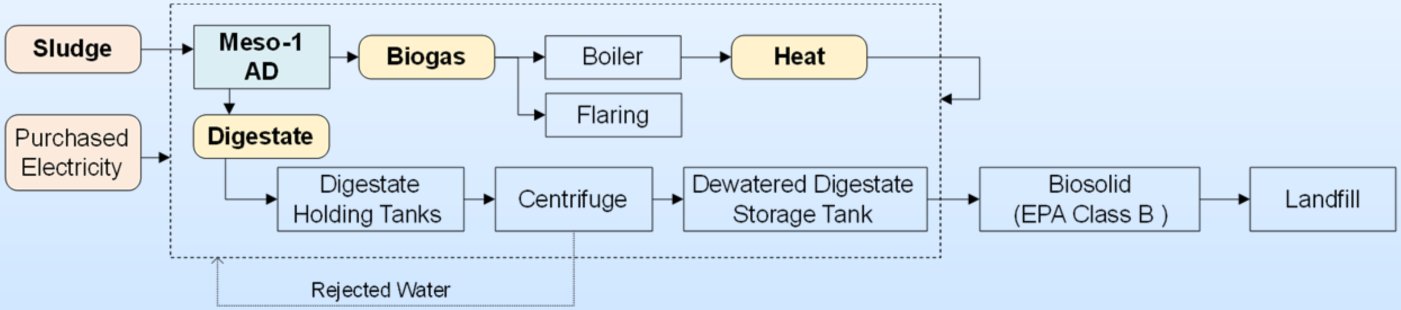
0% 50% 100%

Major practices/end use scenarios:

- **Landfill (42%)**
- **Incineration (14%)**
- **Land application (43%)**: *for biosolids after Anaerobic digestion (AD)*

Wastewater Sludge: BAU Management Practices

- **Anaerobic digestion (AD)**
  - Key assumptions of *Single-stage mesophilic AD*
    - *Biogas yield from AD provides the onsite thermal demand; excess biogas is flared*
    - *Purchased grid electricity to satisfy electricity demand*



Flow diagram for counterfactual scenario of sewage sludge AD treatment in GREET

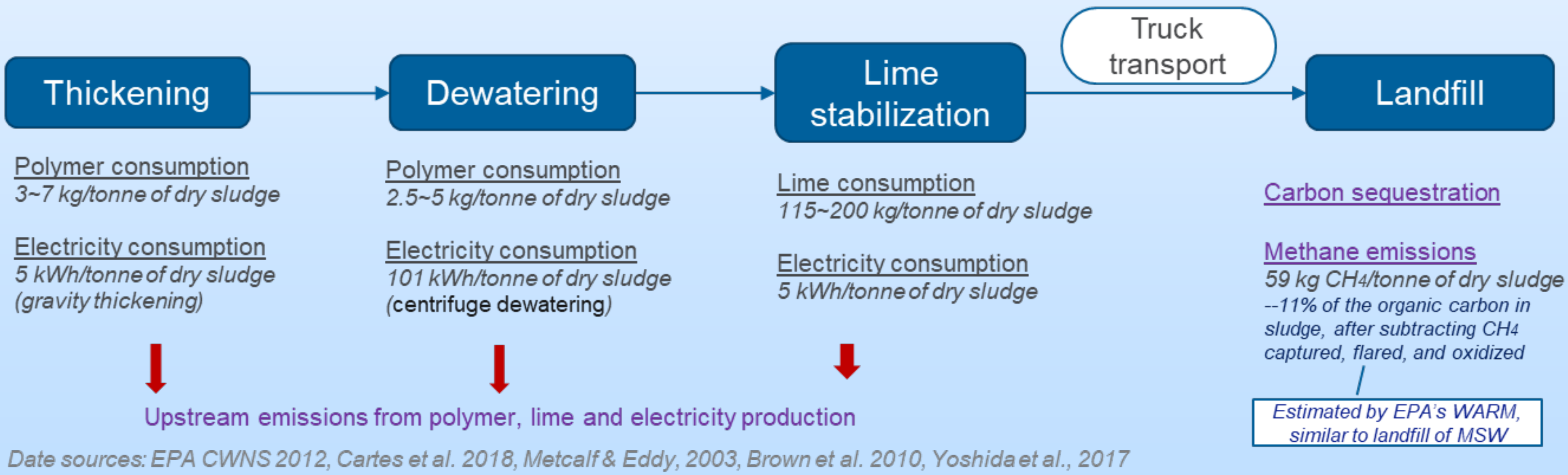
GHG emissions of the default BAU scenario: 405 g CO_2e/kg VS (volatile solid in sludge):

- *Electricity consumption: 120 g CO_2e/kg VS*
- *Biogenic methane leakage (1%): 509 g CO_2e/kg VS*
- *Carbon sequestration: -226 g CO_2e/kg VS*

Wastewater Sludge: BAU Management Practices

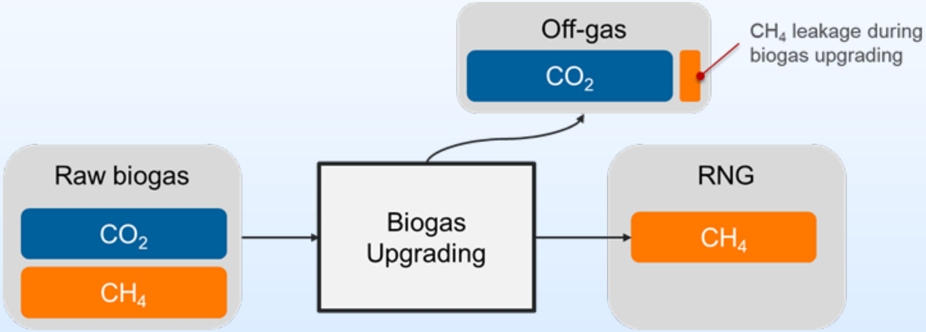
- **Landfill**
  - Small-scale WWTPs, with flow rates below 1 MGD, typically use landfill for treatment
  - Co-filled with municipal solid waste (MSW): 95%
  - 4% of the landfilled sludge is treated with electricity generation during the process

Typical technique processes for wastewater sludge landfill:



Methane Leakage from Biogas Upgrading

- **Raw biogas produced from AD contains CH_4 and CO_2**
- **CO_2 is separated in raw biogas upgrading to increase the CH_4 concentration**
- **In biogas upgrading, a fraction of CH_4 ends up in off-gas, leading to CH_4 loss**
- **CH_4 loss rate mainly depends on the separation technology:**
  - Pressure swing adsorption (PSA)
  - Water scrubber
  - Chemical (amine) scrubber
  - Membrane

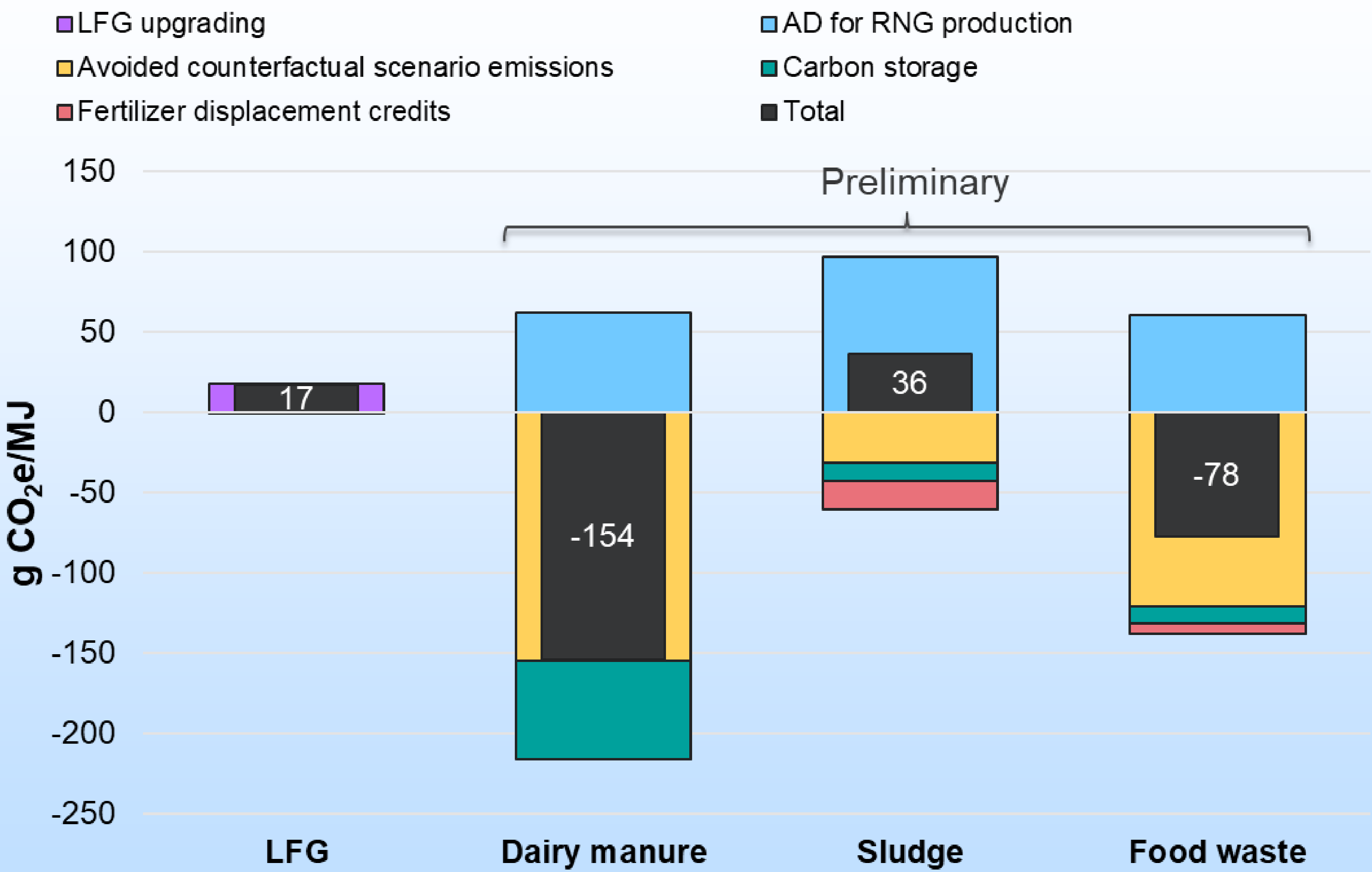


CH_4 loss rates (% of the total production) varies according to the biogas

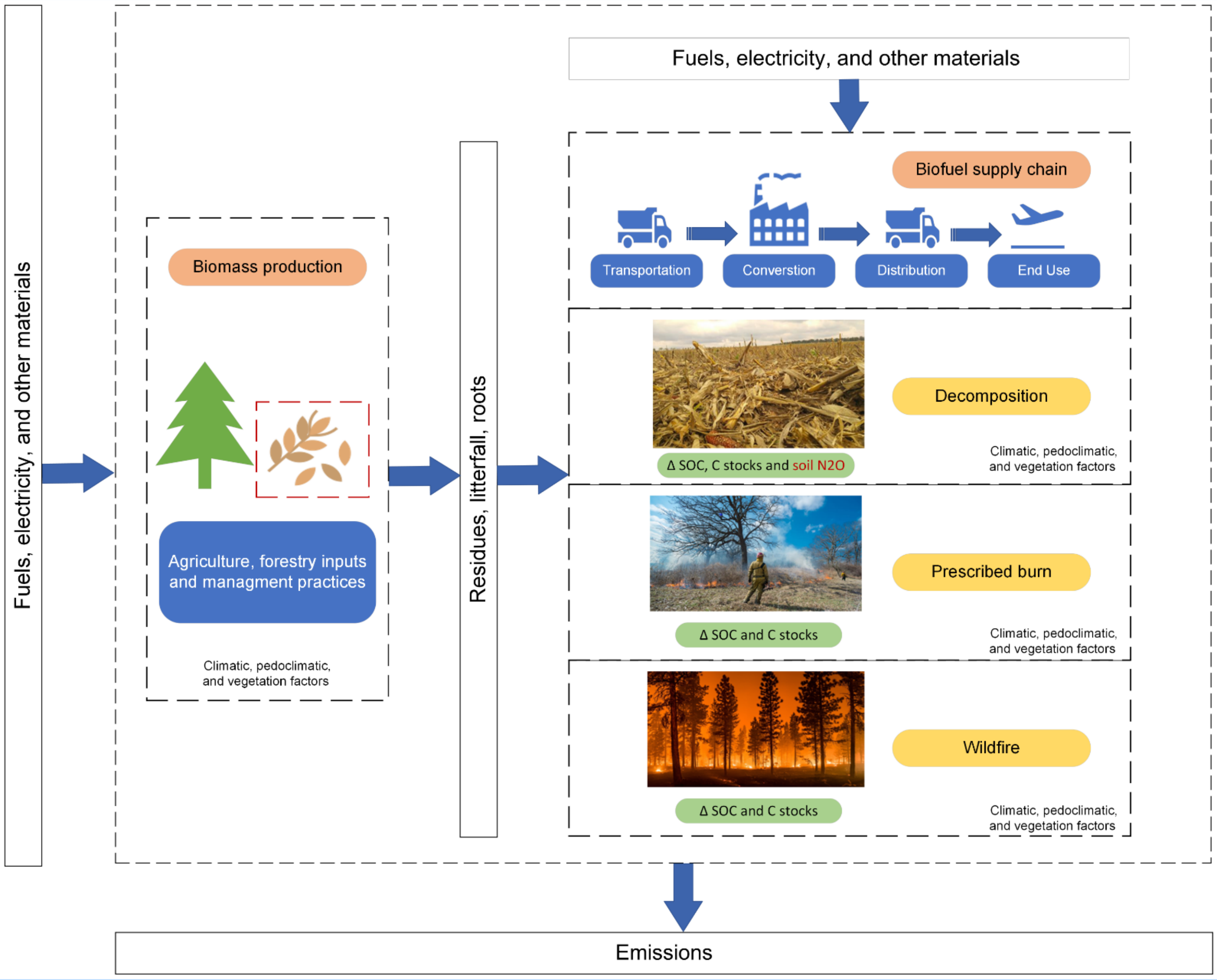
	25th percentile	**Median**	**75th percentile**
PSA	0.008	0.13	1.50
Chemical scrubber	0.09	0.14	0.60
Water scrubber	1.29	1.97	2.09
Membrane	0.33	0.36	0.46

Values in the table were from Bakkaloglu et al., 2022

Carbon Intensities of Waste-to-RNG



Next Steps: Counterfactual Scenarios of Crop/Forest Residues



Advance R&D GREET LCA and Applications

- ❑ Perform life cycle performance of current and emerging technologies to present their value proposition and inform R&D and business decisions by stakeholders
- ❑ Build LCA modeling capacity for DOE, other agencies, and R&D community
- ❑ Use a consistent LCA platform with reliable, widely accepted methods/protocols
- ❑ Conduct detailed LCA and to document data sources, modeling and analysis approaches, and results/conclusions
- ❑ Maintain openness and transparency of LCA by making R&D GREET, its data, and publications publicly available

Outreach and Workforce Development Efforts or Achievements

- Outreach
  - Engaged RNG producers and stakeholders to vet and validate key assumptions;
  - Engaged industry such as wastewater treatment plants and MSW-based electricity producers to vet and validate key assumptions regarding management practices, energy consumption, and emission implications;

- Workforce Development
  - Hired two postdocs;
  - Hired two summer intern students;
  - Hosted one visiting professor from a HBCU (Prairie View A&M University) via DOE's Visiting Faculty Program is from HB
  - Provided RNG stakeholders with a GREET training in an in-person user workshop

Summary Slide

- **Expansion of the R&D GREET model for annual release on 12/21/2023.**
  - Completed ***landfill gas (LFG)*** counterfactual scenario analysis
  - Completed counterfactual scenario analysis of ***municipal solid waste (MSW)***
    - We developed a comprehensive MSW counterfactual scenario analysis module in the 2023 R&D GREET model and connected it to downstream RNG and renewable energy production technologies that use specific components of MSW as a feedstock.
  - Addressed several key issues in counterfactual scenario analysis of ***animal waste/manure***
  - Addressed several key issues in counterfactual scenario analysis of ***wastewater sludge***

- **Improve analysis fidelity and building consensus of key assumptions and results among key stakeholders**

- The outcome of this effort directly supports the development of the **tax credit version of the GREET model for 45V Clean Hydrogen Provision under the Inflation Reduction Act (called 45VH2-GREET, released to public last December**).

- The on-going analysis effort and outcome will continue to advance R&D GREET development and inform broad applications including policy (e.g., 45Z).

Organization Chart: Argonne's Systems Assessment Center Leads This Effort

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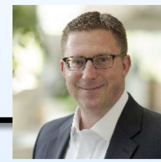

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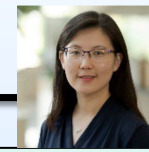

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- Md Rakibul Alam (postdoc)
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- Joseph Braun (AA)
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- Rodrigo Buitrago Tello (postdoc)
- Jose Hernandez (postdoc)
- Tom Sykora (C)

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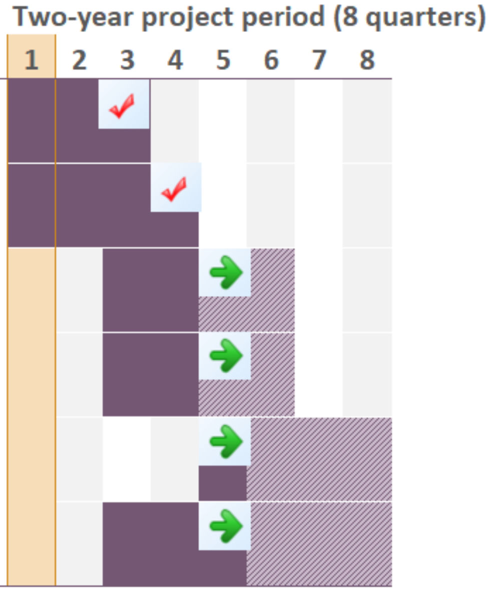
- HFTO;
- Industry stakeholders;
- Student interns (Kristina Merino of UFL and Matthew Sheely of the University of Alabama).

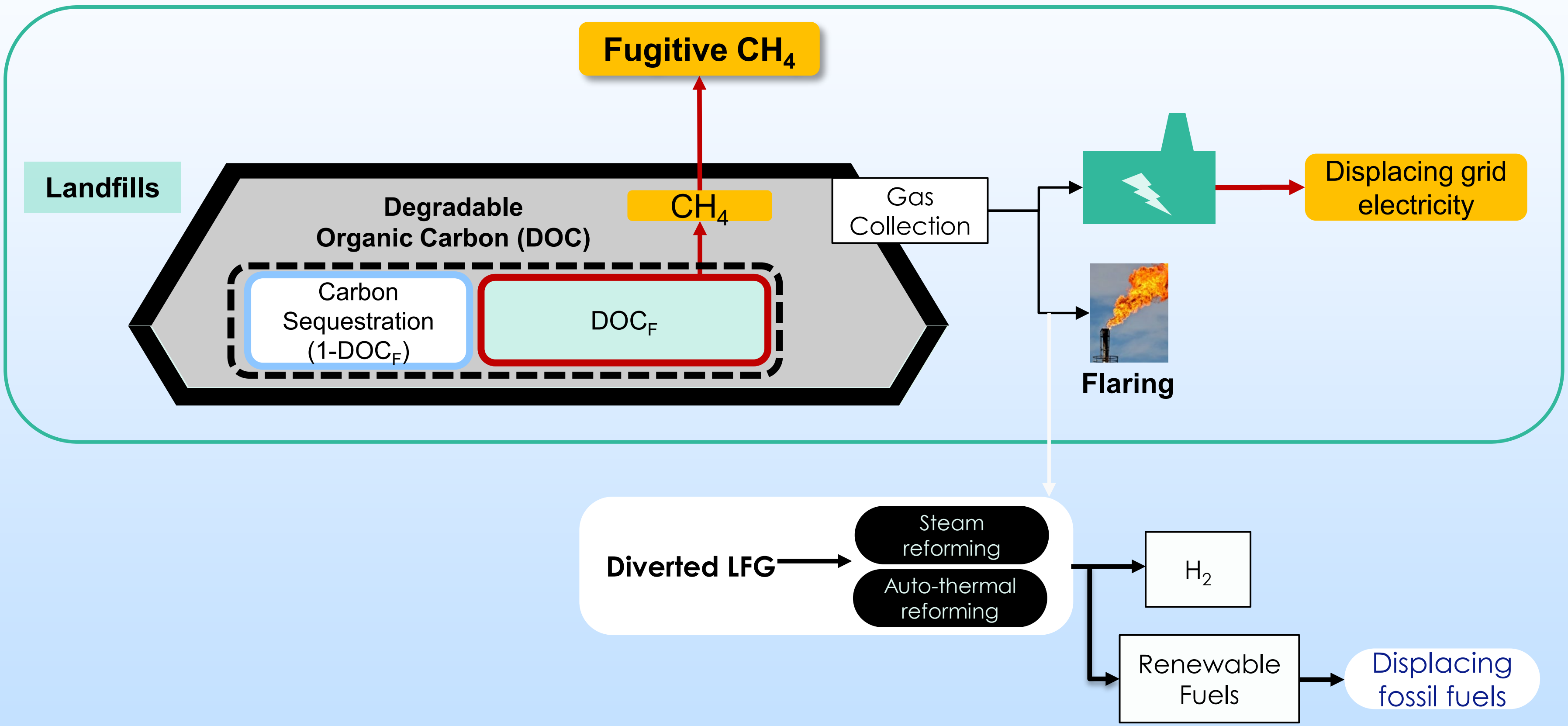
Gantt Chart

Tasks	PLAN START	PLAN DURATION	PERCENT COMPLETE
Task 1. Landfill gas counterfactual scenario analysis	1	3	100%
Task 2. Municipal solid waste counterfactual scenario analysis	1	4	100%
Task 3. Animal manure counterfactual scenario analysis	3	4	70%
Task 4. Wastewater sludge counterfactual scenario analysis	3	4	60%
Task 5. Crop residues and forest residues	5	4	15%
Task 6. GREET Development and Implementation	3	6	59%

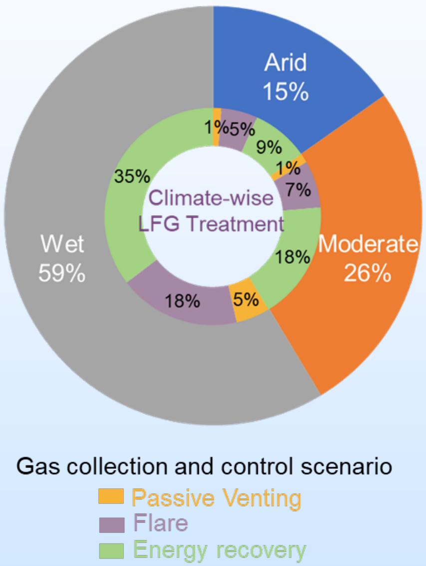


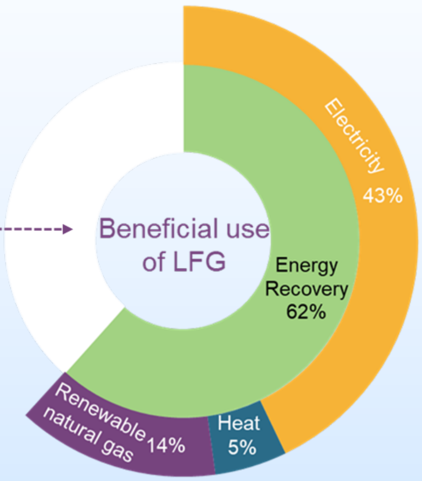
Appendix

Landfills: CH_4 emissions and mitigation approaches



Landfill Gas Collection and Control



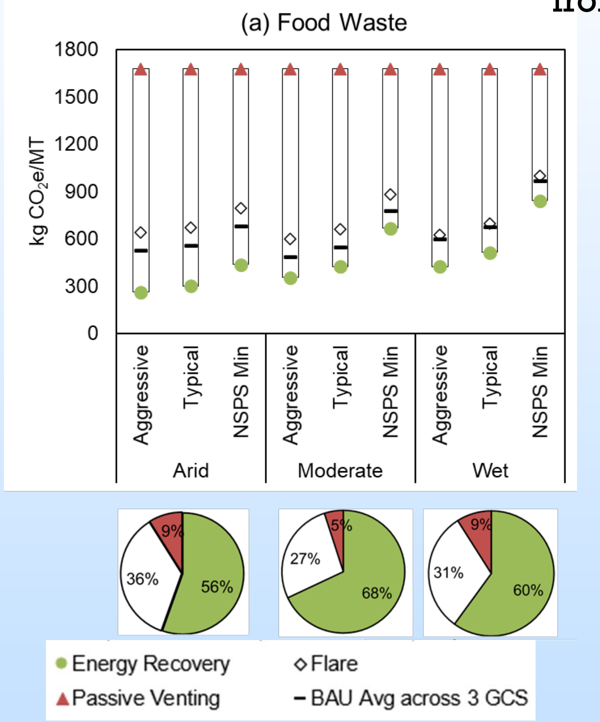


Wang et al., 2024 (to be submitted shortly)

- LFG collection efficiency is affected by climate region, gas treatment scenario, and gas collection schedules.
  - Climate: arid, moderate, and wet (affecting waste decay rate and how gas is effectively collected)
  - Gas treatment scenario: no gas collection (or passive venting), flare, and energy recovery
  - Gas collection schedule: aggressive, typical, and clean air act minimum
- Beneficial use of collected LFG: displacement credits from foregone electricity, heat, and RNG production

Scenario Analysis for Landfilling Food Waste

Impact of climate, gas treatment scenario, and gas collection schedule on the GHG impact from landfilling food waste

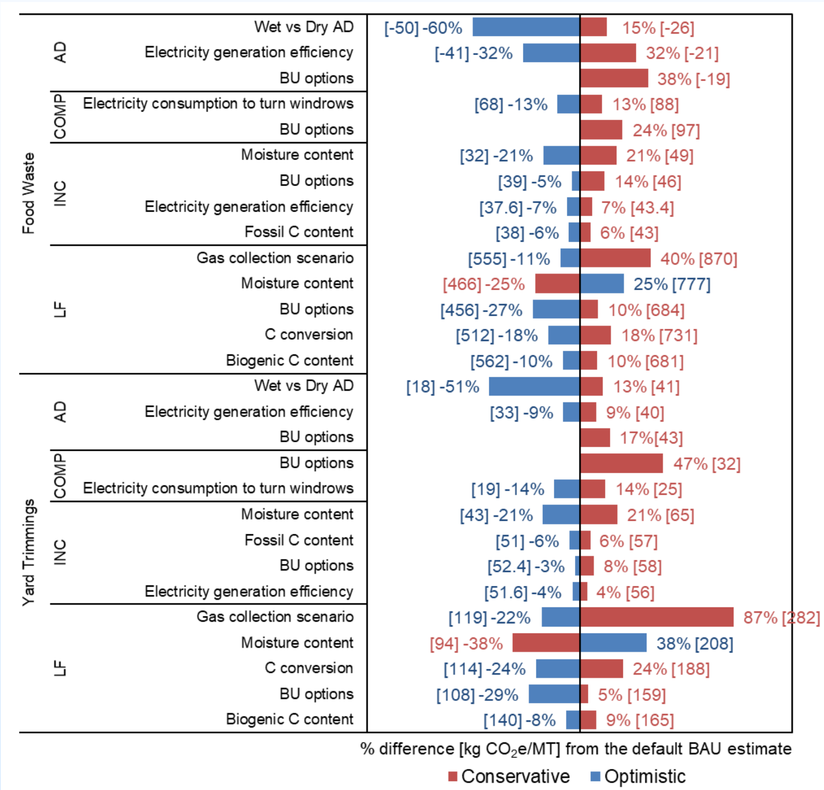


Wang et al., 2024 (to be submitted shortly)

Landfills located in wet regions could be prioritized to improve food waste diversion strategies.

- Waste disposal in a wetter landfill with a gas collection system (GCS) in place leads to the higher GHG emissions than in an arid landfill because majority of the fugitive CH_4 emissions are released before gas collection system is scheduled in place.
- The Aggressive gas collection allows the earlier and longer gas collection to have more LFG captured so can reduce GHG emissions
- Energy recovery scenarios can reduce GHG impacts by 16 - 130% and 50 -110% compared to flare and passive venting scenarios.

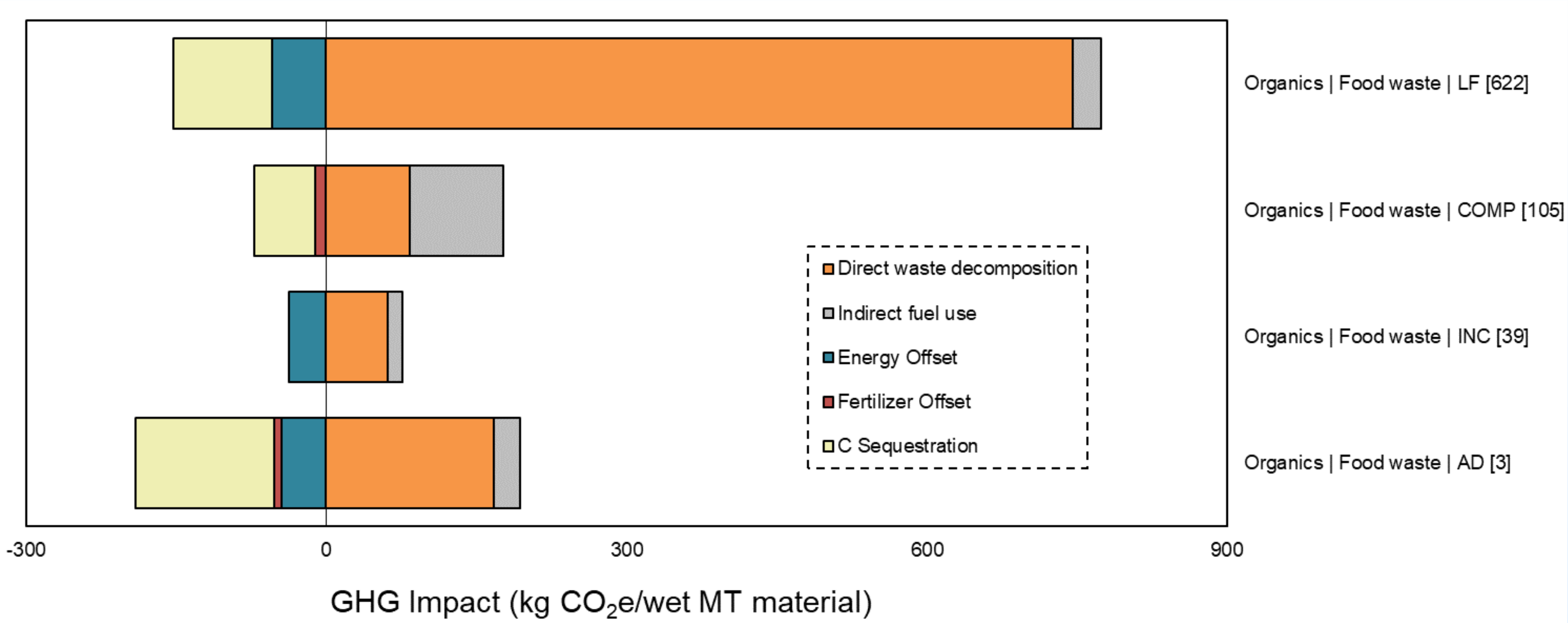
Sensitivity Analysis



- What are the most critical factors that drive the GHG impact for each component in each management practice?
- By how much?

Wang et al., 2024 (to be submitted shortly)

GHG Impact of Food Waste Management



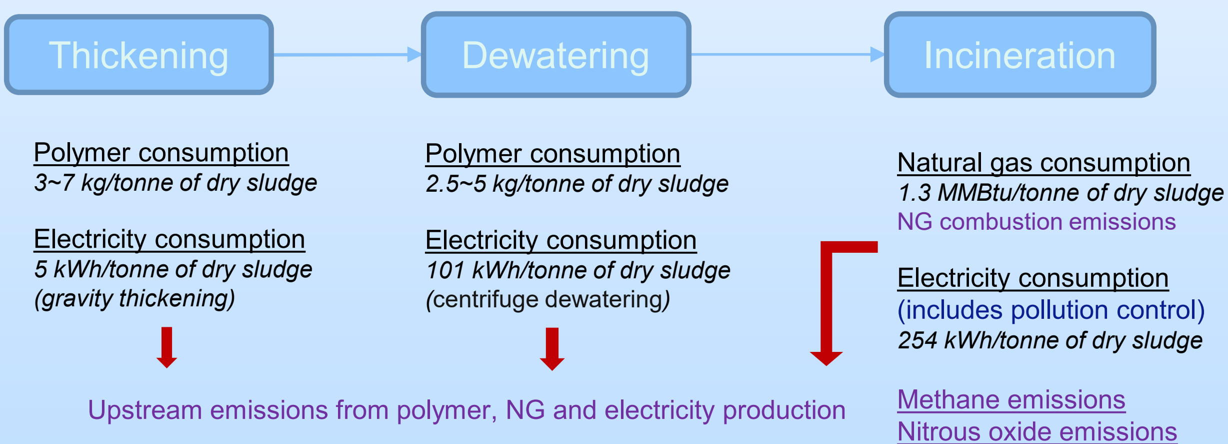
Wang et al., 2024 (to be submitted shortly)

- Landfilling has the largest GHG impact due to great landfill CH_4 emissions from waste biodegradation
- The GHG impact from high biodegradability is greater than the credits from carbon sequestration and energy offset

BAU Wastewater Sludge Management Practices

- **Incineration**
  - Compared to landfill, incineration is generally applied in larger sewage plants.
  - Two types of incineration technologies: *Multiple-hearth incineration (63%); Fluidized bed incineration (37%)*
  - Less than 2% of the incinerated sludge is treated with electricity generation during the process

Typical technique processes for wastewater sludge Incineration:



Date sources: EPA CWNS 2012, Cartes et al. 2018, Metcalf & Eddy, 2003, Brown et al. 2010, Yoshida et al., 2017