Systems Analysis on Biomass Gasification to Carbon-Negative Hydrogen

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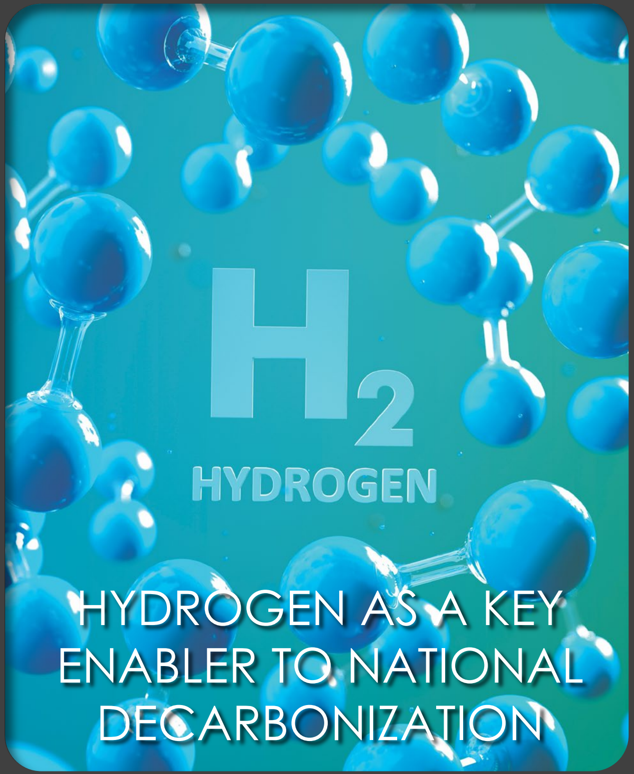


Carbon-Negative Hydrogen Workshop – Golden, CO

June 22nd, 2023

Presentation Outline

- Overview of the NETL Hydrogen Production Baseline Study
  - Ongoing, follow-up analysis activities
- Review of LCA for biomass to Renewable Natural Gas (RNG)
- Alternative biomass to hydrogen strategies for carbon negative hydrogen production

Recent H_2 Production Study Publication

NATIONAL ENERGY TECHNOLOGY LABORATORY

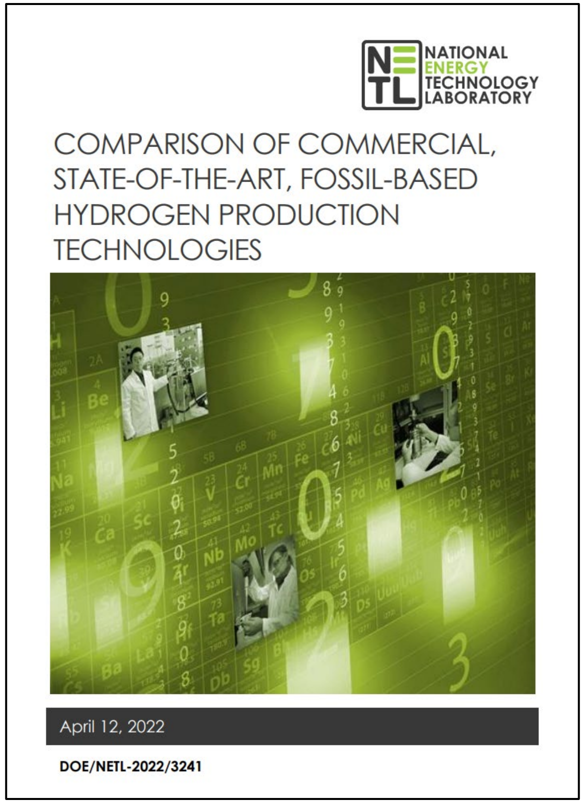
NETL has published a combined techno-economic (TEA) and life cycle analysis (LCA) of commercial, state-of-the-art fossil-based H_2 production technologies[1,2]

Justification

- This TEA/LCA of fossil-to-H_2 production routes using current, commercial technologies provides a basis for DOE FECM R&D program planning to reduce the levelized cost of hydrogen (LCOH) and greenhouse gas (GHG) footprint of future fossil-to-H_2 plants

Objectives

- Develop a reference study of H_2 production technologies using current, commercial technologies[1] with emphasis on coal gasification, co-gasification of coal with an alternative feedstock, and NG technologies using the LCOH (2018 $/kg) as the figure of merit
- Identify areas of R&D to further improve the performance and cost of fossil fuel-based H_2 production, including follow-on analyses


NATIONAL ENERGY TECHNOLOGY LABORATORY

COMPARISON OF COMMERCIAL, STATE-OF-THE-ART, FOSSIL-BASED HYDROGEN PRODUCTION TECHNOLOGIES

April 12, 2022

DOE/NETL-2022/3241

U.S. DEPARTMENT OF ENERGY

[1]Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies, DOE/NETL-2022/3241, April 12, 2022
https://netl.doe.gov/energy-analysis/details?id=ed4825aa-8f04-4df7-abef-60e564f636c9
[2]Funding provided by the DOE Office of Fossil Energy and Carbon Management (FECM)

Study Summary

Case Selection

Case[A]	Plant Type	Feedstock(s)	Reformer Type	Gasifier Type	CO_2 Capture (%)	H_2 Purification	H_2 Production Capacity
1	Reforming	Natural Gas	SMR	-	0	PSA	200 MMSCFD 483,000 kg/day 44,400 lb/hr
2					96.2		
3			ATR		94.5		274 MMSCFD 660,000 kg/day 60,600 lb/hr
4	Gasification	Illinois No. 6 Coal	-	Shell[B]	0		
5					92.5		
6		Illinois No. 6 Coal/Torrefied Woody Biomass			92.6		55 MMSCFD 133,000 kg/day 12,200 lb/hr

[A] Gasification plants are assumed to operate at 80 percent capacity factor and are located at a generic plant site in the midwestern United States.
[B] The Shell gasifier has been used in multiple prior NETL studies. As of May 2018, Air Products has acquired the coal gasification technology licensing business from Shell. To be consistent with prior NETL studies and avoid confusion, the gasifier is labeled the "Shell" gasifier.

Literature Review

Primary Findings

- **H_2 from alternative feedstocks (e.g., biomass, MSW)**
  - No currently operating commercial alternative feedstock gasification facilities producing high-purity H_2 as an end product
    - A few are planned or on hold
    - One produces H_2 as a precursor to ammonia (Showa Denko)
  - Buggenum IGCC (coal/biomass co-gasification - decommissioned) and Eastman Kingsport (coal/waste plastics) are the only examples of commercially operating facilities to co-gasify coal with an alternative feedstock
    - Neither produces H_2 as an end-product

Key Assumptions

Solid Feedstock Characteristics

Rank	Bituminous[1]	
Seam	Illinois No. 6	
Source	-	
Proximate Analysis (weight %)[A]		
	As Received	Dry
Moisture	11.12	0.00
Ash	9.70	10.91
Volatile Matter	34.99	39.37
Fixed Carbon	44.19	49.72
Total	100.00	100.00
Sulfur	2.51	2.82
HHV, kJ/kg (Btu/lb)	27,113 (11,666)	30,506 (13,126)
LHV, kJ/kg (Btu/lb)	26,151 (11,252)	29,444 (12,712)
Ultimate Analysis (weight %)		
	As Received	Dry
Moisture	11.12	0.00
Carbon	63.75	71.72
Hydrogen	4.50	5.06
Nitrogen	1.25	1.41
Chlorine	0.15	0.17
Sulfur	2.51	2.82
Ash	9.70	10.91
Oxygen[B]	7.02	7.91
Total	100.00	100.00

Torrefied Woody Biomass		
	As Received	Dry
Ultimate Analysis (weight %)		
Moisture	5.72	0.00
Carbon	59.89	63.52
Hydrogen	5.11	5.42
Nitrogen	0.41	0.44
Chlorine	0.00	0.00
Sulfur	0.00	0.00
Ash	0.51	0.54
Oxygen	28.36	30.08
Total	**100.00**	**100.00**
Heating Value		
HHV (Btu/lb)	9,749	10,340
LHV (Btu/lb)	9,203	9,825

[A] The proximate analysis assumes sulfur as volatile matter
[B] By difference

Key Assumptions

Plant Design Basis and Economics

- Delivered coal, biomass, and NG costs are consistent with current NETL QGESS methodology1.
  - Biomass costs calculated using an existing NETL model that considers centralized production of the design feedstock and distribution to the H2 plant
- Plants are in an attainment area, and include Best Available Control Technologies for emissions, per New Source Review
- The hydrogen product is 99.9% pure and compressed to 6.4 MPa (925 psig) for pipeline injection, with contaminant levels consistent with ammonia-grade hydrogen to avoid catalyst poisoning
- No revenues generated from the sale of air gases (e.g., N2, Ar), steam, or pipelined CO2.
- No CO2 emissions penalties, tax credits for CCS (e.g., 45Q) or clean H2 production (e.g., 45V) are included
- Sensitivity analyses quantify the economic impact from several of these factors

[1]Quality Guidelines for Energy System Studies: Fuel Prices for Selected Feedstocks in NETL Studies (Program Document) | OSTI.GOV

Key Assumptions

Life Cycle Emissions

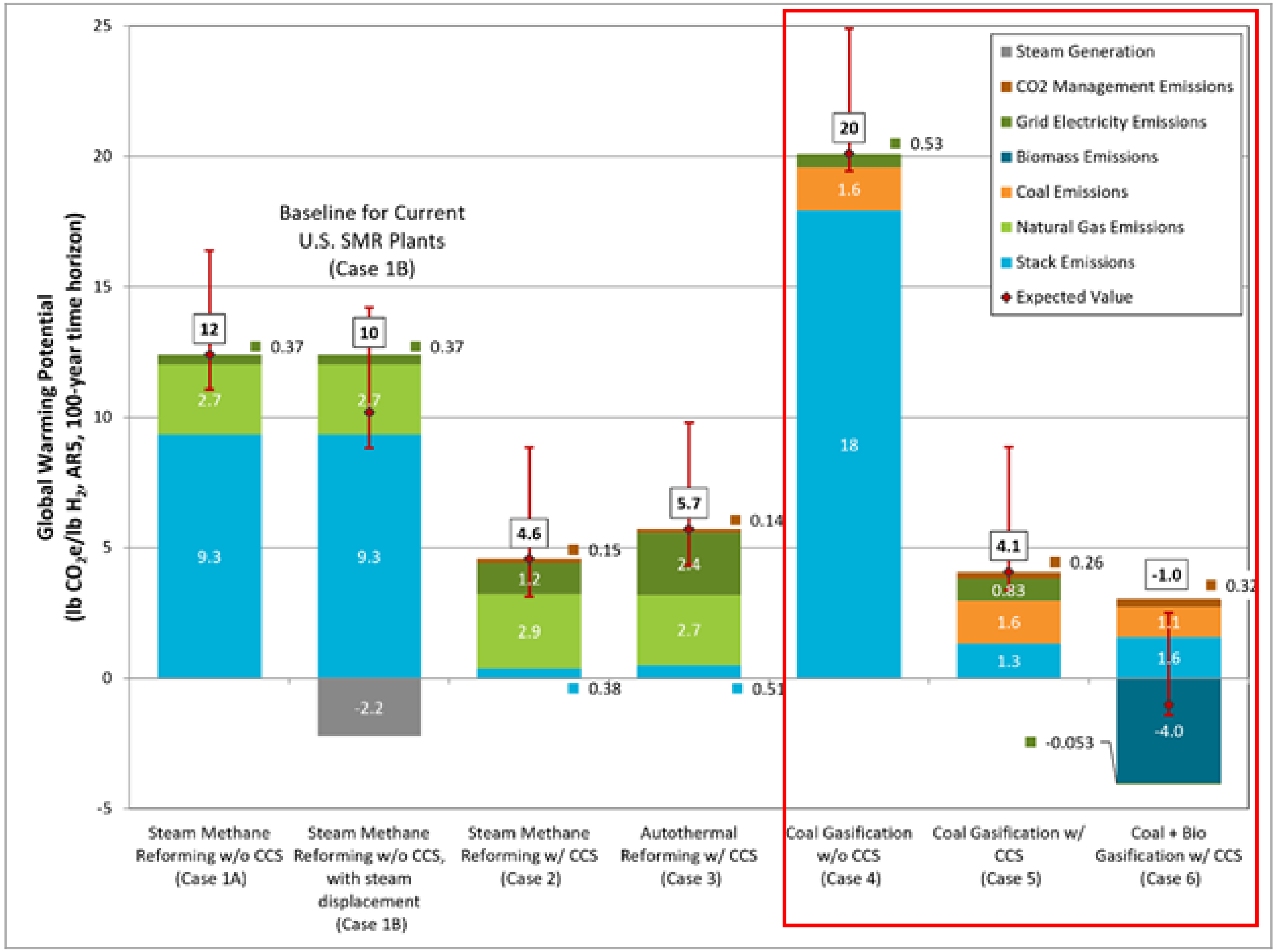
- Overall data is representative of 2016-2017
- Natural gas
  - Model and methods documentation - "Life Cycle Analysis of Natural Gas Extraction and Power Generation," NETL, April 19, 2019
  - Emissions and production data - "Industry Partnerships & Their Role In Reducing Natural Gas Supply Chain Greenhouse Gas Emissions – Phase 2," NETL, February 12, 2021
- Electricity emissions: Assembled from publicly reported emissions and power generation datasets for 2016[1]
- Coal:
  - Model and methods documentation - "Life Cycle Analysis: Supercritical Pulverized Coal (SCPC) Power Plant," NETL, April 13, 2018
  - Coal mine methane emissions are from 2016 EPA GHGRP data
- Torrefied southern yellow pine:
  - Model and methods documentation - "Comprehensive Analysis of Coal and Biomass Conversion to Jet Fuel: Oxygen Blown, Transport Reactor Integrated Gasifier (TRIG) and Fischer-Tropsch (F-T) Catalyst Configurations," NETL, September 8, 2015
  - Background data (e.g., electricity and fuel) from 2016
- Saline aquifer storage
  - Model and methods documentation - "Life Cycle Analysis: Supercritical Pulverized Coal (SCPC) Power Plant," NETL, April 13, 2018

[1]Federal Commons

Primary Results

LCA GHG Emissions (Cradle-to-Gate)

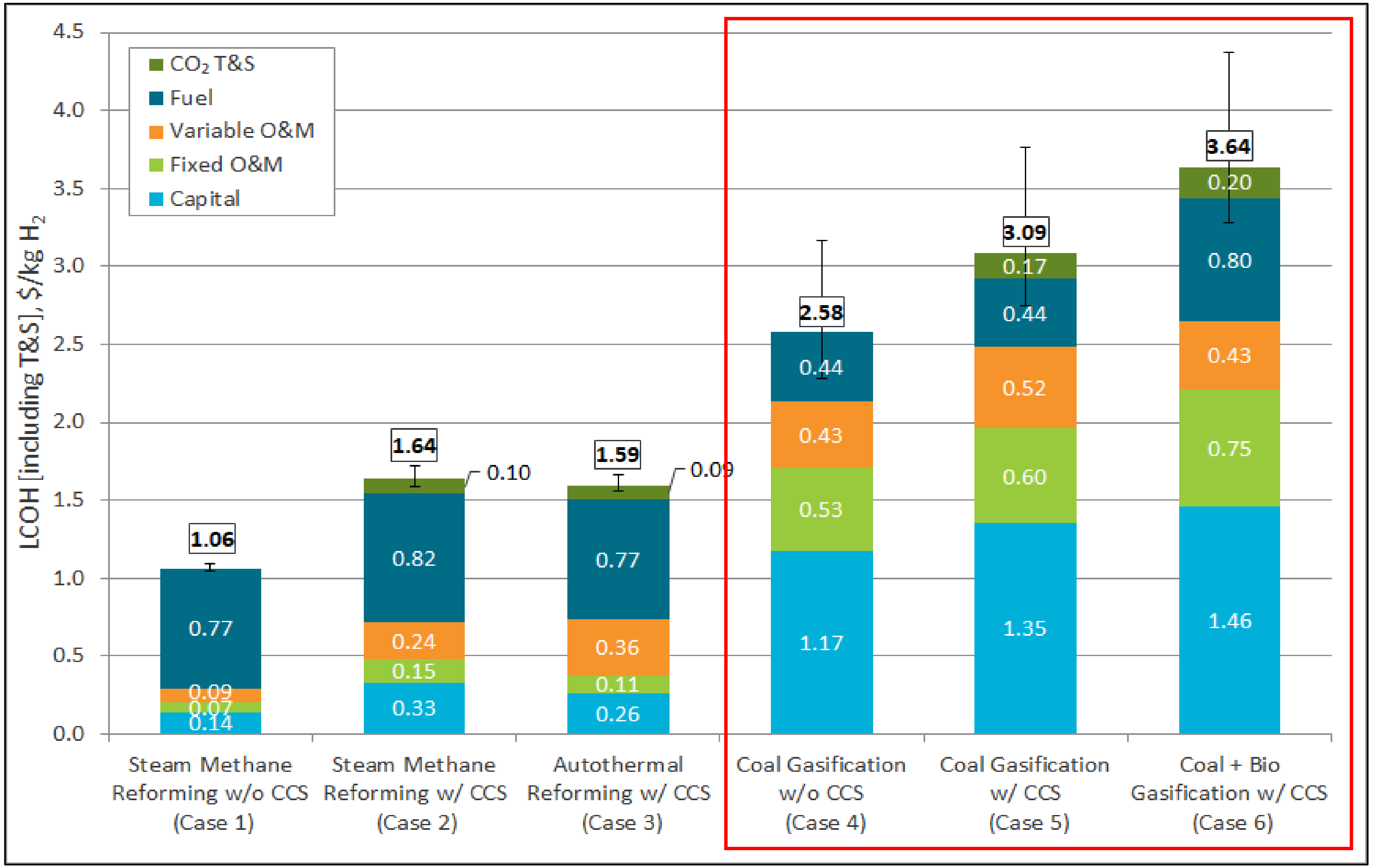
- **Co-gasification of 43.5% torrefied woody biomass enables -1.0 lb CO_{2e}/lb H_2 GHG emissions across the life-cycle**
- **Coal gasification w/ CCS has the lowest GHG emissions over the plant life-cycle of all 100% fossil feedstock cases (4.1 lb CO_{2e}/lb H_2)**
- **Feedstock variability & uncertainty**
  - Natural gas – full product life cycle and regional variability
  - Coal – coal mine methane emissions
  - Southern yellow pine – yield and fertilization rates
  - Electricity – reported emissions



Primary Results

Levelized Cost of Hydrogen

- **Coal/biomass co-gasification w/ CCS has the highest LCOH ($3.64/kg H_2) of all cases. Primary cost drivers are:**
  - Greater biomass feedstock cost
  - Smaller plant capacity
- **Coal gasification w/o CCS achieves the lowest LCOH ($2.58/kg H_2) of all gasification cases**



[1]LCOH error bars depict TOC uncertainty ranges of -15%/+25% (AACE Class 4) and -25%/+50% (AACE Class 5) for reforming and gasification cases, respectively

Study Conclusions

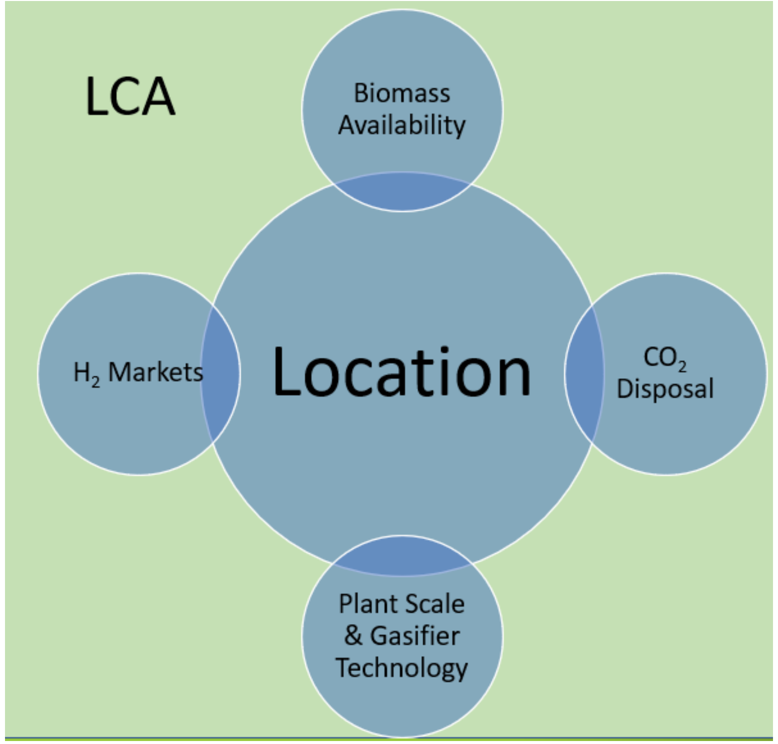
Net-Zero H_2 from Alternative Feedstock Gasification

- Biomass co-gasification with other feedstocks enables CCS through economies of scale, though ongoing studies are more explicitly investigating the effects of scale on product cost.
- Gasification-to-H_2 approaches are generally more costly than natural gas approaches
- However, 2035 net-zero GHG power sector and 2050 economy-wide Administration goals, and consideration of other socioeconomic benefits (e.g., energy justice), creates additional value propositions for gasification technologies; particularly, by using carbon neutral and waste feedstocks
- While it may be challenging to meet the Hydrogen Shot™ goal using biomass co-gasification approaches, the are readily applicable to meeting Carbon Negative Shot™ and Clean Fuels and Products Shot™ goals
  - Hydrogen Shot™: \$1/kg H_2 by 2031
  - Carbon Negative Shot™: <\$100/kg $CO_{2,e}$
  - Clean Fuels & Products Shot™: 85% GHG reduction by 2035

Current Work

Net-Zero H2 from Alternative Feedstock Gasification

- To address the cost challenge, NETL is developing analyses that will:
  - Characterize cost and performance of current, state-of-the art gasification pathways using alternative, carbonaceous feedstocks (e.g., biomass, MSW, and waste plastics) capable of achieving net-zero GHG H2 production
  - Characterize current market conditions for the utilization of such feedstocks as well as competing alternatives
  - Formulate strategies for reducing the levelized cost of net-zero H2 through technology R&D (e.g., process intensification, advanced CO2 capture)
- Analysis Activities:
  - Characterization of MSW, Waste Plastic, and Biomass Properties
  - Matching Feedstocks to Gasifier Feed Systems/Gasifiers
  - Reference Cases for Biomass to H2 and MSW to H2
  - Biomass Gasification to H2 Pathway
    - Gasification only briefly covered in Thermal Conversion Approaches H_2 Pathway Study
  - National Potential for Biomass Gasification-Based Hydrogen Production



LCA Impacts of RNG Production Pathways

Publication[1] Review

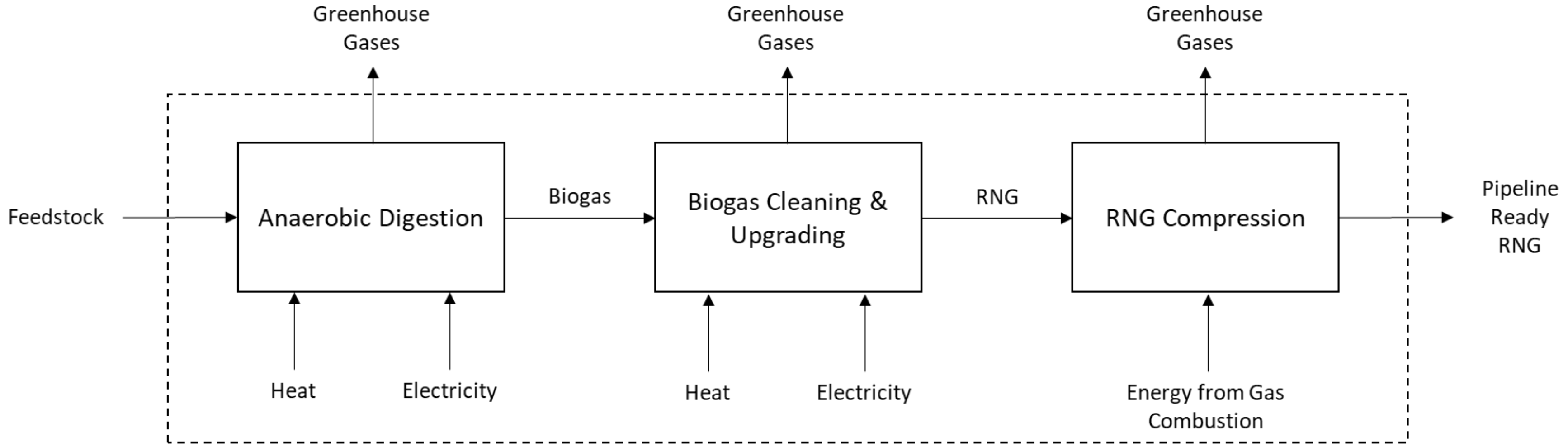
- An attributional and consequential life cycle assessment (LCA) of three RNG pathways with multiple feedstocks and technologies.
- The three proposed pathways are:
  1. Anaerobic Digestion (AD)
  2. Thermal Gasification (TG)
  3. Power-to-Gas (P2G)
- Proposed pathways have a functional unit of 1 MJ of compressed RNG that is ready to be injected in the natural gas transmission network.
- Proposed pathways are compared to their corresponding business-as-usual (BAU) pathways which have a functional unit of 1 MJ of processed fossil natural gas and waste management of the same amount of feedstock that is needed in its corresponding proposed pathway to produce 1 MJ of RNG.
- Data Sources: GREET, U.S. EPA, NETL Unit Processes, Journal Articles
- Outcome: A novel model and paper that compares multiple RNG pathways amongst themselves and with fossil natural gas while maintaining consistent modeling techniques and system boundaries.

[1]Srijana Rai, Danny Hage, James Littlefield, Gabrielle Yanai, and Timothy J. Skone, "Comparative Life Cycle Evaluation of the Global Warming Potential (GWP) Impacts of Renewable Natural Gas Production Pathways," Environ. Sci. Technol. 2022, 56, 8581−8589

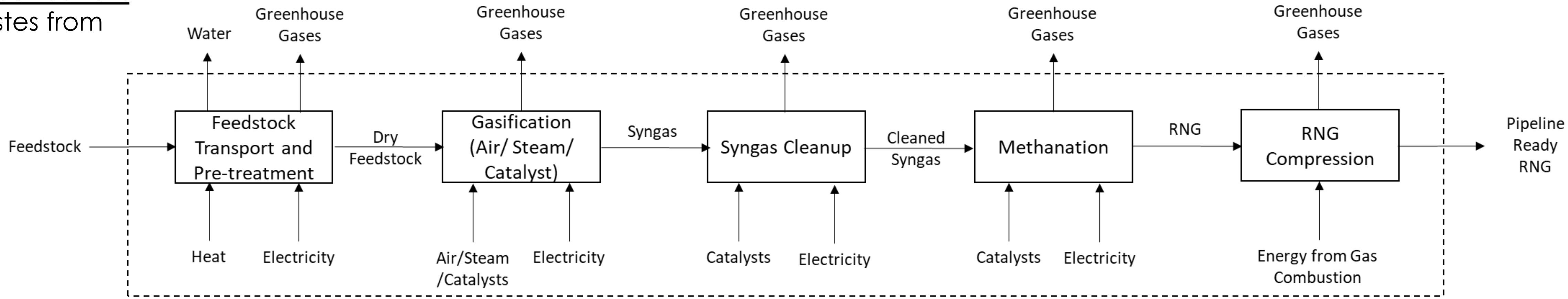
System Boundaries

Biomass Conversion to Renewable Natural Gas

Anaerobic Digestion:
Animal Manure (AM)
Landfill Gas (LFG)
Municipal Solid Waste (MSW)
Wastewater Sludge (WWS)

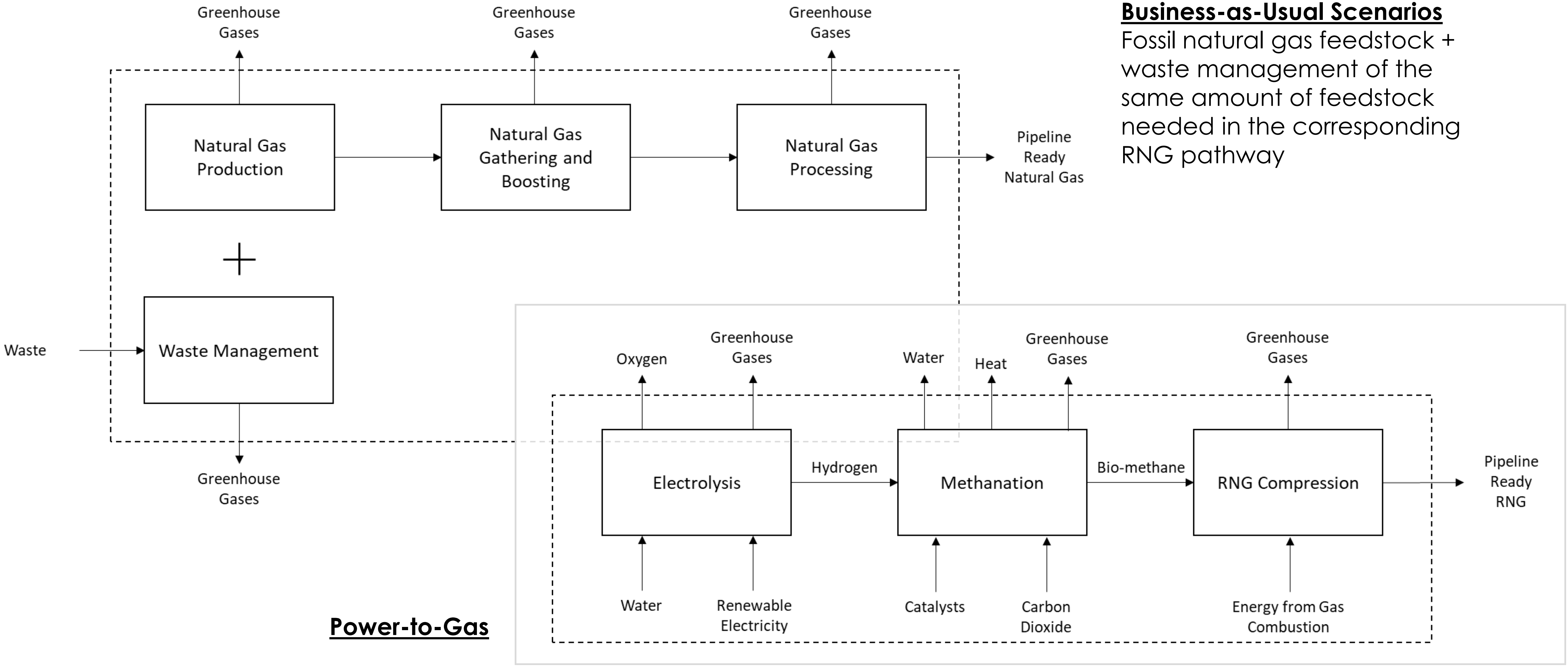


Thermal Gasification:
Wood Wastes from Landfills



System Boundaries

Power and Business as Usual (BAU) Conversion to Renewable Natural Gas



Business-as-Usual Scenarios

Fossil natural gas feedstock + waste management of the same amount of feedstock needed in the corresponding RNG pathway

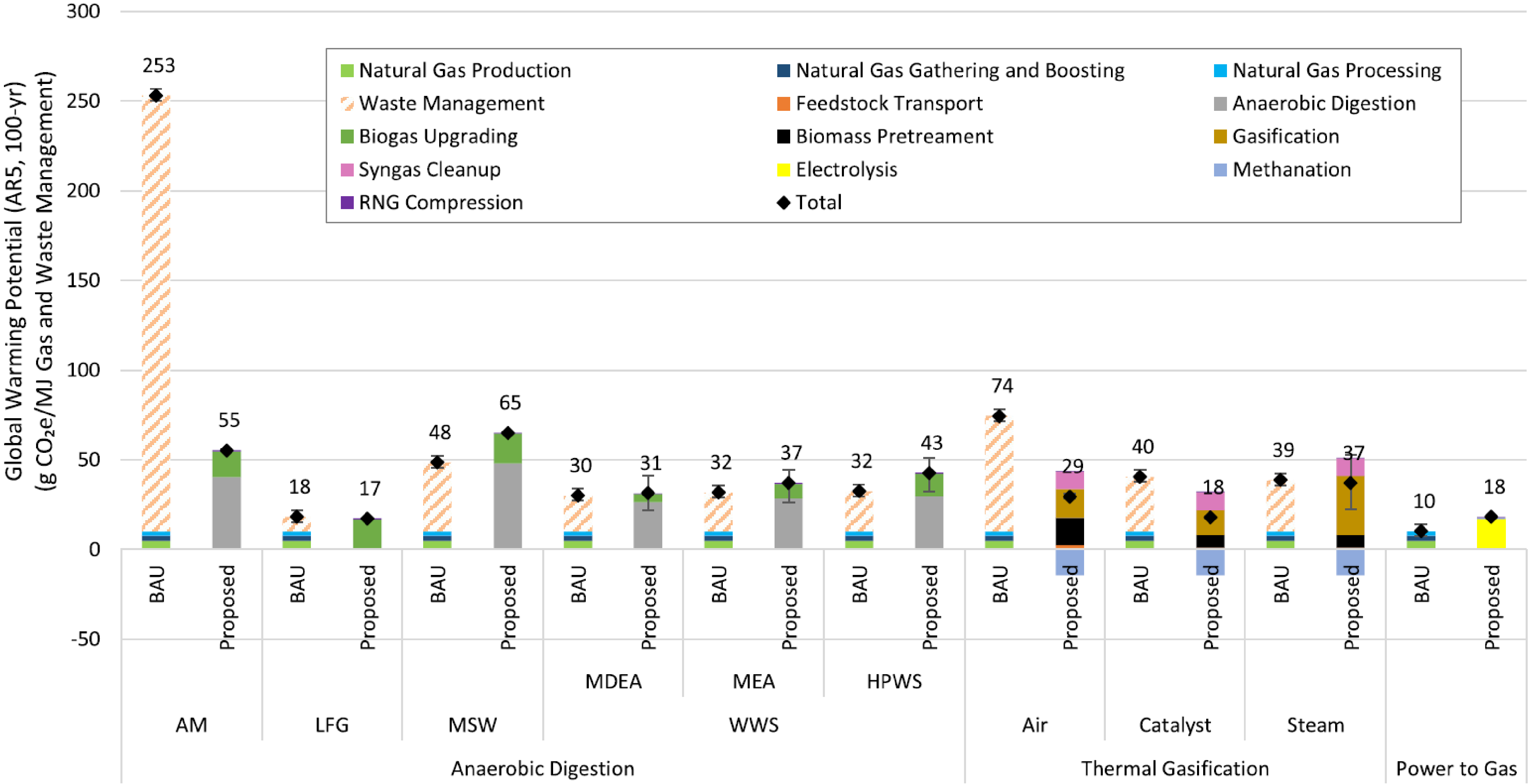
Conventional Waste Management

- Animal Manure
  - Used GHGI emissions data to estimate an emission rate of 0.12 g CO_2e/g of animal manure for conventional management of feedstock.
- Landfill Gas, Municipal Solid Waste, and Wood Wastes
  - Used U.S. EPA GHGRP data to estimate an emission rate of 0.27 g CO_2e/g of landfill waste for the conventional management of these feedstocks.
- Wastewater Sludge
  - Based on literature, assumed land application and estimated an emission rate of 0.009 g CO_2e/g of untreated liquid sludge.

Pradel, M., & Reverdy, A. L. (2012). *Assessing GHG emissions from sludge treatment and disposal routes: the method behind GESTABoues tool. ORBIT2012, Global assessment for organic resources and waste management*. https://hal.archives-ouvertes.fr/hal-00781673/document. Rennes, France.

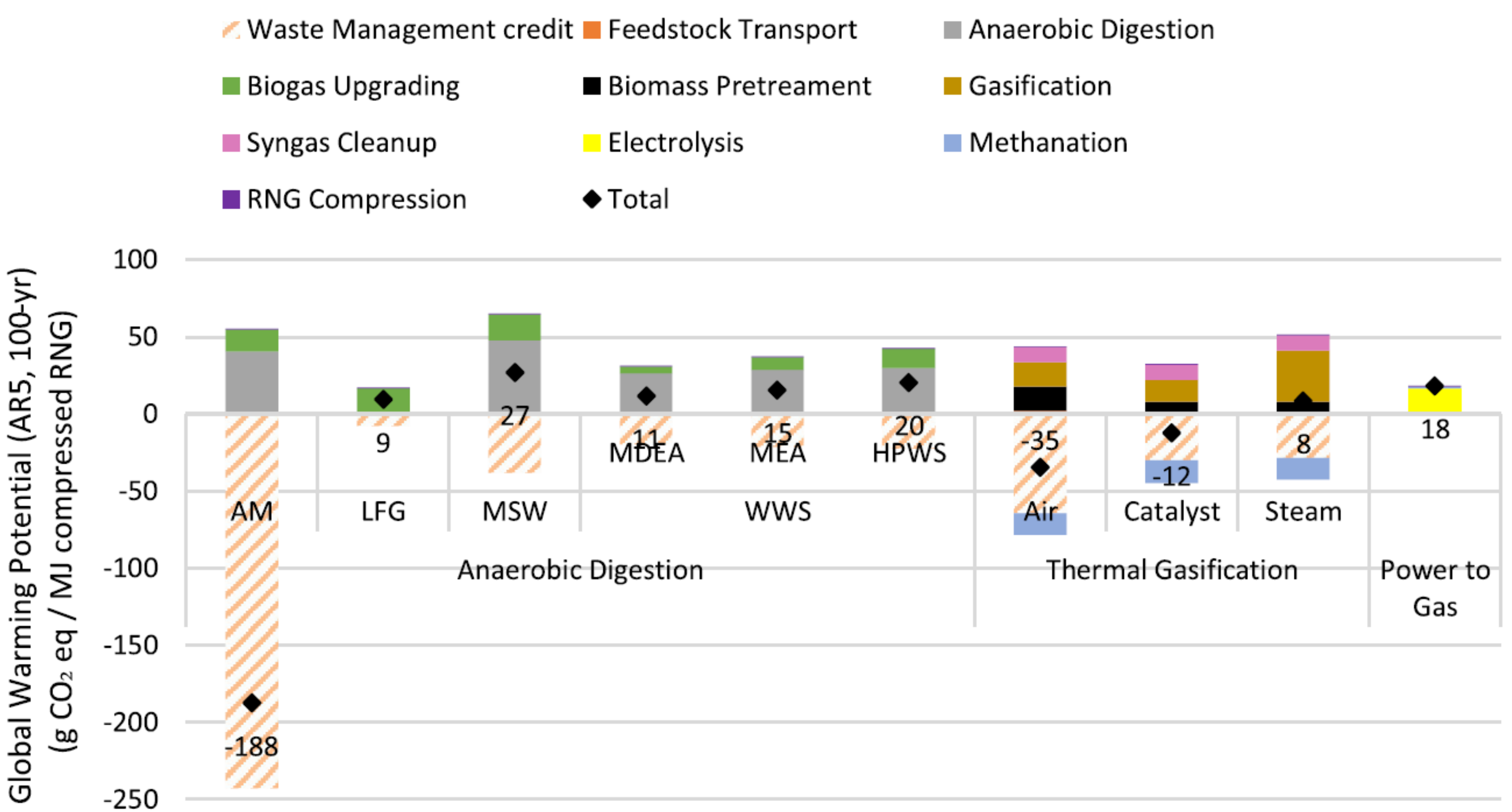
Attributional LCA of RNG Pathways

Using purchased fossil NG to meet internal heat requirements



System Expansion LCA of RNG Pathways

Using purchased fossil NG to meet internal heat requirements



- Anaerobic Digestion of animal manure is the least impactful pathway, with a net GWP impact of -188 g CO_2e/MJ compressed RNG
- Thermal Gasification of wood waste is also a low-impact pathway
- Anaerobic Digestion of municipal solid waste is the most impactful pathway, with a net GWP impact of 27 g CO_2e/MJ compressed RNG

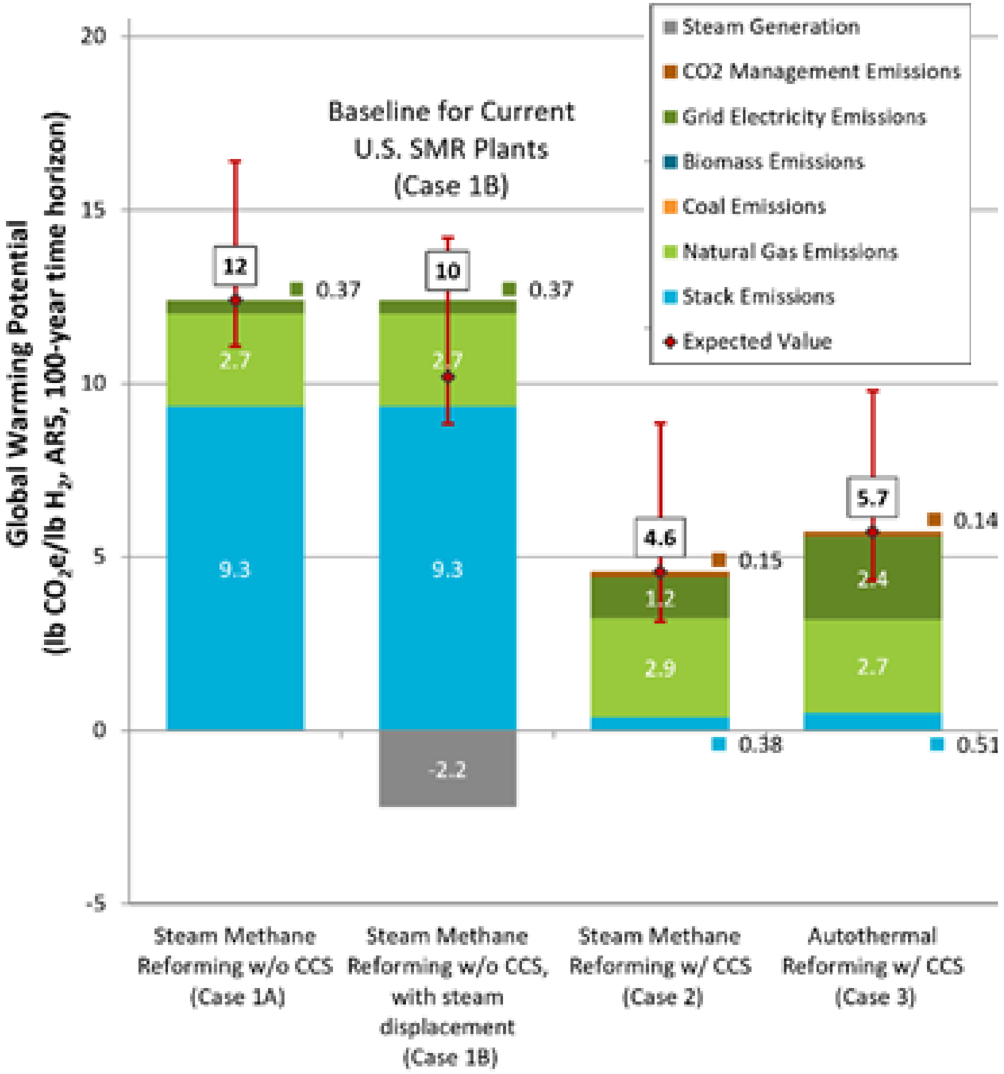
Study Conclusions

- Results are also provided for use of parasitic RNG flow to meet internal heat requirements, rather than purchased fossil NG.
- Not all pathways of producing RNG are beneficial as compared to the business-as-usual or are carbon neutral or negative.
- Out of the 10 scenarios evaluated in this work:
  - 3 scenarios have a net negative GHG impact.
  - 2 scenarios have positive GHG impacts but their impacts are lower than the U.S. average fossil natural gas supply chain with similar boundaries (10 g CO_2e/MJ).
  - 5 scenarios have GHG impacts higher than fossil natural gas.
- More research is needed to identify emissions mitigation strategies in the RNG supply chain to make the net positive pathways more favorable.

Biomass to RNG to Carbon-Negative Hydrogen

Potential Alternative Strategies

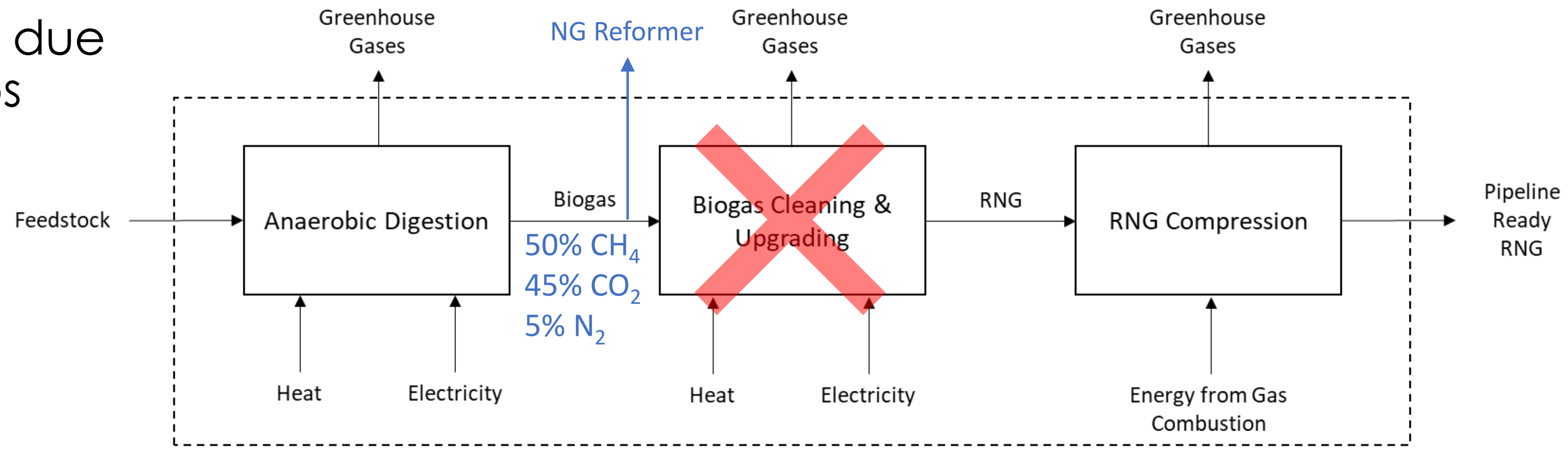
- Properly sourced RNG can produce carbon-negative hydrogen from blended NG/RNG reforming with CCS
  - Blending of RNG into a larger NG reforming system provides more economic CCS
  - Similar to adding biomass to coal gasification with CCS to produce net-zero or net-negative hydrogen
  - Need sufficient RNG quantities to offset upstream NG infrastructure emissions
- Cost-effective mechanism to capture hydrogen production tax credits
  - With sufficient RNG to capture \$1/kg H_2 tax credit (0.45–1.5 $kgCO_2e/kgH2$) from an Autothermal Reforming plant (\$1.58/kg H_2), hydrogen cost is <\$1/kg, even with higher RNG fuel cost



Biomass to Biogas to Carbon-Negative Hydrogen

Potential Alternative Strategies

- Significant GHG emissions are associated with biogas upgrading processes
  - 100% of LFG to RNG emissions, 25% of MSW to RNG emissions
- Raw biogas (or minimally processed biogas) can be blended with NG feedstock to capture its inherent biogenic CO_2 as well
  - For LFG with ~50/50 CH_4/CO_2 content, this doubles its carbon reduction potential
  - Co-siting of NG reforming and anaerobic digestion source (e.g., landfill) favored for economic overall process
  - Reduces biogas cost due to fewer refining steps
  - Requires additional study to quantify the resulting LCOH, with tax credits



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