Renewable Natural Gas Supply Assessment

Final Report

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American Gas Foundation

ICF

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List of Abbreviations and Acronyms

Acronym	Description
AD	Anaerobic Digestion
AG	Agricultural
AGA	American Gas Association
AGF	American Gas Foundation
ANL	Argonne National Laboratory
AR	Assessment Report (from the Intergovernmental Panel on Climate Change)
BCF	Billion Cubic Feet
BoP	Balance of Plant
BTR	US Department of Energy's Billion-Ton Report 2016
Btu	British Thermal Unit
CAPEX	Capital Expenditures
CARB	California Air Resources Board
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilization and Storage
CF	Capacity Factor
CH_4	Methane
CHP	Combined Heat and Power
CI	Carbon Intensity
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
CWNS	US EPA's Clean Watersheds Needs Survey
DOE	US Department of Energy
DT	Dry Tons (metric)
EIA AEO	US Energy Information Administration's Annual Energy Outlook
EPA	US Environmental Protection Agency
EREF	Environmental Research & Education Foundation
GAL	Gallon
GCCSI	Global CCS Institute
GCO_2E	Gram of Carbon Dioxide Equivalent
GHG	Greenhouse Gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies Model by Argonne National Laboratory
GWP	Global Warming Potential
H_2	Hydrogen
H_2S	Hydrogen Sulfide
IPCC	Intergovernmental Panel on Climate Change
KDF	Bioenergy Knowledge Discovery Framework
kg CO_2e	Kilogram of Carbon Dioxide Equivalent
kWh	Kilowatt-hour

Acronym	Description
LCA	Life Cycle Assessment
LCFS	Low Carbon Fuel Standard
LCOE	Levelized Cost of Energy
LFG	Landfill Gas
LMOP	US EPA's Landfill Methane Outreach Program
MCF	Methane Conversion Factor
MGD	Million Gallons per Day
MMCF	Million Cubic Feet
MMBtu	Million British Thermal Units
MMT	Million Metric Ton
MSW	Municipal Solid Waste
MT	Metric Ton
MW	Megawatt
NERC	North American Electric Reliability Corporation
NG	(Geologic) Natural Gas
N_2	Nitrogen
N_2O	Nitrous Oxide
OPEX	Operational Expenditures
O_2	Oxygen
PEM	Proton Exchange Membrane
PSA	Pressure Swing Adsorption
P2G	Power-to-Gas *(refers explicitly power-to-hydrogen for methanation in this study)*
RFS	US Renewable Fuel Standard
RNG	Renewable Natural Gas
SCFM	Standard Cubic Feet per Minute
SNG	Synthetic Natural Gas
TBtu	Trillion British Thermal Units
TCF	Trillion Cubic Feet
TCO_2e	Metric Ton of Carbon Dioxide Equivalent (also written as $MTCO_2e$)
TG	Thermal Gasification
T&D	Transmission & Distribution
USDA	US Department of Agriculture
WRRF	Water Resource Recovery Facility
WTW	Well-to-wheels

Executive Summary

This study updates and expands on the 2019 AGF assessment of renewable natural gas (RNG), which is derived from biomass or other renewable resources and is a pipeline-quality gas that is fully interchangeable with conventional natural gas. The study incorporates a revised assessment of supply potential, recent advancements in technology, and shifts in policy landscapes. The focus of the study is on assessing the volumetric potential of RNG production from diverse feedstocks and technologies, examining the broader implications for greenhouse gas (GHG) emission reductions, and analyzing the cost-effectiveness of RNG implementation across various timescales.

This report is structured across four areas: a) the national RNG production potential from various feedstocks, b) the corresponding GHG emission reduction potential, c) the estimated costs of bringing RNG supply into production, and d) the potential to reduce and/or eliminate technological barriers to RNG development.

ICF developed RNG production potential estimates by mirroring the low and high supply potential scenario logic of the 2019 AGF study and a third scenario that was designed to achieve more ambitious GHG emission reductions. Overall, the estimated pool of biomass available for bioenergy, including RNG, increased by 17% since the 2019 study, reflecting updated data sources and more granular estimates of a variety of feedstocks. Despite the rise in overall biomass availability, the data incorporates more stringent sustainability criteria as well as updated and generally more conservative assumptions across feedstocks that can be used to produce RNG.

ICF estimated the supply potential scenarios by considering constraints unique to each RNG feedstock, based on factors such as accessibility, competition, market drivers, practical constraints, and the economics of production using the feedstock. These constraints were then used to develop utilization assumptions regarding each feedstock, forming the basis for supply scenarios from 2025 to 2050.

In the Low Scenario, ICF estimates that 1,628 trillion Btu (tBtu) of RNG can be produced annually for pipeline injection by 2050, reflecting utilization of approximately 10% of total available biomass that could be used for bioenergy production. In the High Scenario, ICF estimates that 3,728 tBtu of RNG can be produced annually for pipeline injection by 2050, reflecting utilization of approximately 23% of total available biomass that could be used for bioenergy production. Under the Ambitious Emissions Reduction Scenario that may be consistent with policies to promote significant emissions reductions including net-zero goals, ICF estimates that 7,061 tBtu of RNG can be produced annually for pipeline injection by 2050, reflecting utilization of approximately 43% of total available biomass that could be used for bioenergy production. By way of comparison, ICF notes that the ten-year average for natural gas consumption (2015-2024) in the domestic residential sector was about 4,840 tBtu.

In addition to biomass-based feedstocks used for RNG production, ICF assessed the RNG supply potential from the methanation of hydrogen produced via power-to-gas (P2G). In this analysis, ICF developed RNG production potential by considering hydrogen produced via electrolysis (powered by wind, solar, and nuclear resources) and carbon dioxide from various sources (biogenic, industrial capture, and direct air capture) in a methanation reaction. In the absence of a more specific constraint like that which exists for biomass, ICF made the simplifying assumption that 15-25% of electricity generation from wind, solar, and nuclear resources could be used for P2G. This was used as a proxy for the technical potential for RNG produced via the methanation of hydrogen and carbon dioxide. Based on the electricity generation reported by the US Energy Information Administration's (EIA) Annual Energy Outlook (AEO) 2023,[1] ICF estimates about 1,420 tBtu/y of RNG production. Furthermore, ICF assumed in the Low, High, and

[1] Annual Energy Outlook 2023, https://www.eia.gov/outlooks/aeo/. (EIA did not publish an AEO in 2024, thus the 2023 model was the latest available at the time of this analysis, https://www.eia.gov/pressroom/releases/press537.php.)

Ambitious Emissions Reduction Scenarios that 10%, 20%, and 40% of the proxy for technical potential via the methanation hydrogen pathway would be used to make RNG—amounting to about 118 tBtu/y, 236 tBtu/y, and 472 tBtu/y, respectively.

ICF conducted a bottom-up assessment of the GHG emission reduction potential from RNG across the three scenarios, assuming the displacement of geologic (fossil) natural gas. ICF evaluated GHG emission reductions using life cycle carbon intensities (CIs), or a cradle-to-grave assessment, for the various RNG feedstocks and production methods. The RNG CIs used to estimate the GHG reduction are based on standard assumptions, and broadly consistent with regulatory mechanisms relevant to RNG.

ICF estimates that RNG deployment could deliver 82 to over 328 million metric tons (MMT) of GHG emission reductions annually in 2050, based on the deployment scenarios developed in this analysis. When factoring in the potential displacement of geologic natural gas with methanated hydrogen (produced via power-to-gas), an additional 6 to 32 MMT of GHG emission reductions could be achieved annually by 2050.

ICF developed assumptions for the capital and operational expenditures for RNG production from the various feedstock and technology pairings outlined previously, and developed supply curves (i.e., supply as a function of production costs) for RNG with an outlook to 2050. ICF characterized costs based on a series of assumptions regarding the production facility sizes (as measured by gas throughput in units of standard cubic feet per minute [SCFM]), gas conditioning and upgrading costs (depending on the type of technology used, the contaminant loadings, etc.), compression, and interconnect for pipeline injection. ICF also included operational costs for each technology type.

ICF estimates that 75% of the RNG production potential in the Low Scenario and High Scenario could be produced at an average cost less than $20/MMBtu and at an average cost of $23/MMBtu in the Ambitious Emissions Reduction Scenario. Generally speaking, ICF finds that landfill gas projects and wastewater projects will have the lowest RNG production costs and populate the front end of the supply curve. ICF's analysis shows that RNG produced from other feedstocks like animal manure, food waste, and the thermal conversion of biomass will have higher production costs but will still be competitive in the range of $25-$40/MMBtu. ICF also reports a cost-effectiveness or abatement cost for RNG in the range of $70-$400/ton on a lifecycle basis or combustion basis. The range of abatement costs reflects the variation amongst the carbon intensity value for RNG from different feedstocks and the framework considered (i.e., lifecycle basis or combustion basis). RNG will be an attractive decarbonization strategy across many sectors, with importance in buildings, commercial activities, like industrial processes with high heat demands, and transportation like shipping and trucking.

Relative to the 2019 AGF RNG Assessment, the overall available biomass supply that could be used to produce RNG has increased by 17%. While biomass-based RNG is inherently constrained by biomass availability, there are significant and diverse feedstocks that could support the wide-scale deployment of RNG nationally. The utilization of biomass to produce large volumes of RNG, as indicated in the High and Ambitious Emissions Reduction scenarios, does not preclude the use of biomass for other bioenergy end-uses, such as liquid biofuels.

The findings in this study related to production costs and emission reductions indicate that RNG and methanated hydrogen have the potential to play pivotal, cost-effective, and increasing roles in the decarbonization of the gas system, and the economy more broadly. Decarbonization pathways that deliver net-zero GHG emissions by mid-century necessitate the roll-out of multiple and diverse emission reduction measures, covering new technologies, fuels, and behaviors. Emissions abatement costs are a critical consideration for jurisdictions and stakeholders working to significantly reduce greenhouse gas emissions across the economy. Despite production costs being higher than comparative conventional (fossil) fuels, the emission reduction abatement costs of RNG and P2G are competitive and cost-effective relative to other measures.

ICF's research identified multiple opportunities to reduce RNG production costs through innovation and technological advancements, however, the magnitude of the aggregate opportunity for cost reductions is unclear. ICF identified several pathways to improve the prospects of potential improvements in RNG production pathways and associated cost reductions of outlook for RNG production costs, including a clearer statement of costs and benefits of emerging technologies, coordinated technology readiness level assessments focused on opportunities beyond anaerobic digestion, and coordinated action between producers and policymakers to identify barriers that prevent further innovation and investment in technologies that will reduce RNG production costs.

1 Introduction

Renewable natural gas (RNG) is derived from biomass or other renewable resources and is a pipeline-quality gas that is fully interchangeable with conventional natural gas. The American Gas Association (AGA) uses the following definition for RNG:

> *"Pipeline-compatible gaseous fuel derived from biogenic or other renewable sources that has lower life cycle carbon dioxide equivalent (CO_2e) emissions than geological natural gas."* [2]
>
> — AGA

In 2019, ICF conducted an assessment for the American Gas Foundation (AGF) to outline the potential for RNG to contribute to greenhouse gas (GHG) emission reduction initiatives across the country, entitled *Renewable Sources of Natural Gas: Supply and Emissions Reduction Assessment* (2019 AGF RNG study). Building upon that previous work, this report is focused on assessing a) the national RNG production potential from various feedstocks, b) the corresponding GHG emission reduction potential, c) the estimated costs of bringing RNG supply into production, and d) the potential to reduce and/or eliminate technological barriers to RNG development. ICF developed RNG production potential estimates by mirroring the low and high supply potential scenario logic of the 2019 AGF study and another more ambitious scenario aligned with the "what we might see in a net-zero future" RNG supply case from the study ICF conducted for the AGA in 2021 (*Net-Zero Emissions Opportunities for Gas Utilities*).

Consequently, the three scenarios leveraged in this study are labeled "Low," "High," and "Ambitious Emissions Reduction". The scenarios incorporate a variety of constraints regarding accessibility to feedstocks, the time that it would take to deploy projects over the timeframe contemplated, the development of technology that would be required to achieve higher levels of RNG production, and consideration of likely project economics—with the assumption that the most economic projects will come online first. With respect to timeframe, this study extends the consideration of RNG supply to 2050 from the previous study, which looked out to 2040.

ICF leveraged the latest available feedstock supply data, including a renewal of the US Department of Energy (DOE) Bioenergy Technology Office's (BETO) Billion-Ton Report, published in early 2024 but referred to here as the 2023 Billion-Ton Report (BT23). As before, ICF developed resource potential scenarios by considering RNG production from eight (8) feedstocks and two production technologies. The feedstocks include landfill gas (LFG), animal manure, water resource recovery facilities (WRRFs), food waste, agricultural residues, forestry and forest product residues, energy crops, and the biogenic fraction of municipal solid waste (MSW). These feedstocks were assumed to be processed using one of two technologies to produce RNG: anaerobic digesters or thermal gasification systems. In addition, ICF explored power-to-gas (P2G) in combination with a methanation system as another source of pipeline-quality renewable methane, CH_4; specifically, sourced from renewable electricity (including nuclear resources) in tandem with carbon from biogenic or point-source waste CO_2 (i.e., captured CO_2).

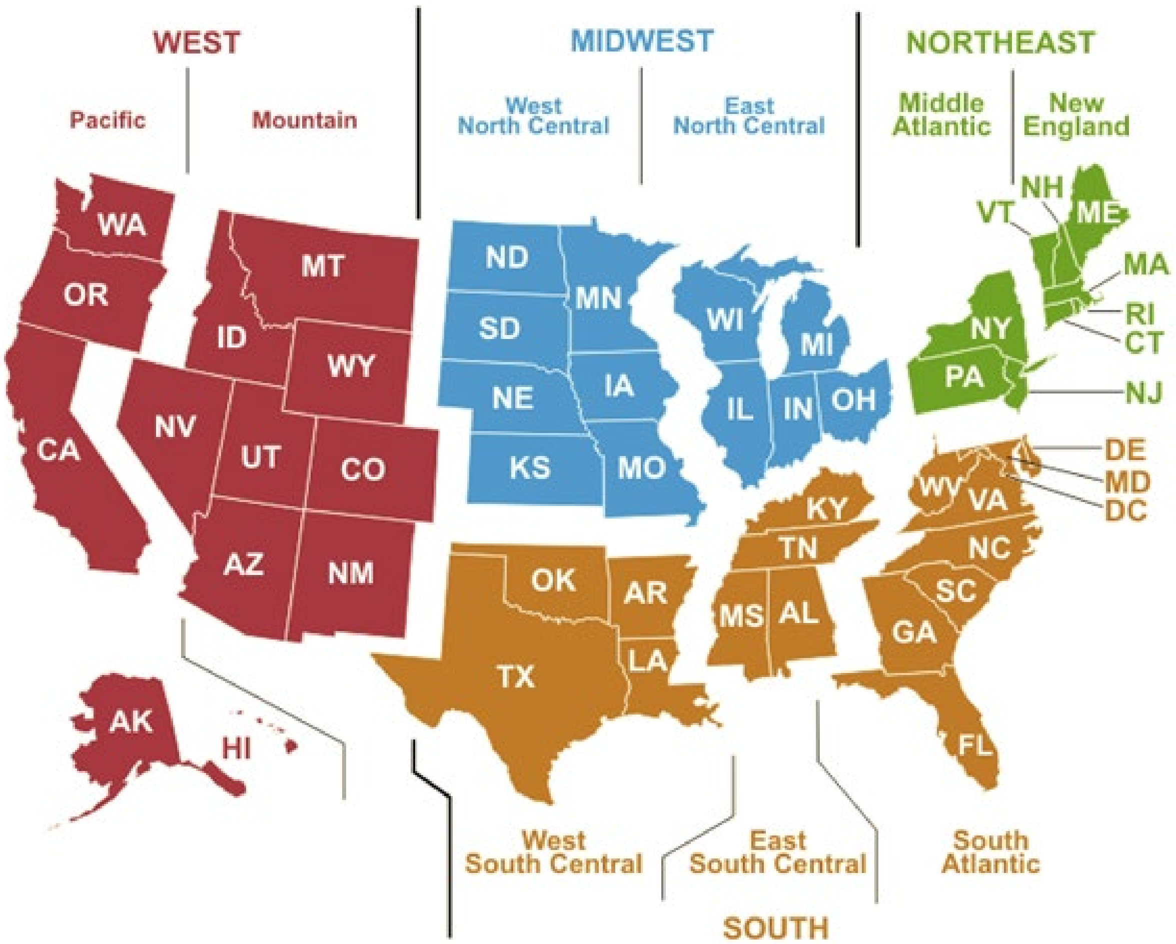
It is important to note that ICF's analysis is not meant to be prescriptive but rather illustrative in terms of how the market for RNG production potential might evolve given our understanding of the feedstocks that can be used and the current state of technology development. Consider, for instance, that many

2 AGA, 2019. RNG: Opportunity for Innovation at Natural Gas Utilities, https://pubs.naruc.org/pub/73453B6B-A25A-6AC4-BDFC-C709B202C819

anaerobic digester projects use a combination of animal manure and agricultural residues as feedstocks—the analysis presented here only considers the anaerobic digestion of animal manure and the thermal gasification of agricultural residues. ICF recognizes that these types of multi-feedstock considerations will continue to exist in the market; however, ICF needed to make simplifying distinctions for the purposes of the resource assessment.

ICF developed resource potential scenarios by considering constraints unique to each RNG feedstock—these constraints were based on factors such as feedstock accessibility and the economics of RNG production using the feedstock. These constraints are summarized as utilization assumptions that were used to develop the three scenarios. The resource potential reported is also a function of the conversion efficiency of the production technology to which each feedstock is paired. ICF also presents a technical resource potential, which does not consider accessibility or economic constraints. The resource assessment was conducted using a combination of national-, regional-, and state-level information regarding the availability of different feedstocks; and the information is presented using the nine (9) US Census Divisions (see Figure 1).

Figure 1. US Census Divisions[3]



The report is structured as follows:

- In **Section 2**, ICF introduces the RNG production technologies considered—anaerobic digestion (AD) and thermal gasification (TG), as well as RNG produced via combination power-to-gas (P2G) and methanation.

[3] US Census Bureau via US Energy Information Administration, https://www.eia.gov/consumption/commercial/maps.php

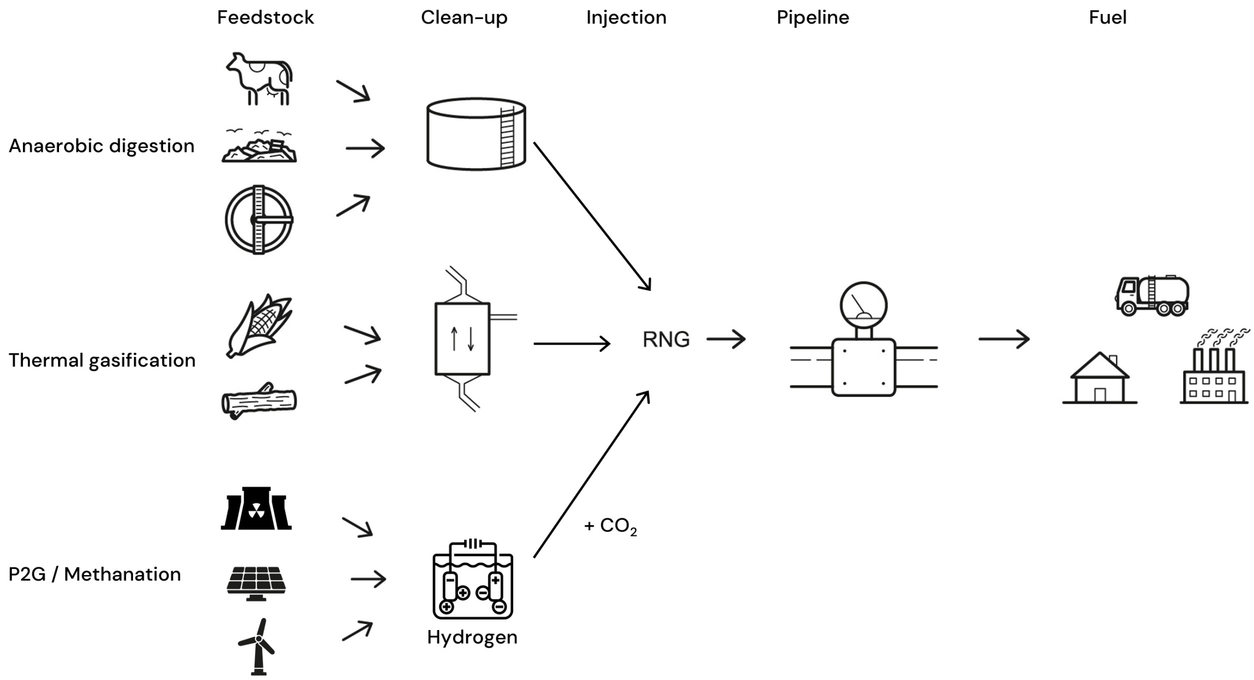
- In **Section 3**, ICF estimates the GHG emissions and GHG emission reductions for each RNG production pathway and feedstock combination.
- In **Section 4**, ICF describes its production cost modeling and the results of its analysis using a levelized cost of energy approach. The production cost results are summarized as supply curves.
- In **Section 5**, ICF presents its findings of a technology assessment, with a focus on technologies that might help reduce RNG production costs in the near- to mid-term future, or those that might increase RNG production domestically.
- In **Section 6**, ICF reviews its key takeaways.

2 RNG Supply Potential

2.1 RNG Production Pathways

ICF focused on three production pathways for RNG, including anaerobic digestion, thermal gasification, and power-to-gas paired with methanation (see Figure 2).

Figure 2. Overview of RNG Production



2.1.1 Anaerobic Digestion

Anaerobic digestion (AD) is a mature technology that has been used in commercial applications since the late 1800s and is the most common way to produce RNG today. Anaerobic digestion occurs when microorganisms break down organic material in an environment without oxygen. The four key processes in anaerobic digestion are hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Hydrolysis is the process whereby longer-chain organic polymers are broken down into shorter-chain molecules like sugars, amino acids, and fatty acids that are available to other bacteria. Acidogenesis is the biological fermentation of the remaining components by bacteria, yielding volatile fatty acids, ammonia, carbon dioxide, hydrogen sulfide, and other byproducts. Acetogenesis of the remaining simple molecules yields acetic acid, carbon dioxide, and hydrogen. Lastly, methanogens use intermediate products from hydrolysis, acidogenesis, and acetogenesis to produce methane, carbon dioxide, and water.

Anaerobic digestion is the most common way to produce RNG today. The process for RNG production generally takes place in a controlled environment, referred to as a digester or reactor, including landfill gas facilities. When organic waste, a biosolid, or livestock manure is introduced to the digester, the material is broken down over time (e.g., days) by microorganisms, and the gaseous products of that process contain a large fraction of methane and carbon dioxide. The biogas requires capture, subsequent conditioning, and upgrade before pipeline injection. The conditioning and upgrading help to remove any contaminants and other trace constituents, including siloxanes, sulfides and nitrogen, which cannot be injected into common carrier pipelines, and increase the heating value of the gas for injection.

2.1.2 Thermal Gasification

Biomass thermal gasification (TG) is an approach to thermal conversion of biomass to produce RNG over a series of generic steps.[4] In thermal conversion, there is generally a feedstock pre-processing step to prepare the feedstock for thermal treatment. In the next step, gasification (or pyrolysis) generates synthetic gas (syngas), consisting largely of hydrogen and carbon monoxide, and trace amounts of methane and carbon dioxide. The syngas is then sent for filtration and purification to remove excess dust or ash generated during the gasification (or pyrolysis) stage and to remove potential contaminants like hydrogen sulfide and carbon dioxide. In the final step, methanation occurs, whereby the upgraded syngas is converted to methane and dried prior to pipeline injection.

The thermal conversion of biomass into RNG via processes like gasification is at an early stage of commercialization, with the gasification and purification steps presenting challenges. More recently, however, several thermal gasification projects are in the late stages of planning and development in North America.

- REN Energy International Corp is proposing to build a modular thermal gasification facility in British Columbia using wood waste to produce pipeline-quality RNG for the local natural gas utility, FortisBC. [5]
- Sierra Energy's thermal gasification and biorefinery facility in Nevada produces RNG and liquid fuels using municipal solid waste as a feedstock.
- West Biofuels has several demonstration and research projects using biomass to produce RNG, as well as commercialized thermal gasification facilities producing other renewable fuels.

2.1.3 Power-to-Gas with Methanation

Power-to-gas (P2G) refers here to the production of hydrogen via electrolysis, powered by renewable electricity. In this study, ICF assumes that renewable hydrogen is then paired with a carbon dioxide source in a methanation process to yield renewable methane or RNG. To be clear, the term "P2G" generally refers to the production of renewable hydrogen via electrolysis. For this RNG study, ICF exclusively considered the case of the methanation of renewable hydrogen to yield RNG.

Renewable hydrogen production is in its early deployment stages in the United States, with several projects being developed domestically. For instance,

- Florida Power & Light completed the Cavendish NextGen Hydrogen Hub in early 2024, using solar energy to power electrolyzers and produce green hydrogen. (Reported electrolyzer capacity of 25 MW.)
- The SoHyCal facility in Southern California is producing green hydrogen from solar energy. (Reported electrolyzer capacity of 7.5 MW.)
- Plug Power operates a green hydrogen facility in Camden County, Georgia. (Reported electrolyzer capacity of 40 MW.)

Methanation is also a commercially available technology in various applications and is used in chemical applications like ammonia synthesis. The access to carbon dioxide needed for the methanation step is also in the early stages of deployment. Though the various components of the power-to-gas with methanation pathway have been deployed at varying commercialization levels, there are likely less than 15

[4] Biomass can also be converted to biomethane via pyrolysis, another form of thermal conversion.
[5] FortisBC, 2020. Filing of a Biomethane Purchase Agreement between FEI and REN. Though the project has been delayed after first being announced in 2020, FortisBC confirmed as recently as March 2024 that they remain committed to the project. Information accessed online at https://www.bcuc.com/Documents/Proceedings/2020/DOC_57461_B-1-FEI-REN-Sec-71-BPA-Application-Confidential-Redacted.pdf.

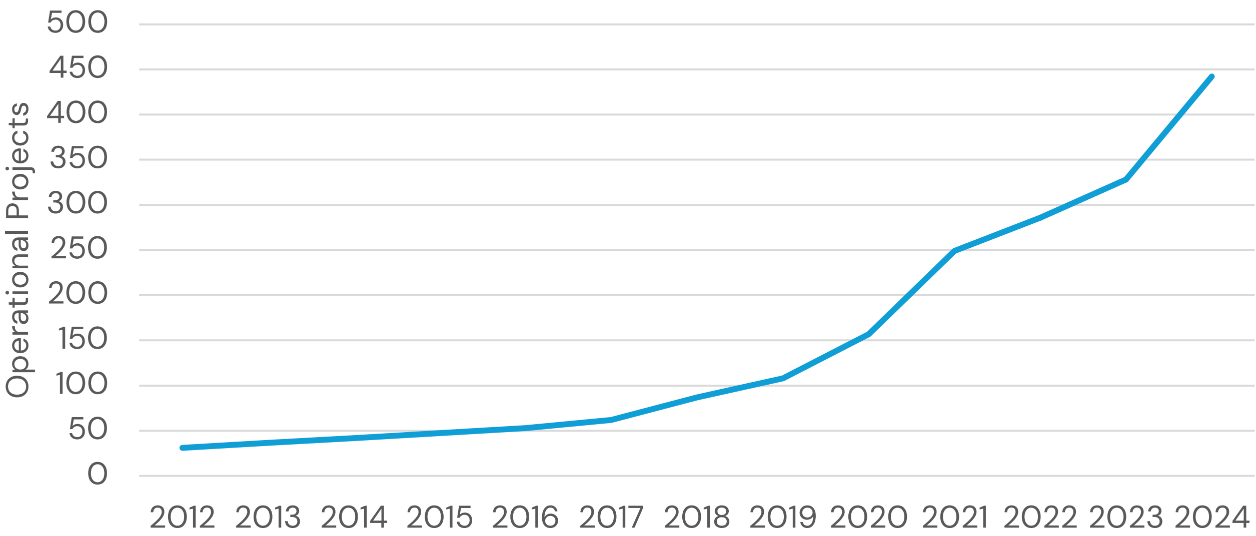
projects globally that would include two of these three components, all with electrolyzer capacities of less than 2.5 MW.

2.2 RNG Feedstocks

2.2.1 RNG from Anaerobic Digestion and Thermal Gasification

RNG is derived from biomass or other renewable resources and, when processed accordingly, is a pipeline-quality gas that is fully interchangeable with conventional natural gas. RNG is a "drop-in" replacement for natural gas and can be safely employed in any end-use typically fueled by natural gas, including electricity production, heating and cooling, industrial applications, and transportation. ICF estimates that RNG production in the United States is 120-140 trillion British thermal units (tBtu) annually from landfills, animal manure digesters, and WRRFs, and has sustained a compound annual growth rate of 25-35% since 2013.

Figure 3. Operational RNG Facilities in North America, via Coalition For Renewable Natural Gas[6]



RNG can be produced from a variety of renewable feedstocks; for the purposes of this report, ICF considered animal manure, food waste, landfill gas (LFG), wastewater at water resource recovery facilities (WRRFs), agricultural residues, energy crops, forestry and forest product residues, and municipal solid waste (MSW). These feedstocks are shown in Table 1 with a brief description of each feedstock, including definitions and methodology, outlined in Section 2.3.

Table 1. Conventional RNG Feedstock Types

Feedstock for RNG		Description
Anaerobic Digestion	Animal manure	Manure produced by livestock, including dairy cows, beef cattle, swine, sheep, goats, poultry, and horses.
	Food waste	Commercial, industrial and institutional food waste, including from food processors, grocery stores, cafeterias, and restaurants.
	Landfill gas	The anaerobic digestion of organic waste in landfills produces a mix of gases, including methane (40–60%).

[6] ICF analysis of data presented by RNG Coalition and American Biogas Council.

Feedstock for RNG		Description
	Wastewater	Wastewater consists of waste liquids and solids from household, commercial, and industrial water use; in the processing of wastewater, a sludge is produced, which serves as the feedstock for RNG.
Thermal Gasification	Agricultural residue	The material left in the field, orchard, vineyard, or other agricultural setting after a crop has been harvested. Inclusive of unusable portion of crop, stalks, stems, leaves, branches, and seed pods.
	Energy crops	Inclusive of perennial grasses, trees, and annual crops (such as biomass sorghum, energy cane, eucalyptus, miscanthus, pine, poplar, switchgrass and willow) that can be grown to supply large volumes of uniform and consistent feedstocks for energy production.
	Forestry and forest product residue	Biomass generated from logging, forest and fire management activities, and milling. Inclusive of logging residues, forest thinnings, and mill residues. Also, materials from public forestlands, but not specially designated forests (e.g., roadless areas, national parks, wilderness areas).
	Municipal solid waste	Refers to the biogenic fraction of waste that would be landfilled after the diversion of other waste products (e.g., food waste or other organics), including paper and paperboard, and yard trimmings.

Inventory Methodology

ICF used a combination of existing studies, government data, and industry resources to estimate the current and future supply of feedstocks for RNG production. Table 2 below summarizes some of the resources that ICF drew from to conduct the resource assessment, broken down by RNG feedstock:

Table 2. List of Data Sources for RNG Feedstock Inventory

Feedstock for RNG	Resources for Assessment
Animal manure	• US Environmental Protection Agency (EPA) AgStar Project Database • US Department of Agriculture (USDA) Census of Agriculture, 2022
Food waste	• US Department of Energy (DOE) 2023 Billion-Ton Report (BT23) • Bioenergy Knowledge Discovery Framework (KDF)
Landfill gas	• US EPA Landfill Methane Outreach Program (LMOP) • Environmental Research & Education Foundation (EREF)
Wastewater	• US EPA 2022 Clean Watersheds Needs Survey (CWNS) • Water Environment Federation
Agricultural residue	• US DOE 2023 Billion-Ton Report • Bioenergy Knowledge Discovery Framework
Energy crops	• US DOE 2023 Billion-Ton Report • Bioenergy Knowledge Discovery Framework
Forestry and forest product residue	• US DOE 2023 Billion-Ton Report • Bioenergy Knowledge Discovery Framework
MSW	• US DOE 2023 Billion-Ton Report • Waste Business Journal

Note that the DOE Billion-Ton Report, USDA Census of Agriculture, EPA CWNS, and LMOP Database, among other data sources, have been updated since the 2019 AGF RNG study.

This RNG feedstock inventory does not estimate resource availability—in a competitive market, resource availability is a function of factors, including but not limited to demand, feedstock costs, technological development, and the policies in place that might support RNG project development. ICF assessed the RNG resource potential of the different feedstocks that could be realized given the necessary market considerations (without explicitly defining what those are), outlined in Section 2.3.4.

2.2.2 RNG from Methanated Hydrogen (P2G)

ICF limited the methanated hydrogen feedstocks considered in this study to dedicated renewable electricity and select sources of carbon oxides. ICF's scope considered dedicated electricity produced from wind, solar, and nuclear resources. Furthermore, ICF assumed that the carbon dioxide sources for methanation would either be biogenic (e.g., from an ethanol production facility), carbon capture from industrial processes, or via direct air capture. This is not an exhaustive list of feedstocks for RNG from P2G (for example, curtailed renewable electricity may not always be precluded as a feedstock for P2G in practice) but these feedstocks were deemed as reasonably feasible resources to consider in a prospective future methanated hydrogen RNG supply within the limitations of this study.

2.3 RNG Technical Potential

ICF estimated the technical resource potential for RNG production using the three production pathways outlined previously. Section 2.3.1, below, outlines changes from the 2019 AGF Study, whereas Section 2.3.2 and Section 2.3.3 cover the RNG technical potential via anaerobic digestion and thermal gasification pathways, respectively. Those two subsections are broken down by feedstocks. The RNG technical potential from these pathways are linked to the biomass inventory that ICF developed for each respective feedstock (see Section 2.2). In Section 2.3.4, ICF turns to its approach to estimating RNG technical potential from the P2G/methanation pathway. ICF developed an approach whereby renewable hydrogen was considered the limiting factor in the P2G/methanation pathway for RNG technical potential.

The technical potential estimates shown in the figure and table below, in units of tBtu/y, reflect the total maximum RNG that could be produced from the 100% utilization of all feedstocks, irrespective of practical, economic or market constraints on feedstock availability or production capacity. The technical potential is a theoretical maximum of RNG production potential and is a starting point to create specific supply scenarios, rather than a realistic supply scenario in and of itself. A variety of technical and economic constraints are applied to develop these scenarios, which are discussed in more detail in the following subsections below.

Figure 4 summarizes the maximum theoretical RNG potential for each conventional biomass-based feedstock and production technology across the United States. This total represents over 16,000 trillion British thermal units per year (tBtu/y)[7] of natural gas per year. Table 3 that follows below breaks down the maximum technical potential for the eight feedstocks by census region.

ICF notes that the maximum technical potential from P2G is not included in the following figure and table as it does not face similar or consistent production constraints compared to the eight biomass-based RNG feedstocks.

[7] 1 tBtu is equivalent to about 1 billion cubic feet (BCF) of natural gas.

Figure 4. US RNG Technical Potential by Biogenic Feedstock (tBtu/y)

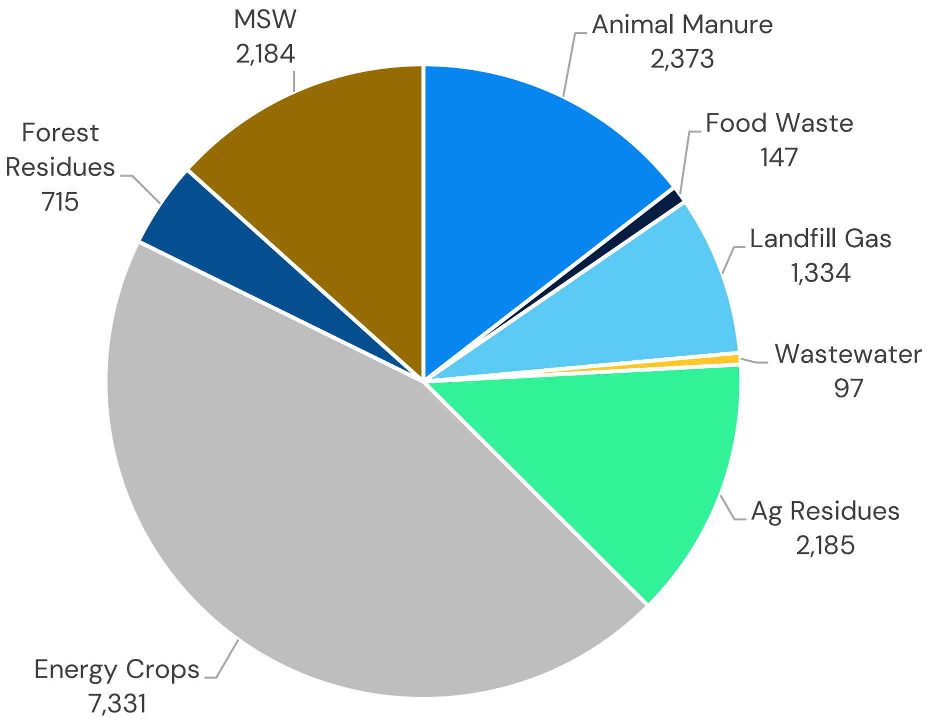


Table 3. Maximum RNG Production Potential by Feedstock (tBtu/y)

	Potential Feedstock for RNG (tBtu/y)	New England	Mid Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific	National Total
Anaerobic Digestion	Animal Manure	12.2	94.3	454.3	439.6	251.8	180.1	458.8	276.0	206.4	2,373.3
	Food Waste	6.1	16.8	17.8	9.7	30.9	8.0	21.3	12.1	24.7	147.4
	Landfill Gas	19.3	97.1	272.6	86.6	239.5	87.6	187.1	123.9	220.2	1,333.9
	Wastewater	4.0	13.2	21.4	7.1	15.8	5.4	10.8	5.8	13.6	97.2
	AD Subtotal	**46.0**	**213.4**	**772.5**	**555.6**	**534.0**	**289.7**	**677.7**	**418.4**	**444.5**	**3,951.8**
Thermal Gasification	Ag Residues	0.9	24.5	703.3	1,113.9	44.7	54.0	90.8	56.4	96.9	2,185.4
	Energy Crops	22.1	152.8	577.0	2,327.5	684.0	599.8	2,660.0	308.0	0.0	7,331.1
	Forest Residues	56.9	100.2	79.8	22.2	217.6	93.5	69.7	39.9	35.1	715.0
	MSW	41.6	176.2	283.8	138.2	518.8	138.5	385.6	202.2	298.6	2,183.6
	TG Subtotal	**121.5**	**453.7**	**1,643.9**	**3,601.9**	**1,465.0**	**885.9**	**3,206.1**	**606.5**	**430.6**	**12,415.1**
Total RNG from biogenic resources		167.5	677.0	2,416.4	4,157.4	1,999.0	1,175.6	3,883.8	1,024.9	875.1	16,366.9
Total RNG from P2G		N/A; P2G technical potential dependent on market developments beyond scope of study									

2.3.1 Changes from the Previous Assessment

Figure 5 below shows a comparison of the technical potential from the 2019 AGF Study. Overall, there has been a combined 17% increase in technical potential across the eight feedstocks. Updated data for all feedstocks from sources including the DOE BT23, USDA Census of Agriculture, EPA CWNS and LMOP Database are the main drivers of this increase in technical potential compared to the 2019 AGF RNG study.

- For example, landfill gas and wastewater also both increased due to updated data sources and modeling approaches, +4% and +16%, respectively, while animal manure declined, at -8%, due mainly to lower livestock headcounts.
- BT23 revised upwards the maximum biomass potential for energy crops (+59%), forestry residue (+10%), and MSW (19%) while decreasing maximum potential for agricultural residue (-15%).
- ICF notes that the maximum technical potential for food waste has decreased by 60%, driven by changes in resource availability linked to the BT23 update.

Figure 5. Total Technical Potential in 2040 Across Studies

2.3.2 Feedstocks Used in Anaerobic Digestion Production Pathway

Animal Manure

ICF considered animal manure from a variety of animal populations, including beef and dairy cows, broiler chickens, layer chickens, turkeys, and swine. Animal populations were derived from the USDA National Agricultural Statistics Service. ICF used information provided from the most recent census year (2022) and extracted total animal populations on a state-by-state basis.[8]

The main components of the anaerobic digestion of manure include manure collection, the digester, effluent storage (e.g., a tank or lagoon), and gas handling equipment. A variety of livestock manure processing systems are employed at farms today, including plug-flow or mixed plug-flow digesters, complete-mixed digesters, covered lagoons, fixed-film digesters, sequencing-batch reactors, and induced-blanked digesters. Most dairy manure projects today use plug-flow or mixed plug-flow digesters.

[8] USDA, 2022. 2022 Census of Agriculture, https://www.nass.usda.gov/Publications/AgCensus/2022/index.php

ICF developed the maximum RNG potential using animal manure production and the energy content of dried manure taken from a California Energy Commission report prepared by the California Biomass Collaborative.[9] These inputs are summarized in Table 4 below with the formula and an example calculation of a 10,000-head dairy farm included for reference:

$$10{,}000\ head\ \times 3{,}020\ \frac{kg\ (dry)}{head} \times 16{,}111\ \frac{Btu}{kg\ (dry)} \times \frac{1}{1.0^6} = 486{,}491\ MMBtu$$

Table 4. Key Parameters for Animal Manure Resource RNG Potential

Animal Type	Volatile Solids (kg/head/year)	Higher Heating Value (HHV) (Btu/kg, dry basis)
Dairy	3,020	16,111
Other Cattle: • Beef • Other (including heifers)	 1,674 750	 16,345 16,345
Swine	149	15,077
Poultry • Layer Chickens (including pullets) • Broiler Chickens • Turkeys	 8.3 9.1 25.0	 14,689 15,077 14,830
Sheep & Goats	242	9,362

The following table provides a summary of livestock headcount across each census division. Note that livestock headcount is indicative of RNG production potential within a given feedstock category i.e., that there is expected to be more RNG potential from swine in the West North Central census division than from New England, per the following table. However, the relationship between headcount and RNG production varies by livestock type. One hundred cows generate a different waste profile than 100 chickens. Further, the RNG potential yield by headcount can vary even when considering the same species, as will be demonstrated further in the following sections when considering feasible manure collection for the supply scenarios. For example, because of the different farming practices between cattle kept for dairy and cattle kept for beef, 100 beef cattle do not, in practice, necessarily have the same RNG production potential as 100 dairy cattle.

9 Williams, R. B., B. M. Jenkins and S. Kaffka (California Biomass Collaborative). 2015. An Assessment of Biomass Resources in California, 2013 – DRAFT. Contractor Report to the California Energy Commission. PIER Contract 500-11-020. Available online here.

Table 5. Livestock Headcount by Census Division (000s)[10]

	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
Dairy cattle	130	1,090	2,892	492	294	77	686	1,434	2,062
Beef (cattle and other)	196	1,638	10,080	21,200	4,956	5,480	18,663	10,547	5,592
Swine	19	1,378	46,601	10,998	8,683	922	3,488	366	43
Poultry Layers	333	33,182	163,143	18,823	53,074	15,129	44,792	9,207	19,703
Sheep & Goats	47	172	648	514	213	165	680	1,660	723

The table below shows the maximum RNG potential in each census division, with a national total of 2,373 tBtu/y. Note that the maximum RNG potential does not account for the numerous limiting factors that would constrain RNG production via animal manure e.g., collecting the feedstock.

Table 6. RNG Production Potential, Animal Manure (tBtu/y)

	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
Maximum RNG Potential (tBtu/y)	12.2	94.3	454.3	439.6	251.8	180.1	458.8	276.0	206.4

Food Waste

Food waste includes biomass sources from commercial, industrial, and institutional facilities, including food processors and manufacturers, grocery stores, cafeterias, and restaurants. Food waste from residential sources is not reflected in this analysis but could be an additional resource for food waste biomass with the implementation of effective waste diversion policies.

Food waste is a major component of MSW—accounting for about 15% of MSW streams. More than 75% of food waste is landfilled. Food waste can be diverted from landfills to a composting or processing facility where it can be treated in an anaerobic digester. ICF limited its consideration to the potential for utilizing the food waste that is currently landfilled as a feedstock for RNG production via AD, thereby excluding the 25% of food waste that is recycled or directed to waste-to-energy facilities. In addition, food waste that is potentially diverted from landfills in the future as they reach capacity is not included in the landfill gas analysis (outlined in more detail below), thereby avoiding any issues around double counting of biomass from food waste.

As food waste is generated from population centers and typically diverted at waste transfer stations rather than delivered to landfills, it is challenging to identify specific facilities or projects that will generate RNG from food waste. However, food waste can potentially utilize existing or future AD systems at LFG and WRRF facilities.

ICF extracted county-level information from the US DOE's Bioenergy Knowledge Discovery Framework (KDF), which includes information collected as part of the US DOE's 2023 Billion-Ton Report (BT23, updated in 2023). The Bioenergy KDF includes food waste at tipping fee price points ranging from $70/ton, with a long price tail up to $500/ton. ICF assumed a high heating value of 12.04 MMBtu/ton (dry). Note that

[10] USDA, 2022. 2022 Census of Agriculture, https://www.nass.usda.gov/Publications/AgCensus/2022/index.php

the values from the Bioenergy KDF are reported in dry tons, so the moisture content of the food waste has already been accounted for in the DOE's resource assessment.

ICF also modified its approach to estimating RNG production potential from landfills, as outlined in more detail in the text in the following subsection and summarized here. ICF assumed that waste acceptance rates were constant over time, and ICF tracked accumulated waste-in-place against approved capacity of landfills accordingly. When a landfill reached its rated capacity, ICF did not assume that existing landfills would expand nor that new landfills would be developed. Rather, ICF allowed the RNG production potential to decrease accordingly.

ICF was careful in the analysis to ensure that its RNG production potential estimates derived from landfill gas and food waste do not conflict or overlap. ICF notes, however, that successful waste diversion policies would increase the RNG resource potential and improve the opportunity for RNG production from dedicated AD systems processing diverted food waste. The table below shows the maximum RNG potential by census division, with a national total of 147 tBtu/y in 2050, noting that no limiting factors were applied to the RNG potential

Table 7. RNG Production Potential, Food Waste (tBtu/y)

	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
Maximum RNG Potential (tBtu/y)	6.1	16.8	17.8	9.7	30.9	8.0	21.3	12.1	24.7

Landfill Gas

The Resource Conservation and Recovery Act of 1976 (RCRA, 1976) sets criteria under which landfills can accept municipal solid waste and nonhazardous industrial solid waste. Furthermore, the RCRA prohibits open dumping of waste, and hazardous waste is managed from the time of its creation to the time of its disposal. Landfill gas (LFG) is captured from the anaerobic digestion of biogenic waste in landfills and produces a mix of gases, including methane, with a methane content generally ranging from 45% to 60%.[11] The landfill itself acts as the digester tank—a closed volume that becomes devoid of oxygen over time, leading to favorable conditions for certain micro-organisms to break down biogenic materials.

The composition of the LFG is dependent on the materials in the landfill, and other factors, but is typically made up of methane, carbon dioxide (CO_2), nitrogen (N_2), hydrogen, CO, oxygen (O_2), sulfides (e.g., hydrogen sulfide or H_2S), ammonia, and trace elements like amines, sulfurous compounds, and siloxanes.[12] RNG production from LFG requires advanced treatment and upgrading of the biogas via removal of CO_2, H_2S, siloxanes, N_2, and O_2 to achieve a high-energy (Btu) content gas for pipeline injection. The table below summarizes landfill gas constituents, the typical concentration ranges in LFG, and commonly deployed upgrading technologies in use today.

11 Biogas captured from dedicated anaerobic digesters tends to have a higher percent methane content (~60%), especially compared to landfill gas. That said, upgrading technology for other types of biogas is like that used for landfill gas.
12 Siloxane only exists in biogas from landfills and WRRF.

Table 8. Landfill Gas Constituents and Corresponding Upgrading Technologies

LFG Constituent	Typical Concentration Range	Upgrading Technology for Removal
Carbon dioxide, CO_2	40% – 60%	• High-selectivity membrane separation • Pressure swing adsorption (PSA) systems • Water scrubbing systems • Amine scrubbing systems
Hydrogen sulfide, H_2S	0 – 1%	• Solid chemical scavenging • Liquid chemical scavenging • Solvent adsorption • Chemical oxidation-reduction
Siloxanes	<0.1%	• Non-regenerative adsorption • Regenerative adsorption
Nitrogen, N_2 Oxygen, O_2	2% – 5% 0.1% – 1%	• PSA systems • Catalytic removal (O_2 only)

ICF utilized data from the US EPA's Landfill Methane Outreach Program (LMOP) to assess the RNG potential from LFG. This database encompasses over 2,000 landfills. ICF applied the EPA's LandGEM model to quantify methane emissions from these landfills. The LandGEM model calculates methane emissions using a first-order decomposition rate equation based on the annual waste accepted by each landfill. This method represents a more accurate approach compared to the methodology used in the 2019 study, which assumed that the waste-in-place levels and the linked RNG production potential were constant over time. This revised approach accounts more accurately for the dynamics of methane production in landfills.

For the analysis, ICF incorporated annual waste acceptance rates for each landfill from 2010 through 2050 until the landfill's closure year, or when the landfill reached capacity, whichever occurred first. ICF only included waste acceptance for landfills that have not yet reached their maximum capacity as of 2025. If a landfill reached its maximum capacity in the analysis, ICF fixed the waste-in-place and no longer incorporated additional waste into that landfill. As a result, ICF observed slight decreases in certain regions that have landfill capacity constraints—this generally occurred in the mid-2030s. Though it is conceivable that this waste would be rerouted to a nearby landfill with capacity or that a jurisdiction may require waste diversion via regulatory or policy interventions, ICF did not make any such assumptions for the LFG assessment. Furthermore, ICF did not assume that landfills were expanded, nor did it assume that additional landfills would be built. Ultimately, this assumption means this assessment likely underestimates the amount of RNG that could be produced from landfilled waste.

The table below summarizes the number of landfills in each census division, including the total number in the LMOP database, as well as the number of 'eligible' large landfills, defined as having more than one million tons of waste in place that are open, or closed after 2005. This timing constraint was imposed to account for how the decomposition of total vs eligible waste in a landfill produces sufficient methane concentrations for about 20-25 years, meaning this is the period during which waste-to-energy projects are most viable.[13] While landfills continue to emit methane for 50 years or more, this constraint limits the potential for the assessment to overestimate the production from older landfills where the methane concentration in biogas declines to a level to which it is impractical to capture and upgrade/condition.

[13] US EPA Landfill Methane Outreach Program, LFG Energy Project Development Handbook, Chapter 1, Available online at https://www.epa.gov/sites/production/files/2016-07/documents/pdh_chapter1.pdf

Table 9. Number of Landfills by Census Division

	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
Eligible & Large	33	81	178	101	211	95	150	88	122
Total	154	188	374	305	471	237	231	240	401

The table below shows the maximum RNG potential by census division, with a national total of 1,334 tBtu/y.

Table 10. RNG Production Potential, Landfill Gas (tBtu/y)

	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
Maximum RNG Potential	19.3	97.1	272.6	86.6	239.5	87.6	187.1	123.9	220.2

Wastewater

Wastewater is created from residences and commercial or industrial facilities and consists primarily of waste liquids and solids from household water usage, commercial water usage, or industrial processes. Depending on the architecture of the sewer system and local regulations, it may also contain storm water from roofs, streets, or other runoff areas. The contents of the wastewater may include anything that is expelled (legally or not) from a household and enters the drains. If storm water is included in the wastewater sewer flow, it may also contain components collected during runoff: soil, metals, organic compounds, animal waste, oils, and solid debris such as leaves and branches.

Wastewater is processed and treated at dedicated facilities, including sewerage treatment plants and wastewater treatment plants, covered by the umbrella term of water resource recovery facilities (WRRFs). Processing of wastewater influent to a WRRF is comprised typically of four stages: pre-treatment, primary, secondary, and tertiary treatments. These stages consist of mechanical, biological, and sometimes chemical processing.

- Pre-treatment removes all the materials that can be easily collected from the raw wastewater that may otherwise damage or clog pumps or piping used in treatment processes.
- In the primary treatment stage, the wastewater flows into large tanks or settling bins, thereby allowing sludge to settle while fats, oils, or greases rise to the surface.
- The secondary treatment stage is designed to degrade the biological content of the wastewater and sludge and is typically done using water-borne micro-organisms in a managed system.
- The tertiary treatment stage prepares the treated effluent for discharge into another ecosystem, and often uses chemical or physical processes to disinfect the water.

The treated sludge from the WRRF can be landfilled, and during processing it can be treated via anaerobic digestion, thereby producing methane, which can be put to beneficial use with the appropriate capture and conditioning systems put in place.

ICF used the Clean Watersheds Needs Survey (CWNS) conducted in 2022 by the US EPA, an assessment of capital investment needed for wastewater collection and resource recovery facilities to meet the water quality goals of the Clean Water Act that includes more than 14,500 WRRFs. ICF distinguishes between facilities based on location and facility size as a measure of average flow (in units of million gallons per day, MGD). ICF also reviewed more than 1,200 facilities that are reported to have anaerobic digesters in place, as reported by the Water Environment Federation. In contrast to the 2012 CWNS, the 2022 survey does not provide existing waste flows, only existing capacity. Subsequently, ICF estimated waste flows using median facility utilization rates from the 2012 survey. Overall, since the 2012 survey, the number of WRRFs has increased by 13%, with capacity expanding by 10%. The table below shows the number of WRRFs in each census division, broken out by size based on estimated waste flows.

Table 11. Number of WRRFs by Census Division and Existing Waste Flow

	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
Large (>7.5 MGD)	42	87	138	57	183	51	96	58	126
Medium (3.5-7.5 MGD)	41	75	119	53	145	54	113	37	89
Small (<3.5 MGD)	494	836	2,894	3,533	1,651	836	2,478	1,207	932
Total	577	998	3,151	3,643	1,979	916	2,687	1,302	1,147

To estimate the amount of RNG produced from wastewater at WRRFs, ICF used data reported by the US EPA,[14] a study of WRRFs in New York State,[15] and previous work published by AGF.[16] ICF used an average energy yield of 7.003 MMBtu/MG of wastewater.

The table below shows the maximum RNG potential by census division from wastewater, with a national total of 97 tBtu/y in 2050.

Table 12. RNG Production Potential, Wastewater (tBtu/y)

	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
Maximum RNG Potential (tBtu/y)	4.0	13.2	21.4	7.1	15.8	5.4	10.8	5.8	13.6

2.3.3 Feedstocks used in Thermal Gasification Pathway

The biomass feedstocks for RNG production potential via thermal gasification include agricultural residues, energy crops, forestry and forest product residues, and the non-biogenic fraction of MSW. Given that biomass gasification technology is at an early stage of commercialization, RNG production potential for these feedstocks cannot be determined to a facility-specific level, in contrast to other feedstocks such as LFG and WRRFs. However, sources of thermal gasification feedstocks can be approximated at a regional level based on existing land use patterns and population levels. The specific approach for each feedstock is outlined below.

To estimate the RNG production potential, ICF assumed a 65% efficiency for thermal gasification systems. This factor is based in part on the 2011 AGF Report on RNG, indicating a range of thermal gasification efficiencies in the range of 60% to 70%, depending upon the configuration and process conditions. The report authors also used a conversion efficiency of 65% in their assessment. More recently, GTI Energy

14 US EPA, Opportunities for Combined Heat and Power at Wastewater Treatment Facilities, October 2011. Available online here.
15 Wightman, J and Woodbury, P., Current and Potential Methane Production for Electricity and Heat from New York State Wastewater Treatment Plants, New York State Water Resources Institute at Cornell University. Available online here.
16 AGF, The Potential for Renewable Gas: Biogas Derived from Biomass Feedstocks and Upgraded to Pipeline Quality, September 2011.

estimated the potential for RNG from the thermal gasification of wood waste in California and assumed a conversion efficiency of 60%.[17]

Agricultural Residues

Agricultural residues include the material left in the field, orchard, vineyard, or other agricultural settings after a crop has been harvested. More specifically, this resource is inclusive of the unusable portion of crops, stalks, stems, leaves, branches, and seed pods. Agricultural residues (and sometimes crops) are often added to anaerobic digesters.

ICF extracted information from the US DOE Bioenergy KDF, including the following agricultural residues: barley straw, corn stover, non-citrus residues, tree nut residues and wheat straw (outlined in Table 13 below). These estimates are based on modeling undertaken as part of the BT23 Study and utilize the Policy Analysis System (POLYSYS), a policy simulation model of the US agricultural sector. The POLYSYS modeling framework simulates how commodity markets balance supply and demand via price adjustments based on known economic relationships and is intended to reflect how agricultural producers respond to new and different agricultural market opportunities, such as for biomass. Available biomass is constrained to not exceed the tolerable soil loss limit of the USDA Natural Resources Conservation Service and to not allow long-term reduction of soil organic carbon.

Changes from the previous 2016 BTR dataset include updated biomass removal constraints to align with updated soil loss constraints and avoid any long-term reductions in soil organic carbon. These changes have reduced the overall biomass potential from about 2,569 tBtu to 2,185 tBtu, a decline of 15%.

POLYSYS simulates exogenous price changes introduced as a farmgate price, which then solves for biomass supplies that may be brought to market in response to these prices. The farmgate price is held constant nationwide in all counties over all years of the simulation to allow farmers to respond by changing crops and practices gradually over time. [18]

Agricultural residue volumes are then derived from these estimates at a county level, and reflect total aboveground biomass produced as byproducts of conventional crops, and then limited by sustainability and economic constraints. Not all agricultural residues are made available, as crop residues often provide important environmental benefits, such as protection from wind and water erosion, maintenance of soil organic carbon, and soil nutrient recycling.

In the simulations, no land use change is assumed to occur, except within the agricultural sector (i.e., forested land is not converted to agricultural land for agricultural residue or energy crop purposes).

To summarize, the DOE modeling approach attempts to capture the economic and environmental of biomass over time, reflected through the introduction of escalating economic incentives to collect and aggregate various agricultural residues at a granular (farm) level. An increase in economic incentive (measured in dollars per dry ton of biomass) leads to the rising availability of biomass, which in turn could be directed towards RNG production (among other productive end uses). The updated BT23 dataset shows all agricultural residue biomass becomes available at $70 per dry ton, with this parameter forming the basis for the supply scenarios.

The table below lists the energy content on a higher heating value (HHV) basis for the various agricultural residues included in the analysis. The energy content is based on values applied in the BT23 and reported by the California Biomass Collaborative.

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17 GTI, Low-Carbon Renewable Natural Gas from Wood Wastes, February 2019, available online at https://www.gti.energy/wp-content/uploads/2019/02/Low-Carbon-Renewable-Natural-Gas-RNG-from-Wood-Wastes-Final-Report-Feb2019.pdf
18 DOE, 2016. 2016 Billion-Ton Report, https://www.energy.gov/eere/bioenergy/2016-billion-ton-report.

Table 13. Heating Values for Agricultural Residues

Agricultural Component	MMBtu/ton, dry
Barley straw	14.89
Corn stover	15.72
Cotton field residues	14.89
Cotton gin trash	14.12
Oats straw	14.89
Pruning residues	17.37
Rice hulls	13.62
Rice straw	14.89
Sorghum stubble	14.83
Wheat straw	14.89

The national volume of agricultural residue was extracted at the county level and grouped by the nine census divisions. Using the heating values outlined above and assuming a 65% efficiency for thermal gasification systems, ICF estimated the RNG production potential from agricultural residue feedstocks at the $70/dt biomass price, shown in the table below by census division, for a national total of 2,185 tBtu/y.

Table 14. RNG Production Potential, Agricultural Residues (tBtu/y)

	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
Maximum RNG Potential (tBtu/y)	0.9	24.5	703.2	1,113.9	44.7	54.0	90.8	56.4	96.9

Energy Crops

Energy crops are inclusive of perennial grasses, trees, and some annual crops that can be grown specifically to supply large volumes of uniform, consistent quality feedstocks for energy production. Energy crop estimates are based on the same modeling framework used to derive the agricultural residue estimates, outlined in the previous section. In general, biomass from energy crops has the potential to be utilized in different end-use applications, including liquid biofuels and other gaseous biofuels beyond RNG. Bioenergy, including RNG from energy crops, likely has a significant role to play in the long-term decarbonization process, and biomass from feedstocks such as energy crops will be in high demand across the bioenergy value chain. However, RNG is well-positioned to be a highly competitive end-use for biomass, as it is a drop-in fuel with an established infrastructure network.

To estimate the RNG potential from energy crops, ICF extracted data from the DOE's Bioenergy KDF, updated from the 2016 BTR used in the 2019 AGF Study to the BT23 Study. The Bioenergy KDF includes numerous and significant constraints on energy crop biomass, consistent with those applied for agricultural residues noted above.

In addition to the constraint of available land, there are annual constraints (5% of permanent pasture, 20% of cropland pasture, 10% of cropland) and cumulative constraints (40% of permanent pasture, 40% of cropland pasture, 10% of cropland) applied to the BT23 modeling regarding land that can be converted to energy crops. These constraints are also bound by the management-intensive grazing (MiG) constraint of 1.5 acres of MiG required for one acre of pasture converted to energy crops. Eligible pasture is defined as having greater than or equal to 25 inches of annual precipitation, which excludes irrigated pasture acres amounting to 47.1 million acres of land nationally. With respect to land use change, rather than shifting existing agricultural production (e.g., corn and soy) to energy crop production, DOE's modeling also shows that energy crops are largely grown on idle or available pasture lands, particularly at lower farmgate prices.

Relative to the 2016 BTR, updated data from the BT23 Study delivers a significant increase in biomass potential from energy crops, rising from 4,601 tBtu/y equivalent to 7,331 tBtu/y. This 60% increase is driven by:

- Increased biomass from existing energy crops through higher yields, multiple crop rotations and enhanced crop viability on marginal lands due to improved production techniques combined with more detailed and real-world understanding of energy crop potential; and
- New types of energy crops, including camelina, carinata, and pennycress (noting some new biomass sources in BT23 have been excluded from this RNG-focused analysis, such as micro- and macro-algae).

ICF extracted data from the Bioenergy KDF at a minimum price point of $70/dry ton of biomass, up to $400/dt. The table below lists the energy content on an HHV basis for the 11 energy crops included in BT23.

Table 15. Heating Values for Energy Crops

Energy Crop	MMBtu/ton, dry
Biomass sorghum	16.42
Camelina	24.49
Carinata	24.03
Energy cane	16.66
Eucalyptus	17.28
Miscanthus	16.66
Pennycress	23.29
Pine	18.22
Poplar	16.90
Switchgrass	16.42
Willow	17.30

Using the heating values outlined above and assuming a 65% efficiency for thermal gasification systems, ICF estimated the maximum RNG production potential from energy crop feedstocks by census division, shown in the following table. As part of the scenario analysis, ICF assumed the potential for varying levels of competition from other bioenergy types and only allowed for a relatively limited share of energy crop biomass to be directed towards RNG production, even in the most optimistic scenarios.

Table 16. RNG Production Potential, Energy Crops (tBtu/y)

	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
Maximum RNG Potential (tBtu/y)	22.1	152.8	577.0	2,327.5	684.0	599.8	2,660.0	308.0	0.0

Forestry and Forest Product Residues

Forestry and forest product residues include biomass generated from logging, forest and fire management activities, and milling. Logging residues (e.g., bark, stems, leaves, branches), forest thinnings (e.g., removal of small trees to reduce fire danger), and mill residues (e.g., slabs, edgings, trimmings, sawdust) are also considered in the analysis. This includes materials from public forestlands (e.g., state, federal), but not specially designated forests (e.g., roadless areas, national parks, wilderness areas) and includes sustainable harvesting criteria as described in BT23.

Forestry residues as a biomass resource in BT23 include the following sustainability criteria:

- Biomass retention levels defined by slope class (e.g., slopes with between 40% and 80% grade include 40% biomass left on-site, compared to the standard 30%).
- No reserved (e.g., wild and scenic rivers, wilderness areas, USFS special interest areas, national parks) and roadless designated forestlands, forests on steep slopes and in wet land areas (e.g., wetlands, stream management zones), and sites requiring cable systems.
- Only thinnings for over-stocked stands and no removals greater than the anticipated forest growth in a state.
- No road building greater than 0.5 miles.

In addition, relative to the 2016 BTR, BT23 includes greater granularity on road access to forestry resources, as well as refined assumptions related to forestry residue biomass potential. These additional sustainability criteria provide a more realistic assessment of available forestland than other studies.

ICF extracted information from the US DOE Bioenergy KDF, which includes information on forest residues such as thinnings, mill residues, and different residues from woods (e.g., mixedwood, hardwood, and softwood). The Bioenergy KDF estimates are based on ForSEAM, a linear programming model constructed to estimate forestland production over time, including both traditional forest products but also products that meet biomass feedstock demands. The model assumes that projected traditional timber demands will be met and estimates costs, land use, and competition between lands. The forestry and forest product residue estimates also reflect a cost minimization framework that minimizes the total costs (harvest costs and other costs) under a production target goal in addition to land, growth, and other constraints. The cost minimization framework includes the POLYSYS model as well as IMPLAN, an input-output model that estimates impacts to the economy.

ICF extracted data from the Bioenergy KDF at price points, from $30/ton to $70/ton for forest and forest product residue biomass. The biomass data showed minimal resource availability at prices less than $50/ton, with all biomass becoming available at $70/ton.

The table below lists the energy content on an HHV basis for the various forest and forest product residue elements considered in the analysis. To estimate the RNG production potential, ICF assumed a 65% efficiency for thermal gasification systems.

Table 17. Heating Values for Forestry and Forest Product Residues

Forestry and Forest Product	MMBtu/ton, dry
Fire reduction thinnings	17.38
Forest processing waste	18.22
Logging residues	17.37
Other forest waste	17.37
Small diameter trees	17.00

Using the heating values outlined above and assuming a 65% efficiency for thermal gasification systems, ICF estimated the maximum RNG production potential from forestry and forest product residue feedstocks of 715 tBtu/y, a 10% increase from the 2016 BTR estimate used in the 2019 AGF Study. The table below shows the maximum potential broken down by census division.

Table 18. RNG Production Potential, Forestry and Forest Product Residue (tBtu/y)

	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
Maximum RNG Potential (tBtu/y)	56.9	100.2	79.8	22.2	217.6	93.5	69.7	39.9	35.1

Municipal Solid Waste

MSW represents the trash and various items that household, commercial, and industrial consumers throw away—including materials such as paper and paperboard, plastics, rubber and leather, textiles, urban wood waste, and yard trimmings. Nationwide, about 25% of MSW is currently recycled, 9% is composted, and 13% is combusted for energy recovery, with the roughly 50% balance landfilled.

ICF limited its consideration of MSW to only the potential for utilizing waste that is currently landfilled as a feedstock for thermal gasification; this excludes MSW that is recycled or directed to waste-to-energy facilities.

ICF extracted information from the US DOE's Bioenergy KDF, which includes information collected as part of US DOE's Billion Ton Study, updated in 2023. The Bioenergy KDF includes the following waste residues: paper and paperboard, plastics, rubber and leather, textiles, urban wood waste and yard trimmings. ICF extracted data from the Bioenergy KDF at price points between $30/ton and $300/ton. While existing MSW is currently aggregated, an assumption included in the DOE analysis is that the rising value associated with the different types of MSW will create an increasing economic incentive to divert useful MSW waste streams towards productive end-uses, such as RNG production.

The table below lists the energy content on an HHV basis for the various components of MSW. To estimate the RNG production potential, ICF assumed a 65% efficiency for thermal gasification systems.

Table 19. Heating Values for MSW Components

MSW Product	MMBtu/ton, dry
Paper and paperboard	14.20
Plastics	27.98
Rubber and leather	17.50
Textiles	15.00
Urban wood waste	16.00
Yard trimmings	5.60

Using the heating values outlined above and assuming a 65% efficiency for thermal gasification systems, ICF estimates the maximum RNG production potential from MSW at 2,184 tBtu/y, a 19% increase on the maximum technical potential used in the 2019 AGF Study. This increase is driven by BT23 assumptions related to waste production and waste growth across multiple sub-categories, including paper and paperboard, yard trimmings, and plastics. Urban wood waste is also a new MSW feedstock subcategory, contributing to the overall increase in technical potential. The table below shows the 2,184 tBtu/y maximum, broken out by census division.

Table 20. RNG Production Potential, MSW (tBtu/y)

	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
Maximum RNG Potential (tBtu/y)	41.6	176.2	283.8	138.2	518.8	138.5	385.6	202.2	298.6

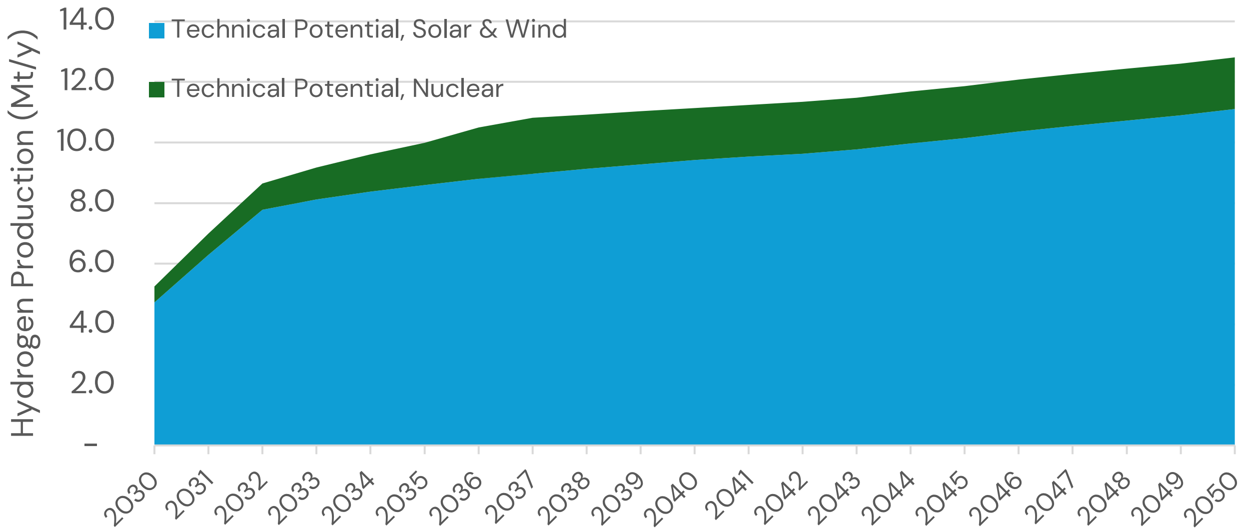
2.3.4 RNG Produced via Methanated Hydrogen

As outlined previously, there are three main components of this pathway—renewable hydrogen via electrolysis, carbon dioxide from various sources, and methanation. Unlike the AD and TG RNG production pathways described previously, which are derived from the chemical and physical processing of biomass, RNG production via P2G/methanation does not have a clear analogous resource constraint tied to some inherent limit to a particular resource. In the absence of a natural resource constraint, ICF focused on renewable hydrogen production as the limiting factor in its estimates for the RNG technical potential derived from P2G/methanation. This constraint imposed was two-fold:

- **Renewable Electricity Constraint**: ICF used annual forecasts for solar, wind, and nuclear power from the Annual Energy Outlook (AEO) Reference Case, with 2023 being the most recent year for which data are available. ICF assumed that 25% of solar and wind resources would be available for hydrogen production and about 17% of nuclear resources would be available for hydrogen production.
- **Technology Readiness Constraint**: ICF estimated the annual installation of hydrogen plants using a database of announced hydrogen projects, categorized by technology and state, assuming no resource limitations.

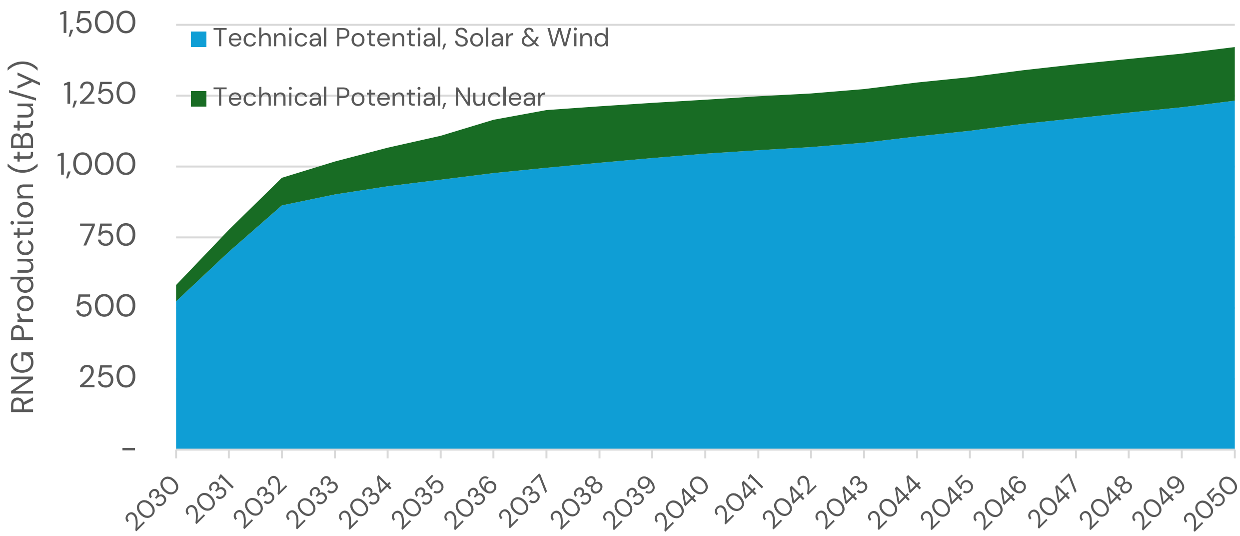
For each year, the most conservative forecast from these two constraints was selected to develop a proxy for the technical potential forecast for hydrogen. In the early years of the analysis, the technology readiness constraint was the limiting factor, but over time, the renewable electricity constraint became more conservative. ICF notes that it also only considered RNG from the P2G/methanation pathway starting in 2030 and through 2050.

Figure 6. Hydrogen Potential from Renewables and Nuclear (tBtu/y)



Based on the stoichiometric conversion of the methanation reaction, ICF reports a proxy technical potential for RNG of 1,420 tBtu/y by 2050—with 1,230 tBtu/y from wind and solar resources and 190 tBtu/y from nuclear resources.

Figure 7. RNG Production from Methanated Hydrogen (tBtu/y)



2.4 RNG Supply Scenarios

ICF developed RNG supply estimates for three separate scenarios for each feedstock in the RNG inventory at the national and census division levels. The RNG production potential included in the analysis is based on an assessment of multiple factors, including but not limited to demand, feedstock costs, technological development, and the policies in place that might support RNG project development. ICF assessed the RNG resource potential of the different feedstocks that could be realized, given the necessary market considerations (without explicitly defining what those are). The three scenarios for each feedstock—with varying assumptions that influence the level of feedstock utilization relative to the RNG inventory — defined by ICF are as follows:

- **Low Scenario**. Represents a low level of feedstock utilization. Utilization levels depending on feedstock, with a range from 30% to 60% for feedstocks that were converted to RNG using anaerobic digestion technologies. The utilization rate of feedstocks for thermal gasification in this scenario is between 5% to 30% of the biomass available at moderate biomass prices. Overall, the Low Scenario captures 10% of the technical potential for RNG production from aggregated feedstock supply (see Figure 4).
- **High Scenario.** Represents balanced assumptions regarding feedstock utilization. Utilization ranges from 50% to 80% for feedstocks that were converted to RNG using anaerobic digestion technologies. The utilization rates of feedstocks for thermal gasification in this scenario are 15% to 50% of the biomass available at moderate prices. Overall, the High Scenario captures 23% of the technical potential for RNG production from aggregated feedstock supply (see Figure 4).
- **Ambitious Emissions Reduction Scenario.** Represents optimistic assumptions regarding feedstock utilization. This scenario is reflective of a future with aggressive climate policies pursuing a wide range of emission reduction opportunities. Utilization ranges from 70% to 95% for feedstocks that were converted to RNG using anaerobic digestion technologies. The utilization rates of feedstocks for thermal gasification in this scenario are 25% to 70% of the biomass available at higher prices. Overall, the Ambitious Emissions Reduction Scenario captures 43% of the technical potential for RNG production from aggregated feedstock supply (see Figure 4).

The following three tables include the estimated RNG supply available by 2050 across the nine census divisions. Results are shown separately for Low, High, and Ambitious Emissions Reduction Scenarios, and show the development potential of each feedstock separately. Appendix B has state-level supply results at the technical potential level and by scenario.

Table 21. Low Scenario Annual RNG Production Potential by 2050 (tBtu/y)

RNG Feedstock		New England	Mid Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific	National Total
Anaerobic Digestion	Animal Manure	1.5	11.6	44.1	30.1	26.7	16.8	36.9	23.3	22.5	213.4
	Food Waste	1.9	3.5	0.8	1.0	5.1	0.4	2.0	1.1	5.6	21.3
	Landfill Gas	3.8	28.4	80.8	21.1	74.3	27.0	59.0	46.1	69.4	409.9
	Wastewater	1.0	4.4	6.7	1.8	4.4	1.3	2.6	1.6	4.5	28.3
	AD Subtotal	**8.2**	**47.8**	**132.3**	**53.9**	**110.5**	**45.5**	**100.4**	**72.2**	**102.0**	**672.9**
Thermal Gasification	Ag Residues	0.1	3.7	105.4	167.0	6.7	8.1	13.6	8.5	14.5	327.6
	Energy Crops	1.1	7.1	22.0	107.1	32.4	28.4	131.6	15.4	0.0	345.0
	Forest Residues	8.5	15.0	12.0	3.3	32.6	14.0	10.5	6.0	5.3	107.2
	MSW	7.2	20.2	21.0	10.4	39.3	6.6	24.2	15.0	31.3	175.3
	TG Subtotal	**17.0**	**46.0**	**160.4**	**287.7**	**111.0**	**57.1**	**179.9**	**44.9**	**51.1**	**955.0**
Total RNG from biogenic resources		25.2	93.8	292.7	341.6	221.5	102.6	280.3	117.0	153.1	1,627.8

Table 22. High Scenario Annual RNG Production Potential by 2050 (tBtu/y)

Potential Feedstock for RNG (tBtu/y)		New England	Mid Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific	National Total
Anaerobic Digestion	Animal Manure	3.0	23.1	88.0	60.0	53.2	33.6	73.6	46.6	45.0	426.1
	Food Waste	3.2	5.6	2.4	2.6	10.8	1.4	6.1	3.0	8.6	43.6
	Landfill Gas	6.7	49.7	141.3	36.9	130.0	47.2	103.2	80.7	121.3	717.0
	Wastewater	1.6	6.0	9.2	2.6	6.6	2.1	4.1	2.3	6.2	40.5
	AD Subtotal	**14.4**	**84.4**	**240.9**	**102.0**	**200.6**	**84.2**	**186.9**	**132.6**	**181.1**	**1,227.1**
Thermal Gasification	Ag Residues	0.4	9.8	281.1	445.2	17.9	21.6	36.3	22.5	38.7	873.5
	Energy Crops	3.3	21.3	66.0	321.2	97.1	85.1	394.8	46.1	0.0	1,034.9
	Forest Residues	22.7	40.0	31.9	8.9	87.0	37.4	27.9	16.0	14.0	285.8
	MSW	12.0	33.7	35.6	19.2	66.5	15.8	45.4	26.2	52.2	306.7
	TG Subtotal	**38.4**	**104.8**	**414.7**	**794.5**	**268.5**	**159.9**	**504.4**	**110.8**	**105.0**	**2,500.9**
Total RNG from biogenic resources		52.8	189.2	655.6	896.5	469.1	244.1	691.3	243.4	286.0	3,728.1

Table 23. Ambitious Emissions Reduction Scenario Annual RNG Production Potential by 2050 (tBtu/y)

Potential Feedstock for RNG (tBtu/y)		New England	Middle Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific	National Total
Anaerobic Digestion	Animal Manure	4.1	31.7	152.7	147.8	84.7	60.6	154.3	92.8	69.4	798.1
	Food Waste	4.3	11.7	12.4	6.8	21.6	5.6	14.9	8.4	17.3	103.1
	Landfill Gas	9.7	70.6	200.9	53.1	185.7	68.4	146.9	115.8	172.7	1,023.9
	Wastewater	2.8	10.9	16.6	4.6	11.9	3.7	7.3	4.1	11.2	73.2
	AD Subtotal	**20.9**	**124.9**	**382.7**	**212.4**	**303.9**	**138.2**	**323.4**	**221.1**	**270.7**	**1,998.3**
Thermal Gasification	Ag Residues	0.5	14.7	421.7	667.9	26.8	32.4	54.4	33.8	58.1	1,310.3
	Energy Crops	5.5	35.5	110.0	535.3	161.9	141.8	657.9	76.9	0.0	1,724.9
	Forest Residues	39.8	70.1	55.8	15.6	152.2	65.4	48.8	27.9	24.6	500.1
	MSW	29.1	123.2	198.5	96.7	362.9	96.9	269.7	141.4	208.9	1,527.4
	TG Subtotal	**74.9**	**243.5**	**786.1**	**1,315.4**	**703.8**	**336.5**	**1,030.9**	**280.1**	**291.5**	**5,062.6**
Total RNG from biogenic resources		95.9	368.4	1,168.8	1,527.8	1,007.7	474.7	1,354.3	501.2	562.2	7,060.9

2.5 Summary of RNG Potential by Scenario

Figure 8 through Figure 10 below show the total RNG production potential for each AD/TG feedstock by scenario from 2025 out to 2050.

In the Low Scenario (Figure 8), RNG production via anaerobic digestion of feedstocks drives deployment to 2035, with landfill gas making up a large proportion of RNG supply potential, and then declining out to 2050. Commercialization of the thermal gasification production technology after 2035 sees the increased deployment of feedstocks expected to utilize that technology, with agricultural residues and energy crops a larger share of total potential. Overall, the Low scenario delivers a maximum supply of 1,628 tBtu/y, or 10% of aggregated biomass feedstock that could be used for RNG production.

Similar to the Low Scenario, the High Scenario assumes RNG production is driven by anaerobic digestion of feedstocks in the next decade, but with an increased deployment of RNG via thermal gasification of biomass taking place post-2035 (Figure 9). The increased utilization of biomass—including agricultural residues, energy crops and to a lesser extent MSW—helps to increase RNG production potential in the High Scenario. Nearly 70% of RNG is derived from biomass thermal gasification in 2050 in the High Scenario. The High Scenario utilizes 20% of available biomass, delivering maximum annual RNG production of 3,728 tBtu/y.

The Ambitious Emissions Reduction Scenario reduces constraints across all feedstocks, resulting in similar trends to the High Scenario but on a larger scale, particularly for thermal gasification feedstocks. This scenario reflects the aggressive economic environment where all available emission reductions from RNG in combination with those from other decarbonization measures are leveraged to deliver net-zero emissions by mid-century, including the large-scale deployment of bioenergy across multiple fuels and end uses, not just for RNG. In this scenario, energy crops and MSW become the largest individual sources of RNG, although limiting assumptions for all feedstocks are relaxed. The Ambitious Emissions Reduction Scenario delivers maximum annual RNG production of 7,061 tBtu/y, but still only utilizes 43% of overall biomass potential for RNG production.

Figure 8. Low Scenario Annual RNG Production, 2025-2050 (tBtu/y)

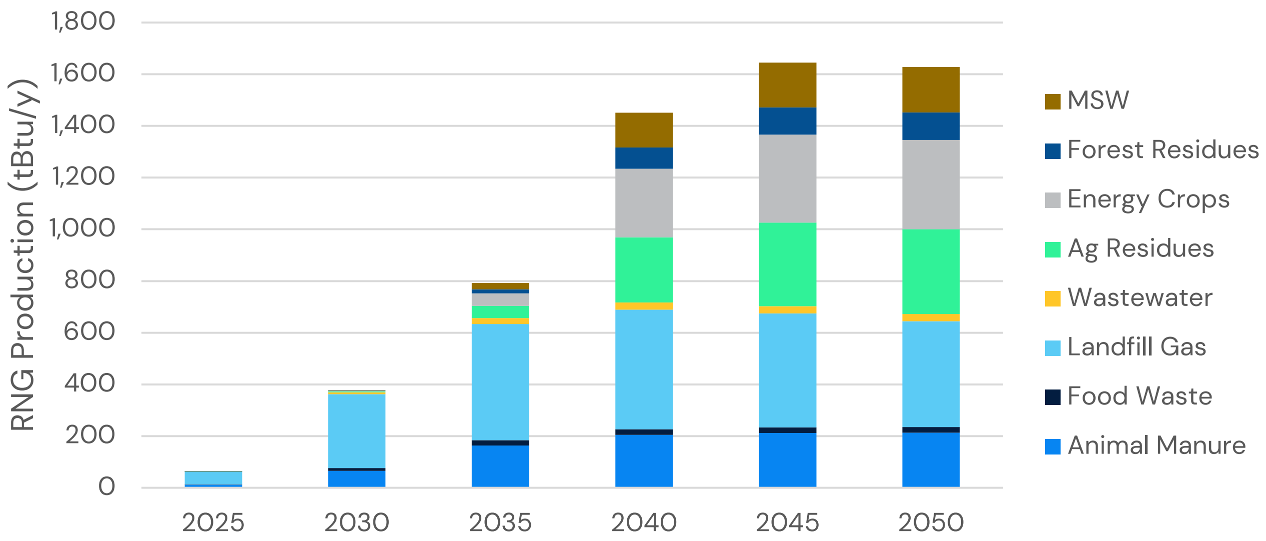


Figure 9. High Scenario Annual RNG Production, 2025-2050 (tBtu/y)

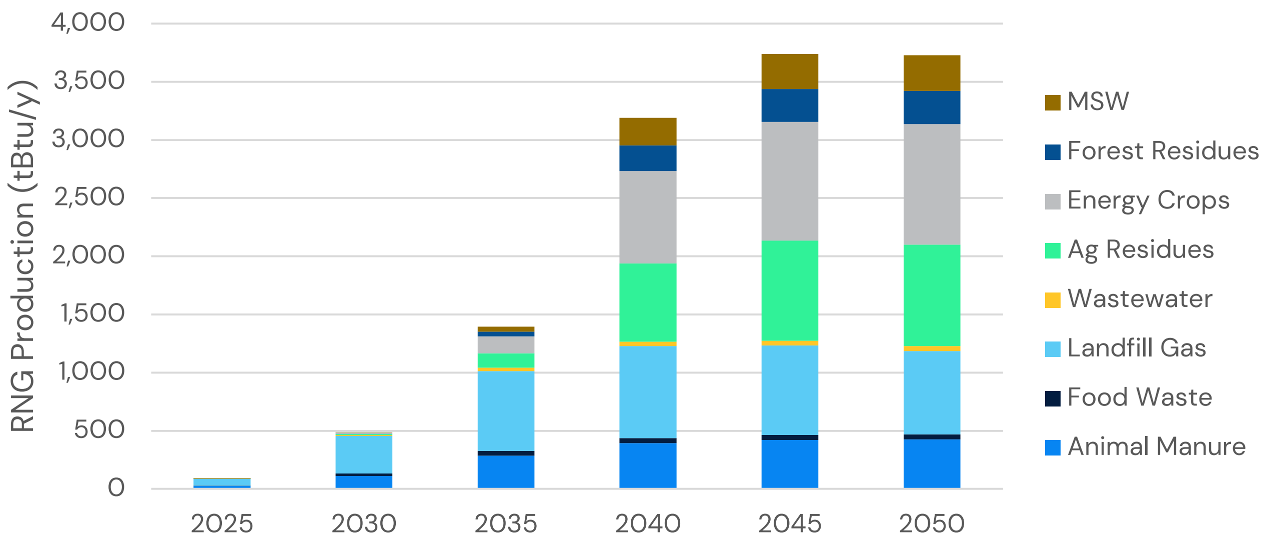
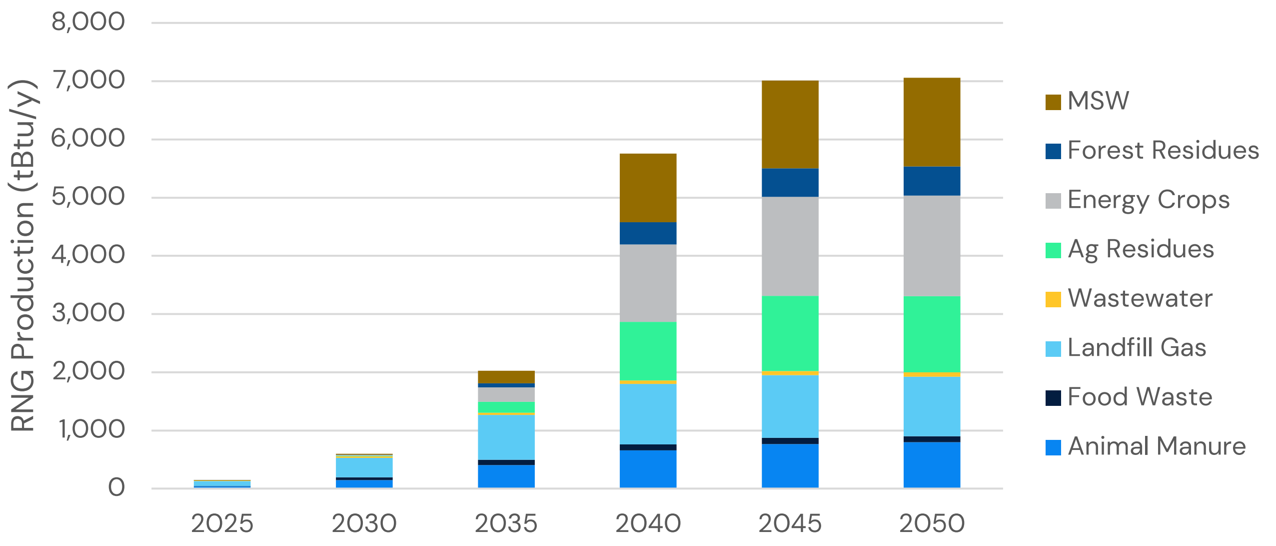


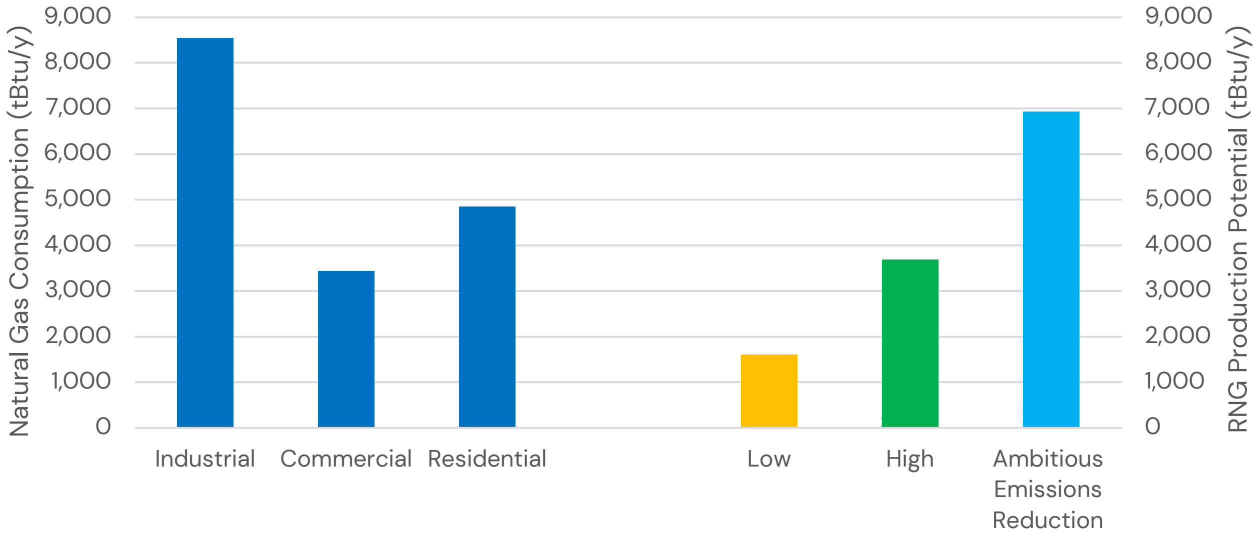
Figure 10. Ambitious Emissions Reduction Scenario Annual RNG Production, 2025-2050 (tBtu/y)



Ultimately, market conditions, technology development, and policy structures will determine the extent to which each of the feedstocks considered can be utilized. Figure 11 below shows how the RNG production potential in each of the scenarios in ICF's analysis compared to the 10-year average[19] of domestic natural gas consumption in different sectors: industrial, commercial, and residential.

[19] Ten-year averages derived from data reported by the Energy Information Administration. https://www.eia.gov/dnav/ng/ng_cons_sum_dcu_nus_a.html. Accessed February 2025.

Figure 11. Average Natural Gas Consumption (2015-2024) vs. RNG Production Potential (tBtu/y)



The following three figures show the maximum annual RNG production potential for each scenario, broken out by census division and feedstock. Across the three scenarios, the figures show a diversity in feedstock potential by geography. Census divisions with centralized and large populations – such as the Mid-Atlantic, South Atlantic, and Pacific divisions – have higher proportions of feedstocks from population waste-based streams, including landfills, MSW, and WRRFs. Census divisions with greater geographic footprints as well as significant agricultural activities generally have a higher proportion of "land-based" feedstocks, including agricultural residues, animal manure and energy crops. However, ICF notes that these trends are not mutually exclusive, in that most census divisions have a reasonable spread of feedstocks.

Figure 12. Low Scenario Maximum Annual RNG Production by Region (tBtu/y)

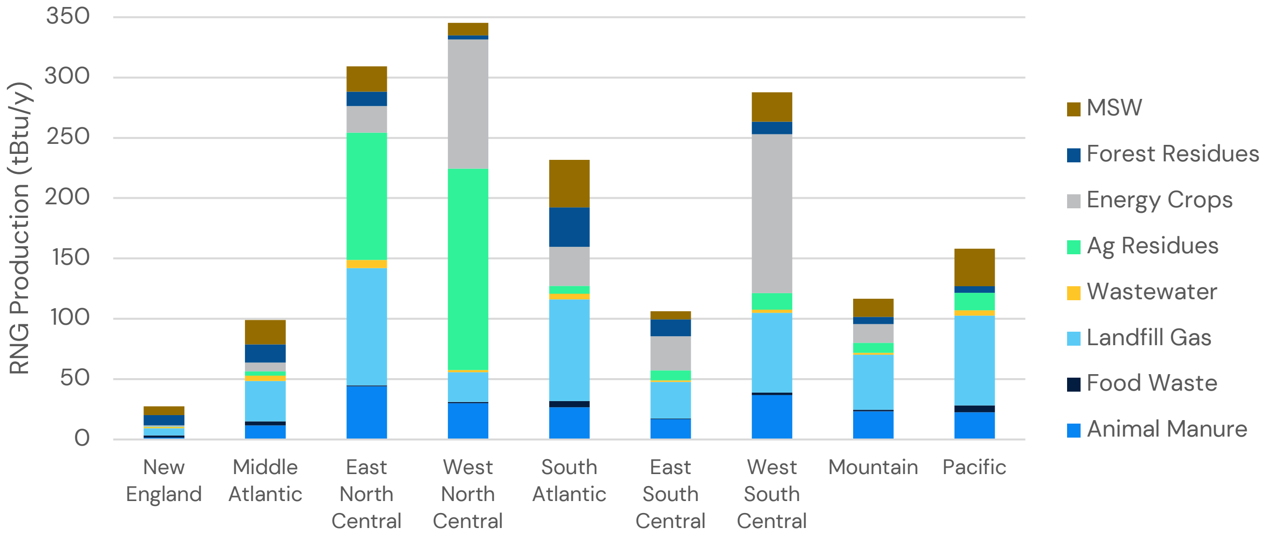


Figure 13. High Scenario Maximum Annual RNG Production by Region (tBtu/y)

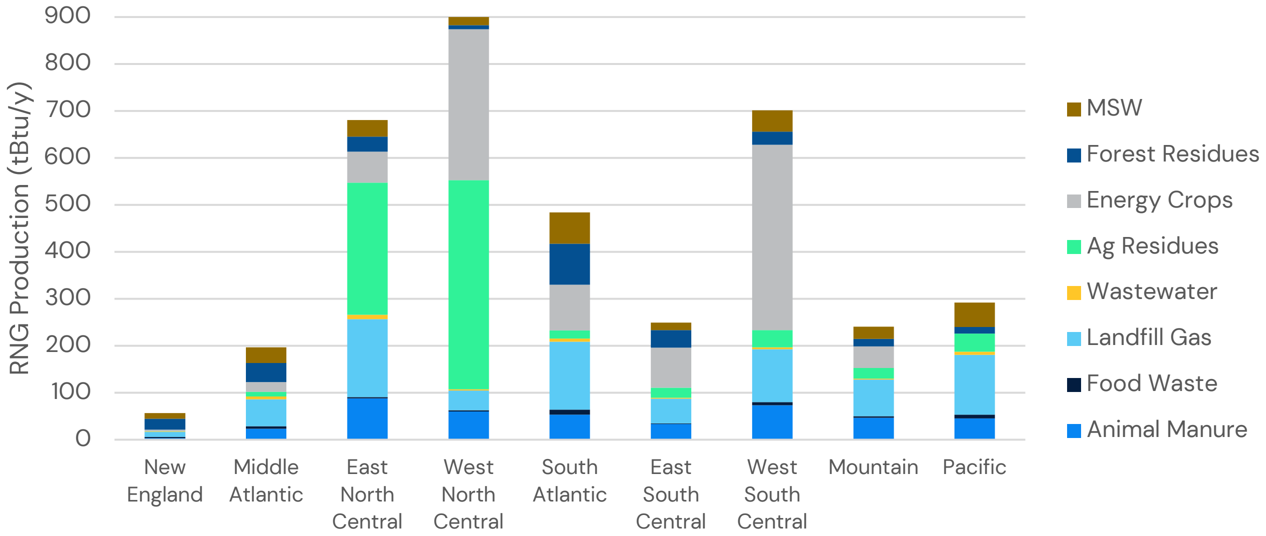
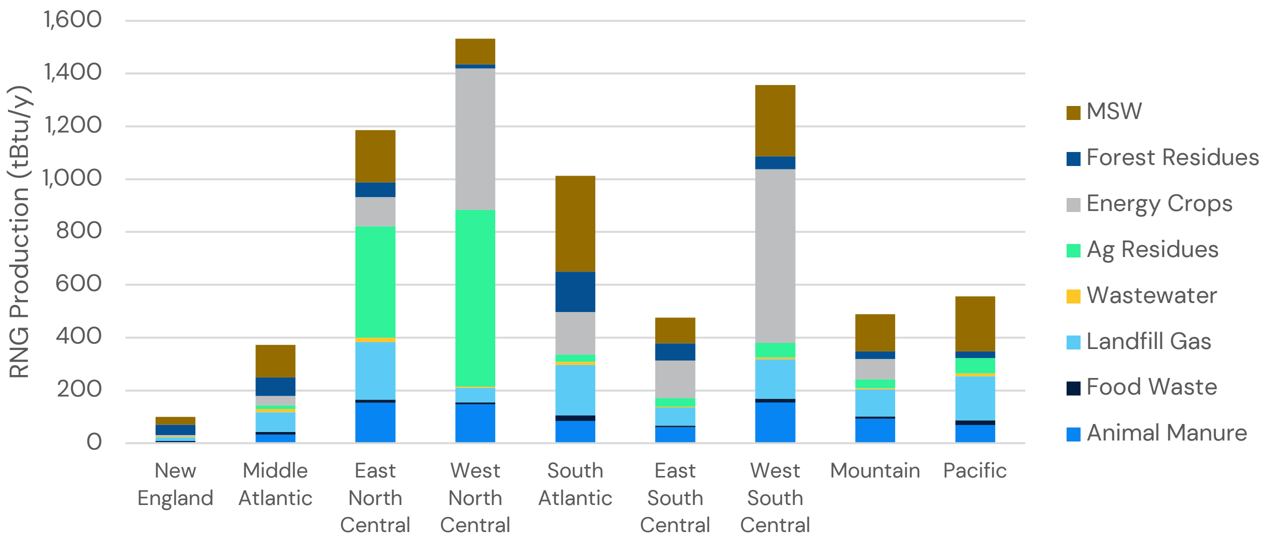


Figure 14. Ambitious Emissions Reduction Scenario Maximum Annual RNG Production by Region (tBtu/y)



2.5.1 RNG via Anaerobic Digestion of Biogenic Resources

Animal Manure

Prior to the application of economic and market constraints for animal manure as an RNG feedstock, ICF applied technical availability factors to each manure type to reflect that not all animal manure can be collected due to practical considerations such as small farming operations and the inability to collect manure from grazing animals. After applying these technical availability factors for each animal manure type, the total available animal manure potential is reduced by over half.

ICF developed the following assumptions for resource potentials for RNG production from the anaerobic digestion of animal manure in the three scenarios.

- In the Low Scenario, ICF assumed that RNG could be produced from 30% of the animal manure, after accounting for the technical availability factor.
- In the High Scenario, ICF assumed that RNG could be produced from 60% of the animal manure, after accounting for the technical availability factor.

- In the Ambitious Emissions Reduction Scenario, ICF assumed that RNG could be produced from 75% of the animal manure, after accounting for the technical availability factor.

Figure 15 shows the national resource potential from animal manure between 2025 and 2050 for the three scenarios. The three figures that follow show annual resource potential between 2025 and 2050 for each scenario, broken out by census division.

Figure 15. National RNG Production Potential from Animal Manure (tBtu/y)

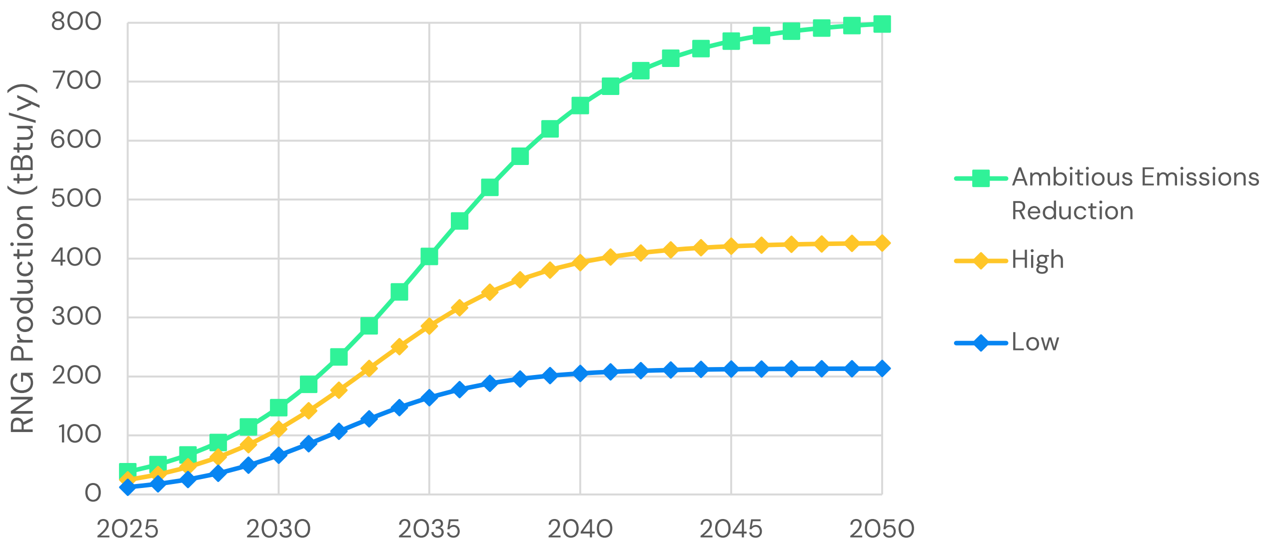


Figure 16. RNG Production Potential from Animal Manure by Census Division, Low (tBtu/y)

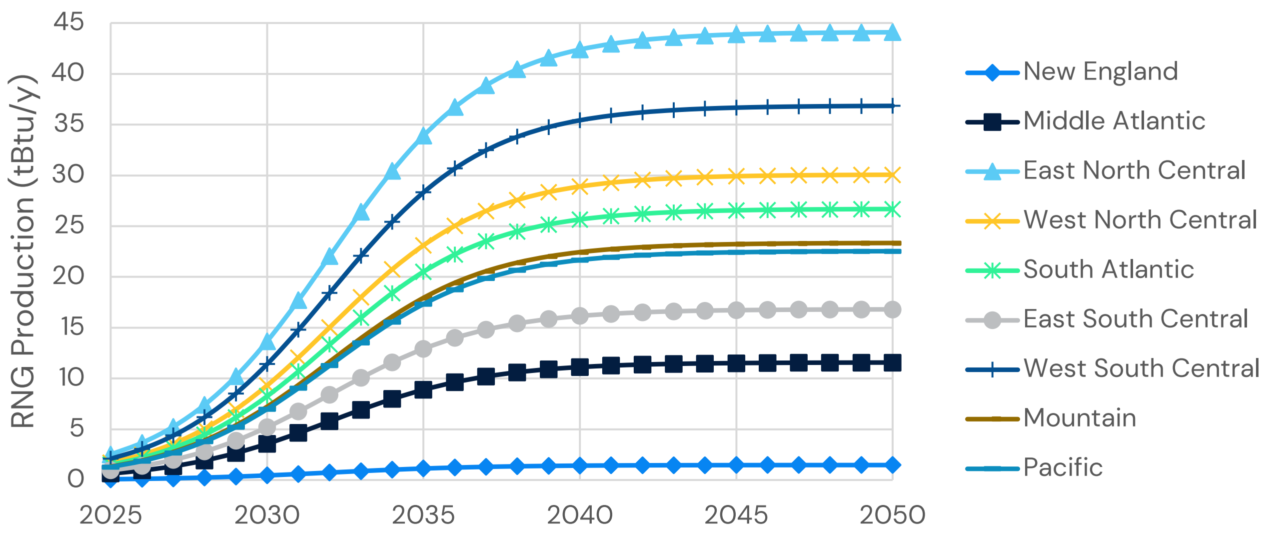


Figure 17. RNG Production Potential from Animal Manure by Census Division, High (tBtu/y)

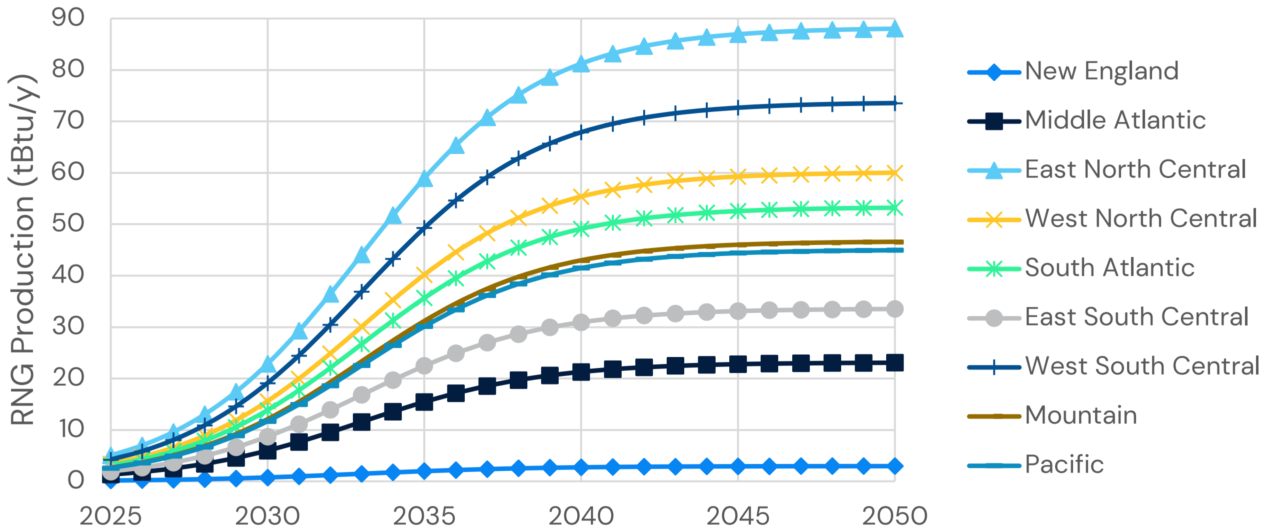
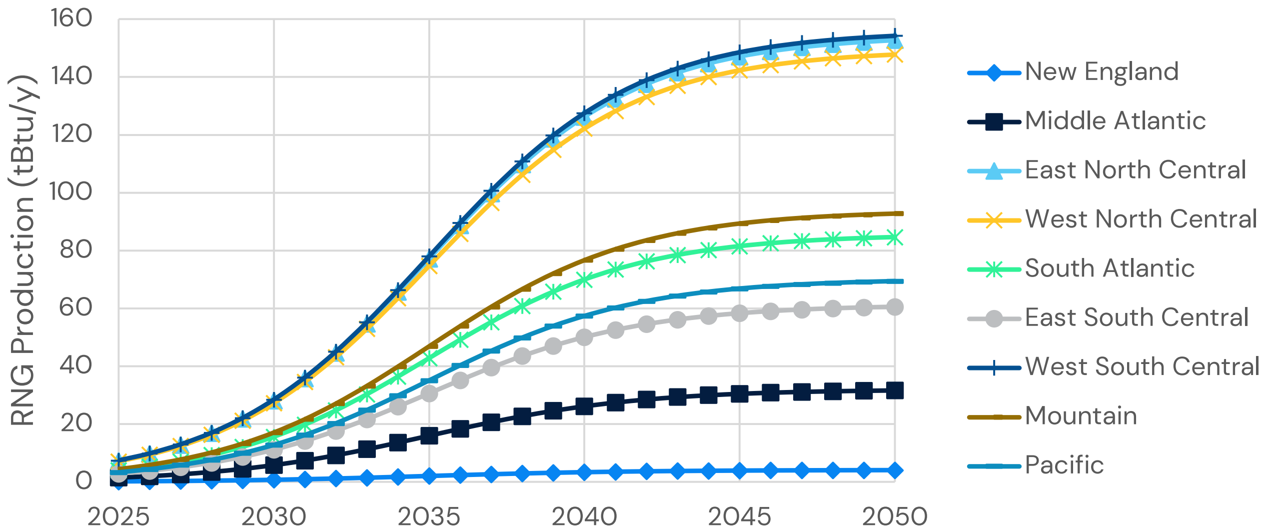


Figure 18. RNG Production Potential from Animal Manure by Census Division, Ambitious Emissions Reduction (tBtu/y)



Food Waste

ICF developed the following assumptions for the RNG production potential from food waste in the three scenarios:

- In the Low Scenario, ICF assumed that 60% of available food waste available at a biomass price of $100/dt would be diverted to AD systems.
- In the High Scenario, ICF assumed that 80% of available food waste available at a biomass price of $200/dt would be diverted to AD systems.
- In the Ambitious Emissions Reduction Scenario, ICF assumed that 70% of available food waste available at a biomass price of $500/dt would be diverted to AD systems.

Figure 19 shows three resource potential scenarios from the anaerobic digestion of food waste between 2025 and 2050. The three figures that follow show annual resource potential between 2025 and 2050 for each scenario, broken out by census division.

Figure 19. National RNG Production Potential from Food Waste (tBtu/y)

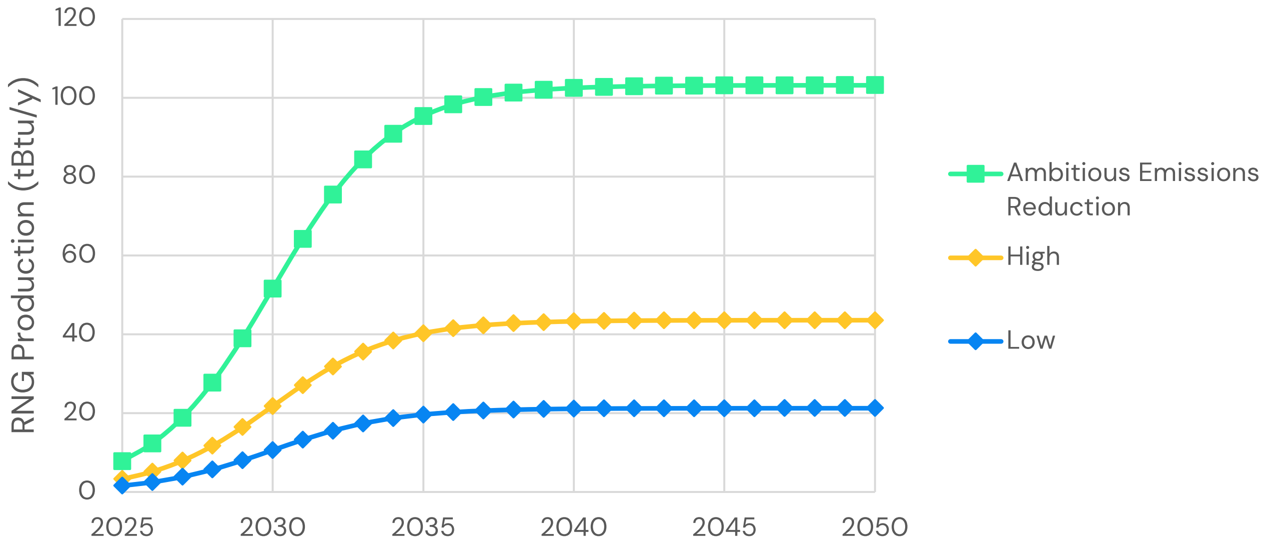


Figure 20. RNG Production Potential from Food Waste by Census Division, Low (tBtu/y)

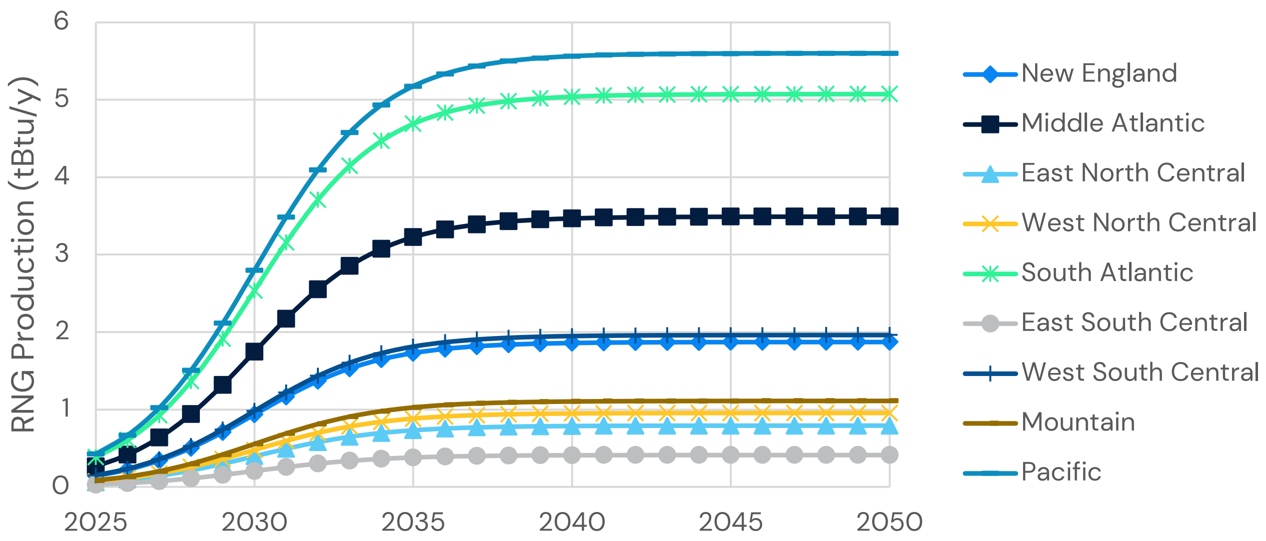


Figure 21. RNG Production Potential from Food Waste by Census Division, High (tBtu/y)

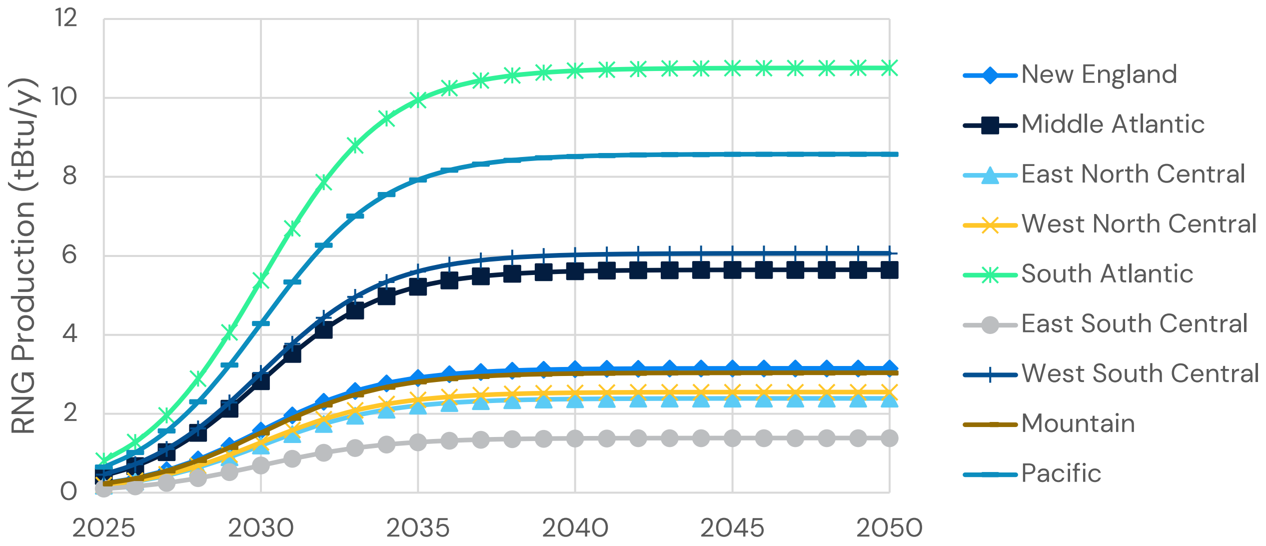
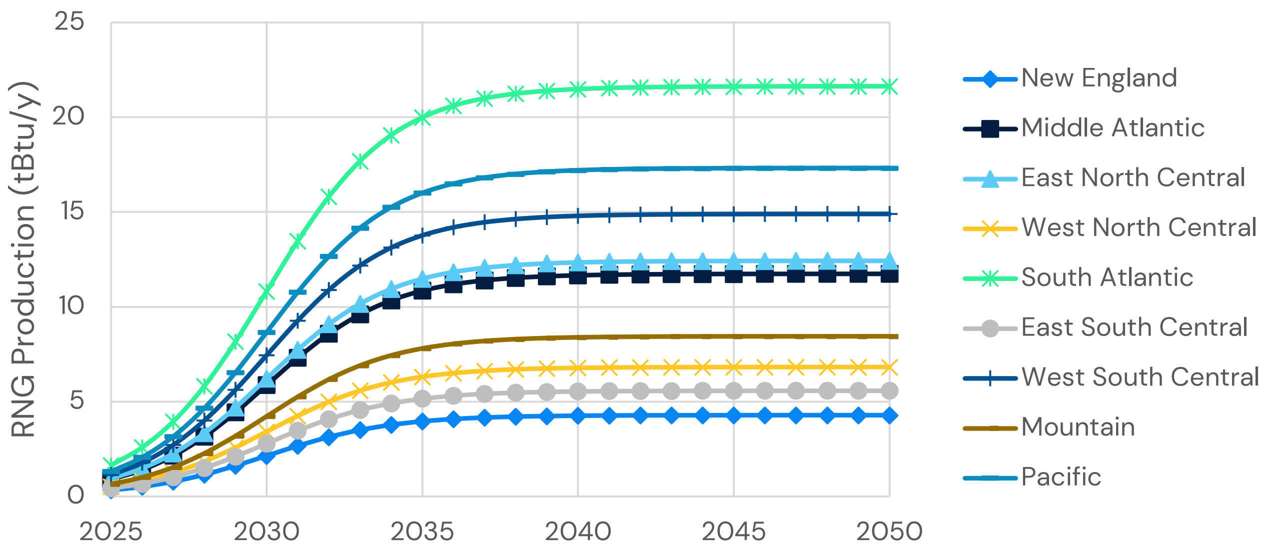


Figure 22. RNG Production Potential from Food Waste by Census Division, Ambitious Emissions Reduction (tBtu/y)



Landfill Gas

To develop the RNG potential from LFG for each scenario, ICF utilized data from the US EPA's LMOP. This database encompasses over 2,000 landfills, where ICF applied the EPA's LandGEM model to quantify methane emissions from these landfills. In this model, landfill gas is assumed to consist of approximately 50% methane and 50% carbon dioxide, with trace amounts of other air pollutants. The LandGEM model calculates methane emissions using a first-order decomposition rate equation based on the annual waste accepted by each landfill. This method represents a more accurate approach compared to the methodology used in the 2019 study.

For the analysis, ICF incorporated annual waste acceptance rates for each landfill from 2010 through 2050 or until the landfill's closure year. The model only includes waste input for landfills that have not yet reached their maximum capacity. Additionally, as outlined in the food waste section, 24% of the waste stream is diverted to food waste management, leaving 76% as input for the LandGEM model to calculate methane emissions.

For each scenario ICF then applied additional constraints on the results from the LandGEM model, which also reflects only eligible landfills with more than one million tons of waste in place that are open or closed after 2005.

- In the Low Scenario, ICF assumed that 40% of eligible LFG facilities would produce RNG.
- In the High Scenario, ICF assumed that 70% of eligible LFG facilities would produce RNG.
- In the Ambitious Emissions Reduction Scenario, ICF assumed that 95% of eligible LFG facilities would produce RNG.

ICF notes that landfills today generally direct landfill gas to electricity, though there is a trend of landfill gas-to-electricity projects switching over to RNG projects, particularly as their electricity projects reach their end of life. Current regulatory and policy incentives provide a lot more value for RNG from landfill gas, rather than electricity from landfill gas. Assumptions related to the scenarios reflect this trend.

Figure 23 below shows the RNG resource potential from LFG between 2025 and 2050 across the three scenarios. The three figures that follow show annual resource potential between 2025 and 2050 for each scenario, broken out by census division.

Figure 23. Annual RNG Production Potential from Landfills (tBtu/y)

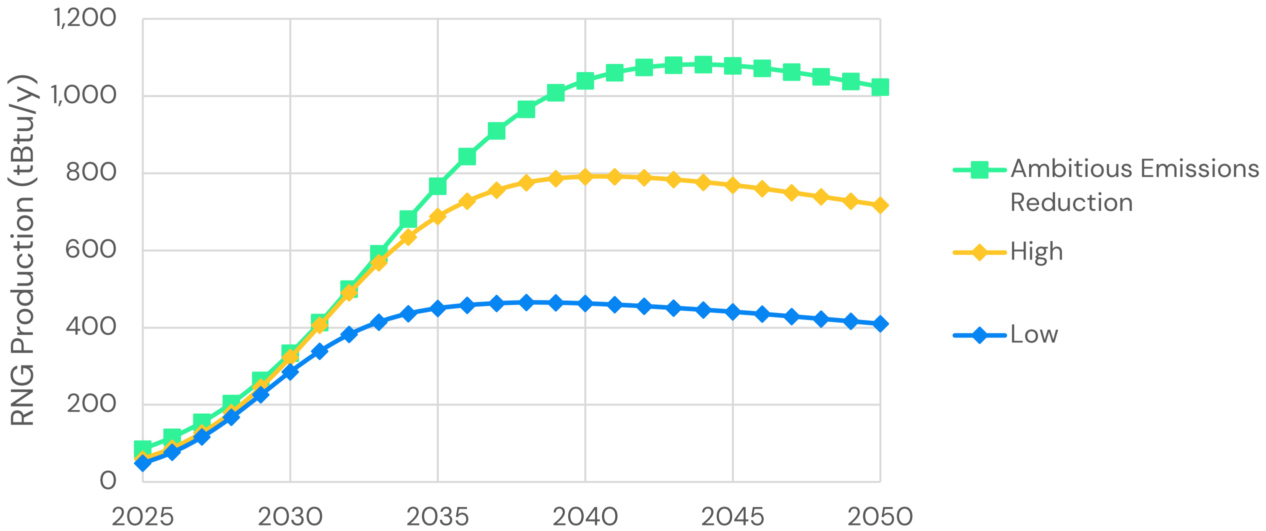


Figure 24. RNG Production Potential from Landfills by Census Division, Low (tBtu/y)

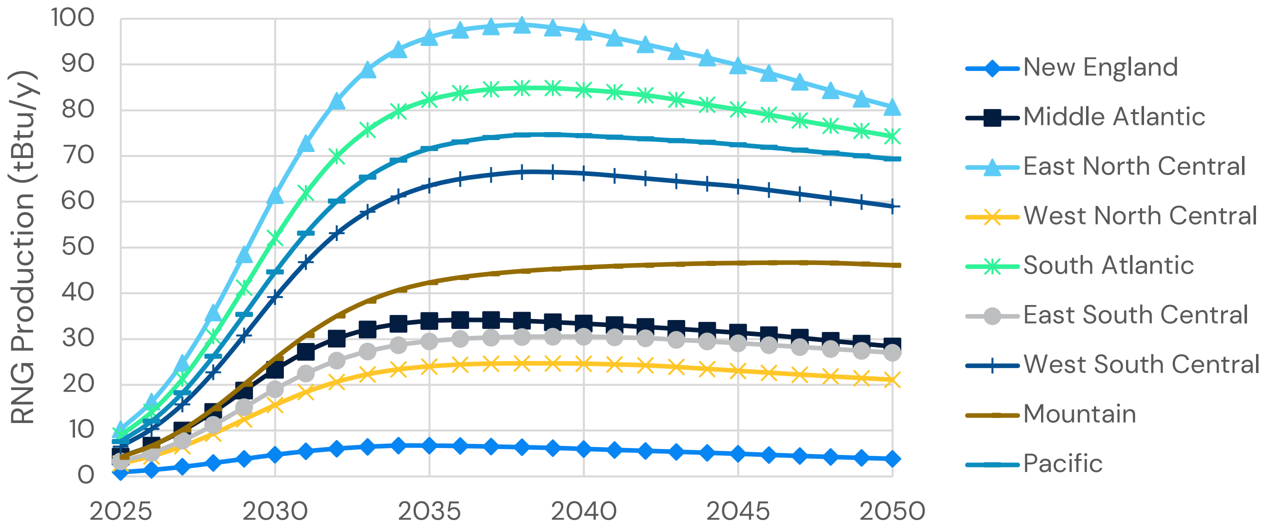


Figure 25. RNG Production Potential from Landfills by Census Division, High (tBtu/y)

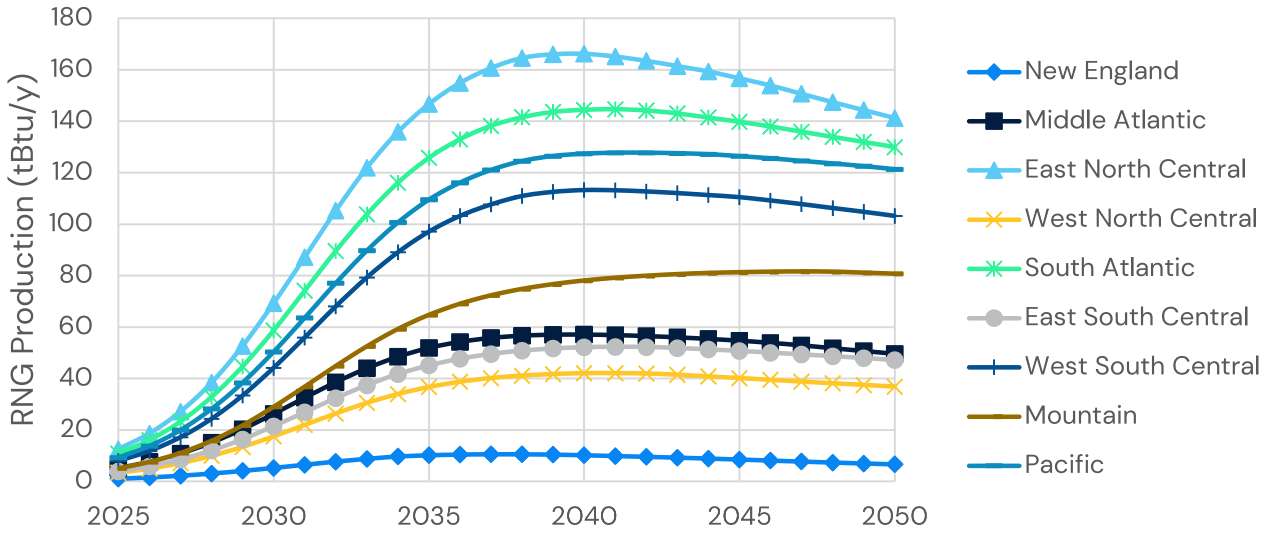
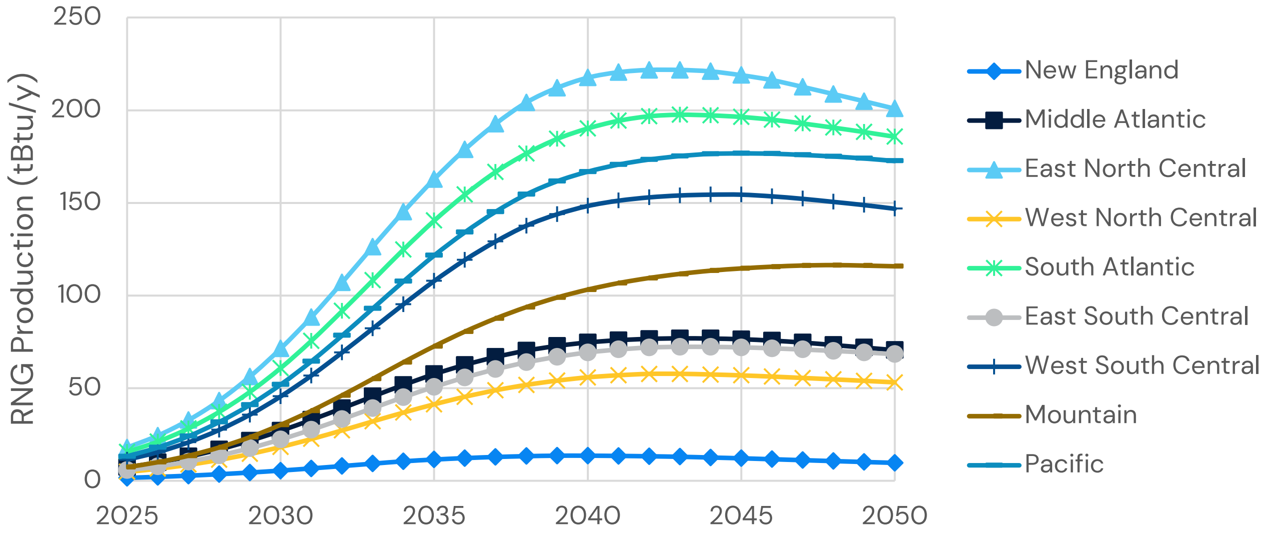


Figure 26. RNG Production Potential from Landfills by Census Division, Ambitious Emissions Reduction (tBtu/y)



Wastewater

ICF developed the following assumptions for the resource potentials for RNG production from wastewater at WRRFs in the three scenarios:

- In the Low Scenario, ICF assumed that 30% of WRRFs with a capacity greater than 7.5 MGD would produce RNG.
- In the High Scenario, ICF assumed that 50% of WRRFs with a capacity greater than 3.5 MGD would produce RNG.
- In the Ambitious Emissions Reduction Scenario, ICF assumed that 95% of WRRFs with a capacity greater than 3.5 MGD would produce RNG.

Figure 27 below shows the RNG resource potential from WRRFs between 2025 and 2050 across the three scenarios. The three figures that follow show annual resource potential between 2025 and 2050 for each scenario, broken out by census division.

Figure 27. Annual RNG Production Potential from WRRFs (tBtu/y)

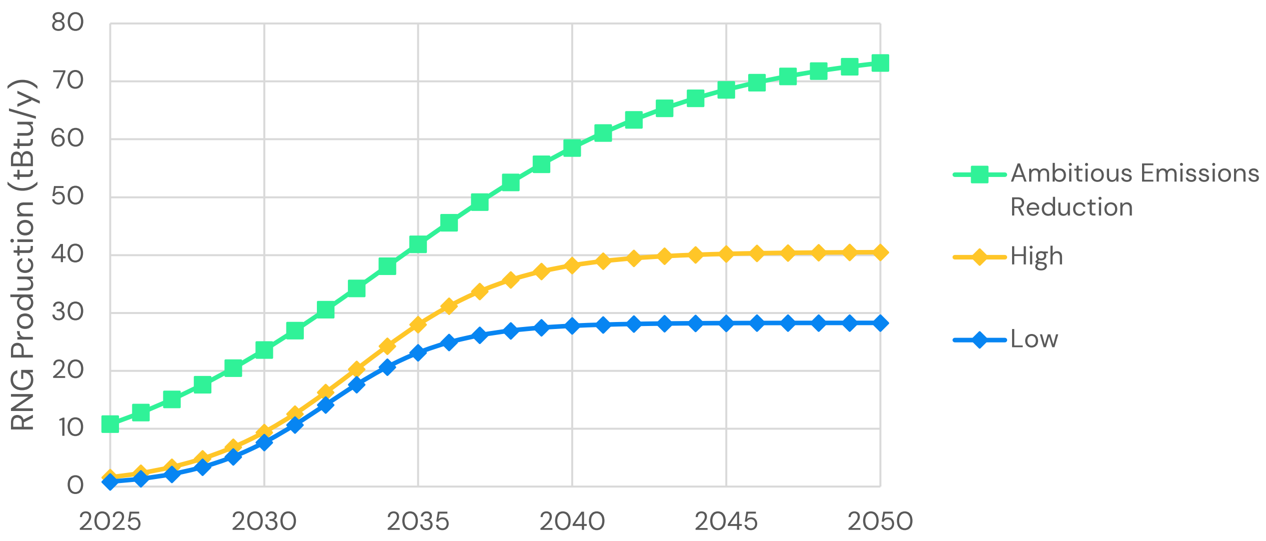


Figure 28. RNG Production Potential from WRRFs by Census Division, Low (tBtu/y)

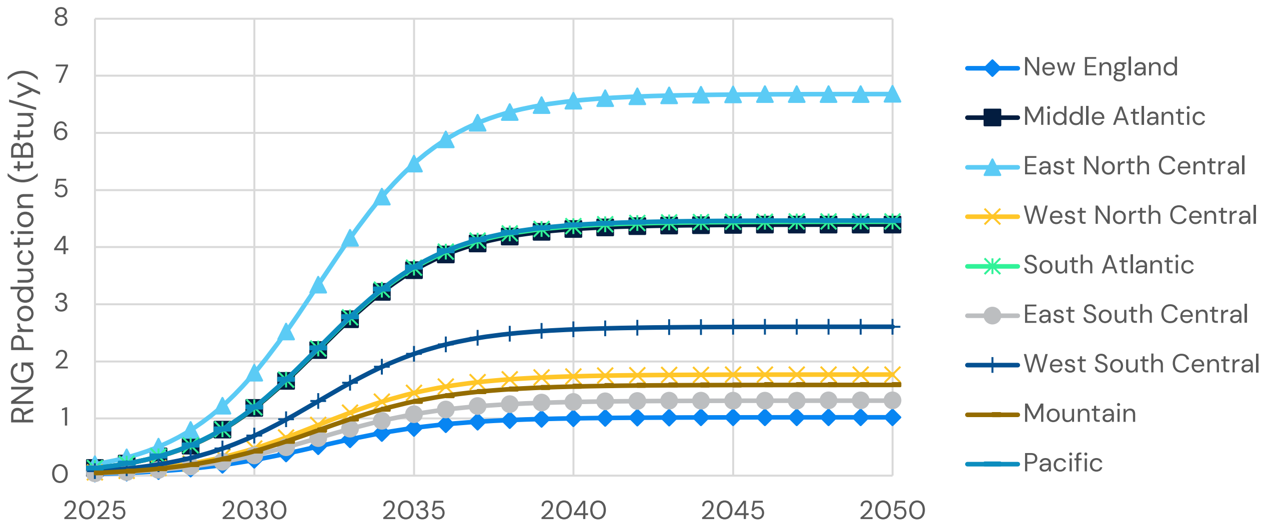


Figure 29. RNG Production Potential from WRRFs by Census Division, High (tBtu/y)

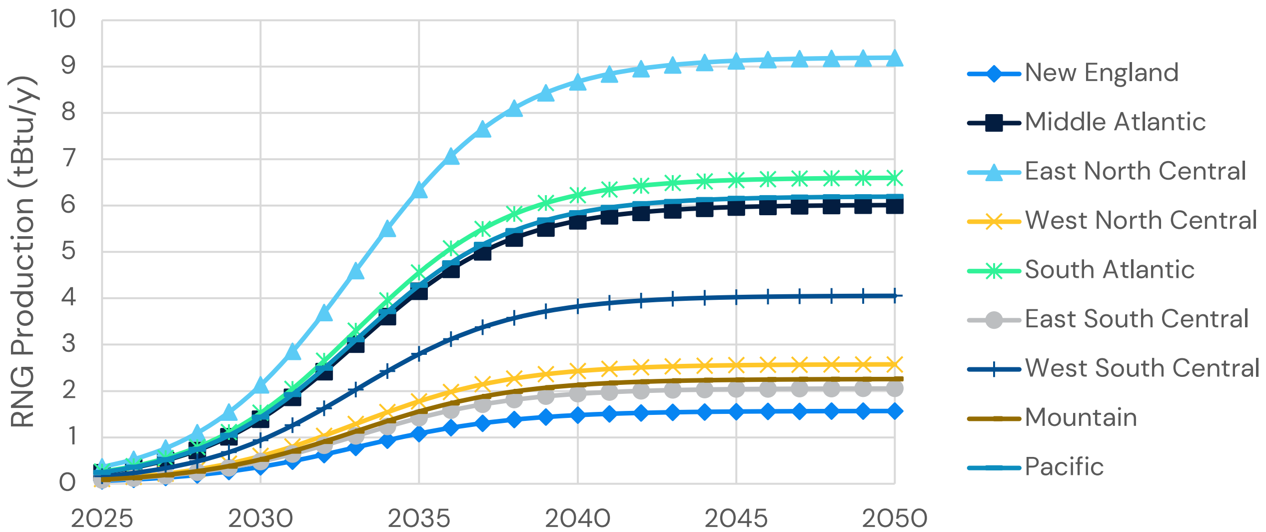
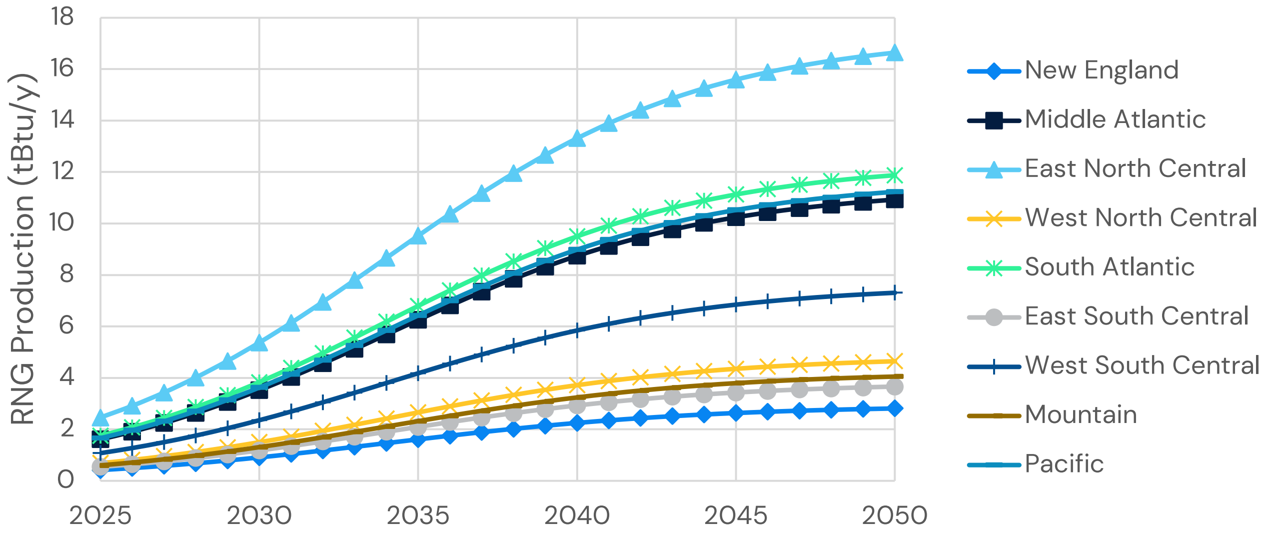


Figure 30. RNG Production Potential from WRRFs by Census Division, Ambitious Emissions Reduction (tBtu/y)



2.5.2 RNG via Thermal Gasification of Biogenic Resources

Thermal gasification is an emerging RNG production technology. To date, small-scale pilot projects (e.g., for combined heat and power, CHP) have been established. There are no significant active thermal gasification projects for the feedstocks considered in this analysis.[20] Gasification itself is commercialized, but its commercialization at a large scale for RNG generation is limited by tar accumulation. Thus, biomass pre-treatment and catalysts are key areas of investment focus for thermal gasification to reach commercialization, as they may be able to reduce tar production.

Agricultural Residues

ICF developed the following assumptions for the RNG production potential from agricultural residues in the three scenarios.

- In the Low Scenario, ICF assumed that 15% of the agricultural residues available at $70/dry ton would be diverted to thermal gasification systems.
- In the High Scenario, ICF assumed that 40% of the agricultural residues available at $70/dry ton would be diverted to thermal gasification systems.
- In the Ambitious Emissions Reduction Scenario, ICF assumed 60% of the agricultural residues available at $70/dry ton would be diverted to thermal gasification systems.

Figure 31 below shows the RNG resource potential from the thermal gasification of agricultural residues between 2025 and 2050 across the three scenarios. The three figures that follow show annual resource potential between 2025 and 2050 for each scenario, broken out by census division.

[20] Some TG feedstocks outlined below are being directed towards directed towards existing AD systems (such as WRRFs) to bolster the systems' RNG production, but not at significant volumes.

Figure 31. National RNG Production Potential from Agricultural Residues (tBtu/y)

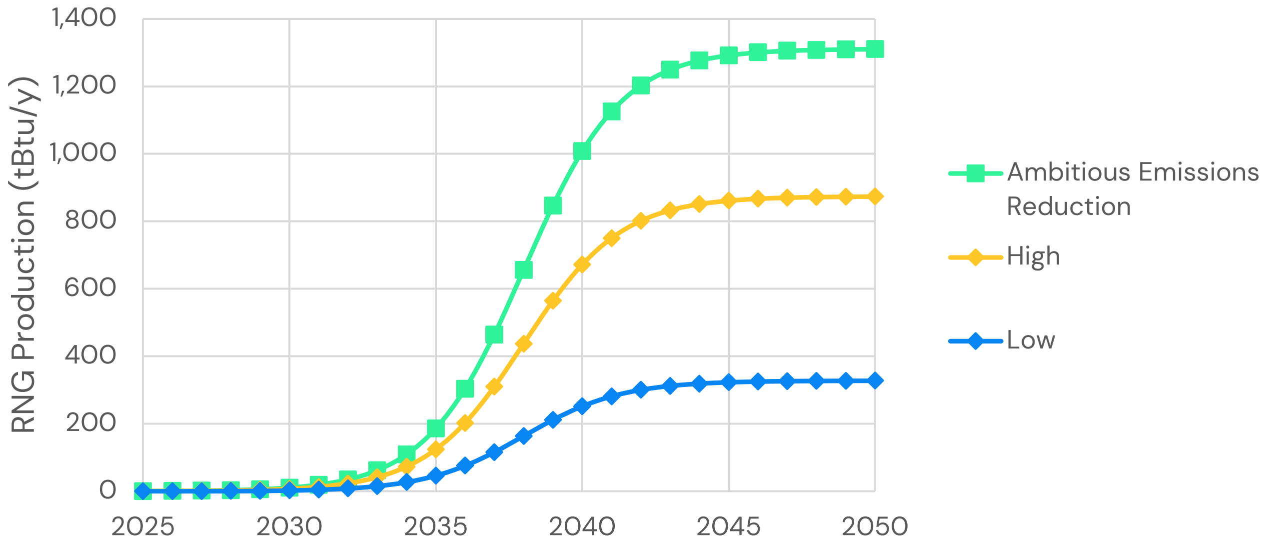


Figure 32. RNG Production Potential from Agricultural Residues by Census Division, Low (tBtu/y)

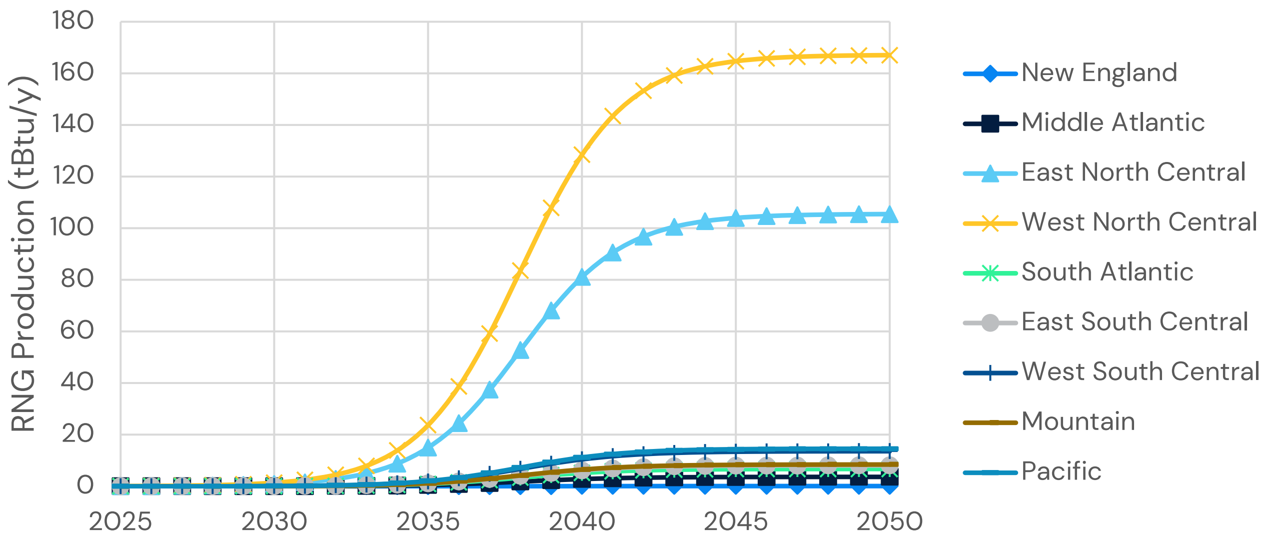


Figure 33. RNG Production Potential from Agricultural Residues by Census Division, High (tBtu/y)

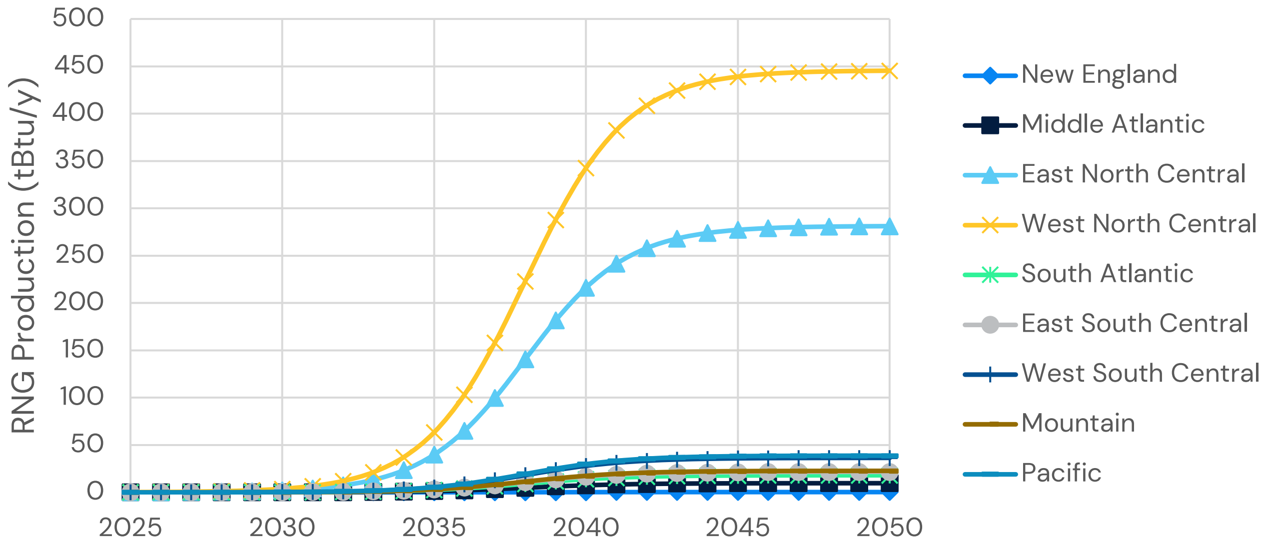
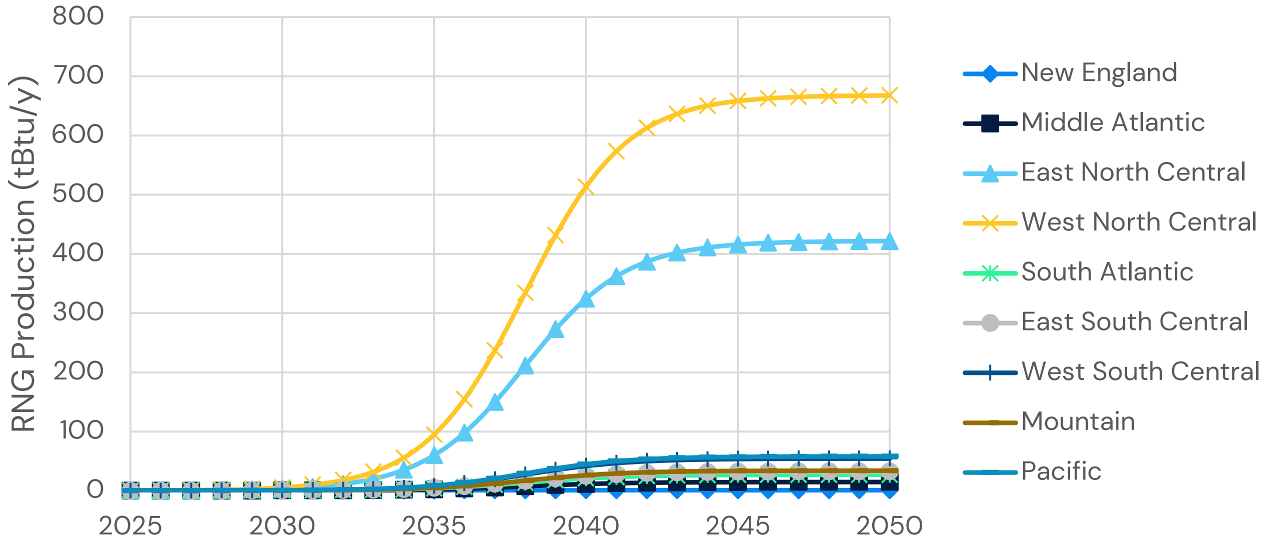


Figure 34. RNG Production Potential from Agricultural Residues by Census Division, Ambitious Emissions Reduction (tBtu/y)



Energy Crops

Energy crops are inclusive of perennial grasses, trees, and some annual crops that can be grown specifically to supply large volumes of uniform, consistent quality feedstocks for energy production. ICF developed assumptions for the RNG production potential from energy crops for the three scenarios:

- In the Low Scenario, ICF assumed that 5% of the energy crops available at $70/dry ton would be diverted to thermal gasification systems.
- In the High Scenario, ICF assumed that 15% of the energy crops available at $70/dry ton would be diverted to thermal gasification systems.
- In the Ambitious Emissions Reduction Scenario, ICF assumed that 25% of the energy crops available at $70/dry ton would be diverted to thermal gasification systems.

Figure 35 shows the RNG resource potential from the thermal gasification of energy crops between 2025 and 2050 in the three scenarios. The three figures that follow show annual resource potential between 2025 and 2050 for each scenario, broken out by census division.

Figure 35. Annual RNG Production Potential from Energy Crops (tBtu/y)

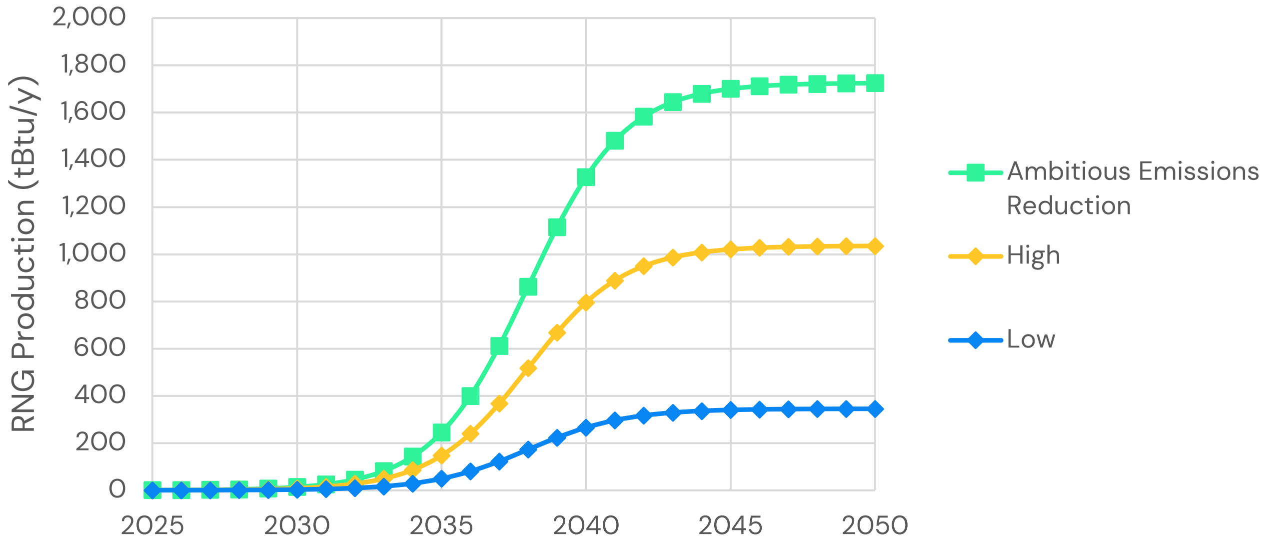


Figure 36. RNG Production Potential from Energy Crops by Census Division, Low (tBtu/y)

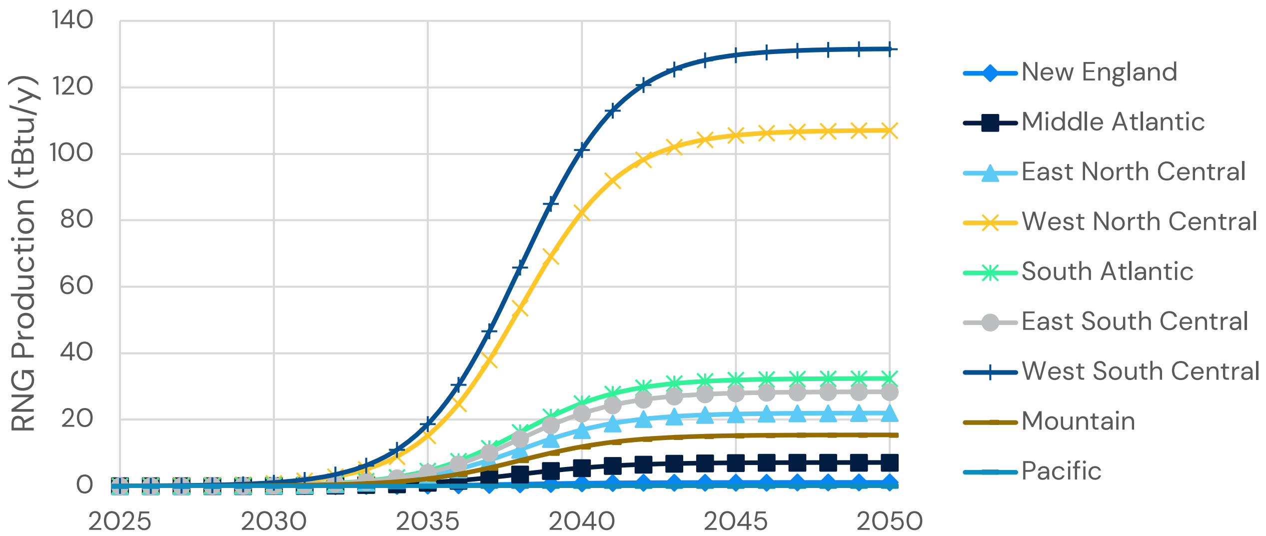


Figure 37. RNG Production Potential from Energy Crops by Census Division, High (tBtu/y)

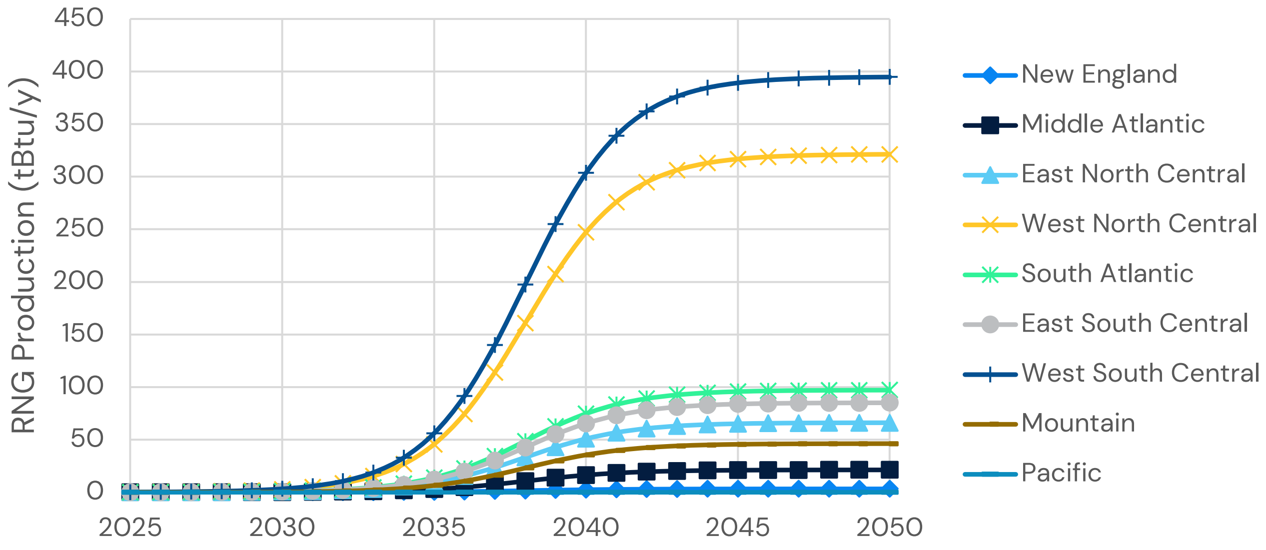
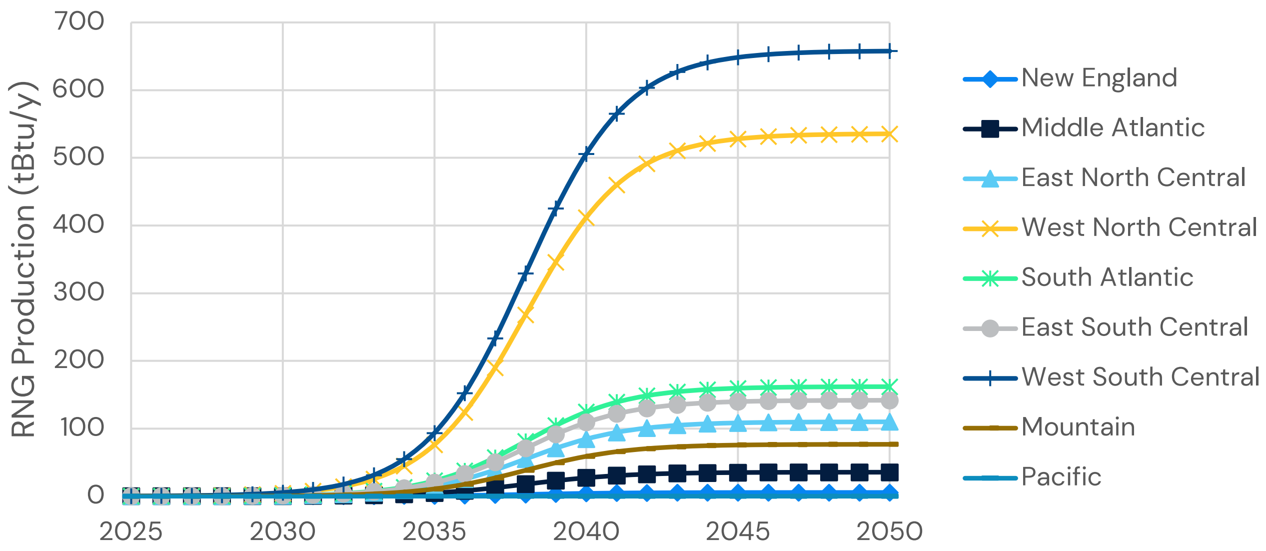


Figure 38. RNG Production Potential from Energy Crops by Census Division, Ambitious Emissions Reduction (tBtu/y)



Forestry and Forest Product Residues

ICF extracted information from the US DOE Bioenergy KDF, which includes information on forest residues such as thinnings, mill residues, and different residues from woods (e.g., mixedwood, hardwood, and softwood).

ICF developed the following assumptions for the RNG production potential from forest residues in the three scenarios:

- In the Low Scenario, ICF assumed that 15% of the forest and forestry product residues available at $70/dry ton would be diverted to thermal gasification systems.
- In the High Scenario, ICF assumed that 40% of the forest and forestry product residues available at $70/dry ton would be diverted to thermal gasification systems.
- In the Ambitious Emissions Reduction Scenario, ICF assumed that 70% of the forest and forestry product residues available at $70/dry ton would be diverted to thermal gasification systems.

Figure 39 shows the RNG resource potential from the thermal gasification of forestry and forest product residues between 2025 and 2050 in three scenarios. The three figures that follow show annual resource potential between 2025 and 2050 for each scenario, broken out by census division.

Figure 39. Annual RNG Production Potential from Forestry Residues (tBtu/y)

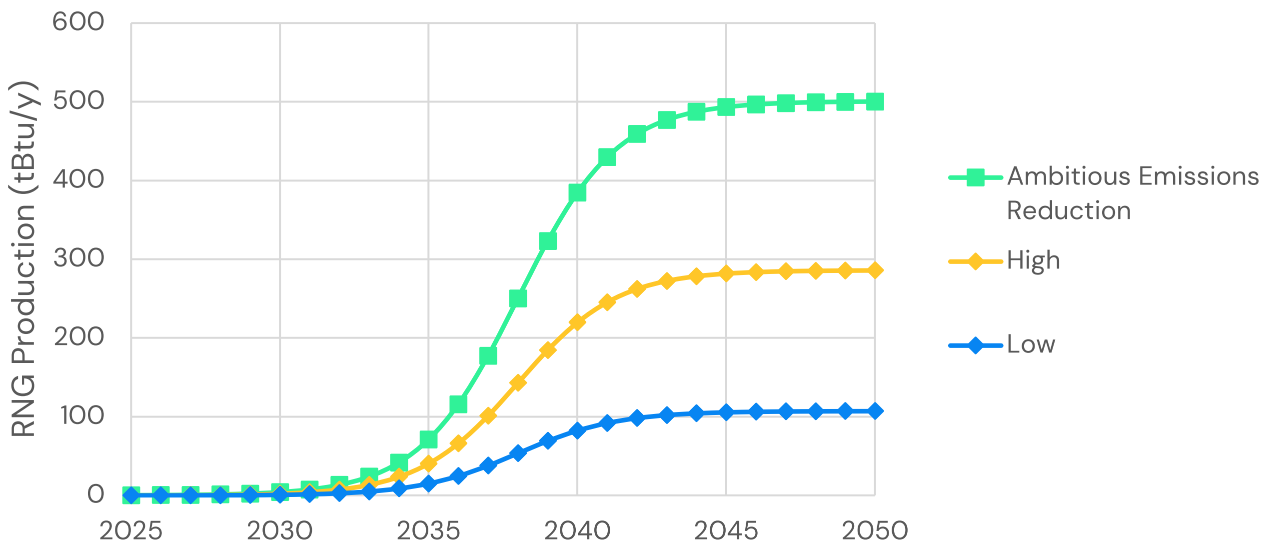


Figure 40. RNG Production Potential from Forestry Residues by Census Division, Low (tBtu/y)

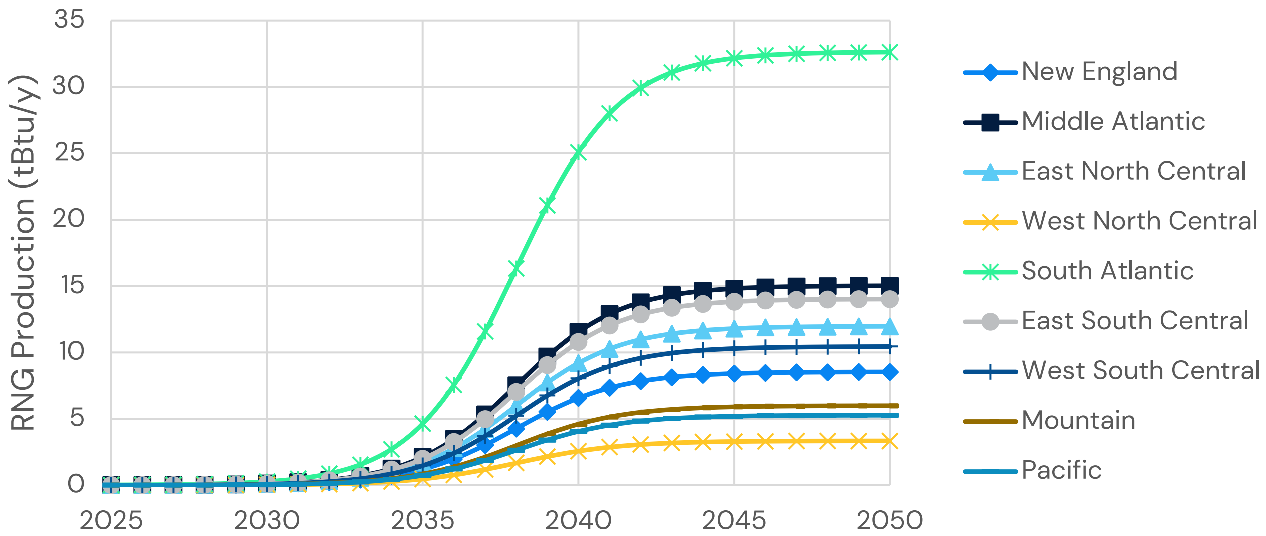


Figure 41. RNG Production Potential from Forestry Residues by Census Division, High (tBtu/y)

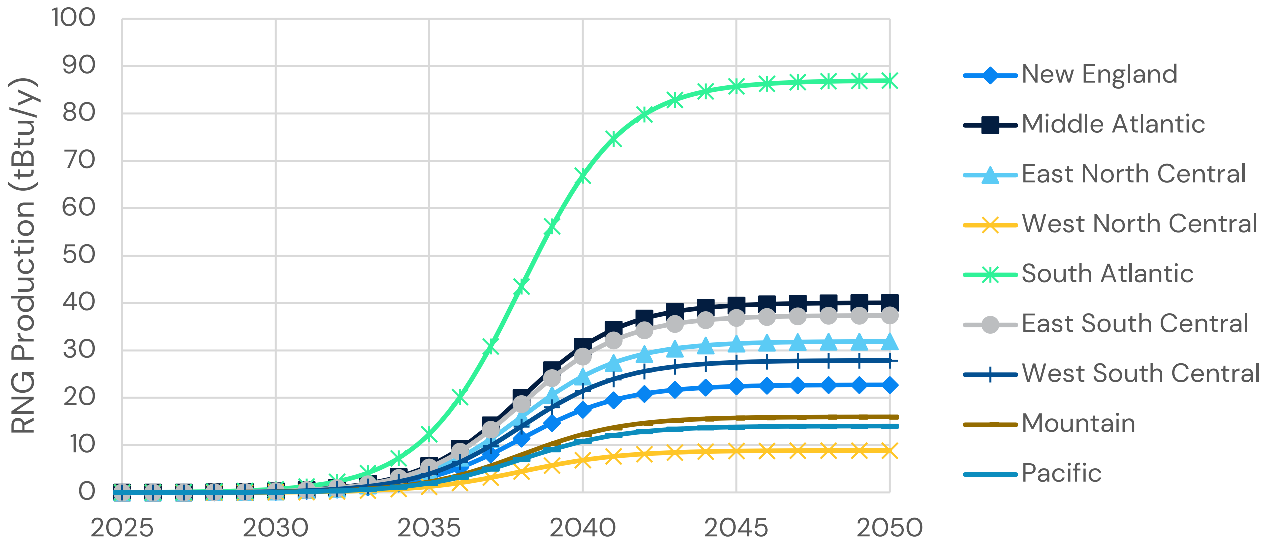
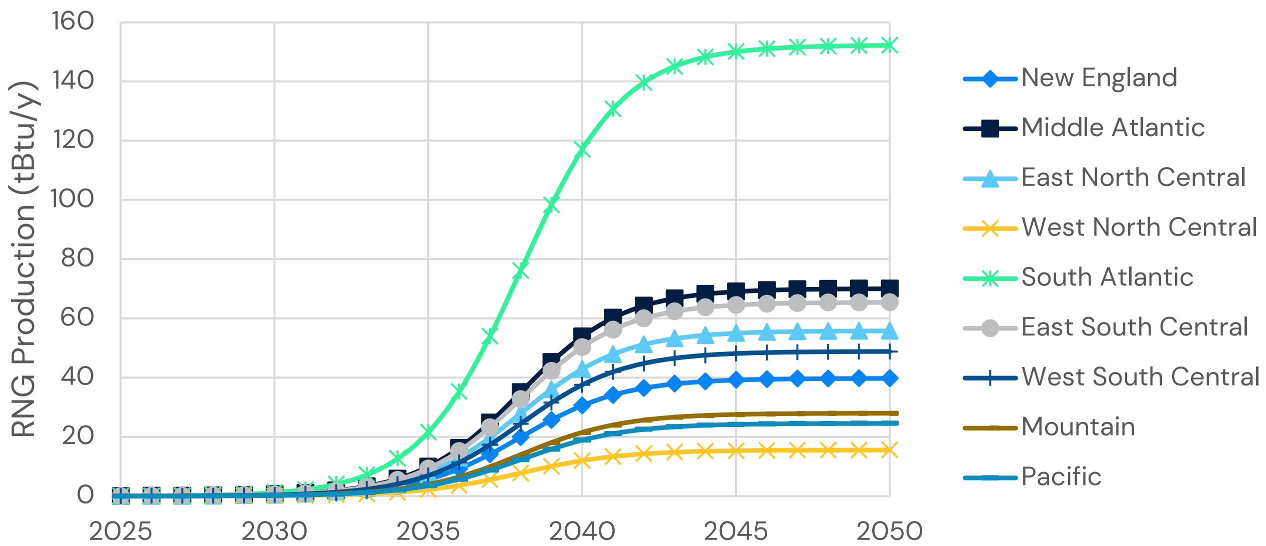


Figure 42. RNG Production Potential from Forestry Residues by Census Division, Ambitious Emissions Reduction (tBtu/y)



Municipal Solid Waste

ICF extracted MSW information from the US DOE's Bioenergy KDF, which includes information collected as part of BT23. ICF limited its consideration to the potential for utilizing MSW that is currently landfilled as a feedstock for thermal gasification; this excludes MSW that is recycled or directed to waste-to-energy facilities. The MSW volumes available at different prices are derived from a variety of sources, including county-level tipping fees and costs associated with sorting.

ICF developed assumptions for the RNG production potential from MSW for the three scenarios:

- In the Low Scenario, ICF assumed that 30% of the biogenic fraction of MSW available at $50/dry ton would be gasified.
- In the High Scenario, ICF assumed that 50% of the biogenic fraction of MSW available at $70/dry ton would be gasified.

- In the Ambitious Emissions Reduction Scenario, ICF assumed 70% of the biogenic fraction of MSW available at $500/dry ton would be gasified.

Figure 43 shows the RNG resource potential from the thermal gasification of MSW between 2025 and 2050 in the three scenarios. The three figures that follow show annual resource potential between 2025 and 2050 for each scenario, broken out by census division.

Figure 43. Annual RNG Production Potential from MSW (tBtu/y)

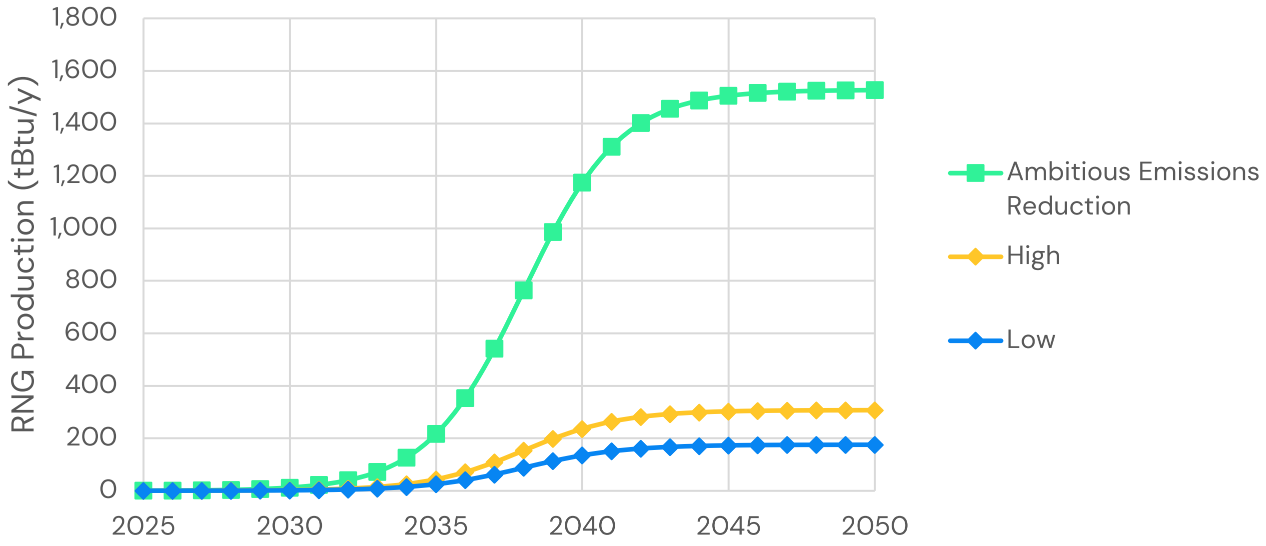


Figure 44. RNG Production Potential from MSW by Census Division, Low (tBtu/y)

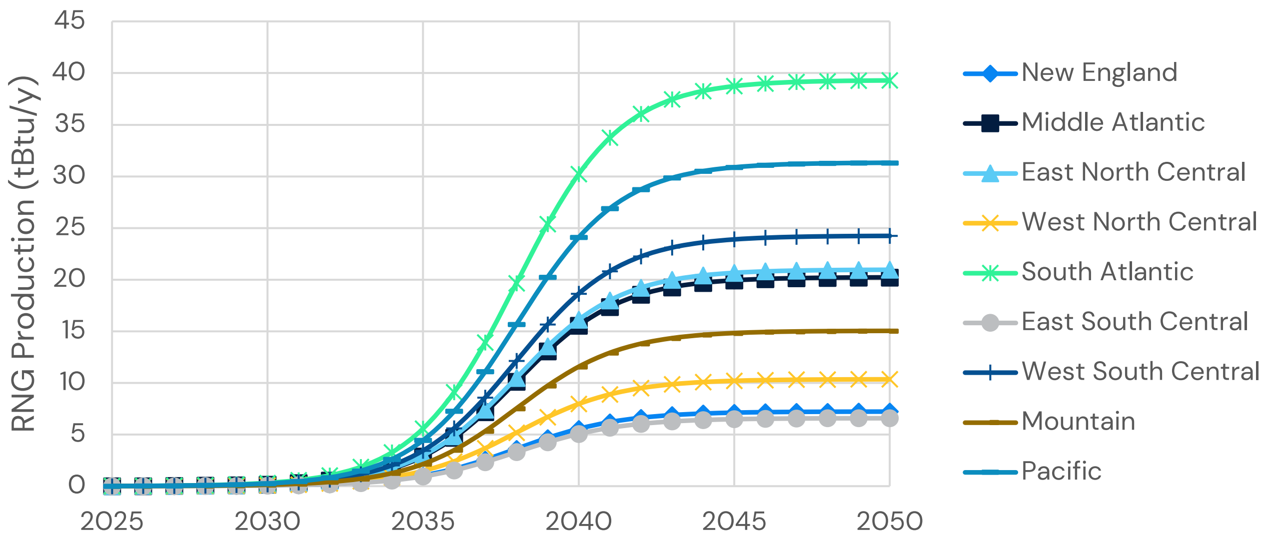


Figure 45. RNG Production Potential from MSW by Census Division, High (tBtu/y)

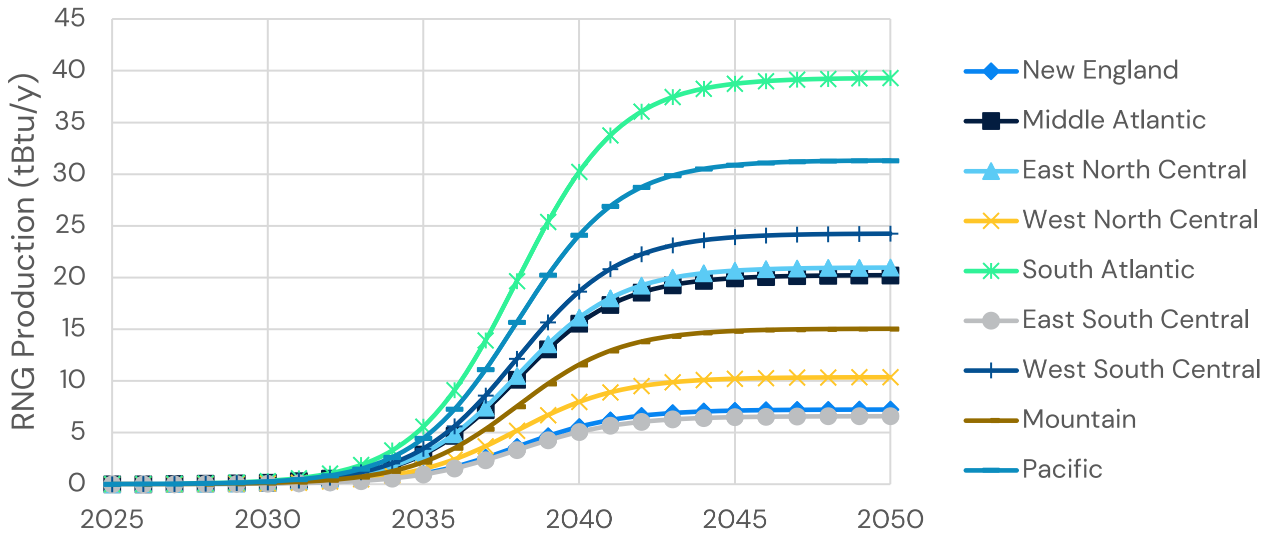
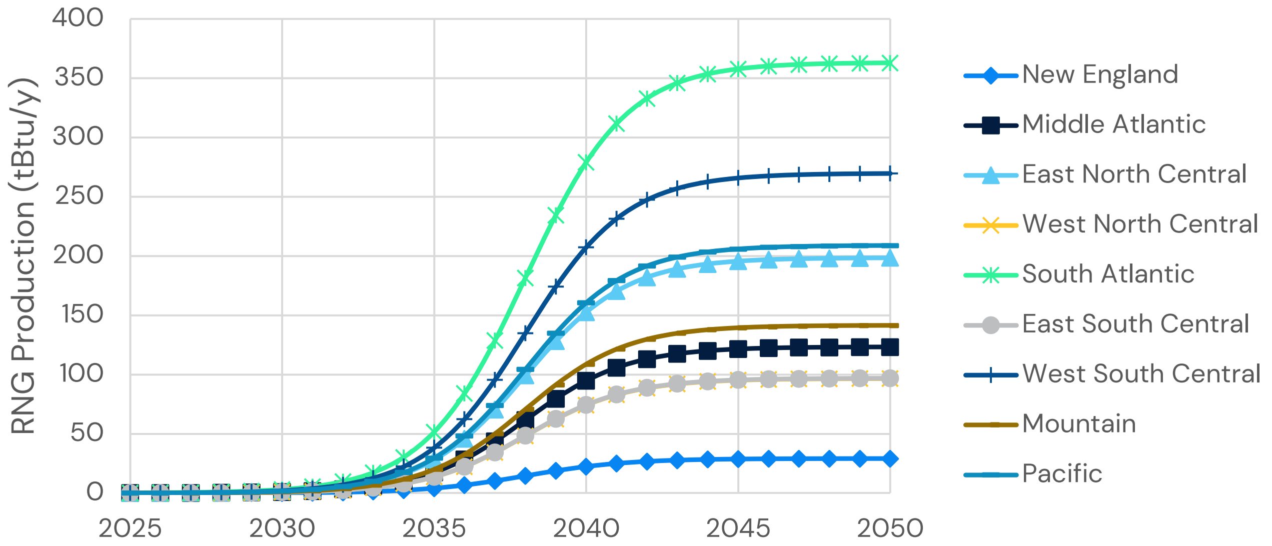


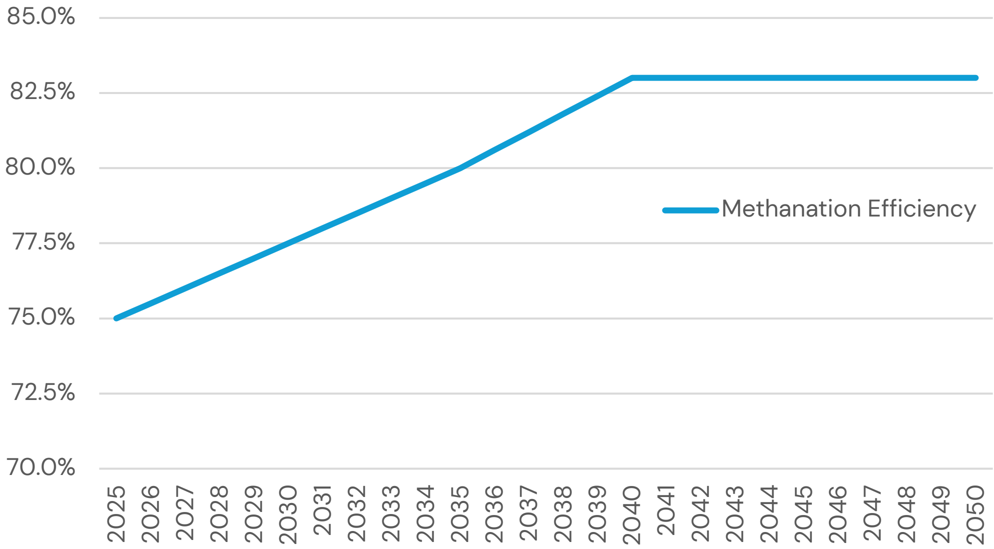
Figure 46. RNG Production Potential from MSW by Census Division, Ambitious Emissions Reduction (tBtu/y)



2.5.3 RNG via Methanated Hydrogen

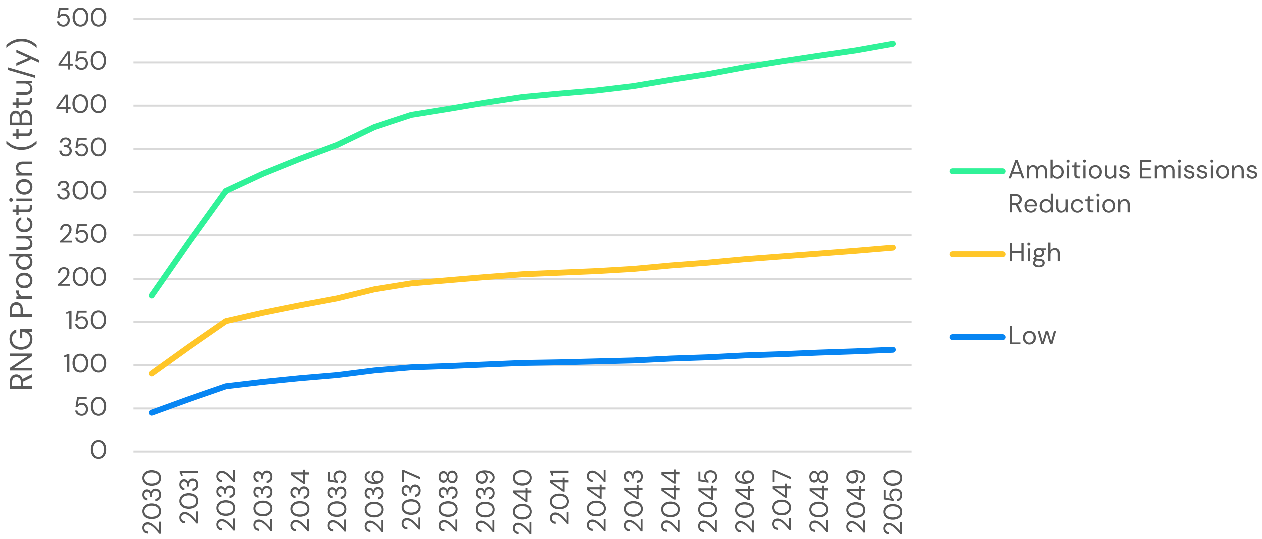
In the absence of analogous constraints for the methanated hydrogen pathway and the biomass-based pathways in the previous subsections, ICF applied simple scalars for the Low, High, and Ambitious Emissions Reduction Scenarios that were largely consistent with the AD/TG biomass utilization estimates for these scenarios. In other words, ICF assumed that 10%, 20%, and 40% of the technical potential of RNG produced from the P2G/methanation pathway is available in each of the respective scenarios. The technical potential was modified further based on an assumption regarding the energy efficiency of the methanation reaction. The figure below shows the assumed improvement over time in the efficiency of the methanation reaction.

Figure 47. Assumed Efficiency of Methanation Reaction in ICF Analysis



The figure below shows the RNG potential domestically from the methanated hydrogen production pathway using the assumptions outlined previously for the Low, High, and Ambitious Emissions Reduction Scenarios.

Figure 48. RNG Potential from Methanated Hydrogen (tBtu/y)



ICF reports a production potential that increases from 45-180 tBtu/y in the 2030 timeframe to around 120-470 tBtu/y by 2050 in the Low, High, and Ambitious Emissions Reduction Scenarios.

3 Greenhouse Gas Emissions Assessment

Greenhouse gas (GHG) emission accounting is a common practice that is used to evaluate the respective GHG impacts of various energy sources or fuels and to enable comparison between them. GHG emission accounting is used in practice by regulators and private actors for a variety of reasons, including to develop GHG emission inventories, as part of broader environmental reports, and to track carbon as an environmental commodity in carbon markets. GHG emission accounting is applied in practice by multiplying a GHG emissions factor (often referred to as carbon intensity) and the associated activity data for the fuel of interest. In other words, the total GHG emissions are calculated as a product of the emissions factor and the amount of energy consumed; the equation below highlights this for the case of natural gas, with the GHG emissions factor in units of kilograms of carbon dioxide equivalents per unit energy of natural gas, in units of million British thermal units ($kgCO_2e$/ MMBtu).

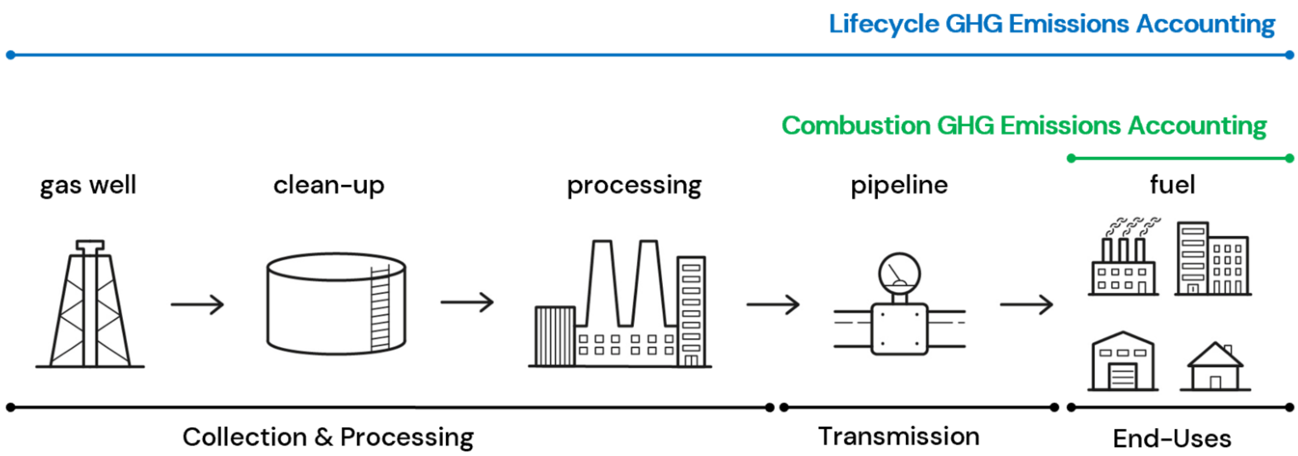
$$GHG\ Emissions = GHG\ Emissions\ Factor\ ^{Lifecycle}_{Combustion} \left[\frac{kgCO_2e}{mmBtu}\right] \times Activity\ \left[mmBtu\right]$$

As noted in the equation above (as part of the *GHG Emissions Factor*), there are two distinct GHG emission accounting approaches in use today: the combustion approach and the lifecycle approach. The framework of these two approaches is consistent across fuel types. However, the inputs vary and lead to different GHG emission profiles. These two different GHG emission accounting approaches are currently driving the conversation regarding GHG emissions associated with RNG. It is important to understand that neither accounting approach is the "correct" one to use. Rather, the fact that both accounting approaches are used frequently can create confusion.

3.1 Combustion vs. Life Cycle GHG Accounting Approaches

To better understand the two approaches, we can use geologic natural gas as an example because it is a process with which most stakeholders are familiar. Figure 49 highlights the three stages of the natural gas supply chain: collection and processing, transmission via pipeline, and the end-use.

Figure 49. Overview of Natural Gas Supply Chain



Source: Modified from the US Energy Information Administration

The two GHG emission accounting approaches are indicated along the top of Figure 49. The **green** line shows the boundary applicable to the combustion approach, and the **blue** line shows the boundary of the lifecycle approach.

- Using a ***combustion approach***, GHG emissions are attributable to the combustion of natural gas at the end-use, such as in a home, business, or industrial facility. When determining the combustion GHG emissions factor, the GHG emissions attributable to the use of the fuel are divided by the amount of energy in the finished fuel. The US EPA reports GHG emission factors for various end uses and reports a combustion GHG emissions factor for natural gas of 53.1 $kgCO_2e$/MMBtu.[21]
- A ***lifecycle approach*** generally accounts for GHG emissions generated from a fuel's production through its end-use, the full life of the fuel. The lifecycle approach for GHG emission accounting is often referred to as a "cradle-to-grave," "well-to-wheels," or "full fuel cycle" approach, though some life cycle assessments (LCAs) may specify their focus on a segment of the subject's life cycle.[22] The full LCA approach accounts for all the GHG emissions produced or avoided from the production, collection and processing, pipeline transmission and delivery, and ultimate use of a fuel (e.g., in combustion). When determining the lifecycle GHG emissions factor, the GHG emissions are summed across each stage and divided by the amount of energy in the finished fuel. In this case, the lifecycle GHG emissions factor for natural gas in a stationary application (end-use) is 72.9 $kgCO_2e$/MMBtu according to the 2023 R&D Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model. This natural gas lifecycle CI is shown in more detail in Appendix C.

3.2 Life Cycle Carbon Intensities of RNG from AD, TG, and P2G Processes

For this study, ICF evaluated life cycle carbon intensities (CIs) for the RNG feedstocks and production methods of interest identified in Section 2. Specifically, ICF used a life cycle assessment methodology to calculate the GHG emissions derived from all stages of the RNG production process up to the end-use combustion of the final product. Carbon intensity was then quantified in terms of the mass of GHGs as carbon dioxide equivalents (CO_2e) emitted per unit of fuel energy: $kgCO_2e$/MMBtu of RNG.

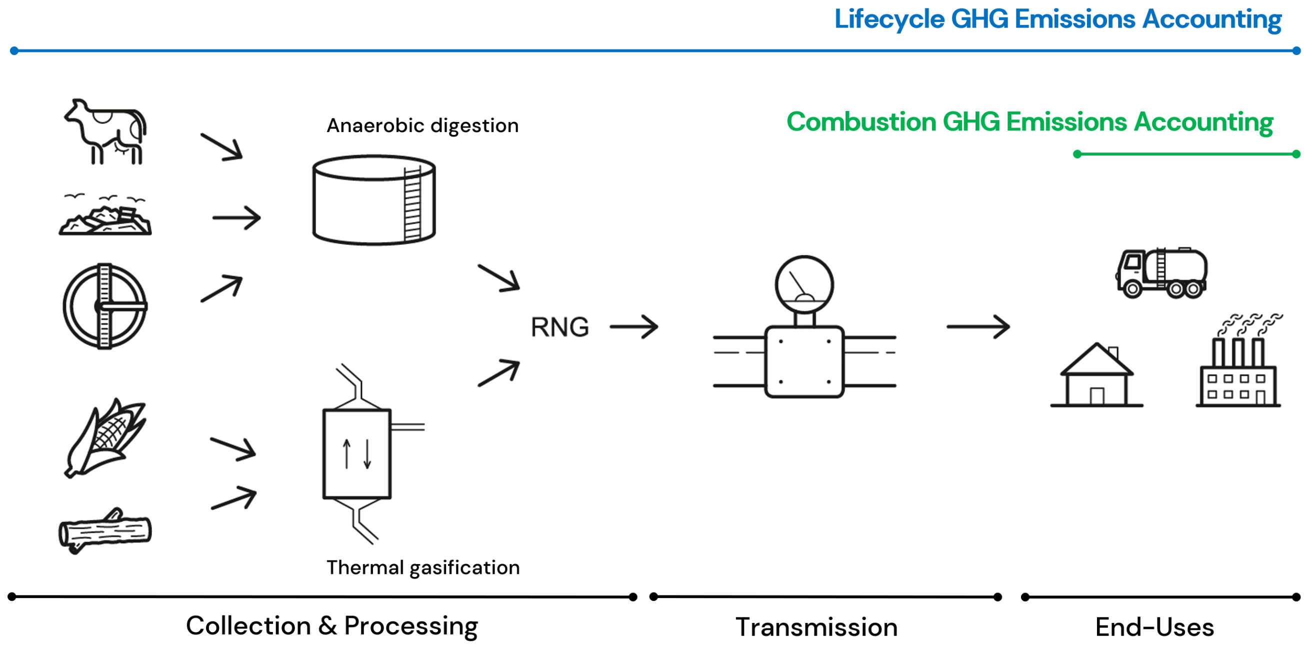
Further, it is worth noting that, in the context of this report, LCA refers only to the accounting of GHG emissions within each stage of the RNG cradle-to-grave process, whereas in other contexts an environmental LCA may refer to the complete accounting of all environmental impacts including, for example, water usage or impact assessment of pollutants, etc.

Rationale for the Inclusion of RNG Life Cycle Assessments in this Study

- Life cycle emissions accounting characterizes the full picture of GHG emission sources and sinks from RNG projects.
- As more attention is placed on all three Greenhouse Gas Protocol Scopes (direct Scope 1 and indirect Scopes 2 and 3), life cycle accounting facilitates the discernment of different direct and indirect GHG profiles between RNG feedstocks and projects. See Appendix D for GHGs itemized by life cycle stage for archetypical RNG projects.
- Life cycle accounting is leveraged in multiple regulatory frameworks concerned with RNG, such as the Inflation Reduction Act.

[21] US EPA Emission Factors for Greenhouse Gas Inventories, 2025. ghg-emission-factors-hub-2025.pdf
[22] Cradle-to-grave differs in system boundary from other LCA methodologies such as the cradle-to-gate framework, in which accounting stops at the end of the production process and prior to end use. The cradle-to-gate system boundary is generally employed to simplify the comparison of LCAs of multiple subjects when the emissions from the end use stage (e.g., combustion) are the same across all subjects, as is shown in Figure 52, below, when ICF compares archetypical RNG LCAs.

Figure 50. Lifecycle vs. Combustion Accounting System Boundaries for RNG



As shown in Figure 50, life cycle emissions from RNG can be generated along the three key stages of the RNG supply chain.

1. **Production:** Energy use required to collect feedstock material and then produce and process RNG by way of digestion and processing for anaerobic digesters and landfills, or synthetic gas (syngas) processing as it relates to thermal gasification. Sometimes, RNG production is also credited for avoiding emissions (like methane) that would otherwise have been released in the feedstock's business-as-usual management practices.
2. **Pipeline transmission and distribution (T&D):** Methane leaks primarily during transmission. Methane leaks can occur at all stages in the supply chain, from production through use, but are generally focused on leakage during transmission.
   - ICF limited its explicit consideration to leaks of methane as those that occur during transmission through a natural gas pipeline, as other methane losses that occur during RNG production are captured as part of efficiency assumptions. The life cycle carbon intensity calculations generated for this study include assumptions for natural gas pipeline leaks synthesized by Argonne National Laboratory based on best-available data from scholarly work and the US EPA.
   - As utilities focus their attention on driving down emissions on their systems, the potential for gas utilities and RNG project developers to reduce the T&D and other methane leaks assumed here could improve upon the estimated carbon emissions intensities estimated in this report.
3. **End-use:** RNG combustion. The GHG emissions attributable to RNG combustion are straightforward: CO_2 emissions from the combustion of biogenic renewable fuels are considered zero, or carbon neutral. In other words, the GHG emissions from the combustion of biogenic fuels are limited to CH_4 and N_2O emissions.[23]

[23] IPCC. 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Available at: Publications - IPCC-TFI

It should be noted when reviewing the results of this LCA that carbon intensities for RNG are highly project-specific and sensitive to actual feedstock and operational characteristics. Knowing that there are industry-wide commonalities in farming, waste management, anaerobic digestion and thermal conversion technologies, and other aspects of the RNG production process, ICF leveraged the industry-standard Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model's pathway defaults, industry data, and in-house expertise to define the parameters of archetypical RNG project GHG LCAs based on standard assumptions, where possible.

Accounting for Biogenic Carbon in Fuel Sources

- Intergovernmental Panel on Climate Change (IPCC) guidelines state that CO_2 emissions from biogenic fuel sources (e.g., biogas or biomass based RNG) should not be included when accounting for emissions in combustion.
- This is to avoid any upstream double counting of CO_2 emissions that occur in the agricultural or land use sectors per IPCC guidance.
- Other approaches exclude biogenic CO_2 in combustion as it is assumed that the CO_2 sequestered by the biomass during its lifetime offsets combustion CO_2 emissions.

Argonne National Laboratory's GREET Model

In this study, LCAs were conducted using R&D GREET1_2023, the latest GREET model version released by Argonne National Laboratory (ANL), to estimate the carbon intensity of RNG. Emission factors for different processes are obtained from GREET as well. The GREET model, developed at ANL, is an analytical tool that simulates the life cycle of energy use and emissions output of vehicle/fuel systems. The GREET model is widely recognized as a reliable tool for life cycle analysis, also known for transportation applications as well-to-wheels (WTW) analysis, of transportation fuels and has been used by several regulatory agencies (e.g., by the US Environmental Protection Agency for the Renewable Fuel Standard and by the California Air Resources Board for the Low Carbon Fuel Standard) for evaluation of various fuels.

3.2.1 RNG LCA Assumptions

For RNG pathways using AD, four feedstocks were considered (as shown in Table 24): animal manure, food waste, LFG, and wastewater sludge from WRRF. Since these pathways are well established under the GREET model, most of the default assumptions were used. Consumption rate of fossil natural gas and grid electricity for RNG pathways was adjusted to align with ICF's standard assumptions (outlined in Appendix C).

For RNG pathways using thermal gasification, energy crops (including willow, poplar, switchgrass, and miscanthus), agriculture residue (including corn stover), forest residue, and MSW feedstocks were evaluated. Fuel production efficiency and energy consumption assumptions were made using industrial data and publications.[24] Emission factors for all stages of the LCA, including feedstock farming, collection and handling, RNG production and processing, RNG transmission and distribution, and end use, were pulled from the GREET model.

For RNG pathways using P2G, pink hydrogen (generated through electrolysis of water using nuclear power as the energy source) and green hydrogen (generated through electrolysis of water using solar power as the energy source) were selected as the hydrogen sources, whereas both biogenic CO_2 (captured from the ethanol fermentation plant [EtOH]) and non-biogenic CO_2 (captured from the iron/steel plant) were selected as the carbon sources. The "synthetic natural gas" pathway established in the GREET model and its accompanying default assumptions for fuel production were used.

[24] GTI Energy. Low-Carbon Renewable Natural Gas (RNG) from Wood Wastes (February 2019). Available at: Low-Carbon Renewable Natural Gas (RNG) From Food Wastes (gti.energy)

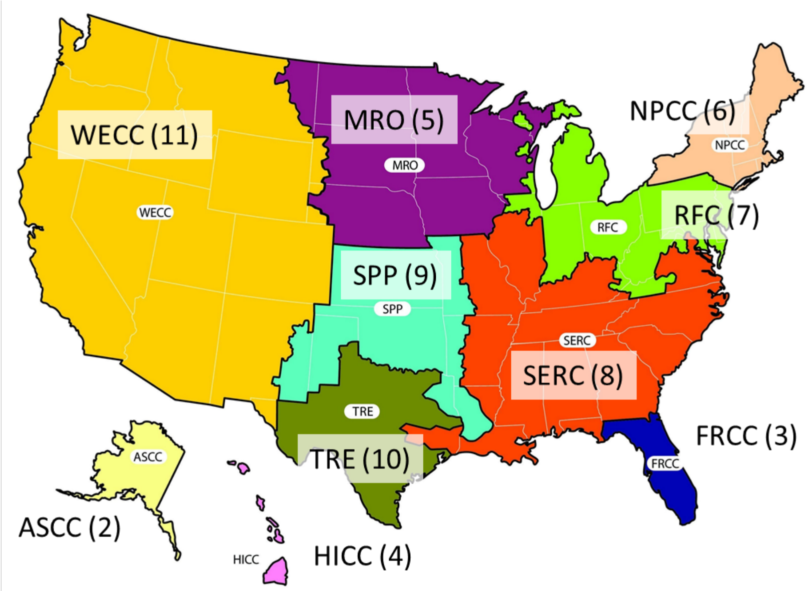
Table 24. GREET RNG LCA Modeling Approach and Model Modifications

<table>
<tr><th>Production Process</th><th>RNG Feedstock</th><th>GREET Approach</th></tr>
<tr><td rowspan="4">Anaerobic Digestion</td><td>Animal manure</td><td rowspan="4">• Largely relied on GREET 2023 default values with adjustments to grid electricity mix to accommodate regional sensitivities. Consumption rate of fossil NG and grid electricity for RNG pathways were adjusted to align with ICF's standard assumptions.
• For wastewater at WRRFs, the baseline scenario was adjusted to ensure the heating energy source for the baseline AD is the same as under the RNG pathway.
• Additionally, for dairy and swine manure, regional average baseline manure management practices were adjusted using a state supply-weighted average based on the results of the feedstock resource supply assessment (see Section 2).</td></tr>
<tr><td>Food waste</td></tr>
<tr><td>Landfill gas</td></tr>
<tr><td>Wastewater</td></tr>
<tr><td rowspan="4">Thermal Gasification</td><td>Agricultural residue</td><td rowspan="4">• GREET model has no established pathways for RNG via TG.
• LCA calculations were performed based on emissions factors from the GREET model and fuel production data from publicly available documents.</td></tr>
<tr><td>Energy Crops</td></tr>
<tr><td>Forest Residue</td></tr>
<tr><td>Municipal Solid Waste (MSW)</td></tr>
<tr><td rowspan="4">Power to Gas with Methanation</td><td>CO_2 from EtOH + Pink H_2</td><td rowspan="4">• GREET includes the fuel pathway for synthesizing NG using hydrogen and carbon dioxide.
• Biogenic CO_2, industrial off-gas CO_2, green H_2, and pink[25] H_2 are used as feedstocks to analyze the carbon intensities under different combinations.</td></tr>
<tr><td>CO_2 from EtOH + Green H_2</td></tr>
<tr><td>CO_2 from Iron/Steel Plant off gas + Pink H_2</td></tr>
<tr><td>CO_2 from Iron/Steel Plant off gas + Green H_2</td></tr>
</table>

All feedstocks and production processes listed above included adjustment for regional grid electricity. The GREET model uses U.S EPA defined regions for grid electricity aligned with the North American Electric Reliability Corporation (NERC) and calculates generation mix based on the EPA's 2023 AEO.

[25] Pink H_2: A nuclear power plant is used as the electricity source in PEM electrolysis for H2 production. The nuclear technology selected in the model is the light water reactor (LWR), which is commonly used in commercial applications.

Figure 51. NERC Regions, via ANL GREET



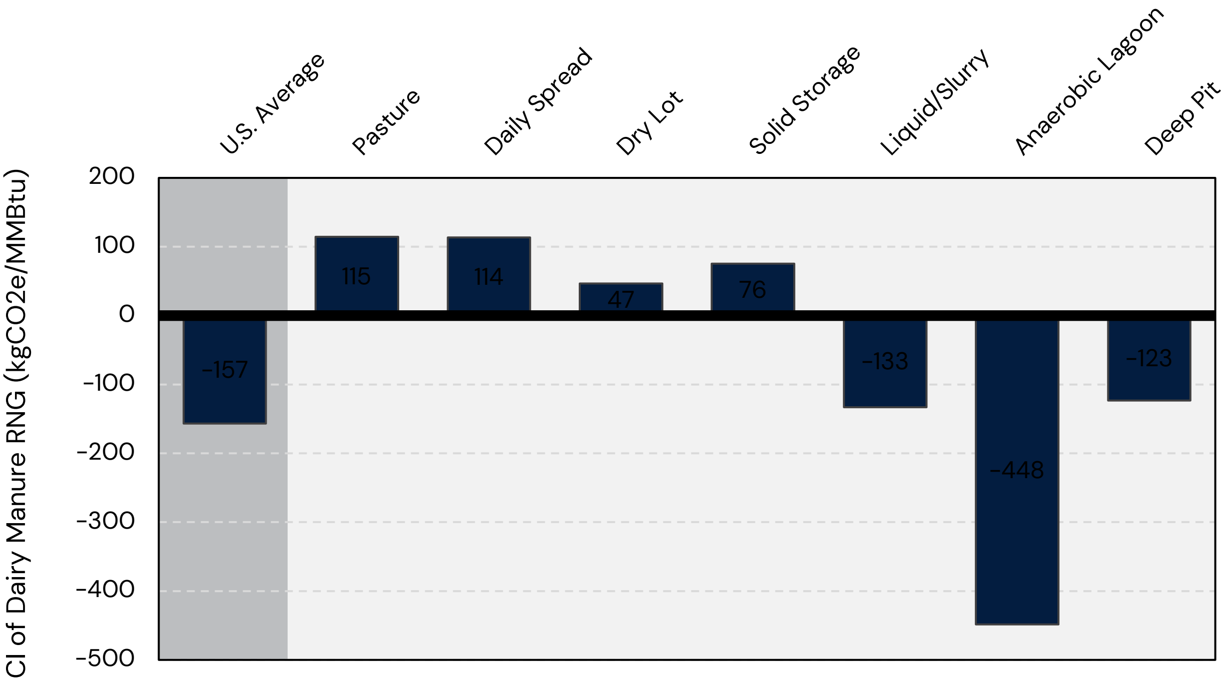
ICF assumed the following regional breakdown for the continental United States, as grouped by NERC regions to model RNG CI values.

Table 25. CI Modeling Assumption of Regional Breakdown for Grid Mix and Manure Management

3-FRCC	5-MRO	6-NPCC	7-RFC	8-SERC	9-SPP	10-TRE	11-WECC
Florida	North Dakota South Dakota Nebraska Minnesota Iowa Wisconsin	Maine Vermont New Hampshire Massachusetts New York Connecticut Rhode Island	New Jersey Pennsylvania Delaware Maryland West Virginia Ohio Michigan Indiana	Alabama Georgia Mississippi Missouri North Carolina South Carolina Tennessee Arkansas Illinois Kentucky Louisiana Virginia	Kansas Oklahoma	Texas	Washington Oregon California Idaho Montana Utah Wyoming Nevada Arizona Colorado New Mexico

In addition to grid electricity variation, ICF considered regional variation in manure management practices when modeling GHG emissions from the anaerobic digestion of dairy, swine, poultry, and other cattle manure for RNG production. RNG from the anaerobic digestion of animal waste has expanded significantly in the last decade, with its growth mainly driven by methane-reduction policies across North America. These policies facilitate redirecting manure from methane-emissive farm management practices towards RNG projects instead. In California, for instance, the introduction of avoided methane crediting in the 2018 amendments to the Low Carbon Fuel Standard program and in accompanying LCA models, has helped support the steady displacement of RNG from landfill gas with RNG from animal manure in the transportation fuels market due to its ultra-low (negative) CI. In fact, through 2024 (the most recent year for which data are available), the RNG volume reported in California from animal manure was more than double the volume from landfills; and the amount of Low Carbon Fuel Standard credits generated by RNG from dairy and swine manure, specifically, was more than 20 times the credits generated by RNG from landfill over the same period.[26]

Figure 52. Impacts of Various Baseline Manure Management Approaches on Dairy RNG CI ($kgCO_2e$/MMBtu)



Avoided methane credits can be substantial for some types of animal manure RNG projects. For dairy and swine manure RNG, as mentioned in the previous section, the avoided methane credit from a counterfactual scenario (or baseline) has the most significant impact on the CI calculation. Since the magnitude of avoided methane credit for a project is directly associated with its baseline manure management approaches, dairy and swine RNG projects' life cycle CIs are highly sensitive to the farm's counterfactual manure management practices. Take dairy manure, for example, as illustrated in Figure 52. If one assumes that 100% of the dairy manure in a project is managed with a single approach, the highest uncontrolled methane emissions come from manure that is managed anaerobically without methane recovery (e.g., anaerobic lagoon, liquid/slurry pond, and deep pit) as a Baseline. According to the Inventory of US Greenhouse Gas Emissions and Sinks,[27] most dairy farms across the US have been managing their manure anaerobically without methane recovery. Interestingly, avoided methane credits are not the biggest driver of CI across all animal waste feedstocks, only those that may be managed in a methane-emissive baseline practice. For example, the avoided methane credit has little to no impact on the CI of RNG from poultry litter because none of the poultry manure baseline management practices emit much methane.

The 2023 R&D GREET model includes estimates of current average manure management split by state across the seven practices for each manure type; for example, the management practices for dairy cows are shown in Figure 52. ICF utilized the state-level animal manure results from its RNG supply potential analysis (see Section 2) to generate a weighted average split in baseline manure management practices

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[26] Low Carbon Fuel Standard quarterly data summary and spreadsheet. https://ww2.arb.ca.gov/resources/documents/low-carbon-fuel-standard-reporting-tool-quarterly-summaries

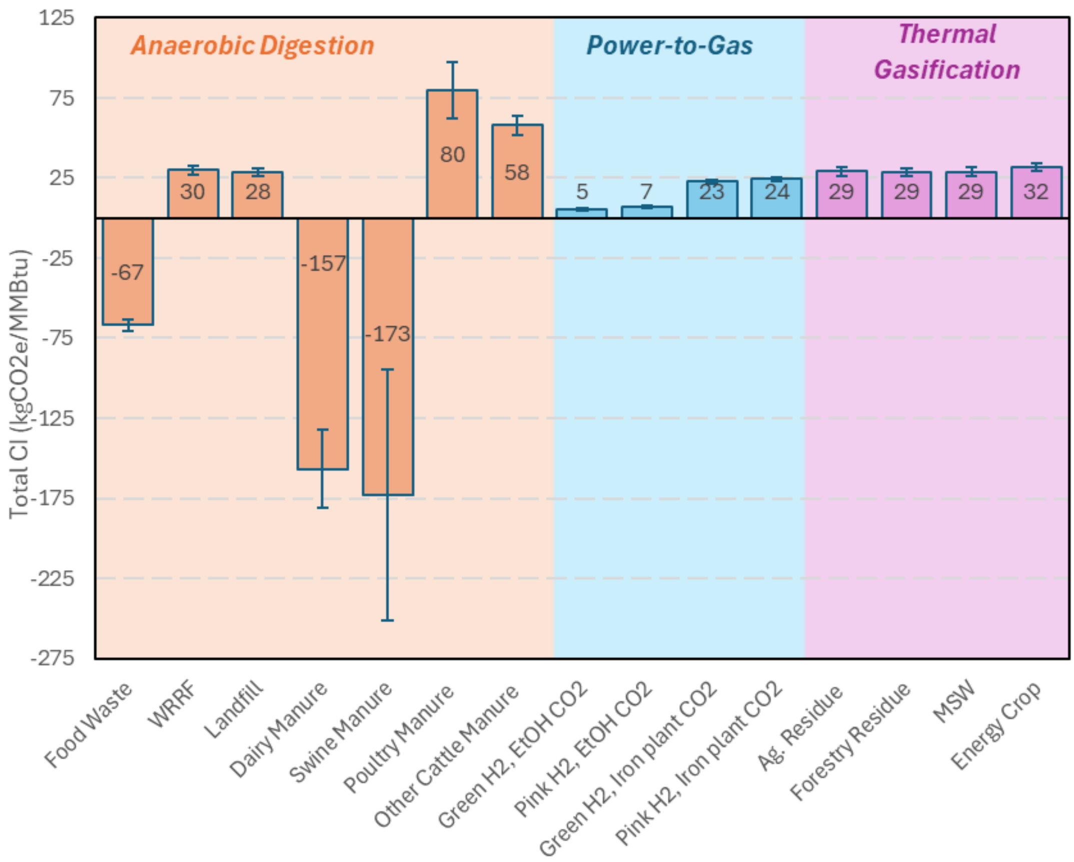
[27] Inventory of US Greenhouse Gas Emissions and Sinks. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks

for each type of animal manure across the NERC regions. The final manure management assumptions used in the modeling process for dairy manure are presented in Figure 55 in the following sub-section.

3.2.2 LCA Results

Figure 53 provides an overview of the archetypical CI results for the three RNG production processes of interest using the RNG archetype GREET models developed by ICF with the built-in regional considerations described previously. The LCAs were conducted on a cradle-to-grave basis using a small industrial boiler to profile the end use for combustion, and are shown by life cycle stage in Appendix C. In general, negative carbon intensity scores are typical of AD projects for animal waste and food waste due to the consideration of avoided emissions from conventional baseline waste management practices. Because the combustion emissions across RNG types are both constant and negligible (limited to trace amounts of CH_4 and N_2O) compared to upstream emissions, Figure 53 is simplified to show cradle-to-gate CI numbers.

Figure 53. CIs for RNG, by Feedstock / Technology (US Average, $kgCO_2e$/ MMBtu)



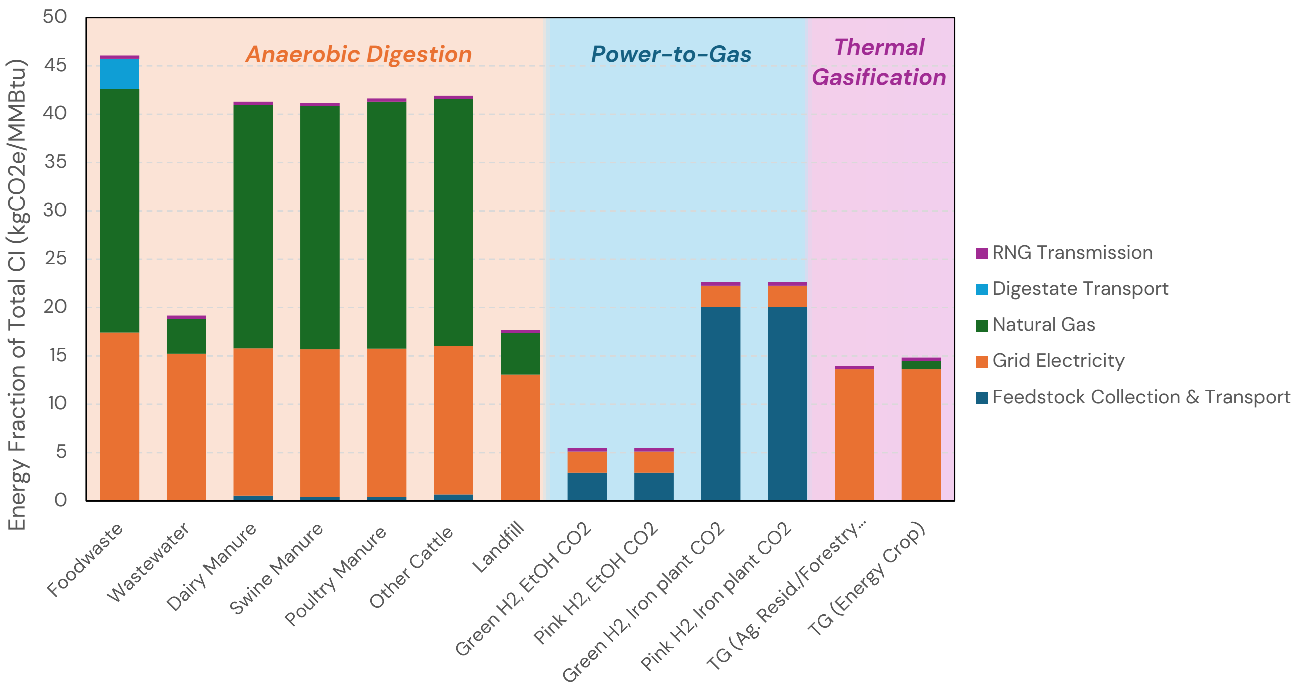
Overall, the avoided emissions credit from the counterfactual Baseline scenario has the most significant impact on the RNG CIs, especially for RNG generated from anaerobic digestion. For comparison purposes, shared processes and energy input across all pathways are illustrated in Figure 54, based on a US average. Geologic natural gas has the largest footprint for AD pathways that require additional heating of the digester (WRRF is assumed to supply a portion of its thermal energy for digester heating from the combustion of its biogas onsite). If biogas is used parasitically in place of geologic natural gas for heating in the RNG production process, the GHG emissions from energy use decline, but so does the amount of RNG produced; in terms of a $kgCO_2e$/MMBtu CI, both the numerator and denominator decline. Depending on the amount of process heat needed, using biogas in place of geologic natural gas generally improves (or lowers) RNG's CI score. The choice to use biogas for process heat is not currently commonplace, as producers historically have chosen to prioritize increased RNG production over the marginal improvement in CI. Furthermore, considering the net value/cost of geologic natural gas vs. RNG, many producers choose to heat their digesters using geologic natural gas to maximize the profitability of their RNG, but that is a dynamic decision, influenced by the price of available RNG incentives for a project. Digester heating is not used in places with warmer weather, like California and Texas; climate also determines the digester design.

Grid electricity is essential to all AD and TG pathways, but it plays a less critical role in P2G pathways, as the power for hydrogen production and methanation is low CI (either nuclear, solar, or wind); in addition, the non-biogenic CO2 capture (and clean up) from the iron/steel plant requires a large amount of natural gas as process energy, which drives the correlating P2G pathway CI up significantly.

Thermal gasification has two major steps: biomass gasification to produce syngas, and syngas upgrading to RNG. In ICF's modeling, the biomass gasification step assumes all energy comes from biomass (biogenic), whereas syngas upgrading consumes grid electricity and natural gas, which explains the relatively low CIs across all RNG produced from TG. In addition, the upstream anthropogenic emissions (e.g., farming) are included in the CI for RNG produced via thermal gasification of energy crops, whereas other feedstock types for thermal gasification (e.g., agricultural residue, forest residue, and MSW) are treated as waste materials and their CIs do not include similar upstream emissions.

Based on these LCA assumptions and the results shown in Figure 54, one may deduce that RNG CIs from P2G and TG would be higher if the renewable process energy sources (e.g., solar/nuclear, biomass) are replaced by natural gas and/or grid electricity.

Figure 54. Impact of Various Sources of Energy Consumption on RNG CI (Energy-Usage Fraction Only, US Average, $kgCO_2e$/ MMBtu)



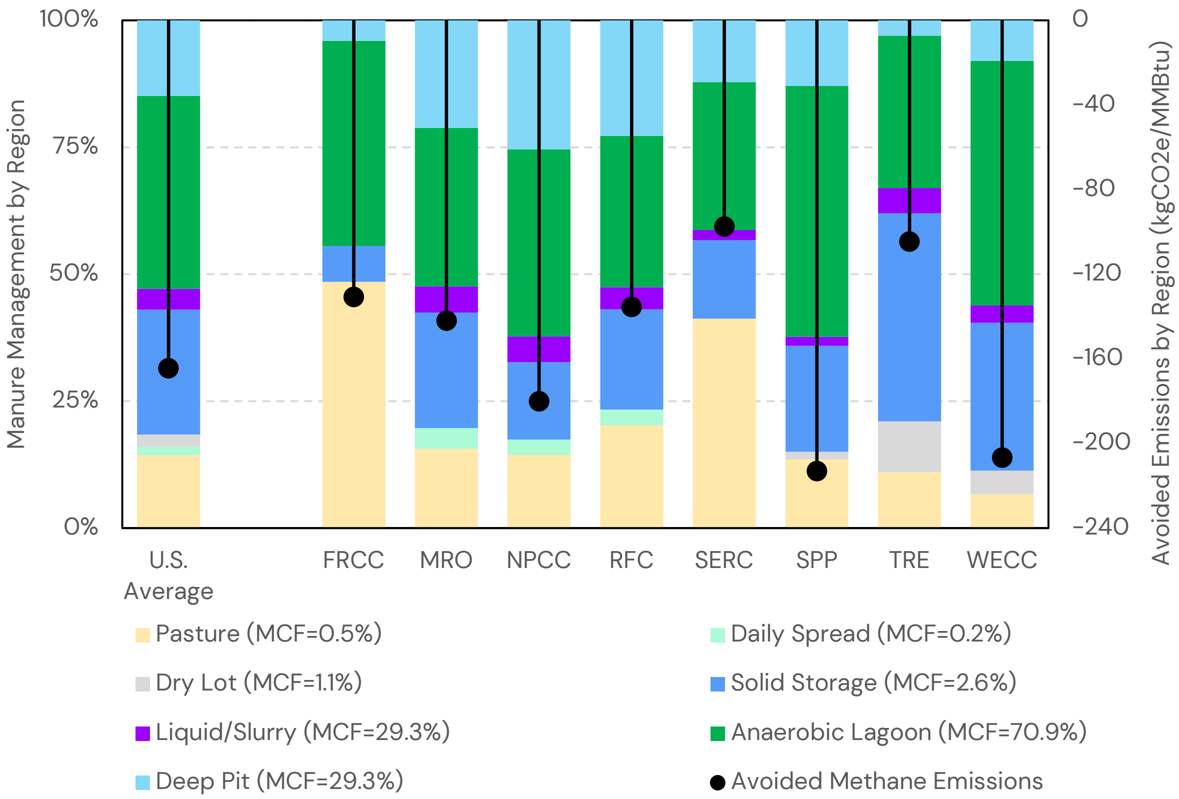
Regional Impact of Grid Electricity

The CI methodology assumes each feedstock and technology combination has a defined energy demand. For instance, the anaerobic digestion of food waste requires approximately 23 kWh of grid electricity per MMBtu of RNG produced, regardless of the location of the digestion facility; however, the GHG emission factors vary across regions (Table 25), resulting in different CI impacts from the grid electricity: a lower-carbon intensity of electricity generation in certain regions (Northeast/NPCC: mainly natural gas and nuclear; West/WECC: mainly natural gas, hydropower, and solar) has a lower magnitude of GHG impact on the overall CI than regional grid mixes that have a relatively higher carbon intensity (Midwest/MRO: mainly coal and natural gas). With that said, the standard deviation of the grid electricity GHG impact across studied regions in the continental US is less than 3 $kgCO_2e/MMBtu$, which is considerably lower than that of baseline manure management across the same regions (24 kgCO2e/MMBtu for dairy, 79 $kgCO_2e/MMBtu$ for swine, measured in standard deviation).

Regional Impact of Baseline Manure Management for Dairies

Based on the US EPA GHG inventory, each state has a distinct manure management profile. For example, in the state of New York, 38% of dairy farms manage their manure in an anaerobic open lagoon, 25% in deep pit, 15% as solid storage, 14% in pasture, 5% as liquid/slurry, and 3% as daily spread. Each manure management practice is associated with a methane conversion factor (MCF) that ultimately determines the magnitude of baseline avoided methane emissions credit. ICF grouped states within the same NERC region (Alaska and Hawaii are not considered in this evaluation) and the results (Figure 55) indicate the southwest (SPP) and west (WECC) regions have more dairy farms using anaerobic lagoons for their manure management, resulting in more avoided methane emissions credit potentials; in comparison, southeast (SERC) and Texas (TRE) have more dairy manure left on pasture or for aerobic solid storage, resulting in significantly lower avoided emissions credit potentials (which yields higher overall CI values).

Figure 55. Impact of Dairy Manure Management on Baseline Avoided Emissions in Select Regions



3.3 Aggregate Potential GHG Reductions from RNG Production

ICF estimated the aggregate GHG emission reductions from the potential deployment of RNG based on the results from the three supply scenarios discussed previous (see Section 2.3.4). ICF applied the LCA GHG emission accounting methodology outlined above, assuming the displacement of geologic natural gas. For a given volume of RNG supply, each feedstock's supply potential is scaled by the difference between its archetypical lifecycle CI and the lifecycle CI of geologic natural gas. Figure 56 to Figure 58 below show annual GHG emission reductions potential from RNG deployment in each of the three scenarios, relative to the emissions of equivalent consumption of geologic natural gas (as indicated by the red dashed line).

As shown in the figures below, ICF estimates that RNG deployment could deliver 82-328 million metric tons (MMT) of GHG emission reductions annually in 2050 using the lifecycle approach, based on the Low, High and Ambitious Emissions Reduction Scenarios. When factoring in the potential displacement of geologic natural gas with RNG via methanated hydrogen, an additional 6-32 MMT of GHG emission reductions could be achieved by 2050.

The cumulative impact of RNG supply deployment delivers a 70% to 75% reduction in GHG emissions compared to geologic natural gas, on a lifecycle GHG emission accounting basis. The variance in emission reductions across the scenarios is driven by the different CIs for each feedstock and their associated proportion of supply. For example, the Low Scenario has a higher relative proportion of low-CI RNG from animal manure, delivering greater emission reductions per unit of geologic natural gas displaced when compared to the High Scenario and the Ambitious Emissions Reduction Scenario.

In the figures below, the green line (—) shows the GHG emissions of RNG deployment in each scenario and the red dashed line (--) shows the GHG emissions of the equivalent amount of geological natural gas. The difference between these lines represents the GHG emission reduction potential of RNG in each scenario, whereas the wedges between the green line and the red line show the contribution of RNG derived from the corresponding feedstock towards the total GHG emission reduction potential. In other words, the wider the wedge, the larger contribution that feedstock makes towards GHG emission reductions in that particular scenario.

Figure 56. Life Cycle GHG Emission Reductions Potential, Low Scenario ($MMTCO_2e$)

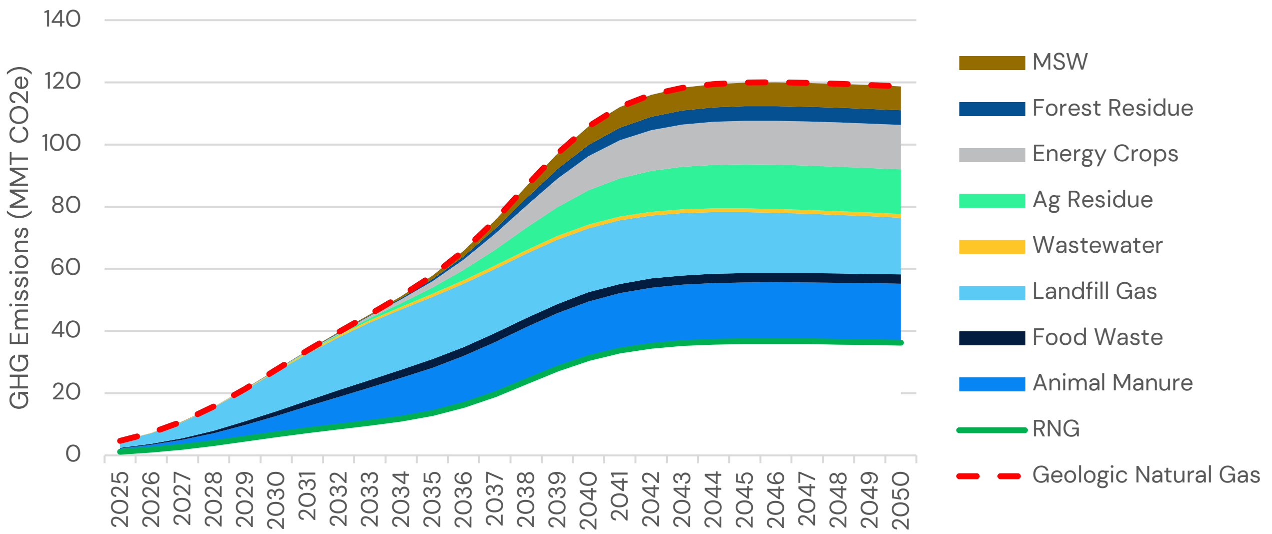


Figure 57. Life Cycle GHG Emission Reductions Potential, High Scenario ($MMTCO_2e$)

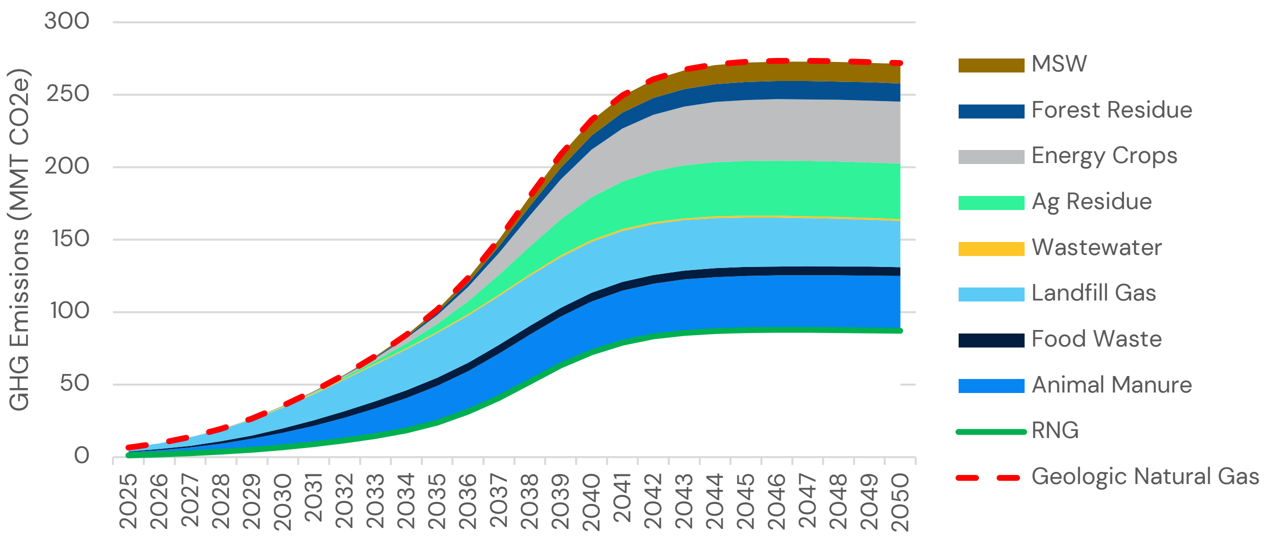
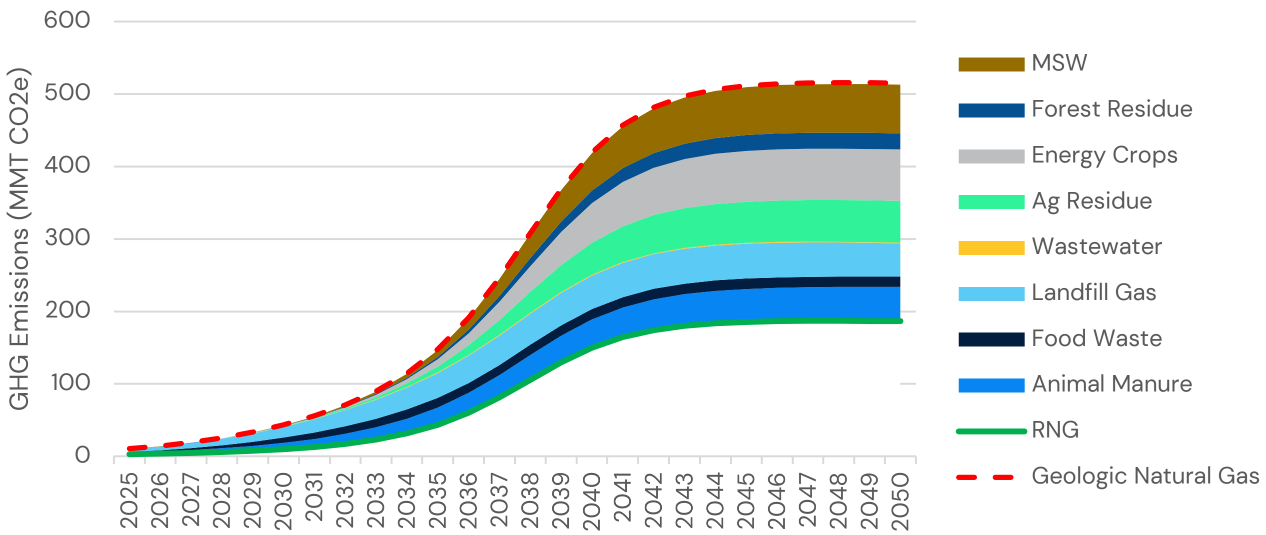


Figure 58. Life Cycle GHG Emission Reductions Potential, Ambitious Emissions Reduction Scenario ($MMTCO_2e$)



The GHG emission reductions achieved by displacing geologic natural gas varied slightly across feedstocks. For the Ambitious Emissions Reduction Scenario, RNG from energy crops provides the largest potential GHG emissions reduction by 2050 at about 71 MMT CO_2e with the next highest reduction potential being the RNG from MSW at about 67 MMT CO_2e by 2050. The magnitude of feedstock supply is the core driver of emissions impacts in this scenario.

The Low Scenario and High Scenario show similar trends with respect to the GHG emission reduction potential. In the Low Scenario, the largest potential GHG emission reduction comes from RNG derived from landfill gas with a reduction potential of 18.2 MMT CO_2e by 2050. Wastewater, with modest RNG production potential based on ICF's analysis, yields a GHG emissions reduction potential of about 0.9 MMT CO_2e by 2050.

ICF notes that applying a different accounting framework, such as combustion accounting, would deliver different emission reduction results, but the overall finding remains the same: widescale deployment of RNG would lead to significant emission reductions. In the case of combustion GHG accounting, RNG from all eight biomass feedstocks would yield biogenic CO_2 combustion emissions, functionally displacing the combustion emissions from an equivalent supply of geologic natural gas. As this effect is consistent across biogenic RNG feedstocks, the GHG emissions reduction potential of RNG on a combustion basis is more straightforward and directly correlates with the supply of each of the eight biomass feedstocks in all scenarios.

4 Production Costs and Supply Curves

4.1 RNG Cost Assessment

ICF developed assumptions for the capital expenditures and operational costs for RNG production from the various feedstock and technology pairings outlined previously—and developed supply-cost estimates for RNG with an outlook to 2050. ICF characterizes costs based on a series of assumptions regarding the production facility sizes (as measured by gas throughput in units of standard cubic feet per minute [SCFM]), gas upgrading and conditioning and upgrading costs (depending on the type of technology used, the contaminant loadings, etc.), compression, and interconnect for pipeline injection. ICF also included operational costs for each technology type. The table below outlines some ICF's baseline assumptions that it employed in its RNG costing model for anaerobic digestion systems and thermal gasification systems.

Table 26. Illustrative Cost Assumptions Developed to Estimate RNG Production Costs in 2050

Cost Parameter	ICF Cost Assumptions
Facility Sizing	• Differentiate by feedstock and technology type: AD and TG • Prioritize larger facilities to the extent feasible, but driven by resource estimate
Gas Conditioning and Upgrade	• These costs depend on the feedstock and the technology required.
Compression	• Capital costs for compressing the conditioned/upgraded gas for pipeline injection.
Operational Costs	• Costs for each equipment type–digesters, conditioning equipment, collection equipment, and compressors–as well as utility charges for estimated electricity consumption.
Feedstock	• Feedstock costs (for thermal gasification) ranging from $57 to $100 per dry ton.
Financing	• Financing costs, including carrying costs of capital (assuming a 60/40 debt/equity ratio and an interest rate of 7%), an expected rate of return on investment (set at 10%), and a 20-year repayment period.
Interconnection	• Costs of interconnection—representing the point of receipt and any pipeline extension. This cost is in line with financing, constructing, and maintaining a pipeline of about 1-mile in length. The costs of delivering the same volumes of RNG that require pipeline construction greater than 1-mile will increase, depending on feedstock/technology type, with a typical range of $1-5/MMBtu.
Project lifetimes	• 20 years. The levelized cost of gas was calculated based on the initial capital costs in Year 1, annual operational costs discounted at an annual rate of 5% over 20 years, and biogas production discounted at an annual rate of 5% over 20 years.
Inflation Reduction Act	• For all facilities, ICF assumed a 30% ITC is applied to the capital costs

ICF notes that its cost estimates are not intended to replicate a developer's estimate when deploying a project. For instance, ICF recognizes that the cost category "conditioning and upgrading" represents an array of decisions that a project developer would have to make with respect to CO_2 removal, H_2S removal, siloxane removal, N_2/O_2 rejection, deployment of a thermal oxidizer, etc. Furthermore, ICF understands that project developers have reported a wide range of interconnection costs, with numbers as low as $200,000 reported in some states and as high as $9 million in other states. ICF appreciates the variance between projects, including those that use anaerobic digestion, thermal gasification, or power-to-gas technologies, and these supply-cost curves are meant to be illustrative rather than deterministic. This is especially true of the outlook to 2050—ICF has not included significant cost reductions that might occur due to rapidly growing RNG market, nor did we seek to capture any technological breakthroughs. ICF has made some assumptions in line with those in the publicly available literature regarding potential decreases in the costs of P2G systems; however, for anaerobic digestion and thermal gasification systems, ICF has focused on projects that have reasonable scale, representative capital expenditures, and reasonable operations and maintenance estimates.

ICF's cost estimates in the following sections are shown for 2050 (reported in 2024 dollars), and ICF made only modest assumptions with respect to the potential for RNG cost reductions. The most significant assumption in ICF's outlook to 2050 is the presumption that the underlying structure of the market will change. Today in the US, there is no standard market price for RNG—rather, the market is largely driven by the value of environmental commodities such as those derived from participating in the federal Renewable Fuel Standard and/or California's LCFS program. For instance, many landfill gas projects are estimated to produce RNG at a cost of $10-20/MMBtu, and dairy manure projects may produce RNG at a cost closer to $40/MMBtu. ICF reports substantial RNG production volumes at prices lower than $30/MMBtu (see below).

4.1.1 RNG from Anaerobic Digestion

Animal Manure

ICF developed assumptions for each region by distinguishing between animal manure projects, based on a combination of the size of the farms and assumptions that certain areas would need to aggregate or cluster resources to achieve the economies of scale necessary to warrant an RNG project. There is some uncertainty associated with this approach because an explicit geospatial analysis was not conducted; however, ICF did account for considerable costs in the operational budget for each facility assuming that aggregating animal manure would potentially be expensive.

The table below includes the main assumptions used across regions—including national average estimates for the cost per MMBtu across the various buckets. ICF has included the number of dairy cows as a reference to help contextualize the results for the reader; note, however, that the final analysis will involve manure from dairy cows, beef cows, chickens (layers and boilers), turkey, and swine.

Table 27. Cost Consideration in Levelized Cost of Gas Analysis for RNG from Animal Manure

Factor	Cost Elements Considered	Costs
Performance	• Capacity factor	• 90%
Installation Costs	• Installation and Owner's Cost	• 40% of uninstalled costs of equipment
Gas Upgrading	• CO2 separation • H2S removal • N2/O2 removal	• $2.3 to $7.0 million, depending on facility • $0.3 to $1.0 million, depending on facility • $1.0 to $2.5 million, depending on facility
Utility Costs	• Electricity: 35 kWh/MMBtu • Natural Gas: 35% of product	• National average • National average
Operations & Maintenance	• 1 FTE for maintenance • Miscellany	• 20% of installed capital costs
For Injection	• Interconnect • Pipeline • Compressor	• $3.0 million • $2 million • $0.5-$1.5 million
Other	• Value of digestate • Tipping fee	• Valued for dairy at about $100/cow/y • Excluded from analysis
Financial Parameters	• Rate of Return • Discount Rate	• 10% • 7%

ICF reports a range of costs for RNG from animal manure at $47/MMBtu to $170/MMBtu.

Food Waste

ICF made the simplifying assumption that food waste processing facilities would be purpose-built and be capable of processing 60,000 tons of waste per year—ICF estimates that these facilities would produce either 250, 500 or 1000 standard cubic feet per minute (SCFM) of biogas for conditioning and upgrading before pipeline injection. In addition to the other costs included in other AD systems, ICF also included assumptions about the cost of collecting food waste and processing it accordingly.

Table 28. Cost Consideration in Levelized Cost of Gas Analysis for RNG from Food Waste

Factor	Cost Elements Considered	Costs
Performance	• Capacity factor • Processing Capability	• 90% • 60,000 tons per year
Dedicated Equipment	• Organics Processing • Digester	• Varies by facility size • Varies by facility size
Installation Costs	• Installation and Owner's Cost	• 40% of uninstalled costs of equipment
Gas Upgrading	• CO_2 separation • H_2S removal • N_2/O_2 removal	• $2.3 to $7.0 million • $0.3 to $1.0 million • $1.0 to $2.5 million
Utility Costs	• Electricity: 35 kWh/MMBtu • Natural Gas: 20% of product	• National average • National average
Operations & Maintenance	• 1.5 FTE for maintenance • Miscellany	• 20% of installed capital costs
Other	• Tipping fees	• Varied by region;
For Injection	• Interconnect • Pipeline • Compressor	• $3.0 million • $2 million • $0.5 to $1.5 million

Financial Parameters	• Rate of Return • Discount Rate	• 10% • 7%

ICF assumed that food waste facilities would be able to offset costs with tipping fees. ICF used values presented by an analysis of municipal solid waste landfills by the Environmental Research & Education Foundation (EREF). The tipping fees reported by EREF for 2023 are shown in the table below.

Table 29. Average Tipping Fee by Region[28]

Region	Tipping Fee, 2023
Pacific: AK, AZ, CA, HI, ID, NV, OR, WA	$62.28
Northeast: CT, DE, ME, MD, MA, NH, NJ, NY, PA, RI, VA, WV	$84.44
Midwest: IL, IN, IA, KS, MI, MN, MO, NE, OH, OH, WI	$57.24
Mountains / Plains: CO, MT, ND, SD, UT, WY	$49.86
Southeast: AL, FL, GA, KY, MS, NC, SC, TN	$43.18
South Central: AR, LA, NM, OK, TX	$45.25
National Average (ton-weigthed)	$57.63

ICF assumed that anaerobic digesters discounted the tipping fee compared to MSW landfills and applied a 20% discount to the values listed in the table.[29]

ICF reports an estimated cost of RNG from food waste of $19.4/MMBtu to $28.3/MMBtu.

Landfill Gas

ICF developed assumptions for each region by distinguishing between four types of landfills: candidate landfills[30] without collection systems in place, candidate landfills with collection systems in place, landfills[31] without collection systems in place, and landfills with collections systems in place.[32] For each region, ICF further characterized the number of landfills across these four types of landfills, distinguishing facilities by estimated biogas throughput (reported in units of standard cubic feet per minute of biogas).

For utility costs, ICF assumed 35 kWh per MMBtu of RNG injected and 6% of geological or fossil natural gas used in processing (measured as a percentage of RNG production). Electricity and delivered natural gas costs were reflective of industrial rates reported at the state level by the EIA.

The table below summarizes the key parameters that ICF employed in its cost analysis of LFG.

Table 30. Cost Consideration in LCOG Analysis for RNG from Landfill Gas

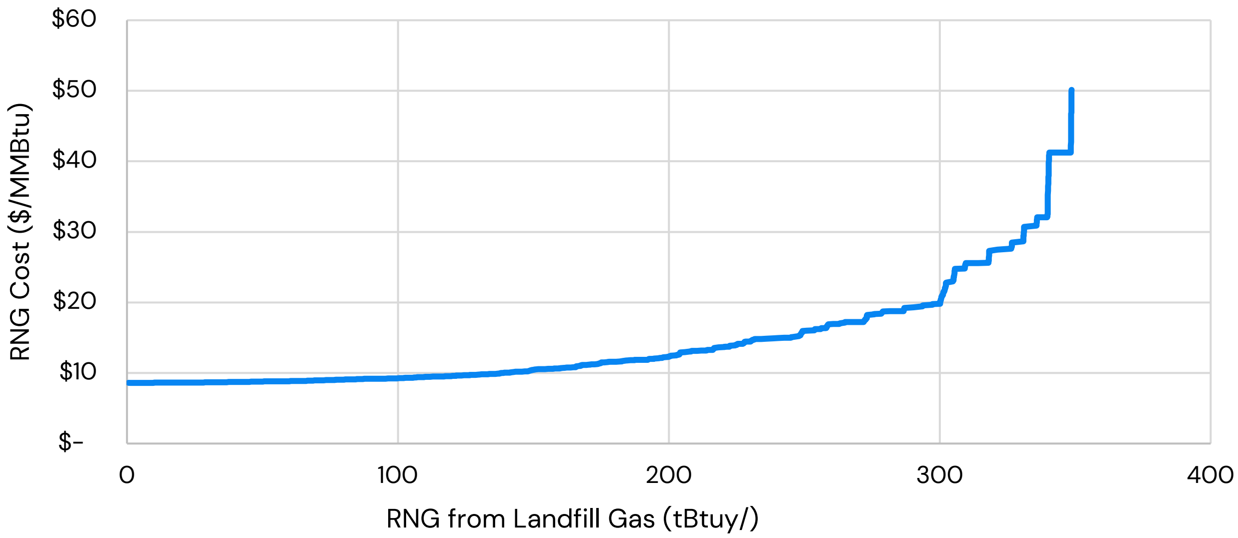
Factor	Cost Elements Considered	Costs
Performance	• Capacity factor	• 90%
Installation Costs	• Installation and Owner's Costs	• 40% of installed costs of equipment

[28] As reported by EREF; available online at https://www.waste360.com/landfill-operations/eref-study-shows-continued-increase-average-msw-landfill-tip-fees.
[29] A report entitled Business Analysis of Anaerobic Digestion in the USA by Renewable Waste Intelligence notes that "a lower tipping fee (approximately by $10) than landfill is required in order to incentivize waste management companies to separate" waste from trash and deliver it to an AD facility. ICF assumed a 20% discount from the tipping fees reported would be a sufficient incentive to deliver the feedstock to an AD facility.
[30] The EPA characterizes candidate landfills as one that is accepting waste or has been closed for five years or less, has at least one million tons of WIP, and does not have an operational, under-construction, or planned project. Candidate landfills can also be designated based on actual interest by the site.
[31] Excluding those that are designated as candidate landfills.
[32] Landfills that are currently producing RNG for pipeline injection are included here.

Gas Upgrading	• CO2 separation • H_2S removal • N_2/O_2 removal	• $2.3 to $7.0 million, depending on facility • $0.3 to $1.0 million, depending on facility • $1.0 to $2.5 million, depending on facility
Utility Costs	• Electricity: 35 kWh/MMBtu • Natural Gas: 6% of product	• 5—6 ¢/kWh • $3.00-$4.00/MMBtu
Operations & Maintenance	• 1 FTE for maintenance • Miscellany	• 20% of installed capital costs
For Injection	• Interconnect • Pipeline • Compressor	• $3 million • $2 million • 0.0004*SCFM + 0.49
Financial Parameters	• Rate of Return • Discount Rate	• 10% • 7%

The figure below includes ICF's analysis for the RNG supply curve associated with production via landfill gas. ICF reports an estimated cost of RNG from food waste of $8.60/MMBtu to $51.20/MMBtu.

Figure 59. Supply Curve, RNG from Landfill Gas in 2050 ($/MMBtu vs tBtu)



Wastewater

ICF developed assumptions for each region by distinguishing between wastewater at water resource recovery facilities based on the throughput of the facilities. The table below includes the main assumptions used across regions—including national average estimates for the cost per MMBtu across the various facility sizes.

Table 31. Cost Consideration in Levelized Cost of Gas Analysis for RNG from WRRFs

Factor	Cost Elements Considered	Costs
Performance	• Capacity factor	• 90%
Installation Costs	• Installation and Owner's Cost	• 40% of uninstalled costs of equipment
Gas Upgrading	• CO_2 separation • H_2S removal • N_2/O_2 removal	• $2.3 to $7.0 million • $0.3 to $1.0 million • $1.0 to $2.5 million
Utility Costs	• Electricity: 45 kWh/MMBtu • Natural Gas: 50% of product	• National average • National average

Factor	Cost Elements Considered	Costs
Operations & Maintenance	• 1 FTE for maintenance • Miscellany	• 20% of installed capital costs
For Injection	• Interconnect • Pipeline • Compressor	• $3.0 million • $2 million • $0.5 to $1.5 million
Financial Parameters	• Rate of Return • Discount Rate	• 10% • 7%

ICF reports a range of costs for RNG from WRRFs at $7/MMBtu to $97/MMBtu.

4.1.2 RNG from Thermal Gasification

ICF used similar assumptions across the thermal gasification of feedstocks, including agricultural residue, forestry residue, energy crops, and MSW. There is considerable uncertainty around the costs for thermal gasification of feedstocks, as the technology has only been deployed at the pilot scale to date or in the advanced stages of demonstration at the pilot scale. This is in stark contrast to the AD technologies considered previously. ICF reports here on the three illustrative facilities that ICF employed for conducting the cost analysis—distinguished by the amount of feedstock processed daily (in units of tons per day, TPD). For this analysis, ICF modeled facilities that process 200, 1,000, and 2,000 TPD. Cost minimums and maximums in the table below reflect the assumptions for the low 200 TPD facility and high 2,000 TPD facility.

Table 32. Cost Consideration in Levelized Cost of Gas Analysis for RNG from Thermal Gasification

Factor	Cost Elements Considered	Costs
Performance	• Capacity factor • Processing Capability	• 90% • 2,000 tpd
Dedicated Equipment & Installation Costs	• Feedstock Handling (drying, storage) • Gasifier • CO_2 removal • Syngas Reformer • Methanation • Other (cooling tower, water treatment) • Miscellany (site work, etc.) • Construction/ engineering	• $9–43 million • $26–125 million • $11–51 million • $4–20 million • $8–41 million • $3–16 million • $4–21 million • $41–192 million
Utility Costs	• Electricity: 38 kWh/MMBtu • Natural Gas: 25% of product	• National average • National average
Operations & Maintenance	• Feedstock • 3 FTE for maintenance	• $57/dry ton • 10–20% of installed capital costs
For Injection	• Interconnect • Pipeline • Compressor	• $3.0 million • $2 million
Financial Parameters	• Rate of Return • Discount Rate	• 10% • 7%

ICF applied these estimates across each of the four feedstocks, their corresponding feedstock cost estimates, and assumed that the smaller facilities processing 200 tons per day would represent 20% of the processing capacity and that the larger facilities processing 1,000 and 2,000 tons per day would represent 40% of the processing capacity each. The number of facilities built in each region was constrained by the resource assessment.

ICF reports estimated levelized costs of RNG from thermal gasification as follows:

- Agricultural residues: $22/MMBtu to $46/MMBtu
- Forestry and forest residues: $22/MMBtu to $46/MMBtu
- Energy crops: $22/MMBtu to $46/MMBtu
- MSW: $22/MMBtu to $46/MMBtu

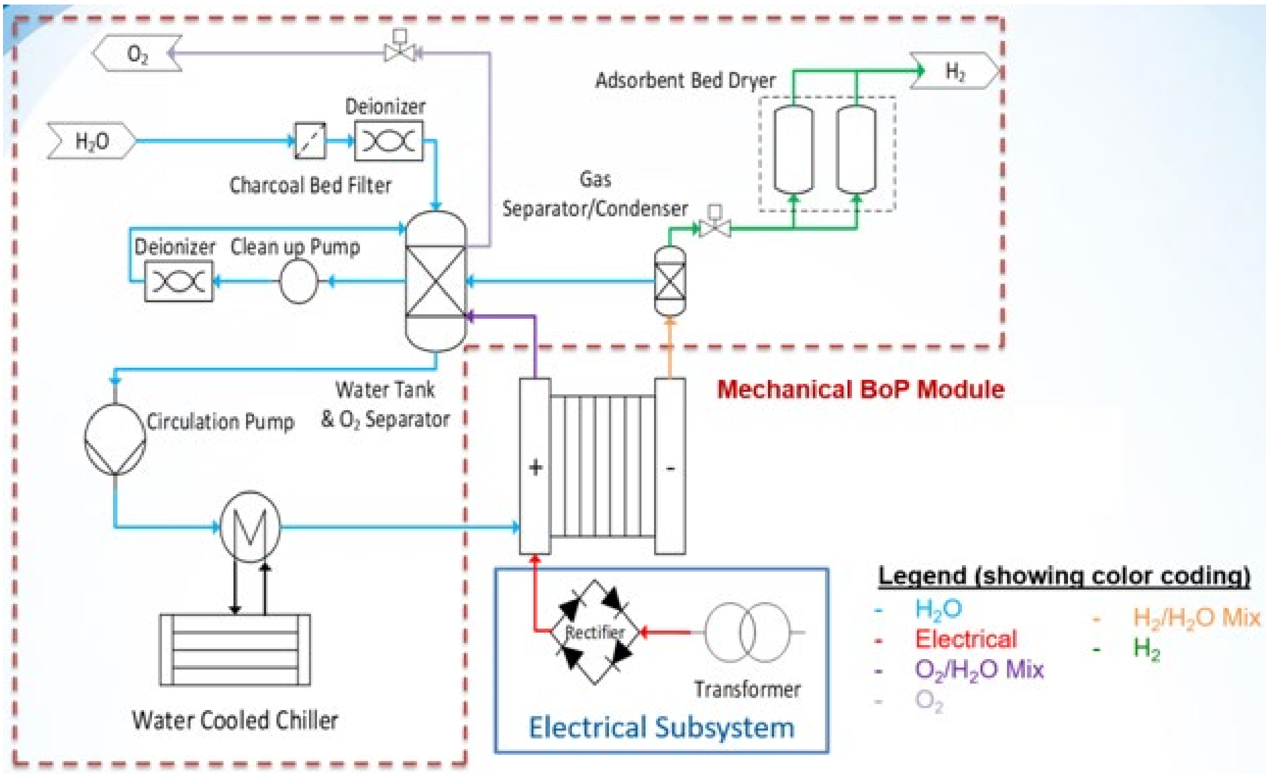
4.1.3 RNG from Methanated Hydrogen (P2G)

The RNG from methanated hydrogen pathway has multiple components, introduced here as hydrogen from renewable resources and carbon dioxide. The last subsection incorporates the renewable hydrogen components into the methanation step, and includes the various cost elements to produce RNG.

Hydrogen from Renewable Resources

ICF has developed hydrogen production cost models for hydrogen produced using renewable and nuclear energy and electrolyzer technology. An electrolyzer facility includes the electrolyzer system along with the mechanical and electrical balance of plant (BoP). The electrolyzer requires deionized water and typical equipment manufacturers include a water treatment and recirculation system as part of the mechanical BoP. Once the deionized water feeds into the electrolyzer, the electrolyzer splits the water into hydrogen and oxygen. Oxygen and hydrogen are then treated to be separated from water. The oxygen could be captured and sold or vented out into the atmosphere. The hydrogen goes through dryers to remove moisture and is collected or compressed as a product. The electrical BoP consists of a transformer and rectifier used to convert AC to DC voltage. Figure 60 shows the typical block flow diagram to produce hydrogen, including electrolyzer and BoP equipment.[33]

Figure 60. Sampled PEM Electrolyzer Facility for Hydrogen Production



The cost of renewable hydrogen produced via electrolysis is highly dependent on the cost of the electrolyzer units, the utilization of the electrolyzer units, and the price of electricity used in production. The potential for "numbering up" architecture of including multiple electrolyzer stacks within a larger

[33] Analysis of Advanced Hydrogen Production and Delivery Pathways (energy.gov)

electrolyzer house is expected to drive significant per-unit cost reductions in the future. These cost reductions are typically modeled using "learning rates" which are calculated by determining the capital cost reduction for each doubling of capacity. It is also expected that economies of scale and learning efficiencies from the equipment manufactures as the technology develops could also decrease costs.

ICF assumes that renewable costs are procured for hydrogen at the levelized cost of energy (LCOE). The LCOE represents the minimum price a renewable resource must earn to recover all costs and provide the required rate of return to its investors. AEO costs were used to develop LCOEs for wind and solar power and ICF developed costs for nuclear using NREL's technology data.[34] ICF also assumed capacity factor (CF) on a national basis using data from EIA[35] as shown in the table below.

Table 33. Average Capacity Factors for Resources included in ICF analysis

Geography	Solar PV	Wind	Nuclear
United States	24.4%	35.9%	92%

ICF's analysis was prepared assuming 3% annual maintenance as a percentage of capital expenditures and uses an electrolyzer cost of $1,050/kW, based on average bid prices from recent projects with which ICF is familiar and a total installed cost factor range of 2—2.7 times the electrolyzer cost for greenfield, grid-connected electrolyzer plants with which ICF is also familiar.

The levelized cost of hydrogen projection is based on a 220 MW electrolyzer facility with a learning curve rate of 22% and a water cost of $5.63/kgal and includes an annual escalation of approximately 1%.[36] The electrolyzer stack membranes are assumed to be replaced every 7-10 years; this is included in ICF's assumptions by accounting for as a major maintenance cost of 30% of the direct capital expenditures, the cost for which is allocated evenly as an annualized cost. The labor cost for this specific analysis was assumed to be approximately $2 million annually. However, labor costs are subject to regional differences. Based on electrolyzer experience in other analog industries such as the chlor-alkali business, continuous deionization and reverse osmosis systems used to produce clean water, and academic studies,[37] it is ICF's expectation that industrial proton exchange membrane (PEM) electrolyzer maintenance will require between 3-5% of capex on an annual basis for preventative and corrective maintenance. Preventative and corrective maintenance components include but are not limited to cleaning of contamination or impurities within PEM system, and regular maintenance for the water treatment system, compressor, hydrogen dryer and other BoP components. The cost includes electrolyzer membrane stack replacement, which is funded as a major maintenance item.

Table 34. Electrolyzer Facility Production Cost Inputs

Input	Value	Comments
Sample Facility Size		
Electrolyzer Size	220 MW	Based on projects with which ICF is familiar
Annual Production Target	20,000,000 kg	Based on projects with which ICF is familiar
Energy and Water Inputs		
Renewable Power Capacity Factor	Dependent on energy resource and location	Assuming energy from solar, wind and nuclear sources

[34] Nuclear | Electricity | 2024 | ATB | NREL
[35] https://www.eia.gov/state/seds/data.php?incfile=/state/seds/sep_fuel/html/fuel_cf.html&sid=WA
[36] https://www.osti.gov/servlets/purl/1975260
[37] Optimized electrolyzer operation: Employing forecasts of wind energy availability, hydrogen demand, and electricity prices - ScienceDirect

Input	Value	Comments
Electrolyzer Energy Consumption Rate	53 kWh/kg	Based on projects with which ICF is familiar and ranges from OEMs
BoP Energy Consumption Rate	8 kWh/kg	Based on projects with which ICF is familiar and ranges from OEMs
Electricity Cost	Dependent on resource type (solar, wind, nuclear or RECs)	Based on AEO projections for solar and wind LCOEs and ICF estimates from NREL for nuclear LCOE; RECs assumed to come at a placeholder value of 5% premium to the LCOE
Water Intake Rate	2.64 gal/kg	Based on projects with which ICF is familiar and ranges from OEMs
Water Cost	\$5.63/kgal	Industrial utility water with approximately 1% annual escalation, from US DOE Office of Scientific and Technical Information
Operation Inputs		
Stack Membrane Life	10 years	Based on projects with which ICF is familiar
Life of Electrolyzer Equipment	80,000 hours	Based on projects with which ICF is familiar
Annual Degradation Rate	1%	Conservative estimate; levelized degradation factor is assumed to have minimal impact and not included in analysis
Operating year	333-353 days	Based on projects with which ICF is familiar
Annual Labor Costs	\$2.95 million	ICF's estimate for standalone electrolyzer facility with ~25 staff
Membrane Replacement Cost as % of Direct Capex	30%	Based on projects with which ICF is familiar
Annual Maintenance as % of Capex	3%	Based on projects with which ICF is familiar
Project Finance and Capital Costs		
PEM Electrolyzer	\$1050/kW	Based on projects with which ICF is familiar (and OEM bids)
Total Installed Cost Factor	2	Based on projects with which ICF is familiar; can range from 2 – 2.7 depending on BoP
Learning Curve Rate for Total System	22%	ICF's internal model
WACC	10%	
Loan Duration	20 years	

ICF assumed that electrolyzer costs will scale linearly with capacity. Electrolyzer units are additive, much like solar facilities. Additional units are added to increase capacity, rather than scaled up volumetrically by a factor similar to that of industrial plants such as combined cycle gas plants. Similar to solar where panels are added to increase the output, electrolyzer units can be added to increase the size of the hydrogen production facility. The BoP can be scaled up, which may result in some cost savings; however, ICF has included BoP costs in the total installed cost factor as a percentage of the electrolyzer capital cost in ICF's assumptions.

ICF included two sets of tax credits in the renewable hydrogen model.

- The renewable electricity production tax credit is a per kilowatt-hour (kWh) federal tax credit included under Section 45 of the US tax code for electricity generated by qualified renewable energy resources. ICF levelized the tax credit over 20 years and includes $20.86/MWh annual tax credit from 2025 to 2045.
- The Section 45V Hydrogen Production Tax Credit was introduced in the Inflation Reduction Act of 2022 to incentivize the production of low-carbon hydrogen. The credit offers a financial benefit based on the lifecycle carbon intensity (CI) of hydrogen produced, with higher credits awarded to lower-carbon production processes. ICF levelized the tax credit over 20 years. The tax credit by CI is summarized in the table below. Since hydrogen projects must be under construction by the end of 2032 to qualify for 45V credits, 45V tax credits were modeled until 2035 as a conservative estimate assuming every new hydrogen facility beginning construction after 2032 may not qualify for the tax credit.

Table 35. Hydrogen Investment Tax Credit and Production Tax Credit via 45V

Life Cycle Emissions, kg CO_2e / kgH_2		Value of Incentive			
Low	High	ITC%	PTC $/kg	PTC $/MMBtu	Levelized PTC $/MMBtu
2.50	4.00	6.0%	$0.60	$4.45	$2.90
1.50	2.50	7.5%	$0.75	$5.57	$3.63
0.45	1.50	10.0%	$1.00	$7.42	$4.84
0.00	0.45	30.0%	$3.00	$22.26	$14.51

Carbon Dioxide

ICF considered several sources for carbon dioxide as part of the P2G pathway in the analysis. The first step in this process is to capture the CO_2 from various possibles sources including:

- Flue gases of power plants and industrial facilities burning fossil fuels or biomass/biofuel,
- Process gas streams from industrial facilities (natural gas processing plants, ammonia plants, methanol plants, petroleum refineries, steel mills, cement plants, ethanol plants, etc.)
- Hydrogen plants using fossil fuels or biomass as feedstocks
- Air (through the application of direct air capture).

After capturing CO_2, the next steps typically are to purify and dehydrate the CO_2, compress it for transportation and then either (a) to inject it underground into an appropriate geological storage site, where it is trapped and permanently stored in porous rock or (b) utilize it in various pathways.

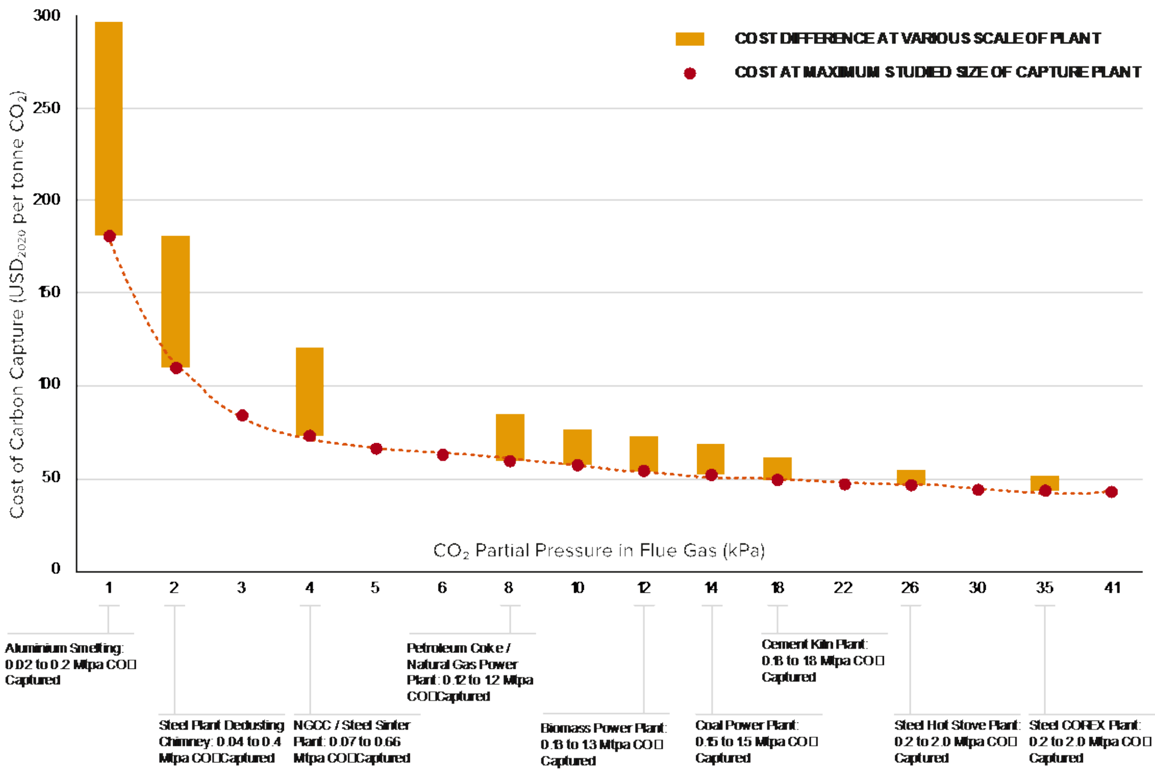
There are many technologies available to capture CO_2 from flue gas and process gas streams including several kinds of post-combustion capture (e.g., absorption by chemical solvents, adsorption by solid sorbents, membrane separation, cryogenic separation, and pressure swing adsorption). The major competitor to post-combustion technologies is oxy-fuel combustion in which pure oxygen combustion air is used to produce a nitrogen-free flue gas that can be transported and stored after relatively inexpensive dehydration and treatment steps. The main drawback to oxy-firing is the large amounts of energy use and high cost associated with separating oxygen from air.

The economic modeling of carbon capture costs for this analysis is based on post-combustion capture by absorption by chemical solvents. This is the most mature and widely used process. The basis for the cost estimates is the Global CCS Institute's (GCCSI) Technology Readiness and Costs of CCS report from

2021.[38] Capture costs were modeled as largely a function of CO_2 partial pressure[39] and the volume of CO_2 being captured. The GCCSI cost estimate was based on an aqueous solution of 30% by weight of monoethanolamine, a chemical solvent that has wide commercial availability and performs well over a range of CO_2 partial pressures.

The cost of capturing CO_2 as calculated by GCCSI is shown in the figure below in units of dollars per metric ton of captured CO_2. These costs include annualized capital costs, operating and maintenance costs, costs for consumables, and energy costs. The graph shows that high-volume gas streams with high CO_2 partial pressures can be captured at a cost of under $50/MT of CO_2, while gas stream gas with lower partial pressures and/or smaller stream volumes will have higher capture costs of $50 to $100/MT of CO_2 or more.

Figure 61. CO_2 Capture Cost from Industrial and Power Plant Flue Gas and Process Gas Streams



Source: GCCSI. Costs are for capture only and exclude dehydration and compression, transportation, and geologic storage.

The costs shown above are only to capture the CO_2 and do not include costs for dehydration, compression, transport, and storage. GCCSI also estimated these, as shown below in Table 36. Costs after the capture step will add an additional $16 to $69 per metric ton of stored carbon dioxide. This brings total CCS cost for large volume industrial and power combustion flue gas streams and industrial process gas streams to $60 to $150 per MT per GCCSI estimates.

[38] Global CCS Institute, Technology Readiness and Costs of CCS, March 2021. Available online at https://scienceforsustainability.org/w/images/b/bc/Technology-Readiness-and-Costs-for-CCS-2021-1.pdf

[39] Partial pressure is measured as the percent concentration of CO_2 (or any other gas) in a gas stream times the pressure of that gas stream. A gas stream with high partial pressure of CO_2 means that it will be easier and less expensive to capture the CO_2 because less external energy is required compared to streams with lower CO_2 concentrations and/or lower pressures.

Table 36. CO_2 Compression, Dehydration, Transport, and Storage Costs ($/MT$CO_2$)[40]

Step	Low	High	Average, Low-High
Compression & Dehydration	$10.00	$22.50	$16.25
Pipeline Transport, 30 km	$2.50	$24.00	$13.25
Injection & Geologic Storage	$2.00	$18.00	$10.00
Monitoring & Verification	$2.00	$4.00	$3.00
Total	$16.50	$68.50	$42.50

The estimated geologic storage capacity in the Lower 48 states is about 8,215 billion metric tons of carbon dioxide based on ICF analysis of the most recent data from DOE. [41] The analysis of storage volumes is conducted by regional carbon sequestration partnerships as overseen by NETL in Morgantown, West Virginia. State-level onshore and offshore capacity volumes are reported for storage in oil and gas reservoirs and deep saline formations. Most storage volume capacity is in deep saline formations, which are present in many states and in most states with oil and gas production. In the most recent version of the Atlas, offshore storage capacity volumes have also been broken out by DOE into the Gulf of Mexico, Atlantic, and Pacific Outer Continental Shelf regions. ICF conducted a separate analysis to break out CO_2 enhanced oil recovery storage potential from the total potential in oil and gas reservoirs reported in the National Carbon Sequestration Database.

Geologic Storage Costs

ICF has computed geologic storage costs in terms of levelized[42] dollars per metric ton of stored CO_2. These costs are largely a function of the geologic characteristics of each project and assumptions used in the costing algorithms for individual construction and operating components of geologic sequestration of CO_2. The largest economic drivers are the costs of well operation, injection and monitoring well construction costs, and the costs of site monitoring. Depending on the nature of each cost element, “unit costs” are specified as dollars per storage site, dollars per square mile, dollars per foot as a function of well depth, dollars per labor hour, or other kinds of specifications or algorithms. The unit cost specification module includes data and assumptions for about 105 cost elements falling within the following ten general cost categories:

- Geologic Site Characterization
- Area of Review Study & Corrective Action
- Injection Well Construction
- Operation of Injection Wells & Pumps
- Water Management Capex & Opex
- Monitoring & Reporting Capex and Opex, includes mechanical integrity tests
- Financial Responsibility
- Post-Injection Site Care & Site Closure
- General & Administrative Costs

The weighted average geologic storage cost for saline aquifers in the Lower 48 is $16.70 per metric ton computed on a levelized basis.

[40] *Ibid.*
[41] DOE, Carbon Sequestration Atlas of the United States and Canada Version 5. See https://www.netl.doe.gov/coal/carbon-storage/strategic-program-support/natcarb-atlas
[42] In mathematical terms, the levelized cost produces a net present value of cash inflows (discounted at the operator’s weighted average cost of capital) that exactly equals the net present value of cash outflows (also discounted at the operator’s weighted average cost of capital).

Treatment of Tax Credits

Under the Inflation Reduction Act (IRA), the 45Q tax credit was raised to $60/metric ton for carbon dioxide used in enhanced oil recovery or other industrial operations and to $85/metric for permanently stored CO_2 such as in saline aquifers or abandoned oil and gas fields. The carbon capture utilization and storage (CCUS) credit is available for CCUS projects beginning construction before January 1, 2033, and is to be applied to CO_2 quantities stored in the first 12 years of a project's operation.

The output of the cost analysis is the before-tax-credit dollar per metric ton levelized cost for capture, transport and storage. Also provided in a second column is the levelized cost after the tax credit is applied. Note that the tax credit is applied on a levelized basis. That is, the 12 years of credits are spread over the expected 20 operating years for each CCUS project. Based on that assumption, the $85/MT credit becomes $59/MT on a levelized basis.

As the processes of capturing, dehydrating, compressing, transporting, and storing carbon dioxide require energy, the net effect of capturing and storing 1 metric ton of CO_2 is NOT -1 CO_2e metric ton. This net effect is because additional energy is required for the ongoing operation of CCUS facilities, with associated GHG emissions from this energy, primarily from natural gas and electricity consumption. On average this the net benefit is about -0.93 CO2e per metric ton captured and stored.

CO_2 Transportation

ICF's pipeline transportation cost estimates rely on standard engineering calculations to determine the pipeline diameter required for a given CO_2 flow volume, combined with assumptions about how CO_2 volumes from individual power plants and other sources are aggregated into larger, long-distance pipelines. In the ICF cost model, the capital cost of CO_2 pipelines is expressed in dollars per inch-mile; a corresponding tariff rate is then derived using standard discounted cash flow methods, incorporating these capital costs as well as projected operating and maintenance expenses for CO_2 pipelines.

Methanation

ICF developed assumptions for the capital expenditures and operational costs for methanation of renewable hydrogen and various CO_2 sources. ICF characterizes costs based on a series of assumptions regarding the production facility sizes, gas upgrading and conditioning and upgrading costs, compression, and interconnect for pipeline injection. ICF also included operational costs for each technology type. The table below outlines some of ICF's baseline assumptions employed in its RNG via methanation costing model.

Table 37. ICF Methanation Cost Assumptions

Factor	Cost Elements Considered	Costs
Performance	• Capacity factor • Facility size	• 92% • Varies: 200-2,000 tons per day
Installation Costs	• Construction / Engineering • Owner's cost	• 30% of installed equipment costs • 15% of installed equipment costs
Biomass	• Handling/drying • Syngas cooling / cleaning • Syngas shifting • Co2 removal • Methanation / compression • Dehydration • Misc	• $13 - $61 million • $38 - $178 million • $6 - $29 million • $16 - $73 million • $13 - $58 million • $0 - $1 million • $42 - $193 million
Utility Costs	• Electricity: 38-45 kWh/MMBtu • Natural Gas: 25% of product	• National average (c/kWh) • National average ($/MMBtu)
Operations & Maintenance	• 1 FTE for maintenance • Miscellany	• 10-20% of installed capital costs – gasification and biomass handling
For Injection	• Interconnect • Pipeline • Compressor	• $2.0 million • $2.6 million • $0.1–$0.7 million
Financial Parameters	• Rate of return • Discount rate	• 10% • 7%

The table below shows the results of ICF's levelized cost analysis using the assumptions outlined above. ICF notes that the costs increase between 2030 and 2050 largely due to the assumed expiration of the 45V production tax credit for hydrogen.

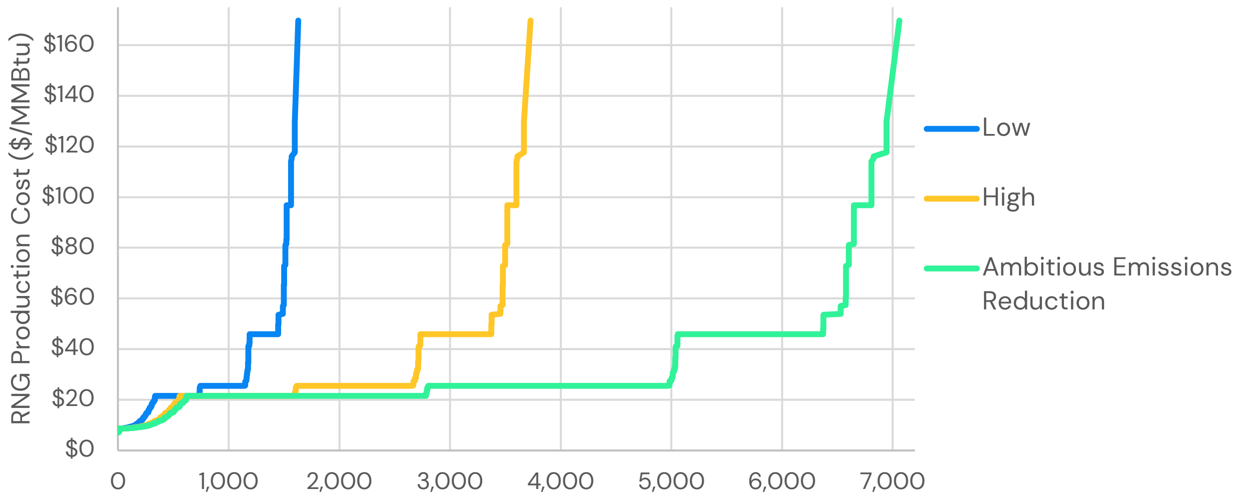
Table 38. Levelized Cost of Gas for Methanated Hydrogen (P2G) Pathway ($/MMBtu)

Electricity source	2030	2050
Wind	$31-$43	$54-$81
Solar	$21-$30	$45-63
Nuclear	$35-$43	$58-$77

4.2 Combined Supply Curves

The supply curves presented in the figure below show the RNG production potential from anaerobic digestion and thermal gasification pathways and exclude the methanated hydrogen (P2G) pathway. ICF estimates that more than half of the RNG production potential in the High Scenario could be available at a production cost of less than $30/MMBtu, as shown in the figure below. For reference, the front end of the supply curves shown below tend to be a mix of landfill gas projects and WRRF-sited projects. As the reported production costs increase on the y-axis, the supply curve includes the thermal gasification pathways, some of the larger animal manure projects and food waste projects. The highest cost RNG supply will likely come from smaller animal manure and food waste projects.

Figure 62. RNG Supply Curves for the Low, High, and Ambitious Emissions Reduction Scenarios



ICF estimates that 75% of the RNG production potential in the Low Scenario and High Scenario could be produced at an average cost less than $20/MMBtu and at an average cost of $23/MMBtu in the Ambitious Emissions Reduction Scenario.

As a reminder, ICF's production cost assumptions are generally conservative because it does not make assumptions about co-digestion or clustering opportunities that could reduce production costs. For instance, consider that California Bioenergy (CalBio) operates seven (7) clusters of RNG projects in California with 60-65 digesters in place. In this case, multiple digesters operate separately, but the biogas is captured and conditioned and upgraded at a shared facility amongst the digesters, thereby streamlining operations and reducing costs. There are other clusters operated by other developers in which a single digester is used to process animal manure from multiple farms, and there is a shared conditioning and upgrading facility to streamline operations and reduce costs.

4.3 GHG Cost-Effectiveness

The GHG cost-effectiveness or abatement cost is reported on a dollar per ton basis and is calculated as the difference between the GHG emissions attributable to RNG and geologic natural gas. ICF presents the cost-effectiveness in two ways: 1) using the LCA framework outlined previously (and the associated CI values) and using a framework consistent with IPCC guidelines whereby biogenic CO2 emissions are excluded entirely. We refer to the former as the cost-effectiveness in a lifecycle approach (Cost-Effectiveness$_{\text{Lifecycle}}$) and combustion approach (Cost-Effectiveness$_{\text{Combustion}}$), respectively. The cost-effectiveness calculations are simply as follows

Cost-Effectiveness$_{\text{Lifecycle}}$ = $\Delta(RNG_{cost}, Geologic\ NG_{cost}) \big/ (0.07295\ MT\ CO_{2e} - CI(RNG)\ MT\ CO_{2e})$, and

Cost-Effectiveness$_{\text{Combustion}}$ = $\Delta(RNG_{cost}, Geologic\ NG_{cost}) \big/ 0.05306\ MT\ CO_{2e}$

where the RNG_{cost} is the cost from the estimates reported previously in this section. For the purposes of this report, we use a geological natural gas price equal to the average Henry Hub spot price (2024 to

2050) reported by the EIA in the 2025 Annual Energy Outlook's Reference Case, calculated as $3.97/MMBtu (in 2024 dollars).[43]

- For the front end of the supply-cost curve is showing RNG is around $10/MMBtu and it is generally represented by landfill gas and wastewater. On a lifecycle basis, this represents about $135-$140/ton, whereas on a combustion basis this represents about $115/ton.
- For RNG price around $25/MMBtu, the cost-effectiveness varies by feedstock on a lifecycle basis. Pathways with avoided methane emissions, like dairy manure and swine manure have an abatement cost of about $85-$95/ton whereas food waste is around $150/ton. On a combustion basis, the $25/MMBtu is around $400/ton.

The GHG cost-effectiveness of RNG as a mitigation strategy varies depending on the framework considered (i.e., lifecycle basis or combustion basis) and the feedstock. RNG will be an attractive decarbonization strategy across many sectors, with importance in buildings, commercial activities, like industrial processes with high heat demands, and transportation like shipping and trucking. Abatement costs in some sectors are expected to be at least $200/ton and higher.[44] In this context, RNG will be a competitive abatement strategy.

[43] Energy Information Administration, 2025 Annual Energy Outlook, see Table 13. Available online https://www.eia.gov/outlooks/aeo/excel/aeotab13.xlsx.
[44] For instance, Evolved Energy Research for EDF, Marginal Abatement Costs for US Net-Zero Energy Systems, August 2021; Tore Langva *et al* 2024 Maritime Transp Res. ***6***, 100112; Michael Blackhurst *et al* 2025 Environ. Res.: Energy 2 015012

5 Technology Assessment

Historically, RNG producers have generated value via federal- and state-level programs like the federal Renewable Fuel Standard (RFS) and the California LCFS. The incentives from these programs have provided significant value to the RNG producers, however, the programs have not necessarily prioritized innovation with the explicit intent of reducing costs. For instance, mixed feedstocks often increase biogas yields compared to single feedstocks in anaerobic digesters; however, due to eligibility of the final product and how it is valued in the federal RFS, multi-feedstock digesters are rare in the United States. In addition to the mismatch between current programs and maximizing cost reductions, the RNG production industry has faced the same inflationary cost pressures as other industries over the last several years.

Over the next several years, as RNG demand increases across various sectors and the industry faces increased competition in these sectors, ICF anticipates that RNG producers will increasingly seek to reduce production costs. Although the potential for cost declines may be limited in cases where existing production technologies are mature, standardized and scaled manufacturing, additional research, development, and demonstration, or changes to policy could yield efficiencies and cost declines in some production pathways or some technologies. For instance,

- digesters represent a mature technology that has modest potential for cost reduction. The digester is one of the largest costs that RNG producers for anaerobic digestion face. Notably, one of the reasons that landfills provide one of the more cost-effective forms of RNG production is because the landfill itself acts as the digester.[45] The digester is sized based on the volume of feedstock it is going to handle. The costs are linked to the size of the digester and the material from which it is made. Additional costs include any components required for mixing, heating, and safety systems. These are difficult to reduce substantially.
- On the other hand, the market has moved away from the entirely bespoke nature of RNG deployment domestically that characterized the industry from the early 2010s. As the market continues to move to more standardized approaches, there are likely opportunities to increase the production of various components in the RNG production process, which could help yield the cost reductions associated with the learning curves observed in mass production in other industries.

ICF conducted a technology assessment across several components of RNG production, distinguished by production pathway with an objective to characterize the maturity and scalability of select technologies that drive RNG production:

- For anaerobic digestion, the review includes a) co-digestion of multiple feedstocks, b) enhanced biomethane production via methanation of carbon dioxide in biogas, and c) conditioning and upgrading of biogas to biomethane.
- For thermal gasification, it is important to note that technological improvements are critical to commercialization at a broader scale. Recognizing that broader improvements are required to commercialize thermal gasification, our review focused on a) pre-processing of feedstock(s)[46] and b) reduced tar formation in gasification.
- ICF also reviewed the need for gas quality and monitoring to help support RNG deployment in various market segments.
- ICF notes that RNG production via the methanated hydrogen pathway requires a variety of commercial developments, including but not limited to cost reductions for electrolyzers, advances in carbon capture for beneficial use, and improvements in the efficiency of methanation pathways.

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[45] The reduced cost of not having to build a digester notwithstanding, ICF does not intend to diminish the complexity of landfill gas collection systems and other on-the-ground challenges associated with large waste management facilities.
[46] ICF notes that pre-processing feedstocks is exclusively a benefit to thermal gasification. More specifically, the anaerobic digestion of food waste is improved by pre-processing.

The potential for these advancements is covered elsewhere and were deemed outside the scope of this study.

5.1 Anaerobic Digestion

5.1.1 Co-digestion to boost biogas yields

Although not considered in the RNG production potential estimates outlined previously, mixing animal manure with other organic materials (e.g., food waste or agricultural residues) can boost yield. Historically, this has not been pursued in the United States in part because of issues associated with constraints imposed by the EPA in the management of the RFS program—mixed digesters created regulatory hurdles that developers sought to avoid. As part of the recent Biogas Regulatory Reform Rule finalized by EPA in 2023, there are clearer rules for mixed digesters, and this may be an area where RNG producers start to realize increased biogas yields, thereby improving project economics (and reducing production costs).

ICF anticipates that there will be a significant increase in projects looking to incorporate co-digestion as a means to increase biogas yields in the near-term future. This will also become more widespread as RNG production yields supply that exceeds demand in the transportation sector, and producers are less beholden to the more restrictive reporting requirements of the Biogas Regulatory Reform Rule.

5.1.2 Conditioning and Upgrading Technologies

RNG projects today use a mix of membrane separation, pressure swing adsorption (PSA), amine scrubbing, and water scrubbing (or water wash) to condition and upgrade biogas mixtures to higher methane content for injection into the pipeline. There is limited information available regarding expected technological improvements in conditioning and upgrading technologies. Even the research that is presented demonstrates only modest cost reductions. For instance, the California Energy Commission sponsored a study that showed a novel metal-organic framework for carbon dioxide separation via adsorption—the study estimated that the approach could reduce capital and operational expenditures for upgrading by 15% and 38%, respectively.[47] Similarly, some researchers have focused on advanced membrane technologies targeted as multiple constituents in biogas, but these are at the research scale and have no indication of cost reductions that may be achieved.

5.1.3 Enhanced Methane Production from Anaerobic Digestion

As noted previously, biogas includes a mixture of gases including methane and carbon dioxide. Some researchers and companies have advanced concepts to capture the methane and then react the carbon dioxide with hydrogen in a methanation reaction as a means to increase RNG yields.

- The Bioenergy Technology Office funded work for an Advanced Pretreatment / Anaerobic Digestion process as Washington State University. Pretreatment occurs via advanced wet oxidation and stream explosion. With that pretreatment alone, researchers demonstrated a 101% increase in methane yield via two-step AD process converting wastewater sludge at wastewater plants; after incorporating methanation, they increased methane yield by 216%.[48]
- Electrochaea has a proprietary biocatalyst that selectively converts hydrogen and carbon dioxide into methane. In other words, if paired with an anaerobic digester as the carbon dioxide source, Electrochaea's technology is capable of increasing RNG production by converting it to methane in the presence of hydrogen.

[47] McDonald, Thomas, Carly Anderson, Zoey Herm, Graham Wenz. 2020. Efficient Biogas Upgrading Technology Based on Metal-Organic Frameworks. California Energy Commission. Publication Number: CEC-500-2020-054.
[48] Ahring, B. An Advanced Pretreatment / Anaerobic Digestion Technology for Increased Conversion of Sewage Sludge, BETO 2023 Peer Project Review.

These types of pathways combine multiple novel technologies—pre-treatment with methanation, for instance—but are in pre-commercialization or early commercialization stages. These types of projects require cost reductions, especially for hydrogen sourcing/production (e.g., via electrolysis) to be more cost-effective in the future, so that the improved RNG production economics can offset the costs of inputs.

5.2 Thermal Gasification

5.2.1 Pathway Pre-processing of feedstock

Anaerobic digestion and thermal gasification pathways receiving mixed municipal waste presents challenges, especially if the waste stream includes mixed organics and inorganics. New approaches are needed to improve sorting and to identify those feedstock components that have sufficient high heating values, especially for gasification. GTI Energy, for instance, is developing a predictive model using artificial intelligence and machine learning to correlate specific MSW components to proximate heating values for thermal gasification.[49]

For anaerobic digestion and thermal gasification pathways, pre-processing feedstocks can help boost biogas yield, though these often require additional costs—and there are project-specific parameters that determine the viability of a given pathway. Pre-processing can be considered via the following categories:

- Physical and mechanical: this is a key component for both anaerobic digestion and biomass gasification, whereby the bulk density characteristics of the biomass are changed, thereby increasing the surface area accessible to further processing. The most common pre-treatment is milling to reduce biomass size; however, other pre-treatments included microwave irradiation and extrusion.
- Chemical: Chemical pre-treatment helps accelerate biodegradation of the biomass, and includes acidification, alkaline, oxidative, and ozonation. Generally, these pre-treatment pathways seek to accelerate the release of organics for further processing e.g., via increase susceptibility to enzymatic processes.
- Biological: Introducing microorganisms to enhance the degradation of organic materials can improve biogas yields.

These processes are essential for heterogeneous feedstocks like biomass used in gasification. Further study of commercial applications of these types of pre-treatment will help spur broader adoption if the pre-treatment is determined to be cost-effective.

5.2.2 Reduced Tar Formation in Gasification

Biomass thermal conversion typically yields a residual tar, which can foul downstream equipment. Furthermore, the presence of tar effectively precludes the use of a commercialized methanation unit. The high cost of conditioning the syngas in the presence of these tars has limited the potential for biomass thermal conversion to RNG. Over the last several years, however, a few commercialized technologies have been deployed to increase syngas quantity and prevent the fouling of other equipment by removing the residual tar before methanation.

Biomass thermal gasification technology is at an early stage of commercialization, but if it continues to improve and scale accordingly, then this production pathway to unlock additional RNG production potential. The gasification and purification steps pose challenges and have stalled the technology's development over the past decades, but more recently a handful of thermal gasification projects are in the late stages of planning and development in North America.

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[49] GTI Energy, Carbonaceous Chemistry Improvement of Municipal Solid Waste with an Artificial Intelligence (AI) for Gasification.

5.3 Gas Quality and Monitoring

There is no existing industry-wide standard for RNG quality and gas composition, and with sometimes limited access to operational data, some concerns remain regarding RNG injection into a pipeline system. That said, different gas quality requirements across jurisdictions likely preclude an industry-wide standard that suits all needs. For example, some states have strict limits on oxygen concentration in pipelines that are state-regulated—these limits apply to both conventional and renewable natural gas. While these different standards may confound RNG producers, it is impractical to compel regulators to modify injection standards unreasonably to accommodate RNG. However, the lack of a consistent approach to evaluate RNG quality and constituent composition remains a challenge to the broader acceptance of different RNG feedstocks and may be a factor in the development of RNG as a source for pipeline throughput. The gas industry continues to learn about RNG and its impact on pipeline infrastructure and end use, and should continue research, collaboration, and dissemination of biogas processing and RNG pipeline injection experience, particularly as more RNG facilities come online.

5.4 Insights

ICF recognizes that this was a high-level technology assessment, and that RNG producers seek to maximize production and maximize revenue while reducing costs where possible. However, ICF's review finds that publicly available data offer only partial insight into systematic cost-reduction pathways for RNG production. More research and data sharing would assist in mapping potential future cost declines. ICF has formulated the following insights based on our review and experience working with industry stakeholders:

- ***Stakeholders need to more clearly present the costs and benefits of emerging approaches to reduce RNG production costs.*** ICF found that there was limited information regarding the costs and benefits of various approaches being considered to reduce RNG production costs. Stakeholders, including industry, research institutions, and national laboratories could more clearly articulate the extent to which innovation will reduce RNG production costs. There are clearly multiple technological pathways being pursued across the RNG production processing ecosystem. ICF found information on pre-processing of feedstocks, the potential for co-digestion, and various technologies being contemplated to improving conditioning and upgrading. ICF reviewed projects, for instance, that have received funding via the Department of Energy's Bioenergy Technologies Office. There was limited information available regarding the cost-benefit considerations of emerging technologies, approaches, etc.
- ***Improve coordination to identify the technology readiness level of pathways beyond anaerobic digestion.*** ICF's RNG production potential analysis conducted here has similar findings as the previous 2019 study: Anaerobic digestion has significant growth potential; however, the pathway for greater RNG production potential is inexorably linked to technology advancements for processes like gasification and methanation. ICF finds that there is an opportunity to improve coordination across stakeholders to identify the technology readiness level(s) for processes like thermal gasification and methanation technology pathways, including identifying the best feedstock types for different pathways and synergies between power-to-gas and thermal gasification or anaerobic digestion pathways. ICF believes that this type of improved coordination could identify potentially transformative approaches and significant cost reductions that help to build the bridge between today's opportunities focused on anaerobic digestion, and tomorrow's broader opportunities that incorporate increased sustainable biomass utilization.
- ***Identify constraining policy barriers to broader RNG deployment.*** As noted previously, the RNG industry has been shaped by eligibility under specific programs that incentivize production—including the federal RFS and state-level low carbon fuel programs. ICF's research for this report

purposefully avoids specific policy prescriptions and recommendations. However, our technology assessment highlights that which some stakeholders already recognize: Despite the value generated by existing programs, they are not necessarily designed to encourage innovation in a manner that will help to achieve the supply outlooks contemplated in ICF's assessment. Moving forward, industry and policymakers should seek to improve collaboration on policy barriers that are constraining innovation and RNG deployment.

6 Key Takeaways

There is significant resource potential for RNG production, now and out through 2050, across the United States. ICF conducted a bottom-up national assessment of RNG potential, building on previous studies, and leveraging updated data sources and analytical approaches. Results from this assessment demonstrate that there is a large pool of diverse feedstocks that could be used to produce RNG, even with the application of conservative assumptions related to feedstock utilization and technological advancements.

Relative to the 2019 study, the **biomass supply available to produce RNG has increased by 17%**. While biomass-based RNG production potential is inherently constrained by biomass availability, there are significant and diverse feedstocks that could support the wide-scale deployment of RNG nationally. The utilization of biomass to produce large volumes of RNG, as indicated in the High and Ambitious Emissions Reduction Scenarios, does not preclude the use of biomass for other bioenergy end-uses, such as liquid biofuels.

- In the Low Scenario, ICF estimates that about 1,628 tBtu of RNG can be produced annually for pipeline injection by 2050, reflecting utilization of approximately 10% of total available biomass that could be used for bioenergy production.
- In the High Scenario, ICF estimates that about 3,728 tBtu of RNG can be produced annually for pipeline injection by 2050, reflecting utilization of approximately 23% of total available biomass that could be used for bioenergy production.
- In the Ambitious Emissions Reduction Scenario, ICF estimates that about 7,061 tBtu of RNG can be produced annually for pipeline injection by 2050, reflecting utilization of approximately 43% of total available biomass that could be used for bioenergy production.

By way of comparison, ICF notes that the about 4,800 tBtu/y of natural gas was consumed on average in the residential sector over the last ten years.

ICF's analysis of the potential for methanated hydrogen (via power-to-gas, P2G) indicates that the technology could make a significant contribution to RNG production over the long-term. In addition to biomass-based feedstocks used for RNG production, ICF assessed the supply potential from P2G. In this study, ICF made the simplifying assumption that 25% of hydrogen produced via P2G via dedicated renewable electricity and from nuclear power would be methanated for pipeline injection.

ICF estimates that 75% of the RNG production potential in the Low Scenario and High Scenario could be produced at an average cost less than $20/MMBtu and at an average cost of $23/MMBtu in the Ambitious Emissions Reduction Scenario. Generally speaking, ICF finds the front end of the supply curve to be landfill gas projects and water resource recovery facilities that are poised to move towards RNG production. As the estimated costs move to higher costs, the supply curve includes the thermal gasification pathways, some of the larger animal manure projects and the well-positioned food waste projects. The tail end of the curve, showing the upward sloping to the right captures the less efficient, smaller animal manure and food waste projects that ICF assumes will just start to break that $40/MMBtu level by 2040.

ICF estimates that RNG deployment would deliver 82 MMT CO_2e in the Low Scenario, 185 MMT CO_2e the High Scenario, and 382 MMT CO_2e in the Ambitious Emissions Reduction Scenario. When factoring in the potential displacement of geologic natural gas with RNG from methanated hydrogen, emission reductions increase by another 6 to 32 MMT CO_2e annually by 2050. ICF conducted a bottom-up assessment of the GHG emission reduction potential from RNG across the three scenarios, assuming the displacement of geologic (fossil) natural gas. ICF evaluated emission reductions using life cycle carbon intensities, or a cradle-to-grave assessment, for the various RNG feedstocks and production methods. The RNG CIs used to estimate the GHG reduction are based on standard assumptions, and broadly consistent with regulatory mechanisms relevant to RNG.

ICF reports a cost-effectiveness or abatement cost for RNG in the range of $70-$400/ton on a lifecycle basis or combustion basis. The range of abatement costs reflects the variation amongst the carbon intensity value for RNG from different feedstocks and the framework considered (i.e., lifecycle basis or combustion basis). RNG will be an attractive decarbonization strategy, with particular importance in sectors like industrial processes with high heat demands, and transportation like shipping and trucking.

RNG and P2G have the potential to play pivotal, cost-effective and increasing roles in the decarbonization of the gas system and the economy more broadly. Decarbonization pathways that deliver ambitious GHG emissions by mid-century necessitate the roll-out of multiple and diverse emission reduction measures, covering new technologies, fuels and behaviors. As we progress towards decarbonizing challenging sectors and end-uses, abatement costs inevitably increase. Despite production costs higher than comparative conventional (fossil) fuels, the emission reduction abatement costs of RNG and P2G are competitive and cost-effective relative to other measures.

There are opportunities to reduce RNG production costs through innovation and technological advancements, however, the magnitude of the aggregate opportunity for cost reductions is unclear. ICF's high-level technology assessment demonstrated that there is limited information in the public domain suggesting a clear path to reduce systematically RNG production costs. However, ICF identified several pathways to improve the outlook for RNG production costs, including: a) stakeholders can more clearly elucidate the costs and benefits of emerging approaches to reduce RNG production costs; b) improved coordination amongst industry and research centers can help clarify the technology readiness level of pathways for RNG production beyond anaerobic digestion, namely thermal conversion and methanated hydrogen contemplated in this report; and c) identify policy barriers that are stifling further innovation and investment in technologies that will reduce RNG production costs.

Appendix A – Supply Formulas

ICF developed the RNG potential estimates applying the various feedstock-specific factors (outlined in Section 2.2) and shown in the formulas below, accompanied with example calculations for each feedstock.

Food Waste

$$food\ waste\ volume\ (dry)\ \times heating\ value = RNG\ production\ potential$$

$$100{,}000\ dry\ tons\ \times 12.04\ \frac{MMBtu}{dry\ ton} = 1{,}203{,}600\ MMBtu$$

Landfill Gas (LFG)

$$waste\ in\ place \times biogas\ production\ \times conversion \times 365\ = RNG\ production\ potential$$

$$1{,}000{,}000\ tons\ \times 0.235\ \frac{scf}{day} \times 0.001036\ \frac{MMBtu}{scf} \times 365 = 235{,}434\ MMBtu$$

Water Resource Recovery Facilities (WRRF)

$$wastewater\ flow\ \times energy\ factor = annual\ RNG\ production\ potential$$

$$10\ \frac{million\ gallons}{day} \times 7.004\ \frac{MMBtu}{million\ gallons} \times 365 = 25{,}562\ MMBtu$$

Agricultural Residue

$$biomass\ volume\ \times biomass\ energy\ factor\ \times system\ efficiency = RNG\ production\ potential$$

$$10{,}000\ dry\ tons\ (barley\ stover) \times 14.88\ \frac{MMBtu}{dry\ ton\ (barley\ stover)} \times 65\%\ = 96{,}733\ MMBtu$$

Energy Crops

$$biomass\ volume\ \times biomass\ energy\ factor\ \times system\ efficiency = RNG\ production\ potential$$

$$10{,}000\ dry\ tons\ (poplar) \times 15.55\ \frac{MMBtu}{dry\ ton\ (poplar)} \times 65\%\ = 101{,}075\ MMBtu$$

Forestry & Forest Produce Residue

$$biomass\ volume\ \times biomass\ energy\ factor\ \times system\ efficiency = RNG\ production\ potential$$

$$10{,}000\ dry\ tons\ (forest\ residue) \times 17.19\ \frac{MMBtu}{dry\ ton\ (forest\ residue)} \times 65\%\ = 111{,}761\ MMBtu$$

Municipal Solid Waste (MSW)

$$biomass\ volume\ \times biomass\ energy\ factor\ \times system\ efficiency = RNG\ production\ potential$$

$$10{,}000\ dry\ tons\ (paper) \times 15.28\ \frac{MMBtu}{dry\ ton\ (paper)} \times 65\%\ = 99{,}320\ MMBtu$$

Appendix B – Resource Assessment by State

The tables below summarize the maximum resource production potential for the Low, High and Ambitious Emissions Reduction Scenarios, as well as and technical potential, broken down by state and by feedstock, reported in units of tBtu per year (tBtu/y).

Low Scenario Results, By State

Table 39. RNG Production Potential by State in 2050 (tBtu/y), Low Scenario

State	via Anaerobic Digestion				via Thermal Gasification				Total
	Animal Manure	Food Waste	LFG	WRRFs	Ag Res	Energy Crops	Forest Res	MSW	
Alabama	6.3	0.1	7.6	0.4	0.6	6.7	5.9	1.3	**28.8**
Alaska	0.0	0.0	0.9	0.0	0.0	0.0	0.0	0.4	**1.3**
Arizona	2.2	0.0	13.5	0.5	0.1	1.7	0.5	4.5	**23.0**
Arkansas	7.3	0.0	3.3	0.1	4.0	7.7	4.1	1.1	**27.7**
California	17.1	4.0	49.6	3.4	8.7	0.0	1.3	22.8	**106.9**
Colorado	4.1	0.5	12.3	0.4	3.4	4.8	1.6	4.0	**31.0**
Connecticut	0.2	0.4	0.0	0.2	0.0	0.2	0.1	1.6	**2.8**
Delaware	1.1	0.2	0.7	0.1	0.5	0.1	0.0	0.6	**3.2**
D.C.	0.0	0.4	0.0	0.3	0.0	0.0	0.0	0.0	**0.7**
Florida	3.0	1.7	20.8	1.3	1.5	6.4	5.6	14.0	**54.3**
Georgia	7.0	0.7	17.5	0.8	1.8	3.8	9.8	6.2	**47.6**
Hawaii	0.2	0.0	0.8	0.1	0.0	0.0	0.0	0.9	**2.0**
Idaho	6.7	0.0	2.0	0.1	1.9	0.0	1.9	1.1	**13.6**
Illinois	2.4	0.0	14.2	2.1	51.7	6.1	0.2	5.5	**82.2**
Indiana	4.0	0.2	15.4	0.6	25.2	2.9	2.4	3.2	**53.9**
Iowa	9.5	0.1	5.4	0.3	52.1	6.2	0.2	1.6	**75.4**
Kansas	7.2	0.1	4.8	0.2	9.7	41.0	0.2	1.1	**64.3**
Kentucky	3.8	0.2	7.7	0.3	3.6	8.5	1.2	0.7	**26.0**
Louisiana	1.6	0.3	7.1	0.3	2.5	7.1	2.9	1.2	**23.0**
Maine	0.2	0.0	0.9	0.0	0.1	0.3	4.0	0.6	**6.2**
Maryland	1.7	0.7	1.2	0.4	1.0	0.9	1.0	3.4	**10.3**
Massachusetts	0.1	1.2	0.6	0.6	0.0	0.1	0.9	3.7	**7.2**
Michigan	4.5	0.2	20.7	1.4	7.2	3.7	6.2	4.4	**48.3**
Minnesota	7.4	0.3	1.7	0.4	29.9	4.4	1.9	3.1	**49.1**
Mississippi	3.8	0.0	4.5	0.0	1.4	5.8	4.9	0.8	**21.3**
Missouri	7.5	0.2	5.7	0.8	6.6	26.4	0.9	3.0	**51.0**
Montana	2.9	0.1	1.4	0.0	2.4	2.7	0.0	0.6	**10.2**
Nebraska	7.6	0.0	2.3	0.1	36.1	6.7	0.1	0.9	**53.8**
Nevada	0.8	0.3	7.5	0.1	0.0	0.0	0.0	2.0	**10.7**
New Hampshire	0.1	0.0	1.5	0.0	0.0	0.1	0.8	0.6	**3.2**
New Jersey	0.1	0.8	2.3	1.0	0.1	0.7	0.7	4.5	**10.2**
New Mexico	3.2	0.1	3.8	0.1	0.2	6.0	0.4	0.6	**14.4**
New York	5.4	1.7	8.8	2.6	2.9	1.8	4.9	9.8	**38.0**
North Carolina	7.5	0.5	8.7	0.6	0.7	10.1	7.2	6.0	**41.2**
North Dakota	2.2	0.1	0.4	0.0	8.5	15.7	0.0	0.2	**27.1**
Ohio	4.7	0.2	25.9	1.9	7.7	4.1	0.6	5.1	**50.1**

State	via Anaerobic Digestion				via Thermal Gasification				Total
	Animal Manure	Food Waste	LFG	WRRFs	Ag Res	Energy Crops	Forest Res	MSW	
Oklahoma	6.7	0.0	3.6	0.2	0.6	35.1	0.4	2.4	**48.9**
Oregon	2.3	0.0	9.7	0.3	1.7	0.0	1.6	2.5	**18.1**
Pennsylvania	6.1	1.0	17.2	0.8	0.7	4.6	9.4	5.9	**45.7**
Rhode Island	0.0	0.1	0.2	0.1	0.0	0.0	0.1	0.5	**1.0**
South Carolina	2.1	0.1	7.5	0.2	0.6	4.1	2.8	3.0	**20.4**
South Dakota	5.6	0.1	0.9	0.0	24.3	6.7	0.0	0.5	**38.1**
Tennessee	3.0	0.1	7.2	0.6	2.5	7.3	2.0	3.9	**26.6**
Texas	21.2	1.6	45.1	2.0	6.5	81.7	3.0	19.6	**180.7**
Utah	1.9	0.1	5.3	0.3	0.3	0.0	0.4	1.9	**10.2**
Vermont	0.9	0.1	0.5	0.0	0.0	0.4	2.6	0.3	**4.8**
Virginia	3.4	0.9	15.0	0.8	0.5	5.4	5.5	4.9	**36.4**
Washington	2.9	1.5	8.4	0.6	4.1	0.0	2.4	4.8	**24.7**
West Virginia	0.8	0.1	3.0	0.0	0.0	1.7	0.8	0.8	**7.2**
Wisconsin	11.5	0.2	4.7	0.7	13.7	5.3	2.6	2.8	**41.5**
Wyoming	1.6	0.1	0.3	0.0	0.2	0.2	1.1	0.4	**4.0**

High Scenario Results, by State

Table 40. RNG Production Potential by State in 2050 (tBtu/y), High Scenario

State	via Anaerobic Digestion				via Thermal Gasification				Total
	Animal Manure	Food Waste	LFG	WRRFs	Ag Res	Energy Crops	Forest Res	MSW	
Alabama	12.5	0.3	13.2	0.6	1.5	20.2	15.8	3.8	**67.9**
Alaska	0.0	0.1	1.5	0.1	0.0	0.0	0.0	0.7	**2.4**
Arizona	4.4	0.7	23.6	0.7	0.3	5.0	1.4	7.5	**43.6**
Arkansas	14.6	0.1	5.8	0.3	10.7	23.2	11.0	2.5	**68.2**
California	34.2	6.3	86.8	4.7	23.2	0.0	3.5	37.9	**196.5**
Colorado	8.1	1.2	21.4	0.6	9.1	14.5	4.4	6.7	**66.0**
Connecticut	0.3	0.6	0.1	0.4	0.0	0.6	0.3	2.7	**5.0**
Delaware	2.1	0.4	1.1	0.1	1.2	0.2	0.1	0.9	**6.2**
D.C.	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	**0.4**
Florida	6.0	3.6	36.4	2.0	4.0	19.3	15.0	23.4	**109.7**
Georgia	14.0	1.4	30.5	1.2	4.9	11.3	26.1	10.7	**100.1**
Hawaii	0.4	0.1	1.4	0.2	0.0	0.0	0.0	1.4	**3.5**
Idaho	13.3	0.0	3.5	0.1	4.9	0.0	5.0	1.8	**28.7**
Illinois	4.8	0.1	24.8	2.9	137.9	18.2	0.7	9.2	**198.5**
Indiana	8.0	0.9	26.9	0.9	67.1	8.8	6.3	5.7	**124.6**
Iowa	19.1	0.3	9.4	0.5	138.9	18.7	0.5	2.9	**190.2**
Kansas	14.4	0.4	8.4	0.3	25.8	123.0	0.6	2.4	**175.3**
Kentucky	7.5	0.5	13.5	0.4	9.5	25.6	3.1	3.5	**63.7**
Louisiana	3.2	0.6	12.4	0.4	6.8	21.4	7.7	4.1	**56.7**
Maine	0.5	0.1	1.5	0.1	0.2	0.8	10.6	0.9	**14.7**
Maryland	3.4	1.0	2.1	0.5	2.8	2.6	2.6	5.6	**20.7**
Massachusetts	0.2	2.1	1.1	0.8	0.1	0.4	2.4	6.2	**13.3**
Michigan	9.0	0.5	36.2	1.8	19.3	11.0	16.5	7.3	**101.6**
Minnesota	14.9	0.6	2.9	0.6	79.7	13.1	5.1	5.1	**121.9**
Mississippi	7.6	0.2	7.9	0.1	3.8	17.4	13.0	2.2	**52.2**
Missouri	14.9	0.7	10.0	1.1	17.6	79.3	2.3	4.9	**130.7**
Montana	5.8	0.1	2.5	0.1	6.5	8.2	0.0	1.0	**24.1**
Nebraska	15.2	0.1	4.0	0.1	96.2	20.2	0.3	1.8	**137.9**
Nevada	1.5	0.4	13.2	0.2	0.0	0.0	0.0	3.3	**18.5**
New Hampshire	0.2	0.1	2.7	0.1	0.0	0.2	2.0	1.0	**6.3**
New Jersey	0.2	1.1	4.1	1.3	0.2	2.1	1.9	7.5	**18.4**
New Mexico	6.5	0.1	6.7	0.1	0.5	17.9	1.2	1.5	**34.5**
New York	10.8	2.3	15.5	3.5	7.8	5.5	13.0	16.4	**74.8**
North Carolina	15.0	1.6	15.1	0.9	1.9	30.3	19.2	10.4	**94.4**
North Dakota	4.4	0.3	0.7	0.0	22.7	47.0	0.1	1.1	**76.3**
Ohio	9.3	0.6	45.2	2.6	20.5	12.2	1.5	8.9	**100.9**
Oklahoma	13.3	0.2	6.2	0.3	1.6	105.4	1.1	4.1	**132.2**
Oregon	4.5	0.0	17.0	0.4	4.6	0.0	4.2	4.1	**34.8**
Pennsylvania	12.1	2.3	30.1	1.2	1.8	13.7	25.1	9.8	**96.1**
Rhode Island	0.0	0.1	0.3	0.1	0.0	0.1	0.4	0.8	**1.9**
South Carolina	4.2	0.7	13.1	0.2	1.7	12.2	7.3	5.2	**44.7**

State	via Anaerobic Digestion				via Thermal Gasification				Total
	Animal Manure	Food Waste	LFG	WRRFs	Ag Res	Energy Crops	Forest Res	MSW	
South Dakota	11.2	0.2	1.5	0.0	64.7	20.1	0.1	0.9	**98.7**
Tennessee	6.0	0.5	12.5	0.9	6.7	22.0	5.4	6.4	**60.5**
Texas	42.4	5.0	78.8	3.0	17.3	245.0	8.0	34.9	**434.4**
Utah	3.7	0.4	9.3	0.4	0.8	0.0	1.0	3.7	**19.3**
Vermont	1.7	0.1	1.0	0.0	0.0	1.2	7.0	0.4	**11.4**
Virginia	6.9	1.5	26.2	1.1	1.2	16.2	14.6	8.1	**75.8**
Washington	5.9	2.2	14.7	0.9	10.9	0.0	6.3	8.1	**48.9**
West Virginia	1.6	0.2	5.3	0.1	0.1	5.2	2.1	1.3	**15.9**
Wisconsin	23.0	0.4	8.2	1.0	36.6	15.9	7.0	4.6	**96.7**
Wyoming	3.3	0.1	0.6	0.0	0.4	0.5	3.0	0.6	**8.5**

Ambitious Emissions Reduction Scenario Results, by State

Table 41. RNG Production Potential by State in 2050 (tBtu/y), Ambitious Emissions Reduction Scenario

State	via Anaerobic Digestion				via Thermal Gasification				Total
	Animal Manure	Food Waste	LFG	WRRFs	Ag Res	Energy Crops	Forest Res	MSW	
Alabama	19.1	1.3	18.8	1.0	2.3	33.6	27.7	26.3	**130.1**
Alaska	0.1	0.2	2.2	0.1	0.0	0.0	0.0	6.0	**8.6**
Arizona	7.6	2.4	33.5	1.3	0.4	8.4	2.4	30.4	**86.4**
Arkansas	23.1	0.9	8.2	0.5	16.0	38.7	19.3	13.3	**120.0**
California	49.5	12.7	123.6	8.5	34.9	0.0	6.2	154.4	**389.8**
Colorado	17.5	2.2	30.6	1.1	13.6	24.2	7.6	45.6	**142.5**
Connecticut	0.5	0.9	0.1	0.8	0.0	0.9	0.5	3.9	**7.6**
Delaware	2.4	0.3	1.6	0.2	1.8	0.3	0.2	3.4	**10.3**
D.C.	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	**0.7**
Florida	13.1	7.4	51.8	3.6	6.0	32.1	26.2	123.2	**263.4**
Georgia	19.6	3.5	43.6	2.1	7.3	18.8	45.7	72.6	**213.2**
Hawaii	1.0	0.5	2.0	0.3	0.0	0.0	0.0	6.0	**9.8**
Idaho	21.0	0.5	5.1	0.2	7.4	0.0	8.7	10.1	**53.0**
Illinois	11.0	3.2	35.2	5.2	206.9	30.3	1.1	51.0	**343.9**
Indiana	13.0	1.9	38.3	1.5	100.7	14.6	11.0	41.6	**222.7**
Iowa	43.0	1.0	13.3	0.8	208.4	31.2	0.8	17.8	**316.4**
Kansas	35.8	0.9	12.1	0.5	38.6	204.9	1.0	17.1	**310.9**
Kentucky	16.0	1.3	19.2	0.8	14.3	42.6	5.4	22.6	**122.2**
Louisiana	6.8	1.5	17.7	0.8	10.1	35.7	13.5	27.5	**113.5**
Maine	0.7	0.3	2.4	0.1	0.3	1.3	18.6	2.2	**25.9**
Maryland	4.3	1.9	3.1	1.0	4.2	4.3	4.6	14.8	**38.1**
Massachusetts	0.3	2.2	1.6	1.5	0.1	0.7	4.3	12.0	**22.7**
Michigan	12.7	2.5	51.4	3.3	28.9	18.3	28.8	40.4	**186.3**
Minnesota	26.0	1.8	4.1	1.0	119.5	21.9	8.8	13.5	**196.7**
Mississippi	12.0	0.8	12.4	0.2	5.7	29.1	22.8	14.2	**97.2**
Missouri	34.0	1.7	14.2	2.0	26.5	132.2	4.1	20.1	**234.8**
Montana	15.8	0.3	3.7	0.1	9.8	13.6	0.0	6.4	**49.7**
Nebraska	39.7	0.7	5.7	0.3	144.3	33.6	0.5	15.0	**239.7**
Nevada	3.4	1.1	18.9	0.3	0.0	0.0	0.0	17.6	**41.4**
New Hampshire	0.3	0.3	3.8	0.1	0.0	0.4	3.5	4.7	**13.2**
New Jersey	0.3	2.5	5.8	2.4	0.3	3.5	3.3	26.2	**44.2**
New Mexico	11.3	0.5	9.5	0.2	0.7	29.8	2.1	9.9	**64.0**
New York	14.4	5.7	22.0	6.4	11.7	9.2	22.8	40.4	**132.5**
North Carolina	23.3	3.3	21.8	1.6	2.9	50.5	33.5	48.4	**185.3**
North Dakota	11.9	0.4	1.4	0.1	34.1	78.4	0.2	8.3	**134.8**
Ohio	15.0	3.1	64.2	4.8	30.7	20.4	2.6	41.6	**182.4**
Oklahoma	33.2	1.4	8.9	0.6	2.4	175.7	2.0	25.8	**249.9**
Oregon	9.4	1.3	24.1	0.8	6.9	0.0	7.4	21.0	**70.8**
Pennsylvania	17.0	3.5	42.8	2.1	2.8	22.8	44.0	56.8	**191.9**
Rhode Island	0.0	0.3	0.5	0.2	0.0	0.1	0.6	4.6	**6.4**
South Carolina	6.0	1.7	18.7	0.4	2.6	20.4	12.9	43.2	**105.9**

State	via Anaerobic Digestion				via Thermal Gasification				Total
	Animal Manure	Food Waste	LFG	WRRFs	Ag Res	Energy Crops	Forest Res	MSW	
South Dakota	26.4	0.3	2.3	0.0	97.1	33.6	0.1	5.0	**164.8**
Tennessee	13.5	2.1	17.9	1.7	10.1	36.6	9.5	33.8	**125.2**
Texas	91.2	11.2	112.2	5.5	25.9	408.4	14.0	203.3	**871.6**
Utah	7.1	1.1	13.7	0.7	1.2	0.0	1.8	17.0	**42.6**
Vermont	2.3	0.2	1.4	0.0	0.0	2.0	12.3	1.6	**19.8**
Virginia	12.6	2.7	37.6	2.0	1.8	27.0	25.6	46.8	**156.1**
Washington	9.4	2.5	20.8	1.6	16.4	0.0	11.0	21.7	**83.4**
West Virginia	3.3	0.4	7.7	0.1	0.1	8.7	3.7	9.5	**33.5**
Wisconsin	32.0	1.6	11.7	1.8	54.8	26.5	12.3	24.1	**164.8**
Wyoming	9.0	0.2	0.9	0.1	0.6	0.8	5.3	4.5	**21.4**

Technical Resource Potential Results, by State

Table 42. RNG Production Potential in 2050 (tBtu/y), Technical Resource Potential, by State

State	via Anaerobic Digestion				via Thermal Gasification				Total
	Animal Manure	Food Waste	LFG	WRRFs	Ag Res	Energy Crops	Forest Res	MSW	
Alabama	56.9	1.9	23.8	1.6	3.8	139.1	39.6	37.6	**304.3**
Alaska	0.3	0.3	2.4	0.2	0.0	0.0	0.0	8.5	**11.8**
Arizona	22.5	3.4	34.9	1.7	0.7	33.7	3.4	43.5	**143.7**
Arkansas	68.8	1.3	10.3	0.9	26.6	168.7	27.6	19.0	**323.3**
California	147.3	18.2	164.7	9.9	58.1	0.0	8.8	220.5	**627.5**
Colorado	52.2	3.1	37.3	1.7	22.7	96.9	10.9	65.2	**290.0**
Connecticut	1.4	1.4	0.3	1.0	0.1	3.7	0.7	5.6	**14.1**
Delaware	7.2	0.4	3.5	0.3	3.1	2.3	0.3	4.9	**21.9**
D.C.	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	**0.8**
Florida	39.1	10.6	64.8	4.7	10.0	129.1	37.4	175.9	**471.7**
Georgia	58.2	5.0	52.2	3.0	12.2	79.2	65.3	103.7	**378.8**
Hawaii	2.9	0.7	3.4	0.4	0.0	0.0	0.0	8.6	**16.0**
Idaho	62.5	0.8	6.5	0.4	12.4	0.1	12.4	14.4	**109.4**
Illinois	32.6	4.6	49.0	6.6	344.8	172.5	1.6	72.8	**684.5**
Indiana	38.8	2.7	48.3	2.3	167.8	88.2	15.8	59.5	**423.3**
Iowa	127.9	1.5	38.2	1.5	347.3	171.1	1.2	25.4	**714.0**
Kansas	106.5	1.3	13.7	0.8	64.4	843.8	1.5	24.4	**1,056.4**
Kentucky	47.6	1.8	26.0	1.2	23.8	180.7	7.7	32.3	**321.2**
Louisiana	20.1	2.1	22.3	1.2	16.9	150.2	19.3	39.2	**271.4**
Maine	2.1	0.5	4.5	0.3	0.5	5.4	26.6	3.2	**43.1**
Maryland	12.7	2.7	4.9	1.2	6.9	21.2	6.5	21.1	**77.2**
Massachusetts	1.0	3.2	3.8	1.9	0.2	3.0	6.1	17.2	**36.4**
Michigan	37.8	3.6	74.9	4.0	48.2	89.7	41.2	57.7	**357.2**
Minnesota	77.3	2.5	5.9	1.5	199.1	112.3	12.6	19.3	**430.6**
Mississippi	35.6	1.2	12.7	0.3	9.5	125.1	32.6	20.3	**237.3**
Missouri	101.1	2.5	18.1	2.7	44.1	551.8	5.8	28.7	**754.7**
Montana	47.0	0.5	3.7	0.2	16.3	54.6	0.0	9.2	**131.6**
Nebraska	118.0	1.0	7.4	0.4	240.5	168.6	0.8	21.4	**558.1**
Nevada	10.2	1.6	17.0	0.4	0.0	0.0	0.1	25.2	**54.5**
New Hampshire	0.9	0.5	6.6	0.3	0.0	1.6	5.1	6.8	**21.7**
New Jersey	0.8	3.6	12.2	2.9	0.5	14.8	4.7	37.4	**77.0**
New Mexico	33.6	0.8	9.7	0.4	1.2	119.3	3.0	14.1	**182.1**
New York	42.8	8.1	30.4	7.6	19.4	39.8	32.6	57.7	**238.6**
North Carolina	69.3	4.7	39.6	2.3	4.8	216.9	47.9	69.2	**454.8**
North Dakota	35.4	0.6	1.2	0.1	56.8	321.1	0.2	11.9	**427.4**
Ohio	44.7	4.4	81.7	6.1	51.2	106.3	3.7	59.5	**357.6**
Oklahoma	98.7	1.9	13.4	0.9	4.0	704.9	2.9	36.9	**863.6**
Oregon	27.8	1.9	27.9	1.1	11.5	0.0	10.5	29.9	**110.8**
Pennsylvania	50.6	5.0	54.5	2.6	4.6	98.1	62.8	81.1	**359.5**
Rhode Island	0.1	0.4	1.8	0.3	0.0	0.4	0.9	6.5	**10.5**
South Carolina	17.9	2.4	21.8	0.6	4.3	88.1	18.4	61.7	**215.2**

State	via Anaerobic Digestion				via Thermal Gasification				Total
	Animal Manure	Food Waste	LFG	WRRFs	Ag Res	Energy Crops	Forest Res	MSW	
South Dakota	78.5	0.5	2.2	0.1	161.8	158.7	0.2	7.1	**408.9**
Tennessee	40.1	3.1	25.1	2.2	16.8	154.9	13.6	48.3	**304.2**
Texas	271.1	16.0	141.1	7.7	43.2	1,636.1	20.0	290.5	**2,425.7**
Utah	21.2	1.6	13.8	0.9	2.1	0.0	2.6	24.3	**66.6**
Vermont	6.8	0.2	2.3	0.1	0.0	8.0	17.6	2.4	**37.4**
Virginia	37.5	3.9	45.6	2.5	3.1	112.4	36.6	66.9	**308.3**
Washington	28.1	3.6	21.7	2.0	27.3	0.0	15.7	31.0	**129.4**
West Virginia	9.9	0.6	7.2	0.4	0.2	34.9	5.3	13.5	**72.0**
Wisconsin	95.1	2.3	18.7	2.4	91.4	120.3	17.5	34.4	**382.1**
Wyoming	26.8	0.3	0.9	0.2	1.0	3.3	7.5	6.4	**46.5**

Appendix C – 2019 and 2025 Study Comparison

The figures below compare results from the 2019 AGF RNG Study and 2025 AGF RNG Study Update for the future maximum resource production potential for each feedstock across the Low Scenario, High Scenario and technical potential, reported in units of tBtu per year.

Figure 63. 2019 and 2025 Study Comparison, Animal Manure (tBtu/y)

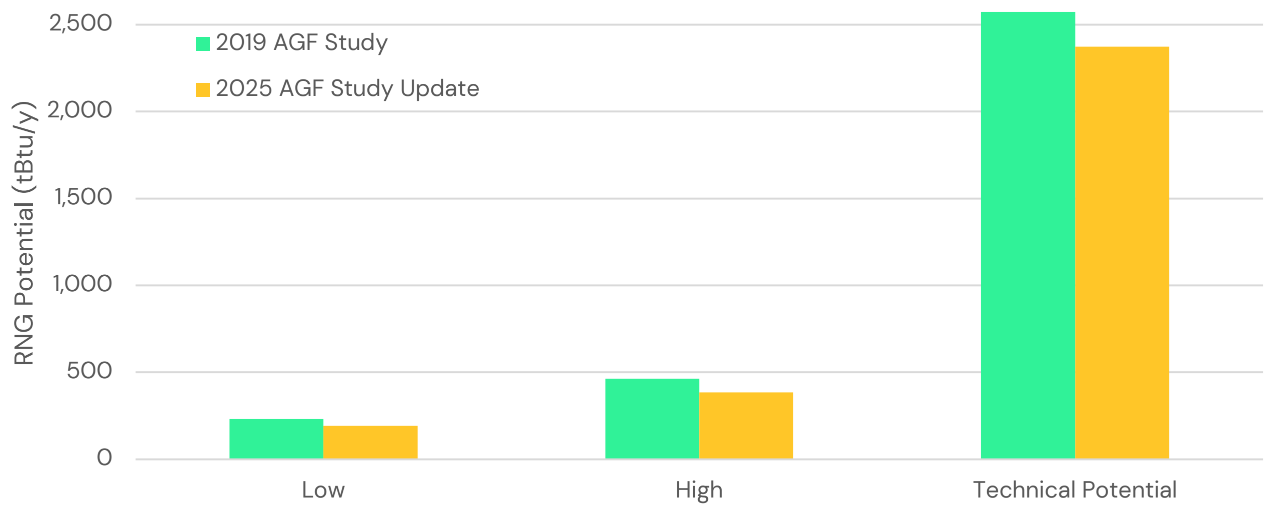


Figure 64. 2019 and 2025 Study Comparison, Food Waste (tBtu/y)

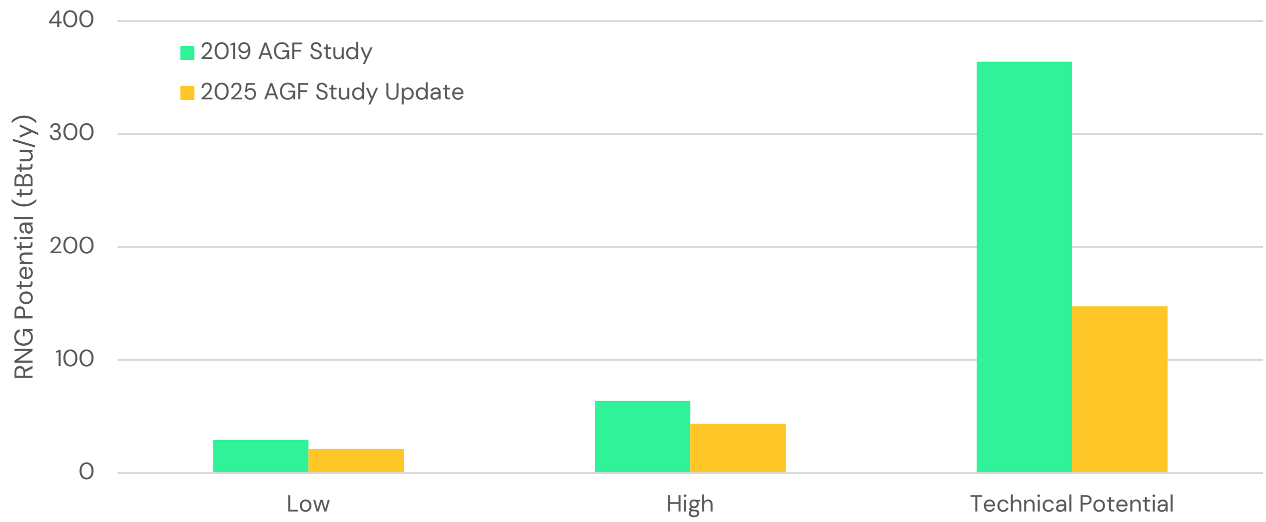


Figure 65. 2019 and 2025 Study Comparison, Landfill Gas (tBtu/y)

Figure 66. 2019 and 2025 Study Comparison, Wastewater (tBtu/y)

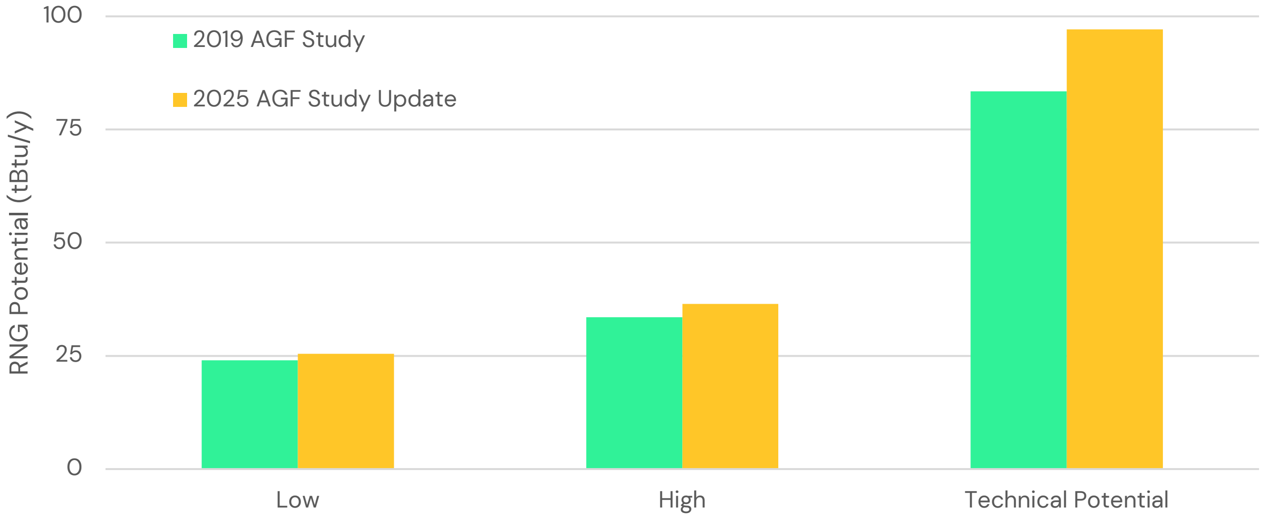


Figure 67. 2019 and 2025 Study Comparison, Agricultural Residue (tBtu/y)

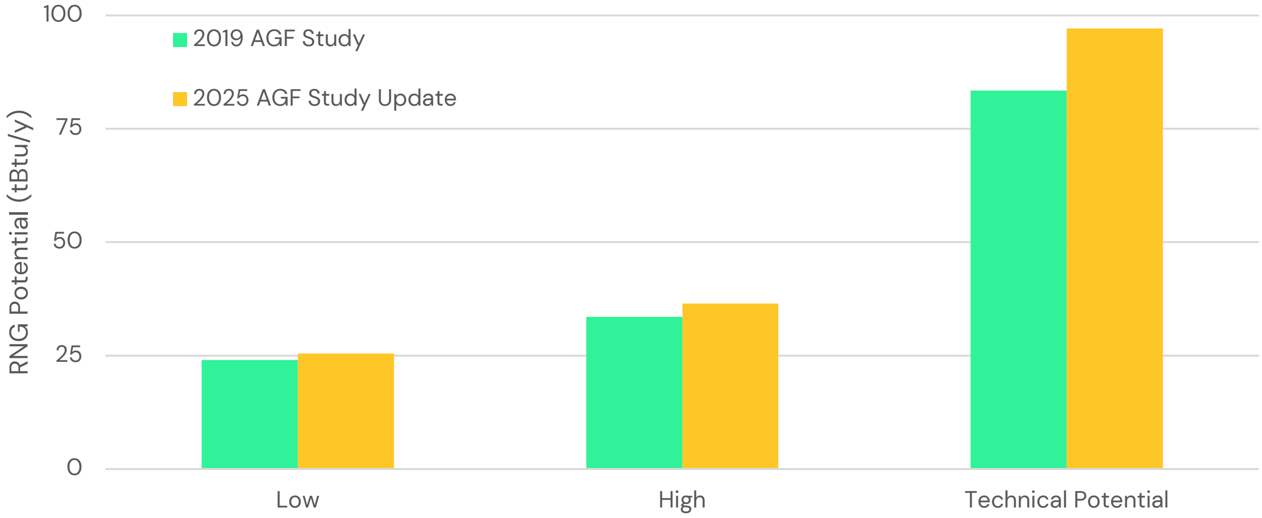


Figure 68. 2019 and 2025 Study Comparison, Energy Crops (tBtu/y)

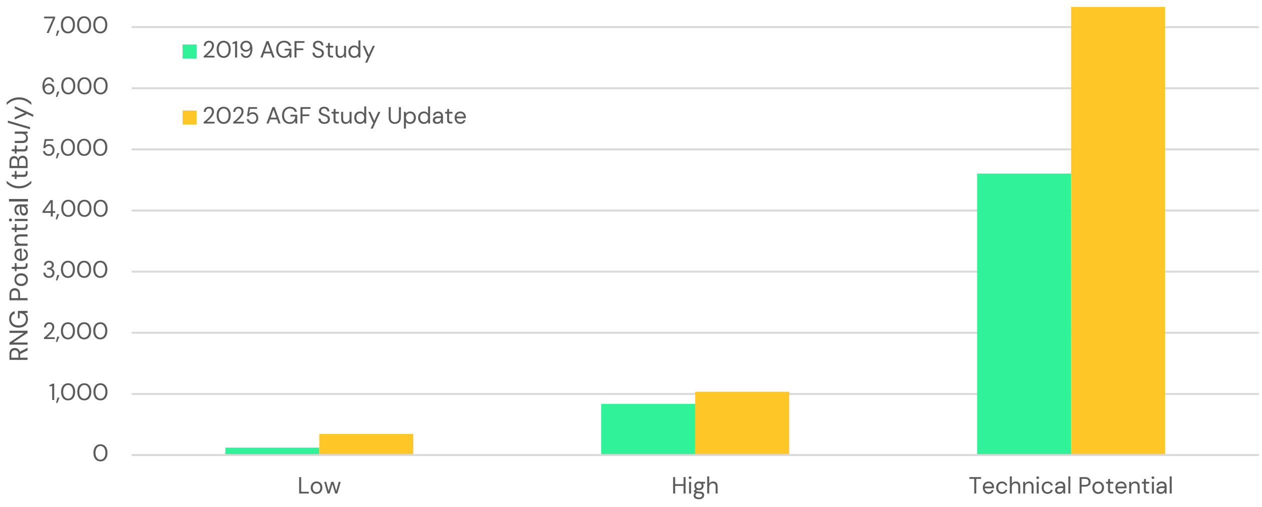


Figure 69. 2019 and 2025 Study Comparison, Forestry Residues (tBtu/y)

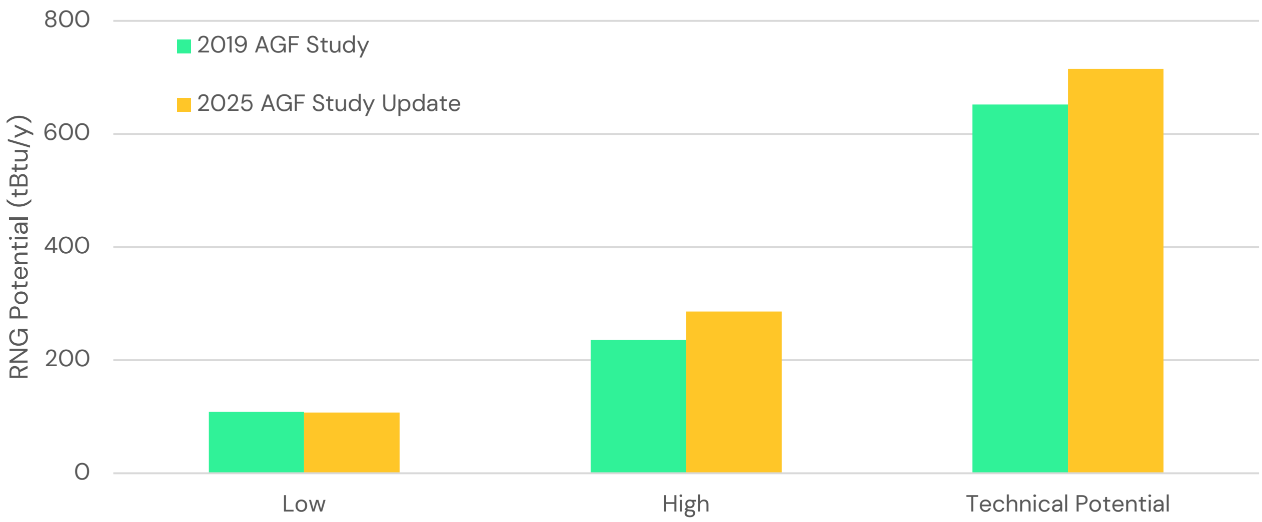
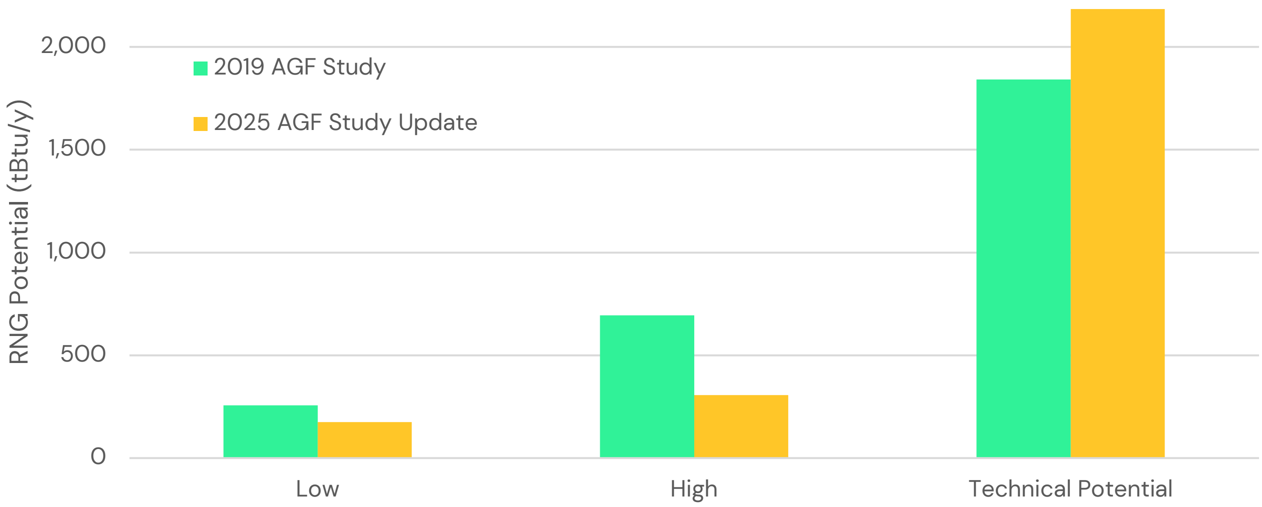


Figure 70. 2019 and 2025 Study Comparison, MSW (tBtu/y)



Appendix D – Carbon Intensity Detailed Results

ICF Standard Assumptions

ICF developed standard assumptions for process fuel quantities based on past supply estimates and assessments of several active production processes. These are included in the life cycle carbon intensity estimates for the various RNG production pathways developed in GREET for this study.

Table 43. ICF Assumptions for Process Fuel Inputs into the GREET model

Feedstock	"Utility Sourced" (Geologic) Natural Gas (MMBtu/MMBtu RNG)	Grid Electricity (kWh/MMBtu RNG)
Dairy Manure	0.35	35
Swine Manure	0.35	35
Poultry Litter	0.35	35
Other Cattle Manure	0.35	35
Food Waste	0.35	40
Landfill Gas	0.06	30
WRRF	0.05	35
All TG Feedstocks	0.01	31

ICF also utilized GREET's default numbers for global warming potential (GWP) based on the IPCC's fifth assessment report (AR5), which ANL cites as follows:

Table 44. GWP Values Used in Life Cycle CIs from 2023 GREET

AR Edition/Type	AR5/GWP
Time Horizon (years)	*100*
CO_2	1
CH_4	30
N_2O	265

CI Results from All Scenarios

ICF developed tables that display the breakdown of upstream and downstream emissions for each feedstock's production pathway, in terms of the archetypical RNG carbon intensities developed by ICF for US average projects.

Table 45. RNG via AD Archetypical CI Breakdown ($kgCO_2e/MMBtu$)

RNG Production Process: Anaerobic Digestion		Poultry Manure	Other Cattle Manure	Dairy Manure	Swine Manure	Food Waste	Landfill Gas	WRRFs	Geologic Natural Gas
Collection & Processing	Feedstock Collection	0.38	0.7	0.6	0.4	0.0	0.0	0.0	13.4
	Digestion & Gas Processing	43.7	56.8	71.7	70.1	78.9	29.1	30.7	
	Avoided Emissions	35.25	44.89	-229.3	-243.8	-146.3	-1.0	-1.1	
Pipeline/ Transmission	Transmission	0.3	0.3	0.3	0.3	0.3	0.3	0.3	
End-user	Combustion	0.1	0.1	0.1	0.1	0.1	0.1	0.1	59.5[50]
Total		79.8	57.9	-156.6	-172.8	-67.08	26.2	30.0	72.9

Table 46. RNG via TG Archetypical CI Breakdown ($kgCO_2e/MMBtu$)

RNG Production Process: Thermal Gasification		Agricultural Residue	Food Residue	Energy Crop	MSW	Geologic Natural Gas
Collection & Processing	Feedstock Collection	2.3	1.9	4.1	2.2	13.4
	Syngas Processing	26.3	26.3	27.2	26.3	
Pipeline/ Transmission	Transmission	0.3	0.3	0.3	0.3	
End-user	Combustion	0.1	0.1	0.1	0.1	59.5
Total		29.1	28.7	31.7	29.0	72.9

[50] Note that, due to slight differences in the methodology used by the US EPA vs. ANL, this GREET-derived estimate of GHGs from geologic natural gas combustion (59.5 $kgCO_2e/MMBtu$) is slightly greater than the 53.1 $kgCO_2e/MMBtu$ cited in the EPA's GHG Emission Factors Hub (ghg-emission-factors-hub-2025.pdf).

Table 47. RNG via P2G Archetypical CI Breakdown ($kgCO_2e/MMBtu$)

<table>
<tr><th colspan="2">RNG Production Process: Power to Gas</th><th>Green H2 and Biogenic CO2</th><th>Pink H2 and Biogenic CO2</th><th>Green H2 and Point-source CO2</th><th>Pink H2 and Point-source CO2</th><th>Geologic Natural Gas</th></tr>
<tr><td rowspan="2">Collection & Processing</td><td>Feedstock Production and Collection</td><td>2.9</td><td>4.6</td><td>20.1</td><td>21.7</td><td rowspan="3">13.4</td></tr>
<tr><td>Syngas Processing</td><td>2.2</td><td>2.2</td><td>2.2</td><td>2.2</td></tr>
<tr><td>Pipeline/ Transmission</td><td>Transmission</td><td>0.3</td><td>0.3</td><td>0.3</td><td>0.3</td></tr>
<tr><td>End-user</td><td>Combustion</td><td>0.1</td><td>0.1</td><td>0.1</td><td>0.1</td><td>59.5</td></tr>
<tr><td colspan="2">Total</td><td>5.6</td><td>7.2</td><td>22.7</td><td>24.4</td><td>72.9</td></tr>
</table>

Regional Carbon Intensities

Table 48. Archetypical CIs by Grid Region – RNG from AD and TG ($kgCO_2e/MMBtu$)

Feedstock	NERC Region								
	FRCC	MRO	NPCC	RFC	SERC	SPP	TRE	WECC	US Average
Anaerobic Digestion Archetypical CI ($kgCO_2e/MMBtu$)									
WRRF	32	35	25	30	31	30	29	27	30
Food Waste	-65	-61	-73	-67	-66	-68	-69	-71	-70
Landfill Gas	30	33	24	29	29	28	27	26	28
Dairy Manure	-121	-129	-177	-127	-88	-206	-98	-202	-157
Swine Manure	-51	-134	-20	-152	-229	-271	-231	-130	-173
Poultry Litter	48	98	83	92	67	60	79	50	80
Other Cattle	64	61	61	61	69	54	53	51	58
Thermal Gasification Archetypical CI ($kgCO_2e/MMBtu$)									
Energy Crops	33	37	27	32	33	31	30	29	32
Agricultural Residue	31	34	24	29	30	29	28	26	29
Forestry Residue	30	34	24	29	30	28	27	26	29
MSW	30	34	24	29	30	29	28	26	29

Table 49. Archetypical CIs by Grid Region – RNG from Methanated H_2 ($kgCO_2e/MMBtu$)

Feedstock	NERC Region								
	FRCC	MRO	NPCC	RFC	SERC	SPP	TRE	WECC	US Average
RNG from Methanated Hydrogen Archetypical CI ($kgCO_2e/MMBtu$)									
Biogenic CO2+Green H2	6	7	4	6	6	5	5	5	6
Biogenic CO2+Pink H2	8	9	5	7	8	7	7	6	7
Industrial off-gas CO2 + Green H2	23	25	21	23	23	23	22	22	23
Industrial off-gas CO2 + Pink H2	25	27	22	24	25	24	24	23	24

Appendix E – RNG Supply Curves by Feedstock

Methodology

The supply curves shown previously in Section 4.2 show the total RNG production potential from the eight feedstocks considered in this analysis. In the subsections that follow, ICF has provided additional detail in the supply curve based on feedstocks—we considered animal manure and landfill gas separately, and then present data for the other feedstocks assumed to be used in an anaerobic digester and those used in thermal gasification.

- Wastewater and food waste processing facilities have a smaller production potential than landfill gas facilities and have similar production cost profiles based on ICF analysis, so we opted to combine the RNG production potential and corresponding production cost into the Other Feedstocks, AD category listed in the figures below.
- RNG produced via the thermal gasification of biomass yields similar production costs across the feedstocks considered in this analysis—agricultural residues, forestry residues, energy crops, and MSW. There are minor differences based on the feedstock costs; however, these differences are difficult to distinguish in this analysis because we are making coarse assumptions about facility sizing and other factors. As such, we opted to present these in a single category, Thermal Gasification, in the figures below.

Most feedstocks appear in multiple places on the supply curve. This is primarily the effect of economies of scale experienced by larger facilities that are assumed to have a lower production cost and appear on the lower end of the supply curve. On the other hand, smaller, and presumably less efficient production facilities using the same feedstock have a higher production cost and appear at the higher end of the supply curve.

RNG Supply Curves by Scenario

Figure 71. Low Scenario Supply Curve

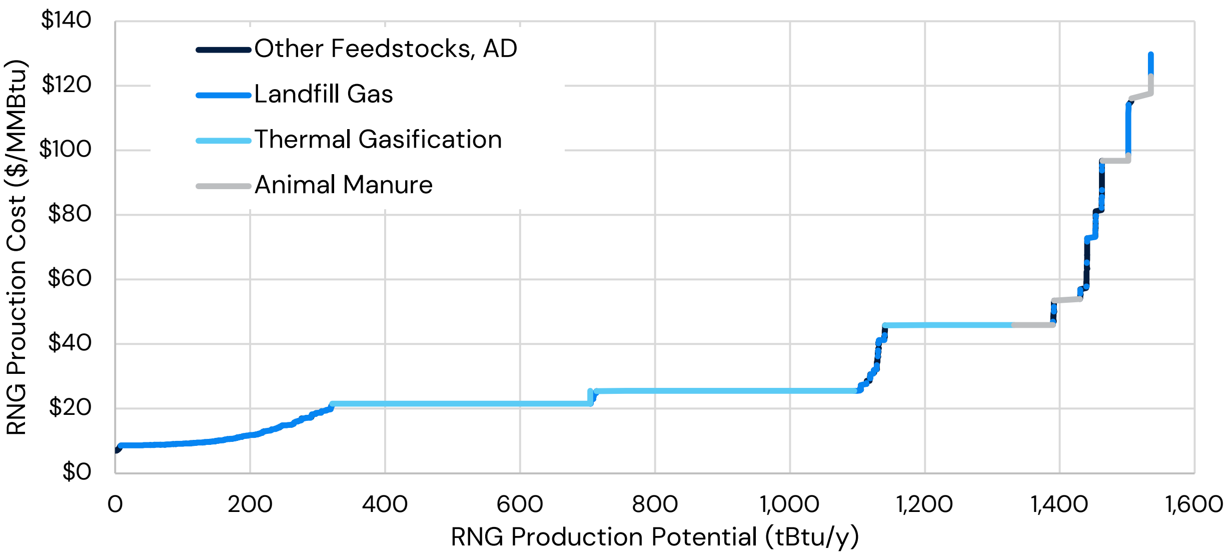


Figure 72. High Scenario Supply Curve

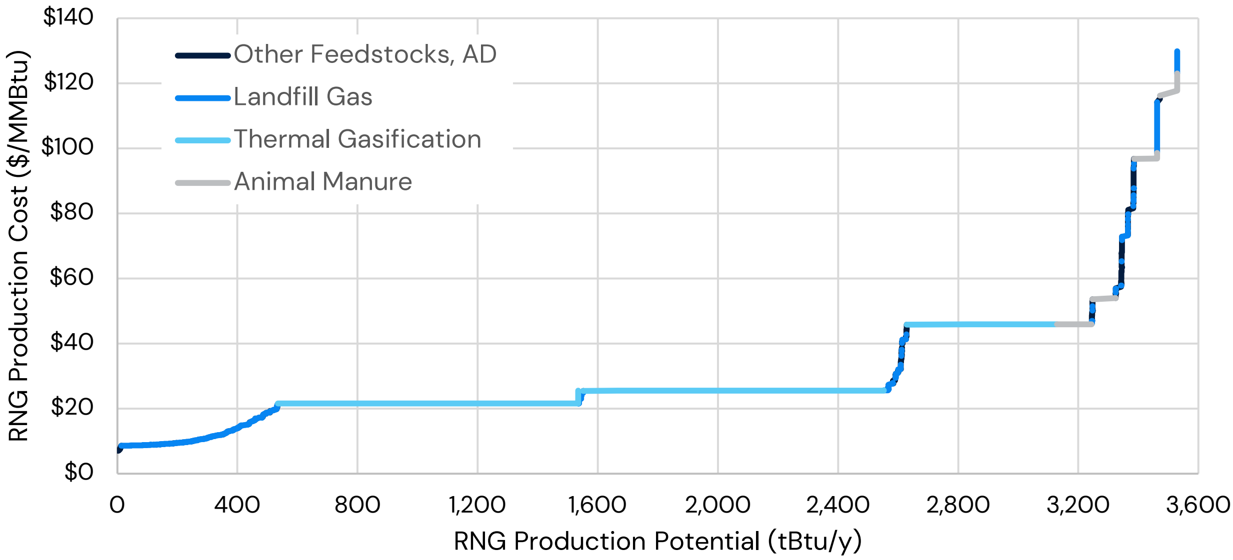
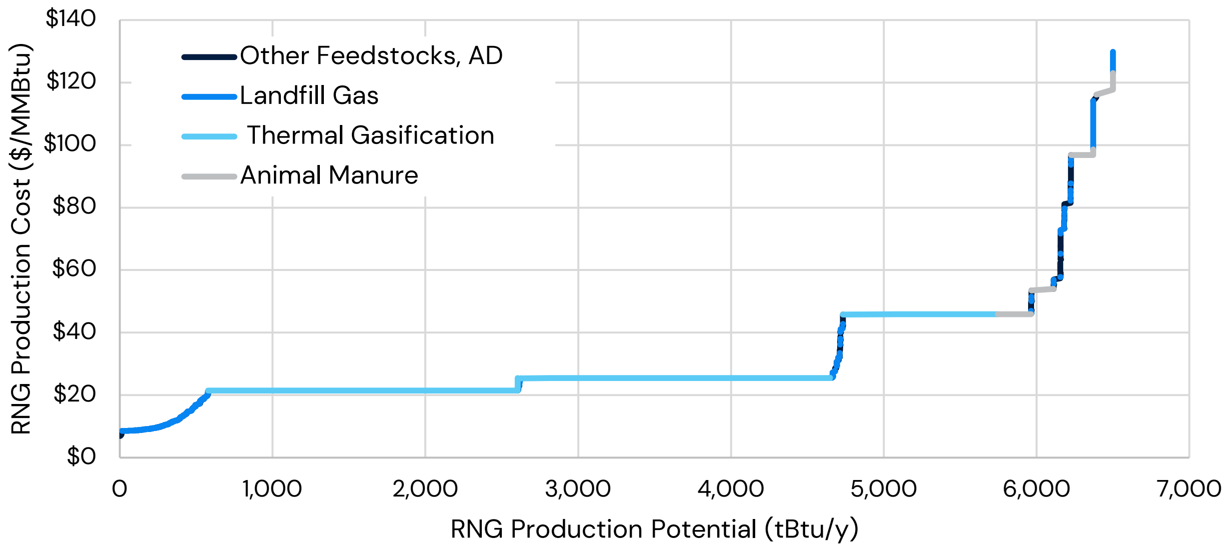


Figure 73. Ambitious Emissions Reduction Scenario Supply Curve



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