American Gas FOUNDATION

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RENEWABLE SOURCES OF NATURAL GAS:

SUPPLY AND EMISSIONS REDUCTION ASSESSMENT

An American Gas Foundation Study Prepared by:

ICF

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Table of Contents

List of Tables

List of Figures

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Executive Summary

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 lifecycle carbon dioxide equivalent (CO2-eq) emissions than geological natural gas.

ICF conducted an assessment to outline the potential for RNG to contribute meaningfully and cost-effectively to greenhouse gas (GHG) emission reduction initiatives across the country. The report serves as an update and expansion to a 2011 report published by the American Gas Foundation (AGF) entitled *The Potential for Renewable Gas: Biogas Derived from Biomass Feedstocks and Upgraded to Pipeline Quality*. Building upon the previous work, this report is focused on assessing a) the RNG production potential from various feedstocks, b) the corresponding GHG emission reduction potential, and c) the estimated costs of bringing RNG supply on to the system. ICF developed production potential estimates by incorporating a variety of constraints regarding accessibility to feedstocks, the time that it would take to deploy projects over the timeline of the study (out to 2040), 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.

ICF developed low and high resource potential scenarios by considering RNG production from nine (9) feedstocks and three production technologies. The feedstocks include landfill gas, animal manure, water resource recovery facilities (WRRFs), food waste, agricultural residues, forestry and forest product residues, energy crops, the use of renewable electricity, and the non-biogenic fraction of municipal solid waste (MSW).[1] These feedstocks were assumed to be processed using one of three technologies to produce RNG, including anaerobic digesters, thermal gasification systems, and power-to-gas (P2G) in combination with a methanation system. It is important to note that ICF's analysis is not meant to be prescriptive, 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 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 type of multi-feedstock considerations will continue to exist in the market; however, we needed to make simplifying distinctions for the purposes of the resource assessment.

ICF estimated low and high resource potential scenarios by considering constraints unique to each potential RNG feedstock—these constraints were based on factors such as feedstock accessibility and the economics of RNG production using the feedstock. These constraints were then used to develop low and high utilization assumptions regarding each feedstock. The resource potential reported is also a function of the conversion efficiency of the production technology to which each

[1] ICF notes that the non-biogenic fraction of MSW does not satisfy AGA's definition of RNG; however, this feedstock was included in the analysis. The results associated with RNG potential from this non-biogenic fraction of MSW are called out separately throughout the report for the sake of transparency.

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-, state-, and regional-level information regarding the availability of different feedstocks; and the information is presented using the nine (9) U.S. Census Regions.

In the **low resource potential scenario**, ICF estimates that about 1,660 trillion Btu (tBtu) of RNG can be produced annually for pipeline injection by 2040 (see Figure 1 below). That estimate increases to 1,910 tBtu per year when including the potential for the non-biogenic fraction of MSW. In the **high resource potential scenario**, ICF estimates that about 3,780 tBtu of RNG can be produced annually for pipeline injection by 2040 (see Figure 2 below). That estimate increases to 4,510 tBtu per year when including the potential for the non-biogenic fraction of MSW. For the sake of comparison, ICF notes that the 10-year average (2009 to 2018) for residential natural gas consumption nationwide is 4,846 tBtu; this is shown as the black-dotted line in Figure 1 and Figure 2 below. Ultimately, market conditions, technology development, and policy structures will determine the extent to which each of the feedstocks considered can be utilized. For the sake of reference, ICF also reports a technical resource potential scenario of nearly 13,960 tBtu—a production potential intended to reflect the RNG production potential without any technical or economic constraints.

The reported RNG resource potential estimates reported here are 90% and 180% increases from the comparable resource potential scenarios from 2011 AGF Study. These changes are largely attributable to improved access to data regarding potential feedstocks for RNG production and are generally not attributable to more aggressive assumptions regarding feedstock utilization or conversion efficiencies. Furthermore, the analysis presented here includes estimates for RNG production from P2G systems using dedicated renewable electricity. While there are multiple studies regarding P2G technology and its uses, we believe this is the first study to quantify RNG production potential nationwide from P2G.

A diverse array of resources can contribute to RNG production—there is a portfolio of potential feedstocks and technologies that are or will be commercialized in the near-term future that will help realize the potential of the RNG market. Figure 1 and Figure 2 below demonstrate the diversity of RNG resource potential as a GHG emission reduction strategy. On the technology side, most RNG continues to be produced using anaerobic digestion paired with conditioning and upgrading systems. The post-2025 outlook for RNG will increasingly rely on thermal gasification of sustainably harvested biomass, including agricultural residues, forestry and forest product residues, and energy crops. The long-term outlook for RNG growth will depend to some extent on technological advancements in power-to-gas systems.[2]

[2] The RNG potential for P2G/methanation is shown as a pattern fill in Figure 1 and Figure 2 because of the way ICF estimates likely project economics for P2G. In reality, however, the low and high resource potential for P2G using dedicated renewable electricity will be constrained by more factors that could be considered in this report; and it is conceivable that the RNG resource potential from P2G is considerably higher than considered here.

Figure 1. Estimated Annual RNG Production, Low Resource Potential Scenario, tBtu/y

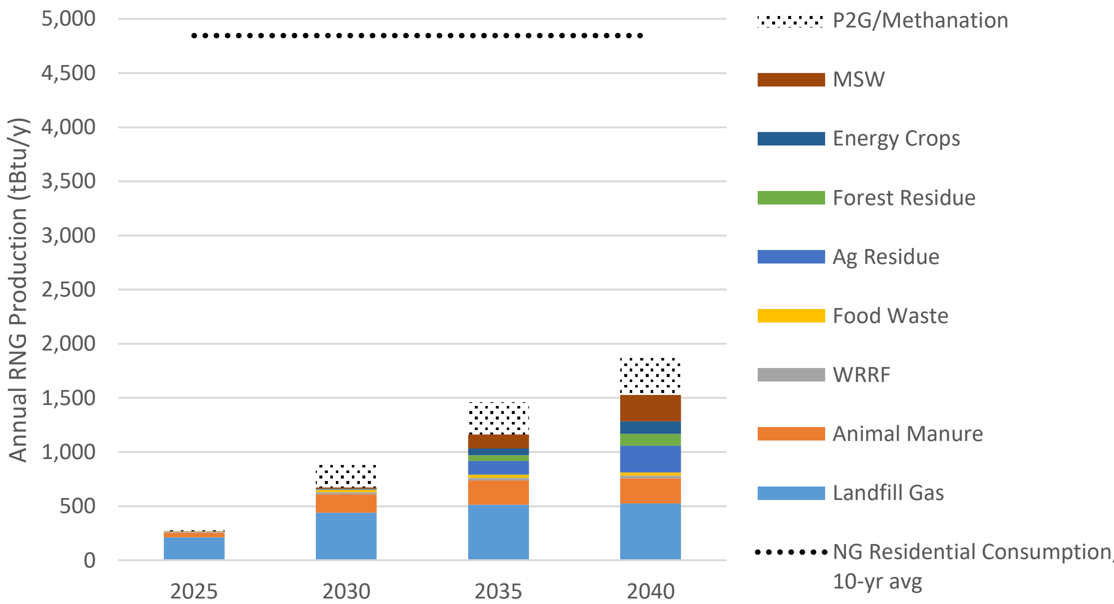
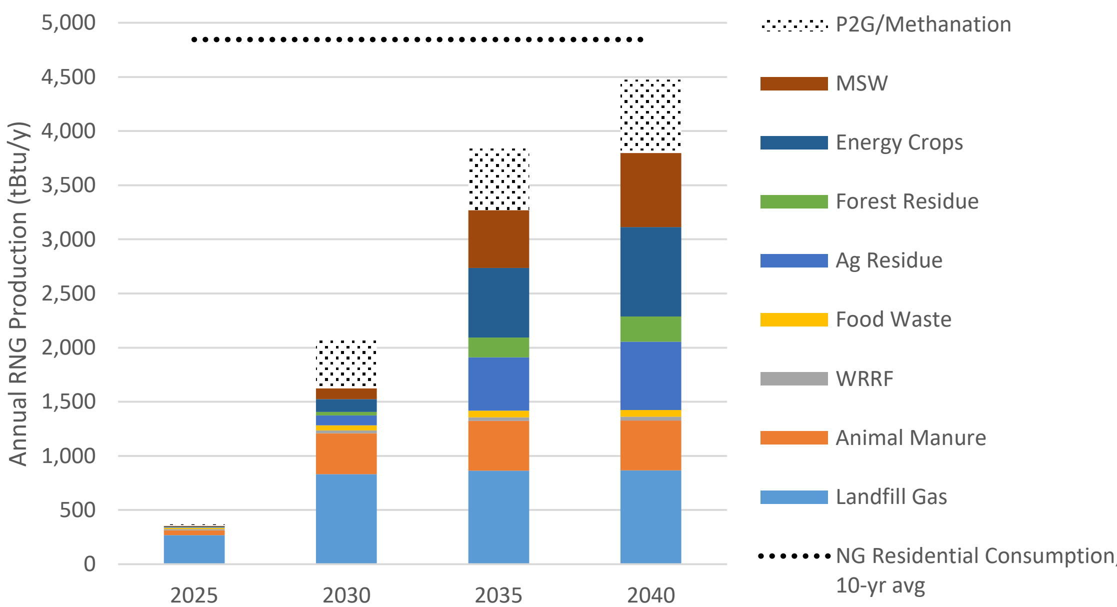


Figure 2. Estimated Annual RNG Production, High Resource Potential Scenario, tBtu/y



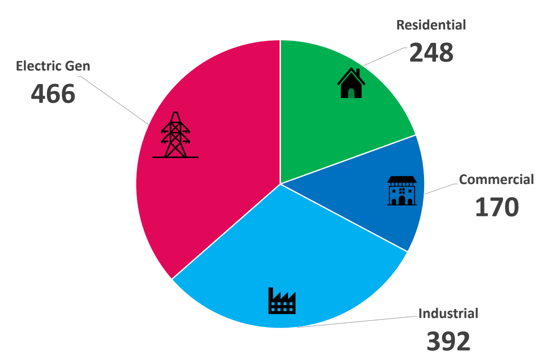
The potential for power-to-gas systems as a contributor to RNG production could be significant. Power-to-gas (P2G) is a form of energy technology that converts electricity to a gaseous fuel. Electricity is used to split water into hydrogen and oxygen, and the hydrogen can be further processed to produce methane when combined with a source of carbon dioxide. If the electricity is sourced from renewable resources, such as wind and solar, then the resulting fuels are carbon neutral. In this study, ICF made the simplifying assumption that all hydrogen produced via P2G would be methanated for pipeline injection. This assumption should not be viewed as a determination of the best use of hydrogen as an energy carrier in the future; rather, it was a simplifying assumption to compare more easily P2G to other potential RNG resources evaluated in this study.

ICF generally finds that the potential for RNG deployment could exceed the estimated high resource potential scenario because we opted to employ moderately conservative assumptions regarding the expected utilization of various feedstocks. These assumptions manifest themselves as constraints on the availability of supply for each feedstock, recognizing there will likely be competition for each feedstock. It is important to note that ICF did not make any assumptions regarding a specific policy or incentive framework that would favor RNG production over some other energy source (e.g., liquid biofuels).

Excluding cost considerations, the deployment of P2G systems for RNG production requires assumptions across a variety of factors, including but not limited to access to renewable electricity, the corresponding capacity factor of the system given the intermittency of renewable electricity generation from some sources (e.g., solar and wind), co-location with (presumably affordable) access to carbon dioxide for methanation, and reasonable proximity to a natural gas pipeline for injection. ICF's analysis did not seek to address all of these project development considerations; rather, we sought to understand the potential for P2G systems assuming access to dedicated renewable electricity production, meaning that these are purpose-built renewable electricity generation systems that are meant to provide dedicated power to P2G systems. ICF did not explicitly consider renewable electricity that could be curtailed from over-supply of renewable electricity as a result of compliance with Renewable Portfolio Standards (RPS). Ultimately, the issue of curtailment is a complicated one, and exploring it in detail was beyond the scope of this analysis. However, ICF's initial assessment indicates that P2G systems running on curtailed renewable electricity will play an important transitional role in helping to deploy the technology and achieve the long-term price reductions that are required to improve the viability of P2G as a cost-effective pathway for RNG production. Despite the importance of curtailed renewable electricity as part of the transition towards more cost-effective P2G systems, ICF's analysis does focus more on the opportunity for, and associated costs of RNG production using P2G systems with dedicated renewable electricity generation. It is important that this assumption by ICF is recognized as a limitation of our analysis, rather than a commentary on how the market will ultimately develop for P2G systems.

ICF estimates that RNG deployment could achieve 101 to 235 million metric tons (MMT) of GHG emission reductions by 2040. The GHG emission reductions were calculated using IPCC guidelines stating that emissions from biogenic fuel sources should not be included when accounting for emissions in combustion. This accounting approach is employed to avoid any upstream "double counting" of emissions that occur in the agricultural or land-use sectors per IPCC guidance. Generally speaking, biogenic carbon in combustion is excluded from carbon accounting methodologies because it is assumed that the carbon sequestered by the biomass during its lifetime offsets emissions that occur during combustion. Figure 3 shows the 10-year average (2009-2018) of carbon dioxide (CO_2) emissions from natural gas consumption across multiple sectors; and most notably that the residential

Figure 3. Average Annual CO_2 Emissions (in MMT) from Natural Gas Consumption, 2009-2018



energy sector on average emitted about 248 MMT of CO_2 emissions nationwide over the 10-years considered.

GHG emission reductions attributable to RNG can be a complicated issue driven by different accounting systems. Although we focus on the GHG emission reductions potential using IPCC guidelines in this report, many stakeholders are likely familiar with the lifecycle accounting approach for GHG emissions that is used by California's Low Carbon Fuel Standard (LCFS) program. In that accounting system, the GHG emissions from production and processing to combustion are accounted for—and fuels like RNG sourced from animal manure generally have a negative emissions factor, which reflects the upstream "crediting" of capturing methane that would have otherwise been vented to the atmosphere. ICF addresses these various accounting systems, and reviews the GHG emission reductions under a lifecycle accounting framework in an appendix.

ICF estimates that the majority of the RNG produced in the high resource potential scenario is available in the range of $7-$20/MMBtu, which results in a cost of GHG emission reductions between $55/ton to $300/ton in 2040. ICF evaluated the potential costs associated with the deployment of each feedstock and technology pairing, and made assumptions about the sizing of systems that would need to be deployed to achieve the RNG production potential outlined in the low and high resource potential scenarios. ICF reports that RNG will be available from various feedstocks in the range of $7/MMBtu to $45/MMBtu. These costs are dependent on a variety of assumptions, including feedstock costs, the revenue that might be generated via byproducts or other avoided costs, and the expected rate of return on capital investments. ICF finds that there is potential for cost reductions as the RNG for pipeline injection market matures, production volumes increase, and the underlying structure of the market evolves.

As noted previously, the opportunity of RNG from P2G systems (and paired with methanation units) warrants further consideration; however, ICF's analysis demonstrates that the combination of production potential and potential cost reductions for P2G systems is promising. With respect to RNG from P2G, the three main drivers for the production costs include: a) the electrolyzer, b) the cost of renewable electricity, and c) the cost of methanation. ICF finds that there is significant cost reduction potential in the P2G market, as the installed capacity (measured in GW, for instance) for electrolyzers increases over the next 10-15 years. ICF assumed that dedicated renewable electricity systems, co-located with P2G systems, could provide electricity at a levelized cost in the range of $10 to $55 per MWh. Lastly, there is significant cost reduction potential for methanation paired with P2G systems.

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 uses the following definition for RNG:

Pipeline compatible gaseous fuel derived from biogenic or other renewable sources that has lower lifecycle carbon dioxide equivalent (CO2e) emissions than geological natural gas.

The primary objective of this report is to characterize the resource and economic potential for RNG as a greenhouse gas (GHG) emission reduction strategy. Further, this report seeks to improve policy makers' understanding of the extent to which delivering RNG to all sectors of the economy can contribute to broader GHG emission reduction initiatives.

The following sub-sections introduce the RNG production technologies and corresponding feedstocks. ICF assessed the production potential for renewable gas into three categories: 1) RNG from renewable feedstocks using anaerobic digestion (AD) and thermal gasification (TG), 2) RNG derived from municipal solid waste (MSW),[3] and 3) RNG produced via combination power-to-gas (P2G) and methanation. For each resource and production technology pairing, ICF estimated the production cost and corresponding range of GHG emissions.

RNG Production Technologies

RNG is produced over a series of steps–namely collection of a feedstock, delivery to a processing facility for biomass-to-gas conversion, gas conditioning, compression, and interconnection and injection into the pipeline.

- The most common way to produce RNG today is via anaerobic digestion, whereby microorganisms break down organic material in an environment without oxygen. In the context of RNG production, the process generally takes place in a controlled environment, referred to as a digester or reactor. When organic material is introduced to the digester, it 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, sometimes referred to as biogas. The biogas is subsequently upgraded and conditioned to yield biomethane, and injected into the common carrier pipeline.
- The thermal gasification of biomass also produces RNG—this includes a broad range of processes whereby a carbon containing feedstock is converted into a mixture of gases referred to as synthetic gas or syngas, including hydrogen, carbon monoxide, steam, carbon dioxide, methane, and trace amounts of other gases. This process generally occurs at high temperatures and varying temperatures (depending on the gasification system).
- Lastly, this assessment considers RNG produced using renewable electricity (as a feedstock) to generate hydrogen via electrolysis, which is methanated for subsequent injection into the pipeline—this process is referred to as power-to-gas (P2G).

[3] Gas produced from the thermal gasification of MSW does not satisfy AGA's definition of RNG because it is not from a biogenic or renewable source; however, it does have lower lifecycle CO2e emissions than geological natural gas. As a result, MSW as a resource was assessed in this study, but is presented separately from the other feedstocks considered.

RNG Feedstocks

RNG can be produced from a variety of renewable feedstocks, as described in Table 1 below. More information about each feedstock and its corresponding contribution to the RNG resource potential is included in Section 0.

Table 1. Summary of Feedstocks Considered for RNG Production

Feedstock for RNG		Description
Anaerobic digestion	Landfill gas (LFG)	The anaerobic digestion of organic waste in landfills produces a mix of gases, including methane (40-60%).
	Animal manure	Manure produced by livestock, including dairy cows, beef cattle, swine, sheep, goats, poultry, and horses.
	Water Resource Recovery Facilities (WRRF)	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.
	Food waste	Commercial food waste, including from food processors, grocery stores, cafeterias, and restaurants, as well as residential food waste, typically collected as part of waste diversion programs.
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.
	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).
	Energy crops	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.
	Municipal solid waste (MSW)	Refers to the non-biogenic fraction of waste that would be landfilled after diversion of other waste products (e.g., food waste or other organics), including construction and demolition debris, plastics, etc.
P2G	Renewable electricity	Renewable electricity (presumably excess generation thereof) serves as feedstock for P2G technologies. P2G produces hydrogen, which can then be blended directly into the pipeline or methanated.

Resource Assessment Scenarios

ICF developed three scenarios for each feedstock—with variations between a low resource and high resource scenario regarding utilization of the feedstock, and a technical resource potential based on the energy content of the resource under consideration. This is substantially similar to the AGF study completed in 2011 regarding RNG, as noted below.

Review of Previous Work

In 2011, the American Gas Foundation (AGF) published *The Potential for Renewable Gas: Biogas Derived from Biomass Feedstocks and Upgraded to Pipeline Quality*, a study aimed at assessing the resource potential of renewable gas which included three scenarios, as described here, and the resource potential results are shown in Table 2 below.[4]

- Non-Aggressive Scenario: This represented a low level of feedstock utilization, with utilization levels reportedly depending on feedstock, with a range from 15%-25% for feedstocks that were converted to renewable gas using anaerobic digestion technologies. The utilization rates of feedstocks for thermal gasification in the non-aggressive scenario ranged from 5-10%.
- Aggressive Scenario: This scenario represented a higher level of feedstock utilization, with utilization levels reportedly depending on feedstock, with a range from 40%-75% for feedstocks that were converted to RNG using anaerobic digestion technologies. The utilization rates of feedstocks for thermal gasification in the aggressive scenario ranged from 15-25%.
- Maximum Scenario: This represents an "absolute upper bound" regarding the energy production potential and was used for illustrative purposes.

Table 2. Summary of RNG Potential from 2011 AGF Study in units of tBtu/year

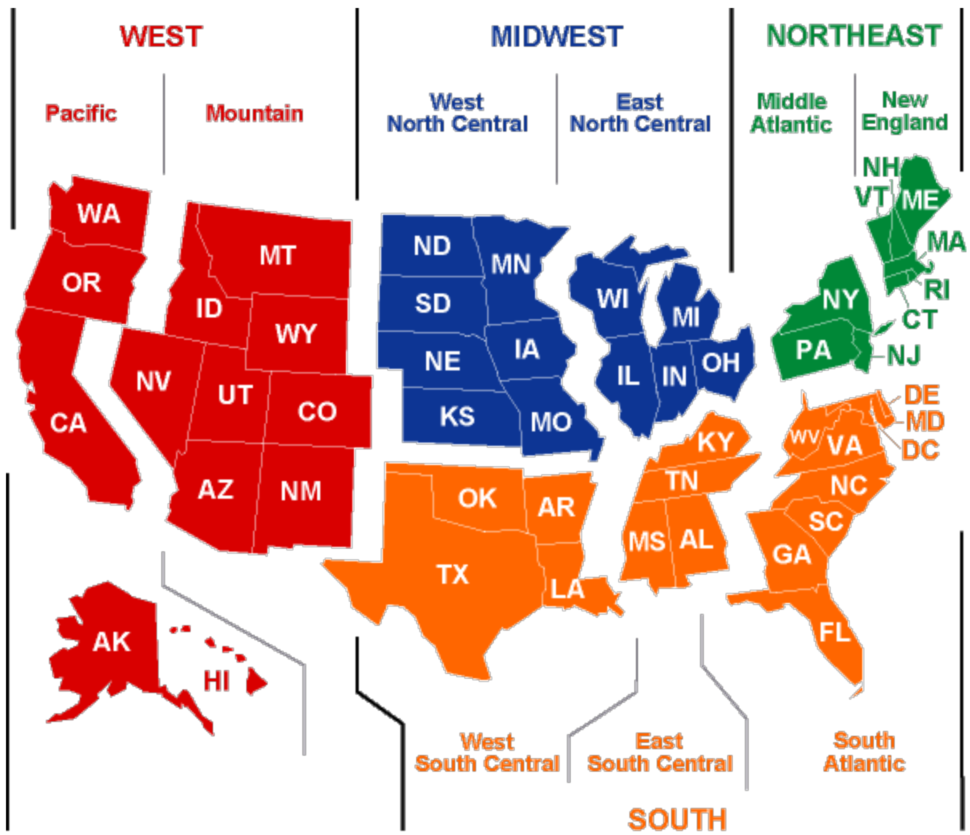
Feedstock	**RNG Production Potential, tBtu/y**	
	Non-Aggressive	**Aggressive**
Landfill Gas	182	364
Animal Manure	148	493
WRRF	4	13
Food Waste	N/A	N/A
Sub-Total, AD	335	871
Ag Residue	401	1,002
Forestry and Forest Residue	82	206
Energy Crops	80	200
MSW	69	207
Sub-Total, TG	632	1,614
Totals	967	2,485

[4] Note that the 2011 RNG assessment did not consider P2G.

Regional RNG Resource Assessment

There are more than 85 projects producing RNG for pipeline injection today, compared to less than a half-dozen in 2010 when AGF first assessed the potential for RNG. In the following sub-sections, ICF outlines the potential for RNG for pipeline injection, broken down by the feedstocks presented previously, and considering the potential for RNG growth over time with 2040 being the final year in the analysis. ICF presents a low and a high RNG potential, varying both the assumed utilization of existing resources, as well as the rate of project development required to deploy RNG at the volumes presented. The resource potential is presented on a national-level and broken down by the nine (9) U.S. Census Regions, as shown in the figure below: New England, Middle Atlantic, East North Central, West North Central, South Atlantic, East South Central, West South Central, Mountain, and Pacific.

Figure 4. U.S. Census Regions



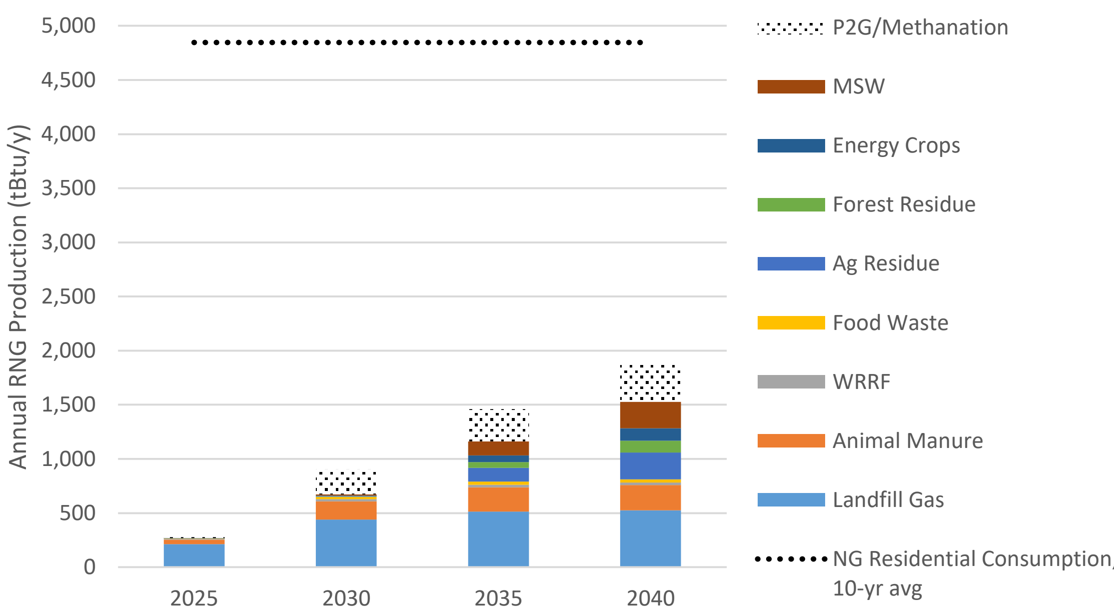
The RNG potential is based on assessment of resource availability—in a competitive market, that resource availability will be a function of factors including, but not limited to demand, feedstock costs, technological development, and the policies in place that might support RNG project development. The intent of ICF's estimates is to outline the RNG potential that could be realized given the right market considerations (without explicitly defining what those are), and then capture the corresponding costs and GHG emissions reductions associated with our production estimates.

For the RNG market more broadly, ICF assumed that the market would continue to grow to 2025 at a compound annual growth rate slightly higher than we have seen over the last 5 years—at a rate of about 35%.[5] This rate is reflective of existing investments in at least 40 new domestic RNG projects coming online, and other announcements that have not yet been made. Based on this assumption, we assume that the potential for RNG injected into the pipeline will be on the order of 220 to 240 tBtu in 2025. For RNG production potential post-2025, ICF used a logistic function to approximate the growth trajectory, whereby the initial stage of growth is approximated as an exponential, and thereafter growth slows to a linear rate, and then approaches a plateau (or limited to no growth) at maturity.

Summary of RNG Potential

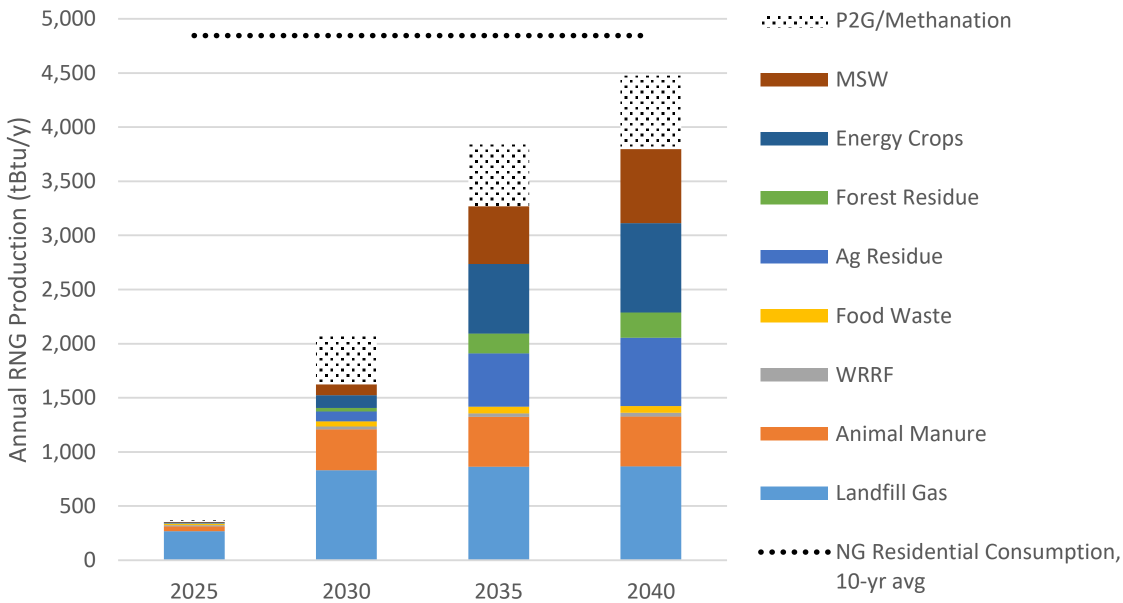
The figures below illustrate ICF's estimates for the low and high potential scenario across each feedstock, reported in units of trillion Btu per year (tBtu/y).

Figure 5. Estimated Annual RNG Production, Low Resource Potential Scenario, tBtu/y



[5] ICF estimates that there were about 17.5 tBtu of RNG produced for pipeline injection in 2016 and that there will be about 50 tBtu of RNG produced for pipeline injection in 2020—this yields a compound annual growth rate of about 30%.

Figure 6. Estimated Annual RNG Production, High Resource Potential Scenario, tBtu/y



ICF estimates that the low and high resource potential scenarios will yield about 1,910 tBtu/y and 4,510 tBtu/y of RNG production by 2040. For the sake of comparison, the United States has consumed on average 15,850 tBtu of natural gas over the last ten years (2009-2018) in the residential (4,846 tBtu), commercial (3,318 tBtu), transportation (36 tBtu), and industrial sectors (7,652 tBtu).[6]

ICF sought to utilize reasonable, and in most cases, conservative assumptions regarding the utilization of different feedstocks. Table 3 below summarizes the utilization of the different feedstocks that ICF used in the analysis.

Table 3. Summary of Feedstock Utilization in the Low and High Resource Potential Scenarios

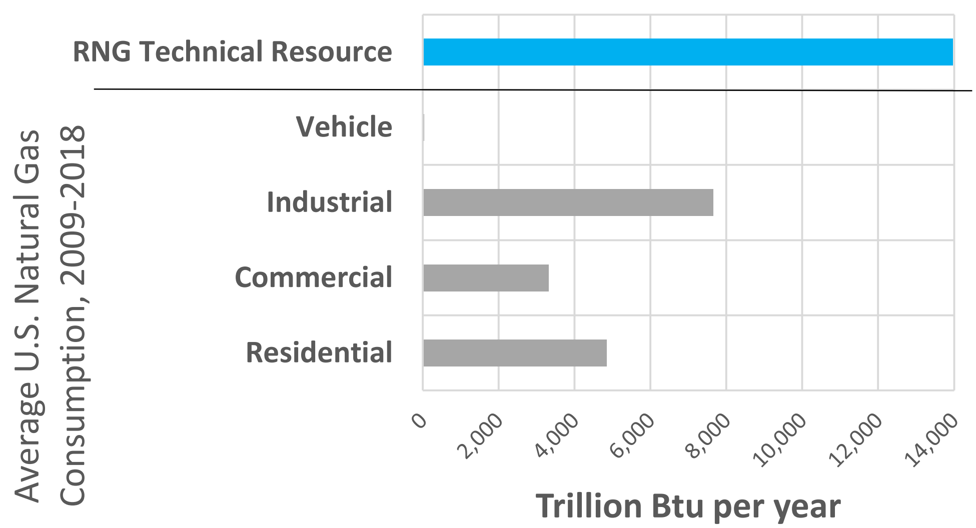
RNG Feedstock	Low Resource	High Resource
LFG	• 40% of the LFG facilities that have collection systems in place • 30% of the LFG facilities that do not have collections systems in place • 50% of EPA's candidate landfills	• 65% of the LFG facilities that have collection systems in place • 60% of the LFG facilities that do not have collections systems in place • 80% of EPA's candidate landfills
Animal manure	• 30% of technically available animal manure	• 60% of technically available animal manure
WRRF	• 30% of WRRFs with a capacity greater than 7.25 million gallons per day	• 50% of WRRFs with a capacity greater than 3.3 million gallons per day
Food waste	• 40% of the food waste available at $70/dry ton	• 70% of the food waste available at $100/dry ton
Agricultural residue	• 20% of the agricultural residues available at $50/dry ton	• 50% of the agricultural residues available at $50/dry ton

[6] Based on data reported by the Energy Information Administration, available online at https://www.eia.gov/dnav/ng/ng_cons_sum_dcu_nus_a.htm.

RNG Feedstock	Low Resource	High Resource
Forestry and forest product residue	• 30% of the forest and forestry product residues available at $30/dry ton	• 60% of the forest and forestry product residues available at $60/dry ton
Energy crops	• 50% of the energy crops available at $50/dry ton	• 50% of the energy crops available at $70/dry ton
Municipal solid waste (MSW)	• 30% of the non-biogenic fraction of MSW available at $30/dry ton	• 60% of the non-biogenic fraction of MSW available at $100/dry ton
P2G	• 50% capacity factor for dedicated renewables	• 80% capacity for dedicated renewables

Ultimately, market conditions, technology development, and policy structures will determine the extent to which each of the feedstocks considered can be utilized. For the sake of reference, ICF also reports a technical resource potential scenario of nearly 13,960 tBtu—an estimate intended to reflect the RNG production potential without any technical or economic constraints. Figure 7 below shows how the RNG technical resource potential compares to the domestic consumption of natural gas in different end uses.[7]

Figure 7. RNG Technical Resource Potential vs Average Domestic Natural Gas Consumption in Different End Uses, 2009-2018 (in tBtu/y)



The tables below summarize ICF's resource assessment for low, high, and technical resource RNG production potential in 2040, broken down by Census Region and by feedstock, reported in units of tBtu per year (tBtu/y). The last row in each table also includes the amount of natural gas consumed in the residential, commercial, transportation, and industrial sectors broken down by Census Region in 2018 for the sake of reference.

[7] The technically achievable RNG production potential excludes P2G as a source.

Low Resource Potential Scenario

Table 4. Low Resource Potential for RNG in 2040, tBtu/y

Feedstock	RNG Potential: Low Scenario (in tBtu/y)									
	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific	Total
RNG from biogenic or renewable resources										
Landfill Gas	13.3	57.5	106.2	28.6	88.4	35.7	65.3	38.3	95.2	528.4
Animal Manure	8.0	12.1	30.3	44.5	31.7	18.9	36.0	28.7	21.0	231.2
WRRF	1.1	4.5	5.5	1.3	3.4	1.0	2.0	1.2	4.0	24.0
Food Waste	1.8	5.0	5.7	1.9	6.0	0.8	1.4	0.9	5.6	29.2
Sub-Total, AD	***24.2***	***79.1***	***147.8***	***76.3***	***129.5***	***56.4***	***104.7***	***69.1***	***125.8***	***812.8***
Ag Residue	0.0	3.7	57.0	144.4	10.0	2.9	10.7	10.9	14.9	254.6
Forestry and Forest Residue	3.6	4.8	9.7	6.5	37.6	20.6	16.3	2.7	6.8	108.6
Energy Crops	0.2	2.2	1.5	35.4	18.1	9.3	56.5	0.2	0.0	123.4
Sub-Total, TG	***3.8***	***10.7***	***68.2***	***186.3***	***65.7***	***32.8***	***83.5***	***13.8***	***21.7***	***486.6***
Renewable gas from MSW										
MSW	14.4	40.6	45.9	17.7	56.9	11.2	15.3	8.8	45.4	256.2
RNG from P2G / Methanation										
P2G / Methanation										357.7
Totals	**42.3**	**130.5**	**261.8**	**280.4**	**252.1**	**100.3**	**203.4**	**91.7**	**192.9**	**1,913.2**

High Resource Potential Scenario

Table 5. High Resource Potential for RNG in 2040, tBtu/y

Feedstock	RNG Potential: High Scenario (in tBtu/y)									
	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific	Total
RNG from biogenic or renewable resources										
Landfill Gas	21.7	94.3	173.8	47.3	145.0	59.1	106.2	32.9	155.2	865.6
Animal Manure	16.0	24.2	60.6	88.9	63.4	37.7	71.9	57.5	42.1	462.3
WRRF	1.6	6.3	6.6	2.0	5.1	1.6	3.1	1.7	5.5	33.5
Food Waste	3.1	8.8	9.9	4.1	13.1	4.2	8.0	2.9	9.8	63.9
Sub-Total, AD	**42.4**	**133.6**	**250.9**	**142.3**	**226.6**	**102.6**	**189.2**	**125.0**	**212.6**	**1,425.3**
Ag Residue	0.1	9.2	142.6	361.0	26.9	7.3	28.8	27.3	37.3	640.5
Forestry and Forest Residue	7.3	9.7	19.3	13.0	75.2	41.3	37.1	19.3	13.6	235.8
Energy Crops	0.5	9.4	64.4	260.0	77.3	91.6	330.5	3.9	0.0	837.6
Sub-Total, TG	***7.9***	***28.3***	***226.3***	***634.0***	***179.4***	***140.2***	***396.4***	***50.5***	***50.9***	***1,713.9***
Renewable gas from MSW										
MSW	32.4	91.6	103.4	46.1	136.3	43.2	83.2	50.1	108.5	694.8
RNG from P2G / Methanation										
P2G / Methanation										678.7
Totals	**80.5**	**245.2**	**569.4**	**819.4**	**532.0**	**283.5**	**658.1**	**222.5**	**359.4**	**4,512.6**

Technical Resource Potential

Table 6. Technical Resource Potential for RNG in 2040, tBtu/y

Feedstock	RNG Potential: Technical Potential (in tBtu/y)									
	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific	Total
RNG from biogenic or renewable resources										
Landfill Gas	32.5	143.4	259.1	70.3	211.7	84.0	154.0	92.0	233.2	1,280.2
Animal Manure	88.9	99.3	285.2	602.7	316.5	207.7	453.5	340.5	178.1	2,572.4
WRRF	4.0	14.4	18.1	5.6	12.3	4.7	7.6	4.5	12.2	83.2
Food Waste	17.7	50.1	56.6	23.5	74.5	23.6	45.5	16.5	56.0	364.1
Sub-Total, AD	***143.1***	***307.2***	***619.0***	***702.1***	***615.0***	***320.0***	***660.6***	***453.5***	***479.5***	***4,300.0***
Ag Residue	0.3	42.1	623.8	1,405.1	93.8	38.7	123.3	115.1	126.3	2,568.5
Forestry and Forest Residue	18.6	24.9	49.5	33.4	192.9	105.8	106.7	85.5	34.7	652.0
Energy Crops	3.0	84.3	872.5	1,508.1	357.1	460.8	1,266.4	48.7	0.0	4,600.9
Sub-Total, TG	***21.9***	***151.3***	***1,545.8***	***2,946.6***	***643.8***	***605.3***	***1,496.4***	***249.3***	***161.0***	***7,821.4***
Renewable gas from MSW										
MSW	85.8	242.7	274.0	122.2	361.2	114.6	220.5	133.1	287.5	1,841.6
RNG from P2G / Methanation										
P2G / Methanation	N/A; dependent on market developments beyond scope of study									
Totals	**250.8**	**701.2**	**2,438.8**	**3,770.9**	**1,620.0**	**1,039.9**	**2,377.5**	**835.9**	**928.0**	**13,963.1**

RNG: Anaerobic Digestion of Biogenic or Renewable Resources

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 disposed of in landfills and produces a mix of gases, including methane, typically with a methane content ranging from 45-60%. 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 (CO2), nitrogen (N2), hydrogen, carbon monoxide (CO), oxygen (O2), sulfides (e.g., hydrogen sulfide or H2S), ammonia, and trace elements like amines, sulfurous compounds, and siloxanes. RNG production from LFG requires advanced treatment and upgrading the biogas via removal of CO2, H2S, siloxanes, N2, and O2 to achieve a high Btu content gas for pipeline injection. Table 7 below summarizes landfill gas constituents, the typical concentration ranges in LFG, and commonly deployed upgrading technologies in use today.

Table 7. Landfill Gas Constituents and Corresponding Upgrading Technologies

LFG Constituent	Typical Concentration Range	Upgrading Technology for Removal
Carbon dioxide, CO2	40-60%	• High-selectivity membrane separation • Pressure swing adsorption (PSA) systems • Water scrubbing systems • Amine scrubbing systems
Hydrogen sulfide, H2S	0-1%	• Solid chemical scavenging • Liquid chemical scavenging • Solvent adsorption • Chemical oxidation-reduction
Siloxanes	<0.1%	• Non-regenerative adsorption • Regenerative adsorption
Nitrogen, N2 Oxygen, O2	2-5% 0.1-1%	• PSA systems • Catalytic removal (O2 only)

To develop the RNG potential from LFG, ICF extracted data from the Landfill Methane Outreach Program (LMOP) administered by the U.S. Environmental Protection Agency (EPA)—which included more than 2,000 landfills. ICF considered only landfills that are either open or were closed post-2000. This constraint was imposed to account for the fact that the phase during which the decomposition of waste in a landfill produces sufficient methane concentrations lasts about 20-25 years, and this is the period during which waste-to-energy projects are most viable.[8] While landfills continue to emit methane for 50 years or more, this constraint limits the potential for the assessment to over-estimate the production from older landfills with a decrease methane

[8] 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

emissions concentration. This constraint reduces the number of candidate landfills to just over 1,500 landfills. The table below includes the number of candidate landfills considered in each Census region.

Table 8. Number of Candidate Landfills by Census Region[9]

Landfill Status	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
Closed (post-2000)	33	16	51	21	54	19	25	24	58
Open	25	79	173	121	221	107	160	162	166

The US EPA's LMOP database shows that there are about 620 operational LFG to energy projects nationwide, however, only 60 (10%) of them produce RNG, and only 52 of those actually inject RNG into the pipeline. Most of the projects capture LFG and combust it in reciprocating engines to make electricity (72%) or have a direct use (18%) for the energy (e.g., thermal use on-site). Moreover, the EPA currently estimates that there are 480 candidate landfills that could capture LFG for use as energy—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 waste-in-place (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. The table below includes LFG to Energy projects and candidate landfills broken down by Census Region.

Table 9. Landfill to Energy Projects and Candidate Landfills by Census Region[10]

LFG to Energy Project Type	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
Electricity	28	64	105	23	101	20	19	18	71
Direct	1	12	26	17	31	6	10	1	5
RNG	1	9	13	5	4	4	19	1	4
Candidate Landfills	8	14	62	46	88	60	95	57	43

ICF developed resource potentials for RNG production at landfills in a low and high scenario, considering the potential at LFG facilities with collection systems in place, without collection systems in place, and at candidate landfills identified by the US EPA.

- In the low scenario, ICF assumed that RNG could be produced at 40% of the LFG facilities that have collection systems in place, 30% of the LFG facilities that do not have collections systems in place, and at 50% of the candidate landfills. Combined, ICF's estimates in the low resource potential scenario represent about 425 of the more than 2,000 landfills included in the US EPA LMOP database.

[9] Based on data from the Landfill Methane Outreach Program at the US EPA (updated February 2019).

[10] Ibid.

- In the high scenario, ICF assumed that RNG could be produced at 65% of the LFG facilities that have collection systems in place, 80% of the LFG facilities that do not have collections systems in place, and at 80% of the candidate landfills. Combined, ICF's estimates in the low resource potential scenario represent about 750 of the more than 2,000 landfills included in the US EPA LMOP database.

To estimate the amount of RNG that could be injected from LFG projects, ICF used outputs from the LandGEM model—which is an automated tool with an MS Excel interface developed by the US EPA to estimate the emissions rates for landfill gas and methane based on user inputs like waste-in-place, facility location (and climate conditions), waste received per year, etc.. The estimated LFG output was estimated on a facility-by-facility basis. About 1,150 facilities report methane content; for the facilities for which no data were reported, ICF assumed the median methane content of 49.6%.

The figures below show the low and high RNG resource potential from landfill gas between 2025 and 2040. The table that follows includes the total annual RNG production potential (in units of tBtu/y) for 2040 in the low, high, and technical resource potential scenarios.

Figure 8. RNG Production Potential from Landfill Gas, Low Resource Potential Scenario, in tBtu/y

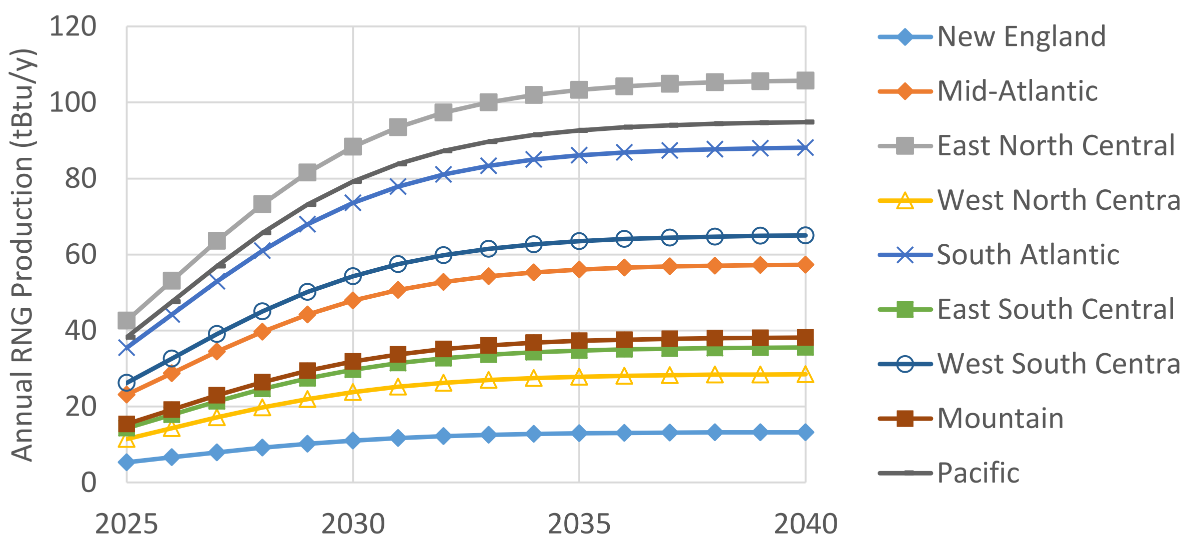


Figure 9. RNG Production Potential from Landfill Gas, High Resource Potential Scenario, in tBtu/y

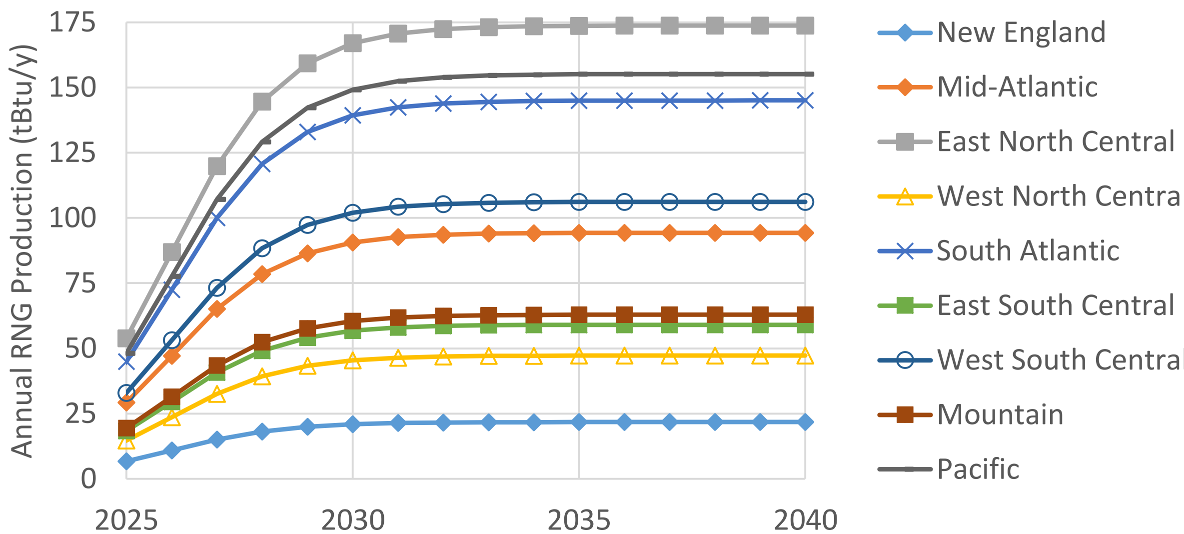


Table 10. Annual RNG Potential from Landfills in 2040, tBtu/y

RNG Potential Scenario	RNG Potential from Landfills, tBtu/y								
	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
Low Resource	12.2	52.2	97.6	27.0	83.4	35.2	60.6	36.2	86.0
High Resource	20.9	89.8	166.8	46.5	141.8	60.0	102.1	61.8	146.8
Technical Resource	32.5	143.4	259.1	70.3	211.7	84.0	154.0	92.0	233.2

ICF estimates that between 528 and 866 tBtu/y of RNG could be produced at the national level by 2040 in the low and high scenarios, respectively from LFG facilities.

Animal Manure

The US EPA lists a variety of benefits associated with the anaerobic digestion of animal manure at farms as an alternative to traditional manure management systems, including but not limited to:[11]

- Diversifying farm revenue: The biogas produced from the digesters has the highest potential value. But digesters can also provide revenue streams via "tipping fees" from non-farm organic waste streams that are diverted to the digesters; organic nutrients from the digestion of animal manure; and displacement of animal bedding or peat moss by using digested solids.
- Conservation of agricultural land: Digesters can help to improve soil health by converting the nutrients in manure to a more accessible form for plants to use and help protect the local water resources by reducing nutrient run-off and destroying pathogens.
- Promoting energy independence: The RNG produced can reduce on-farm energy needs or provide energy via pipeline injection for use in other applications, thereby displacing fossil or geological natural gas.

[11] More information available online at https://www.epa.gov/agstar/benefits-anaerobic-digestion. .

- Bolstering farm-community relationships: Digesters help to reduce odors form livestock manure, improve growth prospects by minimizing potential negative impacts of farm operations on local communities, and help forge connections between farmers and the local community through environmental and energy stewardship.

The main components of anaerobic digestion of manure include manure collection, the digester, effluent storage (e.g., a tank or lagoon), and gas handling equipment. There are a variety of livestock manure processing systems that 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 the plug-flow or mixed plug-flow digesters.

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 United States Department of Agriculture's (USDA) National Agricultural Statistics Service. ICF used information provided from the most recent census year (2017) and extracted total animal populations on a state-by-state basis.

ICF estimated the total amount of animal manure produced based on the animal population, the total wet manure produced per animal, an assumed moisture content, and the energy content of the dried manure. The values in the table below are taken from a California Energy Commission report prepared by the California Biomass Collaborative.[12]

Table 11. Key Parameters to Determine Animal Manure Resource for RNG Production

Animal Type	Total Wet Manure (lb/animal/day)	Moisture Content (% wet basis)	HHV (Btu/lb, dry basis)	Technical Availability Factors
Dairy Cow	140	87	7,308	0.50
Beef Cow	125	88	7,414	0.20
Swine	50	88	7,161	0.20
Poultry, Layer Chickens	10	91	6,839	0.50
Poultry, Broiler Chickens	0.2	75	6,663	0.50
Poultry, Turkeys	0.22	74	6,839	0.50

For the technical resource potential for RNG production, ICF did not account for the technical availability factors included in the table above.

The US EPA AgStar database indicates that there are nearly 250 operational digesters at farms—more than 90% of which produce electricity or use the biogas for cogeneration. Only 5 of the projects (2%) currently inject gas into the pipeline.

[12] 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 12. Summary of AgStar Projects at Farms using AD Systems, by Census Region

AgStar Projects	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
Project Status									
Operational	22	62	69	16	20	5	4	16	34
Construction	2	3	3	7	2	--	--	3	14
Project Type									
Electricity / Cogen	22	57	64	10	19	5	3	15	34
Flared	--	8	10	6	--	--	2	2	
Pipeline	--	--	--	3	1	--	--	--	1
Animal Type									
Dairy	22	55	61	8	6	1	--	11	34
Swine	--	4	2	7	12	1	4	5	--
Poultry	--	1	1	--	2	3	--	--	--
Multiple	--	2	5	1	--	--	--	--	--

ICF developed resource potentials for RNG production from the anaerobic digestion of animal manure in a low and high scenario.

- In the low scenario, ICF assumed that RNG could be produced from 30% of the animal manure, after accounting for the technical availability factor. Generally speaking, this represents the share of animal manure that would be recoverable from the larger farms (e.g., dairy farms with more than 1,000 head of cattle and hog farms with more than 5,000 hogs).
- In the high scenario, ICF assumed that RNG could be produced from 60% of the animal manure, after accounting for the technical availability factor. Generally speaking, this share of the animal manure represents the resources that could be recoverable from the medium to large farms (e.g., dairy farms with more than 500 head of cattle and hog farms with more than 5,000 hogs).

In many cases, anaerobic digesters at dairy farms co-process other substrates (or feedstocks) to boost gas production—the co-digestion of substrates is used to help balance the carbon-to-nitrogen ratio for more favorable anaerobic digestion conditions.[13]

The figures below show the low and high RNG resource potential from animal manure between 2025 and 2040. The table that follows includes the total annual RNG production potential (in units of tBtu/y) for 2040 in the low, high, and technical resource potential scenarios.

[13] US EPA, Increasing Anaerobic Digester Performance with Codigestion, September 2012. Available online: https://www.epa.gov/sites/production/files/2014-12/documents/codigestion.pdf.

Figure 10. RNG Production Potential from Animal Manure, Low Resource Potential Scenario, in tBtu/y

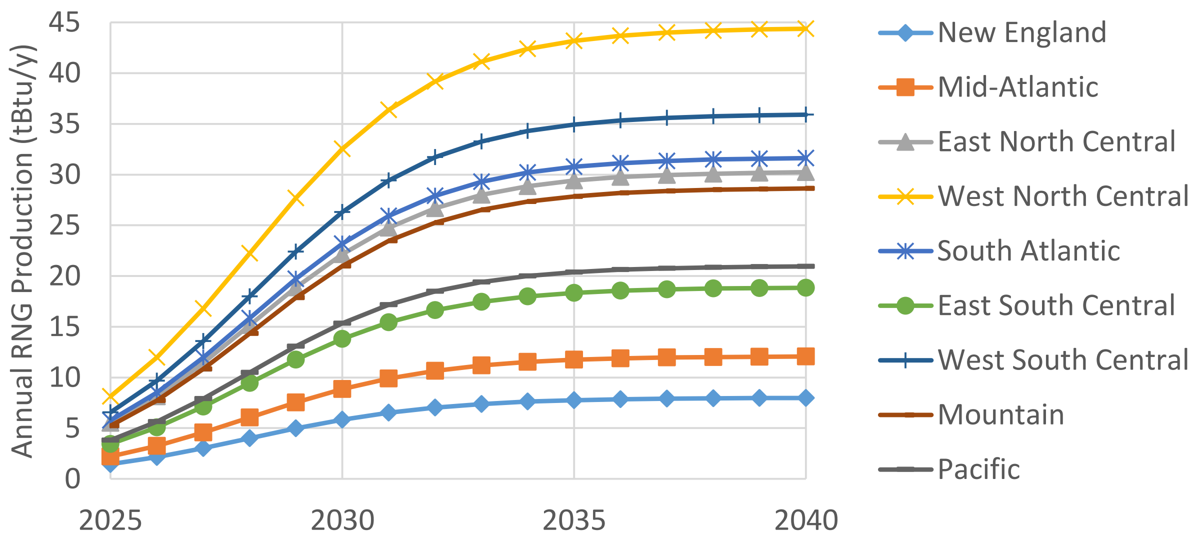


Figure 11. RNG Production Potential from Animal Manure, High Resource Potential Scenario, in tBtu/y

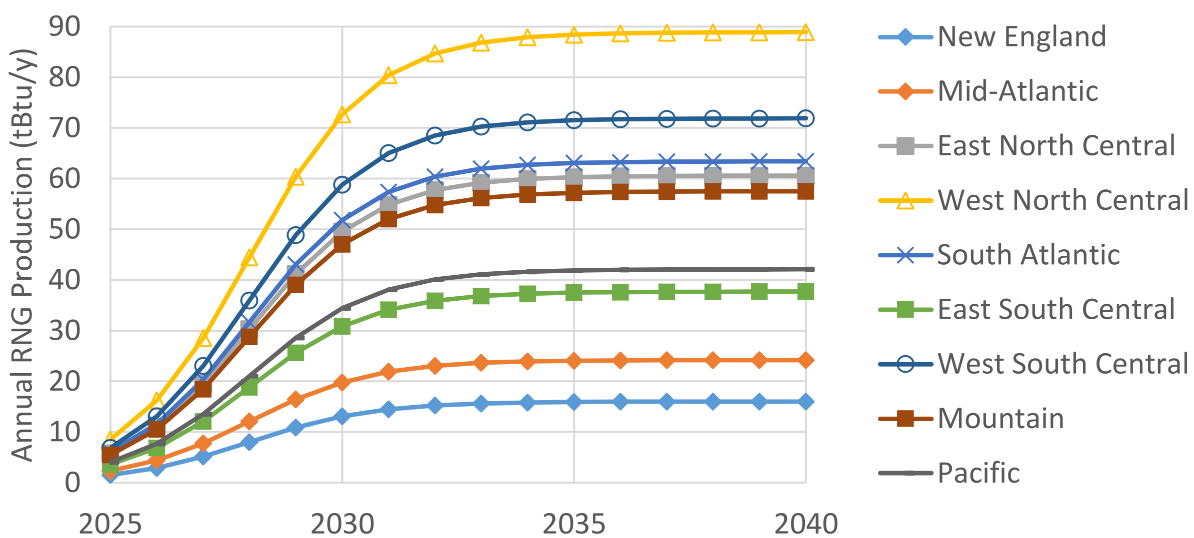


Table 13. Annual RNG Production Potential from Animal Manure in 2040, tBtu/y

RNG Potential Scenario	RNG Potential from Animal Manure, tBtu/y								
	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
Low Resource	8.0	12.1	30.3	44.5	31.7	18.9	36.0	28.7	21.0
High Resource	16.0	24.2	60.6	88.9	63.4	37.7	71.9	57.5	42.1
Technical Resource	88.9	99.3	285.2	602.7	316.5	207.7	453.5	340.5	178.1

ICF estimates that between 231 and 462 tBtu/y of RNG could be produced in the low and high scenarios, respectively from animal manure by 2040.

Water Resource Recovery Facilities

Wastewater is created from residences and commercial or industrial facilities, and it consists primarily of waste liquids and solids from household water usage, from commercial water usage, or from industrial processes. Depending on the architecture of the sewer system and local regulation, it may also contain storm water from roofs, streets, or other runoff areas. The contents of the wastewater may include anything which 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, solid debris such as leaves and branches, etc.

Processing of the influent to a large water resource recovery facility (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 using 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 used for beneficial use with the appropriate capture and conditioning systems put in place.

ICF reviewed more than 14,500 wastewater treatment facilities surveyed as part of the Clean Watersheds Needs Survey (CWNS) conducted in 2012 by the US EPA, an assessment of capital investment needed for wastewater collection and treatment facilities to meet the water quality goals of the Clean Water Act. ICF further distinguished 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. The tables below summarize the key data points from the survey of WRRFs in the United States, broken down by Census Region.

Table 14. Number of WRRFs by Census Region[14]

Facility Size (MGD)	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
<0.02	33	70	169	581	94	46	127	107	32
0.02-0.07	58	255	495	1,125	222	191	362	263	137
0.07-0.18	83	289	607	602	291	224	380	217	145
0.18-1.00	176	555	838	552	569	391	459	308	293
1.01-3.30	109	234	324	160	267	177	178	126	162

[14] Based on data from CNWS 2015.

Facility Size (MGD)	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
3.31-7.25	46	91	122	53	137	68	88	39	78
7.26-34.05	35	67	116	36	112	30	58	36	88
34.05+	5	30	24	9	21	8	15	7	24

Table 15. Total Flow (in MGD) of WRRFs by Census Regions[15]

Facility Size (MGD)	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
<0.02	0	1	2	6	1	0	1	1	0
0.02-0.07	2	10	20	40	9	8	14	10	5
0.07-0.18	9	33	68	66	33	26	42	24	16
0.18-1.00	84	255	380	228	261	170	201	139	135
1.01-3.30	201	440	632	292	511	338	323	238	304
3.31-7.25	231	461	576	259	678	323	439	198	394
7.26-34.05	535	1,009	1,734	569	1,645	424	863	552	1,320
34.05+	494	3,438	3,651	717	1,686	536	1,086	586	2,580

In other words, these tables tell us that despite the more than 14,500 WRRFs nationwide, nearly 45% of the wastewater is being processed at 142 of the facilities, or just 1% of the total WRRFs for which ICF was able to identify data. Furthermore, more than 70% of the wastewater is being processed at just 5% of the facilities.

The table below shows the distribution of the more than 1,250 WRRFs with installed AD systems.

Table 16. WRRFs with Anaerobic Digesters, by Census Regions[16]

	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
AD Facilities	34	231	309	125	133	47	74	82	233

The three tables above illustrate the challenges and opportunities associated with deploying AD systems at WRRFs: Most of the wastewater in the U.S. is treated at a small number of facilities. And of the facilities that already have an AD system installed, they tend to be the larger facilities. However, most of those facilities have AD systems installed that are capturing biogas to produce electricity on-site, rather than for pipeline injection. The database of RNG producing facilities maintained by the Coalition for Renewable Natural Gas indicates that there are 12 operation WRRFs using AD systems to capture and subsequently inject RNG into the pipeline, 5 WRRFs with AD systems under substantial development, and another 5 WRRFs with AD systems under construction.

ICF developed resource potentials for RNG production at WRRFs in a low and high scenario.

[15] Based on data from CNWS 2015.

[16] Based on data from the Water Environment Federation.

- In the low scenario, ICF assumed that AD systems would be deployed at the facilities with larger flow rates (greater than 7.25 MGD), and that presumably some of the systems with AD systems in place would be converted to pipeline injection projects. The underlying assumption is that the economics of RNG production would favor these larger facilities. ICF assumed that RNG could be produced at 30% of the facilities with a capacity greater than 7.25 MGD—this amounts to AD systems with corresponding conditioning and upgrading systems in place to inject RNG into the pipeline at about 200 of the larger sized facilities.
- In the high scenario, ICF assumed that RNG could be produced at 50% of the facilities with a capacity greater than 3.3 MGD. This amounts to AD systems with corresponding conditioning and upgrading systems in place to inject RNG into the pipeline at about 450 of the larger sized facilities, and another 1,000 of the medium-sized facilities. In other words, this is a project deployment trajectory consistent with the current level of deployment of AD systems in place, but with an emphasis on RNG production rather than electricity generation.

To estimate the amount of RNG produced from wastewater at WRRFs, ICF used data reported by the US EPA,[17] a study of WRRFs in New York State,[18] and previous work published by AGF.[19] ICF used an average energy yield of 7.0 MMBtu/MG of wastewater. For the technical resource potential, ICF used all of the wastewater flow reported at the more than 14,500 facilities in the database. The figures below show the low and high resource potential for RNG production from WRRFs between 2025 and 2040. The table that follows includes the total annual RNG production potential (in units of tBtu/y) for 2040 in the low, high, and technical resource potential scenarios.

[17] US EPA, Opportunities for Combined Heat and Power at Wastewater Treatment Facilities, October 2011. Available online here.

[18] 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.

[19] AGF, The Potential for Renewable Gas: Biogas Derived from Biomass Feedstocks and Upgraded to Pipeline Quality, September 2011.

Figure 12. RNG Production Potential from WRRFs, Low Resource Potential Scenario, in tBtu/y

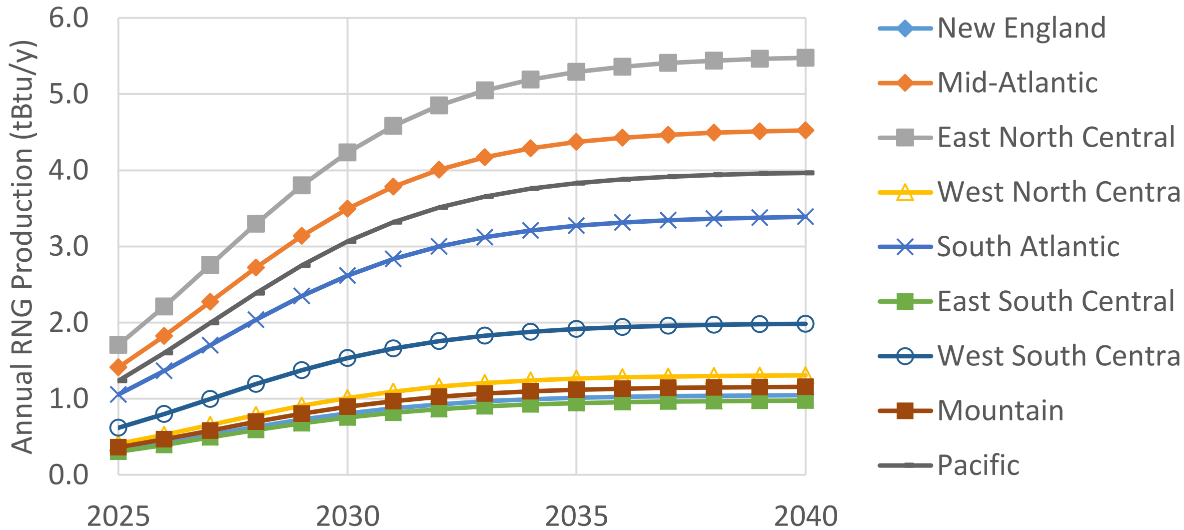


Figure 13. RNG Production Potential from WRRFs, High Resource Potential Scenario, in tBtu/y

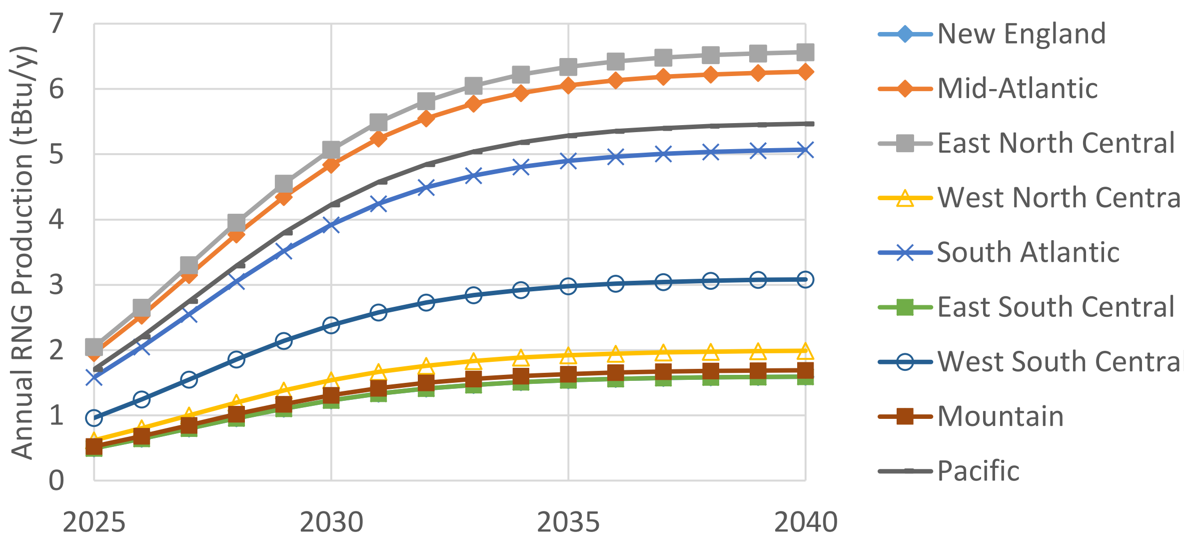


Table 17. Annual RNG Production Potential from WRRFs in 2040, tBtu/y

RNG Potential Scenario	RNG Potential from WRRFs, tBtu/y								
	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
Low Resource	1.1	4.5	5.5	1.3	3.4	1.0	2.0	1.2	4.0
High Resource	1.6	6.3	7.6	2.0	5.1	1.6	3.1	1.7	5.5
Technical Resource	4.0	14.4	18.1	5.6	12.3	4.7	7.6	4.5	12.2

ICF estimates that between 24 and 34 tBtu/y of RNG could be produced in the low and high scenarios, respectively from WRRFs. To achieve this level of RNG production from WRRFs, ICF estimates that 360 and 1,450 facilities would need to install AD systems in the low and high scenarios, respectively.

Food Waste

Food waste is a major component of municipal solid waste (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 our 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.[20] ICF extracted information from the U.S. Department of Energy's (DOE) Bioenergy Knowledge Discovery Framework (KDF), which includes information collected as part of U.S. DOE's Billion-Ton Report (updated in 2016).[21] The Bioenergy KDF includes food waste at price points ranging from $70/ton and $100/ton. ICF assumed a high heating value of 12.04 MMBtu/ton (dry). Note that 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 developed the RNG production potential from food waste in a low and high scenario.

- In the low scenario, ICF assumed that 40% of the food waste available at $70/dry ton would be diverted to AD systems.
- In the high scenario, ICF assumed that 70% of the food waste available at $100/dry ton would be diverted to AD systems.

ICF calculated the technical resource potential for RNG production from food waste in an AD system assuming 100% of the food waste that is currently landfilled is diverted to a processing facility with a digester. The figures below show the low and high RNG resource potential from the anaerobic digestion of food waste between 2025 and 2040. The table that follows includes the total annual RNG production potential (in units of tBtu/y) for 2040 in the low, high, and technical resource potential scenarios.

[20] ICF notes that the diversion of food waste from landfills may limit the *long-term potential* (post-2040) of landfill gas as a viable resource for RNG production. However, for the purposes of this report, and the associated timeframe of the analysis to 2040, ICF used estimates based on existing waste-in-place at landfills, and the corresponding methane production at those landfills. The resource estimates between RNG from landfill gas and food waste do not conflict or overlap; however, ICF notes that successful waste diversion policies would only increase the RNG resource potential and improve the appetite for RNG production from dedicated AD systems processing diverted food waste.

[21] The Billion-Ton Report is a critical national assessment performed by the Department of Energy to calculate the potential supply of biomass in the U.S.. The report finds that the U.S. has the future potential to produce at least one billion dry tons of biomass resources (composed of agricultural, forestry, waste, and algal materials) on an annual basis without adversely affecting the environment.

Figure 14. RNG Production Potential from Food Waste, Low Resource Potential Scenario, in tBtu/y

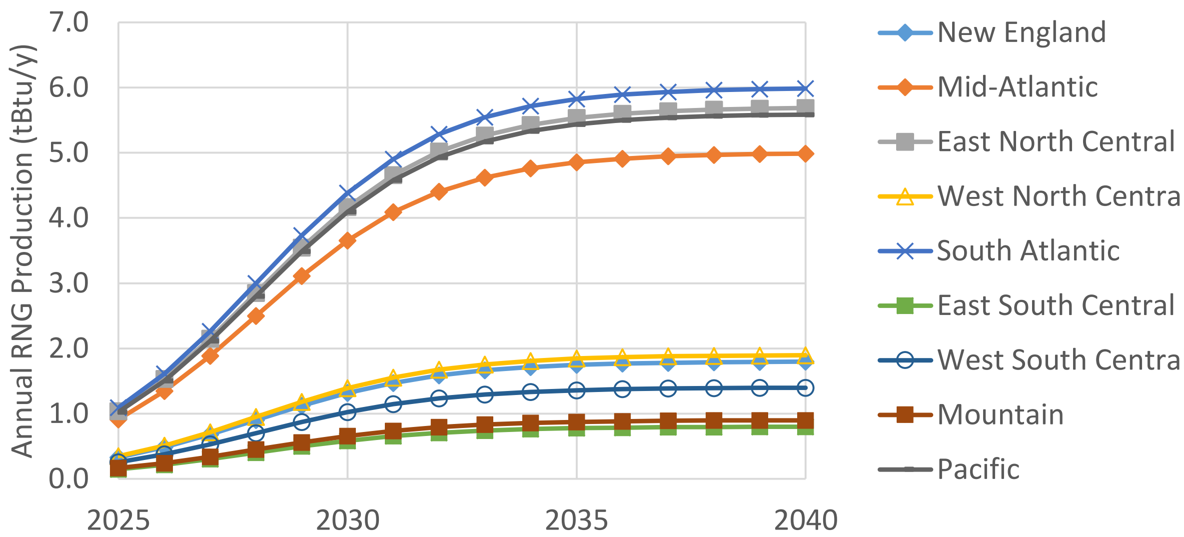


Figure 15. RNG Production Potential from Food Waste, High Resource Potential Scenario, in tBtu/y

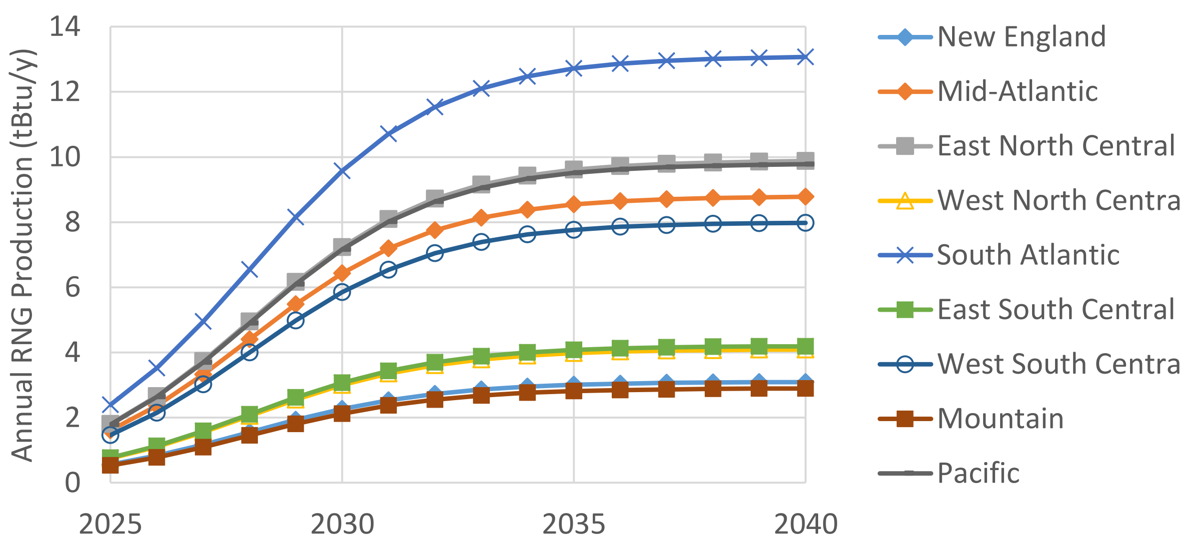


Table 18. Annual RNG Production Potential from Food Waste in 2040, tBtu/y

RNG Potential Scenario	RNG Potential from Food Waste, tBtu/y								
	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
Low Resource	1.8	5.0	5.7	1.9	6.0	0.8	1.4	0.9	5.6
High Resource	3.1	8.8	9.9	4.1	13.1	4.2	8.0	2.9	9.8
Technical Resource	17.7	50.1	56.6	23.5	74.5	23.6	45.5	16.5	56.0

ICF estimates that between 29 and 64 tBtu/y of RNG could be produced by 2040 at the national level in the low and high scenarios, respectively from food waste diverted to anaerobic digesters.

RNG: Thermal Gasification of Biogenic or Renewable Resources

Biomass like agricultural residues, forestry and forest produce residues, and energy crops have high energy content and are ideal candidates for thermal gasification. The thermal gasification of biomass to produce RNG occurs over a series of steps. Thermal gasification typically requires some pre-processing of the feedstock. The gasification process first generates synthesis gas (or syngas), consisting of hydrogen and carbon monoxide. Biomass gasification technology has been commercialized for nearly a decade; however, the gasification process 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 thermal gasification of biomass. For instance, in 1998, Tom Reed[22] concluded that after "two decades" of experience in biomass gasification, "'tars' can be considered the Achilles heel of biomass gasification."

Over the last several years, however, several commercialized technologies have been deployed to increase syngas quantity and prevent the fouling of other equipment by removing the residual tar before methanation. There are a handful of technology providers in this space including Haldor Topsoe's tar reforming catalyst. Frontline Bioenergy takes a slightly different approach and has patented a process producing tar free syngas (referred to as TarFreeGas™). The syngas is further upgraded via filtration (to remove remaining excess dust generated during gasification), and other purification processes to remove potential contaminants like hydrogen sulfide, and carbon dioxide. The upgraded syngas is then methanated and dried prior to pipeline injection.

ICF notes that biomass, particularly agricultural residues, are often added to anaerobic digesters to increase gas production (by improving carbon-to-nitrogen ratios, especially in animal manure digesters). It is conceivable that some of the feedstocks considered here could be used in anaerobic digesters. For the sake of simplicity, ICF did not consider any multi-feedstock applications in our assessment; however, it is important to recognize that the RNG production market will continue to include mixed feedstock processing in a manner that is cost-effective.

Agricultural Residues

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

ICF extracted information from the U.S. DOE Bioenergy KDF including the following agricultural residues: wheat straw, corn stover, sorghum stubble, oats straw, barley straw, citrus residues, noncitrus residues, tree nut residues, sugarcane trash, cotton gin trash, cotton residue, rice hulls, sugarcane bagasse, and rice straw. ICF extracted data from the Bioenergy KDF at three price points: $30/ton, $50/ton and $100/ton. The table below lists the energy content on a high heating value (HHV) basis for the various agricultural residues included in the analysis—these are based on values reported by the California Biomass Collaborative. To estimate the RNG production potential, ICF assumed a 65% efficiency for thermal gasification systems.[23]

[22] NREL, Biomass Gasifier "Tars": Their Nature, Formation, and Conversion, November 1998, NREL/TP-570-25357. Available online at https://www.nrel.gov/docs/fy99osti/25357.pdf.

[23] The 2011 AGF Report on RNG report indicated a range of thermal gasification efficiencies in the range of 60% to 70%, depending upon the configuration and process conditions. And the report authors also used a conversion

Table 19. Heating Values for Agricultural Residues

MSW Component	Btu/lb, dry	MMBtu/ton, dry
Wheat straw	7,527	15.054
Corn stover	7,587	15.174
Sorghum stubble	6,620	13.24
Oats straw	7,308	14.616
Barley straw	7,441	14.882
Citrus residues	8,597	17.194
Noncitrus residues	7,738	15.476
Tree nut residues	8,597	17.194
Sugarcane trash	7,738	15.476
Cotton gin trash	7,058	14.116
Cotton residue	7,849	15.698
Rice hulls	6,998	13.996
Sugarcane bagasse	7,738	15.476
Rice straw	6,998	13.996

ICF developed the RNG production potential from agricultural residues in a low and high scenario.

- In the low scenario, ICF assumed that 20% of the agricultural residues available at $50/dry ton would be diverted to thermal gasification systems.
- In the high scenario, ICF assumed that 50% of the agricultural residues available at $50/dry ton would be diverted to thermal gasification systems.

ICF calculated the technical resource potential for RNG production from agricultural residues assuming that all of the material available at $100/ton could be gasified at 100% efficiency. The figures below show the low and high RNG resource potential from the thermal gasification of agricultural residues between 2025 and 2040. The table that follows includes the total annual RNG production potential (in units of tBtu/y) for 2040 in the low, high, and technical resource potential scenarios.

efficiency of 65%. More recently, GTI estimated the potential for RNG from the thermal gasification of wood waste in California (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), and assumed a conversion efficiency of 60%.

Figure 16. RNG Production Potential from Agricultural Residue, Low Resource Potential Scenario, in tBtu/y

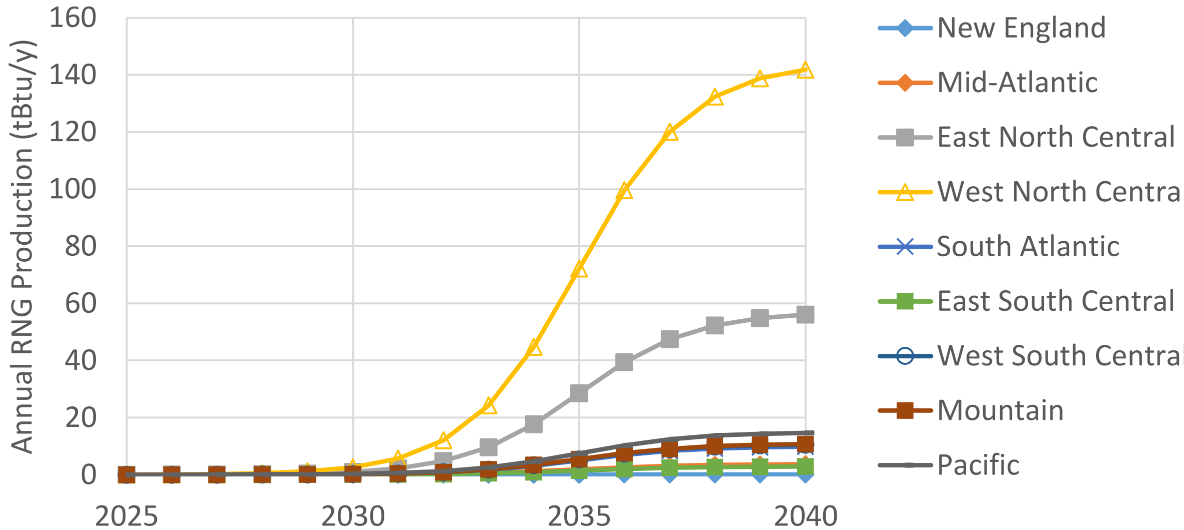


Figure 17. RNG Production Potential from Agricultural Residue, High Resource Potential Scenario, in tBtu/y

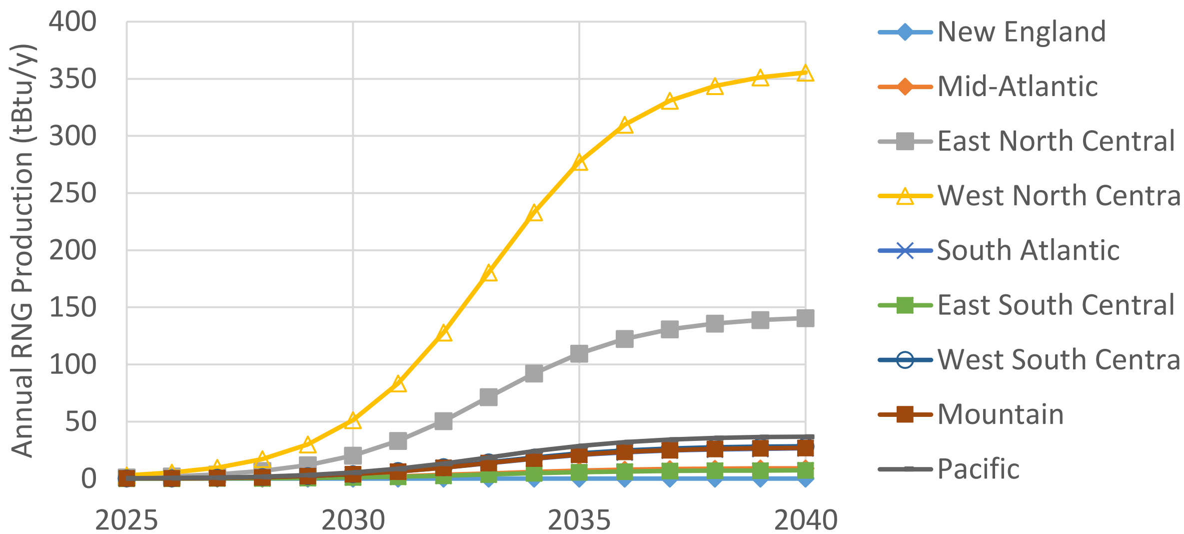


Table 20. Annual RNG Production Potential from Agricultural Residues in 2040, tBtu/y

RNG Potential Scenario	RNG Potential from Agricultural Residue, tBtu/y								
	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
Low Resource	0.1	0.5	0.3	19.5	3.2	0.1	1.0	1.8	12.0
High Resource	0.1	9.2	142.6	361.0	26.9	7.3	28.8	27.3	37.3
Technical Resource	0.3	42.1	623.8	1,405.1	93.8	38.7	123.3	115.1	126.3

ICF estimates that between 255 and 641 tBtu/y of RNG could be produced by 2040 at the national level in the low and high scenarios, respectively from the thermal gasification of agricultural residues.

Forestry and Forest Product Residues

Biomass generated from logging, forest and fire management activities, and milling. Inclusive of 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 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 the U.S. DOE Billion-Ton Update. The updated DOE Billion-Ton study was altered to include additional sustainability criteria. Some of the changes included: [24]

- Alterations to the biomass retention levels by slope class (e.g., slopes with between 40% and 80% grade included 40% biomass left on-site, compared to the standard 30%).
- Removal of 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., stream management zones), and sites requiring cable systems.
- The assumptions only include thinnings for over-stocked stands and didn't include removals greater than the anticipated forest growth in a state.
- No road building greater than 0.5 miles.

These additional sustainability criteria provide a more realistic assessment of available forestland than other studies. ICF extracted information from the U.S. 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 extracted data from the Bioenergy KDF at three price points: $30/ton, $60/ton, and $100/ton. The table below lists the energy content on a 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 21. Heating Values for Forestry and Forest Product Residues

Forestry and Forest Product	Btu/lb, dry	MMBtu/ton, dry
Other forest residue	8,597	17.19
Other forest thinnings	9,027	18.05
Primary mill residue	8,597	17.19
Secondary mill residue	8,597	17.19
Mixed wood, residue	6,500	13.00
Hardwood, lowland, residue		
Hardwood, upland, residue		
Softwood, natural, residue		
Softwood, planted, residue		

[24] Bryce Stokes, Department of Energy, "2011 Billion-Ton Update – Assumptions and Implications Involving Forest Resources," September 29, 2011, http://web.ornl.gov/sci/ees/cbes/workshops/Stokes_B.pdf.

ICF developed the RNG production potential from forest residues in a low and high scenario.

- In the low scenario, ICF assumed that 30% of the forest and forestry product residues available up to $30/dry ton would be diverted to thermal gasification systems.
- In the high scenario, ICF assumed that 60% of the forest and forestry product residues available up to $60/dry ton would be diverted to thermal gasification systems.

ICF calculated the technical resource potential for RNG production from forest and forestry product residues assuming that all of the material available at $100/ton could be gasified at 100% efficiency. The figures below show the low and high RNG resource potential from the thermal gasification of forestry and forest product residues between 2025 and 2040. The table that follows includes the total annual RNG production potential (in units of tBtu/y) for 2040 in the low, high, and technical resource potential scenarios.

Figure 18. RNG Production Potential from Forestry and Forest Product Residues, Low Resource Potential Scenario, in tBtu/y

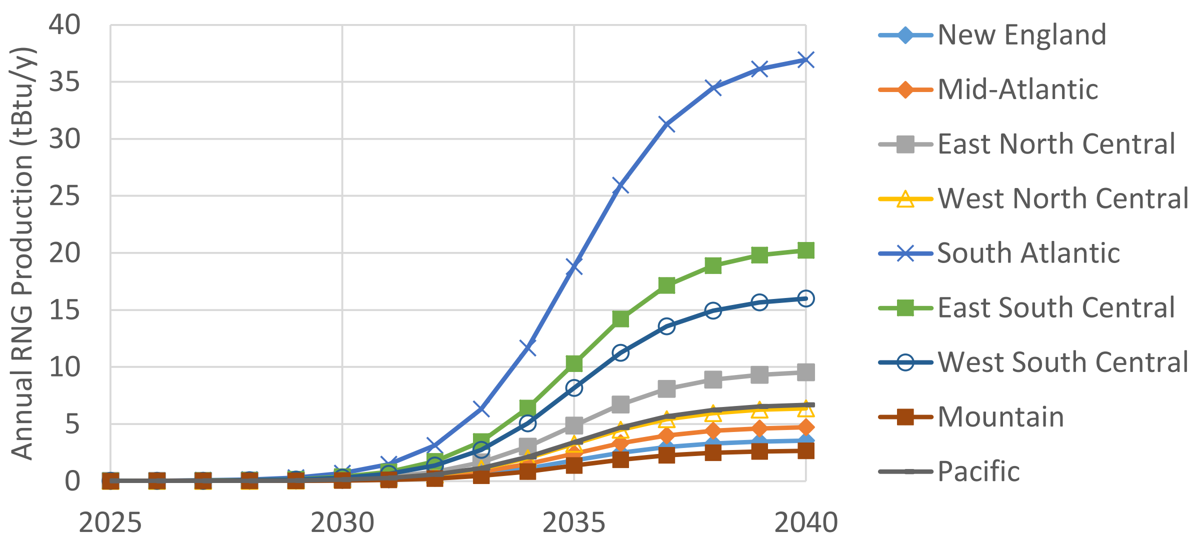


Figure 19. RNG Production Potential from Forestry and Forest Product Residues, High Resource Potential Scenario, in tBtu/y

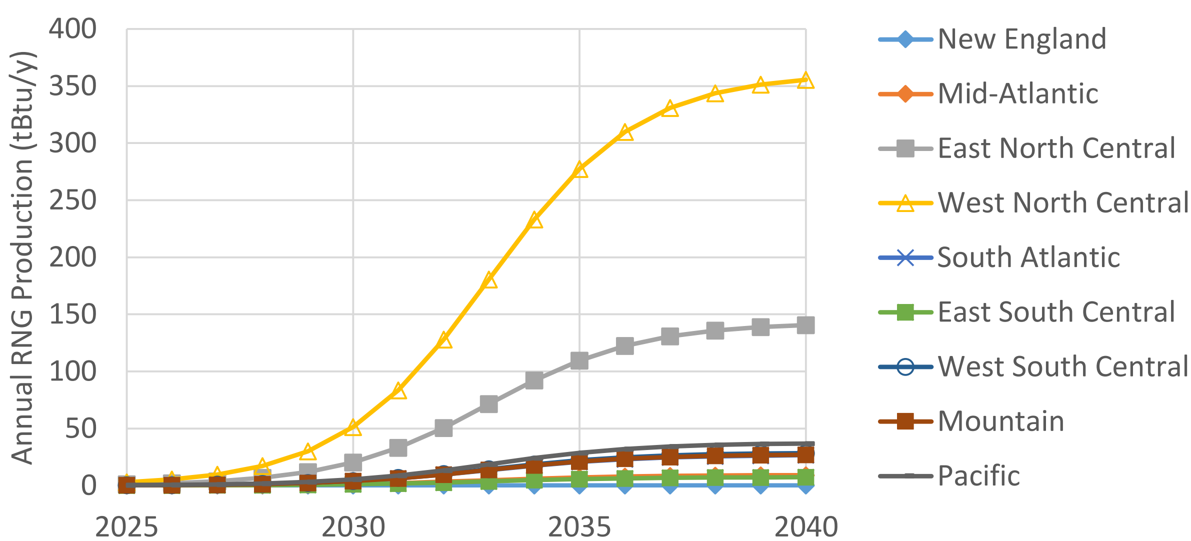


Table 22. Annual RNG Production Potential from Forestry and Forest Product Residues, tBtu/y

RNG Potential Scenario	RNG Potential from Forestry and Forest Product Residues, tBtu/y								
	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
Low Resource	3.6	4.8	9.7	6.5	37.6	20.6	16.3	2.7	6.8
High Resource	7.3	9.7	19.3	13.0	75.2	41.3	37.1	19.3	13.6
Technical Resource	18.6	24.9	49.5	33.4	192.9	105.8	106.7	85.5	34.7

ICF estimates that between 109 and 236 tBtu/y of RNG could be produced by 2040 at the national level in the low and high scenarios, respectively from the thermal gasification of forest and forestry product residues.

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 extracted data from the Bioenergy KDF at three price points: $50/ton, $70/ton and $100/ton. The table below lists the energy content on a HHV basis for the various energy crops included in the analysis. To estimate the RNG production potential, ICF assumed a 65% efficiency for thermal gasification systems.

Table 23. Heating Values for Energy Crops

Energy Crop	Btu/lb, dry	MMBtu/ton, dry
Willow	8,550	17.10
Poplar	7,775	15.55
Switchgrass	7,929	15.86
Miscanthus	7,900	15.80
Biomass sorghum	7,240	14.48
Pine	6,210	12.42
Eucalyptus	6,185	12.37
Energy cane	7,900	15.80

ICF developed the RNG production potential from energy crops in a low and high scenario.

- In the low scenario, ICF assumed that 50% of the energy crops available at $50/dry ton would be diverted to thermal gasification systems.
- In the high scenario, ICF assumed that 50% of the energy crops available at $70/dry ton would be diverted to thermal gasification systems.

ICF calculated the technical resource potential for RNG production from energy crops assuming that all of the material available at $100/ton could be gasified at 100% efficiency. The figures below show the low and high RNG resource potential from the thermal gasification of energy crops between 2025 and 2040. The table that follows includes the total annual RNG production potential (in units of tBtu/y) for 2040 in the low, high, and technical resource potential scenarios.

Figure 20. RNG Production Potential from Energy Crops, Low Resource Potential Scenario, in tBtu/y

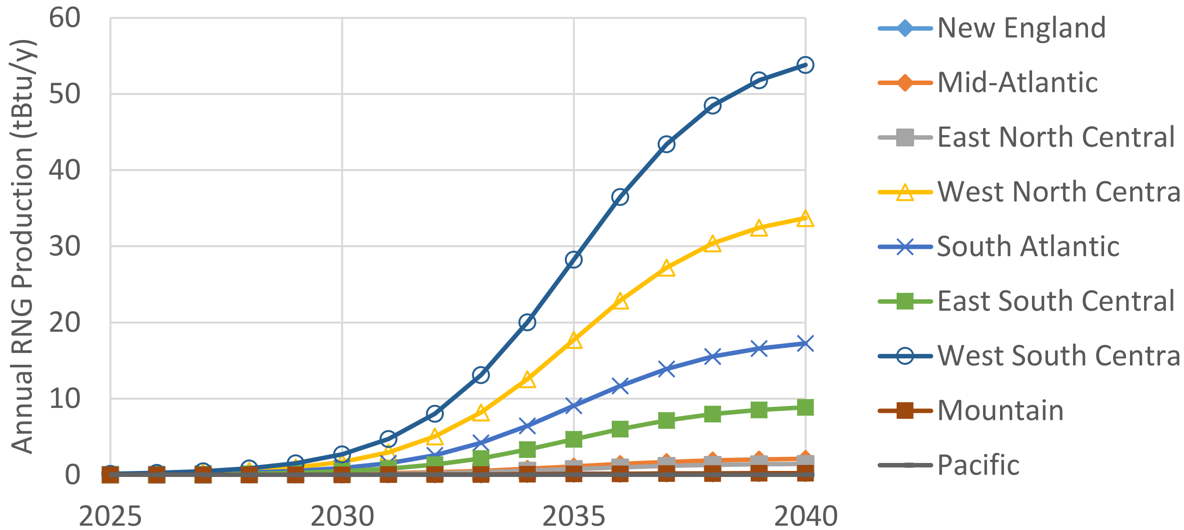


Figure 21. RNG Production Potential from Energy Crops, High Resource Potential Scenario, in tBtu/y

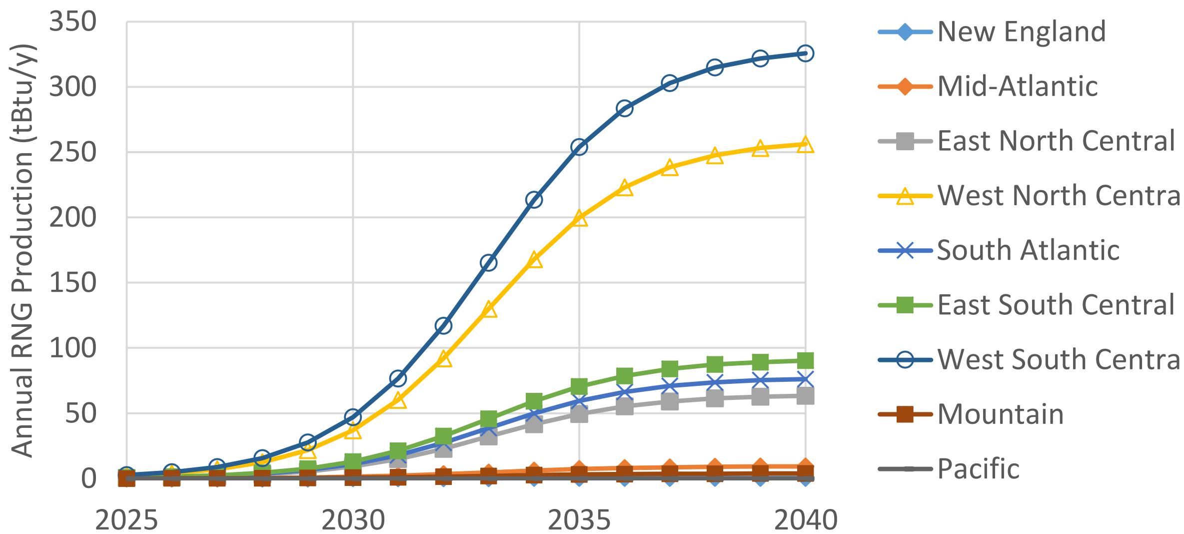


Table 24. Annual RNG Production Potential from Energy Crops, tBtu/y

RNG Potential Scenario	RNG Potential from Energy Crops, tBtu/y								
	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
Low Resource	0.2	2.2	1.5	35.4	18.1	9.3	56.5	0.2	0.0
High Resource	0.5	9.4	64.4	260.0	77.3	91.6	330.5	3.9	0.0
Technical Resource	3.0	84.3	872.5	1,508.1	357.1	460.8	1,266.4	48.7	0.0

ICF estimates that between 123 and 838 tBtu/y of RNG could be produced by 2040 at the national level in the low and high scenarios, respectively from the thermal gasification of forest and forestry product residues.

Renewable gas from MSW

Municipal solid waste (MSW) represents the trash and various items that household, commercial, and industrial consumers throw away—including materials such as glass, construction and demolition (C&D) debris, food waste, paper and paperboard, plastics, rubber and leather, textiles, wood, and yard trimmings. About 25% of MSW is currently recycled, 9% is composted, and 13% is combusted for energy recovery. And the roughly 50% balance of MSW is landfilled.

ICF limited our consideration to the potential for utilizing MSW that would otherwise be landfilled as a feedstock for thermal gasification; this excludes MSW that is recycled or directed to waste-to-energy facilities. ICF also excluded food waste from consideration in this sub-section, and opted to consider that feedstock as a separate resource for AD systems.[25] ICF extracted information from the U.S. DOE Bioenergy KDF, which includes information collected as part of U.S. DOE's Billion-Ton Report (updated in 2016). The Bioenergy KDF includes the following waste residues: C&D debris, paper and paperboard, plastics, rubber and leather, textiles, wood, yard trimmings, and other. ICF extracted data from the Bioenergy KDF at two price points: $30/ton and $100/ton. The table below lists the energy content on a HHV basis for the various components of MSW. To estimate the RNG production potential, ICF assumed a 65% efficiency for thermal gasification systems.

Table 25. Heating Values for MSW Components

MSW Component	Btu/lb, dry	MMBtu/ton, dry
C&D waste	6,788	13.58
Other	5,600	11.20
Paper and paperboard	7,642	15.28
Plastics	19,200	38.40
Rubber and leather	11,300	22.60
Textiles	8,000	16.00
MSW wood	8,304	16.61
Yard trimmings	6,448	12.90

ICF developed the RNG production potential from MSW in a low and high scenario.

- In the low scenario, ICF assumed that 30% of the non-biogenic fraction of MSW available at $30/dry ton from the Bioenergy KDF for relevant waste residues in MSW. ICF notes that at the price of $30/ton, the DOE reports no MSW wood or yard trimmings.
- In the high scenario, ICF assumed that 60% of the non-biogenic fraction of MSW available at $100/dry ton from the Bioenergy KDF for the CD waste, other, paper and paperboard, plastics, rubber and leather, and textiles waste could be gasified; and that 75% of the MSW wood and yard trimmings could be gasified.

[25] ICF notes that because the assessment of thermal gasification is limited to the non-biogenic fraction of MSW, the consideration of this material being diverted from landfills has no material impact on estimated RNG production potential from landfills.

ICF calculated the technical resource potential from RNG production from MSW assuming that all of the material that is currently landfilled for each MSW component could be gasified at 100% efficiency. The figures below show the low and high RNG resource potential from the thermal gasification of the non-biogenic fraction of MSW between 2025 and 2040. The table that follows includes the total annual RNG production potential (in units of tBtu/y) for 2040 in the low, high, and technical resource potential scenarios.

Figure 22. RNG Production Potential from Non-Biogenic MSW, Low Resource Potential Scenario, in tBtu/y

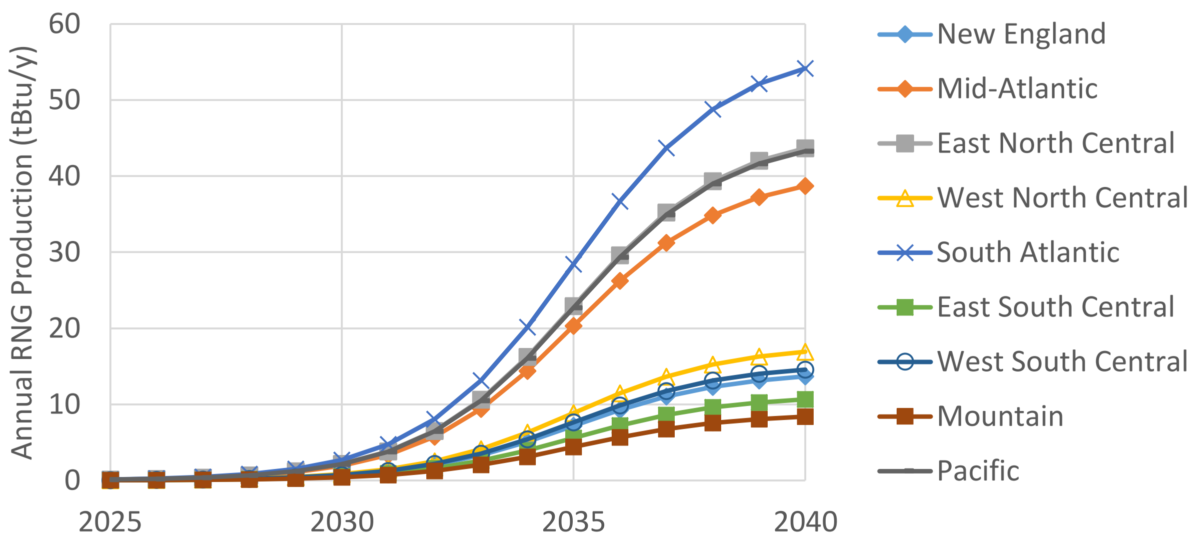


Figure 23. RNG Production Potential from Non-Biogenic MSW, High Resource Potential Scenario, in tBtu/y

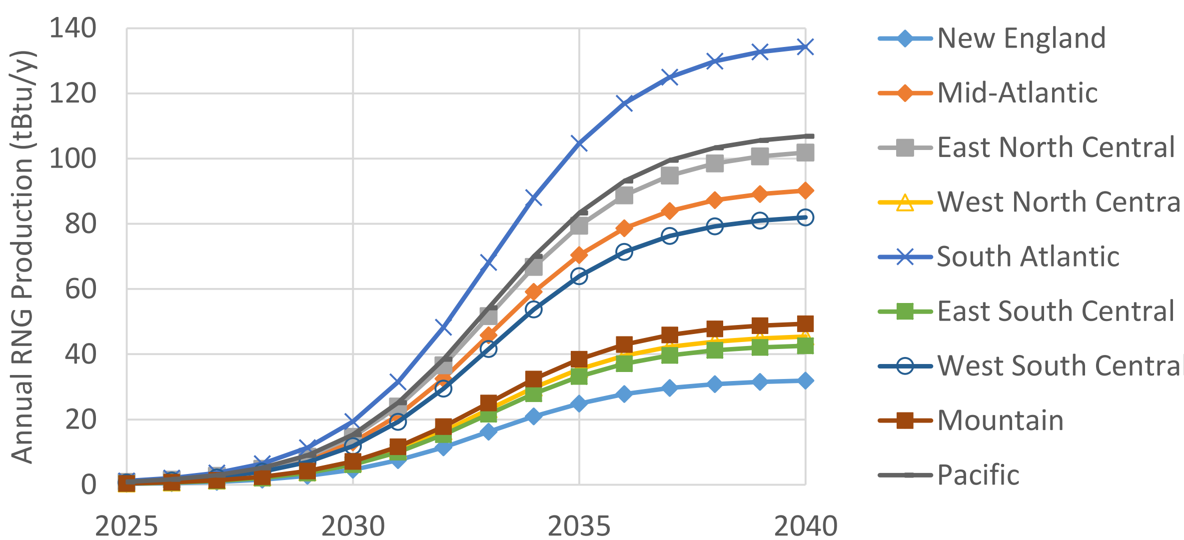


Table 26. Annual RNG Production Potential from MSW, tBtu/y

RNG Potential Scenario	RNG Potential from MSW, tBtu/y								
	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific

Low Resource	14.4	40.6	45.9	17.7	56.9	11.2	15.3	8.8	45.4
High Resource	32.4	91.6	103.4	46.1	136.3	43.2	83.2	50.1	108.5
Technical Resource	81.1	229.6	259.2	115.5	341.6	108.4	208.5	125.6	271.9

ICF estimates that between 256 and 695 tBtu/y of RNG could be produced by 2040 at the national level in the low and high scenarios, respectively from the non-biogenic fraction of MSW via thermal gasification.

RNG from P2G/Methanation

Power-to-gas (P2G) is a form of energy technology that converts electricity to a gaseous fuel. Electricity is used to split water into hydrogen and oxygen, and the hydrogen can be further processed to produce methane when combined with a source of carbon dioxide. If the electricity is sourced from renewable resources, such as wind and solar, then the resulting fuels are carbon neutral. The key process in P2G is the production of hydrogen from renewably generated electricity by means of electrolysis. This hydrogen conversion method is not new, and there are three electrolysis technologies with different efficiencies and in different stages of development and implementation:

- Alkaline electrolysis;
- Proton exchange membrane electrolysis; and
- Solid oxide electrolysis.

The hydrogen produced from P2G is a highly flexible energy product that can be used in multiple ways. It can be:

- Stored as hydrogen and used to generate electricity at a later time using fuel cells or conventional generating technologies.
- Injected as hydrogen into the natural gas system, where it augments the natural gas supply.
- Converted to methane and injected into the natural gas system.

The last option, methanation, involves the combination of hydrogen with carbon dioxide (CO2), and converting the two gases into methane. The methane produced is RNG, and is a clean alternative to conventional fossil natural gas, as it can displace fossil natural gas for combustion in buildings, residences, vehicles and electricity generation. Methanation avoids the cost and inefficiency associated with hydrogen storage and creates more flexibility in the end use through the natural gas system. The P2G RNG conversion process can also be coordinated with conventional biomass-based RNG production by using the surplus CO2 in biogas to produce the methane, creating a productive use for the CO2.

A critical advantage of P2G is that the RNG produced is a highly flexible and interchangeable carbon neutral fuel. With a storage and infrastructure system already established, RNG from P2G can be produced and stored over the long term, allowing for deployment during peak demand periods in the energy system. RNG from P2G also utilizes existing natural gas transmission and distribution infrastructure, which is highly reliable and efficient, and in many cases already paid for.

The flexibility of hydrogen provides advantages beyond as an input to methanation for RNG. Hydrogen can be used in place of natural gas in many applications, and hydrogen can be mixed directly with natural gas in pipeline systems, although there are physical limits to the level of hydrogen blending in natural gas pipeline systems.[26] In addition, currently most commercially produced hydrogen is derived from conventional natural gas and does not have the environmental benefits of carbon neutral hydrogen produced from P2G.

Whether hydrogen or methane is the final product, P2G offers the potential to produce carbon neutral fuels from sustainable resources and leverage existing natural gas infrastructure for long-term and large-scale storage. Competing electric energy storage options, including batteries and pumped hydro storage, are expensive as a long-term energy storage option, and can be more expensive than P2G storage. P2G also offers other benefits, such as a fully dispatchable load capable of supplying grid balancing or ancillary services.

ICF estimated the potential for P2G to contribute towards RNG production over a series of steps. Firstly, ICF utilized our Integrated Planning Model (IPM®), which provides true integration of wholesale power, system reliability, environmental constraints, fuel choice, transmission, capacity expansion, and all key operational elements of generators on the power grid in a linear optimization framework. The model utilizes a Windows™-based database platform and interface that captures a detailed representation of every electric boiler and generator in the power market being modeled. The fundamental logic behind the model determines the least-cost means of meeting electric generation energy and capacity requirements while complying with specified constraints, including air pollution regulations, transmission constraints, and plant-specific operational constraints.

ICF used the IPM platform to develop a supply-cost curve for renewable electricity, starting in 2025 and going out to 2040. We did this over a series of steps. Firstly, the model was constrained by all finalized and on-the-books state-level RPS and Clean Energy Standard (CES) policies and regional carbon markets. The model does not explicitly capture renewable targets announced by municipalities and corporate actors. The RPS demand modeled represents a *floor* on incremental renewable demand, since the model conducts capacity expansion based on relative economics–to the extent that renewable energy is cost competitive relative to other technology types, the model will choose to build renewable energy even in excess of modeled targets. The table below shows the share of generation represented by renewable resource for each region (note that the regions in IPM are distinguished by independent system operator (ISO), regional transmission organization (RTO), reliability council, etc. and are not consistent with the US Census Regions that have been employed elsewhere in the study). The table also includes the share of electricity generation that is attributable to solar and wind.

P2G and Curtailment

P2G discussions often focus on the role and scale of excess (curtailed) renewable electricity as the source for hydrogen and RNG production.

Renewable electricity generation is generally curtailed as a result of system-wide oversupply and local transmission constraints.

The concept is simple: P2G systems could use curtailed renewable electricity generation, and reduce the costs of operating the electrolyzer. This would help to maximize renewable electricity generation, simply by using hydrogen or methane as the renewable energy carrier instead of electrons.

The issue of curtailed renewable electricity, however, is a complicated one. A detailed analysis of expected curtailment rates under increasingly stringent RPS programs was beyond the scope of this report. Instead, we acknowledge the importance of developing and deploying P2G systems to use curtailed electricity in the near term as a transitional

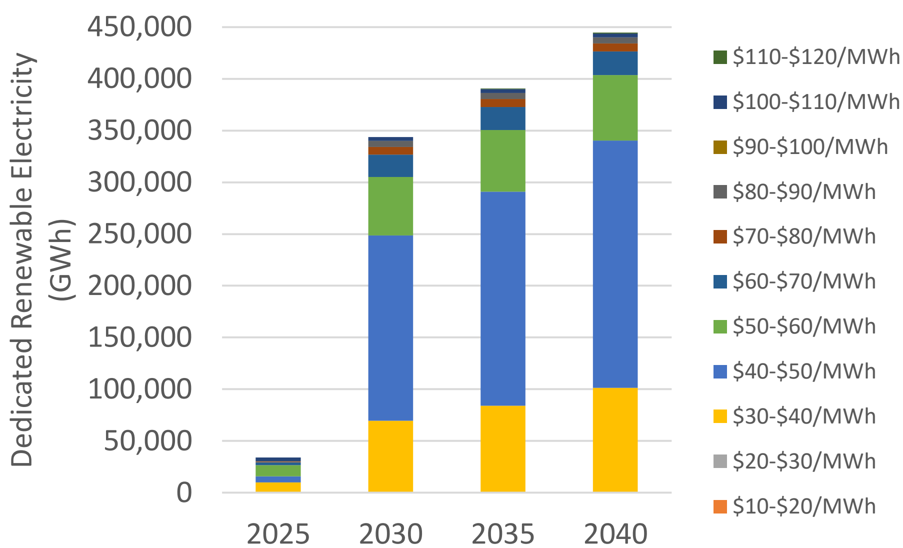
[26] For the purposes of this report, ICF did not assume any hydrogen blending into natural gas pipeline systems.

Table 27. Renewable Share of Electricity Generation in RPS-Compliant Run using IPM

Region	Renewable Share: Electricity Generation			Renewable Share: Solar and Wind		
	2030	2035	2040	2030	2035	2040
US	27%	28%	29%	20%	20%	21%
Non CA- WECC	45%	45%	47%	19%	20%	22%
CAISO	70%	69%	73%	49%	49%	56%
SPP	46%	45%	44%	42%	41%	40%
MISO	28%	29%	31%	24%	25%	25%
SERC	8%	8%	10%	4%	4%	4%
ERCOT	30%	27%	25%	29%	27%	25%
ISONE	44%	47%	49%	30%	34%	36%
NYISO	50%	51%	60%	29%	31%	39%
PJM	13%	14%	14%	11%	12%	12%
FRCC	12%	12%	12%	11%	11%	11%

In the last step of the analysis using the IPM platform, ICF made a simple calculation: We developed a supply-cost curve for renewable electricity generation by extracting the total consumption of renewable electricity (in GWh) by region in 2025, 2030, 2035, and 2040, assuming all RPS and CES policies are achieved on time. ICF then determined what the corresponding levelized cost of energy (LCOE) in $10/MWh increments up to $110/MWh would be to deploy the same number of generating assets to produce the same amount of renewable electricity. ICF used those estimates, as shown in the figure below, to develop an outlook for P2G using dedicated renewable electricity generation.

Figure 24. Supply-Cost Curve for Dedicated Renewable Electricity for P2G Systems, 2025-2040

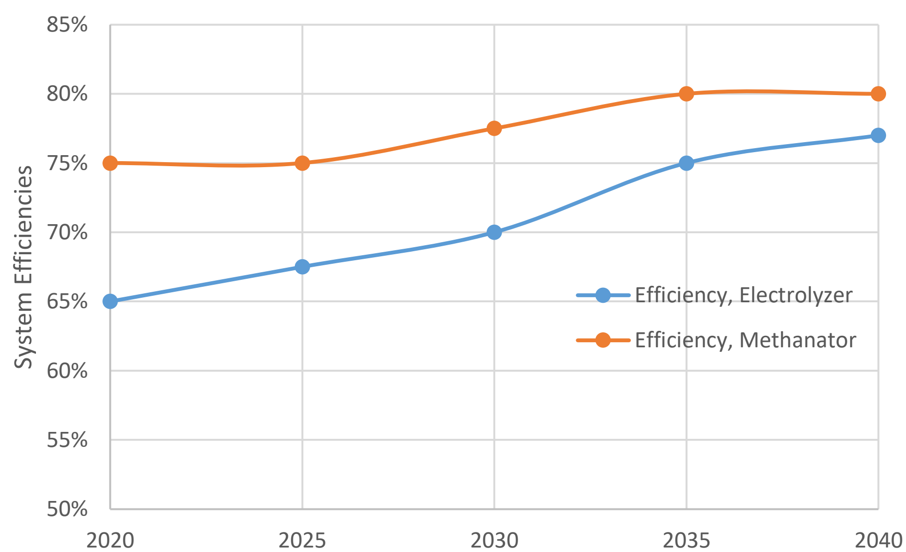


ICF determined how much hydrogen and methane could be produced using P2G / methanation systems based on the supply-cost curve constructed for dedicated renewable electricity generation. We assumed a capacity factor ranging from 50% to 80% for dedicated renewable electricity generation. The energy price in each scenario was based on the LCOE supply curve for renewable electricity generation.

ICF limited our considerations for the low resource potential for RNG derived from P2G and methanation to the curtailed renewable electricity generation available and dedicated renewable electricity generation that is estimated to be available at a LCOE less than $50/MWh. In the high resource potential scenario, we included curtailed renewable electricity generation and dedicated renewable electricity generation that is estimated to be available at a LCOE less than $60/MWh.

ICF assumed that all of the renewable electricity would be available to an electrolyzer to produce hydrogen. Furthermore, ICF assumed the co-location of a methanation unit. The figure below includes the assumed conversion efficiencies for hydrogen production from an electrolyzer (blue) and for the methanation reaction to produce RNG for injection (orange).

Figure 25. Assumed Efficiency for Electrolysis and Methanation, 2020-2040



These assumptions yield the resource potential listed in Table 28 below; which also includes the hydrogen produced in the first step using P2G. The low and the high resource potential estimates are presented assuming capacity factors of 5% and 10% for systems using curtailed electricity and capacity factors of 50% and 80% for systems using dedicated renewable electricity generation.

Table 28. Annual H_2 and RNG Production (in tBtu /y) from P2G using Dedicated Renewable Electricity Generation, 2025-2040

Resource: Dedicated RE	Capacity Factor	2025	2030	2035	2040
Low	50%	11.5	297.1	372.2	447.1
	80%	18.4	475.3	595.6	715.4
High	50%	11.5	364.6	448.7	530.2
	80%	18.4	583.4	718.0	848.3
Max	95%	93.2	935.7	1,064.0	1,210.5
Low	50%	8.6	230.2	297.8	357.7
	80%	13.8	368.4	476.5	572.3
High	50%	8.6	282.5	359.0	424.1
	80%	13.8	452.1	574.4	678.7
Max	95%	74.5	748.5	851.2	968.4

Greenhouse Gas Emissions of RNG

GHG Accounting Framework and Methodology

GHG emission accounting for a given source of emissions relies on the application of an *emission factor* to *activity data*. In the example below, we use the *emission factor* for fossil or geological natural gas to determine the annual GHG emissions associated with an average household's natural gas consumption (the *activity data*) using data from the Environmental Protection Agency (EPA)[27] and the American Gas Association (AGA):[28]

$EmissionFactor\_NG\ \left[\frac{kg\ CO_2e}{MMBtu}\right] \times ActivityData\ \left[\frac{MMBtu}{house}\right] = GHG\_Emissions\ \left[\frac{kg\ CO_2e}{house}\right]$, calculated as:

$$53.11\ \frac{kg\ CO_2e}{MMBtu} \times 63.5\ \frac{MMBtu}{house} = 3{,}372\ \frac{kg\ CO_2e}{house}$$

RNG represents a valuable renewable energy source with a low or net negative emissions factor depending on the feedstock and the accounting framework. The GHG emission accounting method and scope employed can have a significant impact on how GHG emission factors for RNG are reported and estimated.

GHG emissions accounting becomes complex when an assessment scope includes a diverse set of sources. This is most often seen in GHG emission inventories for agencies, corporations, and jurisdictions (e.g., community, city, county, state, country) where entities must account for a wide range of sectors (e.g., transportation, energy, agriculture). Each sector has an array of emissions sources with unique variations in emission factors, activity data, and other aspects to consider.

GHG emission profiles can be complex for specific products or resources, when a scope may consider elements outside of product use, such as emissions from supply chains, co-products, and disposal. For example, California's Low Carbon Fuel Standard (LCFS) relies on a life-cycle assessment approach for estimating carbon intensities of transportation fuels. As a result, LCFS emissions for a specific transportation fuel pathway includes all emission sources in the fuel lifecycle from resource extraction to final consumption in a vehicle.

IPCC Guidelines for Biogenic Fuel Sources

GHG emission accounting for inventories typically relies on guidance from the Intergovernmental Panel on Climate Change (IPCC) developed in 2006.[29] The IPCC provides guidance for different levels of detail depending on the availability of data and capacity of the inventory team for all sectors typically considered in a GHG inventory. GHG emission reporting programs that address a specific sector or subsector, like the LCFS, may have unique guidelines that diverge from IPCC and typical inventories in accounting methods. IPCC guidelines state that CO2 emissions from biogenic fuel sources (e.g., biogas or biomass based RNG) should not be included when accounting for emissions in combustion – only CH4 and N2O are included. This is to avoid any upstream "double counting" of CO2 emissions that occur in the agricultural or land use sectors per IPCC guidance.

[27] US EPA. 2018. Emission Factors for Greenhouse Gas Inventories, Available online at https://www.epa.gov/sites/production/files/2018-03/documents/emission-factors_mar_2018_0.pdf.

[28] Personal communication with AGA.

[29] IPCC. 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Available at: https://www.ipcc-nggip.iges.or.jp/public/2006gl/.

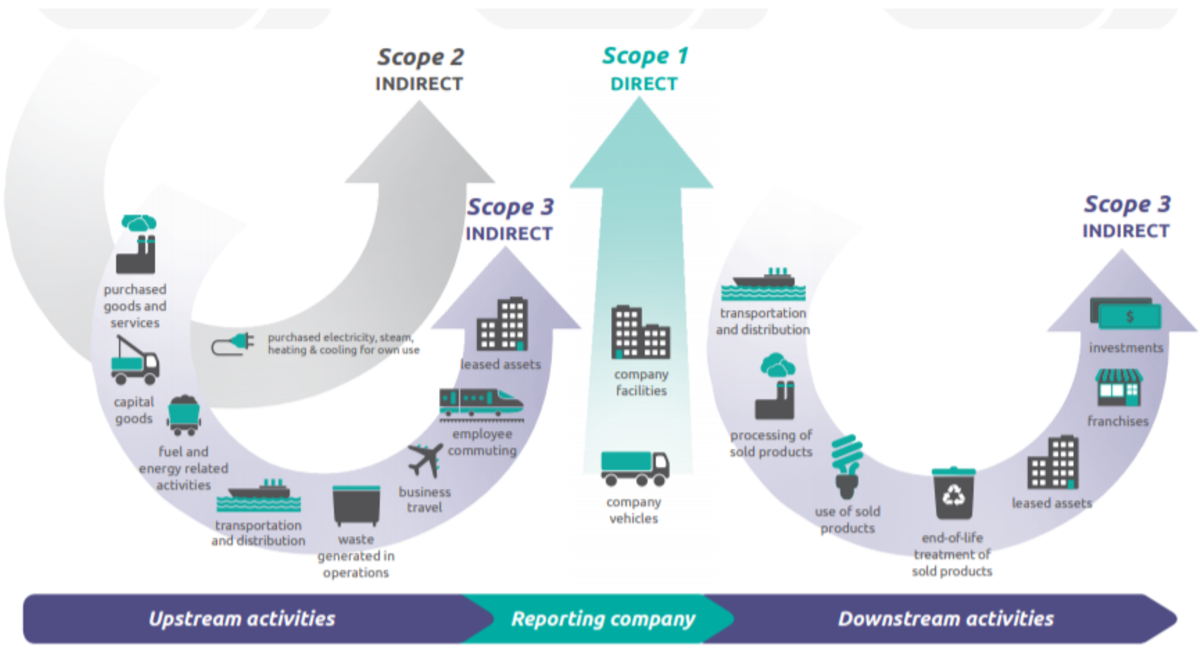
Other approaches exclude biogenic CO2 in combustion as it is assumed that the CO2 sequestered by the biomass during its lifetime offsets combustion CO2 emissions. This method of excluding biogenic CO2 is still commonly practiced for RNG users and producers.

Greenhouse Gas Protocol

The Greenhouse Gas Protocol is a commonly used set of reporting standards developed by the World Resources Institute and the World Business Council for Sustainable Development. A GHG Protocol-based approach is most common with corporations, but still incorporates many of the same sources and emission factors used by jurisdictions and public agencies.

The GHG Protocol uses "Scope" levels to define the different sources and activity data included within an assessment. Instead of thinking in terms of geographic or sector-based boundaries, the Protocol groups emissions in direct and indirect categories through these Scopes. Figure 26 shows how the Protocol groups these emission sources by Scopes, and how they relate to an organization's operations.

Figure 26. Scopes for categorizing emissions under the GHG Protocol (GHG Protocol 2019).



Organizations most often may limit their assessment to Scope 1 and 2 emissions, which includes directly controlled assets. Scope 3 emissions reflect a life cycle assessment approach that includes supply chain activities and associated, but not directly controlled, organizations.

There is often confusion about who can claim and monetize the environmental benefits of RNG production and consumption across various stakeholders and GHG reporting structures. For example, a corporation based in California buys RNG from a fuel distributor to fuel their fleet of shuttle buses. The RNG was produced out of state and transported and sold in California to take advantage of the LCFS credit program. The value of the LCFS credits are owned and monetized by the various actors within the fuel production supply chain. However, the corporation purchasing the RNG as an end-user can still factor in the fuel's low carbon intensity into their corporate emissions accounting by including the volumes purchased in their Scope 1 emissions.

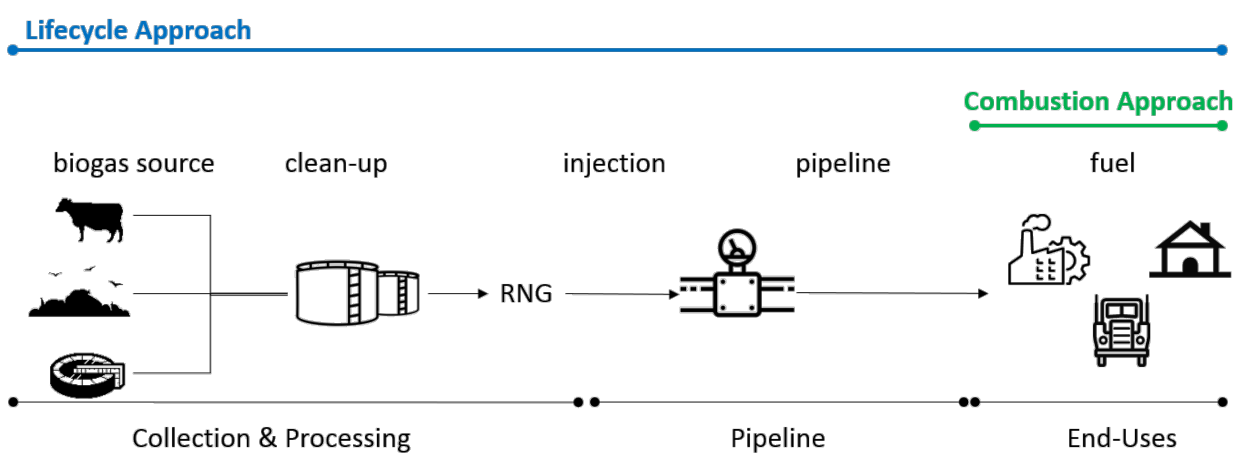
RNG and GHG Accounting

There are two broad methodologies to account for the GHG emissions from RNG: a combustion accounting framework or a lifecycle accounting framework.

- A combustion GHG accounting framework is the standard approach for most volumetric GHG targets, inventories and mitigation measures (e.g., RPS programs, carbon taxes, cap-and-trade programs, etc.) as they are more closely tied to a particular jurisdiction – where the emissions physically occur. Using the combustion framework, the CO2 emissions from the combustion of biogenic renewable fuels are considered zero, or carbon neutral. In other words, RNG has a carbon intensity of zero. This includes RNG from any biogenic feedstock, including landfill gas, animal manure and food waste. Upstream emissions, whether positive (electricity emissions associated with biogas processing) or negative (avoided methane emissions), are not included.
- When using a lifecycle accounting methodology RNG's carbon intensity (i.e., GHG emissions per unit of energy) varies substantially between feedstocks and production methods. Carbon intensities can also vary by location of production and how the fuel is transported and distributed. The GHG accounting methods and scopes previously discussed dictate which of RNG's life-cycle elements are included as a carbon intensity in emissions reporting.

Figure 27 below shows the various steps in RNG production—including the collection and processing of raw biogas, injection into the pipeline, transmission and distribution to end users, and then finally use as a fuel in various applications. The combustion approach (in green) focuses on the end use and recognizes RNG as a biogenic source. The lifecycle approach (in blue) accounts for all the emissions associated with each step in the supply chain associated with RNG production.

Figure 27. Overview of GHG Accounting Frameworks for RNG



GHG Emissions from RNG Resource Assessment

ICF reports the GHG emission reductions for RNG consistent with the combustion approach outlined pre IPCC guidelines stating that emissions from biogenic fuel sources should not be included when accounting for emissions in combustion. This accounting approach is employed to avoid any upstream "double counting" of emissions that occur in the agricultural or land use sectors per IPCC guidance. ICF did account for N_2O and CH_4 emissions during combustion of RNG.

ICF used an emissions factor of 53.06 kg/MMBtu for fossil natural gas. ICF also developed an estimated emissions factor of 15 kg/MMBtu for renewable gas from thermal gasification of MSW and incorporated that into the analysis.

The tables below show the range of GHG emission reductions in units of million metric tons (MMT) for the low and high resource potential scenarios. ICF estimates that in the low resource potential scenario, about 101 MMT of GHG emissions would be reduced through the deployment of RNG; and in the high resource potential scenario, 235 MMT of GHG emissions could be reduced.

The GHG emission reduction potential in the low and high resource potential scenarios is equivalent to displacing 59-95% of the average GHG emissions attributable to natural gas consumption in the residential energy sector nationwide over the ten-year period 2009-2018 (see Figure 28 below).

Figure 28. Average Annual Carbon Dioxide Emissions (in MMT) from Natural Gas Consumption in the U.S. 2009-2018

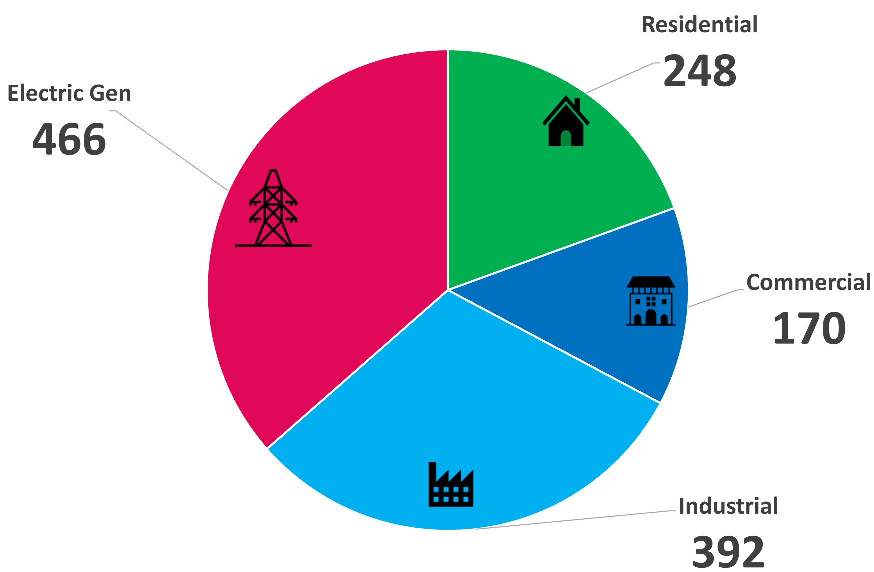


Table 29. GHG Emission Reductions (in MMT) for RNG in the Low Resource Potential Case

Feedstock	Low RNG Resource Case | GHG Emission Reduction Potential, MMT									
	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific	Total
RNG from biogenic or renewable resources										
Landfill Gas	0.7	3.1	5.6	1.5	4.7	1.9	3.5	2.0	5.1	28.0
Animal Manure	0.4	0.6	1.6	2.4	1.7	1.0	1.9	1.5	1.1	12.3
WRRF	0.1	0.2	0.2	0.1	0.2	0.1	0.1	0.1	0.2	1.2
Food Waste	0.1	0.3	0.3	0.1	0.3	0.0	0.1	0.0	0.3	1.5
Ag Residue	0.0	0.2	3.0	7.7	0.5	0.2	0.6	0.6	0.8	13.5
Forestry and Forest Residue	0.2	0.3	0.5	0.3	2.0	1.1	0.9	0.1	0.4	5.8
Energy Crops	0.0	0.1	0.1	1.9	1.0	0.5	3.0	0.0	0.0	6.5
Sub-Total	***1.5***	***4.8***	***11.4***	***13.9***	***10.4***	***4.7***	***10.0***	***4.4***	***7.8***	***68.9***
Renewable gas from MSW										
MSW	0.5	1.5	1.7	0.7	2.2	0.4	0.6	0.3	1.7	9.8
RNG from P2G / Methanation										
P2G / Methanation										22.3
Totals	**2.0**	**6.3**	**13.2**	**14.6**	**12.5**	**5.2**	**10.6**	**4.7**	**9.6**	**100.9**

Table 30. GHG Emission Reductions (in MMT) for RNG in the High Resource Potential Case

Feedstock	High RNG Resource Case | GHG Emission Reduction Potential, MMT									
	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific	Total
RNG from biogenic or renewable resources										
Landfill Gas	1.2	5.0	9.2	2.5	7.7	3.1	5.6	3.3	8.2	45.9
Animal Manure	0.8	1.3	3.2	4.7	3.4	2.0	3.8	3.1	2.2	24.5
WRRF	0.1	0.3	0.4	0.1	0.3	0.1	0.2	0.1	0.3	1.8
Food Waste	0.2	0.5	0.5	0.2	0.7	0.2	0.4	0.2	0.5	3.4
Ag Residue	0.0	0.5	7.6	19.2	1.4	0.4	1.5	1.4	2.0	34.0
Forestry and Forest Residue	0.4	0.5	1.0	0.7	4.0	2.2	2.0	1.0	0.7	12.5
Energy Crops	0.0	0.5	3.4	13.8	4.1	4.9	17.5	0.2	0.0	44.4
Sub-Total	***2.7***	***8.6***	***25.3***	***41.2***	***21.5***	***12.9***	***31.1***	***9.3***	***14.0***	***166.6***
Renewable gas from MSW										
MSW	1.2	3.5	3.9	1.8	5.2	1.6	3.2	1.9	4.1	26.4
RNG from P2G / Methanation										
P2G / Methanation										42.3
Totals	**3.9**	**12.1**	**29.3**	**42.9**	**26.7**	**14.5**	**34.2**	**11.2**	**18.1**	**235.3**

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 2040. 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. We also include operational costs for each technology type. The table below outlines some ICF's baseline assumptions that we employ in our RNG costing model for anaerobic digestion systems and thermal gasification systems.

Table 31. Illustrative Cost Assumptions Developed to Estimate RNG Production Costs in 2040

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 $30 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 15 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% for 20 years.

ICF notes that our 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" actually 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, we understand 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. We appreciate the variance between projects, including those that use anaerobic digestion, thermal gasification, or power-to-gas technologies; and our supply-cost curves are meant to be illustrative, rather than deterministic. This is especially true of our outlook to 2040—we have not included significant cost reductions that might occur as a result of a rapidly growing RNG market, or sought to capture some technological breakthrough or breakthroughs. We have 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 we have 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 2040 (reported in 2019 dollars); and we have made only modest assumptions with respect to the potential for RNG cost reductions. The most significant assumption in our outlook to 2040 is the presumption that the underlying structure of the market will change. Today in the U.S., 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 of closer to $40/MMBtu. ICF reports substantial RNG production volumes at prices lower than $20/MMBtu (see below); so how can we reconcile today's estimated production costs of $10-$40/MMBtu with only 40 tBtu/y of RNG production from AD systems with cost estimates for a market producing up to 4,500 tBtu/y using a combination of AD systems, TG systems, and P2G systems? Clearly, this is a non-trivial exercise. And ultimately, ICF's cost estimates focus on a more mature market with some economies of scale achieved as a result of hundreds of projects being developed to achieve the volumes presented. Further, we assume that contractual arrangements will be considerably different and local/regional barriers with respect to RNG pipeline injection have been overcome. Together, these assumptions help us to develop a reasonable outlook on RNG production costs to 2040.

Achieving Significant RNG Production Cost Reductions

Advanced manufacturing (or the lack thereof) will play an important role in making RNG more cost-competitive with geological natural gas and other fossil-based resource. To help achieve more significant reductions, the various aspects of RNG production (e.g., gas receipt skids, gas separation and upgrading equipment, conversion processes, etc.) need to be modular, autonomous, process intensive and manufactured in large numbers. Consider, for instance, that the DOE's Office of Energy Efficiency and Renewable Energy announced in 2016 that the American Institute of Chemical Engineers was selected to lead a new Manufacturing USA Institute, referred to as the Rapid Advancement in Process Intensification Deployment (RAPID) Institute. The RAPID Institute is focused on developing breakthrough technologies to boost the energy productivity and energy efficiency through manufacturing processes in industries such oil and gas, pulp and paper and various domestic chemical manufacturers. A similar effort dedicated towards RNG and other biomass conversion technologies could help reduce costs substantially.

RNG from Anaerobic Digestion

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 25 kWh per MMBtu of RNG injected and 6% of geological or fossil natural gas used in processing. Electricity costs 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 our cost analysis of LFG.

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

Factor	Cost Elements Considered	Costs
Performance	• Capacity factor	• 95%
Installation Costs	• Construction / Engineering • Owner's Cost	• 25% of uninstalled costs of equipment • 10% 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: 25 kWh/MMBtu • Natural Gas: 6% of product	• 4.6—13.7 ¢/kWh • \$3.00-\$8.25/MMBtu
Operations & Maintenance	• 1 FTE for maintenance • Miscellany	• 10% of installed capital costs
For Injection	• Interconnect • Pipeline • Compressor	• \$2 million • \$1.5 million • \$0.2-0.5 million
Financial Parameters	• Rate of Return • Discount Rate	• 10% • 7%

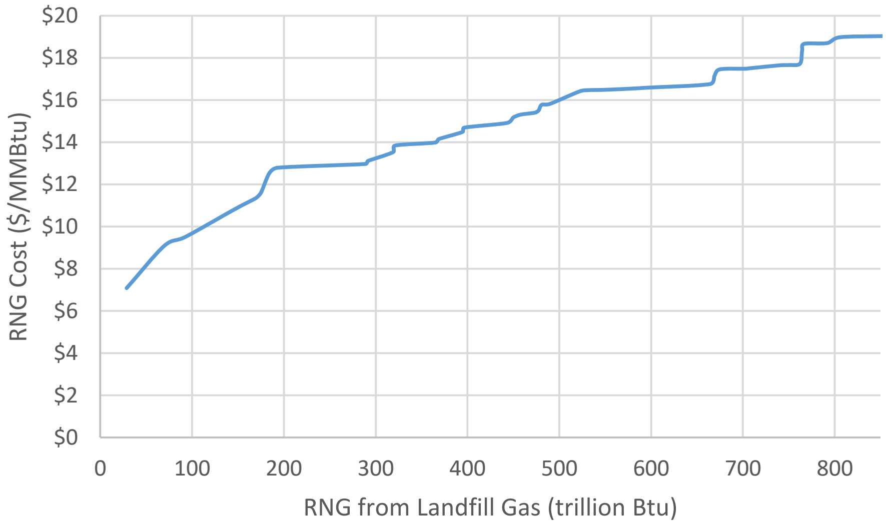
The figure below includes ICF's estimates for the RNG from landfill gas supply curve.

[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.

Figure 29. Supply-Cost Curve for RNG from Landfill Gas ($/MMBtu vs tBtu)



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. We have included the number of dairy cows by way of reference to help contextualize the results for the reader; note, however, that the final analysis will manure from dairy cows, beef cows, chickens (layers and boilers), turkey, and swine.

Table 33. Cost Consideration in Levelized Cost of Gas Analysis for RNG from Animal Manure

Factor	Cost Elements Considered	Costs
Performance	• Capacity factor	• 95%
Installation Costs	• Construction / Engineering • Owner's Cost	• 25% of uninstalled costs of equipment • 10% 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: 30 kWh/MMBtu • Natural Gas: 6% of product	• 4.6—13.7 ¢/kWh • \$3.00-\$8.25/MMBtu
Operations & Maintenance	• 1 FTE for maintenance • Miscellany	• 15% of installed capital costs
For Injection	• Interconnect • Pipeline • Compressor	• \$2.0 million • \$1.5 million • \$0.2-0.5 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 \$18.4/MMBtu to \$32.6/MMBtu.

Water Resource Recovery Facilities

ICF developed assumptions for each region by distinguishing between 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 34. Cost Consideration in Levelized Cost of Gas Analysis for RNG from WRRFs

Factor	Cost Elements Considered	Costs
Performance	• Capacity factor	• 95%
Installation Costs	• Construction / Engineering • Owner's Cost	• 25% of uninstalled costs of equipment • 10% 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: 26 kWh/MMBtu • Natural Gas: 6% of product	• 4.6—13.7 ¢/kWh • \$3.00-\$8.25/MMBtu
Operations & Maintenance	• 1 FTE for maintenance • Miscellany	• 10% of installed capital costs
For Injection	• Interconnect • Pipeline • Compressor	• \$2.0 million • \$1.5 million • \$0.2-0.5 million
Financial Parameters	• Rate of Return • Discount Rate	• 10% • 7%

ICF reports a range of costs for RNG from WRRFs at $7.4/MMBtu to $26.1/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 about 500 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, we also included assumptions about the cost of collecting food waste and processing it accordingly.

Table 35. Cost Consideration in Levelized Cost of Gas Analysis for RNG from Food Waste

Factor	Cost Elements Considered	Costs
Performance	• Capacity factor • Processing Capability	• 95% • 60,000 tons per year
Dedicated Equipment	• Organics Processing • Digester	• $10.0 million • $12.0 million
Installation Costs	• Construction / Engineering • Owner's Cost	• 25% of uninstalled costs of equipment • 10% 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 million • $1.0 million
Utility Costs	• Electricity: 28 kWh/MMBtu • Natural Gas: 5% of product	• 4.6—13.7 ¢/kWh • $3.00-$8.25/MMBtu
Operations & Maintenance	• 1.5 FTE for maintenance • Miscellany	• 15% of installed capital costs
Other	• Tipping fees	• Varied by region;
For Injection	• Interconnect • Pipeline • Compressor	• $2.0 million • $1.5 million • $0.2-0.5 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 Environmental Research & Education Foundation (EREF). The tipping fees reported by EREF for 2018 are shown in the table below.

Table 36. Average Tipping Fee by Region[33]

Region	Tipping Fee, 2018
Pacific: AK, AZ, CA, HI, ID, NV, OR, WA	$68.46
Northeast: CT, DE, ME, MD, MA, NH, NJ, NY, PA, RI, VA, WV	$67.39
Midwest: IL, IN, IA, KS, : MI, MN, MO, NE, OH, OH, WI	$46.89
Mountains / Plains: CO, MT, ND, SD, UT, WY	$43.57
Southeast: AL, FL, GA, KY, MS, NC, SC, TN	$43.32
South Central: AR, LA, NM, OK, TX	$34.80
National Average	$55.11

ICF assumed that anaerobic digesters discounted the tipping fee compared to MSW landfills, and used a 20% discount to those values listed in the table.[34]

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

RNG from Thermal Gasification

ICF used similar assumptions across the thermal gasification of feedstocks, including agricultural residue, forestry residue, energy crops, and municipal solid waste (MSW).[35] There is considerable uncertainty around the costs for thermal gasification of feedstocks, as the technology has only been deployed at pilot scale to date or in the advanced stages of demonstration at pilot scale. This is in stark contrast to the anaerobic digestion technologies considered previously. ICF reports here on the three illustrative facilities that we employed for conducting the cost analysis—distinguished by the amount of feedstock processed daily (in units of tons per day).

[33] As reported by EREF; available online at https://www.waste360.com/landfill-operations/eref-study-shows-continued-increase-average-msw-landfill-tip-fees.

[34] 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.

[35] Note that MSW here refers to the non-organic, non-biogenic fraction of the MSW stream, which is assumed to be a mix of, including, but not limited to construction and demolition debris, plastics, rubber and leather, etc..

Table 37. Cost Consideration in Levelized Cost of Gas Analysis for RNG from Thermal Gasification

Factor	Cost Elements Considered	Costs
Performance	• Capacity factor • Processing Capability	• 90% • 1,000-2,000 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	• $20-22 million • $60 million • $25 million • $10 million • $20 million • $10 million • • • All-in: $335 million for 1,000 tpd
Utility Costs	• Electricity: 30 kWh/MMBtu • Natural Gas: 6% of product	• 4.6—13.7 ¢/kWh • $3.00-$8.25/MMBtu
Operations & Maintenance	• Feedstock • 3 FTE for maintenance • Miscellany: water sourcing, treatment/disposal	• $30-$100/dry ton • 12% of installed capital costs
For Injection	• Interconnect • Pipeline • Compressor	• $2.0 million • $1.5 million • $0.2-0.5 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 1,000 tons per day would represent 50% of the processing capacity, and that the larger facilities processing 2,000 tons per day would represent the other 50% of the processing capacity. The number of facilities built in each region was constrained by the resource assessment.

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

- Agricultural residues: $18.3/MMBtu to $27.4/MMBtu
- Forestry and forest residues: $17.3/MMBtu to $29.2/MMBtu
- Energy crops: $18.3/MMBtu to $31.2/MMBtu
- MSW: $17.3/MMBtu to $44.2/MMBtu

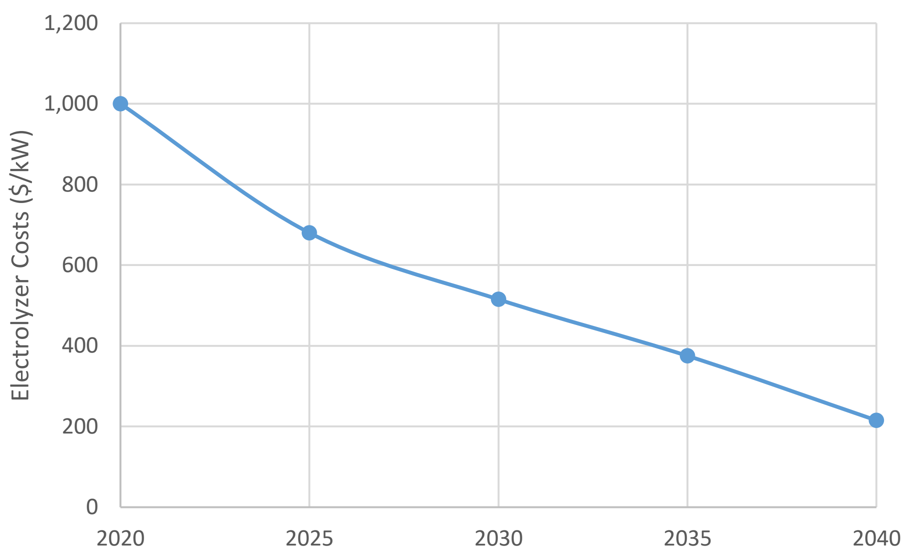
RNG from Power-to-Gas / Methanation

ICF developed the levelized cost of energy for P2G systems using a combination of an electrolyzer and a methanator to produce RNG for pipeline injection. The main cost considerations include: installed cost of electrolyzers on a dollar per kW basis ($/kW), the installed cost of a methanation system on a $/kW basis, the cost of RNG compression and interconnect for pipeline injection, and the cost of electricity used to run the P2G system. ICF also estimated the operations and maintenance (O&M) costs of both the electrolyzer and the methanator. ICF notes that we assume that the renewable electricity is dedicated to the P2G system and co-located, thereby reducing other electricity costs (e.g., transmission and distribution) considerably. ICF did not quantify:

- The costs of CO_2 that would be required for the methanation reaction; the underlying assumption is that the cost of CO_2 would be a marginal contributor to the overall cost of the system, and that it would be available at a low cost (e.g., less than $30 per ton).
- The costs of a heat sink for the waste heat generated from the methanation reaction, or the corresponding benefits of repurposing this heat.

The graph below illustrates ICF's assumptions regarding the installed costs of electrolyzers—we assumed that the resource base for electrolyzers would be some blend of proton exchange membrane (PEM), alkaline systems, and solid oxide systems. Rather than be deterministic about which technology will be the preferred technology, we present the cost as a blended average of the $/kW installed. This is based on ICF's review of literature and review of assumptions developed by UC Irvine. [36]

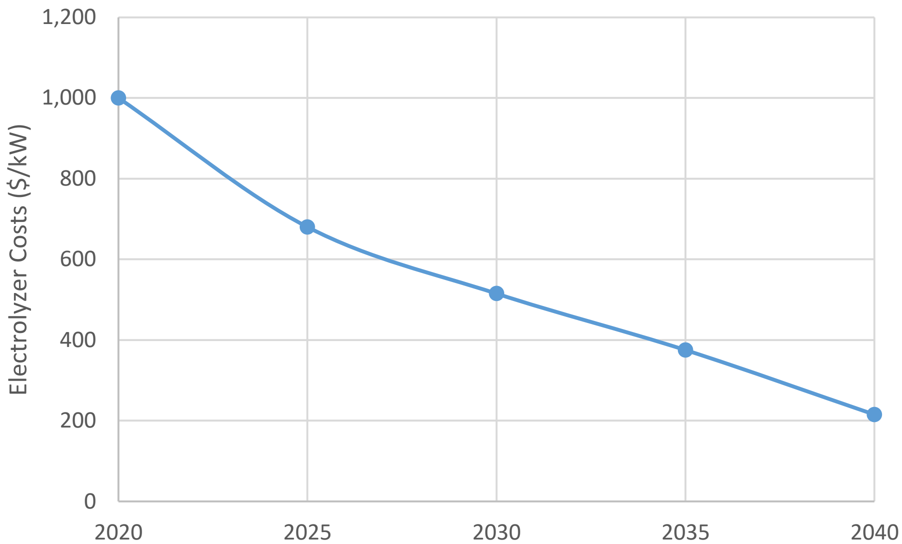
Figure 30. Installed Capacity Cost of Electrolyzers, $/kW, 2020-2040



ICF assumed a decreasing cost of methanation technology consistent with the figure below, presented in units of $/kW.

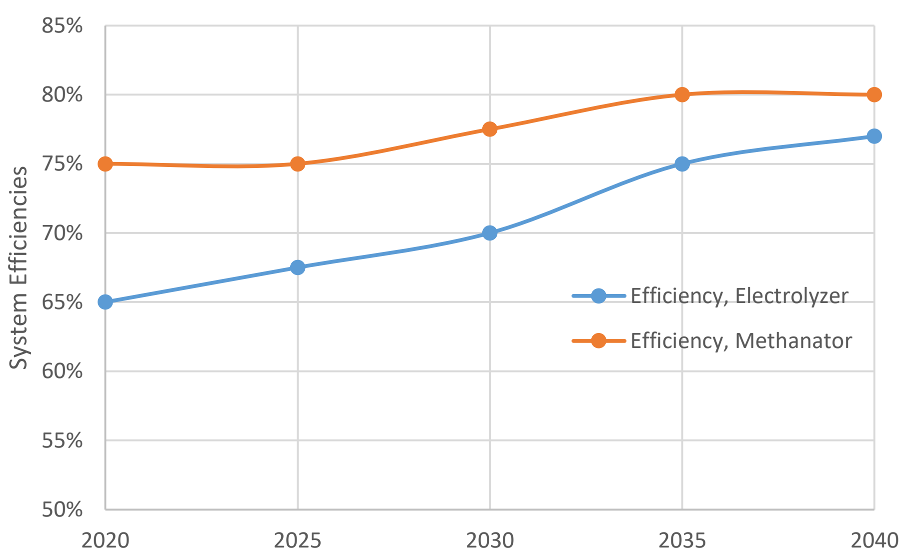
[36] Draft Results: Future of Natural Gas Distribution in California, CEC Staff Workshop for CEC PIER-16-011, June 6, 2019, available online at https://ww2.energy.ca.gov/research/notices/2019-06-06_workshop/2019-06-06_Future_of_Gas_Distribution.pdf.

Figure 31. Installed Capacity Cost of Methanator, $/kW, 2020-2040



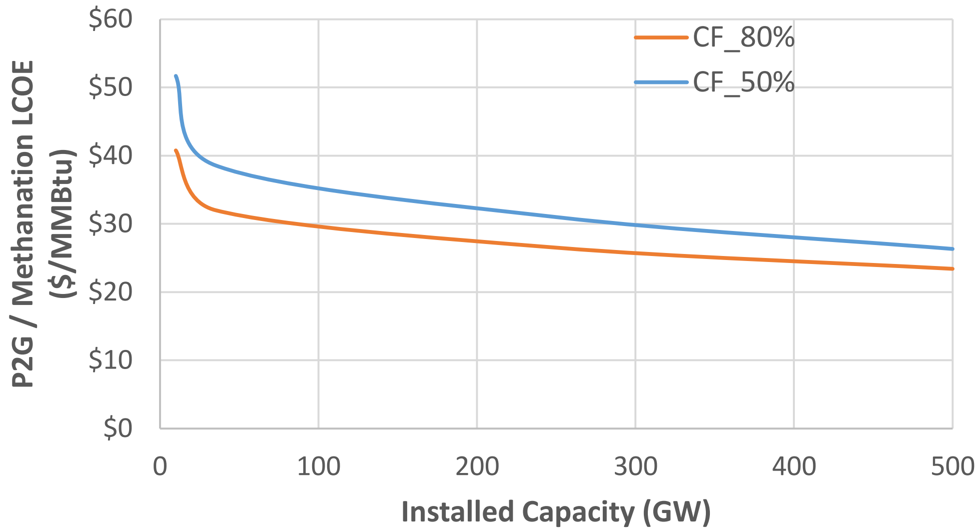
The figure below includes the assumed conversion efficiencies for hydrogen production from electrolyzers (blue) and for the methanation reaction to produce RNG for injection (orange).

Figure 32. Assumed Efficiency for Electrolysis and Methanation, 2020-2040



ICF developed our cost estimates assuming a 50 MW system for P2G co-located with methanation capabilities, and included the costs of compression for pipeline injection, interconnection costs, and pipeline costs. We assumed an electricity cost of $42/MWh based on the supply curve for dedicated renewables that we developed using IPM. We assumed operational costs of 10% and 7% of capex, respectively for the electrolyzer and the methanator; and we assumed operational costs of 5% of capex for pipeline and interconnect systems. The figure below shows the decreasing LCOE for RNG from P2G systems using these baseline level assumptions; the blue line shows the costs assuming a 50% capacity factor for the system and the orange line shows the costs assuming an 80% capacity factor for the system.

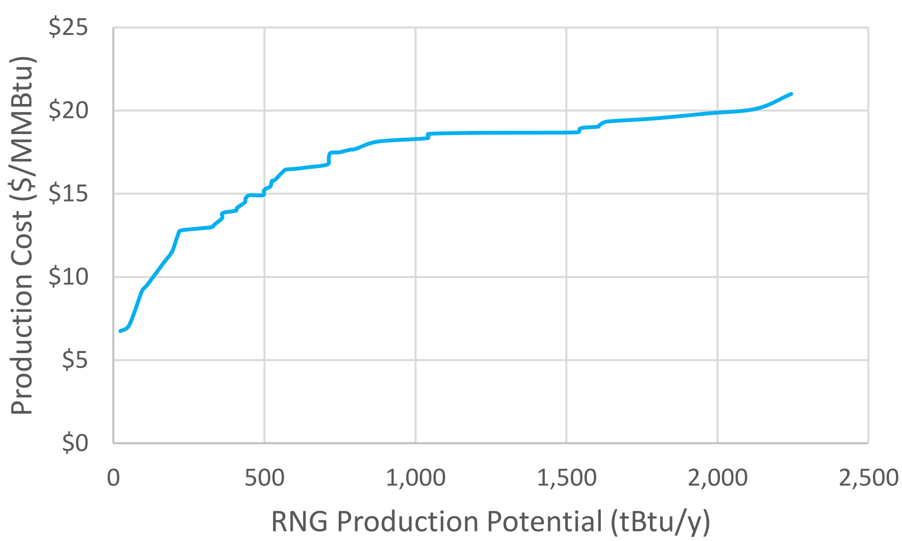
Figure 33. Estimated RNG costs from P2G / Methanation ($/MMBtu) as a function of installed capacity of P2G systems



Combined Supply Curves

ICF estimates that more than half of the RNG production potential in the high resource potential scenario would be available at less than $20/MMBtu, as shown in the figure below. Generally speaking, ICF finds the front end of the supply curve to be landfill gas projects and WRRFs that are poised to move towards RNG production. As the estimated costs move to higher costs, the supply curve includes 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 first tranche of thermal gasification projects that we assume will just start to break that $20/MMBtu level by 2040.

Figure 34. Combined RNG Supply-Cost Curve, less than $20/MMBtu in 2040



GHG Cost-Effectiveness

The GHG cost-effectiveness is reported on a dollar per ton basis, and is calculated as the difference between the emissions attributable to RNG and fossil natural gas. For this report, ICF followed IPCC guidelines and does not include biogenic emissions of CO2 from RNG. The cost-effectiveness calculation is simply as follows

$$\Delta(RNG_{cost}, Fossil\ NG_{cost}) \big/ {0.05306\ MT\ CO_{2e}},$$

where the RNGcost is simply the cost from the estimates reported previously. For the purposes of this report, we use a fossil natural gas price equal to the average Henry Hub spot price reported by the EIA in the 2019 Annual Energy Outlook, calculated as $3.89/MMBtu.

In other words, the front end of the supply-cost curve is showing RNG is just under $7/MMBtu, which is equivalent to about $55-60/ton. As the estimated RNG cost increases to $20/MMBtu, we report an estimated cost-effectiveness of about $300/ton. The GHG cost-effectiveness of RNG as a mitigation strategy is competitive with and in many cases lower than the costs per ton that are associated with other strategies to reduce GHG emissions, such as electrification at $572-806/ton and atmospheric removal of CO_2 at $94-232/ton.[37]

[37] Cost estimates are from *Implications of Policy-Driven Residential Electrification,* AGA, 2018 study. While the cost estimates are not fully "apples-to-apples" comparison as the scope of the referenced study is different from this report, it serves as a useful point of comparison.

Key Findings

ICF's assessment of RNG potential in the United States demonstrate that there is significant resource potential in both the low and the high cases considered—and in both, ICF used moderately conservative assumptions with respect to the utilization of feedstocks and technological advancements.

- In the low resource potential scenario, ICF estimates that about 1,650 trillion Btu (tBtu) of RNG can be produced annually for pipeline injection by 2040. That estimate increases to 1,910 tBtu per year when including the potential for the non-biogenic fraction of MSW.
- In the high resource potential scenario, ICF estimates that about 3,780 tBtu of RNG can be produced annually for pipeline injection by 2040. That estimate increases to 4,510 tBtu per year when including the potential for the non-biogenic fraction of MSW. For the sake of comparison, ICF notes that the 10-year average (2009-2018) of residential natural gas consumption is 4,846 tBtu.

The reported RNG resource potential estimates reported here are 90% and 180% increases from the comparable resource potential scenarios from 2011 AGF Study. These changes are largely attributable to improved access to data regarding potential feedstocks for RNG production and are generally not attributable to more aggressive assumptions regarding feedstock utilization or conversion efficiencies. Furthermore, the analysis presented here includes estimates for RNG production from P2G systems using dedicated renewable electricity. While there are multiple studies regarding P2G technology and its uses, we believe this is the first study to quantify RNG production potential nationwide from P2G.

ICF's updated assessment also illustrates the diversity of RNG resource potential as a GHG emission reduction strategy—there is a portfolio of potential feedstocks and technologies that are or will be commercialized in the near-term future that will help realize the potential of the RNG market. On the technology side, most RNG continues to be produced using anaerobic digestion paired with conditioning and upgrading systems. The post-2025 outlook for RNG will increasingly rely on thermal gasification of sustainably harvested biomass, including agricultural residues, forestry and forest product residues, and energy crops. The long-term outlook for RNG growth will depend to some extent on technological advancements in P2G systems.

ICF's analysis of the potential for P2G systems, paired with methanation suggests that the technology could make a significant contribution to RNG production by 2040. However, ICF notes that the role of P2G systems as a contributor to RNG production requires further analysis and study. Excluding cost considerations, the deployment of P2G systems for RNG production requires assumptions across a variety of factors, including but not limited to access to renewable electricity, the corresponding capacity factor of the system given the intermittency of renewable electricity generation from some sources (e.g., solar and wind), co-location with (presumably affordable) access to carbon dioxide for methanation, and reasonable proximity to a natural gas pipeline for injection. ICF's analysis did not seek to address all of these project development considerations; rather, we sought to understand the potential for P2G systems assuming access to dedicated renewable electricity production, meaning that these are purpose-built renewable electricity generation systems that are meant to provide dedicated power to P2G systems. Curtailment of renewable electricity generation is a complicated issue, and exploring it in detail was beyond the scope of this report. However, ICF's initial assessment indicates that P2G systems running on curtailed renewable electricity will play an important transitional role in helping to deploy the technology and achieve the long-term price reductions that are required to improve the viability of P2G as a cost-effective pathway for RNG production. Despite the importance of curtailed renewable electricity as part of the transition towards more cost-effective P2G systems, ICF's analysis does focus more on the opportunity for, and associated costs of RNG production using P2G systems with dedicated renewable electricity generation. It is important that this assumption by ICF is recognized as a limitation of our analysis, rather than a commentary on how the market will ultimately develop for P2G systems.

In the low resource potential and high resource potential scenarios presented, RNG deployment could achieve 101 to 235 MMT of GHG emission reductions by 2040. For the sake of reference, the high end of the estimate would be the equivalent of reducing GHG emissions from the use of natural gas in the residential sector by 95% from levels observed over the last ten years (2009-2018).

ICF estimates that the majority of the RNG produced in the high resource potential scenario is available in the range of $7-$20/MMBtu, which is equivalent to $55/ton to $300/ton in 2040. ICF evaluated the potential costs associated with the deployment of each feedstock and technology pairing, and made assumptions about the sizing of systems that would need to be deployed to achieve the RNG production potential outlined in the low and high resource potential scenarios. ICF's reported costs are dependent on a variety of assumptions, including feedstock costs, the revenue that might be generated via byproducts or other avoided costs, and the expected rate of return on capital investments. ICF finds that there is potential for cost reductions as the RNG for pipeline injection market matures, production volumes increase, and the underlying structure of the market evolves.

Appendix A—Resource Assessment by State

The tables below summarize ICF's resource assessment for low, high, and technical resource RNG production potentials in 2040, broken down by state and by feedstock, reported in units of tBtu per year (tBtu/y).

Low Resource Potential Scenario, By State

Table 38. Low Resource Potential for RNG in 2040, tBtu/y, by State

State	via Anaerobic Digestion				via Thermal Gasification			
	LFG	Animal Manure	WRRF	Food Waste	Ag Res	Forest Res	Energy Crops	MSW
Alabama	9.561	6.536	0.177	0.121	0.186	7.000	2.508	5.563
Alaska	1.153	0.004	0.030	0.000	0.000	0.000	0.000	0.000
Arizona	10.933	1.943	0.385	0.324	0.222	0.408	0.000	2.621
Arkansas	4.156	7.260	0.077	0.024	0.629	6.219	1.256	2.904
California	76.540	15.917	3.088	4.636	9.770	2.441	0.000	37.480
Colorado	10.962	3.605	0.250	0.247	3.058	0.560	0.000	1.999
Connecticut	1.670	0.864	0.246	0.438	0.009	0.290	0.051	3.539
Delaware	1.326	3.145	0.089	0.112	0.219	0.048	0.015	0.903
D.C.	0.000	--	0.378	0.077	0.000	0.006	0.000	0.625
Florida	23.493	3.481	1.028	2.358	5.957	3.757	3.714	19.059
Georgia	16.914	7.196	0.538	0.230	0.739	8.059	4.756	6.185
Hawaii	2.203	0.124	0.105	0.000	0.000	0.000	0.000	0.000
Idaho	1.544	5.624	0.049	0.000	2.231	0.422	0.000	0.201
Illinois	28.655	2.481	1.869	1.568	23.215	1.155	0.287	12.677
Indiana	15.835	3.027	0.652	0.796	8.288	0.952	0.428	6.438
Iowa	4.899	8.648	0.140	0.027	35.541	0.875	3.042	1.756
Kansas	5.485	5.336	0.142	0.352	6.555	0.334	27.152	2.842
Kentucky	9.435	4.348	0.228	0.534	1.691	4.450	2.004	4.316
Louisiana	8.507	3.860	0.303	0.092	4.262	4.547	3.800	0.742
Maine	1.489	5.205	0.048	0.162	0.010	1.674	0.043	1.308
Maryland	6.286	2.255	0.356	0.718	1.186	0.623	0.390	5.802
Massachusetts	5.673	0.103	0.619	0.811	0.011	0.608	0.039	6.554
Michigan	25.191	4.141	1.179	1.204	7.175	3.198	0.220	9.734
Minnesota	4.661	6.789	0.307	0.655	30.659	2.501	0.013	5.298
Mississippi	5.306	4.410	0.072	0.000	0.624	5.189	2.800	0.000
Missouri	8.499	7.869	0.576	0.734	1.266	2.225	5.058	5.933
Montana	1.430	3.901	0.034	0.000	5.127	0.462	0.000	0.000
Nebraska	3.397	6.225	0.118	0.050	38.201	0.176	0.000	0.406
Nevada	5.291	0.808	0.250	0.148	0.002	0.056	0.000	1.195
New Hampshire	2.334	0.828	0.037	0.161	0.005	0.580	0.021	1.301
New Jersey	10.625	0.917	1.033	1.081	0.088	0.360	0.157	8.740
New Mexico	3.441	8.988	0.106	0.041	0.159	0.258	0.168	1.273
New York	19.739	4.522	2.472	2.388	2.015	1.980	0.598	19.307
North Carolina	14.068	6.943	0.367	1.187	0.833	9.692	4.993	9.599

State	via Anaerobic Digestion				via Thermal Gasification			
	LFG	Animal Manure	WRRF	Food Waste	Ag Res	Forest Res	Energy Crops	MSW
North Dakota	0.783	2.573	0.021	0.000	10.871	0.110	0.000	0.691
Ohio	24.843	4.139	1.364	1.407	10.053	1.308	0.375	11.374
Oklahoma	6.667	6.570	0.186	0.099	0.883	0.829	17.454	2.418
Oregon	6.237	1.962	0.293	0.144	1.060	2.161	0.000	1.164
Pennsylvania	27.171	6.667	1.043	1.555	1.589	2.509	1.397	12.575
Rhode Island	1.447	0.008	0.103	0.128	0.001	0.126	0.007	1.037
South Carolina	7.612	2.305	0.000	0.126	0.357	6.354	2.258	4.650
South Dakota	0.874	7.026	0.012	0.102	21.324	0.281	0.104	0.822
Tennessee	11.368	3.569	0.503	0.161	0.405	3.990	1.990	1.305
Texas	45.927	18.269	1.427	1.142	4.904	4.742	34.003	9.233
Utah	4.185	1.888	0.089	0.117	0.025	0.292	0.000	0.945
Vermont	0.672	1.006	0.000	0.076	0.006	0.351	0.025	0.617
Virginia	15.569	5.430	0.599	1.016	0.691	8.031	0.912	8.213
Washington	9.052	3.034	0.472	0.840	4.100	2.173	0.000	6.791
West Virginia	3.162	0.926	0.052	0.226	0.033	1.050	1.048	1.828
Wisconsin	11.634	16.507	0.443	0.697	8.308	3.043	0.161	5.637
Wyoming	0.500	1.992	0.000	0.070	0.088	0.199	0.000	0.568

High Resource Potential Scenario, By State

Table 39. High Resource Potential for RNG in 2040, tBtu/y, by State

State	via Anaerobic Digestion				via Thermal Gasification			
	LFG	Animal Manure	WRRF	Food Waste	Ag Res	Forest Res	Energy Crops	MSW
Alabama	15.818	13.072	0.322	1.204	0.464	13.999	16.789	12.544
Alaska	1.869	0.008	0.038	0.000	0.000	0.000	0.000	0.000
Arizona	17.879	3.887	0.537	1.397	0.555	4.175	0.000	14.557
Arkansas	6.762	14.520	0.193	0.629	1.573	12.438	18.529	6.549
California	124.841	31.833	4.183	8.113	24.426	4.881	0.000	84.514
Colorado	17.921	7.210	0.368	0.433	7.646	3.121	1.489	11.528
Connecticut	2.756	1.728	0.418	0.766	0.023	0.579	0.052	7.981
Delaware	2.219	6.290	0.119	0.195	0.546	0.096	0.017	2.036
D.C.	0.000		0.473	0.135	0.000	0.011	0.000	1.410
Florida	38.510	6.962	1.685	4.126	14.893	7.513	16.811	42.976
Georgia	27.480	14.392	0.774	2.114	1.848	16.117	16.880	22.024
Hawaii	3.562	0.248	0.163	0.000	0.000	0.000	0.000	0.000
Idaho	2.599	11.248	0.108	0.044	5.578	0.963	0.000	3.430
Illinois	46.987	4.962	2.533	2.744	58.037	2.310	36.042	28.585
Indiana	26.341	6.055	0.962	1.394	20.719	1.904	13.002	14.516
Iowa	7.962	17.296	0.248	0.656	88.851	1.750	19.329	6.830
Kansas	8.997	10.671	0.256	0.615	16.388	0.668	128.067	6.408
Kentucky	15.679	8.697	0.372	0.934	4.228	8.899	30.320	9.733
Louisiana	13.954	7.719	0.480	0.982	10.654	9.095	13.550	10.224
Maine	2.407	10.411	0.091	0.283	0.026	3.348	0.070	2.950
Maryland	10.417	4.510	0.509	1.256	2.966	1.246	1.080	13.082
Massachusetts	9.342	0.205	0.858	1.419	0.027	1.217	0.075	14.779
Michigan	41.000	8.283	1.533	2.107	17.937	6.396	1.170	21.948
Minnesota	7.683	13.579	0.438	1.147	76.646	5.002	2.941	11.947
Mississippi	8.666	8.821	0.195	0.637	1.559	10.379	17.065	6.630
Missouri	14.105	15.739	0.807	1.284	3.165	4.450	96.367	13.379
Montana	2.320	7.801	0.059	0.000	12.817	1.042	0.552	2.232
Nebraska	5.712	12.451	0.166	0.088	95.502	0.352	1.563	4.120
Nevada	8.701	1.616	0.324	0.259	0.005	1.893	0.000	6.118
New Hampshire	3.788	1.656	0.076	0.282	0.013	1.160	0.024	2.934
New Jersey	17.254	1.835	1.414	1.892	0.221	0.720	0.727	19.708
New Mexico	5.651	17.976	0.157	0.444	0.398	2.641	1.805	4.629
New York	32.753	9.044	3.304	4.179	5.038	3.959	3.041	43.536
North Carolina	23.406	13.887	0.640	2.078	2.082	19.384	20.971	21.645
North Dakota	1.333	5.145	0.045	0.150	27.179	0.223	7.115	1.558
Ohio	40.539	8.278	1.968	2.462	25.133	2.616	3.416	25.648
Oklahoma	10.857	13.139	0.305	0.814	2.206	1.748	111.613	8.475
Oregon	10.189	3.925	0.411	0.252	2.651	4.323	0.000	8.657
Pennsylvania	44.319	13.334	1.558	2.722	3.973	5.018	5.681	28.355

State	via Anaerobic Digestion				via Thermal Gasification			
	LFG	Animal Manure	WRRF	Food Waste	Ag Res	Forest Res	Energy Crops	MSW
Rhode Island	2.357	0.016	0.150	0.224	0.003	0.251	0.007	2.337
South Carolina	12.627	4.611	0.000	1.007	0.892	12.707	11.025	10.486
South Dakota	1.470	14.052	0.015	0.178	53.311	0.563	4.632	1.853
Tennessee	18.903	7.138	0.749	1.376	1.012	7.979	27.417	14.333
Texas	74.621	36.538	2.074	5.562	12.260	13.856	186.772	57.940
Utah	7.034	3.777	0.126	0.205	0.063	4.699	0.000	6.340
Vermont	1.099	2.012	0.018	0.133	0.016	0.701	0.277	1.390
Virginia	25.316	10.861	0.834	1.778	1.729	16.062	8.696	18.519
Washington	14.745	6.069	0.694	1.470	10.251	4.347	0.000	15.313
West Virginia	5.072	1.853	0.091	0.396	0.082	2.100	1.855	4.122
Wisconsin	18.906	33.014	0.625	1.220	20.771	6.086	10.807	12.712
Wyoming	0.830	3.984	0.028	0.123	0.220	0.800	0.067	1.281

Technical Resource Potential Scenario, By State

Table 40. Technical Resource Potential for RNG in 2040, tBtu/y, by State

State	via Anaerobic Digestion				via Thermal Gasification			
	LFG	Animal Manure	WRRF	Food Waste	Ag Res	Forest Res	Energy Crops	MSW
Alabama	21.291	21.786	1.054	5.417	1.607	35.895	67.831	31.436
Alaska	2.732	0.013	0.097	0.814	0.000	0.000	0.000	0.000
Arizona	25.738	6.478	1.275	8.045	2.299	19.320	0.000	36.483
Arkansas	9.604	24.200	0.675	3.347	10.304	31.892	151.481	16.412
California	188.144	53.056	8.988	43.954	77.147	12.516	0.000	211.804
Colorado	26.180	12.017	0.952	6.381	34.406	13.136	22.504	28.890
Connecticut	4.085	2.879	0.992	3.945	0.071	1.485	0.249	20.001
Delaware	3.456	10.484	0.266	1.078	3.008	0.245	4.432	5.102
D.C.	0.000		0.946	0.787	0.000	0.028	0.000	3.534
Florida	55.554	11.604	3.991	23.937	45.823	19.265	57.804	107.704
Georgia	39.551	23.987	1.962	11.753	6.971	41.326	66.426	55.195
Hawaii	4.847	0.413	0.352	1.567	0.000	0.000	0.000	0.000
Idaho	4.016	18.746	0.355	1.980	23.672	2.774	0.000	8.647
Illinois	69.628	8.269	5.663	14.045	246.978	5.924	353.618	71.637
Indiana	39.815	10.091	2.458	7.430	110.916	4.881	205.848	36.379
Iowa	11.345	28.826	0.972	3.503	348.543	4.487	293.301	17.116
Kansas	13.258	17.785	0.791	3.219	82.681	1.713	464.248	16.059
Kentucky	22.443	14.495	1.080	4.959	19.345	22.819	154.183	24.392
Louisiana	19.953	12.866	1.271	5.145	38.169	23.320	76.967	25.624
Maine	3.286	17.351	0.348	1.484	0.079	8.584	0.317	7.393
Maryland	15.646	7.517	1.168	6.705	10.173	3.195	21.633	32.786
Massachusetts	14.059	0.342	1.935	7.674	0.082	3.120	0.424	37.037
Michigan	62.029	13.805	3.488	11.081	80.227	16.399	51.785	55.005
Minnesota	11.664	22.632	1.046	6.255	301.824	12.825	108.270	29.941
Mississippi	12.135	14.702	0.673	3.304	8.874	26.612	101.265	16.617
Missouri	21.131	26.231	2.066	6.799	29.302	11.410	367.684	33.528
Montana	3.287	13.002	0.205	1.188	50.944	2.976	18.432	5.593
Nebraska	8.663	20.751	0.493	2.146	352.907	0.903	53.364	10.325
Nevada	13.265	2.693	0.702	3.414	0.014	9.422	0.000	15.332
New Hampshire	5.740	2.759	0.251	1.508	0.039	2.974	0.128	7.352
New Jersey	26.340	3.058	3.099	9.867	1.164	1.847	4.193	49.391
New Mexico	8.150	29.961	0.471	2.318	2.147	12.222	7.031	11.600
New York	50.489	15.073	7.197	21.554	24.327	10.152	33.219	109.106
North Carolina	35.164	23.145	1.683	11.609	10.421	49.703	96.393	54.245
North Dakota	2.007	8.576	0.153	0.841	104.037	0.581	138.829	3.905
Ohio	59.130	13.797	4.788	12.959	103.490	6.709	130.141	64.276
Oklahoma	15.723	21.899	0.914	4.367	15.589	4.713	354.173	21.240
Oregon	15.409	6.541	1.026	4.695	12.034	11.084	0.000	21.695
Pennsylvania	66.587	22.224	4.142	14.170	16.646	12.867	46.920	71.060

State	via Anaerobic Digestion				via Thermal Gasification			
	LFG	Animal Manure	WRRF	Food Waste	Ag Res	Forest Res	Energy Crops	MSW
Rhode Island	3.629	0.026	0.338	1.169	0.008	0.644	0.034	5.857
South Carolina	18.856	7.684	0.000	5.692	4.484	32.583	37.226	26.280
South Dakota	2.257	23.420	0.048	0.987	185.826	1.442	82.444	4.644
Tennessee	28.115	11.897	1.856	7.557	8.845	20.460	137.488	35.921
Texas	108.758	60.897	4.732	32.166	52.667	46.739	683.746	145.205
Utah	10.185	6.294	0.374	3.563	0.198	22.600	0.000	15.888
Vermont	1.696	3.353	0.117	0.694	0.050	1.798	1.842	3.484
Virginia	36.882	18.101	1.891	9.479	6.735	41.186	58.678	46.411
Washington	22.019	10.115	1.692	8.478	37.107	11.145	0.035	38.375
West Virginia	6.576	3.088	0.426	1.982	0.346	5.384	14.524	10.330
Wisconsin	28.451	55.024	1.660	6.450	82.169	15.606	131.091	31.857
Wyoming	1.219	6.639	0.133	0.633	1.451	3.083	0.727	3.210

Appendix B—GHG Emissions using Lifecycle Analysis Approach

The GHG emissions factor of RNG, typically called a carbon intensity (e.g., grams of CO2 equivalents per MJ of fuel), varies primarily based on the source of the fuel (i.e., feedstock), but can be impacted by other factors such as production efficiency and location as well as transmission distances. The assessment method and scope can also have a significant impact on how RNG carbon intensities and emissions are estimated and reported. This section provides a summary of commonly used GHG emission accounting methods and how they relate to the GHG emission profiles of RNG production and consumption.

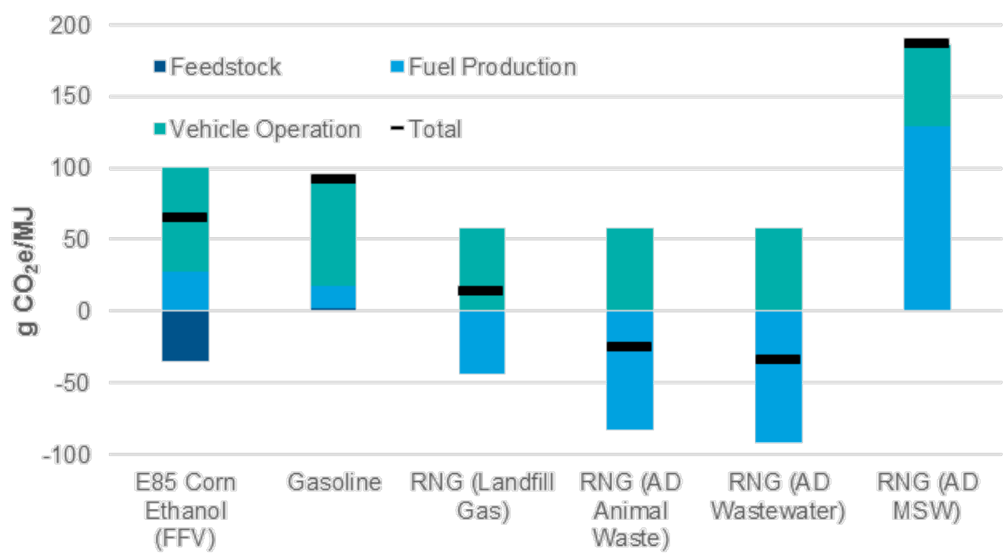
California's LCFS, consumption-based inventories, and GHG Protocol's Scope 3 include all GHG emissions from a product or resource's lifecycle. This relies on an approach called life-cycle assessment (LCA). LCA allows for a holistic GHG accounting approach that considers all life-cycle aspects from raw resource extraction to final disposal (i.e., "cradle to grave"). For RNG and transportation fuels, Argonne National Laboratories' GHGs, Regulated Emissions, and Energy Use in Transportation (GREET) model is the most commonly relied on resource.

RNG's carbon intensity (i.e., GHG emissions per unit of energy) varies substantially between feedstocks and production methods. Carbon intensities can also vary by location of production and how the fuel is transported and distributed. The GHG accounting methods and scopes previously discussed dictate which of RNG's life-cycle elements are included as a carbon intensity in emissions reporting.

Variations in production

Figure 35 shows how these different life-cycle elements contribute to RNG's overall carbon intensity for a selection of RNG sources using Argonne's GREET model: landfill gas, animal waste anaerobic digestion (AD), wastewater sludge AD, and municipal solid waste (MSW) AD. We have also included corn ethanol (E85 blend) and gasoline as reference points. Note that in the GREET model, the original sourcing of RNG is considered "fuel production" and not feedstock operations.

Figure 35. Summary of carbon intensities for transportation fuels across life-cycle stages (ANL 2019).



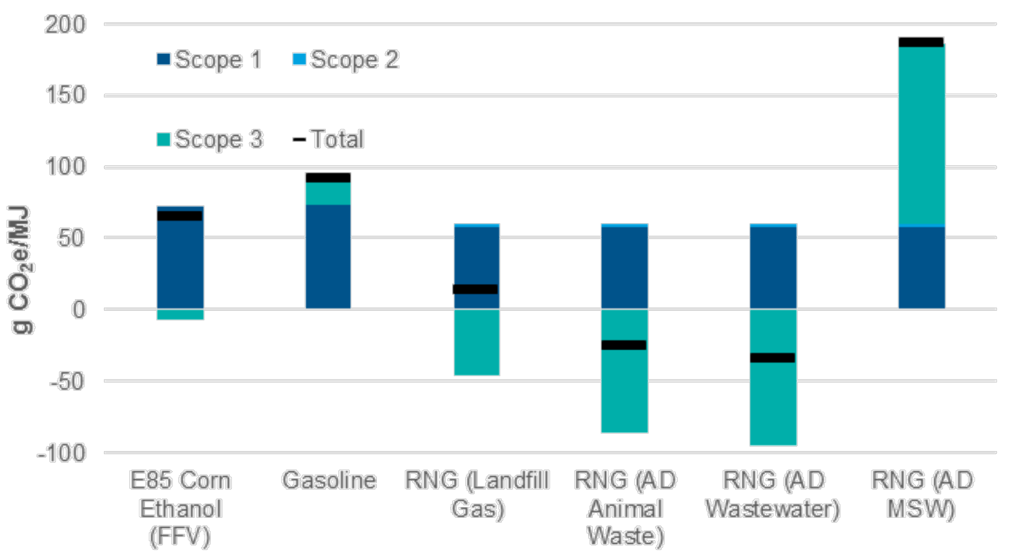
The biggest variations in RNG production come from the associated emissions credits from the different RNG sources. For landfill gas, animal waste, and wastewater sources, GREET assigns a significant credit for the reduction in vented and flared methane (CH4) that would have occurred in absence of the production of RNG.

Depending on the reporting standard and scope, different credits may be included or excluded. The California LCFS has a similar scope in accounting for credits as the GREET results shown above. Other programs or jurisdictional inventories may exclude these credits, or incorporate them into other emission sectors.

Variations based on accounting method

Figure 36 shows the same GREET results from Figure 35 grouped into the GHG Protocol Scopes. Scope 1 is limited to the tailpipe emissions and Scope 3 includes all aspects of feedstock and fuel production activities. For RNG we have grouped the compression of gas before use into Scope 2, assuming electricity is used in compression.

Figure 36. Life-cycle carbon intensity for RNG grouped by different GHG Protocol scopes using GREET results.[38]



As noted in more detail in the previous sub-section, the GHG emissions associated with the production of RNG vary depending on a number of factors including the feedstock type, collection and processing practices, and the type and efficiency of biogas upgrading. For the purposes of this report, ICF determined the lifecycle carbon intensity (CI) of RNG up to the point of pipeline injection. This includes feedstock transport and handling, gas processing, and any credits for the reduction of flaring or venting methane that would have occurred in absence of the RNG fuel production.

The table below presents ranges of lifecycle CIs for different RNG feedstocks up to the point of pipeline injection. These estimates are primarily based on a combination on Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model

[38] GHG Protocol. 2019. Guidance. Available at: https://ghgprotocol.org/guidance-0

(GREET) model,[39] California Air Resources Board's modified California GREET model,[40] and ICF analysis.

Table 41. Range of Lifecycle GHG Emission Factors for RNG from Different Feedstocks and Regions (in units of g/MJ)

RNG Feedstock	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
Landfill gas	18 - 26	15 - 21	28 - 34	28 - 32	22 - 26	26 - 28	26 - 31	21 - 32	13 - 29
Animal manure									
Dairy	-304 - -294	-308 - -300	-292 - -285	-292 - -286	-299 - -294	-294 - -292	-294 - -288	-300 - -286	-310 - -290
Swine	-404 - -394	-408 - -400	-392 - -385	-392 - -386	-399 - -394	-394 - -392	-394 - -388	-400 - -386	-410 - -390
Beef / Poultry	36 - 36	31 - 31	46 - 46	44 - 44	36 - 36	38 - 38	42 - 42	44 - 44	41 - 41
Water resource recovery facilities	18 - 26	15 - 21	28 - 34	28 - 32	22 - 26	26 - 28	26 - 31	21 - 32	13 - 29
Food waste	-97 - -82	-104 - -91	-79 - -68	-79 - -70	-90 - -82	-83 - -79	-83 - -73	-91 - -70	-108 - -76
Agricultural residue	25 - 55	25 - 55	25 - 55	25 - 55	25 - 55	25 - 55	25 - 55	25 - 55	25 - 55
Forestry and forest product residue	25 - 55	25 - 55	25 - 55	25 - 55	25 - 55	25 - 55	25 - 55	25 - 55	25 - 55
Energy crops	25 - 55	25 - 55	25 - 55	25 - 55	25 - 55	25 - 55	25 - 55	25 - 55	25 - 55
Municipal solid waste	25 - 55	25 - 55	25 - 55	25 - 55	25 - 55	25 - 55	25 - 55	25 - 55	25 - 55
P2G / Methanation	0	0	0	0	0	0	0	0	0

ICF notes the following about these emission factors:

- The lowest carbon intensities are from feedstocks that prevent the release of fugitive methane, such as the collection and processing of dairy cow manure.
- RNG from WRRFs has the same CI range as landfill gas because both feedstocks start with raw biogas that is processed by the same type of gas upgrading equipment.
- Agricultural residue, energy crops, forestry products and forestry residues, as well as MSW all have the same CI range based on the thermal gasification process required to create biogas from woody biomass. This is an energy intensive process, but inclusion of renewables and co-produced electricity on-site can reduce the emissions impact of gas production.

After the point of injection, RNG is transported through pipelines for distribution to end-users. The CI of pipeline transmission depends on the distance between the gas upgrading facility and end-use. The GREET model applies 5.8 grams of CO_2e per MMBtu-mile of gas transported as the pipeline transmissions CI factor. If the gas will be used in the transportation sector, and therefore requires compression, another 3-4 gCO_2e is added onto the CI. For the sake of reference, the tailpipe emissions of use in a heavy-duty truck are around 60 gCO_2e/MJ.

ICF applied the GHG emission factors listed in the table above to estimate the GHG reduction potential across each of the RNG potential scenarios and each region, as reported previously in Section 2. The tables below show the range of GHG emission reductions on a lifecycle basis in units of million metric tons, MMT. ICF estimates that in the low RNG resource case, about 86 to 113 MMT of GHG emissions would be reduced through the deployment of RNG; in the high RNG resource case, 170 to 247 MMT of GHG emissions could be reduced.

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[39] https://greet.es.anl.gov/

[40] https://ww3.arb.ca.gov/fuels/lcfs/ca-greet/ca-greet.htm

Table 42. GHG Emission Reductions (in MMT) for RNG in the Low Resource Case

Feedstock	Low RNG Resource Case | GHG Emission Reduction Potential, MMT									
	New England	Mid-Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific	Total
RNG from biogenic or renewable resources										
Landfill Gas	0.5 - 0.5	2.2 - 2.5	3 - 3.5	0.9 - 1	3.1 - 3.4	1.3 - 1.3	2 - 2.3	1.1 - 1.5	3 - 4.3	17 - 20.5
Animal Manure	1.6 - 1.7	3.2 - 3.3	7.2 - 7.4	6 - 6.1	2.9 - 3	0.9 - 0.9	2.6 - 2.7	4.9 - 5.1	5.4 - 5.7	34.9 - 35.7
WRRF	0 - 0	0.2 - 0.2	0.1 - 0.2	0 - 0	0.1 - 0.1	0 - 0	0.1 - 0.1	0 - 0.1	0.1 - 0.2	0.8 - 1
Food Waste	0.3 - 0.3	0.7 - 0.8	0.7 - 0.8	0.2 - 0.3	0.8 - 0.9	0.1 - 0.1	0.2 - 0.2	0.1 - 0.1	0.8 - 0.9	4 - 4.4
Ag Residue	0 - 0	0 - 0.1	0.6 - 2.2	1.4 - 5.6	0.1 - 0.4	0 - 0.1	0.1 - 0.4	0.1 - 0.4	0.1 - 0.6	2.5 - 9.8
Forestry and Forest Residue	0 - 0.1	0 - 0.2	0.1 - 0.4	0.1 - 0.3	0.4 - 1.4	0.2 - 0.8	0.2 - 0.6	0 - 0.1	0.1 - 0.3	1.1 - 4.2
Energy Crops	0 - 0	0 - 0.1	0 - 0.1	0.4 - 1.4	0.2 - 0.7	0.1 - 0.4	0.6 - 2.2	0 - 0	0 - 0	1.2 - 4.8
Sub-Total	*2.4 - 2.7*	*6.4 - 7.2*	*11.7 - 14.5*	*9 - 14.6*	*7.7 - 10*	*2.6 - 3.7*	*5.7 - 8.4*	*6.3 - 7.3*	*9.4 - 12*	*61.4 - 80.3*
Renewable gas from MSW										
MSW	0.1 - 0.6	0.4 - 1.6	0.5 - 1.8	0.2 - 0.7	0.6 - 2.2	0.1 - 0.4	0.2 - 0.6	0.1 - 0.3	0.5 - 1.7	2.5 - 9.9
RNG from P2G / Methanation										
P2G / Methanation										22.3
Totals	2.6 - 3.2	6.9 - 8.8	12.2 - 16.2	9.2 - 15.2	8.3 - 12.2	2.8 - 4.1	5.9 - 9	6.4 - 7.7	9.9 - 13.7	86.3 - 112.5

Table 43. GHG Emission Reductions (in MMT) for RNG in the High Resource Case

Feedstock	**High RNG Resource Case | GHG Emission Reduction Potential, MMT**									
	New England	**Mid-Atlantic**	**East North Central**	**West North Central**	**South Atlantic**	**East South Central**	**West South Central**	**Mountain**	**Pacific**	**Total**
RNG from biogenic or renewable resources										
Landfill Gas	0.8 - 0.9	3.8 - 4.3	5.1 - 6	1.5 - 1.7	5.3 - 5.8	2.2 - 2.3	3.4 - 3.9	1.9 - 2.6	5 - 7.4	28.9 - 35
Animal Manure	3.2 - 3.3	6.4 - 6.6	14.5 - 14.8	12.1 - 12.2	5.9 - 5.9	1.8 - 1.8	5.3 - 5.3	9.8 - 10.2	10.8 - 11.4	69.7 - 71.5
WRRF	0.1 - 0.1	0.3 - 0.3	0.2 - 0.2	0.1 - 0.1	0.2 - 0.2	0.1 - 0.1	0.1 - 0.1	0.1 - 0.1	0.2 - 0.3	1.2 - 1.4
Food Waste	0.3 - 0.3	0.7 - 0.8	0.7 - 0.8	0.2 - 0.3	0.8 - 0.9	0.1 - 0.1	0.2 - 0.2	0.1 - 0.1	0.8 - 0.9	4 - 4.4
Ag Residue	0 - 0	0.1 - 0.4	1.4 - 5.5	3.6 - 13.9	0.3 - 1	0.1 - 0.3	0.3 - 1.1	0.3 - 1.1	0.4 - 1.4	6.4 - 24.7
Forestry and Forest Residue	0.1 - 0.3	0.1 - 0.4	0.2 - 0.7	0.1 - 0.5	0.7 - 2.9	0.4 - 1.6	0.4 - 1.4	0.2 - 0.7	0.1 - 0.5	2.3 - 9.1
Energy Crops	0 - 0	0.1 - 0.4	0.6 - 2.5	2.6 - 10	0.8 - 3	0.9 - 3.5	3.3 - 12.7	0 - 0.2	0 - 0	8.3 - 32.3
Sub-Total	*4.4 - 4.9*	*11.5 - 13.1*	*22.7 - 30.5*	*20.1 - 38.6*	*14 - 19.8*	*5.5 - 9.7*	*12.8 - 24.8*	*12.4 - 14.9*	*17.3 - 21.9*	*120.8-178.2*
Renewable gas from MSW										
MSW	0.3 - 1.2	0.9 - 3.5	1 - 4	0.5 - 1.8	1.4 - 5.2	0.4 - 1.7	0.8 - 3.2	0.5 - 1.9	1.1 - 4.2	6.9 - 26.8
RNG from P2G / Methanation										
P2G / Methanation										42.3
Totals	4.7 - 6.2	12.4 - 16.6	23.7 - 34.5	20.6 - 40.4	15.4 - 25	6 - 11.3	13.7 - 28	12.9 - 16.9	18.3 - 26.1	170.0-247.3