Study on the
Use of Biofuels
(Renewable Natural Gas)
in the Greater Washington, D.C. Metropolitan Area

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Executive Summary

This study was commissioned and completed to fulfill AltaGas Merger Commitment No. 6, as stipulated in Formal Case No. 1142 (Order No. 19396) of the Public Service Commission of the District of Columbia (D.C.)[1] and AltaGas Merger Commitment No. 5, as stipulated in Formal Case No. 9449 (Order No. 88631) of the Public Service Commission of Maryland.[2] To achieve this, ICF characterizes the technical and economic potential for renewable natural gas (RNG) as a greenhouse gas (GHG) emission reduction strategy, with particular focus on local or regional resources in the Greater Washington, D.C. metropolitan area. Further, the study seeks to support AltaGas' efforts to improve understanding of the extent to which delivering RNG to all sectors of the regional economy can contribute to broader GHG emission reduction initiatives.

Washington Gas Light Company (WG) is the largest natural gas local distribution company serving the Greater Washington, D.C. metropolitan area, distributing natural gas to nearly 1.2 million customers. To serve these 1.2 million customer meters, WG has an annual throughput of roughly 165 trillion British thermal units per year (tBtu/y), with WG sales representing over half that volume, and the remainder met by third-party suppliers.

Washington, D.C., Maryland, and Virginia have made climate and clean energy commitments that will play critical roles in determining the pace of GHG emission reductions in each jurisdiction and that will directly impact the natural gas system. Natural gas use in various economic sectors makes up approximately 10% of the GHG emissions in the Greater Washington, D.C. metropolitan area. As such, it is critically important that stakeholders have a clear understanding of the potential role of RNG as a strategy to reduce GHG emissions.

RNG is derived from biomass or other renewable resources and is a pipeline-quality gas that is fully interchangeable with conventional natural gas. As RNG is a "drop-in" replacement for natural gas, it can be safely employed in any end use typically fueled by natural gas, including electricity production, heating and cooling, industrial applications, and transportation. Today, about 50 tBtu per year of RNG from landfills, dairy digesters, and water resource recovery facilities (WRRFs) is injected into pipelines, with production growing year-on-year.

Methodology

To achieve the study's objective, ICF sought to address several questions, including:

- How much RNG is potentially available in the near- to long-term future?
- What is the cost-effectiveness of RNG as a GHG mitigation strategy?
- What are the potential economic and environmental impacts of deploying RNG to help meet decarbonization objectives in the Greater Washington, D.C. metropolitan area?
- What are the key opportunities for and challenges inhibiting RNG deployment?

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[1] Public Service Commission of the District of Columbia, 2019. https://dcpsc.org/Newsroom/HotTopics/AltaGas-WGL-Holdings-Merger-Commitments-Tracking-M.aspx

[2] Public Service Commission of Maryland, 2018. https://www.psc.state.md.us/wp-content/uploads/Order-No.-88631-Case-No.-9449-AltaGas-WGL-Merger-Order.pdf

As a starting point, ICF applied the approach used in our recent American Gas Foundation assessment of the national supply and emission reduction potential of RNG,[3] but with an additional and detailed focus on regional and local RNG resources relevant to the Greater Washington, D.C. metropolitan area.

ICF developed three resource potential scenarios by considering RNG production from nine feedstocks and three production technologies. The feedstocks include landfill gas, animal manure, WRRFs, food waste, agricultural residues, forestry and forest product residues, energy crops, the use of renewable electricity, and the nonbiogenic fraction of municipal solid waste (MSW). These feedstocks were assumed to be processed using one of three technologies to produce RNG: anaerobic digesters, thermal gasification systems and power-to-gas (P2G) in combination with a methanation system.

RNG Potential and Costs

ICF developed three RNG production scenarios: Conservative Low, Achievable, and Aggressive High, varying both the assumed utilization of existing resources as well as the rate of project development required to deploy RNG at the volumes presented. ICF estimates that the resource potential scenarios will yield between 1,890 tBtu/y and 7,160 tBtu/y of RNG production by 2040. For comparison, the United States consumed approximately 17,500 tBtu of natural gas in 2018 in the residential, commercial, transportation, and industrial sectors.

In other words, using ICF's balanced assumptions regarding feedstock utilization and technology deployment in the Achievable scenario, there is enough national RNG production potential to displace upward of 25% of total natural gas consumption in direct use applications today. This does not include any potential reductions attributable to conservation or efficiency measures, nor does it account for the higher volumes in the Aggressive High scenario, which could displace upward of 40% of the conventional natural gas consumption in direct uses domestically today. Relative to the Greater Washington, D.C. metropolitan area, local RNG resources could displace up to 33% of natural gas consumption in the Achievable scenario, without accessing any potential RNG resources from outside the immediate region.

ICF developed assumptions for the capital expenditures and operational costs for RNG production from the various feedstock and technology pairings examined. ICF characterizes costs based on a series of assumptions regarding production facility size, gas conditioning and upgrading costs, compression, and interconnect for pipeline injection. The table below summarizes the estimated cost ranges for each RNG feedstock and technology.

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[3] ICF, 2019. Renewable Sources of Natural Gas: Supply and Emissions Reduction Assessment, https://www.gasfoundation.org/2019/12/18/renewable-sources-of-natural-gas/

Summary of Estimated Cost Ranges by Feedstock Type

	Feedstock	Cost Range ($/MMBtu)
Anaerobic Digestion	Landfill Gas	$7.10 – $19.00
	Animal Manure	$18.40 – $32.60
	Water Resource Recovery Facilities	$7.40 – $26.10
	Food Waste	$19.40 – $28.30
Thermal Gasification	Agricultural Residues	$18.30 – $27.40
	Forestry and Forest Residues	$17.30 – $29.20
	Energy Crops	$18.30 – $31.20
	Municipal Solid Waste	$17.30 – $44.20

GHG Emission Reductions from RNG

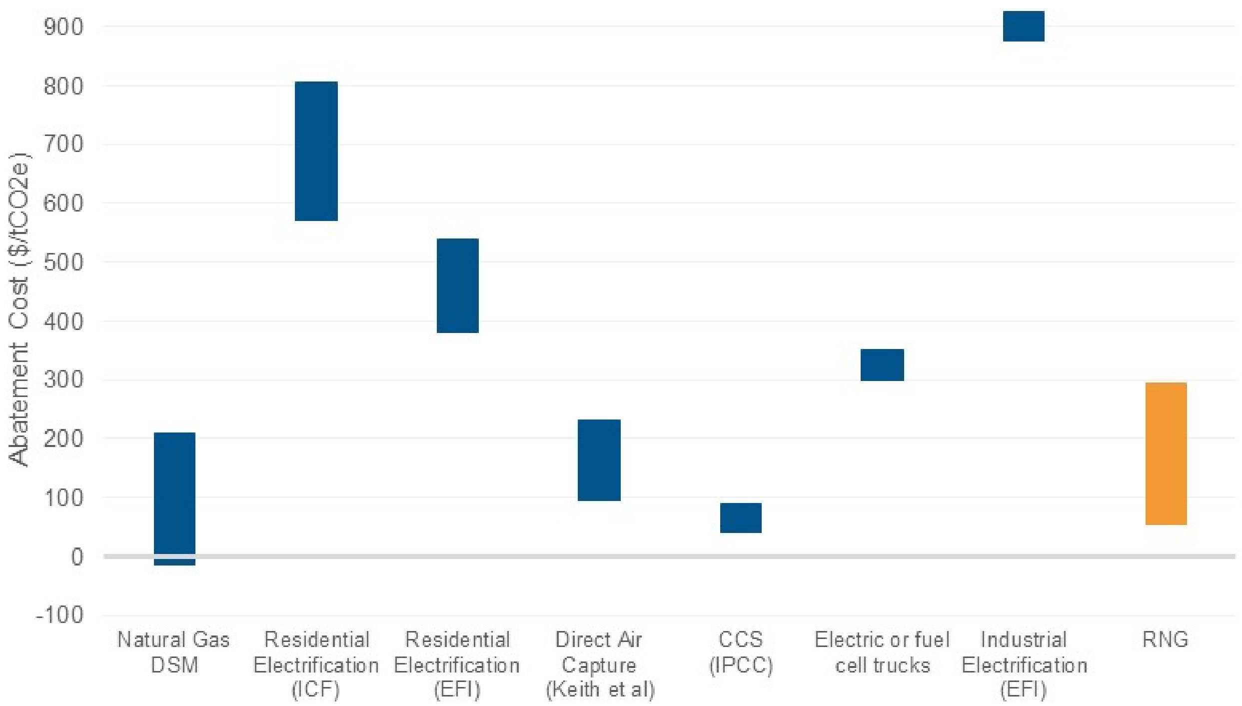
RNG represents a valuable renewable energy source with a low or net negative carbon intensity depending on the feedstock. The GHG emission accounting methodology has a significant impact on how carbon intensities for RNG are estimated, with a lifecycle approach reflecting the full emission reduction potential, such as including credit for avoided methane emissions.

ICF estimates that locally in the Greater Washington, DC. metropolitan area, 0.5 to 2.3 million metric tons (MMT) of GHG emissions could be reduced per year by 2040, and 13 to 44 MMT could be reduced in the South Atlantic region via the deployment of RNG based on the Conservative Low to Aggressive High scenarios. At the national level, 100 to 380 MMT of GHG emissions could be reduced per year by 2040. For comparison, D.C.'s total direct GHG emissions in 2017 were 7.3 MMT, while Greater Washington, D.C. metropolitan area's population-weighted share of Maryland and Virginia GHG emissions were 34 and 59 MMT in 2017 and 2015, respectively.

RNG can play an important and cost-effective role to achieve aggressive decarbonization objectives over the long-term future, with ICF estimating GHG emission reductions at a cost of $55 to $295 per ton of carbon dioxide equivalent (tCO_2e). RNG is more expensive than its fossil counterpart, but in a decarbonization framework the proper comparison for RNG is to other abatement measures that are viewed as long-term strategies to reduce GHG emissions.

In this context, RNG is a cost-competitive option. The figure below shows a comparison of selected measures across various key studies for specific abatement measures that are likely to be required for economy-wide decarbonization by the 2050 timeframe, including natural gas demand side management (DSM), electrification of certain end uses (including buildings and in the industrial sectors), direct air capture (whereby CO_2 is captured directly from the air and a concentrated stream is sequestered or used for beneficial purposes), carbon capture and storage (CCS), battery electric trucks (including fuel cell drivetrains), and RNG (from this study).

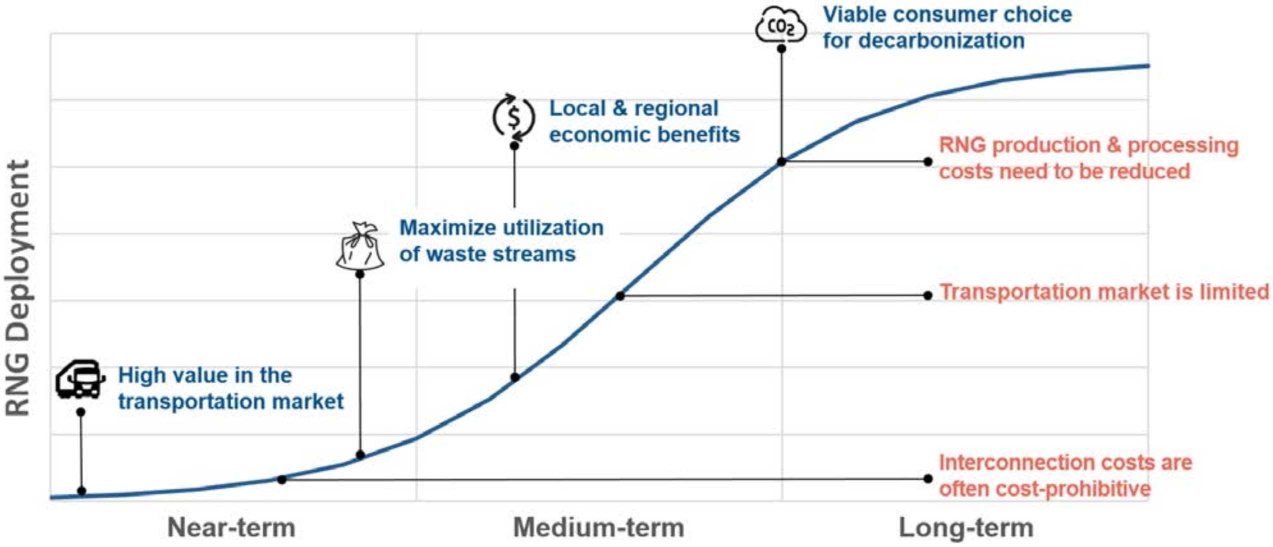
Full GHG Abatement Cost Ranges, Selected Measures, $/tCO$_2$e



Opportunities and Challenges

The figure below illustrates a subset of ICF's key findings across the technical, market, and regulatory and policy aspects of RNG deployment, including both **opportunities** and **challenges** envisioned along an illustrative RNG production potential curve. The table that follows the figure provides more detail regarding the opportunities and challenges for each key aspect of RNG deployment.

Overview of RNG Opportunities and Challenges



RNG Deployment	Opportunities	Challenges
Technical	▪ RNG is available today and is a valuable renewable resource with carbon-neutral, and in some cases carbon-negative, characteristics. ▪ RNG utilizes the same existing infrastructure as fossil natural gas. ▪ The long-term potential for RNG is linked in part to P2G and hydrogen.	▪ The technical potential for RNG production has been constrained to some extent by old policies. ▪ Location, accessibility, and competition of feedstocks will constrain RNG production potential. ▪ P2G and hydrogen technology will require significant cost reductions. ▪ Seasonal variability in systemwide demand will require the RNG production market to adapt.
Market	▪ RNG has high value in the transportation sector, which can be replicated in other end uses. ▪ RNG can deliver cost-effective GHG emission reduction measures for deep decarbonization. ▪ RNG helps maximize the utilization of evolving waste streams. ▪ RNG markets are evolving to thermal use by utilities and other sustainability goals. ▪ RNG helps give suppliers and consumers a viable decarbonization option in a changing market and policy environment.	▪ RNG markets beyond transportation fuel are nascent. ▪ RNG production and processing costs need to be reduced to improve cost-competitiveness. ▪ Limited availability of qualified and experienced RNG developers to expand RNG production in the near term. ▪ RNG costs more than conventional natural gas, when environmental benefits are not valued appropriately. ▪ Interconnection costs for RNG suppliers and developers can be prohibitively high.
Regulatory	▪ Introduction of standardized conditioning and interconnection tariffs. ▪ Legislation and regulations for both mandatory and voluntary RNG programs has emerged. ▪ Transportation policies currently favor RNG over fossil natural gas. ▪ RNG can help achieve aggressive decarbonization policies. ▪ Complementary policies could facilitate RNG feedstock collection (e.g., waste diversion and management). ▪ A robust regulatory framework will encourage deployment of RNG.	▪ The policy pathway promoting RNG in market segments other than transportation is unclear and not uniform. ▪ Some policymakers are singularly focused on electrification and unaware of the costs and benefits of RNG. ▪ Gas utilities are just beginning to gain cost recovery mechanisms for RNG procurement and investments. ▪ Gas safety, reliability, and quality rules and requirements need to be updated in line with current science/evidence.

Recommendations

ICF developed a series of recommendations that are presented across three areas:

- **Strategic direction** for policymakers and industry stakeholders;
- **Market approaches** that will help to advance RNG deployment; and
- **Regulatory actions** that will help to bring near- and long-term certainty needed to realize the potential for RNG as a cost-effective strategy for decarbonization.

Together, these three areas encompass the suite of actions that will help to realize the opportunities and overcome the challenges for RNG deployment in the Greater Washington, D.C. metropolitan area outlined in the previous table.

Strategic Direction for Policymakers and Stakeholders

ICF recommends developing a strategic roadmap for regional policymakers and stakeholders guided by the following vision statement and based on a set of clear principles:

***Vision Statement:** The Greater Washington, D.C. metropolitan area will maximize RNG throughput as a decarbonization strategy while maintaining the safety, reliability, and affordability of gas services.*

Principles:

- Produce and deliver RNG safely and cost-effectively to participants and end-use customers.
- Contribute to broader regional GHG emission reduction objectives.
- Implement a flexible regulatory and legislative structure that values RNG deployment.
- Engage proactively with key stakeholders through the implementation of the RNG strategy.

The roadmap can be implemented through aggressive but attainable RNG throughput targets. The Greater Washington, D.C. metropolitan area can achieve up to 5%, 15%, and 20% RNG throughput by 2025, 2030, and 2035, respectively. ICF's scenario analysis of RNG potential supports the volumes required to achieve these targets.

The strategic roadmap should also have a keen focus on reshaping the policy conversation at all levels to ensure that regulators and policymakers include RNG in federal and state programs that provide support to clean energy development. This includes the broad range of support currently afforded to renewable electricity, including research and development support (e.g., grants), as well as incentives for investment in clean energy commercial deployment in all sectors (e.g., investment tax credits).

Market Approaches to Spur RNG Deployment

- **Develop interconnection standards for RNG projects.** ICF recommends that gas utility stakeholders work closely with project developers to focus on interconnection. A consistent approach to evaluate RNG quality and constituent composition will facilitate the broader acceptance of different RNG feedstocks and encourage the development of RNG as a source for pipeline throughput and larger sources of demand (e.g., thermal use applications).
- **Deploy RNG into the transportation market.** The transportation sector is a natural fit for the near-term focus of RNG deployment in the region: the combination of higher conventional energy costs and existing incentives makes for a clear opportunity. The market

for RNG as a transportation fuel in the Greater Washington, D.C. metropolitan area should take advantage of other market forces, notably that California's market for natural gas as a transportation fuel is nearly saturated with RNG.

- **Establish common tracking across RNG markets**. A system to track and verify RNG in thermal use applications (i.e., outside of transportation and electricity sectors that currently have tracking systems in place) will become increasingly important as multiple sectors and regions seek to deploy RNG across various end uses, particularly for the multiple jurisdictions in the Greater Washington, D.C. metropolitan area.

Regulatory Approaches to Support RNG Deployment

ICF recommends a regulatory approach that stages potential RNG programs over the near-, mid-, and long-term horizons in an effort to reconcile conflicting requirements.

- **Develop pilot or voluntary RNG procurement programs.** ICF recommends a near-term regulatory approach that supports voluntary purchase of RNG through gas utility service providers to help foster market growth, improve customer awareness, and satisfy nascent demand.
- **Expand RNG in the transportation sector through infrastructure investments.** ICF recommends an innovative regulatory structure whereby utilities are able to invest in NGV fueling infrastructure, offer beneficial and attractive tariffs to CNG users, and partner with key stakeholders to deploy CNG in key vehicle market segments.
- **Implement a broad and stable policy framework such as a Renewable Gas Standard.** ICF recommends that the region adopt a Renewable Gas Standard (RGS). This is the most robust policy structure, and it will help drive consistent demand in a diverse set of end uses, and assist the market to transition from a near-term focus on the transportation sector to a mid- to long-term focus on stationary uses in thermal applications. The RGS will act as a utility procurement mechanism, thereby providing supply and price certainty without disrupting the success and market participation in existing programs driving existing RNG deployment.

1. Introduction

ICF was engaged by Washington Gas Light Company (WG) to fulfill AltaGas Merger Commitment No. 6, as stipulated in Formal Case No. 1142 (Order No. 19396) of the Public Service Commission of the District of Columbia (D.C.)[4] and AltaGas Merger Commitment No. 5, as stipulated in Formal Case No. 9449 (Order No. 88631) of the Public Service Commission of Maryland:[5]

> “AltaGas will provide $450,000 to fund a study to assess the development of renewable (bio) gas facilities in the Greater Washington, D.C. metropolitan area. The study will assess the potential environmental benefits of repurposing locally sourced waste streams into pipeline quality renewable gas, compressed natural gas and/or liquefied natural gas that can be used for carbon neutral vehicle fueling and onsite energy production. The study will evaluate the economic viability, identify operating challenges and solutions, and offer recommendations relating to regulatory and market approaches that can facilitate the utilization of renewable sources to support the achievement of local, state, and regional climate and energy plans. This study will be a single study funded by AltaGas with respect to all of the Washington Gas service territories and will be commenced within one year after Merger Close. Neither AltaGas nor any AltaGas affiliate will perform the study. The costs of this study shall not be recovered through Washington Gas’s utility rates.”

The primary objective of this study is to characterize the technical and economic potential for renewable natural gas (RNG) as a greenhouse gas (GHG) emission reduction strategy, with particular focus on local or regional resources in the Greater Washington, D.C. metropolitan area. Further, the study includes a series of deliverables that support AltaGas’ efforts to improve understanding of the extent to which delivering RNG to all sectors of the regional economy can contribute to broader GHG emission reduction initiatives.

Greater Washington, D.C. Metropolitan Area

The Greater Washington, D.C. metropolitan area had a population of over six million people in 2018,[6] making it the sixth largest metropolitan area in the United States and the largest metropolitan area in the Census Bureau’s South Atlantic division.[7] The metropolitan area includes all of D.C., as well as parts of Maryland, Virginia, and West Virginia, covering 24 counties, cities and districts. [8]

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[4] D.C. Public Service Commission, 2019. https://dcpsc.org/Newsroom/HotTopics/AltaGas-WGL-Holdings-Merger-Commitments-Tracking-M.aspx

[5] Public Service Commission of Maryland, 2018. https://www.psc.state.md.us/wp-content/uploads/Order-No.-88631-Case-No.-9449-AltaGas-WGL-Merger-Order.pdf

[6] US Census Bureau, 2019. https://www.census.gov/data/tables/time-series/demo/popest/2010s-counties-total.html

[7] US Census Bureau, 2019. https://www.census.gov/programs-surveys/metro-micro.html

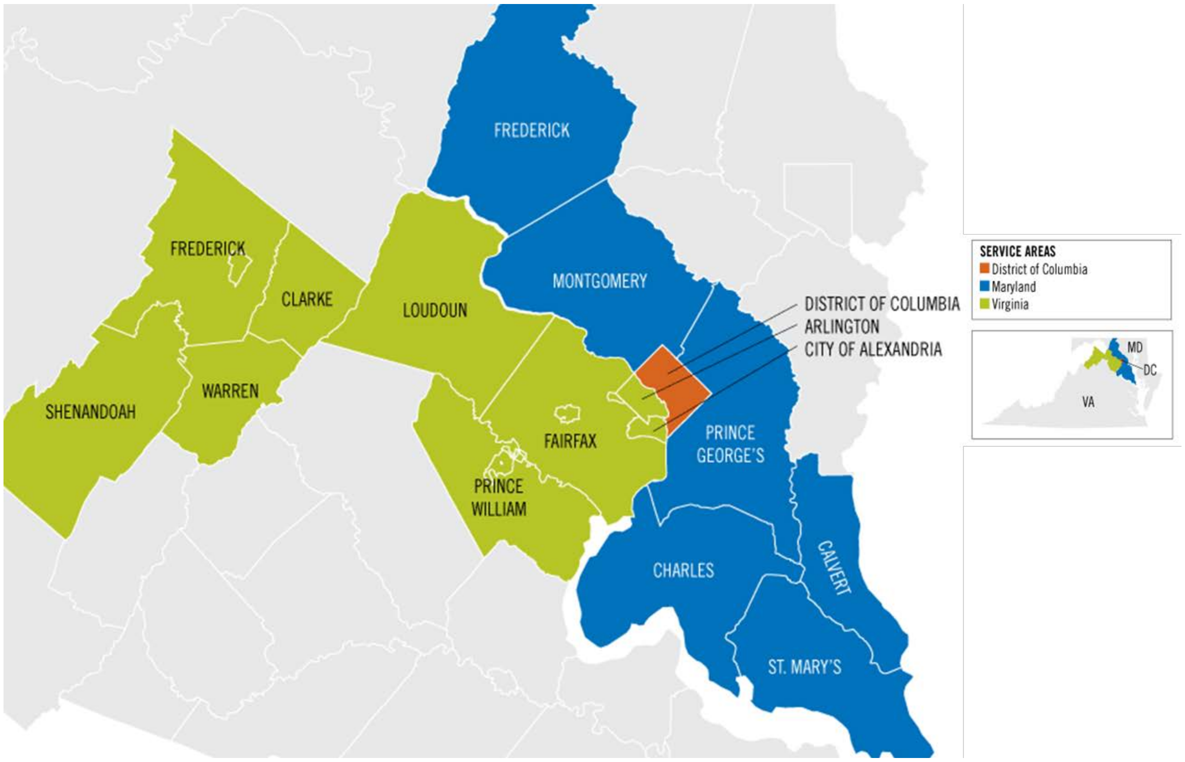
[8] US Census Bureau, 2019. https://www2.census.gov/geo/maps/metroarea/us_wall/Sep2018/CBSA_WallMap_Sep2018.pdf?#

The Greater Washington, D.C. metropolitan area has three major airports, four rail transit systems and over 10 bus transit systems; and it is home to numerous Fortune 500 companies, including AES Corporation, Capital One, Lockheed Martin and General Dynamics. The region is served by multiple electric and natural gas utilities, including WG, Pepco, Dominion and Columbia Gas of Virginia.

Washington Gas Light Company

WG is the largest natural gas local distribution company in the Greater Washington, D.C. metropolitan area, distributing natural gas to nearly 1.2 million customers in a service territory that covers areas of Washington, D.C., Maryland, and Virginia (see Figure 1).

Figure 1. WG Service Territory[9]



To serve these 1.2 million customer meters, WG has an annual throughput of roughly 165 trillion British thermal units per year (tBtu/y), with WG sales representing over half that volume. WG's natural gas system sees a significant winter peak, largely driven by space heating demand during the winter months.

Greenhouse Gas Emissions

The share of GHG emissions for each major emitting sector for Washington, D.C., Maryland, and Virginia is shown in Figure 2. In Maryland and Virginia, the transportation and power sectors account for the majority of GHG emissions. This is also true for D.C., although it is not clear from Figure 2. There is almost no direct power generation in Washington, D.C.; however

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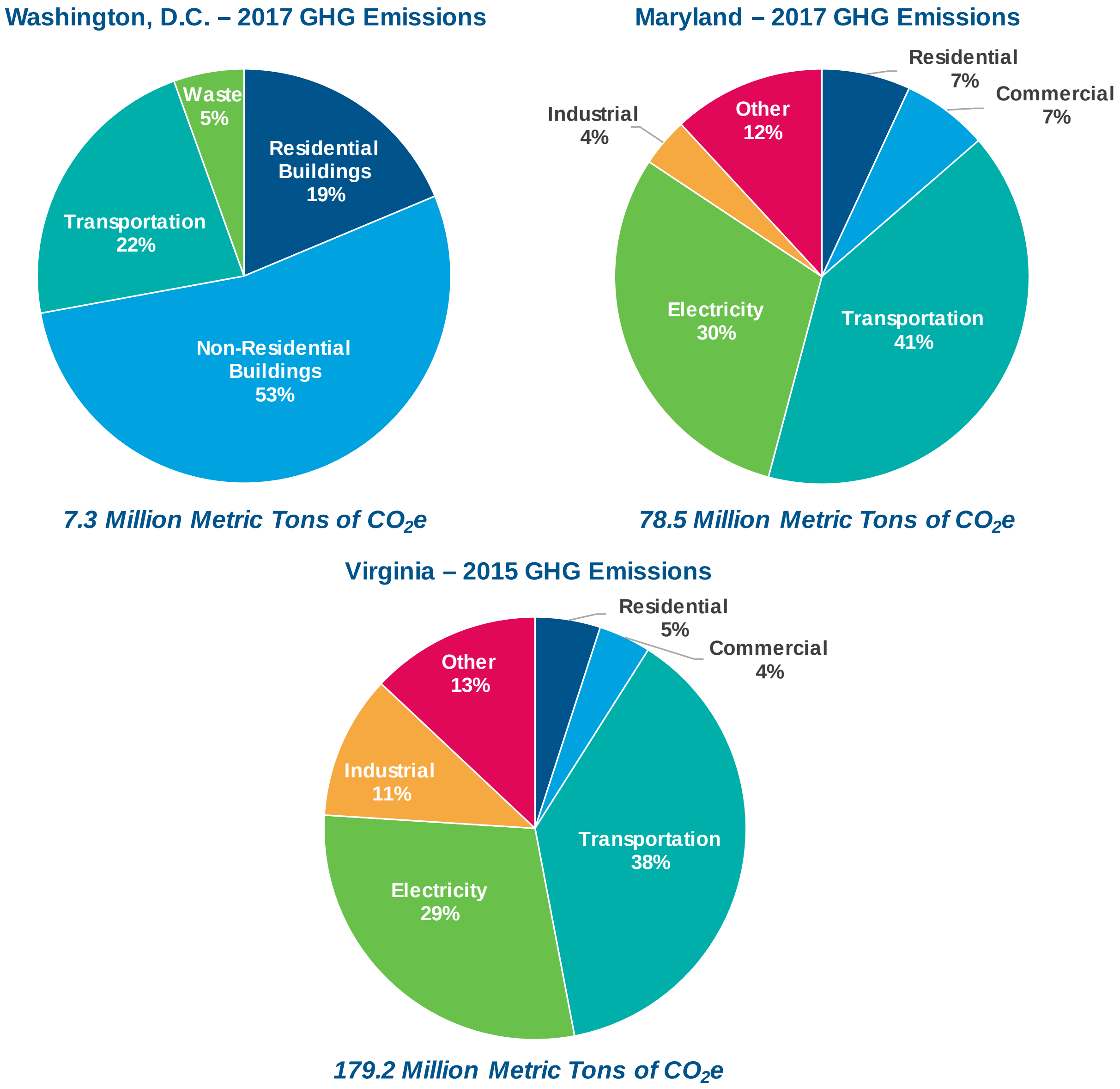
[9] https://www.washingtongas.com/builders-contractors/contractor-services/service-territory

the indirect emissions associated with electricity generation accounted for 60% of the total GHG emissions attributed to D.C. in 2017.[10] The emissions from the generation of the electricity used in D.C. are assigned to the end-use sector using the electricity. In 2017, electricity accounted for 76% of GHG emissions in the residential and nonresidential buildings sectors in D.C., while natural gas accounted for 23% and fuel oil 1% of GHG emissions.

Figure 2. Share of GHG Emissions for Washington, D.C., Maryland and Virginia by Sector[11]



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[10] Since 2013, emissions from power generation in the PJM have declined due to a reduction in coal generation and growth in natural gas generation in the region.

[11] Sources: D.C. Department of Energy and Environment, 2019, GHG Emission Inventory, https://doee.dc.gov/service/greenhouse-gas-inventories; Maryland MDE, 2019, GHG Emission Inventory, https://mde.state.md.us/programs/Air/ClimateChange/Documents/2017%20GHG%20Inventory/MD2017PeriodicGHGInventory.pdf; Virginia DEQ, 2017.

There are key differences between Maryland, Virginia, and D.C. related to emission trends and large emitting sectors. D.C. has the highest share of emissions from the building sector—primarily due to the emissions generated from electricity used in the buildings. The transportation sector accounts for 22% of D.C.'s emissions, a lower than average share when compared to regional and national emission levels. This lower share is a result of the smaller geographic area of D.C. and the high levels of public transportation usage in the Greater Washington, D.C. metropolitan area. In contrast, the share of transportation sector emissions is 41% in Maryland and 38% in Virginia, more in line with national averages.

Climate Policies

In recent years, climate policies have shifted from a national approach to local and regional approaches. In parallel with this geographic trend, there has also been a shift in the types of policies that are being proposed for reducing GHG emissions. National policies were broadly focused on regulation of GHG emissions in the power sector and direct fuel efficiency targets in transportation. There is a much larger degree of variation in approaches at the regional level toward emission reductions measures, although there is a broader national trend toward economy-wide decarbonization. Washington, D.C., Maryland, and Virginia have all made commitments to climate and clean energy goals that will play critical roles in determining the pace of GHG emission reductions in each jurisdiction, and will directly impact WG's natural gas system.

In D.C., there is a goal for 50% GHG emission reductions by 2032, carbon neutral transportation by 2045, and an economy-wide carbon neutrality goal by 2050. In Maryland, there is a goal for 40% GHG emission reductions by 2030 and a carbon neutral goal by 2050. Finally, in Virginia, there is a goal to cut carbon dioxide (CO_2) power plant emissions by 30% by 2030, and also an Executive Order to make 30% of energy production come from renewable resources by 2030 and for 100% of electricity to be produced from carbon-free sources by 2050.

The call for long-term, low-carbon targets will increasingly impact gas utility operations and the role that these companies will be asked to perform in meeting state and local GHG emission reduction targets. Many natural gas distribution companies continue to focus on ways that they can contribute to meeting these goals.

Natural gas utilities have a number of approaches to pursue as part of decarbonization strategies that help meet GHG emission targets. These measures focus on reducing consumer fossil fuel usage (including energy-efficiency measures and fugitive emissions reduction efforts) as well as applying new technologies such as hybrid heating systems or other approaches. However, increasing attention is being given to RNG as a cost effective and impactful option to reduce GHG emissions significantly from natural gas consumption, while maintaining the benefits of the natural gas system.

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. As a point of reference, the American Gas Association (AGA) defines RNG as:[12]

> *Pipeline-compatible gaseous fuel derived from biogenic or other renewable sources that has lower lifecycle carbon dioxide equivalent (CO_2e) emissions than geological natural gas.* [13]

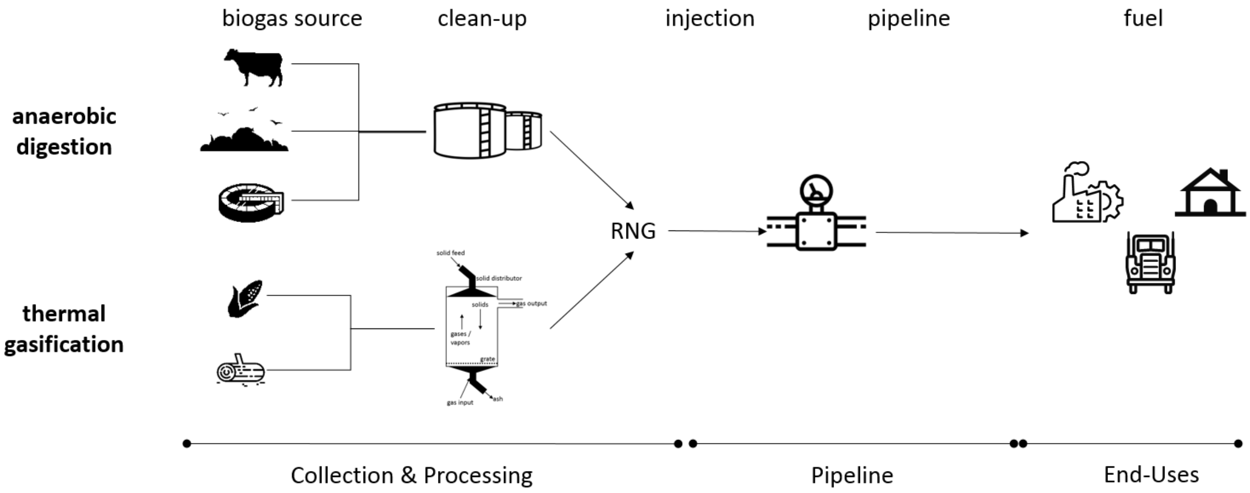
The following subsections introduce the RNG production technologies and corresponding feedstocks. Consistent with the approach undertaken in our recent American Gas Foundation assessment of the national supply and emission reduction potential of RNG, ICF assessed the production potential for renewable gas in two categories:[14]

- RNG from renewable feedstocks using anaerobic digestion and thermal gasification.
- RNG produced via combination of 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 is produced over a series of steps (see Figure 3): collection of a feedstock, delivery to a processing facility for biomass-to-gas conversion, gas conditioning, compression, and injection into the pipeline. ICF considered three production technologies: anaerobic digestion, thermal gasification, and P2G combined with methanation.

Figure 3. RNG Production Process via Anaerobic Digestion and Thermal Gasification



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

[13] ICF notes that this is a useful definition, but excludes RNG produced from the thermal gasification of the nonbiogenic fraction of municipal solid waste (MSW). In most cases, however, the thermal gasification of the nonbiogenic fraction of MSW will yield lower CO_2e emissions than geological natural gas. As a result, MSW is included as an RNG resource in this study.

[14] ICF, 2019. Renewable Sources of Natural Gas: Supply and Emissions Reduction Assessment, https://www.gasfoundation.org/2019/12/18/renewable-sources-of-natural-gas/

Anaerobic Digestion

The most common way to produce RNG today is via anaerobic digestion, whereby microorganisms break down organic material in an environment without oxygen. For example, National Grid's New York City Newtown Creek RNG demonstration project will be one of the first anaerobic digestion facilities in the United States that directly injects RNG into a local distribution system using biogas generated from a water and food waste facility.[15]

The four key processes in anaerobic digestion are:

- Hydrolysis
- Acidogenesis
- Acetogenesis
- Methanogenesis

Hydrolysis is the process whereby longer-chain organic polymers are broken down into shorter-chain molecules like sugars, amino acids, and fatty acids that are available to other bacteria. Acidogenesis is the biological fermentation of the remaining components by bacteria, yielding volatile fatty acids, ammonia, carbon dioxide, hydrogen sulfide, and other byproducts. Acetogenesis of the remaining simple molecules yields acetic acid, carbon dioxide, and hydrogen. Lastly, methanogens use the intermediate products from hydrolysis, acidogenesis, and acetogenesis to produce methane, carbon dioxide, and water, where the majority of the biogas is emitted from anaerobic digestion systems.

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

Thermal Gasification

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:

- Feedstock pre-processing in preparation for thermal gasification (not in all cases).
- Gasification, which generates synthetic gas (syngas) consisting of hydrogen and carbon monoxide (CO).
- Filtration and purification, where the syngas is further upgraded by filtration to remove remaining excess dust generated during gasification and other purification processes to remove potential contaminants like hydrogen sulfide and carbon dioxide.
- Methanation, where the upgraded syngas is converted to methane and dried prior to pipeline injection.

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[15] National Grid, 2019. https://www9.nationalgridus.com/non_html/NG_renewable_WP.pdf

While biomass gasification technology is at an early stage of commercialization, the gasification and purification steps remain challenging. 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 concluded that after "two decades" of experience in biomass gasification, "'tars' can be considered the Achilles heel of biomass gasification."[16] Over the last several years, however, a few commercialized technologies have been deployed to increase syngas quantity and prevent the fouling of other equipment by removing the residual tar before methanation. 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™).

ICF notes that biomass (particularly agricultural residues) is 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 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.

Power-to-Gas/Methanation

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. 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, where two electrodes operate in a liquid alkaline solution,
- Proton exchange membrane electrolysis, where a solid membrane conducts protons and separates gases in a fuel cell, and
- Solid oxide electrolysis, a fuel cell that uses a solid oxide at high temperatures.

The hydrogen produced from P2G is a highly flexible energy product that 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, and
- Converted to methane and injected into the natural gas system.

The last option, methanation, involves combining hydrogen with renewably sourced CO_2 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

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[16] 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.

in buildings, 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 CO_2 in biogas to produce the methane, creating a productive use for the CO_2.

RNG Feedstocks

RNG can be produced from a variety of renewable feedstocks, as described in Table 1.

Table 1. RNG Feedstock Types

Feedstock for RNG		Description
Anaerobic Digestion	Landfill gas (LFG)	A mix of gases, including methane (40–60%), produced by the anaerobic digestion of organic waste in landfills.
	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 annual crops that can be grown to supply large volumes of uniform and consistent feedstocks for energy production.
	Municipal solid waste (MSW) [17]	Refers to the nonbiogenic 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 and plastics.
P2G	Renewable electricity	Renewable electricity (presumably excess generation) serves as feedstock for P2G technologies. P2G produces hydrogen, which can be used as a form of energy storage, injected into the natural gas system, or converted to methane (RNG).

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[17] ICF notes that the nonbiogenic fraction of MSW does not satisfy the American Gas Association's definition of RNG; however, this feedstock was included in the analysis. The results associated with RNG potential from this nonbiogenic fraction of MSW are called out separately throughout the report.

RNG Policy Environment

At both the national and state levels, policy and regulatory frameworks for RNG are developing, albeit inconsistently: RNG producers and consumers often face multiple overlaying policies and regulations that both promote RNG production (or elements thereof) and consumption and create barriers to RNG use.

Current policies direct RNG consumption into the transportation sector, and to a lesser extent for on-site electricity generation. At the national level, the Federal Renewable Fuel Standard (RFS) provides financial incentive for RNG as a transportation fuel, while state programs such as California’s Low Carbon Fuel Standard (LCFS) and Oregon’s Clean Fuels Program (CFP) provide additional incentives for RNG consumption. In addition, there is growing interest from policymakers in other jurisdictions such as New York, Washington, and Colorado to implement LCFS-type programs that would incentivize RNG consumption in transportation markets.

In parallel to the incentives for RNG use in the transportation sector, Renewable Portfolio Standards (RPS) reward biogas combustion to generate on-site electricity as a source of compliance. Methane from landfill and wastewater treatment plants are eligible and participate in the RPSs in D.C. and Maryland.

Other policies are developing to support the potential growth of RNG beyond the transportation sector and on-site electricity generation, including programs that facilitate methane capture from feedstock sites and mandate waste diversion and collection. Jurisdictions and individual utilities are also pursuing regulatory initiatives that support the development of RNG, including voluntary tariffs and procurement programs, and RNG conditioning and interconnection tariffs (Section 6).

The limited policy structure in place today that supports RNG development, primarily as a transportation fuel, has already spurred considerable investment. Since 2015, RNG for pipeline injection has grown at a compound annual growth rate of about 30%, and ICF forecasts that this growth rate will increase slightly in the next two to four years. Despite these impressive gains, ICF considers the current policy structure inadequate to support the level of RNG production that is needed for it to contribute more meaningfully to decarbonization policies. In fact, there are regulations and market structures that hinder RNG production, including limited support for research and development, deficient cost-recovery mechanisms for utility investments in RNG, restrictive or time-consuming pipeline interconnection requirements, and decarbonization policies focused on technology rather than cost (e.g., fuel switching). In particular, the policies that focus on a specific technology as opposed to taking a technology-neutral approach to decarbonization inhibit RNG development. Instead, a technology-neutral approach would promote the utilization of the best technology for each application as determined by a thorough analysis, including elements such as cost, reliability, and resilience.

Even with the success of RNG in the transportation fuels market, the programs in place today do not provide the overall price and supply certainty that is required for larger volumes of RNG to be deployed. Furthermore, many policymakers and stakeholders do not recognize RNG’s broader prospects as a strategy to reduce GHG emissions, most notably those related to the potential supply and corresponding cost of developing those resources.

Policies related to building decarbonization often narrowly focus on electrification, rather than on a broader approach that prioritizes least cost emission reductions over specific technologies. For example, there is a growing trend for local governments—such as various cities in California and Massachusetts—to ban natural gas hookups and equipment in new buildings.[18] There are many opportunities to expand the use of RNG to all sectors of the economy, but one of the limiting factors is that decision-makers do not have adequate access to updated and reliable information regarding the resource potential, technology advancement, and costs of RNG.

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[18] City of Berkeley, 2019. https://www.cityofberkeley.info/.../2019-07-09_Item_21_Adopt_an_Ordinance_adding_a_new.aspx; Town of Brookline, 2019. https://www.brooklinema.gov/DocumentCenter/View/20101/Sustainable-Bldgs-WA-plus-Explanation-as-submitted?bidId=

2. RNG Resource Assessment

Key Takeaways

ICF estimates that there sufficient RNG feedstock resources are available at a local, regional, and national level for both near-term and long-term deployment of RNG to help decarbonize the natural gas system and contribute to the aggressive climate commitments in the region.

ICF anticipates that there is enough RNG production potential to displace upward of 25% of total natural gas consumption in direct uses today. This percentage does not include any potential reductions attributable to conservation or efficiency measures, nor does it account for RNG volumes available if fewer conservative assumptions are applied.

Assessment Methodology

The resource assessment methodology is based on the primary objective: to characterize the technical and economic potential for RNG as a cost-effective and impactful strategy to reduce GHG emissions from the natural gas system, with particular focus on local or regional resources in the Greater Washington, D.C. metropolitan area. The resource assessment is broken down into two areas: production technologies and feedstocks, outlined in Section 1.

ICF used a mix of existing studies, government data, and industry resources to estimate the current and future supply of the feedstocks. The table below summarizes some of the resources that ICF drew from to complete our resource assessment, broken down by RNG feedstock:

Table 2. Illustrative List of Data Sources for RNG Feedstock Assessment

Feedstock for RNG	Potential Resources for Assessment	
LFG	▪ U.S. EPA Landfill Methane Outreach Program	
Animal manure	▪ AgStar Project Database	▪ USDA Livestock Inventory (Cattle, Swine, etc.)
WRRFs	▪ U.S. EPA	▪ Water Environment Federation
Food waste	▪ U.S. DOE 2016 Billion Ton Report	▪ Bioenergy Knowledge Discovery Framework
Agricultural residue	▪ U.S. DOE 2016 Billion Ton Report	▪ Bioenergy Knowledge Discovery Framework
Forestry and forest product residue	▪ U.S. DOE 2016 Billion Ton Report	▪ Bioenergy Knowledge Discovery Framework
Energy crops	▪ U.S. DOE 2016 Billion Ton Report	▪ Bioenergy Knowledge Discovery Framework
MSW	▪ U.S. EPA	▪ Waste Business Journal

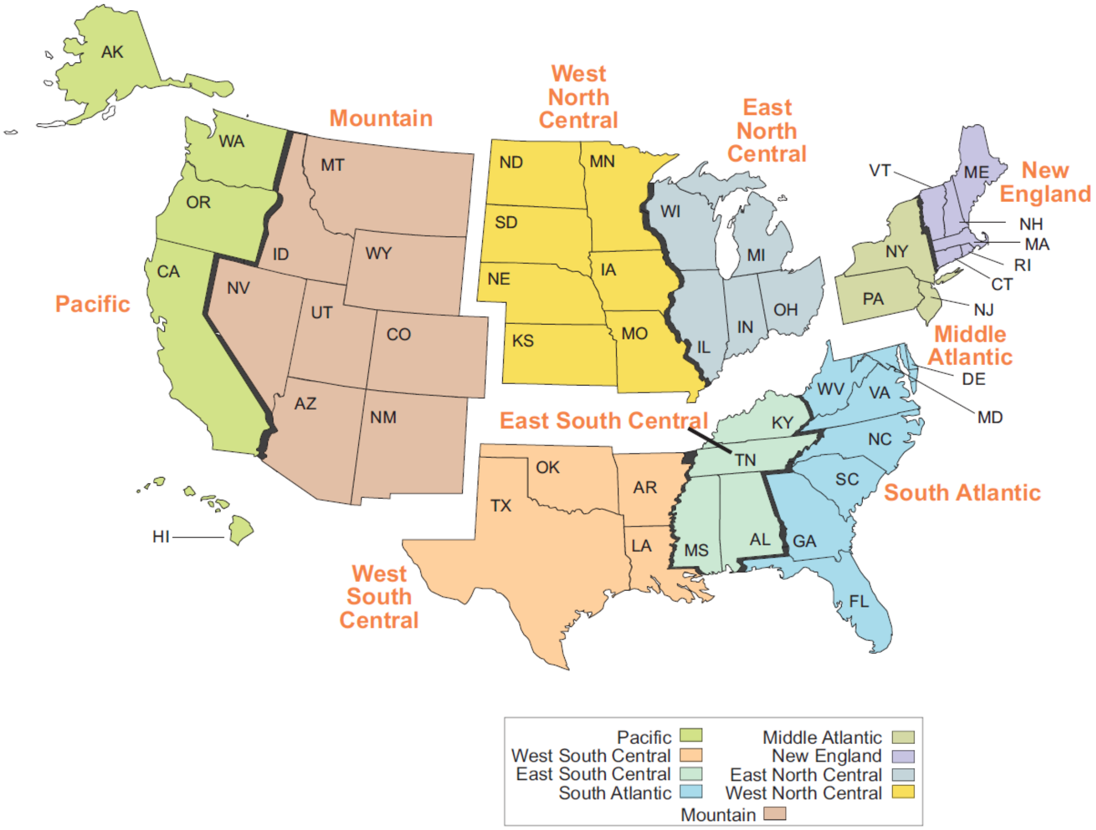
RNG potential is based on an assessment of resource availability—in a competitive market, that resource availability is a function of multiple factors, including but not limited to demand, feedstock costs, technological development, and the policies in place that might support RNG project development. ICF assessed the RNG resource potential of the different feedstocks that could be realized, given the necessary market considerations (without explicitly defining what those are), and then captured the corresponding costs and GHG emission reductions associated with these production estimates.

For the RNG market more broadly, ICF assumed that the market would grow at a compound annual growth rate slightly higher than we have seen over the last five years—a rate of about 35%.[19] ICF applied a logistic function to model the growth potential of the RNG production, 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.

Geographies

We present RNG potential at the local, regional, and national levels. The local level is defined as WG's service territory and is referred to as the Greater Washington, D.C. metropolitan area. The regional level is based on the U.S. Energy Information Administration's (EIA) South Atlantic Census region, shown below. The South Atlantic Census region incorporates all of the Greater Washington, D.C. metropolitan area, with a natural gas consumption level broadly analogous to the natural gas consumption in WG's current long-haul supply and distribution systems. The national level includes all regions other than the South Atlantic Census region.

Figure 4. EIA Census Regions



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[19] ICF estimates that there were about 17.5 trillion Btu (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%.

Scenarios

ICF developed three scenarios for each feedstock—with variations among conservative, balanced, and aggressive assumptions regarding utilization of the feedstock.

- **Conservative Low** represents a low level of feedstock utilization, with utilization levels depending on feedstock, with a range from 25% to 40% for feedstocks that were converted to RNG using anaerobic digestion technologies. The utilization rates of feedstocks for thermal gasification in the Conservative Low scenario ranged from 25% to 50%.
- **Achievable** represents balanced assumptions regarding feedstock utilization, with a range from 50% to 80% for feedstocks that were converted to RNG using anaerobic digestion technologies. The utilization rates of feedstocks for thermal gasification in the Achievable scenario ranged from 50% to 75%. This scenario reflects a plausible resource potential where feedstocks are more efficiently utilized and where there is a more favorable policy and regulatory environment that would deliver RNG resources greater than in the Conservative Low scenario.
- **Aggressive High** represents higher levels of utilization closer to the technical potential of RNG feedstock. Utilization levels vary by feedstock, with a range from 85% to 95% for feedstocks that were converted to RNG using anaerobic digestion technologies. The utilization rates of feedstocks for thermal gasification in the Aggressive High scenario ranged from 80% to 90%. It is worth noting that this scenario does not represent a maximum achievable or technical potential scenario.

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 the Conservative Low, Achievable, and Aggressive High RNG production scenarios, varying both the assumed utilization of existing resources as well as the rate of project development required to deploy RNG at the volumes presented.

Summary of RNG Potential by Geography

The following subsections summarize the RNG potential for each feedstock and production technology by geography of interest.

Greater Washington, D.C. RNG Resource Potential

Table 3 includes estimates for the Greater Washington, D.C. metropolitan area’s RNG potential in the Conservative Low, Achievable, and Aggressive High scenarios. The table shows the development potential of each feedstock in 2040, reported in units of trillion Btu per year (tBtu/y). For reference, with total throughput in WG’s natural gas system at roughly 165 tBtu/y, local RNG resources could displace up to 33% of natural gas consumption in the Achievable scenario without accessing any potential RNG resources from outside the immediate region.

Table 3. Estimated Annual RNG Production in the Greater Washington, DC Metro Area by 2040, tBtu/y

RNG Feedstock	Scenario		
	Conservative Low	Achievable	Aggressive High
LFG	7.0	17.0	24.4
WRRFs	1.2	2.5	4.6
Food Waste	0.3	6.2	7.8
MSW (nonbiogenic)	5.3	29.8	43.5
Total	**13.8**	**55.5**	**80.3**

The Greater Washington, D.C. metropolitan area's RNG resources are focused on waste in an urbanized region, including landfills, WRRFs, food waste, and MSW. Conversely, the local area is resource-limited for specific feedstocks—such as animal manure, agricultural residues, forestry and forest product residues, and energy crops—because it is a predominantly urbanized area. Despite the lack of these resources locally, the local area's access to waste from landfills, wastewater, the potential for diverted food waste, and MSW streams can still provide a significant amount of RNG as part of a broader decarbonization focus.

South Atlantic Regional RNG Resource Potential

Figures 5–7 illustrate ICF's South Atlantic Regional estimates for the Conservative Low, Achievable and Aggressive High potential scenarios. The figures show the development potential of each feedstock out to 2040, reported in units of trillion Btu per year (tBtu/y).

Figure 5. Estimated Annual RNG Production South Atlantic, Conservative Low Scenario, tBtu/y

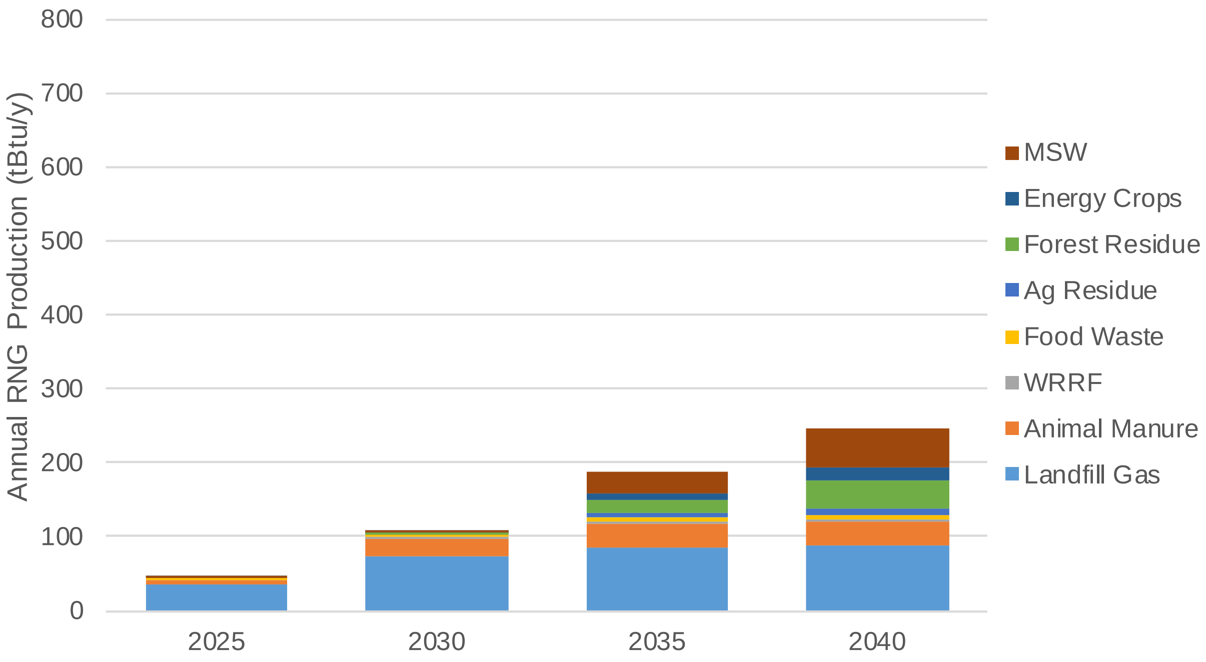


Figure 6. Estimated Annual RNG Production South Atlantic, Achievable Scenario, tBtu/y

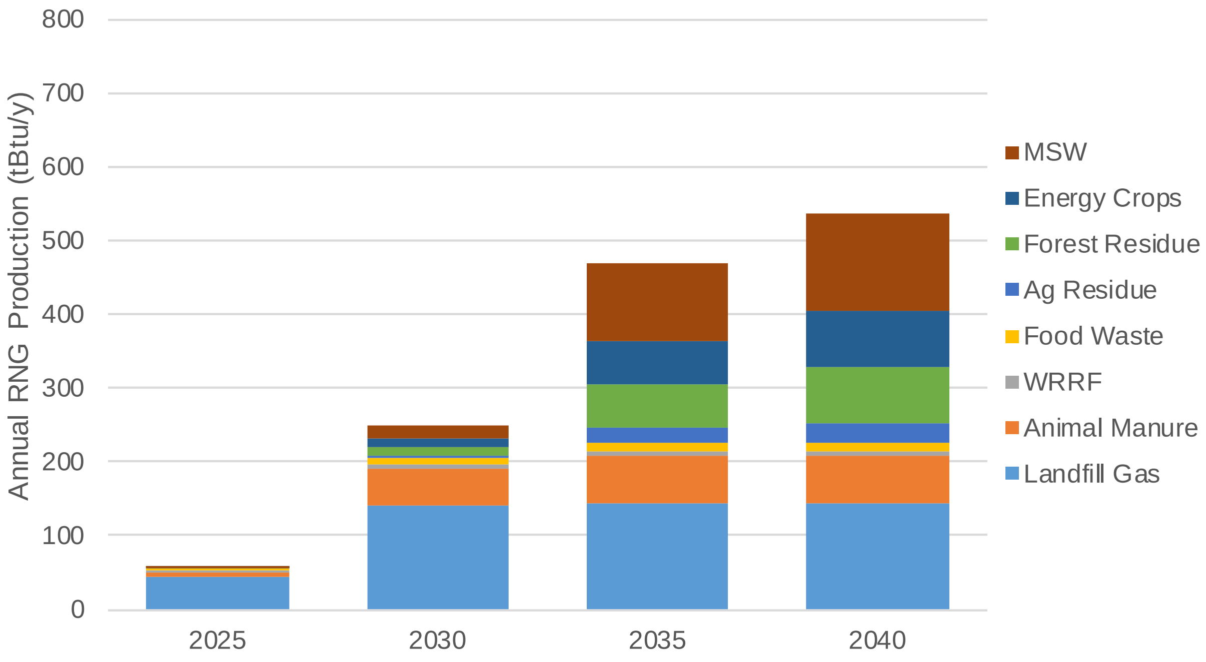
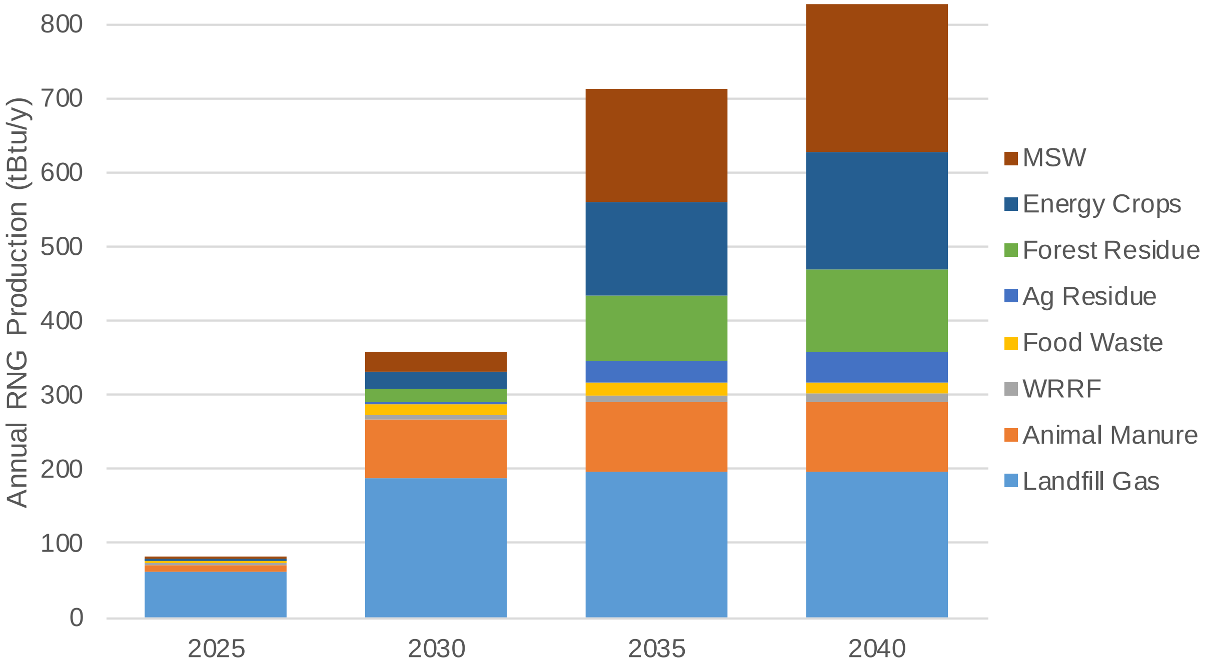


Figure 7. Estimated Annual RNG Production South Atlantic, Aggressive High Scenario, tBtu/y



National RNG Resource Potential

Figures 8–10 illustrate ICF's national estimates for the Conservative Low, Achievable, and Aggressive High potential scenarios. The figures show the development potential of each feedstock out to 2040, reported in units of tBtu/y.

Figure 8. Estimated National Annual RNG Production, Conservative Low Scenario, tBtu/y

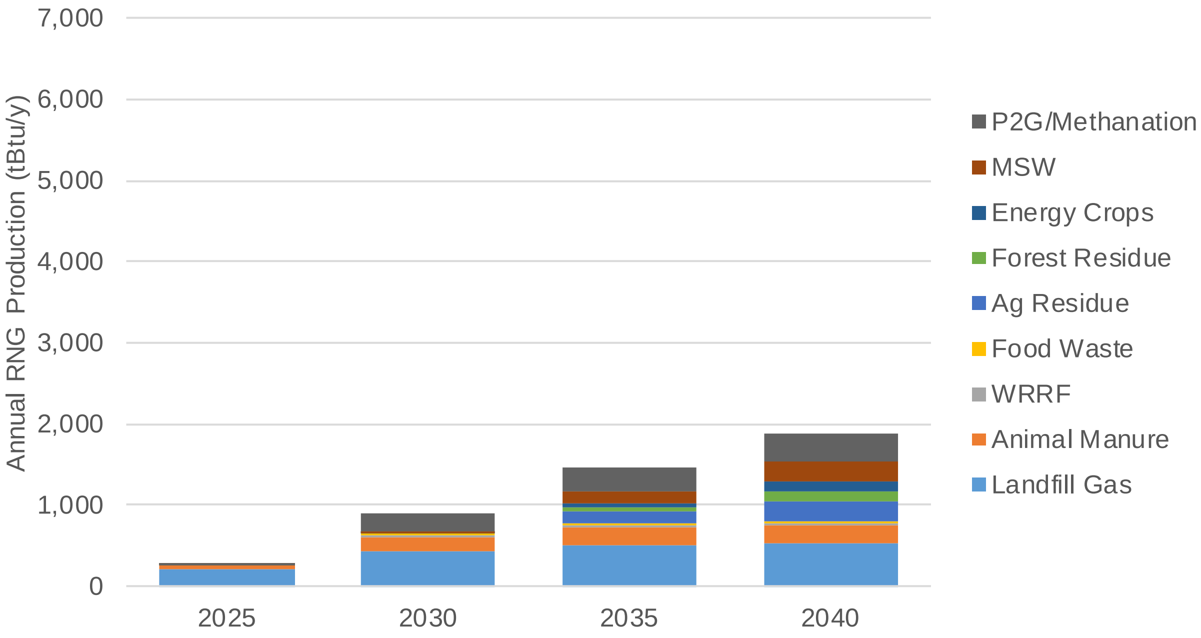


Figure 9. Estimated National Annual RNG Production, Achievable Scenario, tBtu/y

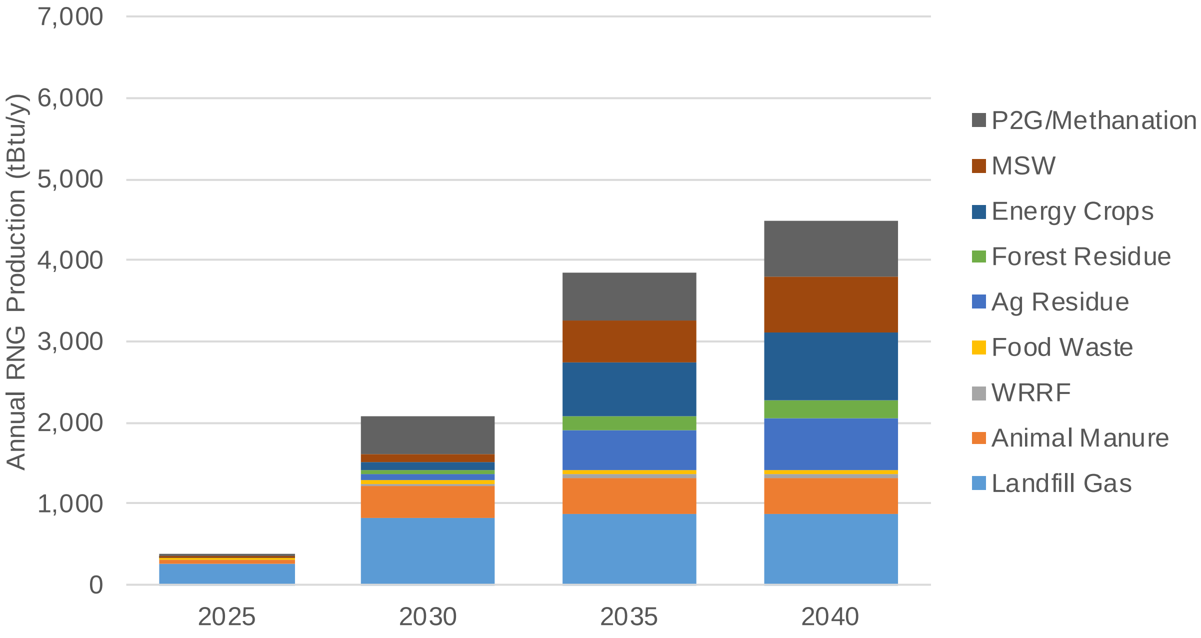
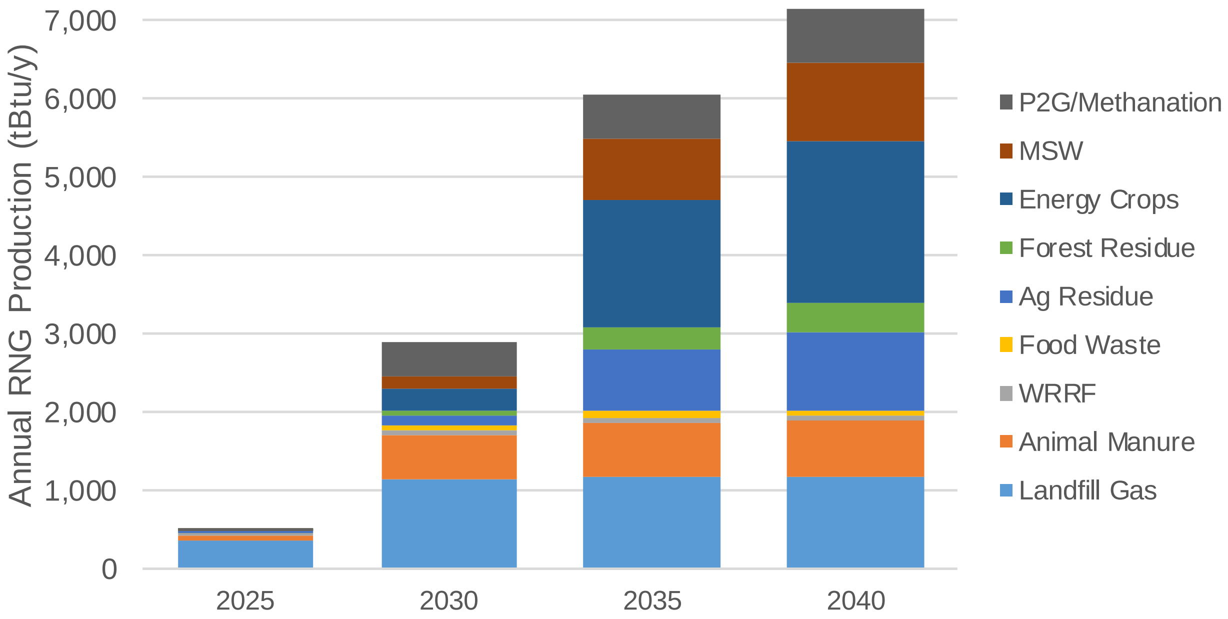


Figure 10. Estimated National Annual RNG Production, Aggressive High Scenario, tBtu/y



ICF estimates that the resource potential scenarios will yield between 1,890 tBtu/y and 7,160 tBtu/y of RNG production by 2040. For the sake of comparison, the United States consumed approximately 17,500 tBtu of natural gas in 2018 in the residential, commercial, transportation, and industrial sectors.[20]

In other words, using ICF's balanced assumptions regarding feedstock utilization and technology deployment in the Achievable scenario, there is enough RNG production potential to displace upward of 25% of total natural gas consumption in direct uses today. This percentage does not include any potential reductions attributable to conservation or efficiency measures, nor does it account for the higher volumes in the Aggressive High scenario, which could displace upward of 40% of the conventional natural gas consumption domestically today. Relative to WG, local RNG resources could displace up to 33% of direct use natural gas consumption in the Achievable scenario, without accessing any potential RNG resources from outside the immediate region.

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[20] 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.

Summary of RNG Potential by Scenario

Conservative Low Scenario

Table 4 below summarizes ICF's resource assessment for the Conservative Low RNG production potential scenario, reported in units of tBtu per year for local-, regional-, and national-level resources.

Table 4. Conservative Low RNG Production Potential Across Multiple Geographies, tBtu/y

RNG Feedstock		Geography		
		Greater D.C.	Regional	National
Anaerobic Digestion	Landfill Gas	7.0	88	528
	Animal Manure	--	32	231
	WRRFs	1.2	3	24
	Food Waste	0.3	6	29
Thermal Gasification	Agricultural Residue	--	10	255
	Forestry and Forest Product Residue	--	38	109
	Energy Crops	--	18	123
	Municipal Solid Waste	5.3	57	256
	Total	**13.8**	**252**	**1,556**

Achievable Scenario

Table 5 summarizes ICF's resource assessment for the Achievable RNG production potential scenario, reported in units of tBtu per year for local-, regional-, and national-level resources.

Table 5. Achievable RNG Production Potential Across Multiple Geographies, tBtu/y

RNG Feedstock		Geography		
		Greater D.C.	Regional	National
Anaerobic Digestion	Landfill Gas	17.0	145	866
	Animal Manure	--	63	462
	WRRFs	2.5	5	34
	Food Waste	6.2	13	64
Thermal Gasification	Agricultural Residue	--	27	641
	Forestry and Forest Product Residue	--	75	236
	Energy Crops	--	77	838
	Municipal Solid Waste	29.8	136	695
	Total	**55.5**	**542**	**3,834**

Aggressive High Scenario

Table 6 summarizes ICF’s resource assessment for the Aggressive High RNG production potential scenario, reported in units of tBtu per year for local-, regional-, and national-level resources.

Table 6. Aggressive High RNG Production Potential Across Multiple Geographies, tBtu/y

RNG Feedstock		Geography		
		Greater D.C.	Regional	National
Anaerobic Digestion	Landfill Gas	24.4	197	1,195
	Animal Manure	--	95	694
	WRRFs	4.6	9	62
	Food Waste	7.8	17	82
Thermal Gasification	Agricultural Residue	--	40	1,019
	Forestry and Forest Product Residue	--	113	381
	Energy Crops	--	163	2,093
	Municipal Solid Waste	43.5	200	1,019
	Total	**80.3**	**833**	**6,544**

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, RCRA prohibits open dumping of waste, and hazardous waste is managed from the time of its creation to the time of its disposal. Landfill gas (LFG) is captured from the anaerobic digestion of biogenic waste in landfills and produces a mix of gases, including methane, with a methane content generally ranging from 45% to 60%. 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 LFG is dependent on the materials in the landfill, and other factors, but is typically made up of methane, CO_2, nitrogen (N_2), hydrogen, CO, oxygen (O_2), sulfides (e.g., hydrogen sulfide or H_2S), ammonia, and trace elements like amines, sulfurous compounds, and siloxanes. RNG production from LFG requires advanced treatment and upgrading of the biogas via removal of CO_2, H_2S, siloxanes, N_2, and O_2 to achieve a high-energy (Btu) content gas for pipeline injection. Table 7 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, CO_2	40% – 60%	▪ High-selectivity membrane separation ▪ Pressure swing adsorption (PSA) systems ▪ Water scrubbing systems ▪ Amine scrubbing systems
Hydrogen sulfide, H_2S	0 – 1%	▪ Solid chemical scavenging ▪ Liquid chemical scavenging ▪ Solvent adsorption ▪ Chemical oxidation-reduction
Siloxanes	<0.1%	▪ Non-regenerative adsorption ▪ Regenerative adsorption
Nitrogen, N_2 Oxygen, O_2	2% – 5% 0.1% – 1%	▪ PSA systems ▪ Catalytic removal (O_2 only)

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. Due to the minimal and declining methane production of waste after 25 years in landfills, ICF considered only landfills that are either open or were closed post-2000. This reduced the number of landfills included in our analysis to just over 1,500.

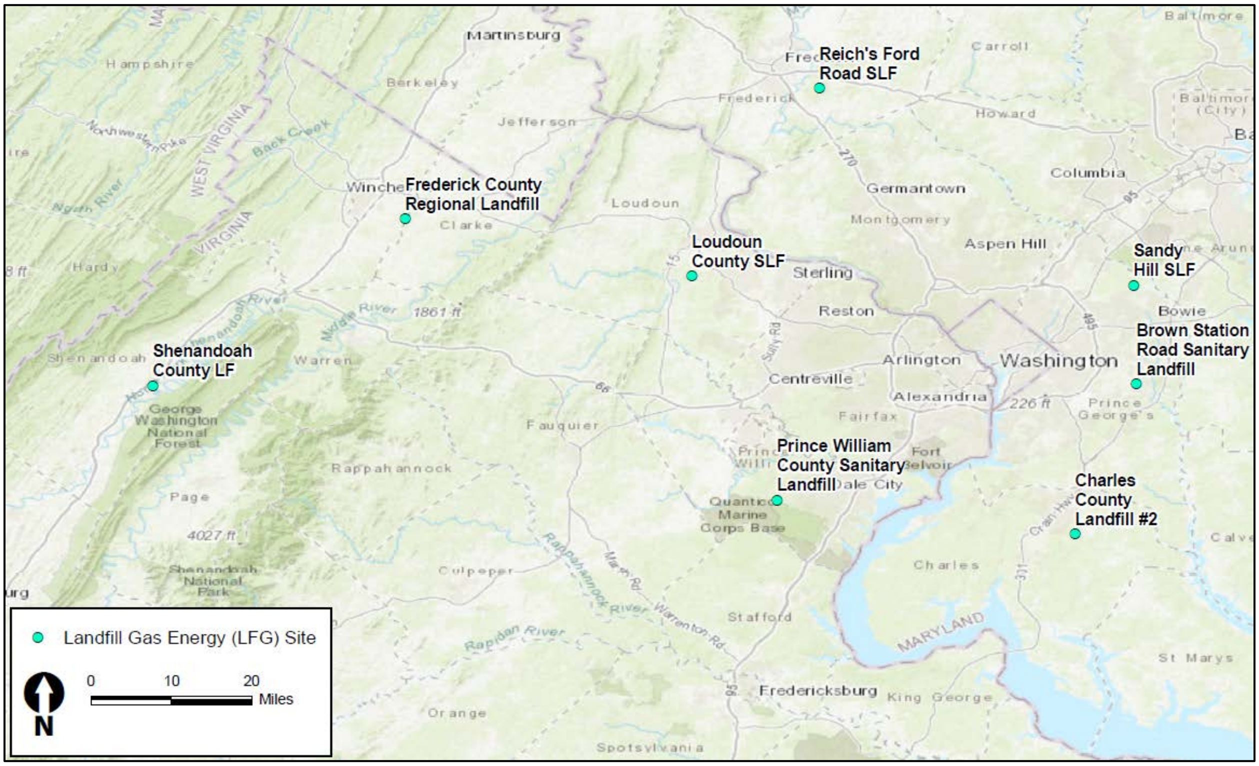
EPA's LMOP database shows that there are about 620 operational LFG to energy projects nationwide; however, only 60 (10%) of them produce RNG, and only 52 of those actually inject RNG into the pipeline. Most of the projects capture LFG and combust it in reciprocating engines to make electricity (72%) 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—EPA characterizes candidate landfills as those that are accepting waste or have been closed for five years or less, have at least one million tons of waste-in-place (WIP), and do not have operational, under-construction, or planned projects. Candidate landfills can also be designated based on actual interest by the site.

Local Landfills as an RNG Resource

Figure 11 shows the eight large landfills in WG's service territory that have more than one million tons of WIP.

Figure 11. Locations of Significant Landfills in the Greater Washington, D.C. Metropolitan Area



Of the eight landfills, five have LFG-to-energy operations, while the other three fall into EPA's candidate landfill category (see Table 8). If the LFG feedstock potential in WG's service territory is fully realized, the three candidate landfills could deliver up to 1 tBtu/y of RNG, while the remaining five LFG-to-energy facilities can deliver close to 5 tBtu/y of RNG into the natural gas pipeline system.

Table 8. Landfills in WG Service Territory

Name	LFG Generated (tBtu/y)	LFG Collection	Notes
Brown Station Rd (Calvert)	1.73	Yes	LFG-to-energy facility
Charles County #2	0.30	No	EPA candidate
Frederick County Regional	0.56	Yes	LFG-to-energy facility
Loudoun County	0.40	Yes	EPA candidate
Prince William County	1.10	Yes	LFG-to-energy facility
Reich's Ford Road (Frederick)	0.58	Yes	LFG-to-energy facility
Sandy Hill (Prince George's)	0.89	Yes	LFG-to-energy facility
Shenandoah County	0.28	Yes	EPA candidate
Total Potential	**5.84**		

Regional and National Landfills as an RNG Resource

The table below includes the number of landfills considered in each Census region.

Table 9. Number of Candidate Landfills by Census Region[21]

Landfill Status	South Atlantic	New England	Mid-Atlantic	East North Central	West North Central	East South Central	West South Central	Mountain	Pacific	National
Closed post-2000	**54**	33	16	51	21	19	25	24	58	**301**
Open	**221**	25	79	173	121	107	160	162	166	**1,214**
Total	**275**	58	95	224	142	126	185	186	224	**1,515**

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

Table 10 includes LFG-to-energy projects and candidate landfills broken down by Census region.

Table 10. LFG-to-Energy Projects and Candidate Landfills by Census Region[22]

Project Type	South Atlantic	New England	Mid-Atlantic	East North Central	West North Central	East South Central	West South Central	Mountain	Pacific	National
Electricity	**101**	28	64	105	23	20	19	18	71	**449**
Direct	**31**	1	12	26	17	6	10	1	5	**109**
RNG	**4**	1	9	13	5	4	19	1	4	**60**
Candidate Landfills	**88**	8	14	62	46	60	95	57	43	**473**

ICF developed assumptions for the resource potentials for RNG production at landfills in the three scenarios, considering the potential at LFG facilities with collection systems in place, LFG facilities without collection systems in place, and at candidate landfills identified by the EPA.

- In the Conservative 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.
- In the Achievable scenario, ICF assumed that RNG could be produced at 65% of the LFG facilities that have collection systems in place, 60% of the LFG facilities that do not have collections systems in place, and at 80% of the candidate landfills.
- In the Aggressive High scenario, ICF assumed that RNG could be produced at 95% of the LFG facilities that have collection systems in place, 85% of the LFG facilities that do not have collections systems in place, and at 90% of the candidate landfills.

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 a Microsoft Excel interface developed by the EPA to estimate the emissions rates for landfill gas and methane based on user inputs including WIP, facility location and climate conditions, and waste received per year. The estimated LFG output was estimated on a facility-by-facility basis. About 1,150 facilities reported methane content; for the facilities for which no data were reported, ICF assumed the median methane content of 49.6%.

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

Figures 12–14 show the Conservative Low, Achievable, and Aggressive High RNG resource potential from LFG between 2025 and 2040. Table 11 includes the total annual RNG production potential (in units of tBtu/y) for 2040 in the scenarios.

Figure 12. RNG Production Potential from Landfill Gas, Conservative Low Scenario, tBtu/y

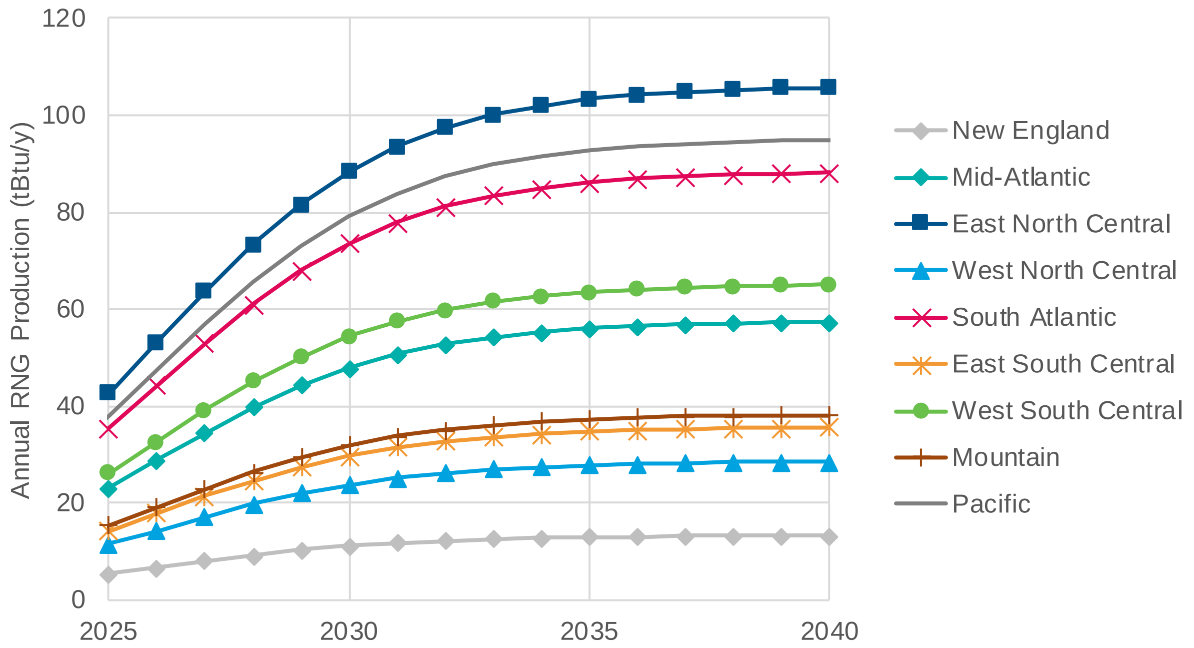


Figure 13. RNG Production Potential from Landfill Gas, Achievable Scenario, tBtu/y

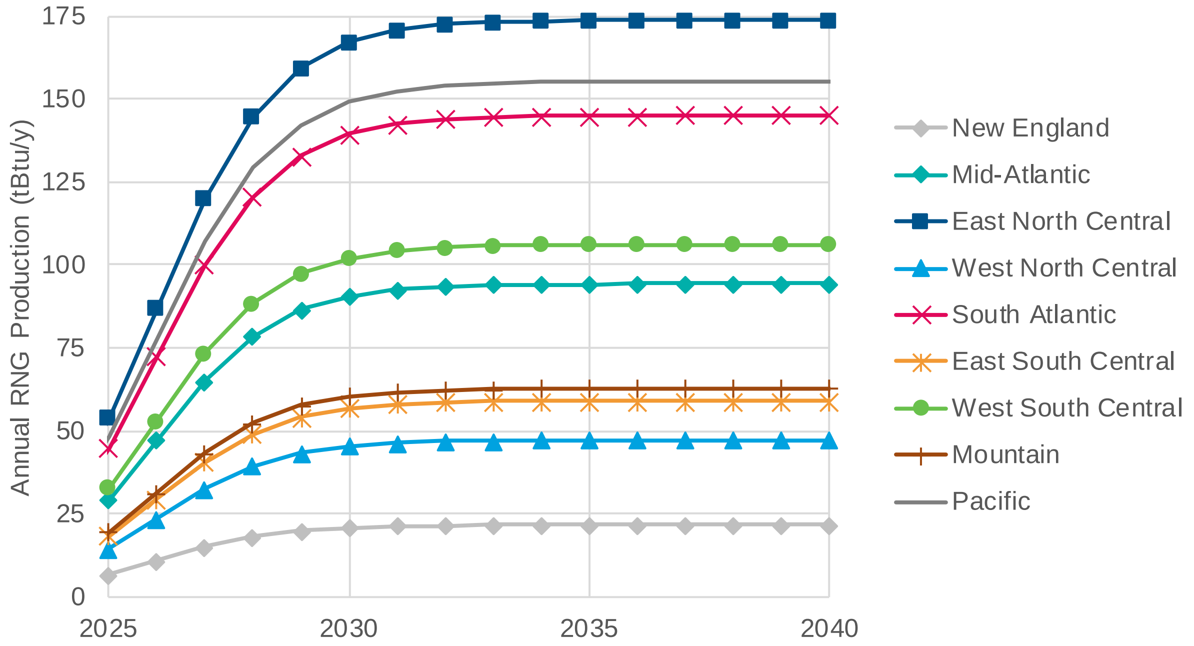
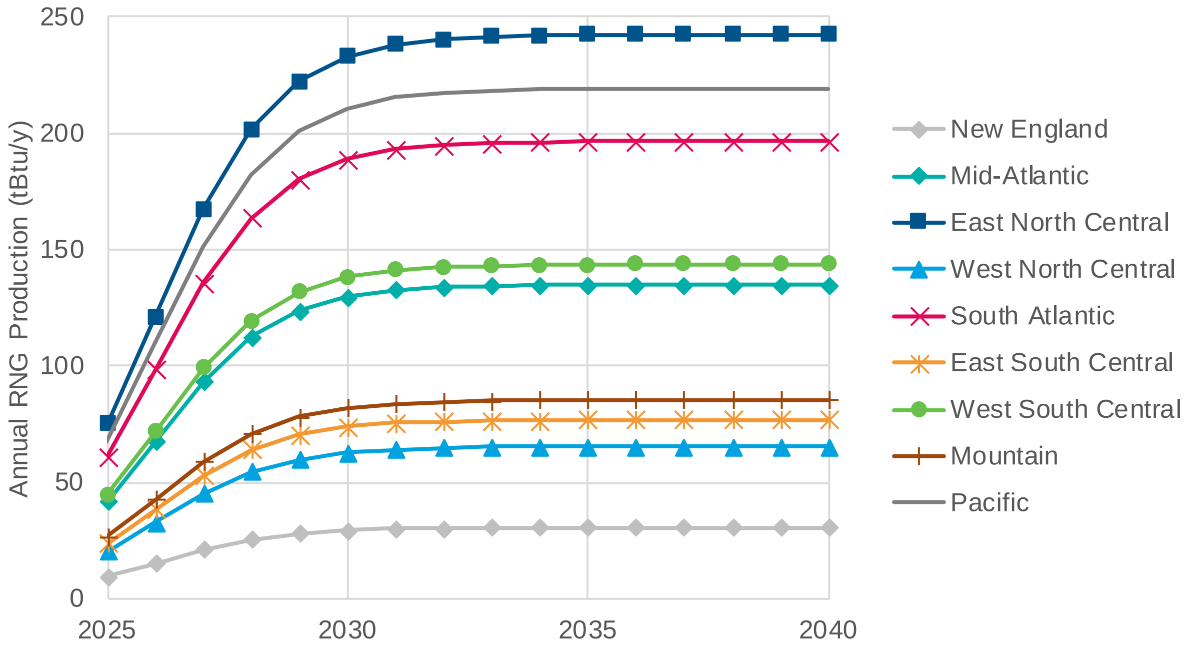


Figure 14. RNG Production Potential from Landfill Gas, Aggressive High Scenario, tBtu/y



As shown in Table 11, ICF estimates that 145 tBtu/y of RNG could be produced from LFG facilities in the South Atlantic Census region by 2040 in the Achievable scenario. At a national level, this increases to 866 tBtu/y of RNG by 2040 in the Achievable scenario, rising to 1,195 tBtu/y in the Aggressive High scenario.

Table 11. Annual RNG Potential from Landfills in 2040, tBtu/y

RNG Potential Scenario	**RNG Potential from Landfills, tBtu/y**									
	South Atlantic	**New England**	**Mid-Atlantic**	**East North Central**	**West North Central**	**East South Central**	**West South Central**	**Mountain**	**Pacific**	**National**
Conservative	**88.4**	13.3	57.5	106.2	28.6	35.7	65.3	36.2	95.2	**528.4**
Achievable	**145.0**	21.7	94.3	173.8	47.3	59.1	106.2	62.9	155.2	**865.6**
Aggressive	**196.5**	30.4	134.9	242.5	65.3	76.7	143.6	85.3	219.4	**1,194.6**

Animal Manure

Animal manure as an RNG feedstock is produced from the manure generated by livestock, including dairy cows, beef cattle, swine, sheep, goats, poultry, and horses. The 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:[23]

- 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

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[23] More information available online at https://www.epa.gov/agstar/benefits-anaerobic-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.
- Bolstering farm-community relationships: digesters help to reduce odors from 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. A variety of livestock manure processing systems are employed at farms today, including plug-flow or mixed plug-flow digesters, complete-mixed digesters, covered lagoons, fixed-film digesters, sequencing-batch reactors, and induced-blanked digesters. Most dairy manure projects today use 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 Table 12 are taken from a California Energy Commission report prepared by the California Biomass Collaborative.[24]

Table 12. Key Parameters for Animal Manure Resource RNG Potential

Animal Type	Total Wet Manure (lb/animal/day)	Moisture Content (% wet basis)	Higher Heating Value (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	10	91	6,839	0.20
Poultry, Layer Chickens	0.20	75	6,663	0.50
Poultry, Broiler Chickens	0.22	75	6,839	0.50
Poultry, Turkeys	0.58	74	6,727	0.50

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[24] 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.

The 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 five of the projects (2%) currently inject gas into the pipeline.

Local, Regional, and National Sources of Animal Manure as an RNG Resource

Although there is only one small-scale animal manure digester operational in the Greater Washington, D.C. metropolitan area, with the resultant biogas consumed on site, there are other animal manure feedstock sources in the regions in proximity of the Greater Washington, D.C. metropolitan area. For example, there are currently more than 30 digesters operational or under construction in Pennsylvania, and another 11 in North Carolina as of late 2019. Also relevant to the development of animal manure RNG in the region is the joint venture between Dominion Energy and Smithfield Foods, which is set to become the largest RNG producer in the United States, with animal manure-based RNG projects in development or proposed in North Carolina, Virginia, and Utah, with plans to expand to California and Arizona.

Figures 15 and 16 show the operational digesters in the region, while

Table 13 provides a summary of the types of projects by Census Region.

Figure 15. AgStar Projects in Surrounding Greater Washington, D.C. Metropolitan Area (North)

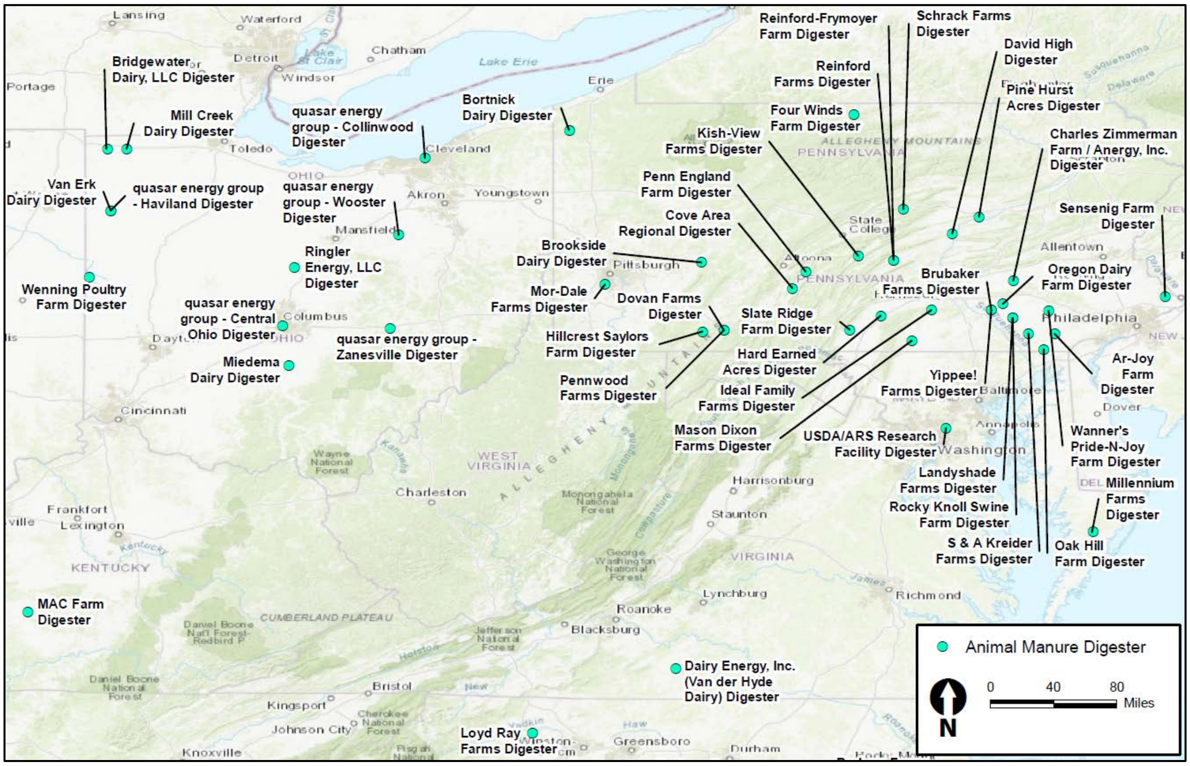


Figure 16. AgStar Project in Surrounding Greater Washington, D.C. Metropolitan Area (South)

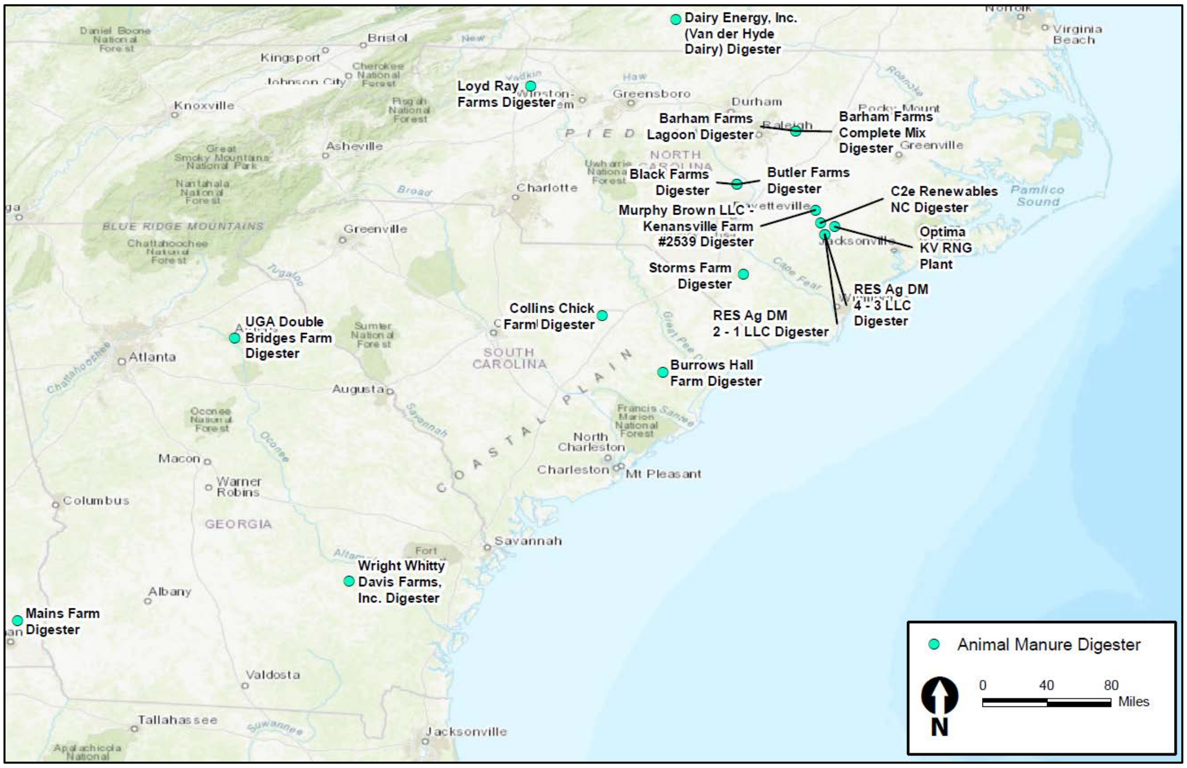


Table 13. Summary of AgStar Projects Using Anaerobic Digestion Systems, by Census Region

AgStar Projects	South Atlantic	New England	Mid-Atlantic	East North Central	West North Central	East South Central	West South Central	Mountain	Pacific	National
Project Status										
Operational	**20**	22	62	69	16	5	4	16	34	**238**
Construction	**2**	2	3	3	7	--	--	3	14	**34**
Project Type										
Electricity/Cogen	**19**	22	57	64	10	5	3	15	34	**229**
Flared	**--**	--	8	10	6	--	2	2		**28**
Pipeline	**1**	--	--	--	3	--	--	--	1	**5**
Animal Type										
Dairy	**6**	22	55	61	8	1	--	11	34	**198**
Swine	**12**	--	4	2	7	1	4	5	--	**35**
Poultry	**2**	--	1	1	--	3	--	--	--	**7**
Multiple	**--**	--	2	5	1	--	--	--	--	**8**

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

- In the Conservative Low scenario, ICF assumed that RNG could be produced from 30% of the animal manure, after accounting for the technical availability factor.
- In the Achievable scenario, ICF assumed that RNG could be produced from 60% of the animal manure, after accounting for the technical availability factor.
- In the Aggressive High scenario, ICF assumed that RNG could be produced from 90% of the animal manure, after accounting for the technical availability factor.

Figures 17–19 below show the Conservative Low, Achievable and Aggressive High 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 scenarios.

Figure 17. RNG Production Potential from Animal Manure, Conservative Low Scenario, tBtu/y

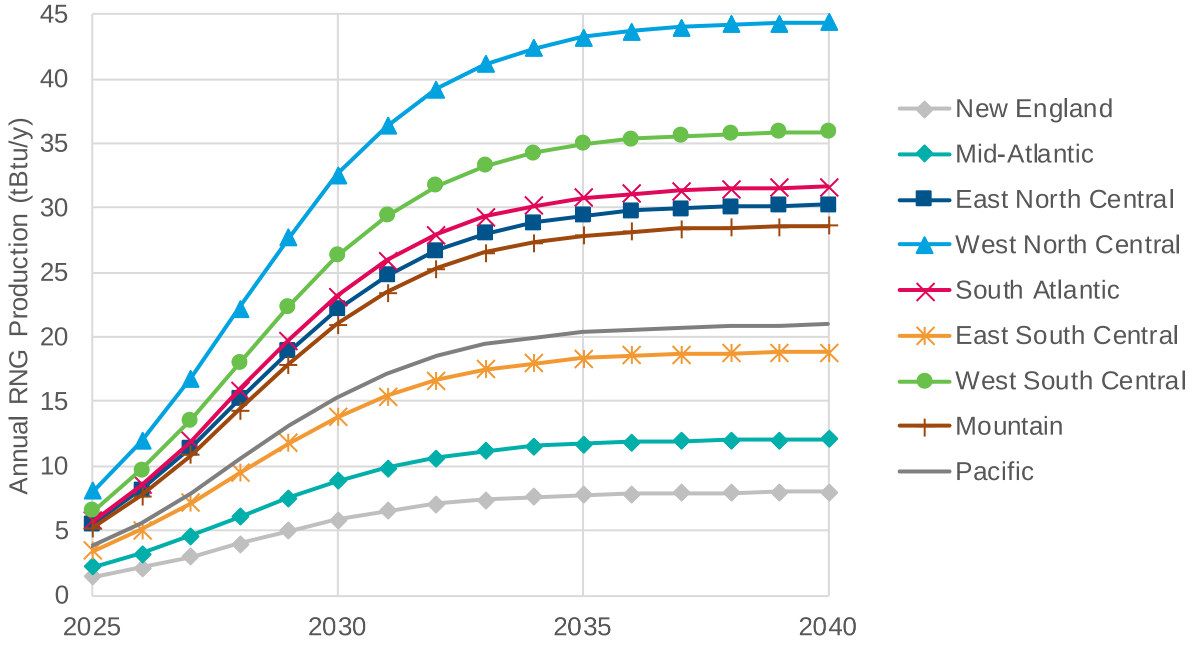


Figure 18. RNG Production Potential from Animal Manure, Achievable Scenario, tBtu/y

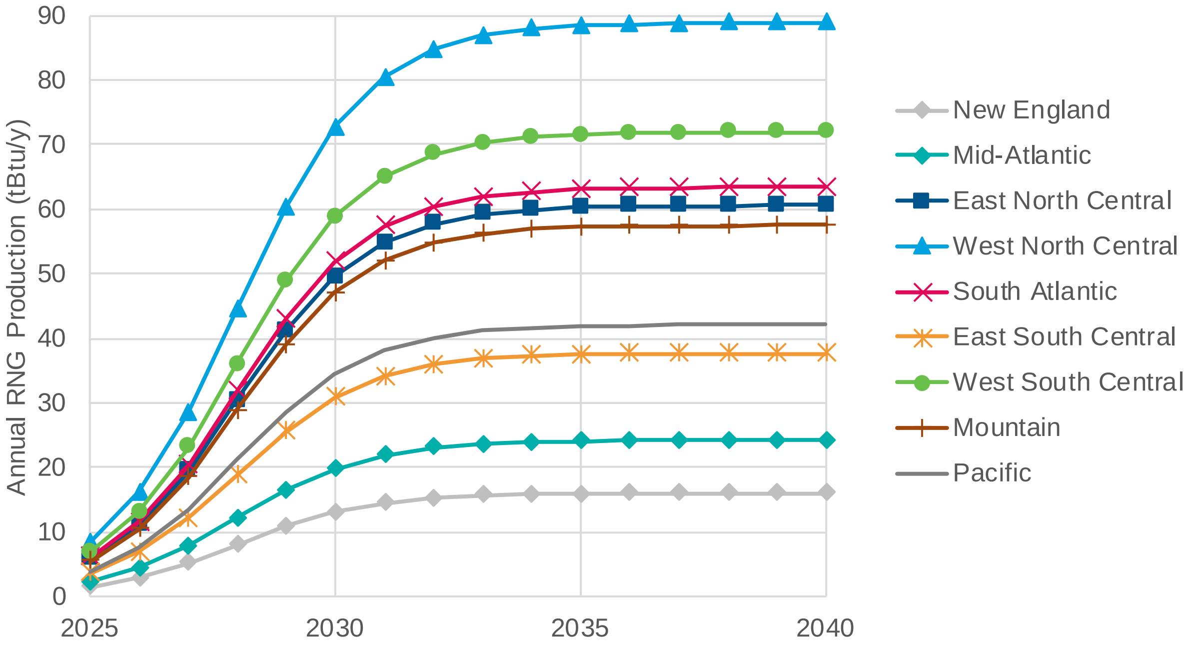


Figure 19. RNG Production Potential from Animal Manure, Aggressive High Scenario, tBtu/y

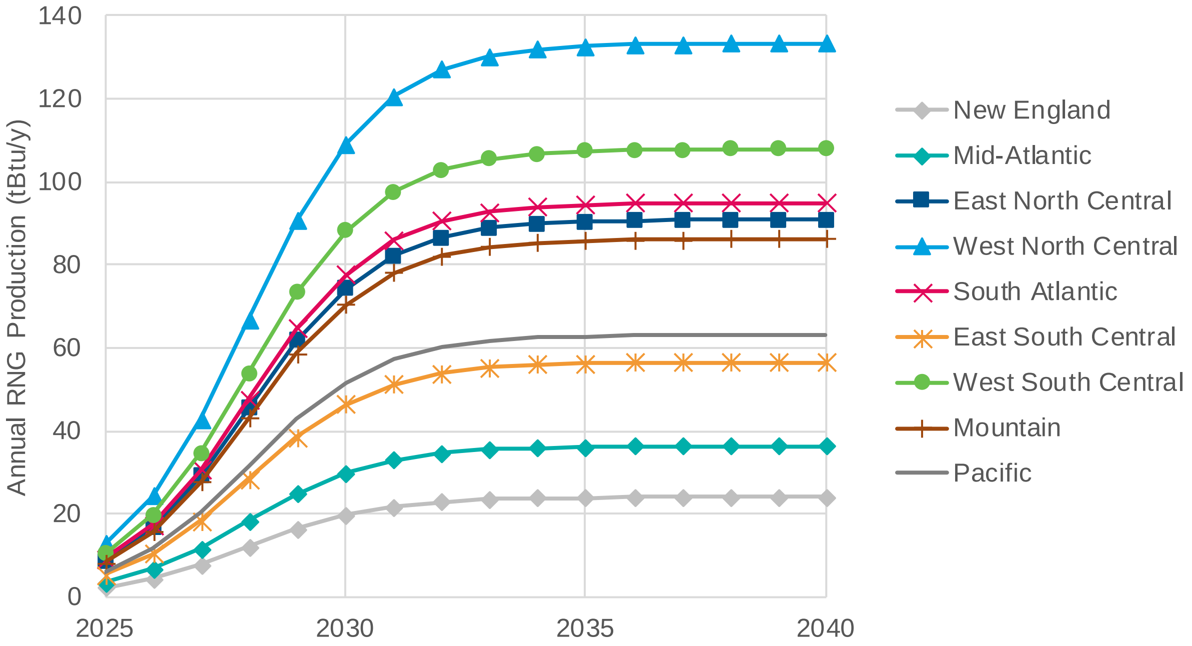


Table 14 shows that in the Achievable scenario, ICF estimates that up to 63 tBtu/y of RNG from animal manure could be produced in the South Atlantic Census region by 2040. This increases to 462 tBtu/y of RNG nationally, rising to 694 tBtu/y in the Aggressive High scenario.

Table 14. Annual RNG Production Potential from Animal Manure in 2040, tBtu/y

RNG Potential Scenario	**RNG Potential from Animal Manure, tBtu/y**									
	South Atlantic	**New England**	**Mid-Atlantic**	**East North Central**	**West North Central**	**East South Central**	**West South Central**	**Mountain**	**Pacific**	**National**
Conservative	**31.7**	8.0	12.1	30.3	44.5	18.9	36.0	28.7	21.0	**231.2**
Achievable	**63.4**	16.0	24.2	60.6	88.9	37.7	71.9	57.5	42.1	**462.3**
Aggressive	**95.0**	24.0	36.3	90.9	133.4	56.6	107.9	86.2	63.1	**693.5**

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, commercial water usage, or 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 that is expelled (legally or not) from a household and enters the drains. If storm water is included in the wastewater sewer flow, it may also contain components collected during runoff: soil, metals, organic compounds, animal waste, oils, and solid debris such as leaves and branches.

Processing of the influent to a large water resource recovery facility (WRRF) is composed typically of four stages: pre-treatment, primary, secondary, and tertiary treatments. These stages consist of mechanical, biological, and sometimes chemical processing.

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

The treated sludge from the WRRF can be landfilled, and during processing it can be treated via anaerobic digestion, thereby producing methane that 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 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.

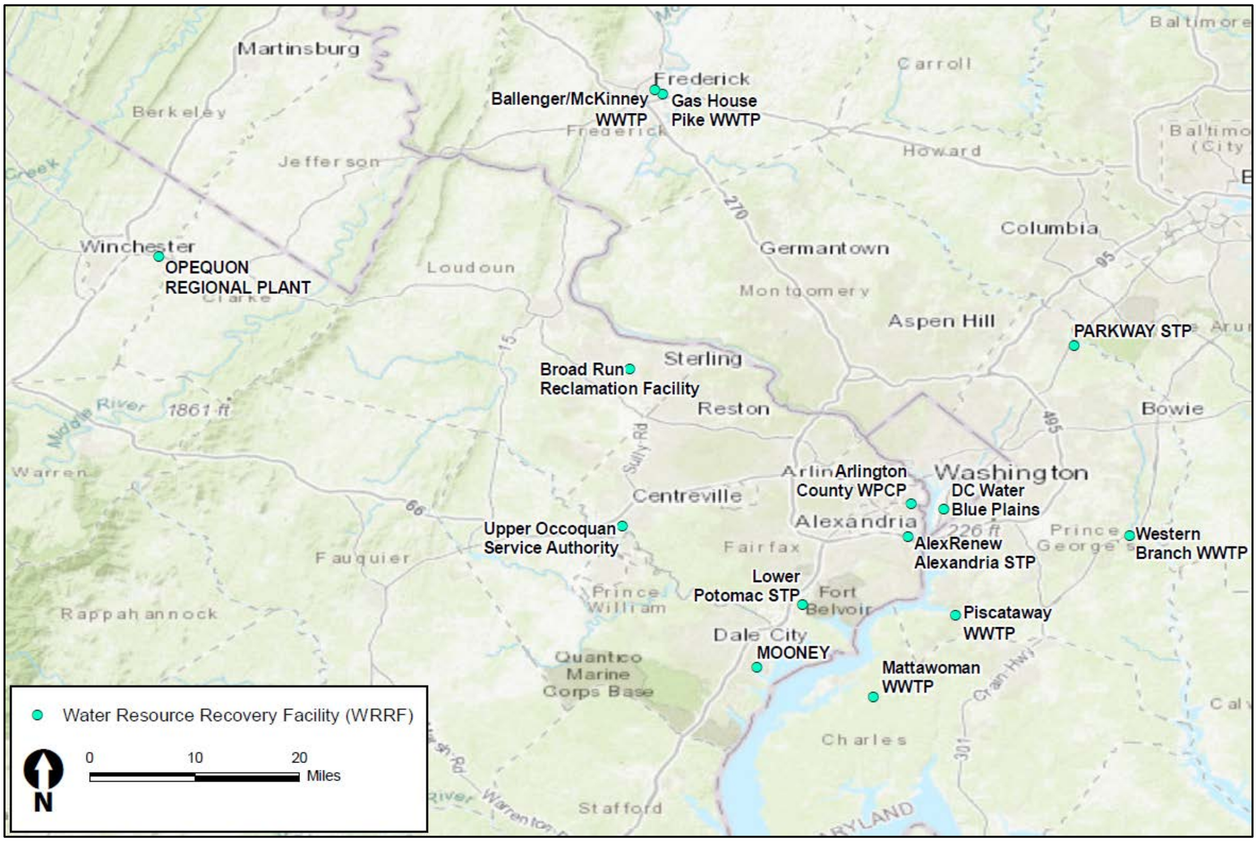
Local WRRFs as an RNG Resource

There are four WRRF facilities in the Greater Washington, D.C. metropolitan area that have anaerobic digestion (AD) systems, with a total flow of 460 MGD. DC Water's Blue Plains Advanced Wastewater Treatment Plant makes up 80% of this flow, with Alexandria City's AlexRenew WRRF and the Upper Occoquan Service Authority's WRRF making up another 18% of this flow (see "Spotlight" box for more detail on the Blue Plains facility).

There are 10 other WRRFs in the Greater Washington, D.C. metropolitan area that have high flow but do not yet have an AD system. These include WSSC's Piscataway WRRF, Arlington's Water Pollution Control Plant, and Fairfax County's Lorton WRRF, which have a combined flow of over 120 MGD.

Figure 20 shows the large WRRFs in the Greater Washington, D.C. metropolitan area, while Table 15 provides more detail on existing flows and RNG potential based on facility capacity.

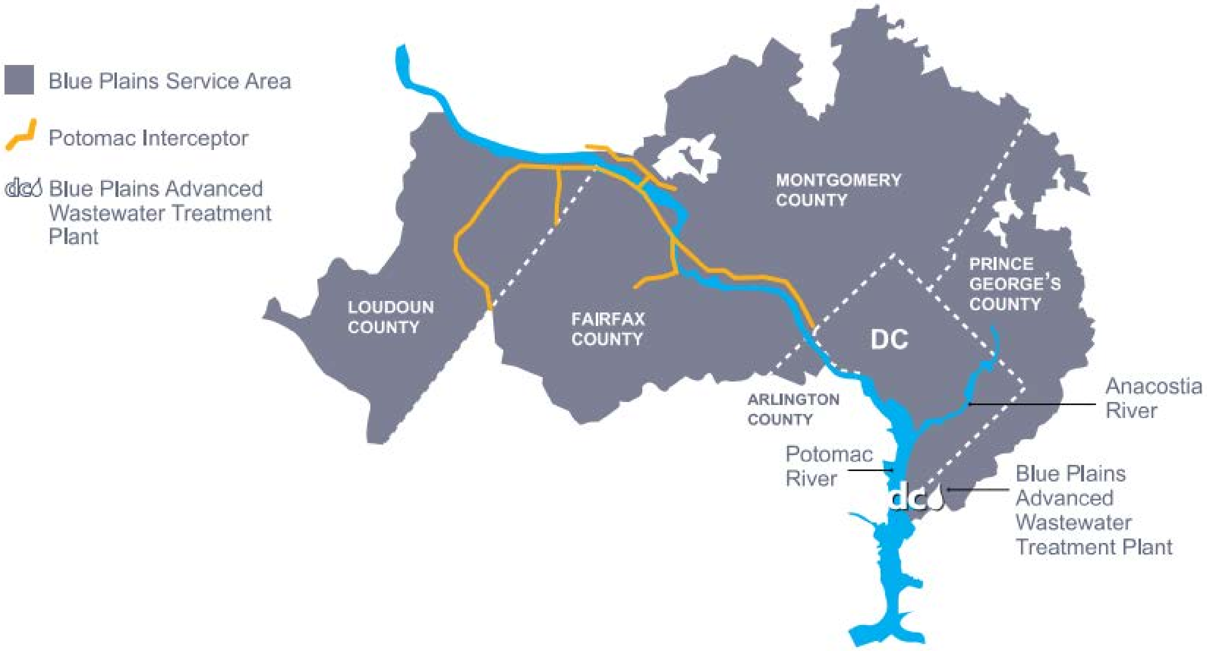
Figure 20. Significant WRRFs in Greater Washington, D.C. Metropolitan Area



SPOTLIGHT: DC Water Blue Plains

DC Water's Blue Plains Advanced Wastewater Treatment Plant in Washington, D.C. is the largest WRRF of its type in the world. The facility treats close to 300 million gallons of wastewater per day and has the potential capacity for significantly higher peak flows, at over 1 billion gallons per day. Wastewater flows are from D.C., Maryland, and Virginia, including Montgomery and Prince George's Counties in Maryland, and Fairfax and Loudoun Counties in Virginia.

Figure 21. DC Water Blue Plains Service Area[25]



In 2015, an AD system was installed at the facility, converting more than half the organic matter to methane for onsite electricity generation and consumption. DC Water is currently assessing opportunities to expand methane production at the facility, and potentially produce pipeline-quality RNG and interconnect with the natural gas system. With successful injection into the gas system, this RNG would displace more carbon-intensive fossil natural gas, delivering GHG emission reduction benefits for the region. The RNG would also potentially generate valuable environmental commodities if used in the transportation sector.

WG is working with DC Water on engineering configurations at the interconnection and gas quality requirements.

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[25] DC Water, 2019. https://www.dcwater.com/sites/default/files/Blue_Plains_Plant_brochure.pdf

Table 15. WRRFs in WG Service Territory with Flow Greater Than 3.3 MGD

Name	County	Existing Flow (MGD)	Max. RNG Potential (tBtu/y)	AD System
DC Water Blue Plains	D.C.	370	0.95	Yes
Upper Occoquan WRRF	Prince William	45	0.14	Yes
AlexRenew STP	Alexandria	37	0.15	Yes
Lower Potomac STP	Fairfax	28	0.17	No
Arlington WPCP	Arlington	22	0.10	No
WSSC Piscataway WRRF	Prince George's	19	0.08	No
Western Branch WWTP	Prince George's	18	0.08	No
Broad Run Reclamation Facility	Loudoun	11	0.06	No
Mattawoman WWTP	Charles	8	0.06	No
Gas House Pike WWTP	Frederick (MD)	7	0.02	Yes
H.L. Mooney Advanced Water Reclamation Facility	Prince William	6	0.06	No
Parkway Wastewater TP	Prince George's	6	0.02	No
Opequon Regional Plant	Frederick (VA)	5	0.02	No
Ballenger/McKinney WWTP	Frederick (MD)	4	0.02	No
Total		**585**	**1.9**	

Regional and National WRRFs as an RNG Resource

Tables 16 and 17 summarize the key data points from the survey of WRRFs in the United States, broken down by Census Region.

Table 16. Number of WRRFs by Census Region[26]

Facility Size (MGD)	South Atlantic	New England	Mid-Atlantic	East North Central	West North Central	East South Central	West South Central	Mountain	Pacific	National
<0.02	**94**	33	70	169	581	46	127	107	32	**1,259**
0.02-0.07	**222**	58	255	495	1,125	191	362	263	137	**3,108**
0.07-0.18	**291**	83	289	607	602	224	380	217	145	**2,838**
0.18-1.00	**569**	176	555	838	552	391	459	308	293	**4,141**
1.01-3.30	**267**	109	234	324	160	177	178	126	162	**1,737**
3.31-7.25	**137**	46	91	122	53	68	88	39	78	**722**
7.26-34.05	**112**	35	67	116	36	30	58	36	88	**578**
34.05+	**21**	5	30	23	9	8	15	7	24	**142**

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[26] Based on data from CNWS 2015.

Table 17. Total Flow of WRRFs by Census Region, MGD[27]

Facility Size (MGD)	South Atlantic	New England	Mid-Atlantic	East North Central	West North Central	East South Central	West South Central	Mountain	Pacific	National
<0.02	**1**	0	1	2	6	0	1	1	0	**13**
0.02-0.07	**9**	2	10	20	40	8	14	10	5	**118**
0.07-0.18	**33**	9	33	68	66	26	42	24	16	**316**
0.18-1.00	**261**	84	255	380	228	170	201	139	135	**1,854**
1.01-3.30	**511**	201	440	632	292	338	323	238	304	**3,279**
3.31-7.25	**678**	231	461	576	259	323	439	198	394	**3,560**
7.26-34.05	**1,645**	535	1,009	1,734	569	424	863	552	1,320	**8,652**
34.05+	**1,686**	494	3,438	2,839	717	536	1,086	586	2,580	**13,961**
Total	**4,824**	1,556	5,647	6,251	2,177	1,825	2,969	1,748	4,754	**31,753**

Table 16 shows that about 90% of the facilities in the database used by ICF have a flow rate of less than 3.30 MGD, representing just under 20% of the total flow of wastewater into WRRFs. The 142 facilities with a flow greater than 34 MGD represent nearly 45% of the entire flow into WRRFs. Table 18 shows the distribution of the more than 1,250 WRRFs with installed AD systems.

Table 18. WRRFs with Anaerobic Digesters, by Census Region[28]

	South Atlantic	New England	Mid-Atlantic	East North Central	West North Central	East South Central	West South Central	Mountain	Pacific	National
AD Facilities	**133**	34	231	309	125	47	74	82	233	**1,268**

The three tables above illustrate the opportunities and challenges associated with deploying AD systems at WRRFs: while fewer than 10% of WRRFs have an AD system, they tend to be the larger systems, representing the bulk of wastewater treated at facilities. Most of these facilities have AD systems in place and are capturing biogas for on-site electricity production rather than for pipeline injection. With an effective policy and regulatory framework, these facilities present a near-term opportunity for RNG to be directed into the pipeline, rather than for on-site electricity production, as shown by DC Water’s Blue Plains facility. The database of RNG-producing facilities maintained by the Coalition for Renewable Natural Gas indicates that there are only 12 operational WRRFs using AD systems to capture and subsequently inject RNG into the pipeline, five WRRFs with AD systems under substantial development, and another five WRRFs with AD systems under construction.

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[27] Based on data from CNWS 2015.
[28] Based on data from the Water Environment Federation.

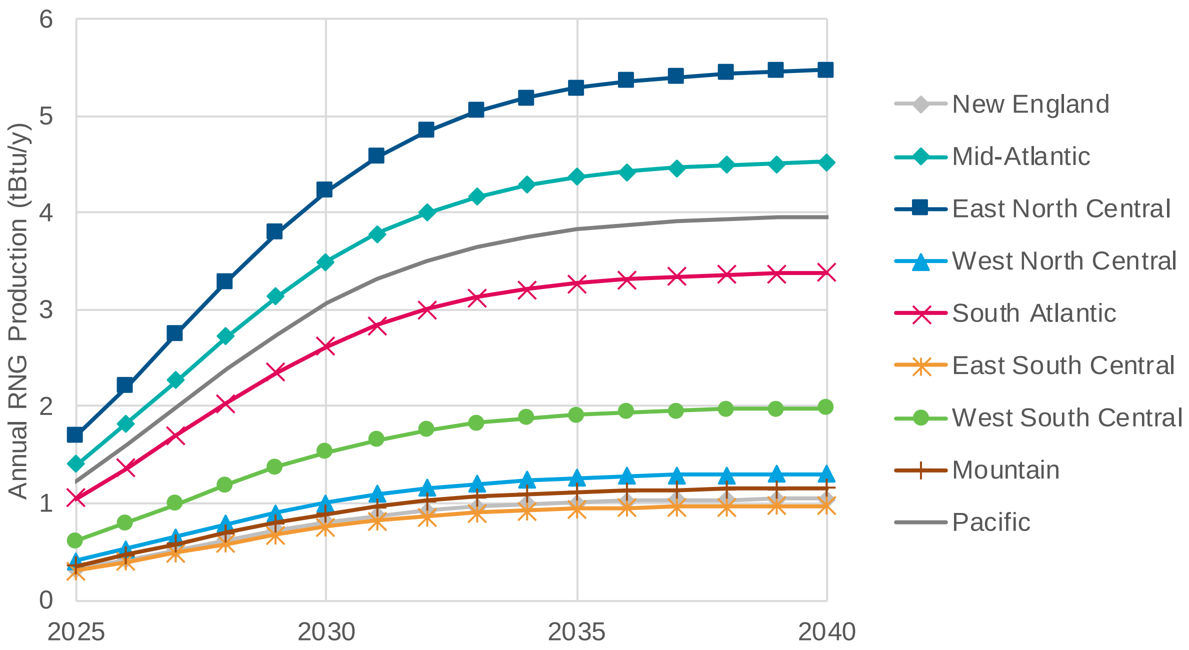
ICF developed the following assumptions for the resource potentials for RNG production at WRRFs in the three scenarios:

- In the Conservative Low scenario, ICF assumed that RNG could be produced at 30% of the facilities with a capacity greater than 7.25 MGD.
- In the Achievable scenario, ICF assumed that RNG could be produced at 50% of the facilities with a capacity greater than 3.3 MGD.
- In the Aggressive High scenario, ICF assumed that RNG could be produced at 90% of the facilities with a capacity greater than 3.3 MGD.

To estimate the amount of RNG produced from wastewater at WRRFs, ICF used data reported by the EPA,[29] a study of WRRFs in New York State,[30] and previous work published by AGF.[31] ICF used an average energy yield of 7.0 MMBtu/MG of wastewater. For the maximum achievable resource, ICF used all of the wastewater flow reported at the more than 14,500 facilities in the database.

Figures 22–24 show the Conservative Low, Achievable, and Aggressive High RNG resource potential from WRRFs between 2025 and 2040. Table 19 includes the total annual RNG production potential (in units of tBtu/y) for 2040 in the three scenarios.

Figure 22. RNG Production Potential from WRRFs, Conservative Low Scenario, tBtu/y



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

[30] 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.

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

Figure 23. RNG Production Potential from WRRFs, Achievable Resource Scenario, in tBtu/y

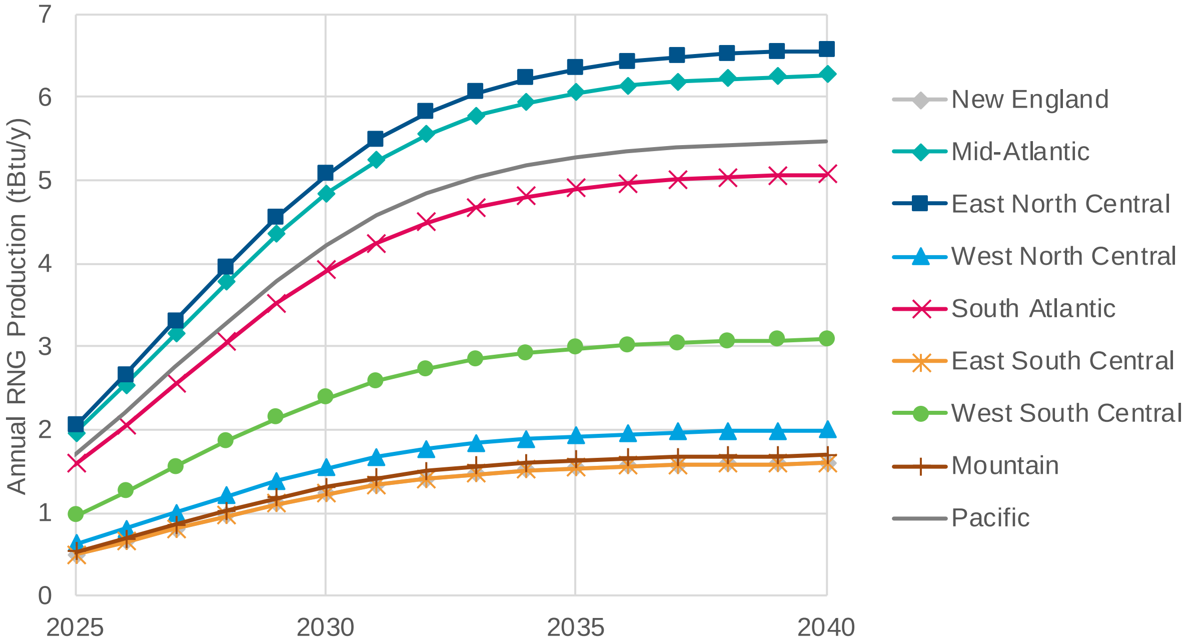


Figure 24. RNG Production Potential from WRRFs, Aggressive High Resource Scenario, in tBtu/y

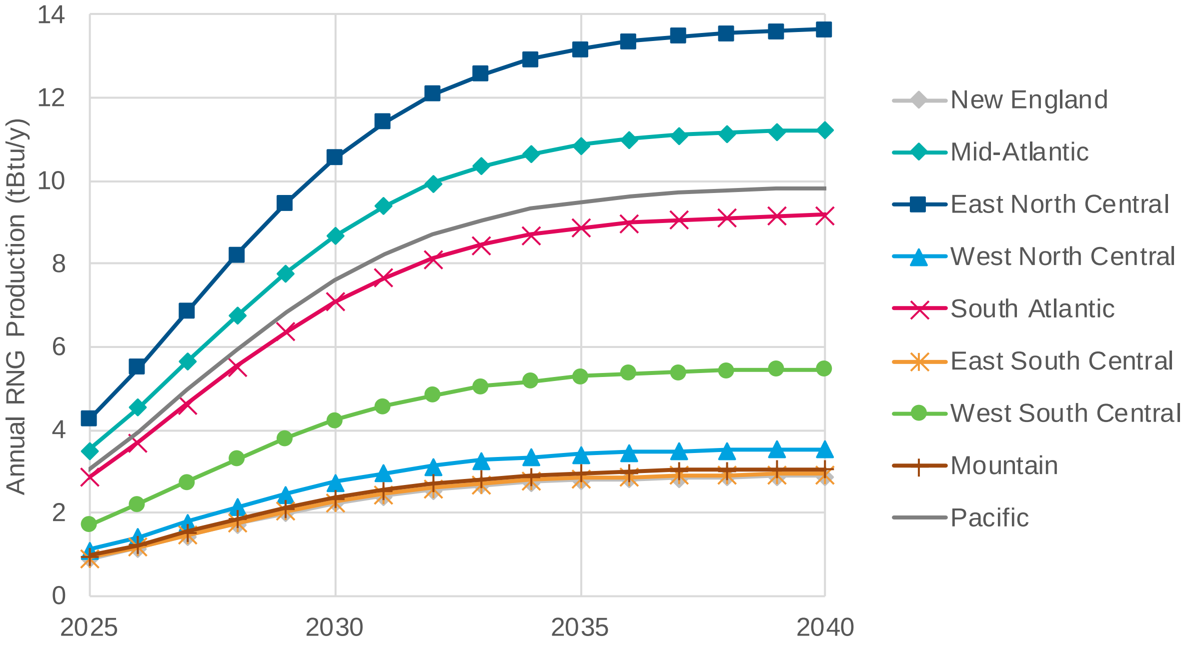


Table 19. Annual RNG Production Potential from WRRFs in 2040, tBtu/y

RNG Potential Scenario	RNG Potential from WRRFs, tBtu/y									
	South Atlantic	New England	Mid-Atlantic	East North Central	West North Central	East South Central	West South Central	Mountain	Pacific	National
Conservative	**3.4**	1.1	4.5	5.5	1.3	1.0	2.0	1.2	4.0	**24.0**
Achievable	**5.1**	1.6	6.3	7.6	2.0	1.6	3.1	1.7	5.5	**34.5**
Aggressive	**9.2**	2.9	11.3	13.7	3.6	2.9	5.5	3.1	9.9	**62.1**

For the South Atlantic Census region, ICF estimates that 5 tBtu/y of RNG could be produced from WRRFs in the Achievable scenario, which would require the installation of AD systems at approximately 180 facilities. On a national scale, this estimate increases to 34 tBtu/y of RNG that could be produced from WRRFs in the Achievable scenario, rising to 62 tBtu/y in the Aggressive High scenario. To achieve this level of RNG production from WRRFs, ICF estimates that 1,450 facilities would need to install AD systems in the Achievable scenario.

Food Waste

Food waste is a major component of MSW—accounting for about 15% of MSW streams. More than 75% of food waste is landfilled. Food waste can be diverted from landfills to a composting or processing facility where it can be treated in an anaerobic digester. ICF limited 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.

ICF extracted information from the U.S. Department of Energy's (DOE) Bioenergy Knowledge Discovery Framework (KDF), which includes information collected as part of DOE's Billion Ton Report (updated in 2016). The Bioenergy KDF includes food waste at tipping fee price points ranging from $70/ton to $100/ton, with higher tipping fees leading to increased feedstock availability. 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 DOE's resource assessment.

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

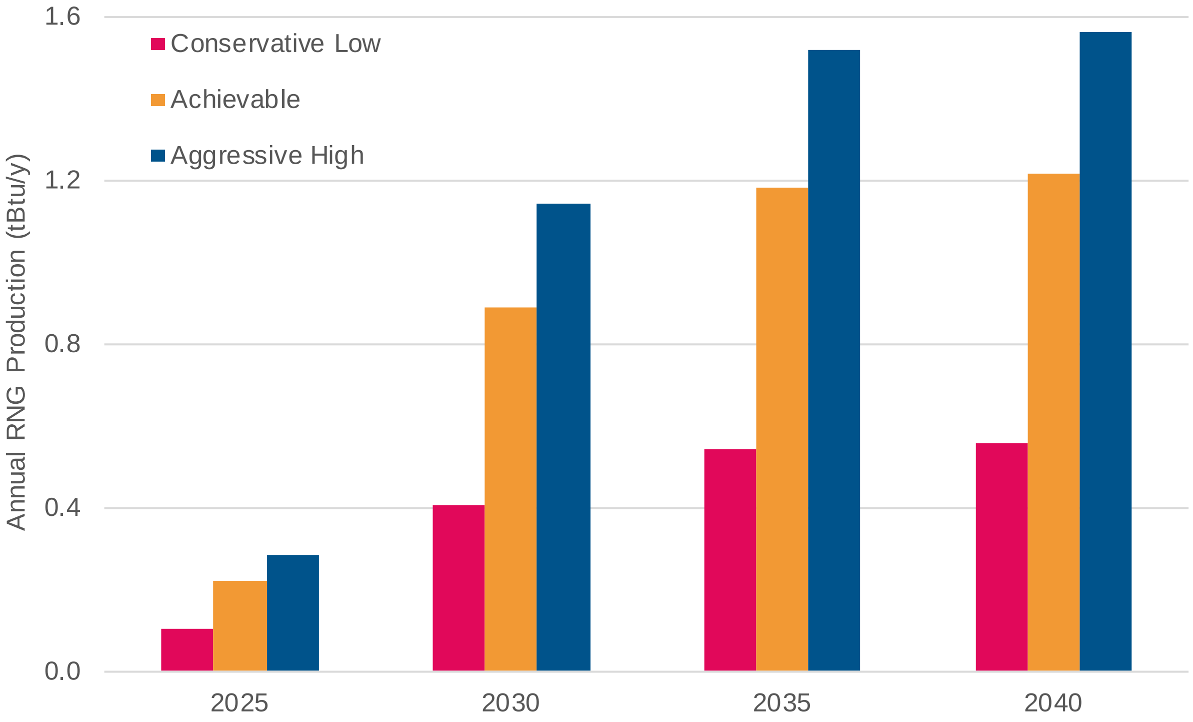
- In the Conservative Low scenario, ICF assumed that 40% of the food waste available at $70/dry ton would be diverted to AD systems.
- In the Achievable scenario, ICF assumed that 70% of the food waste available at $100/dry ton would be diverted to AD systems.
- In the Aggressive High scenario, ICF assumed that 90% of the food waste available at $100/dry ton would be diverted to AD systems.

As food waste is generated from population centers and typically diverted at waste transfer stations rather than delivered to landfills, it is challenging to identify specific facilities or projects in the region that will generate RNG from food waste. However, food waste can potentially utilize existing or future AD systems at LFG and WRRF facilities, as outlined in the previous sections. Adoption of new and expanded waste diversion mandates by municipalities in the Greater Washington, D.C. metropolitan area could spur the development of RNG production from food waste. For example, Sustainable DC's 2.0 Plan identified the need for a new organic waste processing facility to capture diverted food and other waste streams in the region.[32]

Local Sources of Food Waste as an RNG Resource

Figure 25 shows the RNG production potential from food waste in the Greater Washington, D.C. metropolitan area, for the three scenarios out to 2040. These estimates are based on a population-weighted proportion of regional food waste figures.

Figure 25. RNG Potential from Food Waste in Greater Washington, D.C. Metropolitan Area, tBtu/y



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[32] Sustainable DC, 2019. Sustainable DC 2.0 Plan, http://www.sustainabledc.org/wp-content/uploads/2019/04/sdc-2.0-Edits-V5_web.pdf

Regional and National Source of Food Waste as an RNG Resource

Figures 26–28 show the Conservative Low, Achievable, and Aggressive High RNG resource potential scenarios from the anaerobic digestion of food waste between 2025 and 2040, broken down by Census Region. Table 20 includes the total annual RNG production potential (in units of tBtu/y) for 2040 for the three scenarios.

Figure 26. RNG Production Potential from Food Waste, Conservative Low Resource Scenario, in tBtu/y

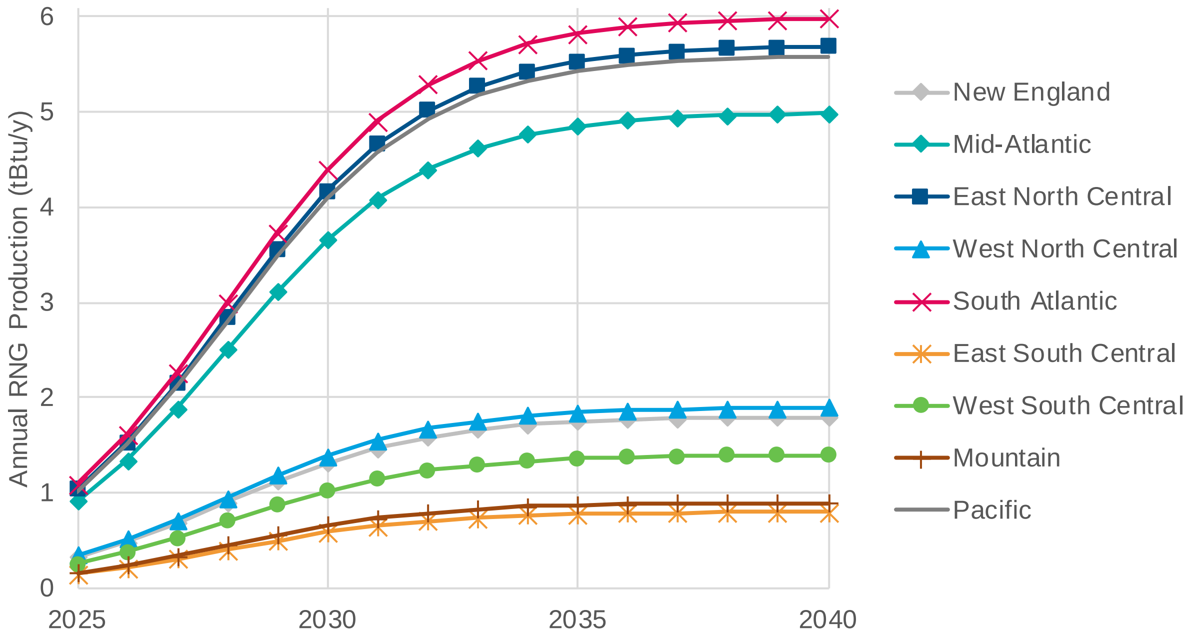

Figure 27. RNG Production Potential from Food Waste, Achievable Resource Scenario, in tBtu/y

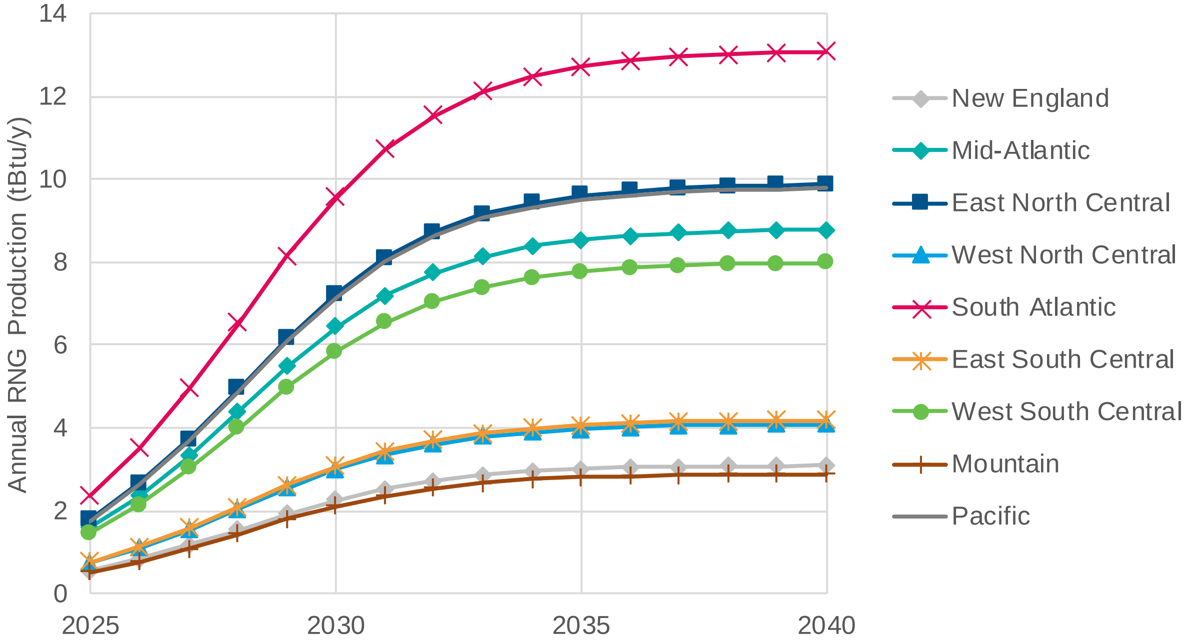

Figure 28. RNG Production Potential from Food Waste, Aggressive High Resource Scenario, in tBtu/y

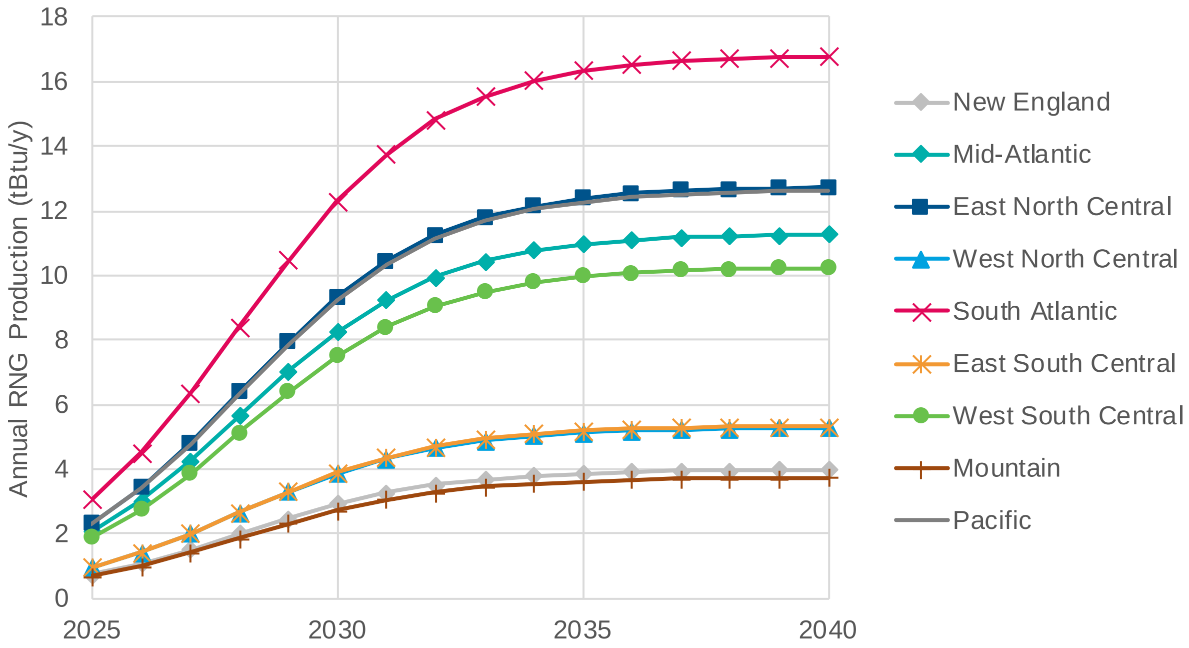

Table 20. Annual RNG Production Potential from Food Waste in 2040, tBtu/y

RNG Potential Scenario	RNG Potential from Food Waste, tBtu/y									
	South Atlantic	New England	Mid-Atlantic	East North Central	West North Central	East South Central	West South Central	Mountain	Pacific	National
Conservative	**6.0**	1.8	5.0	5.7	1.9	0.8	1.4	0.9	5.6	**29.1**
Achievable	**13.1**	3.1	8.8	9.9	4.1	4.2	8.0	2.9	9.8	**63.9**
Aggressive	**16.8**	4.0	11.3	12.8	5.3	5.3	10.3	3.7	12.6	**82.2**

ICF estimates that 13 tBtu/y of RNG could be produced by 2040 in the South Atlantic Census region in the Achievable scenario from food waste diverted to anaerobic digesters. At the national level, this increases to 64 tBtu/y of RNG, rising to 82 tBtu/y in the Aggressive High scenario.

RNG: Thermal Gasification of Biogenic or Renewable Resources

The biomass feedstocks for RNG production potential via thermal gasification include agricultural residues, forestry and forest product residues, energy crops, and the nonbiogenic fraction of MSW. With the exception of MSW, the densely populated Greater Washington, D.C. metropolitan area has limited availability of feedstocks for thermal gasification. However, there is significant potential regionally and nationally—there is nothing inherently limiting about the availability of these feedstocks for RNG production and subsequent delivery to WG's system. There is only limited local production potential from biomass feedstocks given the region's population density. Ultimately, RNG production should be considered no different from conventional natural gas production areas, whereby a robust pipeline infrastructure enables transmission and distribution of natural gas efficiently from various sources.

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 DOE Bioenergy KDF, including the following agricultural residues: wheat straw, corn stover, sorghum stubble, oat straw, barley straw, citrus residues, non-citrus 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. Table 21 lists the energy content on a higher heating value (HHV) basis for the various agricultural residues included in the analysis. The energy content is based on values reported by the California Biomass Collaborative. To estimate the RNG production potential, ICF assumed a 65% efficiency for thermal gasification systems.

Table 21. 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	13.240
Oats straw	7,308	14.616
Barley straw	7,441	14.882
Citrus residues	8,597	17.194
Non-citrus 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 following assumptions for the RNG production potential from agricultural residues in the three scenarios.

- In the Conservative Low scenario, ICF assumed that 20% of the agricultural residues available at $50/dry ton would be diverted to thermal gasification systems.
- In the Achievable scenario, ICF assumed that 50% of the agricultural residues available at $50/dry ton would be diverted to thermal gasification systems.
- In the Aggressive High scenario, ICF assumed that 80% of the agricultural residues available at $50/dry ton would be diverted to thermal gasification systems.

Figures 29–31 show the Conservative Low, Achievable and Aggressive High RNG resource potential scenarios from the thermal gasification of agricultural residues between 2025 and 2040. Table 22 includes the total annual RNG production potential (in units of tBtu/y) for 2040 for the three scenarios.

Figure 29. RNG Production Potential from Agricultural Residue, Conservative Low Scenario, in tBtu/y

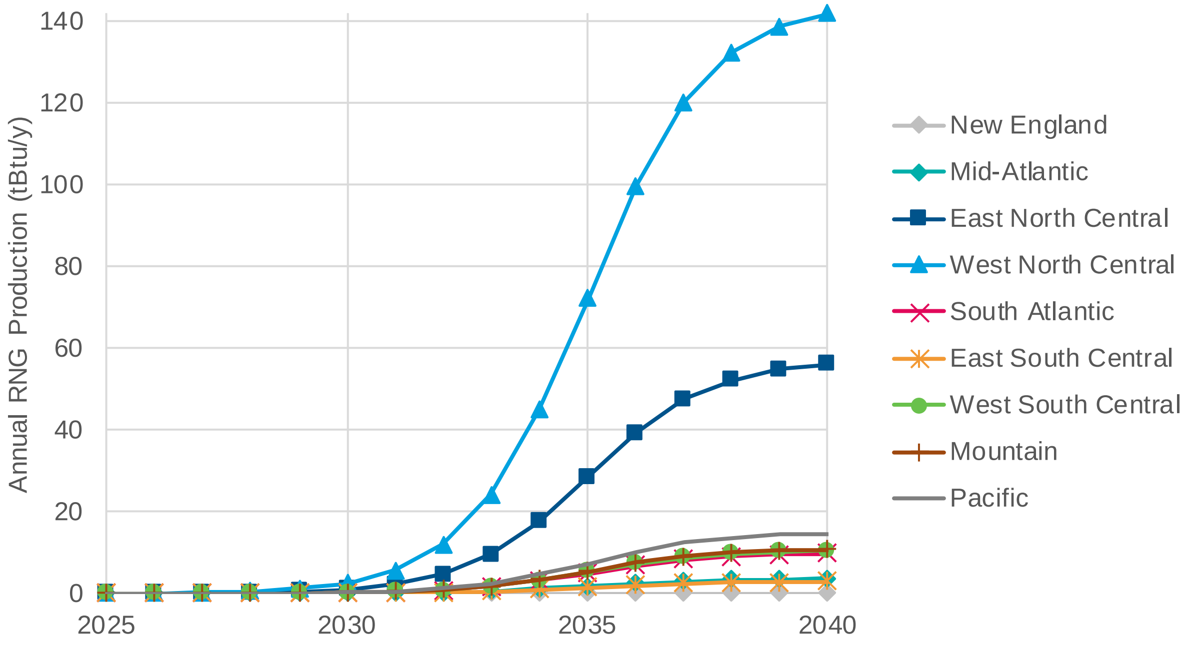

Figure 30. RNG Production Potential from Agricultural Residue, Achievable Scenario, in tBtu/y

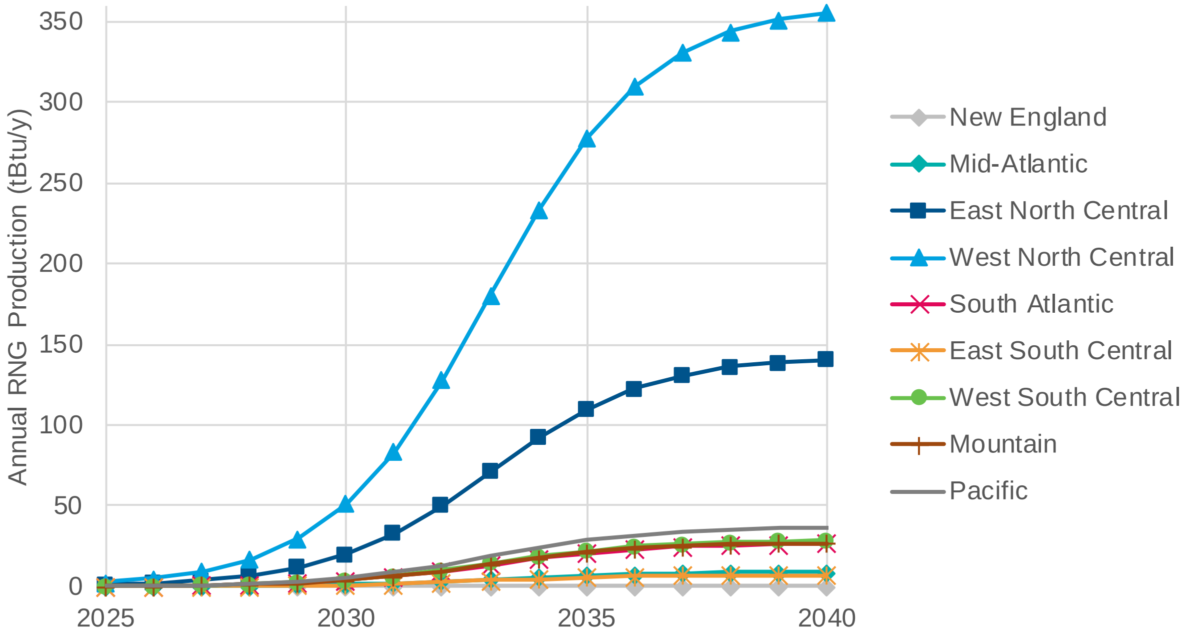

Figure 31. RNG Production Potential from Agricultural Residue, Aggressive High Scenario, in tBtu/y

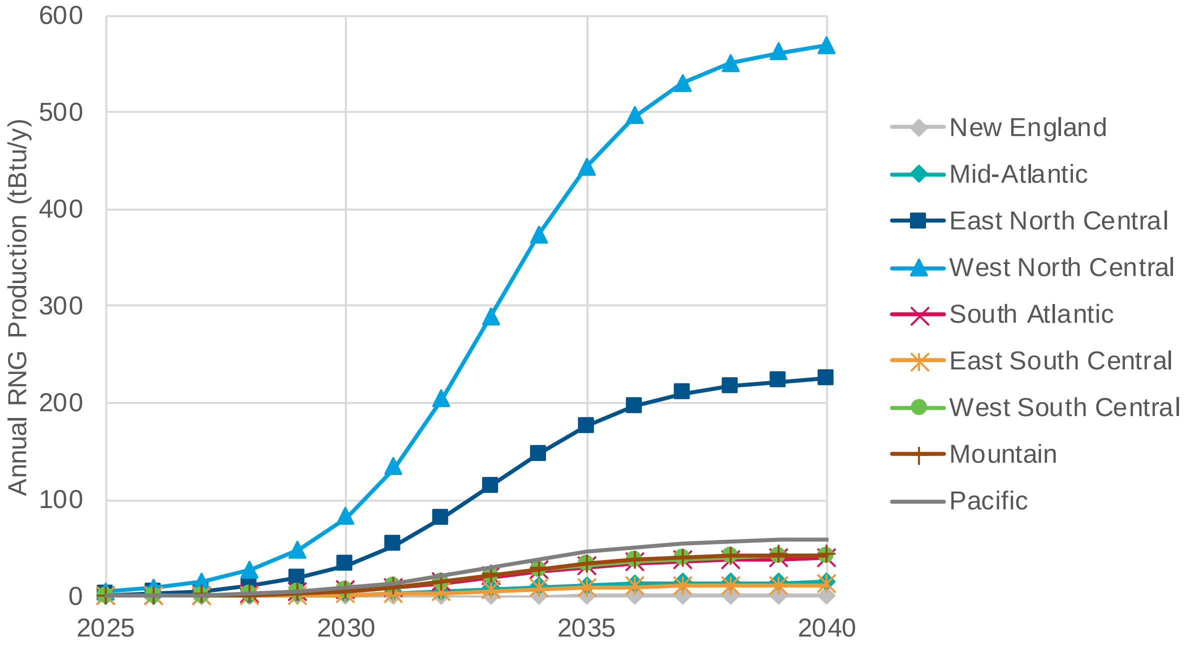

Table 22. Annual RNG Production Potential from Agricultural Residues in 2040, tBtu/y

RNG Potential Scenario	RNG Potential from Agricultural Residue, tBtu/y									
	South Atlantic	New England	Mid-Atlantic	East North Central	West North Central	East South Central	West South Central	Mountain	Pacific	National
Conservative	**10.0**	0.0	3.7	57.0	144.4	2.9	10.7	10.9	14.9	**254.6**
Achievable	**26.9**	0.1	9.2	142.6	361.0	7.3	28.8	27.3	37.3	**640.5**
Aggressive	**40.1**	0.2	14.8	228.2	577.7	11.6	42.7	43.7	59.7	**1,018.5**

ICF estimates that 27 tBtu/y of RNG could be produced by 2040 in the Achievable scenario from the thermal gasification of agricultural residues in the South Atlantic Census region. Nationally, this agricultural residue estimate increases to 641 tBtu/y of RNG by 2040 in the Achievable scenario and rises to 1,019 tBtu/y in the Aggressive High scenario.

Forestry and Forest Product Residues

Forestry and forest product residues include biomass generated from logging, forest and fire management activities, and milling. Logging residues (e.g., bark, stems, leaves, branches), forest thinnings (e.g., removal of small trees to reduce fire danger), and mill residues (e.g., slabs, edgings, trimmings, sawdust) are also considered in the analysis. This includes materials from public forestlands (e.g., state, federal), but not specially designated forests (e.g., roadless areas, national parks, wilderness areas) and includes sustainable harvesting criteria as described in the DOE Billion Ton Update. The updated DOE Billion Ton study was altered to include additional sustainability criteria. Some of the changes included: [33]

- 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, U.S. Forest Service special interest areas, national parks) and roadless designated forestlands, forests on steep slopes and in wetland areas (e.g., stream management zones), and sites requiring cable systems.
- Assumptions only reflect thinnings for over-stocked stands and do not 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 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. Table 23 lists the energy content on an HHV basis for the various forest and forest product residue elements considered in the analysis. To estimate the RNG production potential, ICF assumed a 65% efficiency for thermal gasification systems.

Table 23. 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
Mixedwood, residue	6,500	13.00
Hardwood, lowland, residue		
Hardwood, upland, residue		
Softwood, natural, residue		
Softwood, planted, residue		

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

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

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[33] Bryce Stokes, DOE, “2011 Billion Ton Update – Assumptions and Implications Involving Forest Resources,” September 29, 2011, http://web.ornl.gov/sci/ees/cbes/workshops/Stokes_B.pdf.

- In the Aggressive High scenario, ICF assumed that 90% of the forest and forestry product residues available at $100/dry ton would be diverted to thermal gasification systems.

Figures 32–34 show the RNG resource potential from the thermal gasification of forestry and forest product residues between 2025 and 2040 in the Conservative Low, Achievable and Aggressive High scenarios. Table 24 includes the total annual RNG production potential (in units of tBtu/y) for 2040 in the three scenarios.

Figure 32. RNG Potential from Forestry & Forest Products Residue, Conservative Low Scenario, tBtu/y

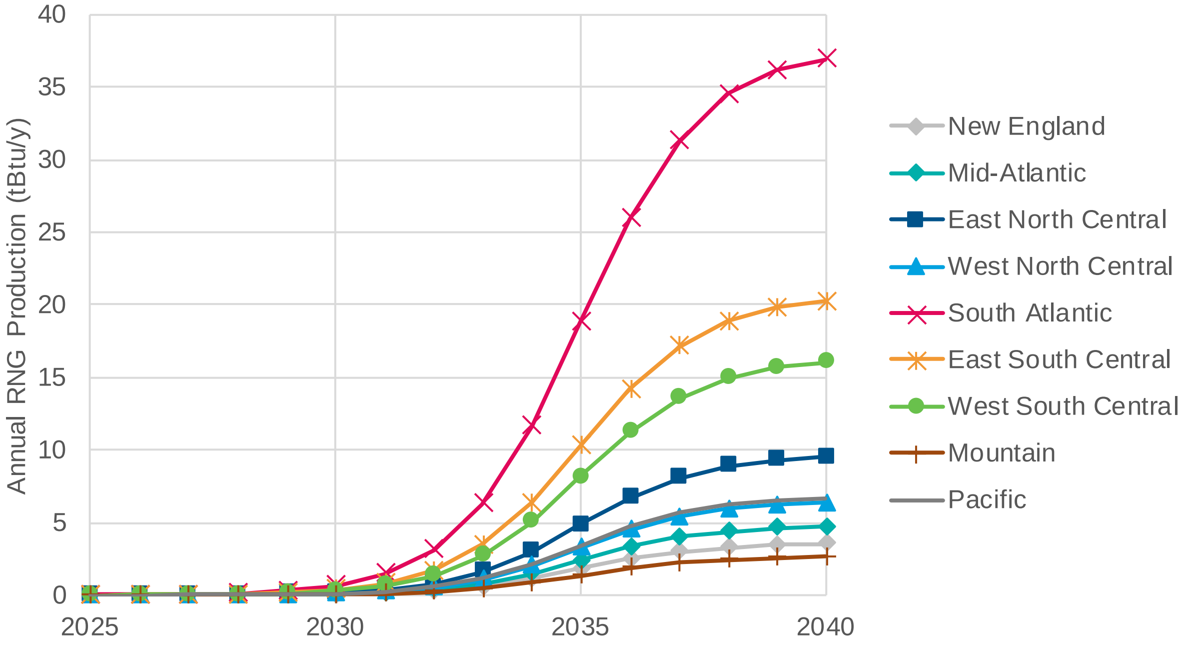

Figure 33. RNG Potential from Forestry & Forest Product Residue, Achievable Scenario, tBtu/y

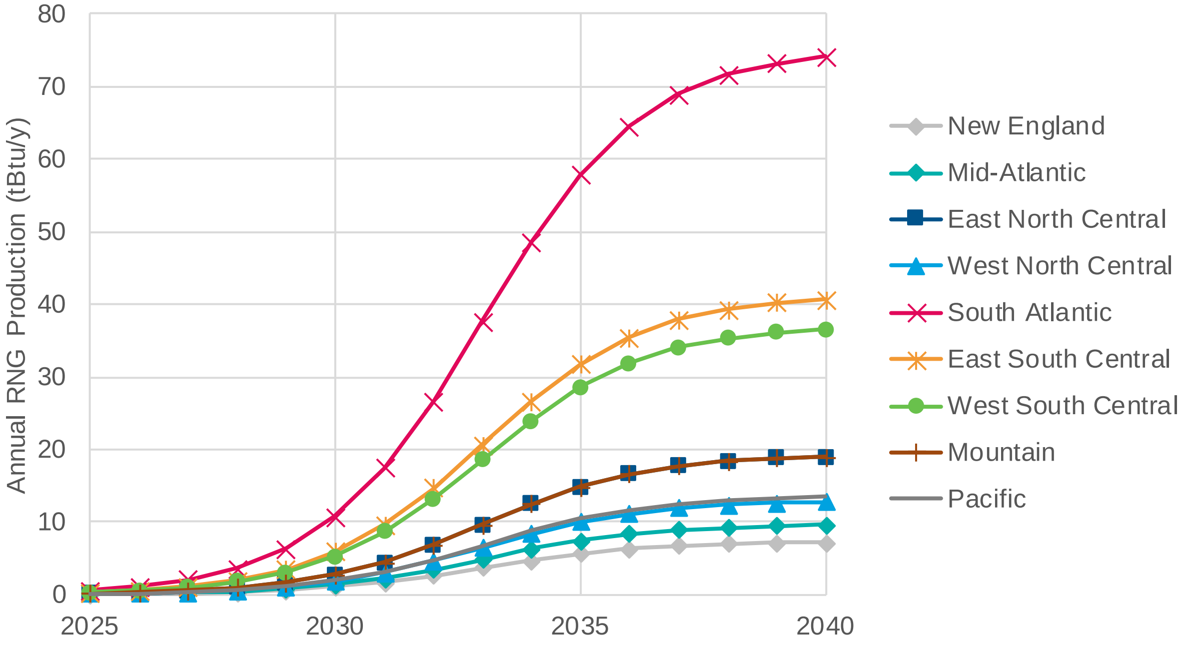

Figure 34. RNG Potential from Forestry & Forest Product Residue, Aggressive High Scenario, tBtu/y

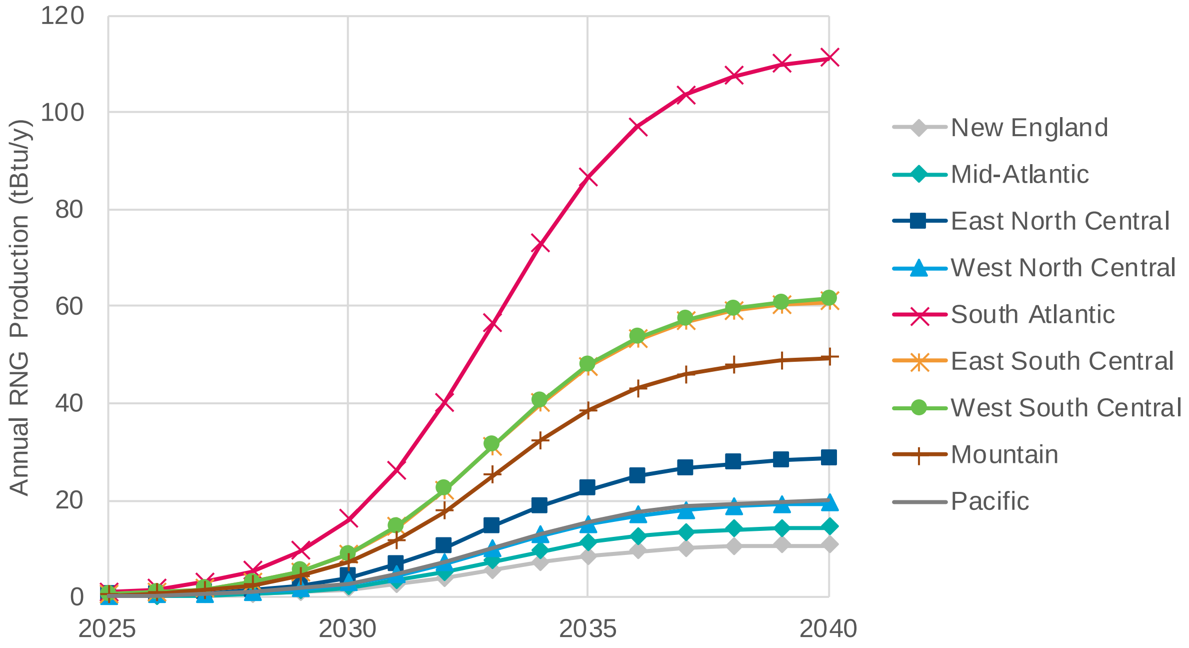

Table 24. Annual RNG Production Potential from Forestry and Forest Product Residues, tBtu/y

RNG Potential Scenario	**RNG Potential from Forestry and Forest Product Residues, tBtu/y**									
	South Atlantic	**New England**	**Mid-Atlantic**	**East North Central**	**West North Central**	**East South Central**	**West South Central**	**Mountain**	**Pacific**	**National**
Conservative	**37.6**	3.6	4.8	9.7	6.5	20.6	16.3	2.7	6.8	**108.6**
Achievable	**75.2**	7.3	9.7	19.3	13.0	41.3	37.1	19.3	13.6	**235.8**
Aggressive	**112.9**	10.9	14.5	29.0	19.5	61.9	62.4	50.0	20.3	**381.4**

ICF estimates that in the Achievable scenario, 75 tBtu/y of RNG could be produced by 2040 in the South Atlantic Census region from the thermal gasification of forest and forestry product residues. This rises to 236 tBtu/y of RNG at the national level by 2040, increasing to 381 tBtu/y in the Aggressive High scenario.

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. Table 25 lists the energy content on an 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. This factor is based in part on the 2011 AGF Report on RNG, indicating a range of thermal gasification efficiencies in the range of 60% to 70%, depending upon the configuration and process conditions. The report authors also used a conversion efficiency of 65% in their assessment. More recently, GTI estimated the potential for

RNG from the thermal gasification of wood waste in California and assumed a conversion efficiency of 60%.[34]

Table 25. 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 assumptions for the RNG production potential from energy crops for the three scenarios:

- In the Conservative Low scenario, ICF assumed that 50% of the energy crops available at $50/dry ton would be diverted to thermal gasification systems.
- In the Achievable scenario, ICF assumed that 50% of the energy crops available at $70/dry ton would be diverted to thermal gasification systems.
- In the Aggressive High scenario, ICF assumed that 70% of the energy crops available at $100/dry ton would be diverted to thermal gasification systems.

Figures 35–37 show the RNG resource potential from the thermal gasification of energy crops between 2025 and 2040 in the Conservative Low, Achievable and Aggressive High scenarios. Table 26 includes the total annual RNG production potential (in units of tBtu/y) for 2040 for the three scenarios.

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[34] 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

Figure 35. RNG Production Potential from Energy Crops, Conservative Low Scenario, in tBtu/y

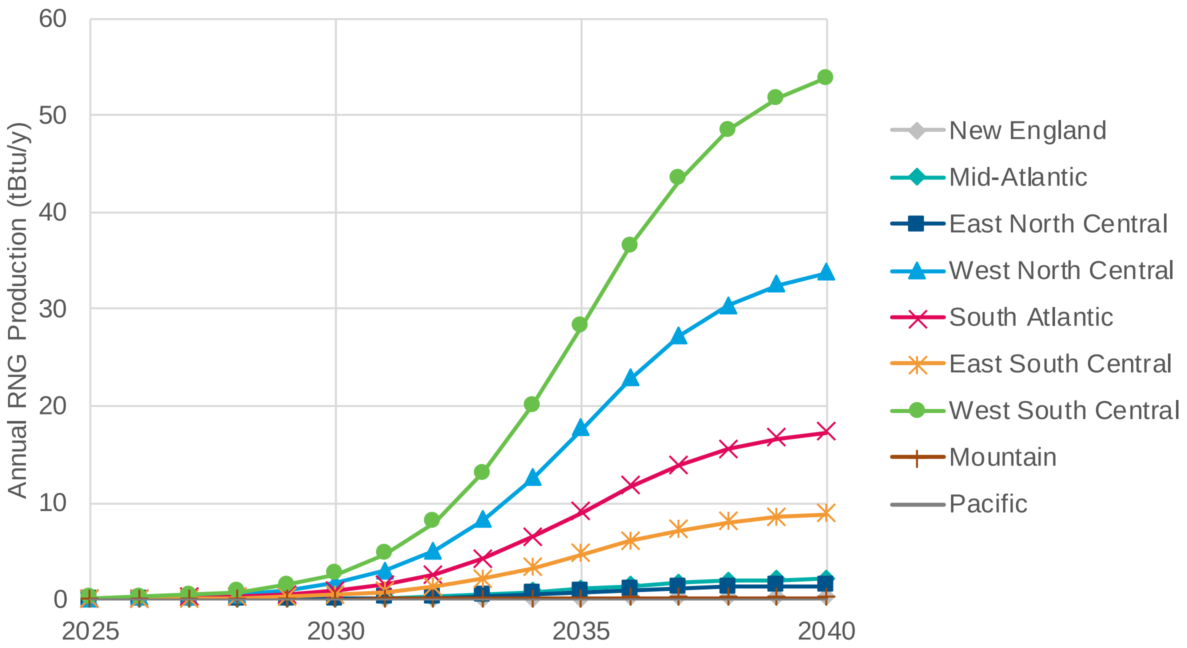

Figure 36. RNG Production Potential from Energy Crops, Achievable Scenario, in tBtu/y

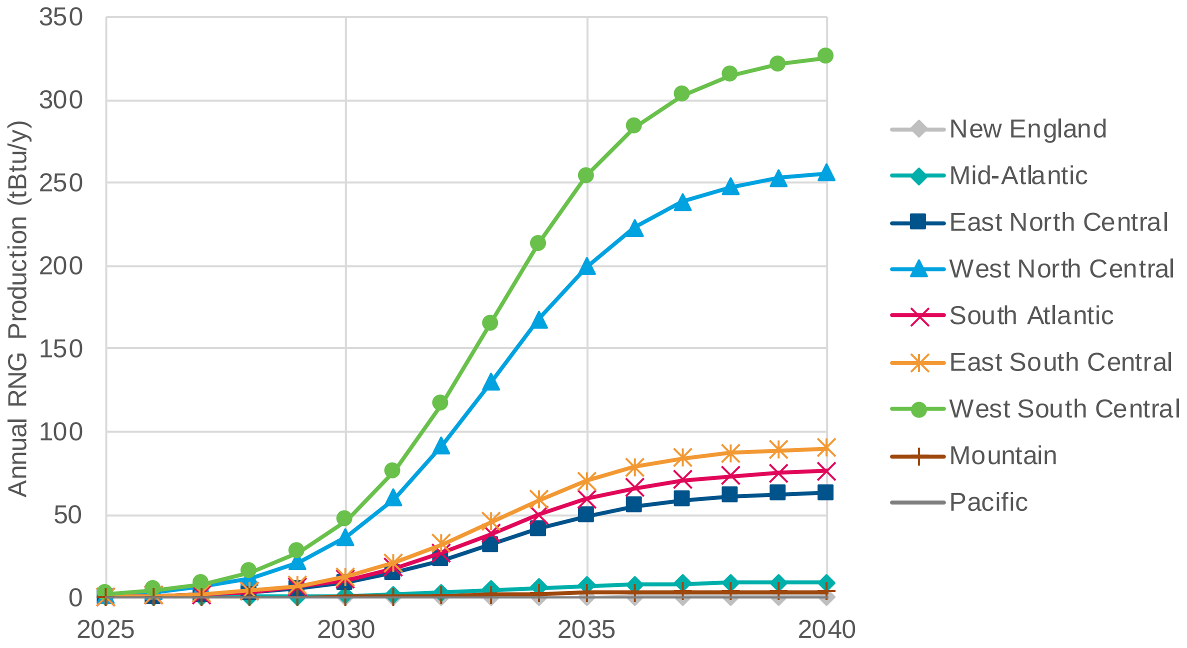

Figure 37. RNG Production Potential from Energy Crops, Aggressive High Scenario, in tBtu/y

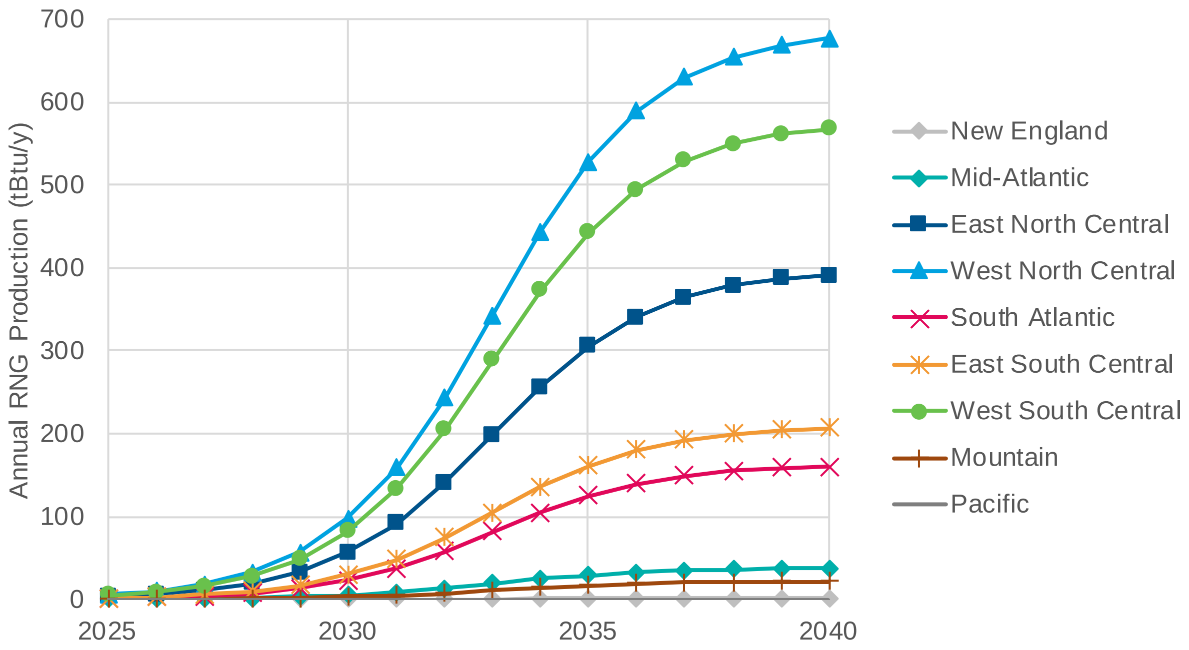

Table 26. Annual RNG Production Potential from Energy Crops, tBtu/y

RNG Potential Scenario	RNG Potential from Energy Crops, tBtu/y									
	South Atlantic	New England	Mid-Atlantic	East North Central	West North Central	East South Central	West South Central	Mountain	Pacific	National
Conservative	**18.1**	0.2	2.2	1.5	35.4	9.3	56.5	0.2	0.0	**123.4**
Achievable	**77.3**	0.5	9.4	64.4	260.0	91.6	330.5	3.9	0.0	**837.6**
Aggressive	**162.5**	1.4	38.4	397.0	686.2	209.6	576.2	22.2	0.0	**2,093.4**

ICF estimates in the Achievable scenario that 77 tBtu/y of RNG could be produced by 2040 in the South Atlantic Census region from the thermal gasification of energy crops. At the national level, this estimate increases to 838 tBtu/y of RNG that could be produced from energy crops, rising to 2,093 tBtu/y in the Aggressive High scenario.

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, with the roughly 50% balance landfilled.

ICF limited our consideration to the potential for utilizing MSW that is currently landfilled as a feedstock for thermal gasification; this excludes MSW that is recycled or directed to waste-to-energy facilities. With a more supportive policy and regulatory framework, MSW waste-to-energy facilities in the region could present a near-term opportunity for RNG to be processed and directed into the pipeline, such as at Covanta's Alexandria/Arlington, Fairfax, and Dickerson waste-to-energy facilities. ICF also excluded food waste from consideration in this sub-section, and opted to consider feedstock as a separate resource for AD systems.

ICF extracted information from the DOE's Bioenergy KDF, which includes information collected as part of 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. Table 27 lists the energy content on an HHV basis for the various components of MSW. To estimate the RNG production potential, ICF assumed a 65% efficiency for thermal gasification systems.

Table 27. Heating Values for MSW Components

MSW Component	Btu/lb, dry	MMBtu/ton, dry
CD 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 assumptions for the RNG production potential from MSW for the three scenarios:

- In the Conservative Low scenario, ICF assumed that 30% of the nonbiogenic fraction of MSW available at $30/dry ton from the Bioenergy KDF for relevant waste residues in MSW could be gasified. ICF notes that at the price of $30/ton, DOE reports no MSW wood or yard trimmings.
- In the Achievable scenario, ICF assumed that 60% of the nonbiogenic fraction of MSW available at $100/dry ton from the Bioenergy KDF for the CD waste, other, paper and paperboard, plastics, rubber and lather, and textiles waste could be gasified, and that 75% of the MSW wood and yard trimmings could be gasified.
- In the Aggressive High scenario, ICF assumed that 90% of the nonbiogenic fraction of MSW available at $100/dry ton from the Bioenergy KDF for the CD waste, other, paper and paperboard, plastics, rubber and lather, and textiles waste could be gasified, and that 90% of the MSW wood and yard trimmings could be gasified.

Figures 38–40 show the RNG resource potential from the thermal gasification of MSW between 2025 and 2040 in the Conservative Low, Achievable and Aggressive High scenarios. Table 28 includes the total annual RNG production potential (in units of tBtu/y) for 2040 for the three scenarios.

Figure 38. RNG Production Potential from MSW, Conservative Low Scenario, in tBtu/y

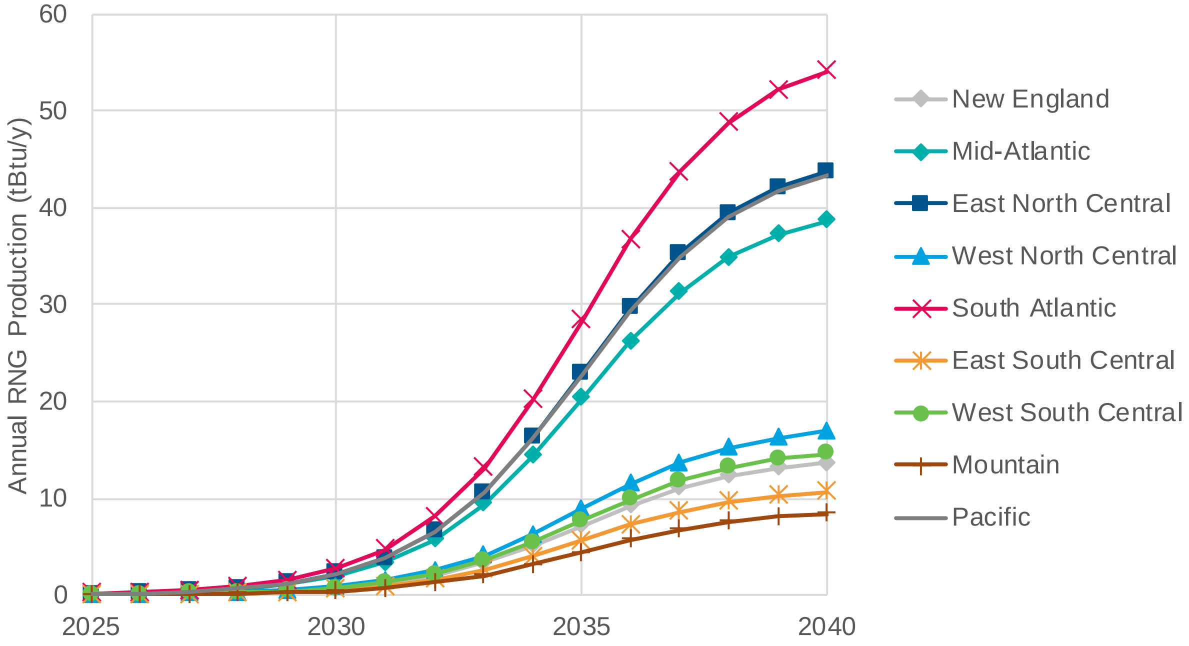

Figure 39. RNG Production Potential from MSW, Achievable Scenario, in tBtu/y

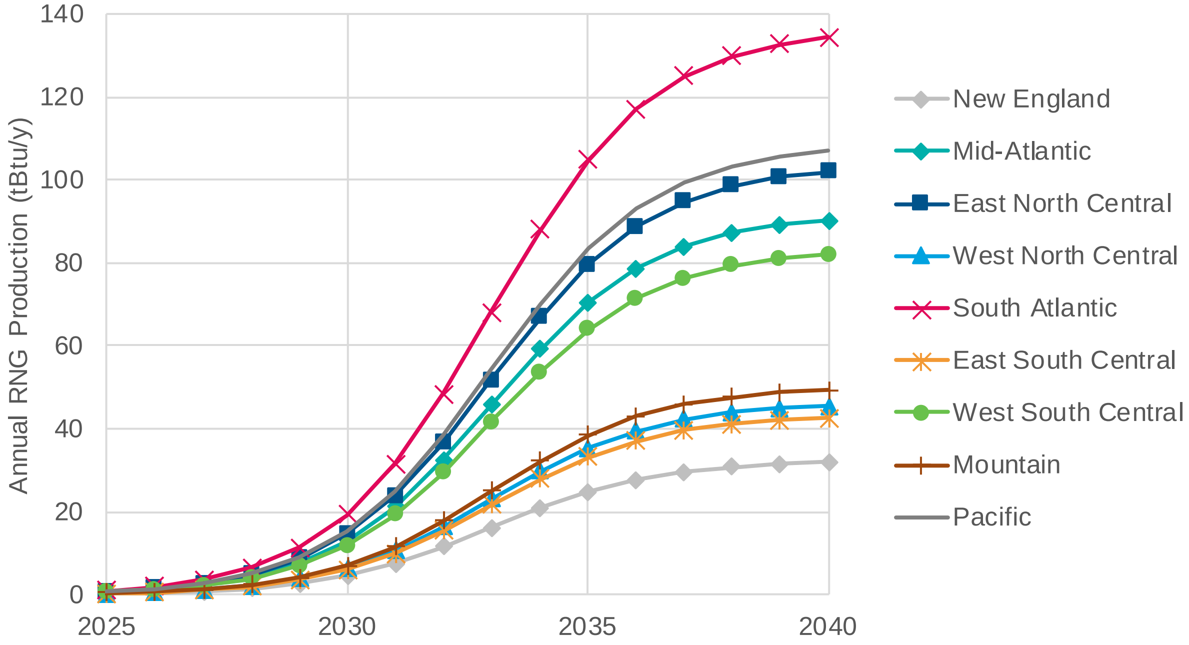

Figure 40. RNG Production Potential from MSW, Aggressive High Scenario, in tBtu/y

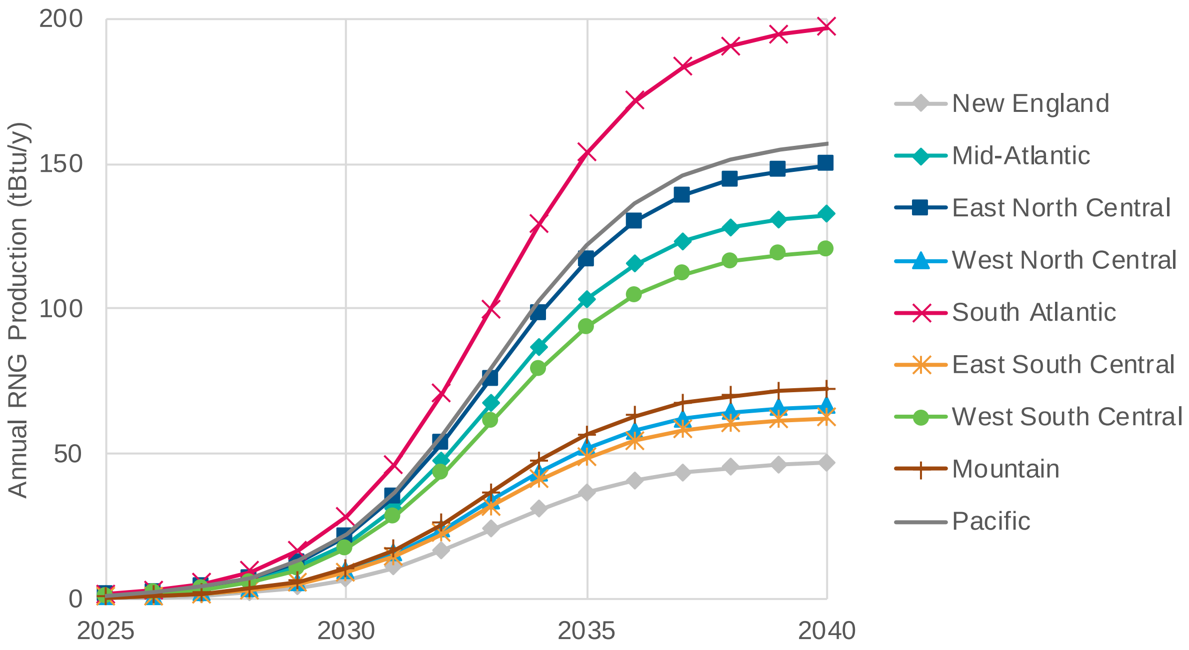

Table 28. Annual RNG Production Potential from MSW, tBtu/y

RNG Potential Scenario	RNG Potential from Nonbiogenic MSW, tBtu/y									
	South Atlantic	New England	Mid-Atlantic	East North Central	West North Central	East South Central	West South Central	Mountain	Pacific	National
Conservative	**56.9**	14.4	40.6	45.9	17.7	11.2	15.3	8.8	45.4	**256.2**
Achievable	**136.3**	32.4	91.6	103.4	46.1	43.2	83.2	50.1	108.5	**694.8**
Aggressive	**199.8**	47.5	134.3	151.6	67.6	63.4	122.0	73.5	159.0	**1,018.7**

As shown in Table 28, ICF estimates in the Achievable scenario that 136 tBtu/y of RNG could be produced from nonbiogenic MSW through thermal gasification by 2040 in the South Atlantic Census region. At the national level this estimate increases to 695 tBtu/y of RNG from nonbiogenic MSW, rising to 1,019 tBtu/y in the Aggressive High scenario.

RNG from P2G and Methanation

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 the highly reliable and efficient existing natural gas transmission and distribution infrastructure, the upfront costs of which have already been incurred.

The flexibility of hydrogen provides advantages beyond being an input to methanation for RNG. Hydrogen can be mixed directly with natural gas in pipeline systems, up to certain recommended blending proportions, and used in place of natural gas in some applications. 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.

P2G discussions often focus on the role and scale of excess (curtailed) renewable electricity as the source for hydrogen and RNG production. The issue of curtailed renewable electricity is a complicated one, and P2G systems are likely to use curtailed electricity in the near term as a transitional approach to develop cost-effective P2G systems. However, for hydrogen and RNG to be produced at meaningful quantities, dedicated renewable electricity generation is likely to be needed. This is particularly the case if P2G will be a key driver for emission reductions in the natural gas system and form part of deep decarbonization strategies.

ICF estimated the potential for P2G to contribute toward RNG production over a series of steps consistent with the approach taken in our recent American Gas Foundation assessment of the national supply and emission reduction potential of RNG, but tailored to reflect the specific policy environment of the Greater Washington, D.C. metropolitan area.[35] First, 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 from 2025 to 2040. We did this over a series of steps. Firstly, the model was constrained by all finalized and on-the-books state-level Renewable Portfolio Standards (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.

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[35] ICF, 2019. Renewable Sources of Natural Gas: Supply and Emissions Reduction Assessment, https://www.gasfoundation.org/2019/12/18/renewable-sources-of-natural-gas/

Table 29 shows the share of generation represented by renewable resources 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 U.S. 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.

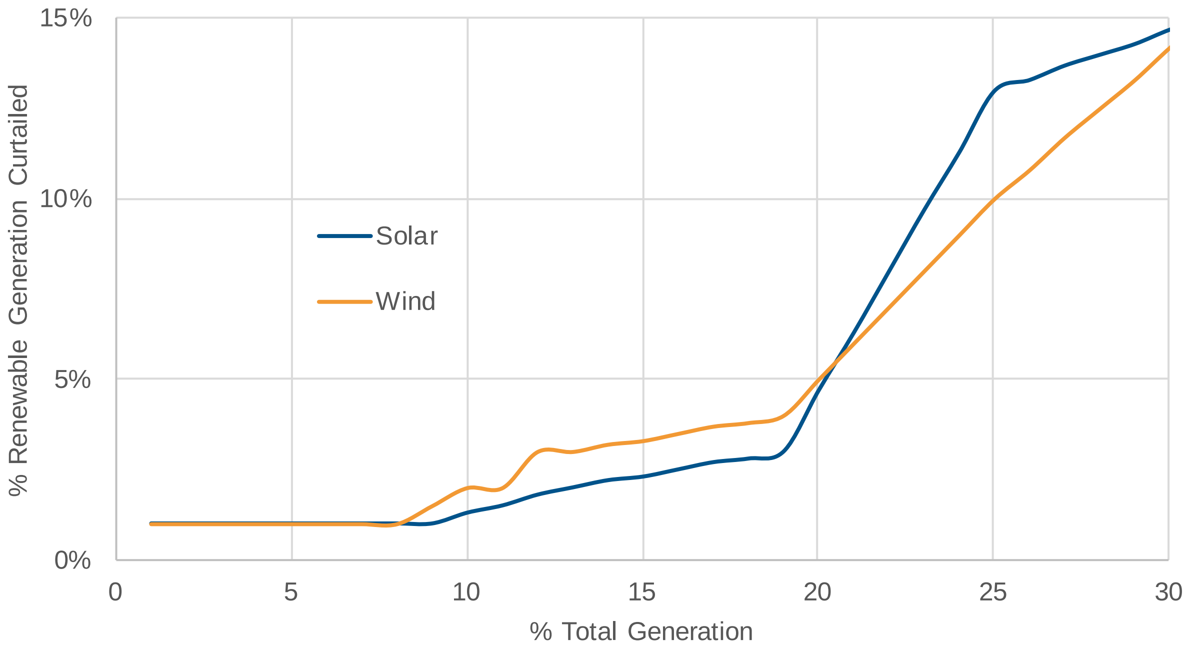
Table 29. Renewable Share of Electricity Generation in RPS-Compliant Run Using IPM

Region	**Renewable Share of 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%

ICF also implemented, as an input to the IPM platform, an assumption regarding the rate of curtailed renewable electricity, differentiated between solar and wind, and the percent of total electricity generation that the renewable resource represents.

As shown in Figure 41, ICF assumed an increasing curtailment rate as the share of renewable generation increased. In other words, the input assumes that when solar and wind electricity generation represent about 20% of total electricity generation, about 5% of the electricity is curtailed. ICF reviewed the current frequency of curtailment events in each region (at the daily time scale) and assumed that the frequency would be similar moving forward.

Figure 41. Assumed Curtailment Rates as a Function of Renewable Electricity Penetration



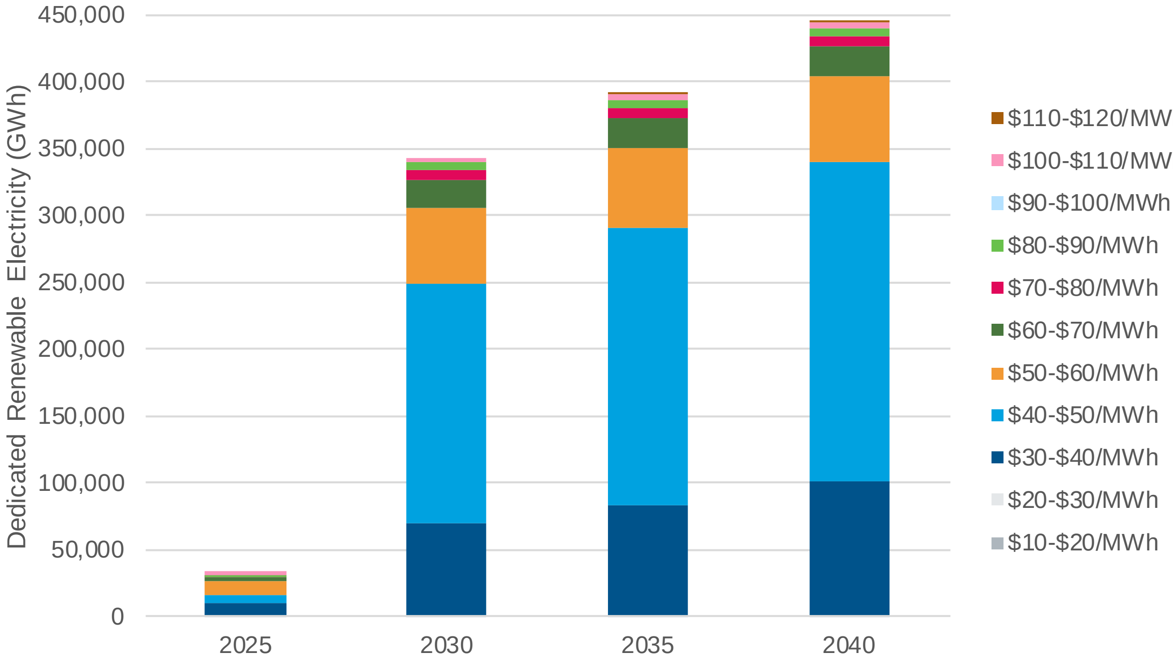
ICF notes that this is likely an over-simplification of curtailment, especially given the interest of regulators to start to impose more stringent RPS or CES policies and energy-efficiency measures, thereby possibly increasing curtailment considerably. Table 30 includes the estimated curtailed renewable electricity generation (reported in units of GWh) available from 2025 to 2040.

Table 30. Estimated Curtailed Renewable Electricity Generation, 2025–2040 in Units of GWh

Region	Estimated Curtailed Renewable Electricity, GWh			
	2025	2030	2035	2040
US	**458.5**	**505.7**	**491.3**	**499.4**
Non-CA WECC	20.7	22.3	22.6	22.9
CAISO	98.3	164.4	170.7	177.3
SPP	164.3	164.6	164.6	164.6
MISO	53.4	44.2	44.7	45.3
SERC	2.9	3.4	3.4	3.4
ERCOT	108.1	88.9	67.6	67.6
ISONE	1.1	1.9	2.4	3.0
NYISO	2.4	2.8	2.8	2.8
PJM	6.9	7.4	7.4	7.4
FRCC	0.4	5.9	5.1	5.1

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 Figure 42, to develop an outlook for P2G using dedicated renewable electricity generation.

Figure 42. Supply-Cost Curve for Dedicated Renewable Electricity for P2G Systems, 2025–2040

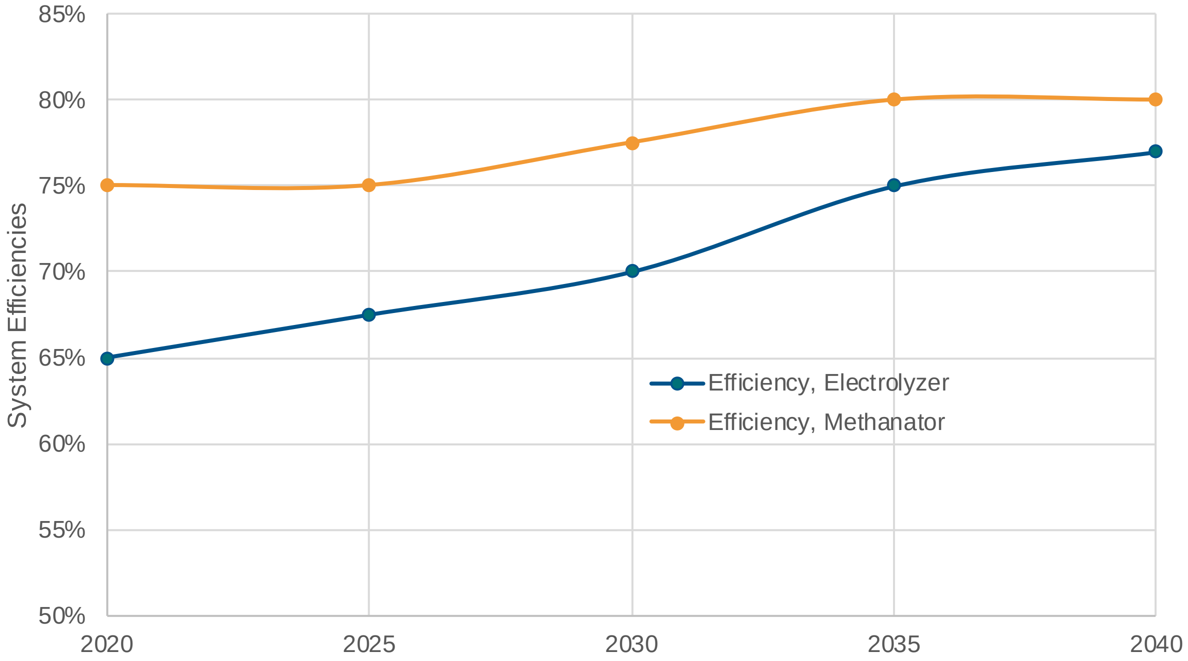


Based on the curtailed electricity estimates and the supply-cost curve constructed for dedicated renewable electricity generation, ICF determined how much hydrogen and methane could be produced using P2G/methanation systems. We assumed a capacity factor of 5% to 10% for curtailed renewable electricity generation and 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 an 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 an 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. Figure 43 includes the assumed conversion efficiencies for hydrogen production from an electrolyzer (blue) and for the methanation reaction to produce RNG for injection (orange).

Figure 43. Assumed Efficiency for Electrolysis and Methanation, 2020–2040



These assumptions yield the resource potential listed in Table 31, 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 31. 2025-2040 Annual Hydrogen and RNG Production from Renewable Electricity P2G, tBtu/y

Resource: Curtailment & Dedicated RE Generation	**Capacity Factors**		**2025**	**2030**	**2035**	**2040**
	Curtailed	**Dedicated**				
Hydrogen						
Low	5%	50%	11.5	297.1	372.2	447.1
	10%	80%	18.4	475.3	595.6	715.4
High	5%	50%	11.5	364.6	448.7	530.2
	10%	80%	18.4	583.4	718.0	848.3
Max	10%	95%	93.2	935.7	1,064.0	1,210.5
RNG						
Low	5%	50%	8.6	230.2	297.8	357.7
	10%	80%	13.8	368.4	476.5	572.3
High	5%	50%	8.6	282.5	359.0	424.1
	10%	80%	13.8	452.1	574.4	678.7
Max	10%	95%	74.5	748.5	851.2	968.4

3. Cost Assessment

Key Takeaways

ICF reports that RNG will be available from various feedstocks in the range of $7/MMBtu to $44/MMBtu. Anaerobic digestion feedstocks, notably from LFG and WRRF, are more cost-effective in the near term. RNG from thermal gasification feedstocks are more expensive, largely reflecting the immature state of thermal gasification as a technology, and the associated uncertainties around cost and feedstock availability.

RNG is more expensive than its fossil counterpart; however, in a decarbonization framework, the proper comparison for RNG is to other abatement measures that are viewed as long-term strategies to reduce GHG emissions (discussed in more detail in Section 4). In addition, ICF anticipates that over time there will be increasing opportunities for cost reductions as RNG technologies mature and the market expands.

Cost Methodology

ICF developed assumptions for the capital expenditures and operational costs for RNG production from the various feedstock and technology pairings outlined previously. 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. Table 32 outlines some ICF's baseline assumptions that we employ in our RNG costing model.

Table 32. Illustrative ICF RNG Cost Assumptions

Cost Parameter	ICF Cost Assumptions
Facility Sizing	▪ Differentiate by feedstock and technology type: anaerobic digestion and thermal gasification. ▪ Prioritize larger facilities to the extent feasible, but driven by resource estimate.
Gas Conditioning and Upgrade	▪ Vary by feedstock type and 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.

Cost Parameter	ICF Cost Assumptions
Delivery	▪ Cost of delivering the biogas at a price of $1.20/MMBtu. 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 biogas 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.

In addition, these cost estimates do not reflect the potential value of the environmental attributes associated with RNG, nor the current markets and policies that provide credit for these environmental attributes. While this section focuses purely on the costs associated with the production of RNG, Sections 4 and 5 discuss in more detail the market prices for RNG and the associated value of the environmental characteristics of RNG.

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 P2G 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 a 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.

To some extent, ICF's cost modeling does presume changes in the underlying structure of project financing, which is currently linked inextricably to revenue sharing associated with environmental commodities in the federal Renewable Fuel Standard market and California's LCFS market. Our project financing assumptions likely have a lower return than investors may be expecting in the market today; however, our cost assessment seeks to represent a more mature market to the extent feasible, whereby upward of 1,000-4,500 tBtu per year of RNG is being produced. In that regard, we implicitly assume that contractual arrangements are likely considerably different and local/regional challenges with respect to RNG pipeline injection have been overcome.

Table 33 provides a summary of the different cost ranges for each RNG feedstock and technology.

Table 33. Summary of Cost Ranges by Feedstock Type

	Feedstock	Cost Range ($/MMBtu)
Anaerobic Digestion	Landfill Gas	$7.10 – $19.00
	Animal Manure	$18.40 – $32.60
	Water Resource Recovery Facilities	$7.40 – $26.10
	Food Waste	$19.40 – $28.30
Thermal Gasification	Agricultural Residues	$18.30 – $27.40
	Forestry and Forest Residues	$17.30 – $29.20
	Energy Crops	$18.30 – $31.20
	Municipal Solid Waste	$17.30 – $44.20

RNG from Anaerobic Digestion

Landfill Gas

ICF developed assumptions for each region by distinguishing between four types of landfills: candidate landfills[36] without collection systems in place, candidate landfills with collection systems in place, landfills[37] without collection systems in place, and landfills with collections systems in place.[38] 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 SCFM 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.

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[36] 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.

[37] Excluding those that are designated as candidate landfills.

[38] Landfills that are currently producing RNG for pipeline injection are included here.

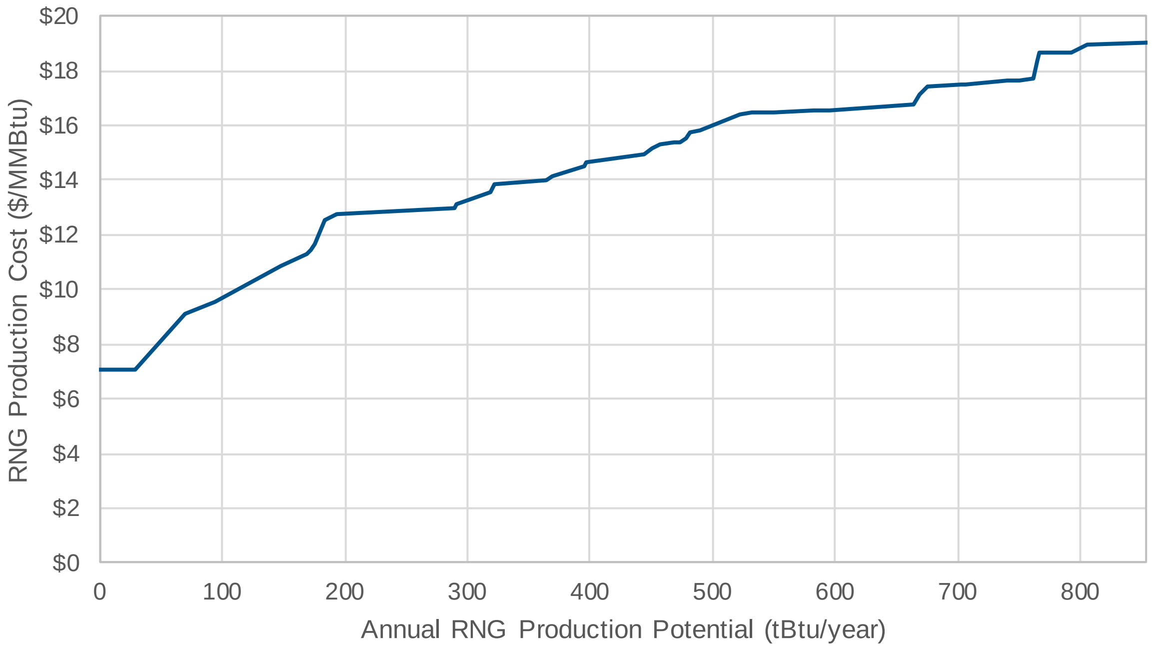
Table 34 summarizes the key parameters that ICF employed in our cost analysis of LFG.

Table 34. 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	▪ CO_2 separation ▪ H_2S removal ▪ N_2/O_2 removal	▪ $2.3 to $7.0 million, depending on facility ▪ $0.3 to $1.0 million, depending on facility ▪ $1.0 to $2.5 million, depending on facility
Utility Costs	▪ Electricity: 25 kWh/MMBtu ▪ Natural Gas: 6% of product	▪ 4.6–13.7 ¢/kWh; average of 6.5 ¢/kWh for region ▪ $3.00–$8.25/MMBtu; average of $4.75/MMBtu for region
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%

Figure 44 includes ICF's estimates for the RNG from landfill gas supply curve.

Figure 44. Supply-Cost Curve for RNG from Landfill Gas, $/MMBtu vs tBtu



ICF reports a range of costs for RNG from LFG at $7.1/MMBtu to $19.0/MMBtu.

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.

Table 35 includes the main assumptions used to estimate the cost of producing RNG from animal manure.

Table 35. 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	▪ CO_2 separation ▪ H_2S removal ▪ N_2/O_2 removal	▪ \$2.3 to \$7.0 million, depending on facility ▪ \$0.3 to \$1.0 million, depending on facility ▪ \$1.0 to \$2.5 million, depending on facility
Utility Costs	▪ Electricity: 30 kWh/MMBtu ▪ Natural Gas: 6% of product	▪ 4.6–13.7 ¢/kWh; average of 6.5 ¢/kWh for region ▪ \$3.00–\$8.25/MMBtu; average of \$4.75/MMBtu for region
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 WRRFs based on the throughput of the facilities. The table below includes the main assumptions used to estimate the cost of producing RNG at WRRFs.

Table 36. 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	▪ CO_2 separation ▪ H_2S removal ▪ N_2/O_2 removal	▪ \$2.3 to \$7.0 million, depending on facility ▪ \$0.3 to \$1.0 million, depending on facility ▪ \$1.0 to \$2.5 million, depending on facility
Utility Costs	▪ Electricity: 26 kWh/MMBtu ▪ Natural Gas: 6% of product	▪ 4.6–13.7 ¢/kWh; average of 6.5 ¢/kWh for region ▪ \$3.00–\$8.25/MMBtu; average of \$4.75/MMBtu for region
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 an estimated cost of RNG from WRRFs of \$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 SCFM of biogas for conditioning and upgrading before pipeline injection. In addition to the other costs included in other anaerobic digestion systems, we also included assumptions about the cost of collecting food waste and processing it accordingly (see Table 37).

Table 37. Cost Consideration in Levelized Cost of Gas Analysis for RNG from Food Waste Digesters

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	▪ CO_2 separation ▪ H_2S removal ▪ N_2/O_2 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; average of 6.5 ¢/kWh for region ▪ $3.00–$8.25/MMBtu; average of $4.75/MMBtu for region
Operations & Maintenance	▪ 1.5 FTE for maintenance ▪ Miscellany	▪ 15% of installed capital costs
Other	▪ Tipping fees	▪ Varied by region; used weighted average of $49.07 (see Table 38)
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 Table 38.

Table 38. Average Tipping Fee by Region ($/ton of MSW unless otherwise noted)[39]

Region	Tipping Fee
Greater Washington, D.C Area	
Frederick County, MD[40]	$69
Frederick County, MD (Food Waste, Separated)[41]	$50
Montgomery County LF, MD[42]	$60
Charles County LF, MD[43]	$75
Brown Station SLF, Prince George's County, MD[44]	$59
Frederick County Regional Landfill, VA[45]	$50
Loudoun County SLF, VA[46]	$62
Shenandoah County LF, VA[47]	$45
Regional	
Maryland, statewide average	$68.57
Virginia, statewide average	$52.22
Northeast: CT, DE, ME, MD, MA, NH, NJ, NY, PA, RI, VA, WV	$67.39
Rest of U.S.	
Pacific: AK, AZ, CA, HI, ID, NV, OR, WA	$68.46
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***

The values listed in Table 38 are generally the fees associated with tipping municipal solid waste—the tipping fees for construction and debris tend to be higher because the materials take up more space in landfills. The only data point for tipping fees for food waste is for the Frederick County landfill in Maryland, which shows a tipping fee of $50/ton for food waste compared to

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[39] Environmental Research & Education Foundation, Analysis of MSW Landfill Tipping Fees–April 2019. Retrieved from www.erefdn.org.

[40] Frederick County, available online at https://frederickcountymd.gov/535/Fees-Payment-Options.

[41] Ibid.

[42] Montgomery County, Maryland, available online at https://www.montgomerycountymd.gov/SWS/Resources/Files/swc/swc-rate-detail.pdf.

[43] Charles County Landfill, https://www.charlescountymd.gov/sites/default/files/pw/FY20%20Landfill%20Fees.pdf.

[44] Prince George's County, MD, https://www.princegeorgescountymd.gov/615/Brown-Station-Road-Sanitary-Landfill.

[45] Frederick County, VA. https://www.fcva.us/departments/public-works/landfill-and-solid-waste#tipping.

[46] Loudoun County, VA, https://www.loudoun.gov/landfill.

[47] Shenandoah County, VA, https://shenandoahcountyva.us/landfill/landfill-fees/.

$69/ton for MSW. ICF notes, however, that the $50/ton reported by Frederick County is for residential customers; they do not list a comparable fee for commercial customers. ICF developed our cost estimates assuming that anaerobic digesters discounted the tipping fee for food waste compared to MSW landfills by 20%.

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 MSW.[48] 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 a range of facilities processing different volumes of feedstock (in units of tons per day, or tpd) that we employed for conducting the cost analysis.

Table 39. Thermal Gasification Cost Assumptions

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%

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[48] Note that MSW here refers to the non-organic, nonbiogenic 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.

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 the 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 <u>not</u> 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.[49]

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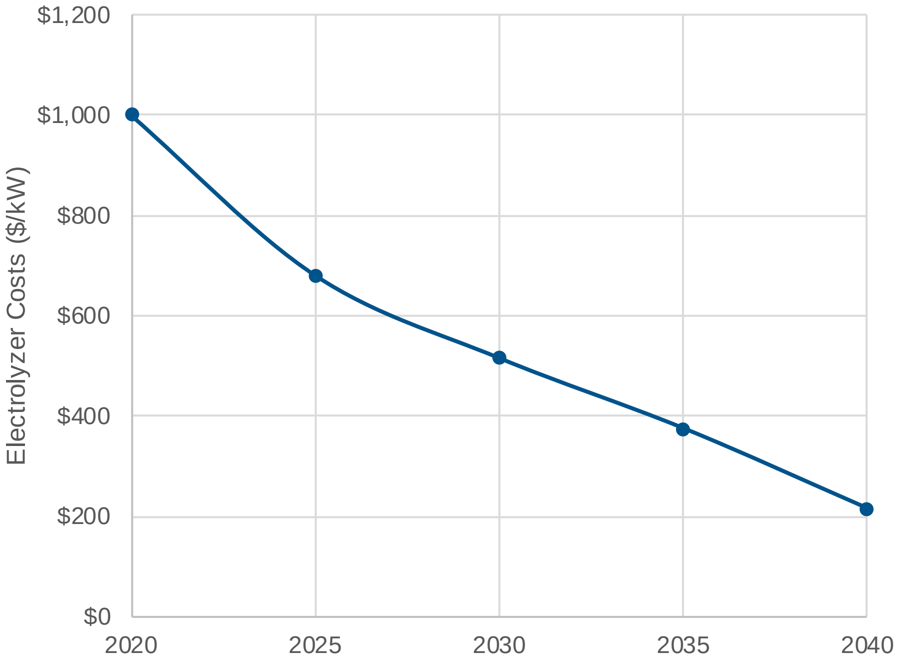
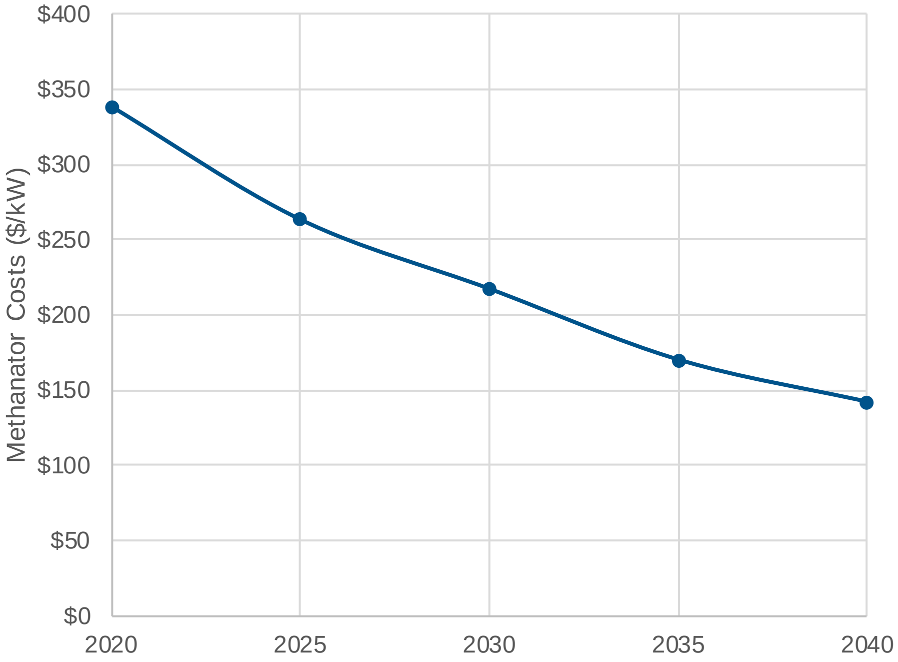
[49] Draft Results: Future of Natural Gas Distribution in California, CEC Staff Workshop for CEC PIER-16-011, June 6, 2019, available online at https://ww2.energy.ca.gov/research/notices/2019-06-06_workshop/2019-06-06_Future_of_Gas_Distribution.pdf.

Figure 45. Installed Capacity Cost of Electrolyzers, $/kW, 2020–2040



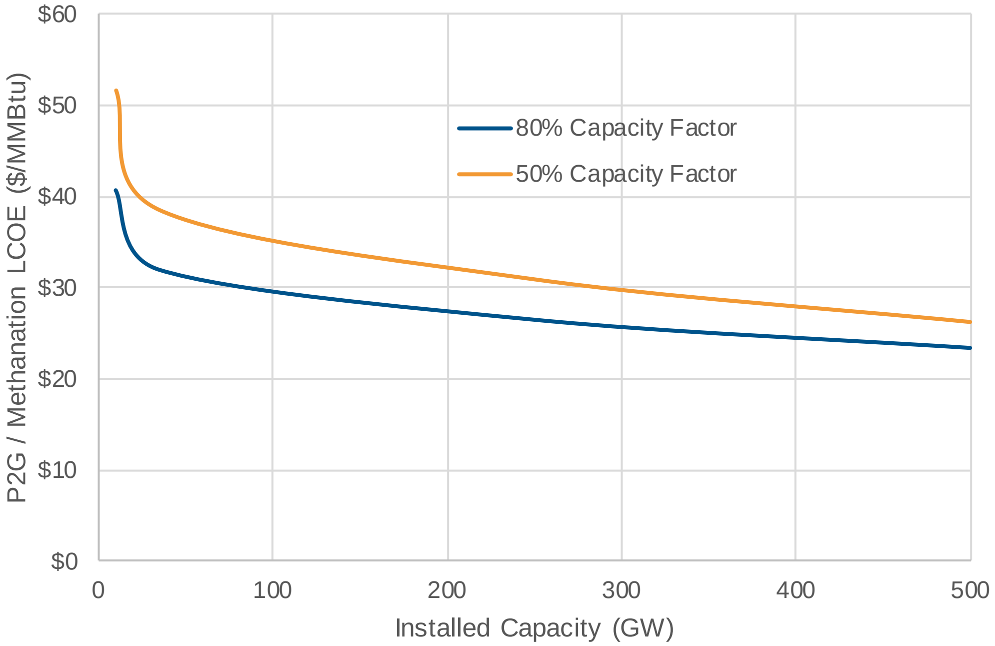
ICF assumed a decreasing cost of Methanation technology consistent with Figure 46, presented in units of $/kW.

Figure 46. Installed Capacity Cost of Methanator, $/kW, 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. Figure 47 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 47. Estimated RNG Costs from P2G/Methanation as a Function of Installed Capacity, $/MMBtu



Combined Supply Curves

ICF developed a supply-cost curve (shown in Figure 48) based on a combination of a) the supply estimates included previously, and b) ICF's bottom-up cost estimates to produce RNG. For each feedstock, ICF calculates the levelized cost of energy (LCOE) by incorporating the capital expenditures from equipment, operations and maintenance (O&M), and financing.[50]

ICF estimates that more than half of the RNG production potential in the Achievable scenario would be available at less than $20/MMBtu, as shown Figure 48. Generally speaking, ICF finds the front end of the supply curve to be landfill gas projects and WRRFs that are poised to move toward 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 slope 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.

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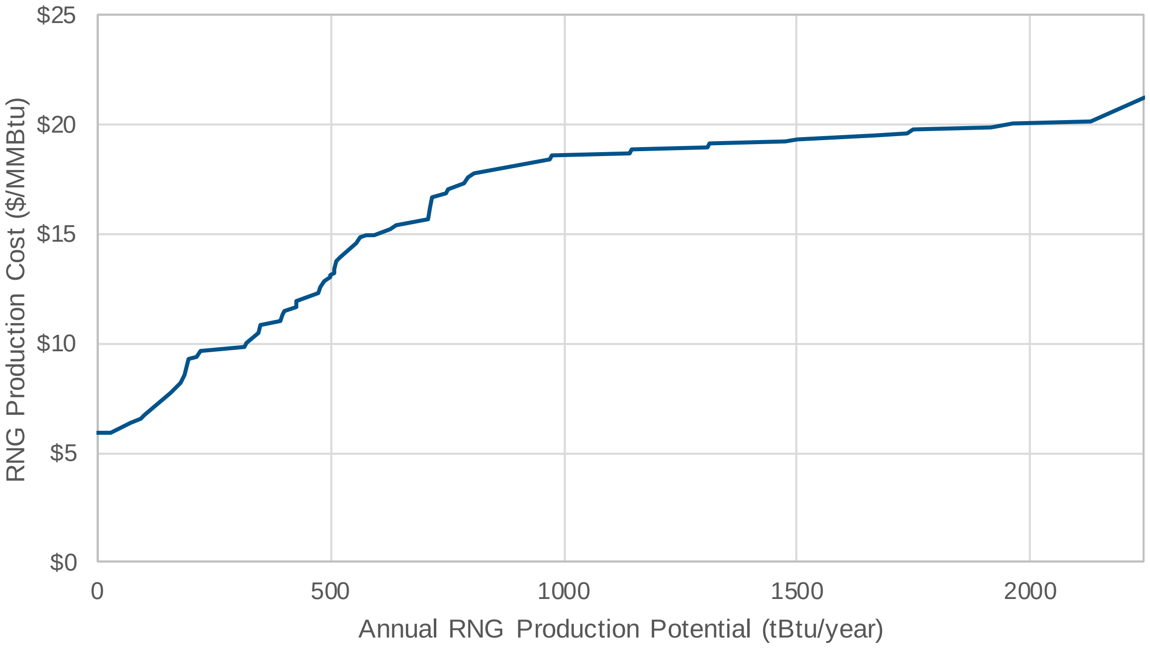
[50] Financing costs are inclusive of factors such as interest rate for financing, typical debt/equity ratios for new projects, and an assumed return on equity.

Figure 48. Combined RNG Supply-Cost Curve, Less Than $20/MMBtu in 2040



RNG Pricing

The RNG production costs outlined previously are illustrative and provide context for RNG as a mitigation strategy and how its introduction might impact costs in the natural gas system. It is important to note, however, that technology breakthroughs and greater RNG deployment could reduce the costs presented by ICF. Apart from cost-reduction considerations, there is another major factor associated with understanding RNG deployment: the price of RNG.

Today, the RNG market is largely driven by contracts that are dependent on the value of environmental commodities generated, assuming, as in most cases for RNG for pipeline injection today, that the fuel ends up in a transportation application. In other words, there is no real reference market price for RNG today as there are for other commodities.

The challenge that utilities and other stakeholders will face is the transitional period during which the market will evolve from shorter-term contracts linked to the price of environmental commodities to longer-term, fixed-price contracts. In other words, the market lacks liquidity and price discovery. As the market becomes more liquid and price discovery improves, there is potential for market swings and uncertainty. This process will occur naturally as the transportation market becomes saturated with RNG and other policies that support RNG production come into play; however, the transition itself may be bumpy.

In principle, the RNG price should reflect the marginal cost of RNG production on the system. However, differences in incentives across various end uses have the potential to skew this fundamental relationship. ICF believes that the near-term RNG price will reflect investors' risk appetites. More specifically, ICF posits that the RNG price will reflect the value of a long-term, fixed-price agreement compared to the discounted value of short-term gains realized from potentially valuable environmental commodities.

On a simplified basis, the current market value of RNG in the transportation sector (based on D3 RIN pricing) is at least $20/MMBtu, with at least another $8–$10/MMBtu available if the RNG can be directed to California or Oregon. This should not be misconstrued as an RNG price. If that were the case, then market actors outside of the transportation sector would have to pay a price upward of $30/MMBtu.

However, this price is out of line with the production costs of some RNG accessible to the Greater Washington, D.C. metropolitan area. ICF estimates that in the next 2–4 years, RNG pricing will be available on a fixed-price, long-term basis in the range of $9–$15/MMBtu. In some cases, this may include the option for additional revenue sharing between counterparties linked to potential environmental commodities.

ICF also estimates that policies incentivizing RNG consumption outside the transportation sector will help yield overall cost reductions, but that the marginal cost of production will increase as more RNG is needed in the system to comply with various commitments. ICF estimates that the mid-term RNG pricing (in 5–10 years) will be available on a fixed-price, long-term basis in the range of $8–$19/MMBtu and will become less dependent on the share of environmental commodities.

RNG pricing post-2030 will be dependent on a variety of market developments that are difficult to forecast—most notably the increased use of RNG outside of the transportation sector. If robust policies are put into place (as discussed in more detail in Sections 6 and 7), then ICF believes that market conditions will support downward pressure on RNG pricing post-2030.

4. GHG Accounting and Cost-Effectiveness

Key Takeaways

RNG represents a valuable and underutilized renewable energy source with a low or net negative carbon intensity, depending on the feedstock. The GHG emission accounting method and scope employed can have a significant impact on how carbon intensities for RNG are reported and estimated. For some feedstocks, applying the lifecycle emission accounting framework captures the full benefit of RNG's emission reduction potential, such as reflecting avoided methane emissions.

RNG can make a significant contribution to the long-term GHG emission reduction objectives in the Greater Washington, D.C. Metropolitan area. When applying a combustion accounting framework, ICF estimates that in the South Atlantic region, 13 to 44 MMT of GHG emissions could be reduced per year in 2040 through the deployment of RNG based on the Conservative Low and Aggressive High scenarios. For abatement cost estimates, RNG at under $7/MMBtu is equivalent to about \$55–\$60/tCO_2e, while RNG at \$20/MMBtu has an estimated cost-effectiveness of about \$300/tCO_2e.

In many instances, policymakers, corporations and RNG stakeholders may not be recognizing the complete benefits of RNG due to a limited assessment and reporting scope. In addition, the cost-effectiveness of RNG as an emission reduction measure is generally underestimated and underappreciated, particularly in comparison to other mitigation approaches over the long term and in a deep decarbonization policy environment.

GHG Accounting Framework and Methodology

The GHG emissions of RNG, typically called a carbon intensity (e.g., grams of CO_2 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.

Overview of Accounting Methods

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 an emission factor for California's average electricity mix to determine the annual GHG emissions associated with an average household's electricity consumption using data from the EPA[51] and EIA:[52]

$$240\ \frac{g\ CO_2e}{kWh} \times 6{,}800\ \frac{kWh}{house} = 1.6 \times 10^6\ \frac{g\ CO_2e}{house}$$

Emissions accounting becomes more 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 LCFS relies on a lifecycle assessment approach for estimating carbon intensities of transportation fuels. As a result, LCFS emissions for a specific transportation fuel pathway include all emission sources in the fuel lifecycle from resource extraction to final consumption in a vehicle.

Lifecycle Assessment

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 lifecycle assessment (LCA). LCA allows for a holistic GHG accounting approach that considers all lifecycle 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.

GHG emission accounting for inventories typically relies on guidance from the Intergovernmental Panel on Climate Change (IPCC) developed in 2006.[53] 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.

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[51] US EPA. 2018. eGRID. Available at: https://www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid.

[52] US EIA. 2009. Household Energy Use in California. Available at: https://www.eia.gov/consumption/residential/reports/2009/state_briefs/pdf/ca.pdf.

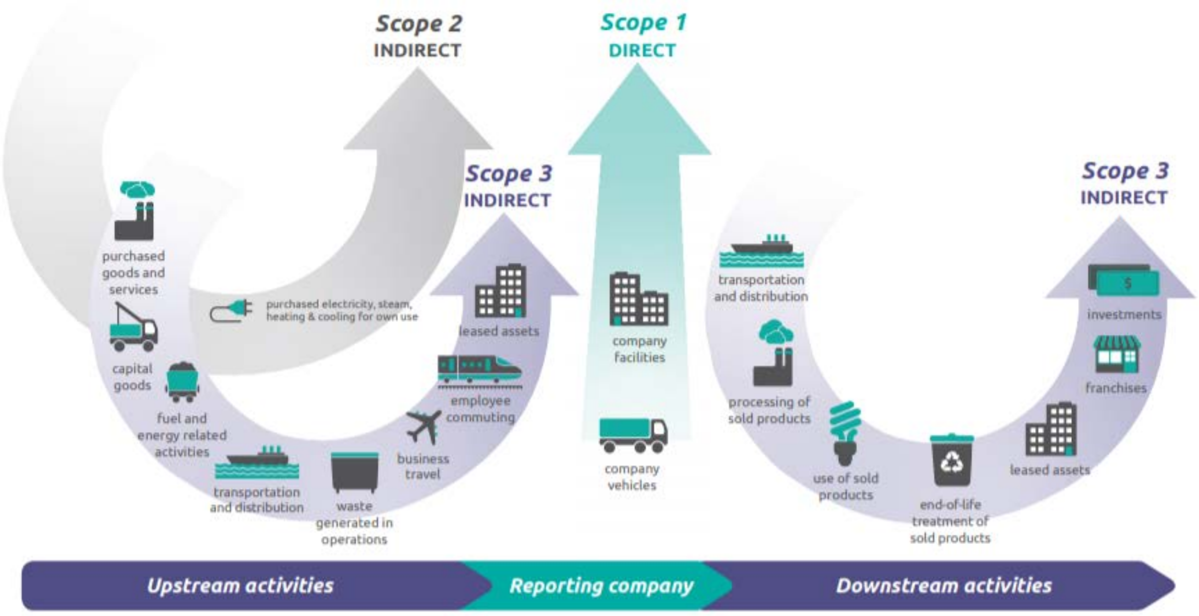
[53] IPCC. 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Available at: https://www.ipcc-nggip.iges.or.jp/public/2006gl/.

Greenhouse Gas Protocol

The GHG 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 49 shows how the Protocol groups these emission sources by Scopes, and how they relate to an organization’s operations.

Figure 49. Scopes for Categorizing Emissions Under the 2019 GHG Protocol



Organizations most often may limit their assessment to Scope 1 and 2 emissions, which includes directly controlled assets. Scope 3 emissions reflect a lifecycle 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. carbon taxes, cap-and-trade programs and RPS programs) as they are more closely tied to a particular jurisdiction—where the emissions physically occur.

Figure 50 details the differences between the two accounting frameworks relative to RNG production.

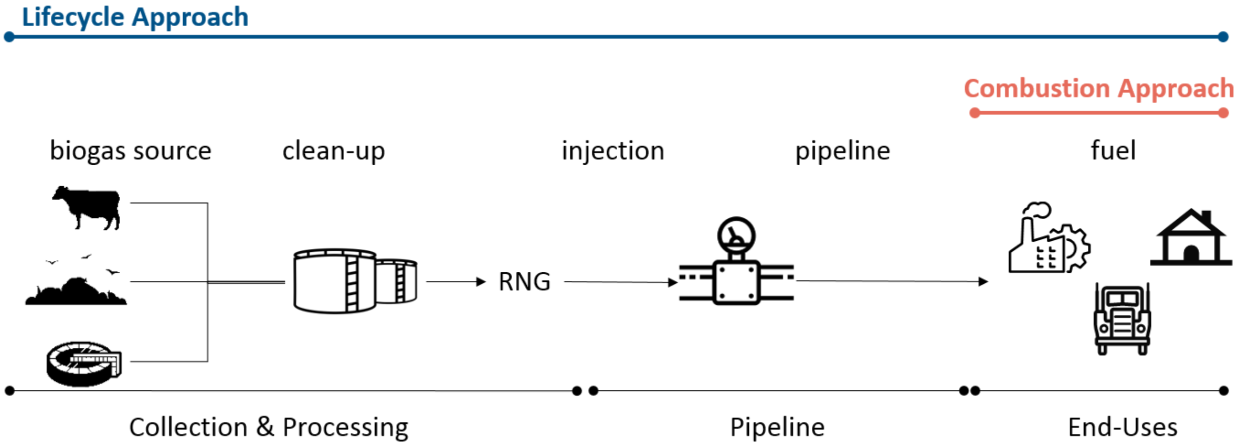
Accounting for Biogenic Emissions

IPCC guidelines state that CO_2 emissions from biogenic fuel sources (e.g., biogas- or biomass-based RNG) should not be included when accounting for emissions in combustion; only CH_4 and N_2O are included.

This is to avoid any upstream "double counting" of CO_2 emissions that occur in the agricultural or land use sectors per IPCC guidance. Other approaches exclude biogenic CO_2 in combustion as it is assumed that the CO_2 sequestered by the biomass during its lifetime offsets combustion CO_2 emissions.

This method of excluding biogenic CO_2 is still commonly practiced for RNG users and producers. For example, LA Metro did not include CO_2 emissions in the combustion of RNG in the agency's most recent CAAP.

Figure 50. GHG Accounting Frameworks for RNG Production



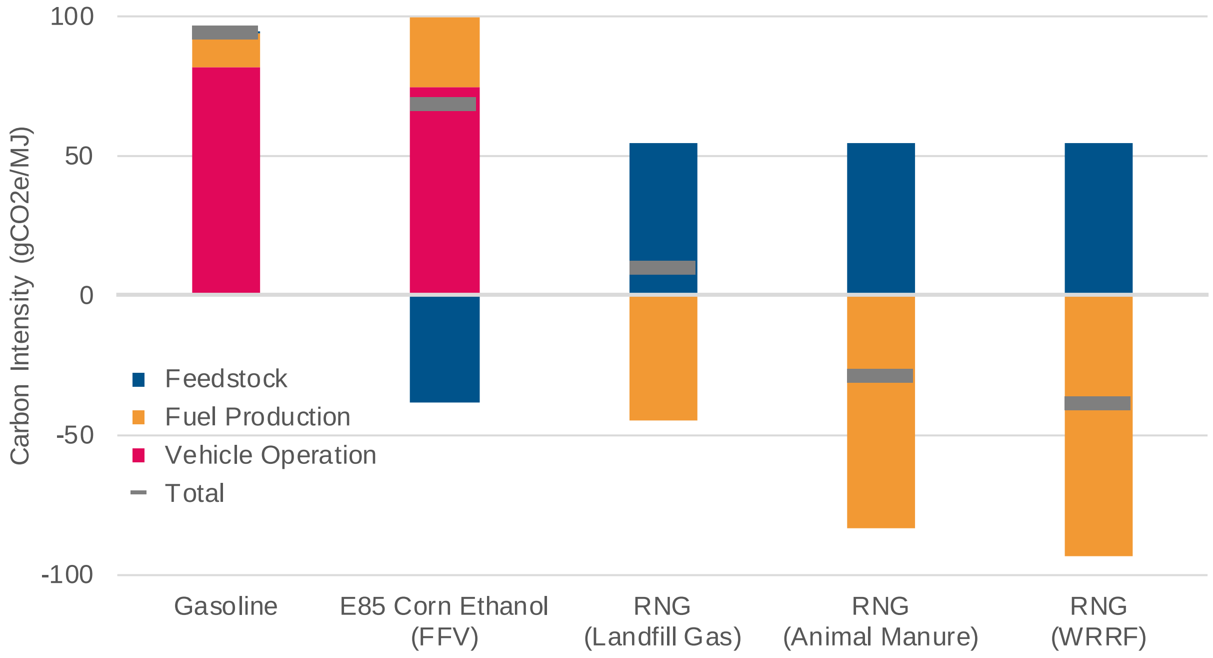
Using the combustion framework, the CO_2 emissions from the combustion of biogenic renewable fuels are considered zero, or carbon neutral. In other words, RNG has a carbon intensity of zero. This includes RNG from any biogenic feedstock, including landfill gas, animal manure, and food waste. Upstream emissions, whether positive (electricity emissions associated with biogas processing) or negative (avoided methane emissions), are not included. RNG procurement strategies do not necessarily need to differentiate RNG by lifecycle carbon intensity, given that RNG in a combustion accounting approach is zero-rated and carbon neutral.

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 the location of production and how the fuel is transported and distributed. The GHG accounting methods and scopes previously discussed dictate which of RNG's lifecycle elements are included as a carbon intensity in emissions reporting.

Variations in Production

Figure 51 shows how these different lifecycle elements contribute to RNG's overall carbon intensity for a selection of RNG sources using Argonne's GREET model[54]: landfill gas, animal waste AD, wastewater sludge AD, and 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 51. Summary of Carbon Intensities for Transportation Fuels Across Lifecycle Stages[55]



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 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.

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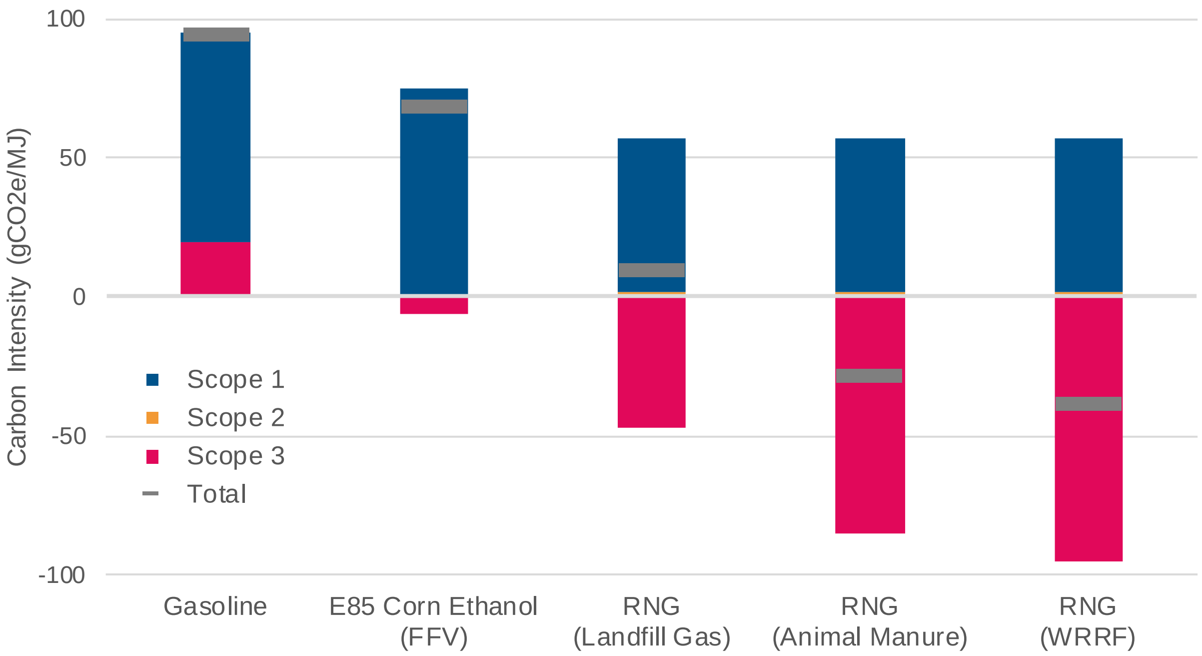
[54] Argonne National Laboratory, 2019. Available at: https://greet.es.anl.gov/
[55] Ibid.

Variations Based on Accounting Method

Figure 52 shows the same GREET results from Figure 51 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 52. RNG Lifecycle Carbon Intensity by Different GHG Protocol Scopes Using GREET Results[56]



Many organizations, jurisdictions, and corporations may limit their emissions reporting to just Scope 1 and Scope 2 emissions, which reflect a production or activity-based accounting approach. Some programs, like the LCFS, include all GHG Protocol Scopes with its lifecycle assessment approach. This means that if Scope 3 or lifecycle emission are excluded in reporting, the potential emission benefits of RNG will not be attributed to that reporting organization. A jurisdiction or organization using a consumption-based approach, or including Scope 3 emissions, would report a lower or negative carbon intensity for RNG, depending on the feedstock.

For example, the Los Angeles County Metropolitan Transportation Authority (LA Metro) is working to shift its entire directly operated bus fleet to RNG as soon as possible. Many of the potential RNG feedstocks that LA Metro may use have a negative carbon intensity under the emissions scope of the LCFS (e.g., animal waste, wastewater anaerobic digestion pathways). However, LA Metro's recent Climate Action and Adaptation Plan[57] included only Scope 1 and 2 emissions, which meant that RNG had net positive emissions from compression and combustion regardless of the feedstock.

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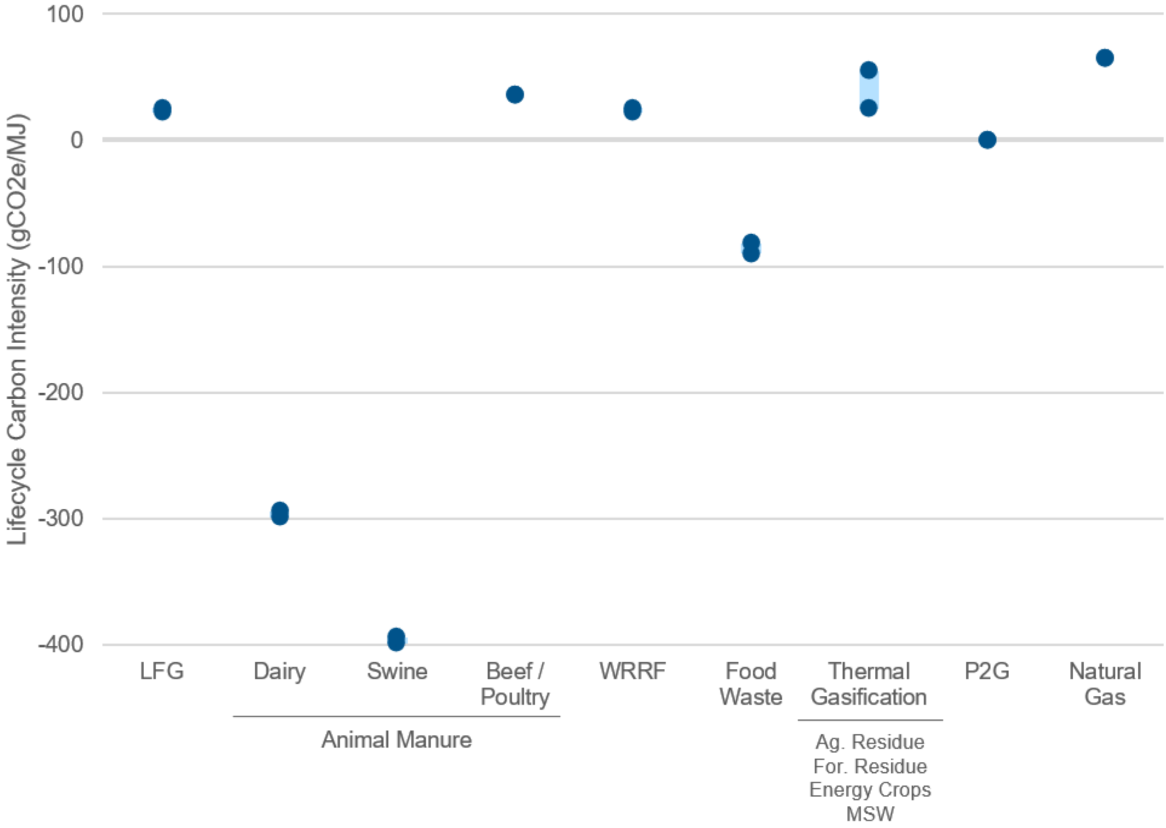
[56] GHG Protocol, 2019. Guidance. Available at: https://ghgprotocol.org/guidance-0
[57] LA Metro, 2019 https://media.metro.net/projects_studies/sustainability/images/Climate_Action_Plan.pdf

Approach to RNG GHG Emission Factors

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.

Figure 53 and Table 40 present ranges of lifecycle CIs for different RNG feedstocks up to the point of pipeline injection. These estimates are primarily based on a combination of Argonne National Laboratory's GREET model, California Air Resources Board's modified California GREET model,[58] and ICF analysis.

Figure 53. Lifecycle GHG Emission Factor Ranges for RNG Feedstocks, South Atlantic Region



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[58] ARB, 2019. https://ww3.arb.ca.gov/fuels/lcfs/ca-greet/ca-greet.htm

Table 40. Lifecycle GHG Emission Factor Ranges for RNG Feedstocks by Region, gCO_2e/MJ

Fuel	**New England**	**Mid-Atlantic**	**East North Central**	**West North Central**	**East South Central**	**West South Central**	**Mountain**	**Pacific**
LFG	18 – 26	15 – 21	28 – 34	28 – 32	26 – 28	26 – 31	21 – 32	13 – 29
Animal Manure								
Dairy	-304 – -294	-308 – -300	-292 – -285	-292 – -286	-294 – -292	-294 – -288	-300 – -286	-310 – -290
Swine	-404 – -394	-408 – -400	-392 – -385	-392 – -386	-394 – -392	-394 – -388	-400 – -386	-410 – -390
Beef/Poultry	36 – 36	31 – 31	46 – 46	44 – 44	38 – 38	42 – 42	44 – 44	41 – 41
WRRF	18 – 26	15 – 21	28 – 34	28 – 32	26 – 28	26 – 31	21 – 32	13 – 29
Food Waste	-97 – -82	-104 – -91	-79 – -68	-79 – -70	-83 – -79	-83 – -73	-91 – -70	-108 – -76
Agricultural Res.	25 – 55	25 – 55	25 – 55	25 – 55	25 – 55	25 – 55	25 – 55	25 – 55
Forestry Res.	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
MSW	25 – 55	25 – 55	25 – 55	25 – 55	25 – 55	25 – 55	25 – 55	25 – 55
P2G	0	0	0	0	0	0	0	0
Natural Gas	65	65	65	65	65	65	65	65

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 reference, the tailpipe emissions of use in a heavy-duty truck are around 60 gCO_2e/MJ.

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 CO_2 from RNG. The cost-effectiveness calculation is simply as follows:

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

where the RNG_{cost} 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 of just under $7/MMBtu, which is equivalent to about \$55–\$60/tCO_2e. As the estimated RNG cost increases to $20/MMBtu, we report an estimated cost-effectiveness of about \$300/tCO_2e. This range in cost for RNG can be converted to provide an equivalent range for the cost-effectiveness of RNG for GHG emission reductions, in dollars per ton of carbon dioxide equivalent.

Estimating the cost-effectiveness of different GHG emission reduction measures is challenging and results can vary significantly across temporal and geographic considerations. Figure 54 shows a comparison of selected measures across various key studies for specific abatement measures that are likely to be required for economy-wide decarbonization in the 2050 timeframe, including natural gas demand side management (DSM), electrification of certain end uses (including buildings and in the industrial sectors),[59,60] direct air capture (whereby CO_2 is captured directly from the air and a concentrated stream is sequestered or used for beneficial purposes),[61] carbon capture and storage,[62] battery electric trucks (including fuel cell drivetrains),[63] and RNG (from this study).

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[59] Energy Futures Initiative, 2019. Optionality, Flexibility & Innovation: Pathways for Deep Decarbonization in California.

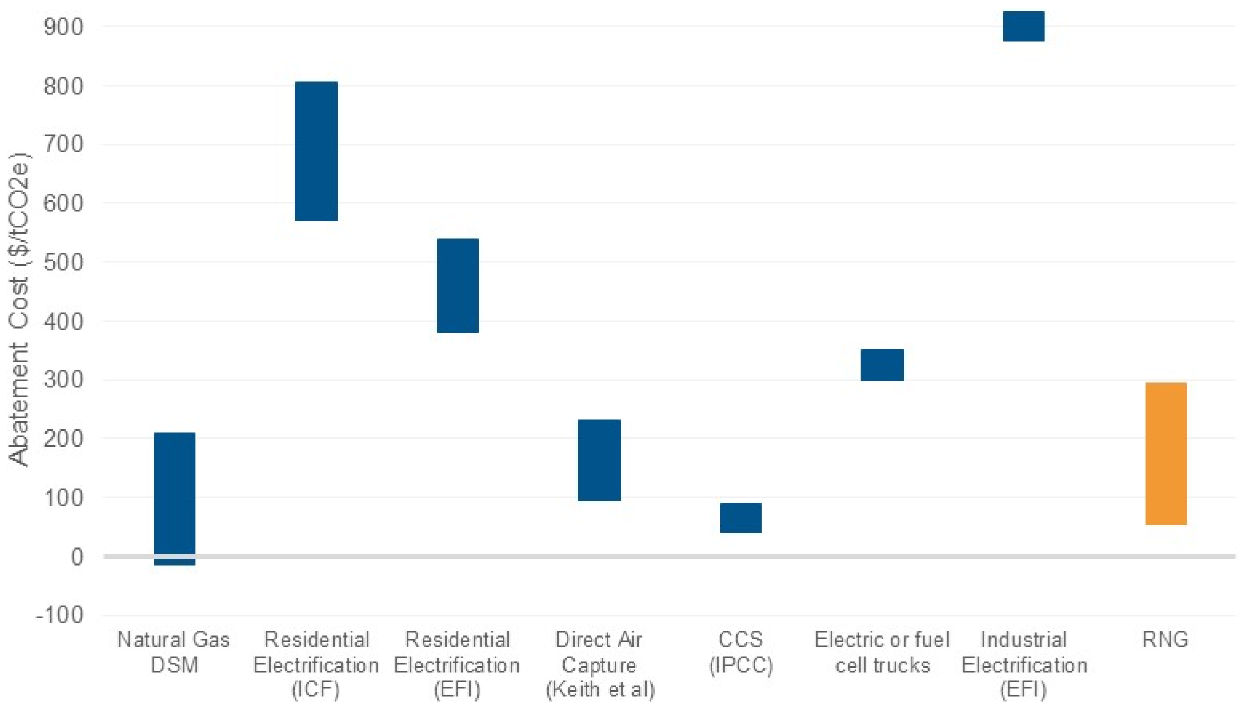
[60] ICF, 2018, Implications of Policy-Driven Residential Electrification, https://www.aga.org/globalassets/research--insights/reports/AGA_Study_On_Residential_Electrification.

[61] Keith, DW; Holmes, G; St Angelo D; Heidel, K; A Process for Capturing CO2 from the Atmosphere, *Joule*, 2 (8), p1573-1594. https://doi.org/10.1016/j.joule.2018.05.006

[62] IPCC, 2005: IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp.

[63] E3, 2018. Deep Decarbonization in a High Renewables Future, https://www.ethree.com/wp-content/uploads/2018/06/Deep_Decarbonization_in_a_High_Renewables_Future_CEC-500-2018-012-1.pdf

Figure 54. GHG Abatement Costs, Selected Measures, $/tCO$_2$e[64]



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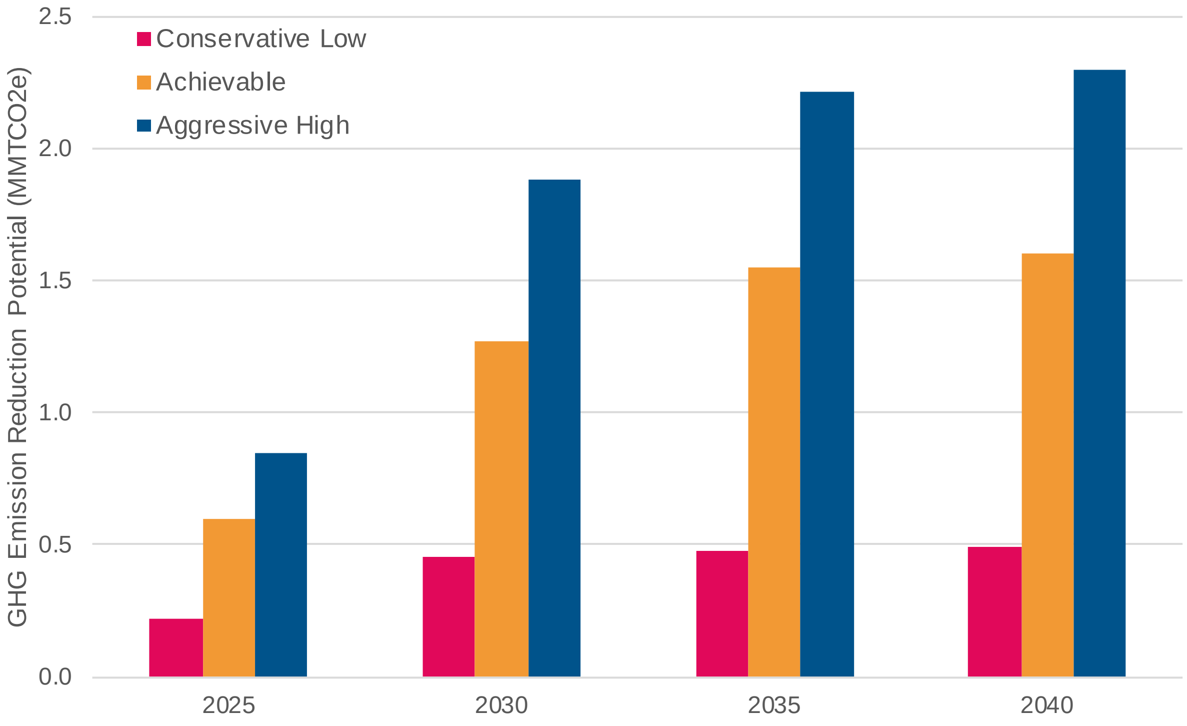
[64] Energy Futures Initiative, 2019. Optionality, Flexibility & Innovation: Pathways for Deep Decarbonization in California, https://static1.squarespace.com/static/58ec123cb3db2bd94e057628/t/5ced6fc515fcc0b190b60cd2/1559064542876/EFI_CA_Decarbonization_Full.pdf; E3, 2018. Deep Decarbonization in a High Renewables Future, https://www.ethree.com/wp-content/uploads/2018/06/Deep_Decarbonization_in_a_High_Renewables_Future_CEC-500-2018-012-1.pdf

GHG Emissions from RNG Resource Assessment

ICF applied the emission factors from the aforementioned “combustion approach” to estimate the GHG reduction potential across each of the RNG potential scenarios for the Greater Washington, D.C. metropolitan area, the South Atlantic Census region, and nationally, as reported previously in Section 2.

Figures 55, 56 and 57 show the range of GHG emission reductions using a combustion accounting framework, in units of million metric tons of CO_2e ($MMTCO_2e$).

Figure 55. Greater Washington, D.C. RNG Emission Reduction Potential by Scenario, $MMTCO_2e$



ICF estimates that in the Greater Washington, D.C. metropolitan area, 0.5 to 2.3 $MMTCO_2e$ of emissions could be reduced per year by 2040 through the deployment of RNG based on the Conservative Low to Aggressive High Scenarios. ICF estimates that 13 to 44 $MMTCO_2e$ and 100 to 380 $MMTCO_2e$ of emissions could be reduced per year by 2040 in the South Atlantic Region and nationwide, respectively, through the deployment of RNG based on the Conservative Low to Aggressive High Scenarios.

By way of comparison, Washington, D.C.’s total direct GHG emissions in 2017 were 7.3 $MMTCO_2e$,[65] while Greater Washington, D.C. metropolitan area’s population-weighted share of Maryland and Virginia GHG emissions were 34 and 59 $MMTCO_2e$ in 2017 and 2015, respectively.[66]

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[65] Washington, D.C. GHG Inventory, 2019. https://doee.dc.gov/service/greenhouse-gas-inventories
[66] Maryland Department of the Environment and Virginia Department of Environmental Quality.

Figure 56. South Atlantic RNG Emission Reduction Potential by Scenario, $MMTCO_2e$

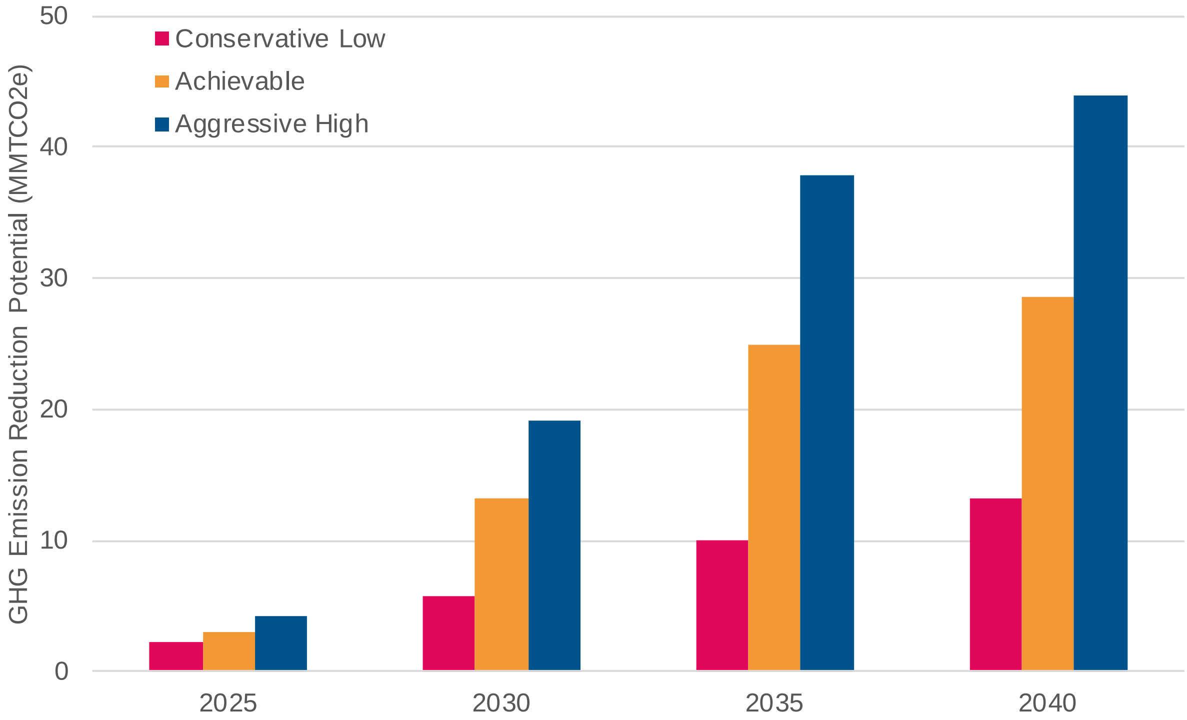
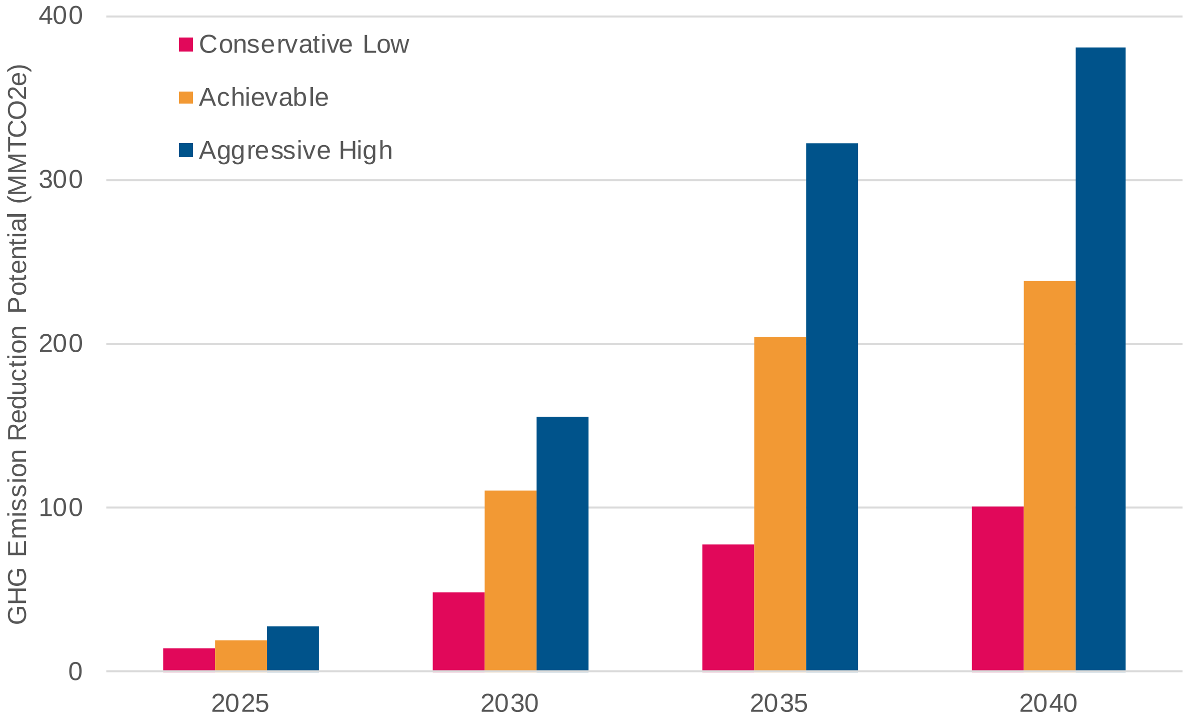


Figure 57. National RNG Emission Reduction Potential by Scenario, $MMTCO_2e$



5. Economic and Market Analyses

Key Takeaways

Historically, anaerobic digestion-based RNG feedstocks have been combusted on-site to generate electricity to comply with various RPS programs nationwide. However, current policies such as the Federal RFS and state LCFS programs favor the direction of RNG consumption into the transportation sector with substantial environmental crediting incentives. Natural gas vehicles (NGVs) can be fueled with RNG with no changes to equipment or performance, with RNG production for use as a transportation fuel increasing nearly six-fold in the last five years

As currently constructed, this policy framework does not encourage RNG use in stationary thermal use applications, such as for building heating and cooling. However, there is growing interest from some policymakers, gas utilities, and industry stakeholders to grow the production of RNG for pipeline injection and stationary end-use consumption. With appropriate incentives that fully capture the environmental benefits of RNG, the end use demand for RNG from stationary thermal applications is substantial, in contrast to the limited demand in the transportation sector.

Assessment of End-Use Markets

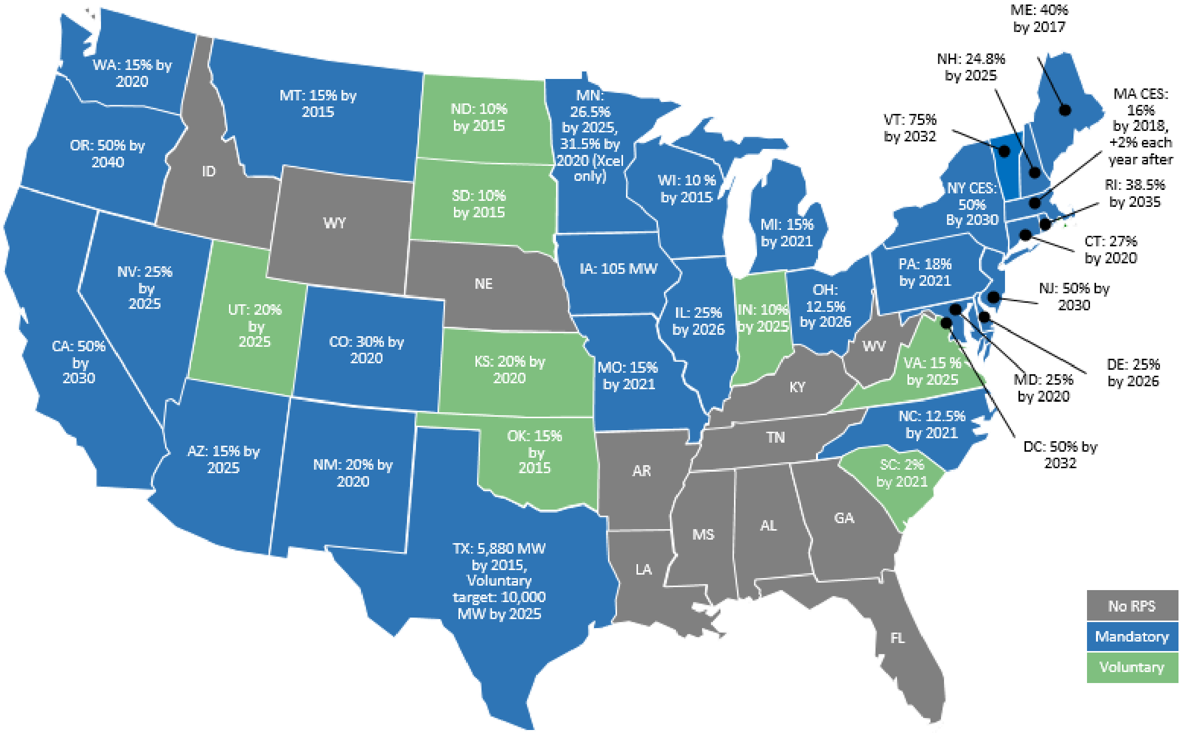
RNG is a pipeline-quality gas that is fully interchangeable with conventional natural gas. As RNG is a “drop-in” replacement for natural gas, it can be safely employed in any end use typically fueled by natural gas, including electricity production, heating and cooling, commercial and industrial applications, and as a transportation fuel. This section discusses the use of RNG for electricity generation, in the transportation market, and for pipeline injection. Interest in RNG has increased considerably over the last several years, especially for use in the transportation sector.

Electricity Generation

Before the recent movement of RNG into the transportation sector, most biogas has been combusted on-site to generate electricity. The renewable electricity is typically used to comply with a Renewable Portfolio Standard (RPS), which requires a certain share of all final end user electricity consumption to come from eligible renewable generation technologies. Twenty-nine states and D.C. have passed mandatory renewable generation requirements or goals and eight more have passed voluntary standards or goals. Most of these programs include landfill gas as an eligible renewable resource, while some also include wastewater treatment plants and anaerobic digestion. Figure 58 shows the RPS requirements across the United States.

The design of each RPS requirement varies by target and timing, type of renewable generation allowed, geographic scope within which a generator might be eligible to meet the standard, enforcement mechanisms, and escape clauses. State RPS programs face a number of near-term changes, two of the largest being the availability of federal tax incentives, namely the Investment Tax Credit and the Production Tax Credit.

Figure 58. Renewable Portfolio Standards



Load-serving entities (LSEs) demonstrate compliance with a state's RPS by retiring Renewable Energy Credits (RECs). One REC is equal to one megawatt-hour of eligible renewable energy generation. RECs can be embedded in contracts for renewable energy or purchased on the open market. If an LSE is unable to acquire the necessary number of RECs, it will have to pay a penalty fee as set by the state. These fees, known as Alternative Compliance Payments (ACPs), act as a ceiling on REC prices.

The history of RECs in the renewable electricity market provides valuable lessons for RNG deployment. Stakeholders contemplated the concept of RECs as California considered an RPS in the mid-1990s, and this continued as multiple utilities and states advanced renewable electricity initiatives. The first retail REC product was sold in 1998.[67] REC markets helped to foster and stimulate growth of renewable power markets, as shown in Figure 59. By 2008, just five years after NREL started tracking renewable power markets in 2003, it was reported that REC markets accounted for nearly 65% of the annual renewable electricity consumed, which was three to four times greater than what was being consumed in utility green pricing programs or in competitive markets. Furthermore, this growth was occurring as the market continued to expand at a compound annual growth rate of 45%.[68,69]

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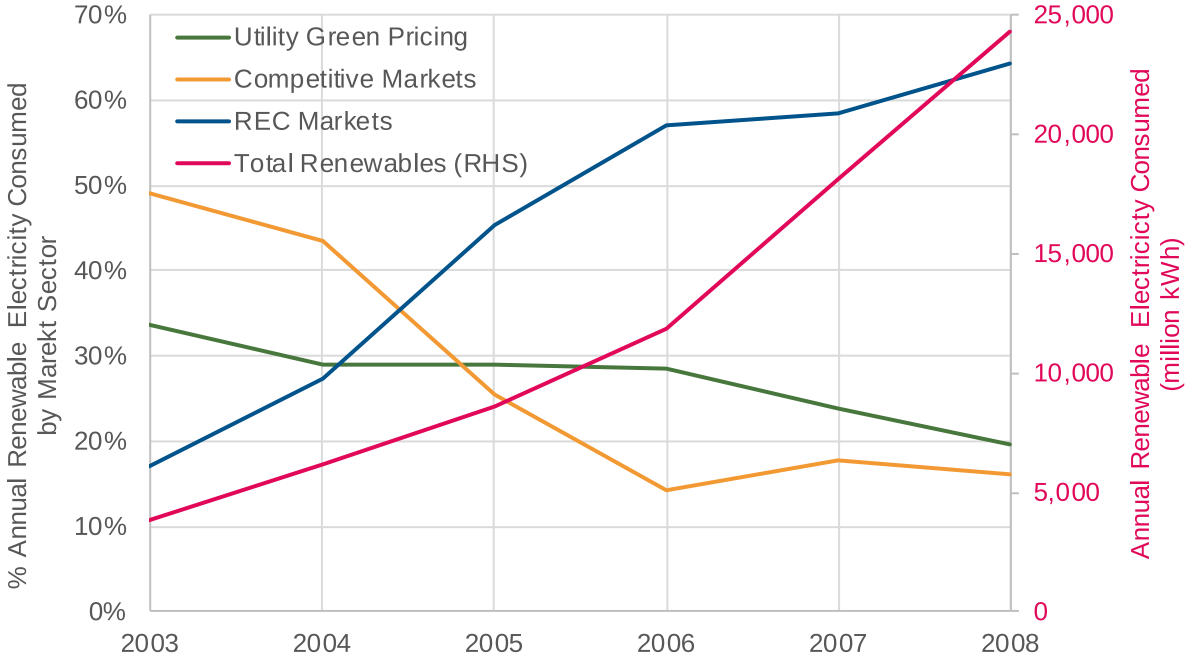
[67] NREL, Emerging Markets for Renewable Energy Certificates: Opportunities and Challenges, January 2005, NREL/TP-620-37388. https://www.nrel.gov/docs/fy05osti/37388.pdf

[68] NREL, Green Power Marketing in the United States: A Status Report (Tenth Edition), December 2007, NREL/TLP-670-42502, https://www.nrel.gov/docs/fy08osti/42502.pdf.

[69] NREL, Green Power Marketing in the United States: A Status Report (2008 Data), September 2009, NREL/TLP-6A2-46851, https://www.nrel.gov/docs/fy08osti/42502.pdf.

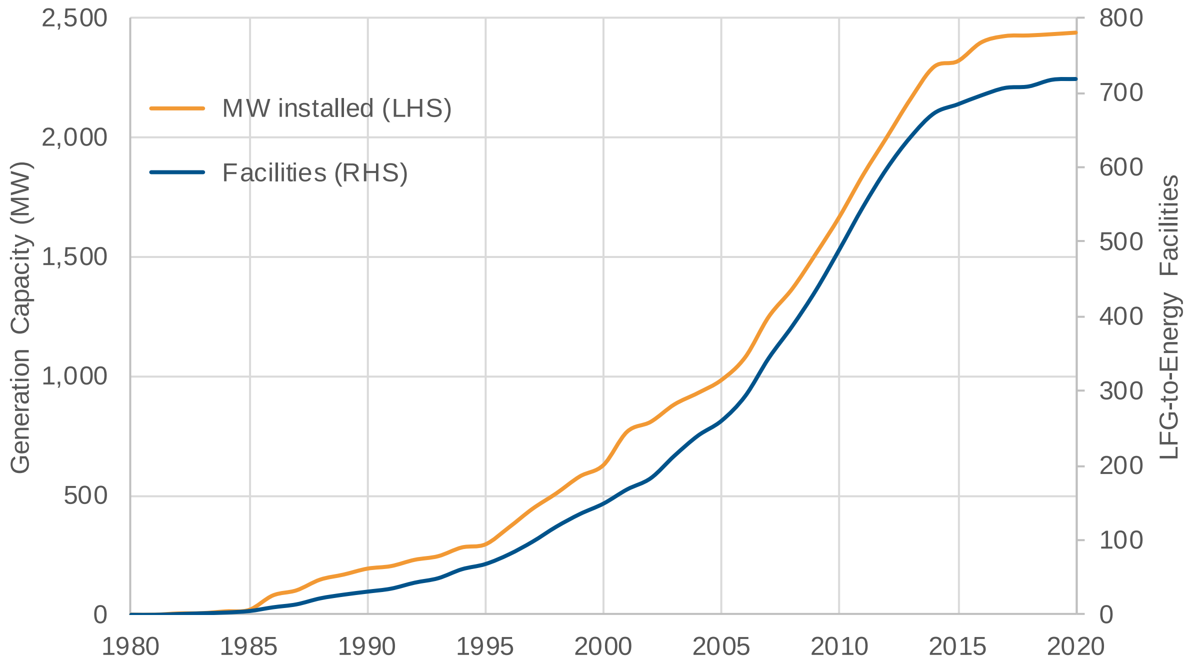
Figure 59. Percent and Total Renewable Electricity Consumption by Market Sector, 2003–2008



A primary feature of RPS policies is the segmentation of the renewable requirements into “Tiers” or “Classes.” These Classes are differentiated by eligibility criteria, which may include technology type, geography, or vintage. RPS Classes may also represent “carve-out” requirements, which require that a subset of the overall RPS target come from a specific technology, such as Landfill Gas or Anaerobic Digestion.

Landfill gas plays a substantive role in many RPS programs. The EPA database of Landfill Gas Energy Projects indicates that there are currently more than 450 operational LFG-to-electricity projects with a capacity exceeding 2,000 MW—see Figure 60. There has been a noticeable decrease in the rate of installed capacity and facilities since 2014. For instance, for the years 2005–2014, an average of 26 new facilities were brought online annually with installed capacity of 318 MW annually. This has decreased to just 4–5 facilities annually over the last four years, with an installed capacity of just 25 MW annually. This is likely due to the availability of RINs and, to a lesser extent, LCFS credits. ICF anticipates this trend to continue plateauing for LFG-to-electricity projects as investors seek out higher value in the LCFS and RIN markets.

Figure 60. Facilities and Installed Capacity of LFG-to-Electricity Facilities[70]



Transportation

NGVs consume natural gas as compressed natural gas (CNG) or liquefied natural gas (LNG). Natural gas as a transportation fuel is primarily used in transit buses and fleet applications (including refuse haulers and over-the-road trucks), with over 175,000 NGVs on U.S. roads today. The more recent expansion of natural gas use in transportation is typically linked to goods movement and regional or short haul applications operating at or near port facilities.

NGVs are the most cost-effective vehicle technology to reduce local air pollutants and smog from heavy-duty trucks and buses. The latest commercially available natural gas engines are 90% cleaner than the EPA's current NOx emissions requirement, and 90% cleaner than the cleanest diesel engine.[71] Figure 61 shows NGV America's comparison of NOx emission reduction costs over the lifetime of different bus technologies and fuels.[72]

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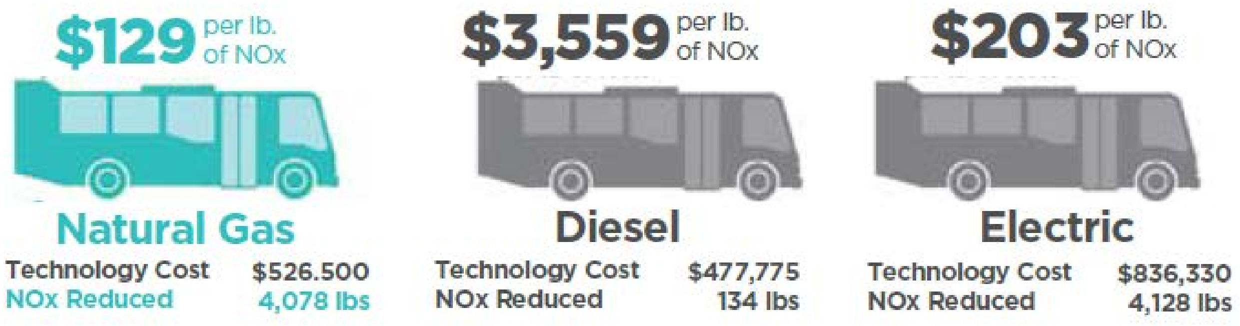
[70] ICF Analysis of LMOP Database.

[71] EPA and California Air Resources Board, 2018.

[72] NGV America, 2019. NGV Transit Buses, https://www.ngvamerica.org/wp-content/uploads/2018/12/NGV-VW-Transit-Buses.pdf

Figure 61. Comparison of NOx Emission Reduction Costs by Vehicle Technology



In addition, NGVs can be fueled with RNG with no changes to equipment or adverse impacts on performance. Over the last five years, RNG production for use as a transportation fuel has increased nearly six-fold, with a third of all NGV fuel use relying on RNG in 2018.[73] This rise in RNG consumption in NGVs has been largely driven by the environmental crediting incentives provided by the federal RFS and carbon constraining policies like California's LCFS and Oregon's CFP, discussed in more detail below.

RFS Program and RIN Prices

The RFS program sets volumetric targets for blending biofuels into transportation fuels across the entire United States—compliance is tracked through the production and retirement of Renewable Identification Numbers (RINs).[74] In most cases, a RIN is generally reported as an ethanol gallon equivalent. In 2013, the EPA determined that RNG qualified as an eligible fuel and could generate 'D3' RINs, with landfill RNG qualifying after meeting cellulosic content and GHG reduction thresholds. This led to a rapid expansion of RNG projects for pipeline injection and subsequent RNG use as a transportation fuel in NGVs.

In 2017, nearly 300 million RINs were generated by RNG projects domestically, with the RINs valued at approximately $2.50–$3.00 each, the equivalent of $29–$35/MMBtu of RNG. In 2018, these RINs traded lower along with other categories of RINs, but remained more resilient than other categories with a range of $2.00–$2.60 per RIN ($23–$30/MMBtu).

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[73] NGV America, 2019. https://www.ngvamerica.org/wp-content/uploads/2019/04/RNG-Driving-Down-Emissions.pdf

[74] The RFS has four nested categories of fuels: renewable biofuels, advanced biofuels, biomass-based diesel and cellulosic biofuels, which are each represented by a different RIN type. RINs are the tradeable commodity in the RFS, with most RINs equivalent to one gallon of ethanol. RNG is eligible to generate D3 RINs, representing the cellulosic biofuel category, with one MMBtu of RNG equivalent to 11.67 gallons of ethanol (or RINs) based on energy density.

In 2019, the D3 RIN price was at historically low levels, around $0.60 per RIN, equivalent to roughly $7/MMBtu. ICF analysis for 2020 suggests that D3 RIN prices should increase to around $1.80–$2.00, based on RFS program fundamentals that reflect supply and demand for D3 RINs, gasoline pricing, and RNG production economics. However, as the EPA under the current administration has increasingly exempted volumes from the federal RFS, the D3 RIN price had collapsed.[75]

ICF modeled a D3 RIN price forecast based on three scenarios:

- The **SREs Continue Case** includes assumptions that the EPA under the current administration will continue to issue SREs at a rate similar to what has been observed over the last 2–3 years, with about 10% of the RVOs exempted as a result of EPA granting hardship waivers.
- In the **Reference Case**, ICF's modeling reflects internal estimates for gasoline pricing to estimate the value of the cellulosic waiver credit (CWC) annually (adjusted for inflation, per the regulation), the anticipated outcome of using biodiesel as the marginal unit of compliance—including factoring in limitations on cheaper imports from Argentina and Indonesia—and we estimate a likely discount of D3 RIN pricing relative to the sum of the CWC and the D5 RIN price.
- In the **Upside Case**, ICF assumed that RNG production economics would drive D3 RIN pricing as the marginal unit of compliance in the absence of a CWC. This assumption is a proxy for a more conservative set of RVOs being established moving forward as part of a programmatic reset. Note that in a reset scenario, in which EPA revises the cellulosic biofuel targets to a lower level, EPA will no longer need to use its Cellulosic Waiver authority, and thus will not issue CWCs. CWCs act as a floor on prices. With the cap removed, D3 RINs will price to the marginal unit of production. ICF assumes that RVOs will still increase with supply (consistent with legal interpretation of the RFS[76]), thereby linking D3 RIN pricing to the marginal unit of RNG supply. In our modeling, these economics are driven by a combination of liquid cellulosic biofuel production and RNG production from the anaerobic digestion of animal manure. In either case, the production economics drive RIN pricing higher.

Figure 62 includes the forecasted pricing for D3 RINs to 2030 for the three cases considered outlined above. These forecasts are reflected as annual averages, and do not necessarily account for the price variation that might be observed throughout a given year.

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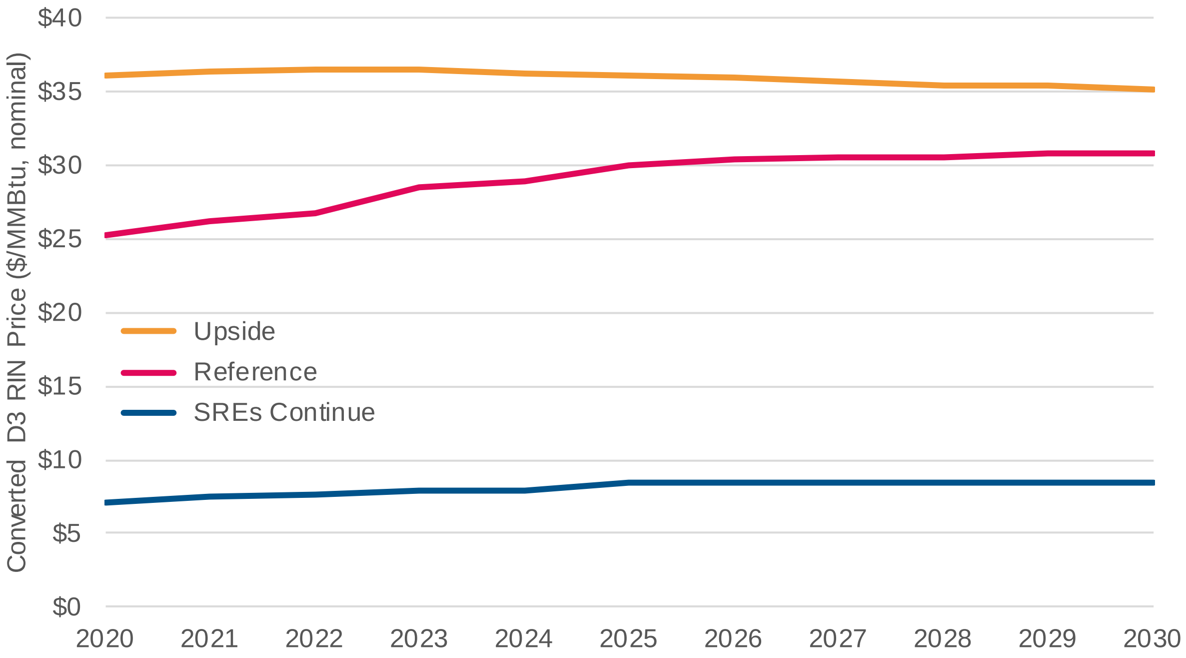
[75] Small refiners (i.e., those with an average annual crude oil input less than 75,000 barrels per day) are allowed to petition the U.S. EPA for an economic hardship waiver from their obligations under the federal RFS—these are referred to as small refinery exemptions (SREs). The rate of SREs submitted and granted have more than quadrupled under the Trump Administration, undercutting the renewable volume obligations (RVO) annually by about 10%. As a result of these exemptions, the D3 RIN market has been significantly over-supplied, and prices have collapsed.

[76] In 2015, the Court of Appeals for the District of Columbia ruled that the so-called "inadequate domestic supply" provision in the Energy and Information Security Act "does not allow EPA to consider the volume of renewable fuel that is available to ultimate consumers or the demand-side constraints that affect the consumption of renewable fuel by consumers."

Figure 62. Forecasted D3 RIN Pricing, 2019–2030, \$/D3 RIN, nominal[77]



California LCFS Program and Credit Prices

In California, carbon emissions are constrained based on a combination of California's Cap-and-Trade program and complementary measures, such as the LCFS program. The LCFS program targets the GHG emissions from transportation fuels. Low carbon fuels—such as ethanol, biodiesel, renewable diesel, and RNG—that are deployed in California have the potential to earn LCFS credits in the state-level LCFS program as well as RINs in the federal RFS program. Fuel providers are able to generate value in both the LCFS and the RFS programs by rule. The programs are implemented by tracking two different environmental attributes: the state-level LCFS program enables fuel providers to monetize the GHG reductions attributable to the fuel, whereas the federal-level RFS program monetizes the volumetric unit of the renewable fuel. This ability to "stack" environmental credits has led to significant increases in the volume of biodiesel, renewable diesel, and RNG consumption in California.

ICF estimates that 65–70% of the 30–35 BCF (390–450 million diesel gallons) of RNG produced in 2018 was delivered to California, generating both the RINs and the LCFS credits. In 2017, LCFS credits traded for \$60–\$115/ton, which was equivalent to about \$3–\$6/MMBtu of RNG from landfills, and \$20–38 for animal manure (dairy) RNG. In 2018, prices rose past \$150 per ton, and traded up into the low \$190s per ton. More recently, throughout 2019 and into 2020, LCFS credits have consistently traded above \$190/ton.

Through the end of 2019, the LCFS market operated with a soft cap of \$200/ton in 2016 dollars (annually adjusted based on the Consumer Price Index, CPI), which was linked to the Credit Clearance Market. ICF generally considered this a soft cap as there was no language in the regulation that precluded parties from buying credits at a value higher than the \$200/ton cap (when adjusted for inflation). Rather, the \$200/ton was used as the maximum price that parties

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[77] Note: D3 RIN price in dollars per gallon of ethanol converted to dollars per MMBtu.

can set when selling credits into the Clearance Market. Because the Credit Clearance Market exposed regulated parties as not being able to fulfill their credit obligations in the program, ICF considered it likely that some parties would have preferred to avoid the public process that defined the Clearance Market and pay a premium in a bilateral transaction.

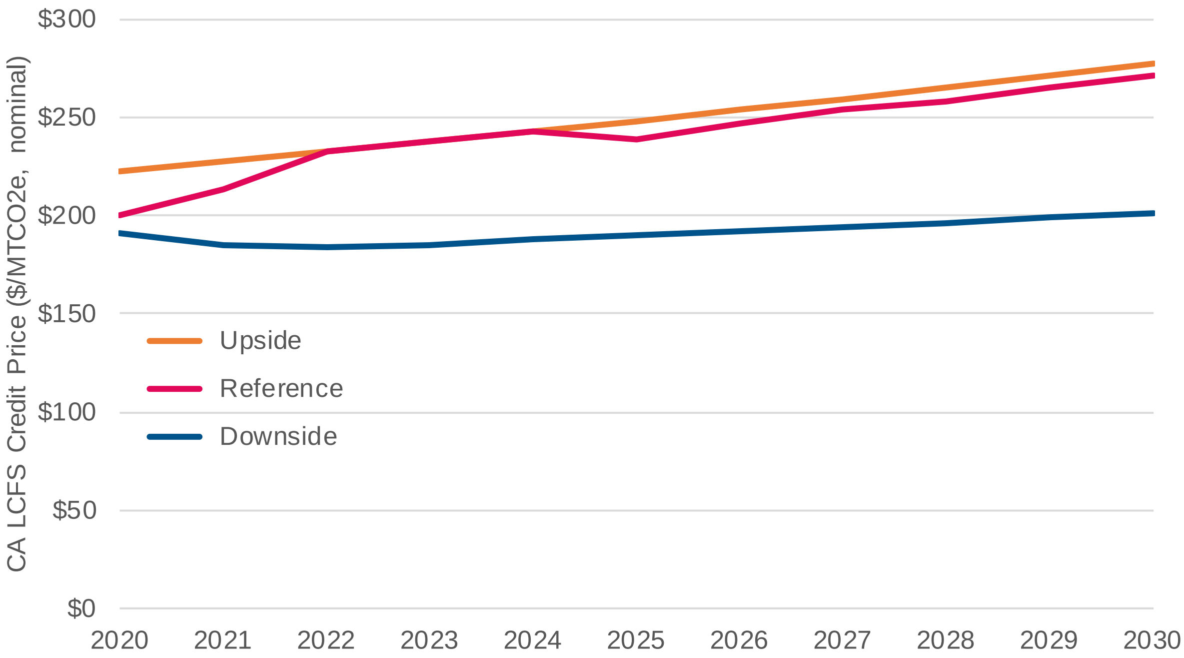
In late 2019, however, CARB considered and adopted a maximum tradeable price for LCFS credits equivalent to the value of credits established in the Credit Clearance Market—equal to $200/ton in 2016 dollars and adjusted for inflation. This went into effect January 1, 2020. This change has transitioned the program to a hard cap. In ICF’s view, there are limited ways that regulated parties could avoid the hard cap and pay a higher price—ICF anticipates that this would require paying a higher price on the physical fuel (e.g., ethanol) being purchased by a regulated party. ICF considers this possible, but unlikely given the risk of drawing the ire of CARB for circumventing the intended cap on credit prices.

ICF conducts forecasting of California LCFS credit prices using an optimization model that considers compliance strategies based on parameters including alternative fuel production costs, fuel supply chains (to California), interactions between programs, alternative fuel pricing, gasoline and diesel pricing, and GHG abatement potential. To do the price forecasting, ICF modeled three cases:

- **Reference Case:** reflects best estimates of the supply, demand, costs, and corresponding constraints of the various compliance pathways in the LCFS program.
- **Upside Case:** assumed more constrained availability of liquid fuels, slower transition to electrification in the light-duty sector, and modest expansion of natural gas as a transportation fuel.
- **Downside Case:** higher penetration of low carbon fuels in the biofuel blending and vehicle replacement buckets. This scenario is designed to represent lower-cost biofuel blending, a faster transition to transportation electrification, and has higher penetration of natural gas as a transportation fuel, which decreases credit prices.

Figure 63 summarizes the derived LCFS credit prices for the various scenarios considered in this analysis. As noted for ICF’s RIN forecasts, these forecasts are reflected as annual averages, and do not necessarily account for the price variation that might be observed throughout a given year.

Figure 63. Forecasted CA LCFS Credit Prices, 2019–2030, \$/MTCO$_2$e, Nominal



RNG Consumption in Transportation

The chart below shows ICF's estimates for total natural gas consumption as a transportation fuel in the U.S. and forecasted RNG production capacity. These estimates are based on a combination of national-level data from the EIA, California-specific data reported via the LCFS program, and ICF's analysis of potential RNG projects. In this scenario, we assume a growth rate of natural gas at about 5% year-over-year out to 2030. For RNG, we show year-over-year growth between 20% and 30% out to 2030.

Figure 64 helps demonstrate the potential for suturing the demand for natural gas as a transportation fuel with RNG production in the 2024–2027 timeline. This rising RNG consumption in the transportation sector is shown by the largest RNG procurement agreement between Clean Energy and logistics company UPS, where UPS will fuel its CNG vehicle fleet with RNG.[78]

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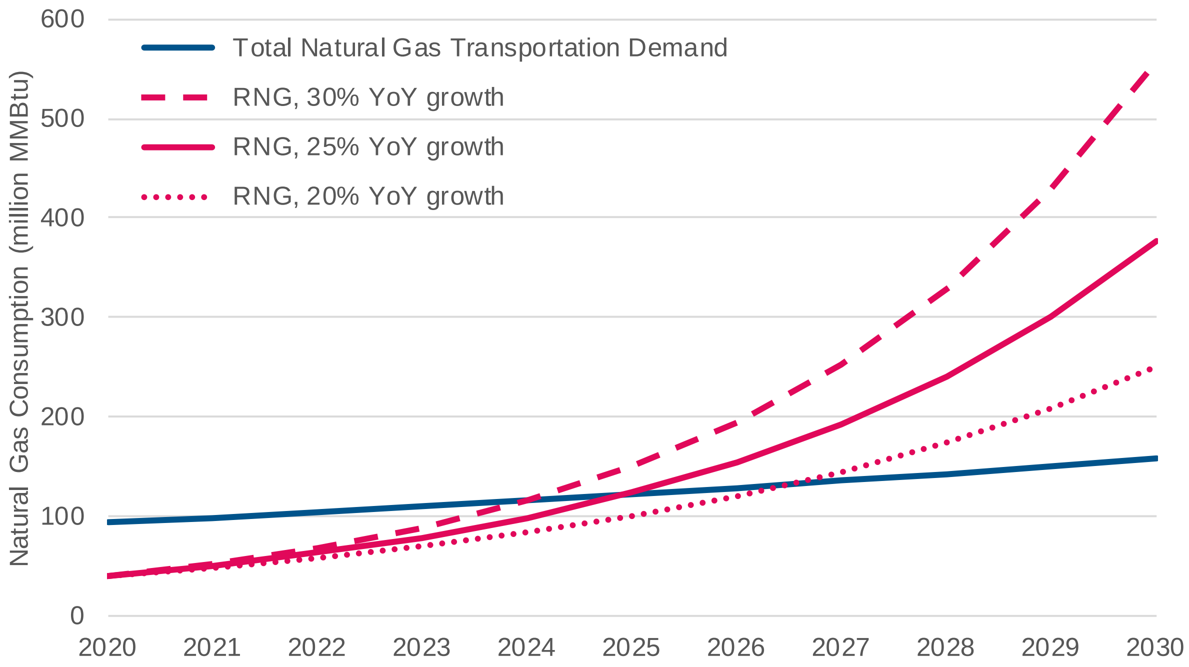
[78] GreenBiz, 2019. 'UPS to buy huge amount of renewable natural gas to power its truck fleet', https://www.greenbiz.com/article/ups-buy-huge-amount-renewable-natural-gas-power-its-truck-fleet

Figure 64. Natural Gas as a Transportation Fuel



Most of the RNG that is currently delivered to and dispensed in California is derived from landfills. ICF anticipates a shift towards lower carbon intensity RNG from feedstocks such as the anaerobic digestion of animal manure and digesters deployed at WRRFs. Over time, these lower-carbon sources will likely displace higher-carbon intensity RNG from landfills. The role of RNG post-2020 in the LCFS program will be determined by the market for NGVs. If steps are taken to foster adoption of NGVs, particularly in the heavy-duty sector(s), then this will be less of an issue. The introduction of the low-NOx engine (currently available as 9L, 12L, and 6.7L engines) from Cummins may help jumpstart the market, especially with a near-term focus on NOx reductions in the South Coast Air Basin, which is in severe non-attainment for ozone standards.

In an RNG transportation saturation scenario, there are many outcomes—we consider two. In one case, a share of the RIN price would have to be dedicated to inducing demand; in another case, the RIN price would have to go up to reflect the higher cost of dispensing a marginal unit of natural gas (rather than just displacing the fueling of fossil natural gas with renewable natural gas). In other words, there is some cost associated with getting additional supply on the system, and that can come out of either existing RIN pricing or increasing RIN pricing to account for that. To summarize, ICF anticipates that for RNG in the transportation sector to continue growing, market actors must be savvier with respect to pricing the fuel more competitively.

Transportation Demand in the Greater Washington, D.C. Metropolitan Area

Based on vehicle registration from IHS Markit, there are nearly 1,600 CNG vehicles in the Greater Washington, D.C. metropolitan area—including D.C. and surrounding nine counties. Roughly 90% of the vehicles are registered in D.C. (65%), Montgomery County (15%), and Fairfax County (10%). Furthermore, nearly 70% of the CNG vehicles are Class 8 heavy-duty vehicles—primarily transit buses, some refuse hauler fleets, and some heavy-duty trucks.

Table 41. Fleets in Different Vocations Using CNG[79]

Fleets Using CNG	No. of Vehicles	Vocation	Est Annual CNG Consumption (M DGE)
Arlington Regional Transit (updated to 2019 data)	72	Transit & Shuttle	0.70
DC Government	7	Refuse	<0.1
	119	Fleet	
Montgomery County	102	Transit	0.27
Smithsonian	7	Fleet (LD)	<0.1
WG (updated to 2019 data)	131	Dedicated	0.14
	160	Bi-fuel	
Washington Metropolitan Area Transit Authority (WMATA)	461	Transit	4.6

The fleets in Table 41 account for more than 60% of the estimated CNG vehicles in the study area, and about 60% of the estimated 9.1 million diesel gallon equivalents of CNG consumed. The remaining share of CNG vehicles are largely from public and private fleets in the region, including logistics companies.

Figure 65 outlines the fleet make-up of NGVs registered in the Greater Washington, D.C. metropolitan area—including the total number of vehicles registered from each model year (MY) 1992 to 2019. The blue dots represent all CNG vehicles and the orange crosses show the Class 8 heavy-duty CNG vehicles registered in each MY. ICF makes the following observations:

- From 2010 to 2015, CNG vehicle population growth was slow, and was driven largely by light-duty vehicles. This is consistent with other regions that showed low rates of growth in new vehicle sales for fleet applications during this timeframe, as many fleets opted to get more mileage out of existing vehicles as they emerged from the Great Recession.
- As light-duty fleet sales slowed and Honda exited the light-duty CNG vehicle market in 2015, a new trend has emerged from 2016 to the present: Class 8 CNG vehicles are driving growth. Fifty percent of the CNG vehicles on the road are MY 2010 or later, and two-thirds of those are Class 8.
- The shift over the last five years has been even more pronounced: a third of the CNG vehicles on the road are MY 2015 or later, and nearly 85% of those are Class 8 NGVs.
- ICF assumes that most of this recent growth is driven by CNG transit bus purchases and refuse hauler fleet purchases.

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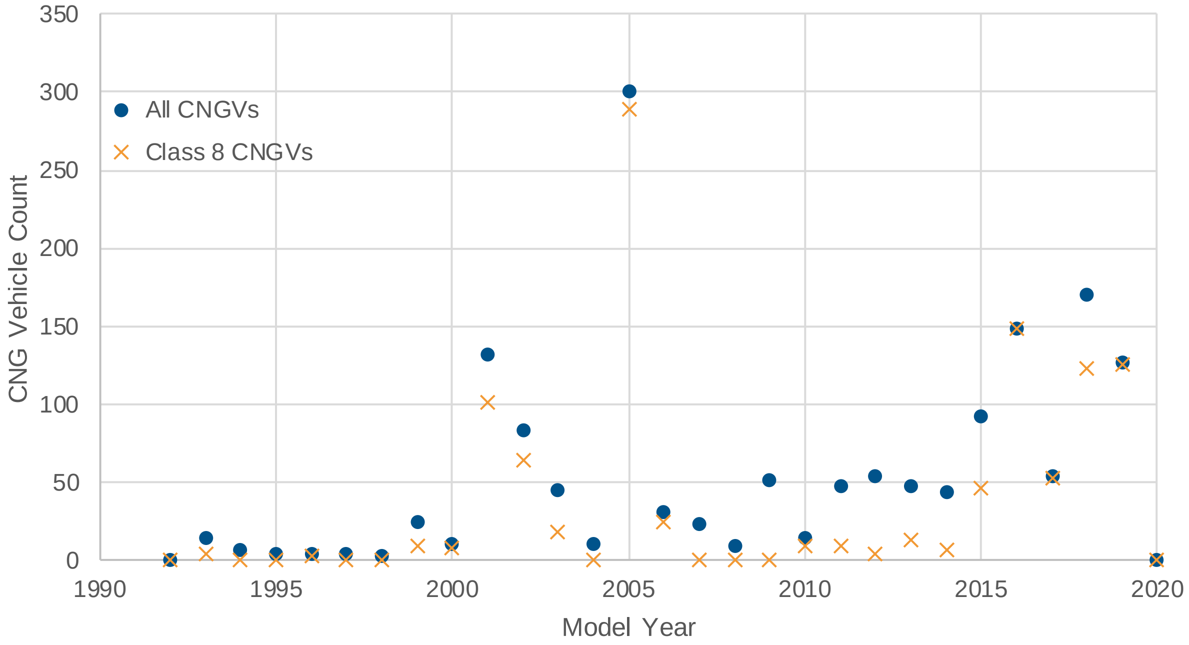
[79] DOE 2017, Greater Washington Region Clean Cities Coalition, 2017 Transportation Technology Deployment Report. Available online at http://www.gwrccc.org/uploads/1/1/9/3/119314124/clean_cities_2017_annual_report_-_dc_-_greater_washington_region_clean_cities_coalition_-_expanded_edition.pdf. Data from 2016 unless otherwise indicated in the table.

- For example, WMATA has a demonstrated commitment to CNG vehicles as part of their overall portfolio, further expanding their CNG vehicle fleet through an order for an additional 75 CNG buses in September 2019.[80]

Figure 65. CNG Vehicle Counts by Model Year in Study Area[81]



Despite its modest demand for natural gas as a transportation fuel, RNG consumption in the transportation sector in the Greater Washington, D.C. metropolitan area appears limited, but with potential for immediate growth. In contrast to other parts of the country, notably California, there is little to no RNG transportation consumption in the region and significant immediate potential for natural gas transportation demand to be supplied by RNG.

ICF estimates that transportation natural gas consumption in the Greater Washington, D.C. metropolitan area is currently about 1.25 bcf per year, and using EIA's 2019 Annual Energy Outlook (AEO), is forecast to grow to over 1.7 bcf by 2030 and nearly 3 bcf in 2050, applying the AEO average annual growth rate of 2.7%.[82] ICF developed a more aggressive growth scenario to reflect the immediate potential of natural gas use in transportation if appropriate policy incentives are implemented and near-term adoption barriers are overcome. In this scenario the growth rate is 5.4% per year out to 2030 and then reduced to 2.7% out to 2050 to moderate year-on-year total growth and reflect the ultimately limited nature of transportation use over the long-term. In this scenario regional transportation demand for natural gas grows to 2.3 bcf in 2030 and 4 bcf in 2050 (see Figure 66–67 and Tables 42–43).

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[80] NGT News, 2019. 'WMATA Places Hefty CNG Bus Order', https://ngtnews.com/washingtons-wmata-places-hefty-cng-bus-order

[81] Based on ICF analysis of vehicle registration data from IHS Markit.

[82] EIA AEO 2019, https://www.eia.gov/outlooks/aeo/

Figure 66. Transportation Natural Gas Demand Moderate Forecast, Greater D.C. Region, tBtu

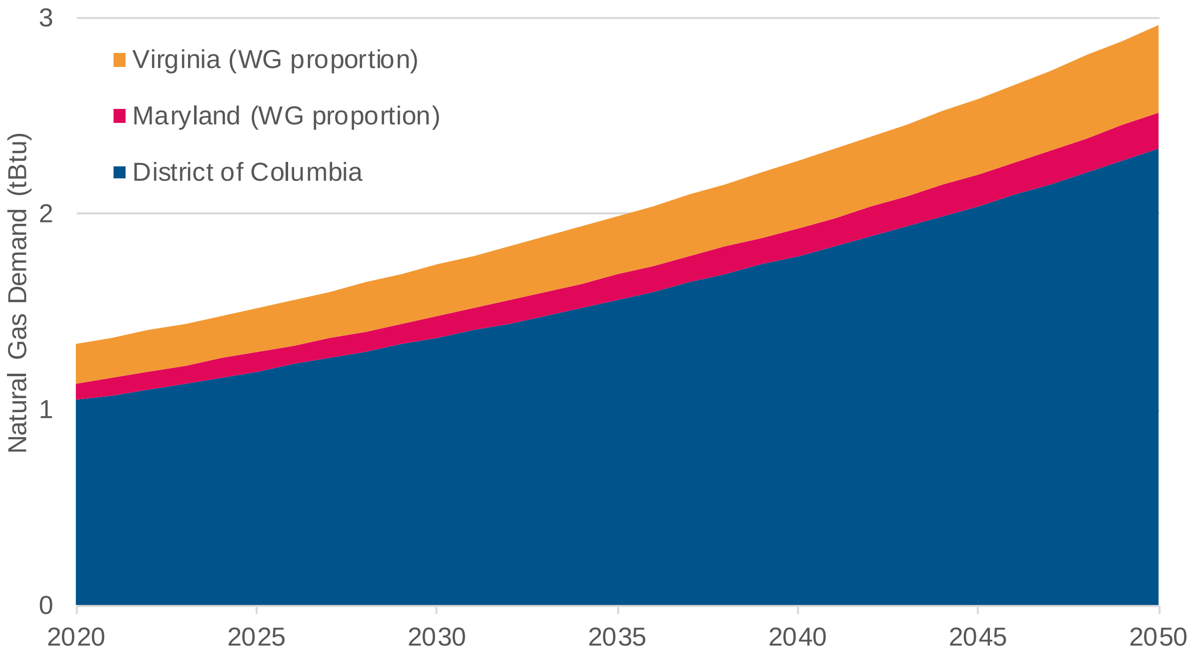


Table 42. Transportation Natural Gas Consumption Moderate Forecast, Dth/day

Dth/day	2020	2030	2040	2050
Greater Washington DC metro	**3,620**	**4,730**	**6,170**	**8,050**
D.C.	2,850	3,720	4,850	6,330
Maryland	230	300	390	510
Virginia	540	710	920	1,200

Figure 67. Transportation Natural Gas Demand Aggressive Forecast, Greater D.C. Region, tBtu

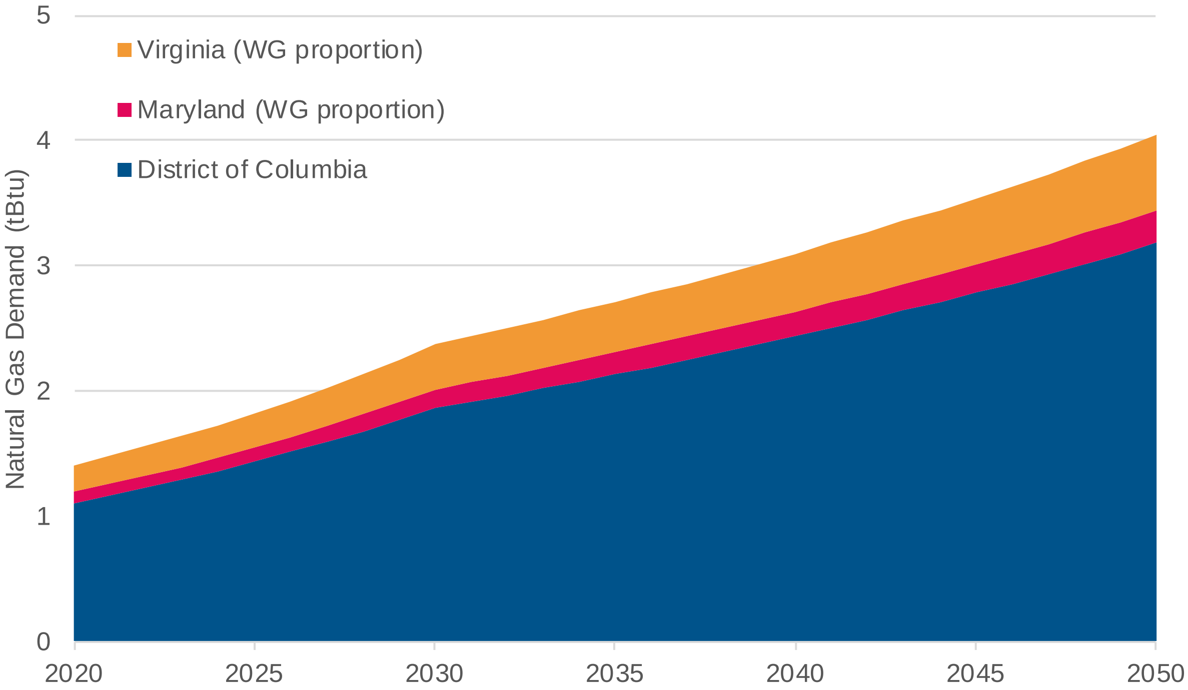


Table 43. Transportation Natural Gas Consumption Aggressive Forecast, Dth/day

Dth/day	2020	2030	2040	2050
Greater Washington DC metro	**3,810**	**6,450**	**8,420**	**10,990**
D.C.	3,000	5,080	6,630	8,650
Maryland	240	410	540	700
Virginia	570	960	1,260	1,640

The transportation sector remains an area of untapped demand for RNG in the Greater Washington, D.C. metropolitan area, and a viable near-term opportunity to direct relatively cost-effective RNG supply. The region is home to operators of large and small NGV fleets, including WMATA, Montgomery County Transit Services, and Arlington Regional Transit, which could provide feasible starting points to drive RNG demand.

SPOTLIGHT: RNG in Heavy-Duty Vehicles

Heavy-duty vehicles, including trucks, buses, and refuse haulers, powered by diesel account for a significant share of GHG emissions in the Greater Washington, D.C. metropolitan area. Furthermore, heavy-duty vehicles like single line-haul trucks can emit more NOx per than 100 cars per mile traveled.

RNG in heavy-duty vehicles has the potential to reduce GHG emissions, and when coupled with the newest natural gas engine technology it can also help achieve drastic reductions in NOx emissions.

Heavy-duty trucks, transit buses, and refuse haulers running on fossil-based CNG reduce GHG emissions by about 10–20% compared to their diesel counterparts. The introduction of RNG amplifies these emission reductions by four to five times (on a direct GHG emission accounting basis; see Figure 50).

For every 1,000 heavy-duty natural gas vehicles powered by RNG that displace diesel consumption in the Greater Washington, D.C. metropolitan area, ICF estimates GHG emission reductions of 20,000–25,000 MT CO_2e. And when coupled with the newer natural gas engine technology that is commercially available today, RNG in heavy-duty vehicles can also help deliver drastic NOx reductions compared to their diesel counterparts.

Pipeline (Stationary)

Lastly and crucially for long-term decarbonization strategies, RNG is also a drop-in replacement for pipeline natural gas used in stationary applications, such as for heating and cooling, and commercial and industrial applications. As currently constructed, the policy framework does not encourage RNG use in these stationary applications, instead directing RNG consumption to the transportation and electricity generation sectors.

However, there is growing interest from some policymakers and industry stakeholders to grow the production of RNG for pipeline injection and stationary end-use consumption. With deep decarbonization goals becoming more prevalent, the ability to use an existing energy system to deliver significant emission reductions is highly valuable. RNG as a decarbonization approach for stationary energy applications provides two critical advantages relative to other measures:

- Utilizes existing natural gas transmission and distribution infrastructure, which is highly reliable and efficient, and already paid for; and
- Allows for the use of the same consumer equipment as conventional gas (e.g., furnaces, stoves), avoiding expensive retrofits and upgrades required for fuel-switching.

There is growing activity outside the transportation sector, and in particular the construct of the LCFS program, where so much attention is paid today. Southern California Gas Company (SoCalGas) announced that they intend to have 5% RNG on their system by 2022 and 20% by 2030. SoCalGas is also seeking approval to allow customers to purchase RNG as part of a voluntary RNG tariff program. Despite the challenges of its bankruptcy, Pacific Gas & Electric is close to announcing a more nuanced approached to its RNG strategy.

Momentum for RNG is not just in California where carbon-constraining policies are the most restrictive in the United States. Gas utilities and local distribution companies (LDCs) are either volunteering or being forced to take a closer look at RNG across the country, with growing interest in the Greater Washington, D.C. metropolitan area:

- Approved in 2017, Vermont Gas offers a voluntary RNG tariff program, providing retail gas customers the opportunity to purchase RNG in amounts proportionate to their monthly requirements.
- Consolidated Edison is very focused on RNG for pipeline injection as part of its consideration for the future of heating.
- National Grid's New York City Newtown Creek RNG demonstration project will be one of the first facilities in the U.S. that directly injects RNG into a local distribution system using biogas generated from a water and food waste facility.
- The joint venture between Dominion Energy and Smithfield Foods is set to become the largest RNG producer in the U.S., developing animal manure-based RNG in North Carolina, Virginia, and Utah, with plans to expand to California and Arizona.

Driven by corporate sustainability goals and customer preferences, a growing number of large end users of natural gas are looking into RNG as an option to reduce GHG emissions. Global cosmetics manufacturer L'Oréal uses RNG from a nearby landfill facility at its plant in Kentucky. L'Oréal's long-term purchase commitment for the RNG was a key underwriting component that led to the financing of the LFG project.

In ICF's view, the renewed focus on pipeline injection and consumption of RNG by utilities, LDCs, and large end users is an overwhelmingly positive signal for the RNG developer community. While there is clearly a near-term focus on reaping the benefits of credits generated in the LCFS program and RINs in the RFS program, the long-term potential for increased volumes of RNG outside the transportation sector is considerably more robust than many stakeholders may realize. With appropriate incentives that fully capture the environmental benefits of RNG, the end-use demand for RNG from stationary applications is substantial, in contrast to the limited demand in the transportation sector.

SPOTLIGHT: Anaerobic Digester Project Development

The RNG production potential for the Greater Washington, D.C. metropolitan area is real and there are significant near-term opportunities that could be pursued. However, these resources must be converted to RNG for pipeline injection. ICF summarizes the process for bringing projects online in three simplified steps: site identification, project due diligence and financing, and project development and execution.

1. **Site identification**. This is the biggest challenge in the RNG market for projects today. In the case of landfills, the site needs to have a variety of characteristics to produce RNG. These include technological considerations like ensuring that the LFG has high energy content (e.g., methane concentration) and that the LFG capture management system is modernized to deliver consistent volumes, and market considerations such as ensuring that the facility can be converted to a pipeline injection project without negatively impacting existing agreements. The highest priority for developers for non-LFG projects, like WRRFs and animal manure for RNG, is for projects to already have a digester in place, for example, for biogas to electricity or some other on-site application. These are the most cost-effective facilities in place. In all cases, the proximity to common carrier pipelines is critical. Most of the stakeholders with whom ICF has spoken have indicated a 6-9 month timeframe for site identification.
2. **Project due diligence and project financing**. After identifying a site, the next critical step is to engage in project due diligence and secure financing. This involves a variety of parties and approaches, which can include a combination of debt or equity financing, depending on the project. At this stage, project developers often conduct a preliminary carbon intensity analysis to estimate potential revenue from the facility if they are able to deliver the gas to a transportation application (ideally in California to maximize revenue). Project developers and their partners also conduct a valuation of the RNG production asset, including the various revenue streams (e.g., environmental commodities like RINs and LCFS credits), and costs (e.g., operating the upgrading and conditioning equipment). ICF estimates this part of the process will take 6-9 months.
3. **Project development and execution**. The timeline for project development and execution depends significantly on site-specific considerations. ICF generally estimates that this process will take 12-20 months, indicative of the time between project financing secured and RNG injected into the pipeline.

ICF estimates that LFG projects have about a 6-24 month timeline, depending on site-specific considerations. However, we estimate that non-LFG projects have about a 24-month timeline from the point of executing an agreement with a viable site to the point of injecting gas. And we assume that the site identification and partnering aspect on the front end is at least a 6-month process, assuming that a facility has a digester in place. ICF notes that for projects without a digester in place, the project lifetime will likely increase by another 6-24 months, depending on construction requirements.

Relevant to the above spotlight, there are several projects in the Greater Washington, D.C. area that have advanced towards RNG for injection. For instance:

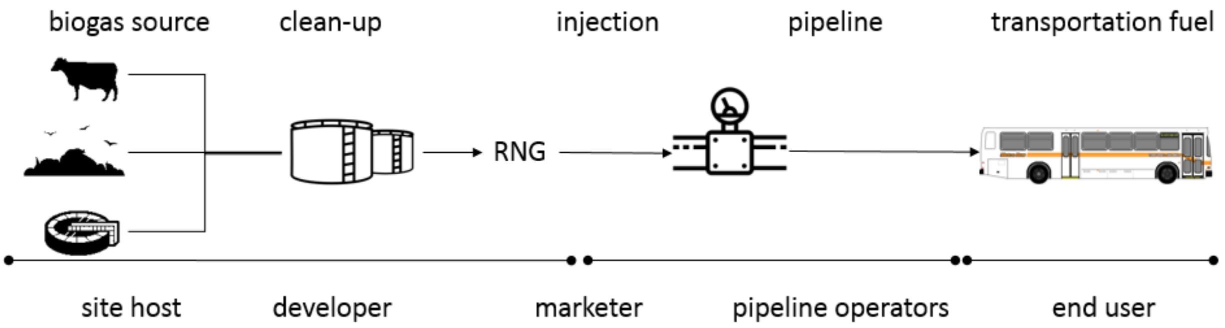
- DC Water issued a Request for Proposal in February 2019 to select a technical and commercial partner for the purposes of initially materializing a program to realize the full value of RNG resources, as well as the full portfolio of energy-related business opportunities to bring value to D.C. and its stakeholders. The project is primarily focused on producing pipeline-quality RNG and maximizing the value of that injected gas through transportation end-uses.
- The WSSC Piscataway WRRF has an RNG project in the design phase, which involves aggregating waste from five existing treatment plants. In its first phase, WSSC is focused on design and early construction (including the demolition of existing on-site facilities and relocation of existing utilities). WSSC report that Phase Two is expected to advance in 2020, and that the entire project should be complete and operational in late 2021.

There are a variety of project structures that could be pursued to deploy RNG produced in the Greater Washington, D.C. metropolitan area. Generally speaking, the key parties include:

- Site host or operator (e.g., a landfill, WRRF, or farmer)
- Developer or technology provider
- Project financing
- LDC, utility or marketer to transport the gas
- End user

Figure 68 highlights these various stakeholders, with the end user being a transportation fuel application for illustrative purposes.

Figure 68. Market Participants in the RNG Supply Chain



The revenue associated with these projects can conceivably be split between the site host, developer, marketer, and end user to ensure that each party shares in the value of the delivered RNG. At the same time, the utility that moves the RNG along its system to an end user in its service territory can benefit from reduced GHG emissions.

Interconnection and Gas Quality

For RNG to be suitable for introduction into the natural gas pipeline network, the initial raw biogas must be adequately processed to meet gas quality and end-use application standards. At a high level, this typically involves concentrating the methane content and removing any problematic constituents.

While RNG is fundamentally interchangeable with conventional natural gas, different RNG feedstocks pose different challenges for gas quality and composition. For example, raw (unprocessed) biogas from a landfill facility is different than biogas from a dairy digester. Biogas constituents of concern vary by feedstock and conversion technology, and testing requirements need to be aligned to optimize results and processing requirements. Gas quality standards and constituents for testing consideration include those listed in Table 44. Acceptable gas quality terms for normal operations will depend on a variety of factors, including the dilution of RNG when injected into the system and the feedstock type. Table 44 shows an example of acceptable limits.

Table 44. Illustrative Gas Quality Considerations for RNG Injection

Gas Quality Term	Generally Acceptable Limit
Hydrogen content	
Heating value	≥ 960 Btu/SCF
Wobbe Number	
Dew point temperature	
Sulfur, including dimethyl sulfide and hydrogen sulfide	Total S: ≤ 20 grains/CCF H_2S: ≤ 0.25 grains/CCF
Carbon Dioxide, CO_2	≤ 3.0%, by volume
Nitrogen, N_2	≤ 4.0%, by volume
Oxygen, O_2	≤ 0.4%, by volume
Ammonia	< 0.001%, by volume
Volatile and semi-volatile organics	
Siloxanes	< 1 mg/m^3
Pesticides	
Temperature	32 to 140 °F
Moisture	< 7 lb/MMSCF

Each element has a differing impact on gas quality and safety, interchangeability, end-use reliability and pipeline integrity. If a constituent is not reasonably expected to be found above background levels at the point of interconnect for the RNG, then testing may not be necessary. An additional challenge is that while some constituents may not present a problem in isolation, the interaction between different constituents could result in negative impacts on the pipeline or end-use applications.

Substantial research, testing and analysis has been done to better understand the composition of raw biogas from different feedstocks compared to traditional pipeline-quality natural gas delivered into the natural gas system. In parallel, significant technology advancements have been achieved in processing and treating raw biogas to address trace constituents and the concerns of pipeline operators and end users.

For example, at the direction of the California Public Utilities Commission, the California Council on Science and Technology (CCST) assessed acceptable heating values and maximum siloxane specifications for RNG. CCST found that keeping the current minimum Wobbe Number requirement for RNG while relaxing the heating value specification to a level near 970 Btu/scf would not likely impact safety or equipment reliability. In relation to siloxanes, the CCST found that some RNG feedstocks are very unlikely to harbor siloxanes (e.g. dairy waste, agricultural residues or forestry residues), and less stringent monitoring requirements would be needed. The CCST also recommended a comprehensive research program to understand the operational, health, and safety consequences of various concentrations of siloxanes, due to inconclusive evidence for other RNG feedstocks.[83]

However, the lack of a consistent approach to evaluate RNG quality and constituent composition remains a challenge to the broader acceptance of different RNG feedstocks and inhibits the development of RNG as a source for pipeline throughput. The industry is still learning about RNG and the impact on pipeline infrastructure and end use, and it is in the industry's best interest to continue research, collaboration, and dissemination of biogas processing and RNG pipeline injection experience, particularly as more RNG facilities come online.

An evidence-based, common-sense framework is needed to assess the composition and interchangeability of RNG with conventional natural gas supplies and pipeline requirements. As currently constructed, the processes, requirements, and agreements that facilitate the pipeline connection of RNG projects are not uniform, resulting in commercial and technical uncertainties for stakeholders that limit the efficiency and, potentially, the viability of different RNG projects.

Instead, a consistent and impartial approach to assess the commercial and technical potential of each project is required to encourage the introduction of RNG from a range of biomass feedstocks, without compromising the safety or reliability of the pipeline or end-use applications. In addition, a uniform approach would provide greater certainty for all parties regarding safety, reliability, and interchangeability.

The Role of RNG in Decarbonization

Objectives of Climate Business Plan Analysis

In parallel to this study on the use of RNG in the Greater Washington, D.C. area, ICF was engaged by WG to develop alternative scenarios to evaluate the effectiveness and implications of different approaches to meet D.C.'s 2032 and 2050 emission reduction targets. To do this, ICF conducted scenario modeling that informed the Climate Business Plan that WG is developing, which examines the effectiveness, comparative costs, and timeframes associated with four different energy scenarios.

As part of this exercise, the objective of ICF's scenario modeling is to characterize a low-carbon energy future for the Greater Washington, D.C. metropolitan area, with a critical focus on the role of natural gas in meeting energy commitments in a decarbonized economy. More specifically, ICF's scenario modeling assesses the following key issues:

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[83] CCST, 2018. Biomethane in California Common Carrier Pipelines: Assessing Heating Value and Maximum Siloxane Specifications, https://ccst.us/reports/biomethane/.

- **The Role of RNG**: The RNG results include the anticipated use of RNG in various sectors, with a focus on transportation and pipeline injection for space heating or other end uses. The results extend beyond the Greater Washington, D.C. metropolitan area to the regional and national level to address the costs and emissions associated with the sources of RNG.
- **Natural Gas Emissions**: Evaluation of natural gas supply options for reducing GHG emissions from the end use of natural gas based on publicly available information.
- **Impact on Peak Electric Load**: One of the major cost drivers of decarbonization efforts is expected to be the need to expand the electric grid to serve the incremental electric load. Currently, this region is a summer peaking electric system. At least initially, conversion of space heating load from fossil fuels to electricity will be able to use existing capacity on the electricity grid without incurring the need to build new peak period capacity. However, after a significant share of space heating is converted, the electric grid shifts from summer peaking to winter peaking, which will likely require major new investments in power generation capacity.
- **Change in Consumer Energy Costs**: The changes in consumer energy costs considered changes in consumption for electricity, natural gas, fuel oil, and transportation fuels due to improvements in energy efficiency and from conversion of fossil fuel applications to electricity.
- **Building Stock Conversion Costs**: Improvements to energy efficiency and conversions from fossil fuel to electricity in existing building stock have different costs based on the type and age of the building and the type and age of the heating system and other appliances. ICF used detailed Census data to disaggregate the building stock by type and age of the building and the heating system when estimating the costs of converting the buildings to electricity.
- **Power Sector Impacts**: The power sector results were extended beyond these jurisdictions to the regional and national level to address the costs and emissions associated with the sources of electric power.

Investments in RNG

Over the last 20 years, a variety of investments in biogas capture systems have been made that have helped the market to its level of maturation today. That said, the RNG market has traditionally been focused on small-scale biogas capture systems at landfills, WRRFs, and animal manure digester systems, with most of those facilities producing electricity. As RNG became eligible for valuable D3 RIN generation (as discussed previously), investors largely focused on diverting existing biogas-to-electricity generation systems to biogas-to-RNG pipeline injection projects. As noted previously, the number of projects domestically injecting RNG into the pipeline is rapidly approaching 100, marking impressive and positive growth over the last 5 to 7 years.

The most telling and positive trend from ICF's perspective over the last 2-3 years has been an increase in and the shift in the types of investors engaged in this market, with notable and established infrastructure investors and renewable energy funds dedicating significant resources and attention to RNG investments. Some of the highlighted investments over the last several years include the following:

- **DTE Biomass Energy** broke ground on its first dairy digester cluster in Wisconsin in 2018 and started producing RNG in September 2019; the indications are that DTE Biomass Energy has at least another five additional dairy projects moving forward. DTE Biomass Energy already operates 21 landfill gas projects, and five of those produce RNG.
- **Generate Capital** in San Francisco has made significant investments in RNG, including acquisition of AMP Americas, LLC and its entities that produce RNG at the Fair Oaks Farms dairy (ampRenew, LLC and RDF Indiana Holdings, LLC).[84]
- **Dominion Energy and Smithfield Foods** have committed to investing up to $500 million through 2028 via their Align Renewable Natural Gas joint venture—including projects in North Carolina, Virginia, Utah, Arizona, and California.
- **Chevron** is working with California Bioenergy LLC (CalBio) to produce RNG from dairy digesters in California, including commitments to fund as many as 18 digesters across clusters in California's dairy-producing counties, including Tulare, Kern, and Kings.
- **BP** acquired Clean Energy's RNG business in 2017, and has been working to expand the company's existing RNG footprint over the last three years.
- Other established players in the landfill gas market, such as **Fortistar, US Gain,** and **Aria Energy**, have expanded their portfolio, and broadened their footprint into other RNG production areas, including RNG from animal manure digesters. These longer-standing players are joined by newer players in the RNG space such as **Brightmark Energy** and **Ultra Capital**, as well as investors that have been active in other renewable energy sectors but are new to RNG, like **Iogen** and **Air Liquide**.

The changes in the diversity of investors, and most notably the combination of existing and new investors, in the RNG market over just the past 2–3 years portend rapid changes to the availability of RNG in multiple applications.

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[84] Federal Trade Commission, https://www.ftc.gov/enforcement/premerger-notification-program/early-termination-notices/20191221.

6. Opportunities and Challenges

Key Takeaways

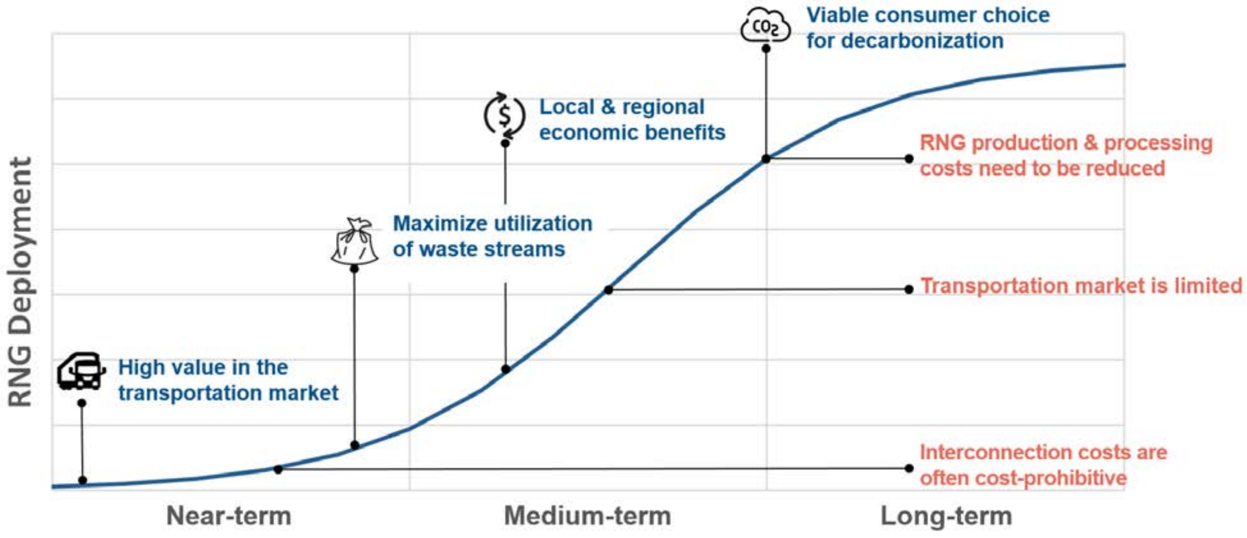
There are multiple opportunities and challenges for the wide-scale deployment of RNG. The physical and environmental characteristics of RNG make for substantial development potential, particularly in relation to the ambitious climate policies in the region. However, challenges remain, including limited capacity in current end-use markets and high pipeline interconnection costs.

These challenges are far from insurmountable with the right direction and leadership from policymakers and industry stakeholders. Some challenges can be overcome in the near-term future, such as a supportive regulatory framework for broad end-use consumption and cost recovery mechanisms for interconnection, while others will be mitigated in the longer term through increased and varied deployment of RNG, including through reduced technology and project costs.

Overview

In this section, ICF considers the highest-value opportunities and the corresponding challenges to realizing the potential of these opportunities in the RNG market. While the technical, market, and regulatory drivers for RNG are inextricably linked, we have distinguished between the key opportunities and challenges across these three broad areas. Figure 69 illustrates a subset of ICF's key findings across the technical, market, and regulatory/policy aspects of RNG deployment, including both **opportunities** and **challenges** envisioned along an illustrative RNG production potential curve.

Figure 69. Overview of RNG Opportunities and Challenges



Technical

The technical potential for RNG over the next five to seven years is constrained primarily by regulatory and market constraints, rather than technical ones. In large part, this is attributable to the fact that there are multiple feedstocks that can be converted to RNG using anaerobic digestion—this is a mature technology. Moving past 2025 and into a post-2030 reality, however, the technical potential for RNG will be constrained by the ability to expand beyond anaerobic digestion of feedstocks like landfill gas, animal manure, WRRFs, and food waste, and into technologies like thermal gasification and P2G. While both thermal gasification and P2G are viable technologies, they would likely be considered in pre-commercial stages or very early commercial deployment. The transition to these types of technologies increases RNG production potential substantially, and can help drive down the long-term costs of RNG.

Opportunities

- **RNG is a valuable renewable resource with carbon neutral (and in some cases, carbon-negative) characteristics.** The GHG benefits of RNG are clear: emissions from RNG are lower than fossil or geological natural gas across the board. When paired with conservation and efficiency improvements, the introduction of RNG has the potential to significantly reduce GHG emissions from the natural gas system and form part of a cost-effective deep decarbonization strategy. Furthermore, these emission reductions are supported by policies that can improve waste management (e.g., landfill diversion), improve utilization of agricultural and forestry products, and generate additional revenue streams for some vulnerable parts of the economy.
- **RNG utilizes the same existing infrastructure as fossil or geological natural gas.** When conditioned and upgraded to pipeline specifications, RNG can use the same extensive system of pipelines for the transmission and distribution of natural gas. Improved and continuous monitoring of potential harmful constituents from RNG production can decrease the technical risks of contamination in the pipeline.
- **The long-term potential for RNG is linked in part to P2G and hydrogen**, which have the potential to increase the flexibility of the natural gas system as a long-term energy storage technology. RNG from anaerobic digestion and thermal gasification make up the majority of production potential considered in this study. However, it is important to note that there is a significant and important role for P2G and hydrogen, driven by the rapid decrease of renewable electricity costs, the need to identify productive uses for CO_2 rather than treating it as a pollutant, and the potential for decreases in electrolyzer costs.

Challenges

- **The technical potential for RNG production is currently constrained to some extent by old policies.** Biogas was originally linked to electricity projects that favored renewable electricity generation, on-site co-generation, and other projects. While this demand for renewable electricity helped to spur investments in landfill gas projects and smaller projects at dairy farms, it has led to the unintended consequence of limiting the near-term potential for production and pipeline injection of RNG.
- **Feedstock location and accessibility will constrain RNG production potential.** The location and availability of RNG feedstocks is mismatched with traditional demand centers for natural gas consumption. For example, many feedstocks are available in predominantly

rural areas whereas demand is focused in urban centers. Some of these feedstocks may be difficult to access, or may require substantial (and in some cases impractical) investments in infrastructure. This issue is similar to challenges around location-constrained resources for renewable electricity generation.

- **Competition for feedstocks will constrain RNG production potential.** There is a diverse array of feedstocks available for RNG production, yet accessing some of those feedstocks can be difficult or prohibitive. Furthermore, as waste diversion policies improve over time, and decarbonization efforts presumably expand in different regions, biogenic and biomass feedstocks will have increasing value, thereby increasing competition for various energy production processes, including for gaseous fuels (i.e., RNG), liquid fuels (e.g., liquid biofuels like renewable diesel), and for renewable electricity. Technological advances in each of these markets will help determine the appropriate use of each feedstock, while the availability of that feedstock will still be constrained by other factors, including the rate of waste produced, agricultural outputs, and forestry outputs.
- **Gas quality and gas composition for RNG remains an engineering concern.** There is no existing standard for RNG gas quality and gas composition, and with limited operational data, some concerns remain regarding RNG injection into a pipeline system.
- **P2G technology will require significant cost reductions.** While P2G holds significant promise, the long-term viability of the technology will require significant near-term deployment of electrolyzers to help drive the necessary cost reductions for the technology to be cost-competitive in a post-2030 market that is increasingly focused on decarbonization. Potential cost reductions for P2G could replicate the trends displayed by other low carbon technologies, such as renewable electricity, with the appropriate and immediate policy and regulatory support.
- **Seasonal variability in the region’s natural gas systemwide demand will require the RNG production market to adapt.** As noted previously, Greater Washington, D.C. metropolitan area’s natural gas system sees a significant winter peak, largely driven by space heating demand. There is a six-fold difference in natural gas demand on the region’s system between winter and summer months, and RNG production facilities do not have the same variability. Current RNG contractual structures are driven by natural gas demand as a transportation fuel, and are not designed to accommodate the type of system variation required for space heating applications. As the RNG market evolves and matures, ICF anticipates that this issue can be solved through book-and-claim accounting, storage, and other considerations. However, as the RNG market transitions from transportation fuel use to more diverse end uses on the natural gas system, there will be growing pains.

Market

There are more than 85 projects producing RNG for pipeline injection today, compared to less than a half-dozen in 2010. In Section 2, ICF provided an outline of RNG potential for pipeline injection, broken down by feedstocks and production technologies. Based on this untapped potential, the RNG market is poised for substantial growth with ICF estimating that as many as 100 new RNG projects will be developed by 2023. The following section outlines the most significant opportunities driving the RNG market, and the most significant challenges that must be overcome.

Opportunities

- **RNG has high value in the transportation sector.** Natural gas consumption as a transportation fuel is modest in the Greater Washington, D.C. metropolitan area; however, there are clear incentives to deploy RNG into the transportation sector, and saturation in other state-level markets will make it increasingly favorable for fleets and other entities to dispense RNG for use as a transportation fuel in that area.
- **RNG can deliver cost-effective GHG emission reductions for deep decarbonization.** RNG is a cost-effective GHG emission reduction measure, and relative to other GHG mitigation measures, RNG can play an important role in helping to achieve aggressive decarbonization out to 2050.
- **RNG helps maximize the utilization of evolving waste streams.** The anaerobic digestion of biomass, including at landfills and WRRFs, helps maximize the use of waste. With growing urban populations and more pressure for landfill diversion, the anaerobic digestion of food waste and thermal gasification of MSW, for instance, has the potential to continue to increase the utilization of waste streams as renewable energy resources.
- **RNG markets are evolving to reflect utilities and corporations with climate and sustainability goals.** There is increasing activity and interest in RNG outside of the transportation sector, and also beyond jurisdictions where carbon constraining policies are influential. Driven by corporate sustainability goals and customer preferences, an increasing number of utilities and large end users of natural gas are looking into RNG as an option to reduce GHG emissions, exemplified by the actions of SoCalGas, Vermont Gas, L’Oréal, and others in the RNG market.
- **RNG helps give suppliers and consumers a viable decarbonization option in an evolving market and policy environment.** There is a growing trend for utilities and large industrial consumers to adopt ambitious decarbonization measures, while small consumers are increasingly aware of their carbon footprint and looking for ways to reduce emissions. In this environment, the introduction of RNG has the potential to provide suppliers and end-use customers with a viable choice toward a balanced energy future that delivers safe and reliable energy, while also reducing GHG emissions, and in a manner that is more cost-effective and equitable than outright bans or restrictive mandates on natural gas use, as recently seen in California at the local level.

Challenges

- **RNG markets beyond transportation fuel are nascent.** The long-term growth potential for RNG is dependent on transitioning to end uses other than transportation. The near-term market potential for RNG deployment in WG’s service territory will help the region satisfy proof of principle, and bolster stakeholder confidence in the ability of RNG to deliver cost-effective GHG emission reductions. However, absent some other markets for RNG consumption, production investments will stall and it will plateau.
- **RNG production and processing costs need to be reduced to improve cost-competitiveness.** The market for RNG will expand beyond the transportation sector through improved technology and complementary policies. However, technology and overall production costs need to decrease over time to maintain competitiveness.
- **RNG is not explicitly included in LDC tariffs governing gas procurement.** LDCs may be required to procure natural gas on a least-cost basis, or least-cost with consideration for

peaking/reliability sources. Given that RNG is likely to exceed the market cost of conventional natural gas, and absent an RNG procurement mandate, it may be necessary to include RNG within LDC tariffs as another legitimate source option that is subject to standard prudent procurement requirements.

- **Limited availability of qualified and experienced RNG developers to expand RNG production in the near-term.** With growing interest in RNG projects, particularly to capture near-term value in the transportation market, there is a lack of experienced project developers (perceived or real) to meet this demand. This issue will ameliorate over time, as the industry expands and project developers gain more experience on RNG projects.
- **RNG costs more than conventional natural gas, when environmental benefits are not valued appropriately.** The capital expenditures and operational costs associated with RNG production are higher than the commodity price for conventional natural gas, greatly restricting the potential for RNG production and consumption. However, the costs of RNG should not be compared directly with conventional natural gas without reflecting the significant GHG emission reduction benefits of RNG. For example, with the environmental attributes valued under the LCFS, RNG is a cost-effective transportation fuel relative to diesel and conventional natural gas.
- **Interconnection costs for RNG suppliers and developers can be prohibitively high.** Interconnection serves a vital role in an RNG project—it is the point at which gas quality is monitored, prevents non-compliant gas from entering the system, and meters the RNG injected. On a project-lifetime basis, interconnection costs are generally small as the cost is amortized, for instance, over a 10- to 20-year project lifetime. However, meeting interconnection costs can be a challenge for project developers.

  There is no “right cost” associated with interconnection. Instead, gas utilities need to work with regulators and project developers to ensure safety and reliability are maintained on the system, and that utilities can recover the costs associated with the system requirement.

  Utilities, along with regulators, have strategic roles to work with potential RNG suppliers and project developers to:

  (i) Research and evaluate suitable site locations;
  (ii) Determine pipeline interconnection distances and pathways;
  (iii) Develop engineering designs and configurations;
  (iv) Determine appropriate flows and pressures; and
  (v) Conduct initial project cost estimates.

Regulatory and Policy

The aforementioned regulatory and policy incentives for the use of RNG as a transportation fuel have helped spur substantial investment in new RNG projects nationwide. However, the demand for RNG as a transportation fuel is limited and tied to the growth of NGVs. Therefore, a regulatory and policy structure that supports the cost-effective use of pipeline-injected RNG as a GHG mitigation strategy is paramount to the long-term success for RNG.

Today, a handful of state-level policies are in place that are helping to shape the outlook for RNG beyond transportation. Table 45 provides information on these policies, including the state in which the bill was enacted, a bill summary, and key programmatic components such as supply, production or interconnection, cost recovery for gas utilities, and end-user benefits.

Table 45. Summary of State Laws Enacted to Support RNG

State / Bill	Brief Description	Supply	Production / Interconnection	Cost Recovery	End-User Benefit
Oregon SB 98	Allows natural gas utility to make “qualified investments” and procure RNG from 3rd parties to meet portfolio targets for the percentage of gas purchased for distribution to retail customers.	Establishes large/small RNG programs and to make “qualified investments” and procure RNG from 3rd parties to meet portfolio targets for the percentage of gas purchased for distribution to retail natural gas customers.	RNG infrastructure means all equipment and facilities for the production, processing, pipeline interconnection, and distribution.	PUC shall adopt rules establishing a process for utilities to fully recover costs. Cost of capital established by PUC from most recent rate case. Affiliates not prohibited from making a capital investment in a biogas production project. Restricted from making additional qualified investments without the approval of the PUC if the program annual costs exceed 5% of the utility’s total revenue requirement in an individual year.	Reduced emissions. RNG portfolio ranging from 5% between 2020 and 2024 to 30% between 2045 and 2050.
Washington HB 1257	Required each gas company to offer by tariff a voluntary renewable natural gas service available to all customers.	To replace any portion of the natural gas that would otherwise be provided by the gas company. Customer charge for an RNG program may not exceed 5% of the amount charged to retail customers for natural gas.	No Reference	No Reference	Commission must assess whether the gas companies are on track to meet a proportional share of the state’s GHG reduction goal.

State / Bill	Brief Description	Supply	Production / Interconnection	Cost Recovery	End-User Benefit
Nevada SB 154	Authorized natural gas utilities to engage in RNG activities and to recover the reasonable and prudent costs of such activities, including the purchased of and production of RNG.	Requires a public utility to “attempt” to incorporate RNG into its gas supply portfolio. Gas which is produced by processing biogas or by converting electric energy generated using renewable energy into storable or injectable gas fuel in a process commonly known as power-to-gas or electrolysis.	Activities which may be approved: contracting with a producer of RNG to build and operate an RNG facility; extending the transmission or distribution system to interconnect with an RNG facility; purchasing gas that is produced from an RNG facility whether the gas has environmental attributes or not.	Utility applies to the Commission for approval of a reasonable and prudent RNG activity that will be used and useful. Must meet one or more: the reduction or avoidance of pollution or GHG; the reduction or avoidance of any pollutants that could impact waters in the state; the alleviation of a local nuisance within the state associated with the emission of odors.	Sell gas from RNG facility directly to the customer. Providing customers with the option to purchase gas produced from an RNG facility with or without environmental attributes. Utility shall attempt to incorporate RNG in its gas supply portfolio: By 2025, not less than 1% of the total amount of gas sold; by 2030, not less than 2%; by 2035, not less than 3%.
California SB 1440	Requires the CPUC to establish biomethane procurement goals or targets on natural gas IOUs to further decarbonize the state’s natural gas sector. Stipulates that the goals and targets need to be a cost-effective means of achieving reductions in short-lived climate pollutants and other GHG emission reductions.	In consultation with the State Air Resources Board, the Commission would consider adopting specific biomethane procurement targets or goals for each gas corporation so that each gas corporation procures a proportionate share of biomethane annually.	To be eligible, the biomethane needs to be delivered through a common carrier pipeline that physically flows within California, or toward the end user in California for which the biomethane was produced. Currently, CA has a 50% by 2050 RPS. Under the RPS, utilities are authorized to meet the requirements using biogas from eligible renewable sources through the state’s Bioenergy Market Adjusting Tariff (BioMAT) program.	The bill would require the PUC, if the PUC adopts those targets or goals, to take certain actions in regard to the development of the targets or goals and the procurement of the biomethane to meet those targets or goals.	A limited biomethane procurement program would help the state reduce methane and ensure that California’s climate policies are met.

State / Bill	Brief Description	Supply	Production / Interconnection	Cost Recovery	End-User Benefit
California AB 1900	Established a program beginning in 2015 that provided $40M for RNG interconnection infrastructure. The bill was intended to address the barriers to allowing RNG to be injected into pipelines and break down barriers to using instate RNG—all while ensuring the supply was non-hazardous to human health.	The bill required the California EPA to compile a list of constituents of concern that could pose risks to human health and that are found in biogas at concentrations that significantly exceed the concentrations of those constituents in natural gas.	A part of this bill would require the PUC to adopt standards to ensure pipeline integrity and safety. The PUC would also adopt pipeline access rules to ensure nondiscriminatory access to all pipeline systems for physically interconnecting with the gas pipeline system and effectuating the delivery of gas.	No reference.	As a health safety initiative, the bill required the PUC to specify the maximum amount of vinyl chloride that may be found in landfill gas.
Utah HB 107	Authorizes gas utilities to establish natural gas clean air programs that promote sustainability through increasing the use of renewable natural gas if those programs are deemed to be in the public interest.	In determining whether a project is in the public interest, the Public Service Commission (PSC) shall consider to what extent the use of renewable natural gas is facilitated or expanded by the proposed project; potential air quality improvements associated with the proposed project; whether the proposed project could be provided by the private sector or would be viable without the proposed incentives; whether any proposed incentives were offered to all similarly situated potential partners and recipients; and potential benefits to ratepayers.	No reference.	The PSC may authorize large-scale utilities to allocate up to $10M annually to a specific sustainable transportation and energy plan. Elements include an economic development incentive rate; R&D of efficiency technologies; acquisition of non-residential natural gas infrastructure behind the utility's meter; the development of communities that can reduce GHG and NOx emissions; a natural gas renewable energy project; a commercial line extension program; or any other technology program. Electric utilities were previously authorized to have similar programs. If the PSC finds that a gas	Reduction of greenhouse gases and NOx emissions.

State / Bill	Brief Description	Supply	Production / Interconnection	Cost Recovery	End-User Benefit
				corporation's request for an NGV rate/clean air programs is less than the full cost of service, remaining costs may be spread to other customers. A previous statute authorizes recovery of expenditures for the construction, operation, and maintenance of natural gas fueling stations and related facilities.	
Vermont PUC Docket# 8667	VT Public Utility Commission authorized a renewable natural gas program for the sale of RNG to customers on a voluntary basis and optional RNG tariff service.	Vermont Gas stated they were seeking to source RNG from landfill gas projects.	Supply from Lincoln and landfill gas projects outside Vermont would be received through the Trans-Canada Pipeline system.	Requires Vermont Gas to file a formal tariff including proposed rates once it has procured RNG in sufficient amounts for estimated customer demand. Adder price for each scf of RNG will be equal to the average RNG commodity cost to VGS less the average commodity cost of natural gas. Also, if Vermont Gas' RNG supply exceeds customer demand, they must first seek to sell the excess at wholesale, and if necessary may seek to flow any remaining inventory amounts through a rate case as part of its cost of service.	Successful implementation can help meet the State's renewable energy policy objectives. Assessment of the voluntary program will assist in determining the feasibility of incorporating RNG as a portion of Vermont Gas' supply mix in the future.

Opportunities

An existing suite of regulatory initiatives and policies could help support RNG deployment in the near- to long-term future. These include conditioning and interconnection tariffs, voluntary offerings paid by customers, and a renewable gas standard. These opportunities are summarized here:

- **Conditioning and Interconnection Tariffs.** As outlined in Section 3, the costs of biogas conditioning and upgrading can be expensive; similarly, interconnection costs can be prohibitive for some project developers. These costs are the primary capital outlays at the outset of a project and have a material impact on the ability of projects to get financed. Under a tariff structure, the producer can avoid the significant upfront capital costs that can often impede project development. Conditioning and interconnection tariffs allow utilities or LDCs to build and operate the upgrading and interconnection facilities, while recovering capital and operation and maintenance costs from the project developer at a pre-determined rate. Examples of where this has been done include:
    - SoCalGas has a biogas conditioning and interconnection tariff; it “is an optional tariff service for customers that allows SoCalGas to plan, design, procure, construct, own, operate and maintain biogas conditioning and upgrading equipment on customer premises.”[85]
    - TECO Peoples Gas in Florida had a tariff for biogas conditioning and upgrading approved in December 2017, and have since made modifications to the tariff to accommodate the receipt of RNG from biogas producers and an updated rate schedule for conditioning services.[86]
    - Southwest Gas Company (SWGC) in Arizona has a biogas services tariff enabling them to enter into a service agreement with a biogas or RNG producer, and includes requirements for access to the production facilities, interconnection facilities, and gas quality testing facilities.[87]
- **Emergence of legislation and regulations for both mandatory and voluntary programs.** Utilities may offer opt-in voluntary programs to customers to help reduce the environmental impact of their energy supply. This is more common for electric utilities, however, similar programs can be developed for gas utilities and RNG consumption. Examples of voluntary programs include:
    - Vermont Gas has had a voluntary program in place since 2018 for various blends of RNG. Vermont Gas customers consume about 6 BCF of RNG, which is sourced from Canada.[88]
    - In early 2019, SoCalGas and San Diego Gas & Electric (SDG&E) submitted a proposal to the CPUC to offer a voluntary RNG Tariff program to their residential, small

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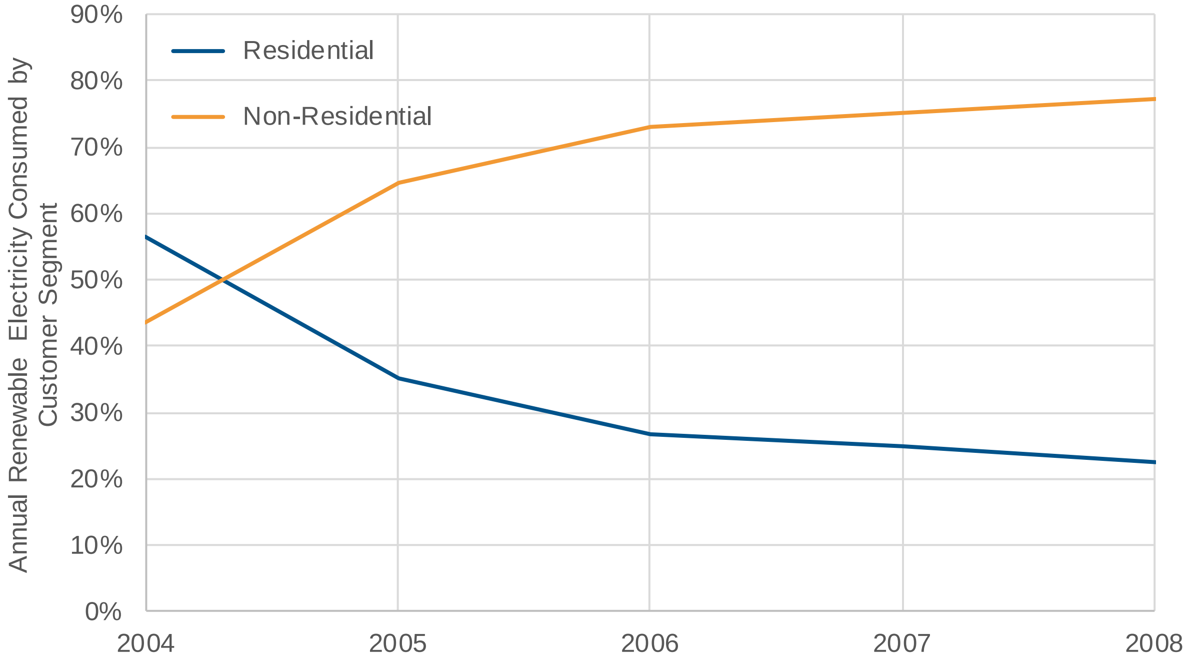
[85] SoCalGas, information retrieved from https://www.socalgas.com/for-your-business/power-generation/biogas-conditioning-upgrading.
[86] TECO Peoples, tariff is available online at https://www.peoplesgas.com/files/tariff/tariffsection7.pdf.
[87] SWGC, Schedule No. G-65, Biogas and Renewable Natural Gas Services , available online at https://www.swgas.com/1409197529940/G-65-RNG-02262018.pdf.
[88] More information is available online at https://www.vermontgas.com/renewablenaturalgas/.

commercial, and industrial customers. SoCalGas and SDG&E have proposed to recoup program costs through rates charged to program participants.

- National Grid proposed a Green Gas Tariff offering in April 2019 that will enable its customers to voluntarily purchase RNG to meet all or a portion of their energy needs. National Grid designed the tariff with four tiers, providing consumers with multiple options regarding the extent to which they want to green their gas.
- Fortis BC, the main gas utility in the Canadian Province of British Columbia, has had a voluntary RNG tariff program since 2011, which has spurred RNG production in the region.[89]

Voluntary markets were critical to the initial growth of renewable electricity, as residential and non-residential customers helped grow demand considerably in the early years of renewable electricity development (see Figure 70).[90,91]

Figure 70. Percent Annual Renewable Electricity Consumption by Customer Segment, 2004–2008



Renewable electricity accounts for more than 20% of today's total electricity generation. However, less than 15 years ago, renewable electricity accounted for less than 1% of total electricity generation as voluntary renewable electricity programs started in earnest. This nascent growth helped achieve some cost reductions, raise consumer awareness, and spur action by non-residential customers. Furthermore, it helped to demonstrate the

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[89] Fortis BC, 2020. https://www.fortisbc.com/services/sustainable-energy-options/renewable-natural-gas

[90] NREL, Green Power Marketing in the United States: A Status Report (Tenth Edition), December 2007, NREL/TLP-670-42502, https://www.nrel.gov/docs/fy08osti/42502.pdf.

[91] NREL, Green Power Marketing in the United States: A Status Report (2008 Data), September 2009, NREL/TLP-6A2-46851, https://www.nrel.gov/docs/fy08osti/42502.pdf.

demand for renewable products, and served as the launching point for more structured regulatory action via renewable portfolio standards.

Renewable Gas Standard (RGS):

The principles of an RGS are straightforward and mimic RPS programs, a common policy tool to introduce a renewable energy procurement requirement for electricity providers. In other words, an RGS would require RNG to be delivered and measured against some benchmark, such as a carbon-based reduction or volumetric target. There are a variety of approaches to RGS implementation, including:

– A free-market approach whereby a procurement target is established and the market simply responds to the price signal according to the supply-cost curve for RNG production.

– A feed-in tariff, or standard offer contracts, would provide clear, reliable pricing for RNG producers. Although this approach provides a clear signal to help producers finance renewable gas projects, without distinguishing between feedstocks, a feed-in tariff has the potential to favor low-cost producers without recognizing the cost-effectiveness of GHG emission reductions.

– The RGS could take on a performance-based approach structure like the LCFS program in California, requiring a percent reduction in the carbon intensity of natural gas by some date. Similarly, the RGS could take on a structure that requires a percent volume target by some date (different from an absolute volumetric target, as is prescribed in the federal RFS program).

– The coverage of an RGS would not necessarily be limited to just utilities and LDCs, but also encompass all suppliers of natural gas, including third-party suppliers such as natural gas marketers, similar to the broad coverage of RPS programs relative to electric load serving entities.

There are two additional aspects of an RGS that ICF considers critical: 1) tracking and verifying progress toward achieving an RGS and 2) understanding the tradeoffs of various performance-based approaches.

– **Thermal RECs to track and verify RNG**. With increased interest in voluntary and compulsory regulations and policies in place supporting the use of RNG, the market for tracking and verifying RNG has advanced rapidly. This will be critical in light of the potential for an RGS. Renewable electricity markets rely on various bodies to track and verify RECs, the primary regulatory currency for RPS programs.

  There is no analogous tracking system for RNG today, however, market actors are advancing the concept rapidly to help grow the market for RNG consumption outside of the transportation sector. The Midwest Renewable Energy Tracking System (M-RETS) has been trialing a thermal REC system since July 2019, which includes RNG used in stationary applications such as building heating and cooling. The intent is to provide the same verification and price transparency to the RNG market as exists in the renewable electricity market.

- **Understanding performance-based approach tradeoffs: volumetric vs carbon intensity targets.** ICF originally researched and wrote about this issue in 2017.[92] A performance-based approach should, in principle, provide clear signals to regulated parties and investors regarding the timeline required to achieve program targets, whether it be a carbon intensity target or volumetric target.

  The downside of a carbon intensity target is that it may introduce undue complexity to the RGS. For instance, consider the boundary conditions of the lifecycle GHG assessment of dairy digester gas. Without regulations in place to capture and burn the methane that is released, the gas receives a lower carbon intensity for being credited with the avoided emissions from *venting* methane. Landfill gas, on the other hand, being regulated and required to be captured and burned, receives a lower carbon intensity for being credited with the avoided emissions from *flaring* methane. The difference in the GHG benefit of avoided methane venting versus avoided methane flaring is tremendous: in the case of the former, you are avoiding methane emissions at a 100-year global warming potential of 25, whereas in the latter you are avoiding carbon dioxide emissions with a global warming potential of 1. Furthermore, if complementary regulations are enacted that improve waste (or manure) management, these could impact the carbon intensity of the RNG, simply by changing the boundary conditions of the analysis.

  Another consideration related to a carbon intensity-based approach is the potential for the intent of the program to be expanded unexpectedly to include upstream emission reductions; e.g., methane leaks in the natural gas pipeline. This could provide additional compliance opportunities for utilities that produce additional GHG benefits, but may detract from the intent of stimulating RNG development. Additionally, and similar to the example above, other regulations and programs that address these system improvements could complicate the benefit calculation, creating moving targets and challenging utilities' assessments of investment value for different compliance pathways.

Apart from the regulatory and policy opportunities outlined above, there are several other key opportunities in the RNG space:

- **Transportation policies currently favor RNG over fossil natural gas.** Despite depressed pricing in the federal RFS program, the environmental commodities generated from the use of RNG as a transportation fuel still generates value upward of \$7/MMBtu. Complementary policies, such as a low carbon fuel standard, can be enacted to support RNG use in the Greater Washington, D.C. metropolitan area to further decarbonize the transportation sector immediately.
- **RNG can help achieve aggressive decarbonization policies.** RNG can play an important and cost-effective role in achieving aggressive decarbonization by 2032 and 2050.
- **Complementary policies could facilitate RNG feedstock collection (e.g., waste diversion and management).** The RNG industry could benefit considerably from complementary policies that help improve the accessibility of feedstocks while improving project development economics. This includes regulations or policies that encourage

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[92] ICF White Paper, Design Principles for a Renewable Gas Standard, 2017.

methane capture, encourage waste diversion and waste utilization, forest management and thinning requirements, etc.

- **A robust RNG regulatory framework will encourage deployment of RNG.** When developing the programs and policies that reduce GHG emissions and help meet aggressive deep decarbonization objectives, policymakers and regulators should consider RNG as a cost-effective alternative and adopt policies to encourage customers and utilities to adopt RNG.

Challenges

- **The pathway for policies and incentives promoting RNG in market segments other than transportation is unclear and not uniform.** Current programs in place do not provide the price and supply certainty that is required for larger volumes of RNG to be deployed, beyond the success of RNG in the transportation fuels market. While voluntary commitments and other drivers may help to increase RNG consumption in non-transportation market segments, the potential for RNG is intrinsically constrained without a strong policy signal in place. Furthermore, the programs that have been proposed or even promulgated are generally lacking or insufficient, and do not recognize or credit the environmental benefits of RNG in a manner that is consistent with the long-term potential of the technology.
- **Some policymakers are singularly focused on electrification and unaware of the cost-effectiveness and other benefits of RNG.** In many policymaking environments today, the path to 2050 is viewed as electrification or bust. There are dubious claims about the supply and cost of RNG that are dismissive at worst, and pessimistic at best. This reinforces the underlying narrative that the best and only path to a decarbonized economy relies on rapid electrification of end uses paired with renewable electricity generation. This study is not intended, and makes no effort, to refute the viability of electrifying various end uses, while increasing amounts of renewable electricity. Instead, this study highlights the fact that the current policy environment creates a situation where RNG production as a viable, large-scale and cost-effective GHG mitigation strategy is potentially marginalized without proper investigation.
- **The applicability of RNG must be considered within existing customer choice programs.** The effectiveness of RNG procurement may be undercut by LDCs if the higher incremental costs are avoided through suppliers in customer choice programs who rely on traditional sourced and lower-cost supply. Regulators and policymakers may need to consider policy constructs that encourage or require all suppliers to procure RNG, or all customers to be allocated the costs of RNG, in order to promote effectiveness.
- **Gas utilities are just beginning to gain cost-recovery mechanisms for RNG procurement and investments.** The rapid expansion of RNG production over the last several years has been impressive; however, the industry will face limits as technical and market constraints limit market participants. Faced with varying pressures to decarbonize, utilities need cost-recovery mechanisms for RNG procurement or investments.

  In particular, natural gas utilities will need a regulatory structure that provides cost recovery for the incremental costs of RNG, interconnection facilities and equipment for RNG to comply with gas quality specifications and standards, and investment in larger facilities such as pipelines and premium gas production, supply facilities, and pipeline capacity costs that would support and facilitate the development of RNG.

- **Gas safety, reliability and quality rules and requirements need to be updated to align with current science/evidence.** The safety and reliability of the natural gas transmission and distribution network of pipelines is paramount to utility operations. Gas quality requirements and standards serve as an important reminder of this. However, it is important that gas quality rules and requirements reflect current science and evidence regarding RNG systems, and their ability to deliver a safe and reliable product. Pilot projects and demonstration programs provide opportunities for additional evidence on the impact of RNG systems, which can be used to update gas rules and requirements accordingly.

7. Recommendations to Deploy RNG

Key Takeaways

Although natural gas has played an important role over the last decade in GHG emission reductions by replacing coal-fired generation, it is still a significant contributor to GHG emissions in the Greater Washington, D.C. metropolitan area, contributing approximately 10% of regional GHG emissions (including a population-weighted share of natural gas consumption in Maryland and Virginia). Washington, D.C., Maryland, and Virginia have all made climate and clean energy commitments that will play critical roles in determining the pace of GHG emission reductions in each jurisdiction and will directly impact the natural gas system.

Stakeholders in the gas supply and distribution industry in the region, including gas utilities, should expect to play a proactive and positive role in supporting the Greater Washington, D.C. metropolitan area's various GHG emission reduction goals and delivering emission reductions from the natural gas system. To be a partner in meeting these climate objectives, gas utilities and associated stakeholders will need a sustainable and innovative business model that helps decarbonize the natural gas system. In parallel, regulators and policymakers must develop innovative approaches that enable the market for RNG to flourish and take full advantage of the full suite of cost-effective decarbonization strategies.

ICF's recommendations to support RNG deployment are structured in three parts:

1. ***Strategic direction for policymakers and industry stakeholders***
2. ***Market approaches***
3. ***Regulatory actions***

Deploying RNG in the Greater Washington, D.C. Area

ICF envisions a strategic roadmap to deploy RNG across the components outlined in Figure 71.

Figure 71. RNG Strategic Roadmap

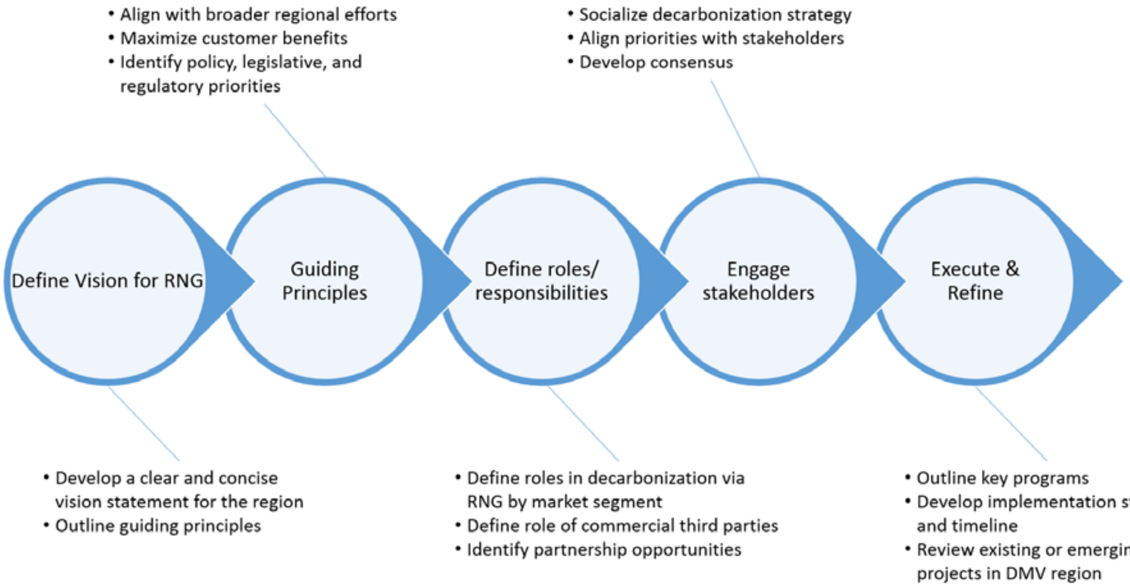

Figure 71 illustrates the Strategic Roadmap process that ICF recommends, including developing a vision statement and guiding principles, defining roles and responsibilities, engaging stakeholders, and executing the plan. ICF notes that the roadmap is portrayed in a linear fashion only for the sake of simplicity. There is nothing about the roadmap or the process that is inherently deterministic. Rather, the roadmap for the region will have to advance iteratively driven by the changing landscape.

The RNG Strategic Roadmap should be socialized across all key stakeholders—with a focus on regulated parties (e.g., gas utilities), key third parties, regulators, and policymakers. The roadmap should also be updated as decarbonization efforts are advanced in earnest across the region.

ICF's overview of the Strategic Roadmap to deploy RNG in the Greater Washington, D.C., metropolitan area is focused on the vision and guiding principles outlined in Figure 71. In the sections that follow, ICF reviews market and regulatory actions that can be taken to deploy RNG. These actions largely (but not exclusively) address the other aspects of the roadmap, including the roles and responsibilities of different stakeholders, how to engage different stakeholders, and execution of various projects to deploy RNG.

As part of this Strategic Roadmap, natural gas industry stakeholders should not just focus on RNG-specific regulations and policies, but adopt a broader perspective and push for the inclusion of RNG in relevant federal and state mechanisms that support clean energy and decarbonization in general. Clean energy grant programs, tax credits, and research and development funding should reflect the critical role that RNG can play in deep decarbonization efforts. For example, RNG investments should receive similar investment tax credits or production tax credits as those currently or previously afforded to renewable electricity generation via wind or solar resources. Similarly, RNG paired with low NOx engines for trucks and buses can help achieve the NOx reduction targets sought through the administration of funds from the Volkswagen settlement and other DOE grants, and help to achieve valuable GHG emission reductions.

A Vision for RNG Deployment

The potential for RNG in the region is clear: many stakeholders are positioned to take immediate action to facilitate the necessary development of RNG consumption in the region and should be guided by the following vision statement:

> ***Vision Statement:*** *The Greater Washington, D.C. metropolitan area will maximize RNG throughput as a decarbonization strategy while maintaining the safety, reliability, and affordability of gas services.*

This vision can be implemented through aggressive but attainable RNG throughput targets as outlined below. The Greater Washington, D.C. metropolitan area (including supply to D.C., and parts of Maryland and Virginia) can potentially achieve:

- Up to 5% RNG throughput by 2025,
- Up to 15% RNG throughput by 2030, and
- Up to 20% RNG throughput by 2035.

ICF's analysis of RNG potential at the local, regional, and national level supports the RNG volumes required to achieve these targets. The market- and regulatory-focused efforts that are required to help achieve these targets are discussed in more detail below.

Guiding Principles

To achieve the vision statement objective and throughput targets outlined above, the Greater Washington, D.C. metropolitan area will need to be guided by a set of consistent and clear principles:

- ***Produce and deliver RNG safely and cost-effectively to participants and end-use customers.*** There is growing interest in RNG from consumers, especially in the commercial and industrial sectors. It is imperative that customers across the region know that market actors are delivering a safe product that helps to cost-effectively reduce the environmental footprint of natural gas operations.
- ***Contribute to broader regional GHG emission reduction objectives.*** The RNG strategy must align with the region's broader objectives with respect to GHG emission reductions.
- ***Pursue a flexible regulatory and legislative structure that values RNG deployment appropriately***. The region should seek to develop and support a regulatory and legislative structure that provides sufficient flexibility to achieve cost-effective GHG emission reductions while maintaining safety and reliability. This economy-wide structure should also be balanced and not focused on particular technologies or fuels, given the uncertainties and long timeframes needed to achieve deep decarbonization goals.
- ***Proactively engage with key stakeholders throughout the implementation of the RNG strategy.*** RNG deployment requires close coordination between regulators and stakeholders like gas utilities, LDCs, and investors. Similarly, an effective engagement strategy is needed with potential RNG suppliers (locally and regionally), potential end users in targeted segments (e.g., RNG in transit buses at WMATA), and key industry groups (e.g., AGA, Coalition for Renewable Natural Gas).

Market-Based Approaches to RNG Deployment

ICF has focused on three areas for RNG deployment with respect to market-based approaches, including a pragmatic near-term approach to develop interconnection standards for RNG projects, deploy RNG in the transportation sector, and to work as part of a broader coalition to establish common tracking and verification of RNG attributes across end uses and markets.

Market-based approaches in these areas would address some of the technical, market and regulatory challenges discussed in this report, notably:

- Maximized and immediate deployment of RNG to cost-effective end uses;
- Development of a framework to facilitate broader and long-term RNG deployment;
- Enhanced market certainty and transparency through a tracking and verification framework;
- Clarity related to interconnection costs and gas quality requirements; and
- Cost reductions, technology developments, and efficiency improvements up and down the supply chain driven by increased industry experience with, and number of, RNG projects.

Develop Interconnection Standards for RNG Projects

ICF recommends that gas utility stakeholders work closely with project developers to focus on interconnection standards. As currently constructed, the processes, requirements, and agreements that facilitate the pipeline connection of RNG projects are not uniform, resulting in commercial and technical uncertainties for stakeholders (particularly project developers) that limit the efficiency and, potentially, the viability of different RNG projects. The process of developing interconnect standards does not need to reinvent the wheel; rather, local and regional stakeholders should build upon work done by peers across the country (including in the Northeast and West Coast) to review gas quality minimum standards, monitoring requirements, and other critical components of interconnection.

Ultimately, local and regional stakeholders will need to develop a consistent and impartial approach to assess the commercial and technical potential of each project to encourage the introduction of RNG from a range of feedstocks, without compromising the safety or reliability of the pipeline or end-use applications. A uniform approach will provide greater certainty for all parties regarding safety, reliability, and interchangeability, and lay the groundwork for expanding RNG consumption into larger and more diverse markets and end uses over the long-term future.

Deploy RNG into the Transportation Market

The transportation sector is a natural fit for the near-term focus of RNG deployment in the region: the combination of higher conventional energy costs and existing incentives makes for a clear opportunity.

Despite its modest demand for natural gas as a transportation fuel, RNG consumption in the transportation sector in the Greater Washington, D.C. metropolitan area has potential for immediate growth. In contrast to other parts of the country, there is currently minimal RNG transportation consumption in the region and significant immediate potential for natural gas transportation demand to be supplied by RNG.

ICF estimates that natural gas transportation consumption in the Greater Washington, D.C. metropolitan area is currently about 1.25 bcf per year and is poised for optimistic growth of between 3% and 5%, with potential for more growth depending on market and regulatory incentives. There are opportunities for expanding natural gas consumption in the medium- and heavy-duty vehicle market segments, thereby acting as a conduit for increased RNG deployment. The combination of the total cost of ownership for NGVs and the fueling infrastructure requirements remains a challenge to higher volumes. However, the appropriate combination of policy and market incentives can induce additional growth in NGVs. The regulatory considerations regarding NGV deployment are outlined in the following sub-section.

The market for RNG as a transportation fuel in the region should take advantage of other market forces, notably that California’s market for natural gas as a transportation fuel is nearly saturated with RNG. Furthermore, the EPA continues to increase the mandated volumetric consumption of transportation biofuels like RNG—meaning that suppliers will be seeking to find markets other than California to maximize value. This will require closer coordination amongst market actors, including project developers and suppliers, gas utilities (to distribute the gas), natural gas station owners, and natural gas fleets.

Establish Common Tracking Across RNG Markets

There is increasing interest in RNG deployment across multiple markets. Most RNG today is used either in the transportation sector (typically via pipeline injection) or combusted to make renewable electricity. In both cases, these markets have tracking and verification through RINs in the federal RFS and RECs in renewable energy markets, respectively. RNG use outside of these markets, however, is not subject to tracking or verification.

Although there is no analogous tracking system for RNG today, market actors are advancing the concept rapidly to help grow the market for RNG consumption outside of the transportation sector. As noted previously, the Midwest Renewable Energy Tracking System (M-RETS) has been trialing a thermal REC system since July 2019 with the intent of providing the same verification and price transparency to the RNG market as exists in the renewable electricity market.

Tracking will become increasingly important as numerous sectors and regions seek to deploy RNG, and RNG markets expand into multiple and broader end uses over the medium- and long-term. Tracking and verification through certification provides market certainty and can also help assure that markets and credits remain fungible. This will be particularly important for stakeholders in the Greater Washington, D.C. metropolitan area because of the multiple jurisdictions in play, including in D.C., Maryland, and Virginia.

Regulatory Approaches to RNG Deployment

Supportive government policies and regulatory certainty are needed to encourage the long-term adoption of RNG as a decarbonized fuel beyond current uses in the transportation sector, namely into stationary thermal use applications, such as building heating and cooling. A supportive regulatory framework would allow for the recovery of cost in procuring RNG, update gas rule requirements, reflect the cost-effectiveness of RNG as a decarbonization strategy relative to other measures, and capitalize on complementary measures. This type of regulatory framework would address many of the challenges discussed in this report, including:

- Capitalize on and expand current cost-effective end uses;
- Expand markets beyond current RNG end uses;
- Maximize RNG feedstock production through complementary measures;
- Provide necessary competition for various RNG feedstocks;
- Facilitate opportunities for cost reductions and technology development, including for P2G;
- Ensure the costs and benefits of RNG are appropriately shared by RNG market participants and energy consumers;
- Financially reward the significant environmental value of RNG; and
- Recognize and reflect the critical role RNG can play in decarbonizing the natural gas system, and the energy system as a whole, over the long-term.

ICF recommends a regulatory approach that stages potential RNG programs in the near-, mid-, and long-term horizons in an effort to reconcile conflicting requirements. In general, regulators (e.g., utility commissions) tend to prefer piloting new customer programs when customer interest, cost assumptions, and the utility’s execution capabilities are unconfirmed. This particularly applies to RNG programs because of the emerging aspects of the technology. Pilot programs are especially pertinent for the development of P2G projects, given the nascent stage of technology development and the uncertain costs associated with P2G.

Utility commissions and ratepayer advocates' concerns, usually driven by prudence and the need to limit or mitigate the risk for costly stranded assets, may not align with a utility's desire to launch broad market transformation efforts. In addition, transitioning from pilots to larger-scale initiatives may involve additional regulatory review, and this has the potential to create a transition period that disrupts progress toward broader RNG deployment by creating delays. Further, these transitions may have a dampening effect on the market as customers delay further RNG investments until new utility programs become available.

Pilot or Voluntary RNG Procurement Programs

As noted previously in Section 6, utilities can offer opt-in voluntary programs to customers to help reduce the environmental impact of their energy supply. This is more common for electric utilities; however, similar programs can be developed for gas utilities and RNG consumption. ICF recommends a near-term regulatory approach that supports voluntary purchase of RNG through gas utility service providers to help foster market growth, improve customer awareness, and to satisfy nascent demand.

Vermont has already approved a voluntary tariff and utilities in New York and California have filed proposals for approval of voluntary RNG tariffs. ICF recommends policymakers and regulators move rapidly to encourage gas utilities in the Greater Washington, D.C. metropolitan area to file voluntary tariffs for RNG deployment, thereby sending a clear and immediate signal to the investor community that the region seeks to be at the forefront of RNG deployment. Voluntary procurement programs will also lay a foundation for establishing RNG demand in end uses beyond the transportation sector.

Expand RNG in Transportation through Infrastructure Investments

As noted in the previous section regarding market-based approaches to deploy RNG, the transportation sector is a clear near-term opportunity for regional RNG deployment. However, the long-term opportunity for RNG in the transportation sector is limited because of low demand growth for natural gas as a transportation fuel. The GHG emission reduction benefits and ancillary air quality benefits of deploying low NOx-emitting trucks presents a unique opportunity for the region. The regulatory market for decarbonizing the transportation sector has favored liquid biofuels at the federal level (via the RFS) and transportation electrification (via the federal tax credit for electric vehicles), with less incentives for natural gas as a transportation fuel.

ICF recommends an innovative regulatory structure to enable utilities to invest and recover costs in fueling infrastructure, offer beneficial and attractive tariffs to CNG users, and partner with key stakeholders to deploy CNG in key vehicle market segments. ICF envisions a regulatory structure analogous to the make-ready approach popularized by transportation electrification assessments whereby the utility helps to defray the costs of deploying fueling infrastructure, but site hosts retain ownership and are responsible for interfacing with the consumer.

Similarly, just as electric utilities are increasingly seeking to offer attractive time-of-use pricing for electric vehicle drivers or design demand response programs that incentivize consumers to charge their electric vehicles at certain times of day, ICF foresees attractive CNG tariffs with provisions requiring a minimal throughput of RNG (e.g., as a percent of total flow). Lastly, ICF recommends that gas utility service providers be afforded the opportunity to partner strategically with third-party fuel providers. Furthermore, ICF recommends a regulatory approach that enables tracking and verification of RNG throughput at CNG stations and enables regulators to impose penalties when minimum RNG throughput targets are not met.

Implementing a Renewable Gas Standard

The RNG market is poised to evolve rapidly over the next three to five years beyond voluntary tariffs and transportation sector demand, and shift into broader stationary end uses. However, in the absence of clearer policy action, RNG deployment has the potential to stall in the same way that emerging renewable energy markets did before RPS programs became more ubiquitous.

Furthermore, the RNG industry faces a difficult transition over the next several years as the transportation sector is increasingly saturated with RNG, and project developers look for new markets and end uses to maximize the value of their project. This transition will be bumpy, and will change the underlying structure of RNG markets in ways that are not entirely understood today. However, the experience of the renewable electricity sector, discussed above, should prove analogous to the opportunities and potential of RNG markets.

In order to smooth the transition to greater RNG deployment over the mid-term future and to achieve the deployment contemplated in the scenarios that ICF developed, an effective and practical policy framework that is conducive for RNG consumption in multiple end uses beyond transportation is required. At a high level, this equates to a regulatory and legislative structure that provides sufficient flexibility to achieve cost-effective GHG emission reductions, and where RNG is viewed as a critical part of broader decarbonization efforts. In this respect, the region’s objective would be:

> *A policy structure that drives consistent demand through a utility procurement mechanism that provides supply and price certainty without disrupting the success and market participation in current programs driving existing RNG deployment.*

A well-designed RGS would meet the above objective and provide access to sustainable and considerable end-use markets outside of the transportation sector. Although there are different policy approaches available, a utility procurement mechanism would drive consistent demand for lowest-cost RNG based on market principles, and provide a robust cost recovery mechanism for utilities. A key advantage of an RGS over other measures, including voluntary programs, is that RGS coverage would not be limited to utilities and LDCs, but also include third-party suppliers such as natural gas marketers, similar to the operation of RPS programs. Over the past five years, different advocacy groups across the U.S. have discussed the concept of an RGS as a procurement policy.

The principles of an RGS are straightforward and mimic renewable portfolio standards. It is important to note that any RNG procurement program would not exist in a vacuum. There is limited, but existing, participation in the RNG market, and there are other goals that must be addressed, including promoting in-state or regional economic development, addressing environmental equity considerations, and reducing short-lived climate pollutants. Any RGS design should be complementary to other programs currently driving RNG development and flexible enough to enable market innovation that will maximize benefits and minimize costs.

As summarized previously, ICF considers three different approaches towards implementing an RGS:

- **Free market approach**. The free market approach suggests that a procurement target is established, and the market simply responds to the price signal according to a supply-cost curve (e.g., see Figure 48). ICF notes that while this approach will incentivize lowest-cost resources (likely landfill gas), a slightly more prescriptive design could enable more across-the-board RNG deployment and help achieve other priorities (e.g., in-state economic development) and deployment (e.g., more diverse feedstock supply).
- **Feed-in tariff**. A feed-in tariff, or standard offer contracts, would provide clear, reliable pricing for RNG producers. Although this approach provides a clear signal to help producers finance renewable gas projects, without distinguishing between feedstocks, a feed-in tariff has the potential to favor low-cost producers without recognizing the cost-effectiveness of GHG emission reductions.

  For instance, to incentivize higher-cost pathways, the feed-in tariff would need to be set at a level that would yield considerable windfall profits to lower-cost pathways (e.g., landfill gas). Some markets have included a degradation mechanism for feed-in tariffs to encourage technology cost reductions; however, it is unclear to what extent a simple degradation mechanism could be effective considering the cost disparities expected for different sources of RNG (see Table 33), which may also have varying levels of technology maturity and cost-reduction pathways.
- **Performance-based approach**. The RGS could take on a structure that requires a percent volume target by some date (different from an absolute volumetric target, as is prescribed in the federal RFS program). Similarly, an RGS could take on a structure like California’s LCFS program, requiring a percent reduction in the carbon intensity of natural gas by some date.
  - Carbon intensity targets and percent volume targets should, in principle, provide clear signals to regulated parties and investors regarding the timeline required to achieve program targets.
  - The downside of a carbon intensity target is that it may introduce undue complexity to the RGS. For instance, consider the boundary conditions of the lifecycle GHG assessment of dairy digester gas. Without regulations in place to capture and burn the methane that is released, the gas receives a lower carbon intensity for being credited with the avoided emissions from *venting* methane. Landfill gas, on the other hand, being regulated and required to be captured and burned, receives a lower carbon intensity for being credited with the avoided emissions from *flaring* methane. The difference in the GHG benefit of avoided methane venting versus avoided methane flaring is significant: In the case of the former, avoided vented methane emissions have a global warming potential of 25, whereas in the latter, you are avoiding carbon dioxide emissions with a global warming potential of 1. In addition, new regulations can inadvertently change the boundary conditions of the analysis.

  - Another consideration related to a carbon intensity-based approach is the potential for the intent of the program to be expanded unexpectedly to include upstream emission reductions, such as methane leaks in the natural gas pipeline. This could provide additional compliance opportunities for utilities that produce additional GHG benefits, but may detract from the intent of stimulating RNG development. Additionally, and similar to the example above, other regulations and programs that address these system improvements could complicate the benefit calculation, creating moving targets and challenging utilities' assessments of investment value for different compliance pathways.

Ultimately, ICF recommends an RGS taking on a hybrid of these approaches with the primary objective of accelerating market development of RNG through supply and price certainty. Despite the success of RNG deployment in the transportation sector, there is still unrealized investment and growth in the sector because of uncertainty linked to existing regulatory programs.

As noted previously, there is clearly a high value proposition for RNG used as a transportation fuel. This value can be leveraged by an RGS to maximize benefits and minimize ratepayer costs, while helping to serve as a diversification strategy for the RNG market. An RGS can provide investors, developers, and utilities with the policy certainty they seek to cost-effectively contribute to decarbonization efforts. The RGS also has the potential to help maintain and build upon the success of the programs that have enabled rapid growth in the RNG market over the last five years.

8. Conclusions

There has been rapid growth in the deployment of RNG projects across the United States over the last five years, with annual growth rates of RNG available for pipeline injection exceeding 25% per year. This rapid growth in the deployment of RNG projects focused on pipeline injection is bolstered by a diverse set of available feedstocks and technologies that can be used to produce RNG.

ICF estimates that there are and will be sufficient RNG feedstock resources at a local, regional, and national level available for both near-term and long-term deployment of RNG to help decarbonize the natural gas system and contribute to the aggressive climate commitments in the Greater Washington D.C. metropolitan area. More specifically, ICF anticipates that there is enough RNG production potential to displace upwards of 25% of total natural gas consumption in direct use applications today. This does not include any potential reductions attributable to conservation or efficiency measures, nor does it account for RNG volumes available if fewer conservative assumptions are applied.

RNG represents a valuable and underutilized renewable energy source with a low or net negative carbon intensity, depending on the feedstock. The GHG emission accounting method and scope employed can have a significant impact on how carbon intensities for RNG are reported and estimated. For some feedstocks, applying the lifecycle emission accounting framework captures the full benefit of RNG's emission reduction potential, such as reflecting avoided methane emissions. RNG can make a significant contribution to the long-term GHG emission reduction objectives in the Greater Washington, D.C. Metropolitan area. When applying a combustion accounting framework, ICF estimates that in the South Atlantic region, 13 to 44 MMT of GHG emissions could be reduced per year by 2040 through the deployment of RNG based on the Conservative Low to Aggressive High scenarios.

In relation to cost, ICF reports that RNG will be available from various feedstocks in the range of \$7/MMBtu to \$44/MMBtu. ICF anticipates that over time there will be increasing opportunities for cost reductions as RNG production technologies mature, access to feedstocks improves, and the market expands. Anaerobic digestion feedstocks, notably from LFG and WRRF, are and will remain more cost-effective in the near-term. RNG from thermal gasification feedstocks are more expensive, largely reflecting the emerging potential of thermal gasification as a technology, and the associated uncertainties around cost and feedstock availability.

Although RNG is more expensive than its fossil counterpart, in a decarbonization framework the proper comparison for RNG is to other GHG abatement measures that are viewed as long-term strategies to reduce GHG emissions. For abatement cost estimates, RNG at or near \$7/MMBtu is equivalent to about \$55–\$60/tCO_2e, while RNG at \$20/MMBtu has an estimated cost-effectiveness of about \$300/tCO_2e.

In many instances, policymakers, corporations and RNG stakeholders may not be recognizing the complete benefits of RNG due to a limited assessment and reporting scope. In addition, the cost-effectiveness of RNG as an emission reduction measure is generally underestimated and underappreciated, particularly in comparison to other more costly mitigation approaches over the long-term.

The policy framework in place today does not encourage RNG use in stationary thermal use applications, such as for building heating and cooling. However, there is growing interest from some policymakers, gas utilities, and industry stakeholders to grow the production of RNG for pipeline injection and stationary end use consumption. With appropriate incentives that fully capture the environmental benefits of RNG, the end-use demand for RNG from stationary thermal applications is substantial, in contrast to the limited demand in the transportation sector.

There are multiple opportunities and challenges for the wide scale deployment of RNG. A supportive regulatory framework for broad end-use consumption and cost recovery mechanisms for interconnection challenges can help mitigate near-term challenges, while helping the market realize existing opportunities. These near-term actions will help realize the long-term opportunity of increased and varied deployment of RNG via reduced technology and project costs.

Industry stakeholders should expect to play a proactive and positive role in supporting the Greater Washington, D.C. metropolitan area’s various GHG emission reduction goals. In parallel, regulators and policymakers must develop innovative approaches that enable the market for RNG to flourish and take full advantage of the full suite of cost-effective decarbonization strategies.

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