Potential of Renewable Natural Gas in New York State

Final Report | Report Number 21-34 | April 2022

NEW YORK STATE | NYSERDA

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Advance clean energy innovation and investments to combat climate change, improving the health, resiliency, and prosperity of New Yorkers and delivering benefits equitably to all.

Potential of Renewable Natural Gas in New York State

Final Report

Prepared for:

New York State Energy Research and Development Authority

Albany, NY

Macy Testani
Project Manager

Prepared by:

ICF Resources, L.L.C.

Fairfax, VA

Maurice Oldham
Senior Consultant—Energy and Transportation

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Abstract

Renewable Natural Gas (RNG) is generally 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 trillion Btu per year (tBtu/yr.) of RNG from landfills, dairy digesters, and water resource recovery facilities (WRRFs) around the United States are injected into pipelines, with production growing from year to year.

New York State has significant potential RNG feedstock resources from food waste, manure, agricultural residues, landfills, WRRF’s as well as woody biomass and municipal solid waste. Based on three production scenarios, ICF estimates a total RNG potential for New York State of between 47 tBtu/yr. and 147 tBtu/yr. with estimated weighted average costs between \$11.29/MMBtu and \$34.56/MMBtu.

Keywords

Renewable natural gas, biomass, food waste, manure, landfills, anaerobic digestion, thermal gasification, biogenic, non-biogenic, municipal solid waste, water resource recovery facilities

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Important Note

Note that, for purposes of this study, the municipal solid waste (MSW) resources used to estimate renewable natural gas (RNG) potential by thermal gasification of MSW include both the biogenic and non-biogenic fractions of the MSW stream. The resulting quantities of MSW used in the analysis are assumed to be a mix of materials, including, but not limited to construction and demolition debris, paper and paperboard, plastics, rubber, leather, textiles, and wood and yard trimmings.

Biogenic refers to material or substances produced by or made from life forms, namely plants or animals, whereas non-biogenic refers to material or substances not derived from life forms. In the context of a greenhouse gas emission analyses, biogenic carbon emissions are emissions related to the natural carbon cycle, as well as those resulting from the combustion, harvest, digestion, fermentation, decomposition or processing of biologically based materials. Thermal gasification of the non-biogenic fraction of MSW is projected to yield lower CO_2e emissions than geological natural gas. As a result, both the biogenic and non-biogenic portions of MSW are included in accessing the potential RNG resources in this study. However, as the non-biogenic portion of MSW is derived from fossil resources, the reader may consider if such sources are appropriate in estimating RNG potential.

Executive Summary

ICF Resources, L.L.C. (ICF) was engaged by the New York State Energy Research and Development Authority (NYSERDA) to assess the potential of renewable natural gas (RNG) in New York State. The project is framed by high-level objectives:

- Determine the economic in-state energy potential of RNG and biogas from anaerobic digestion of the organic waste sector, and from thermal gasification of feedstocks.
- Determine the estimated costs in dollar per thermal units ($/MMBtu) of producing RNG from different feedstock sources in NYS through 2040.

ES.1 Methodology

ICF developed three resource potential scenarios by considering RNG production from eight feedstocks and two production technologies. The feedstocks include animal manure, food waste, landfill gas, water resource recovery facilities (WRRFs), agricultural residues, energy crops, forestry, and forest product residues, and municipal solid waste (MSW), including the non-biogenic fraction of MSW. These feedstocks were assumed to be processed using one of two technologies to produce RNG: anaerobic digesters and thermal gasification systems.

ES.2 Renewable Natural Gas Potential and Costs

ICF developed three RNG production scenarios: Limited Adoption, Achievable Deployment, and Optimistic Growth, 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 47 tBtu/yr. and 147 tBtu/yr. of RNG production in New York State by 2040, shown in the table below. By way of comparison, NYS's natural gas consumption in the combined residential, commercial, industrial, transportation, and electrical generation sectors was 1,280 tBtu in 2017.[1]

Table ES-1. Summary of Estimated Annual Renewable Natural Gas Production Potential in 2040 by Scenario (tBtu/yr.)

RNG Feedstock		Scenario			
		Limited Adoption	Achievable Deployment	Optimistic Growth	Maximum Potential
Anaerobic Digestion	Animal Manure	6.1	9.1	12.1	20.2
	Food Waste	2.4	3.4	4.3	6.1
	LFG	13.9	19.3	24.8	50.5
	WRRFs	1.8	2.4	3.2	7.1
	Subtotal	**24.2**	**34.2**	**44.4**	**83.9**
Thermal Gasification	Agricultural Residue	0.3	7.3	12.0	24.4
	Energy Crops	6.7	18.6	34.0	69.1
	Forestry and Forest Product Residue	1.3	4.8	25.0	42.2
	Municipal Solid Waste	14.9	24.9	31.1	52.7
	Subtotal	**23.2**	**55.5**	**102.2**	**188.4**
Total		**47.4**	**89.8**	**146.6**	**272.3**
Percentage of Total Feedstock		**17.6%**	**33.3%**	**54.4%**	**100%**

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

Table ES.2. Summary of Estimated Cost Ranges and Weighted Average by Feedstock Type

	Feedstock	Cost Range ($/MMBtu)	Weighted Average Cost ($/MMBtu)
Anaerobic Digestion	Animal Manure	$27.11–$50.02	$34.56
	Food Waste	$19.24–$30.24	$23.86
	Landfill Gas	$7.67–$21.53	$11.29
	Water Resource Recovery Facilities	$13.36–$68.69	$27.68
Thermal Gasification	Agricultural Residues	$19.87–$39.78	$25.67
	Forestry and Forest Residues	$19.87–$39.78	$25.67
	Energy Crops	$19.87–$39.78	$25.67
	Municipal Solid Waste	$19.87–$39.78	$25.67

1 Renewable Natural Gas Production and Feedstocks

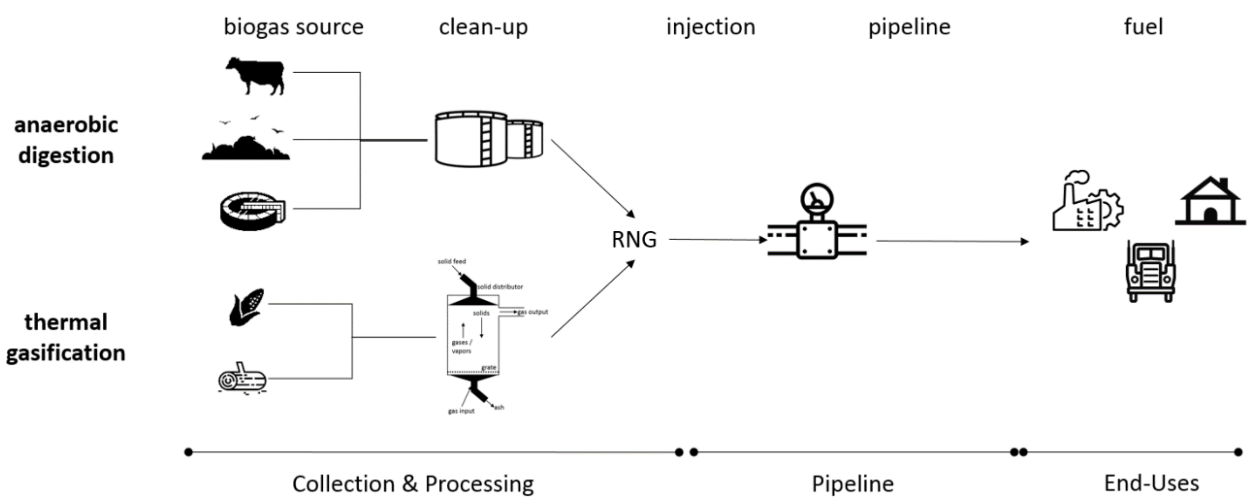
1.1 Renewable Natural Gas Production

RNG is generally derived from organic materials and is a pipeline-quality gas that is fully interchangeable with conventional natural gas. As a point of reference, the American Gas Association (AGA) uses the following definition for RNG:[2]

> Pipeline-compatible gaseous fuel derived from biogenic or other renewable sources that has lower life-cycle carbon dioxide equivalent (CO2e) emissions than geological natural gas.[3]

RNG production sources requires a series of steps (see Figure 1): collection of a feedstock, delivery to a processing facility for feedstock-to-gas conversion, gas conditioning, compression, and injection into the pipeline. In this project ICF considers two production technologies: anaerobic digestion and thermal gasification.

Figure 1. Renewable Natural Gas Production Process via Anaerobic Digestion and Thermal Gasification



1.1.1 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 wastewater and food waste facility.[4]

The four key processes in anaerobic digestion are hydrolysis, acidogenesis, acetogenesis, and methanogenesis.

Hydrolysis is the process whereby longer-chain organic polymers are broken down into shorter-chain molecules like sugars, amino acids, and fatty acids that are available to other bacteria. Acidogenesis is the biological fermentation of the remaining components by bacteria, yielding volatile fatty acids, ammonia, carbon dioxide, hydrogen sulfide, and other byproducts.

Acetogenesis of the remaining simple molecules yields acetic acid, carbon dioxide, and hydrogen. In the last step, during which the majority of the biogas is emitted from anaerobic digestion systems, methanogens use the intermediate products from hydrolysis, acidogenesis, and acetogenesis to produce methane, carbon dioxide, and water. 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 large fractions of methane and carbon dioxide. The biogas requires capture and then subsequent conditioning and upgrading before pipeline injection. The conditioning and upgrading helps increase the heating value of the gas for injection by removing carbon dioxide and also removes any contaminants and other trace constituents, including siloxanes, sulfides, and nitrogen that cannot be injected into common carrier pipelines.

1.1.2 Thermal Gasification

Biomass, such as agricultural residues, forestry and forest product residues energy crops, and biogenic and non-biogenic MSW, 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.

Challenges with the biomass gasification process and syngas purification have limited commercialization of gasification technology. 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[5] concluded that after "two decades" of experience in biomass gasification, "'tars' can be considered the Achilles heel of biomass gasification." Over the last several years, however, 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 some types of organic materials such as food waste, agricultural residues, or energy crops, are sometimes 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 for thermal gasification could instead be used in anaerobic digesters. For simplicity, ICF did not consider any multi-feedstock applications in the resource 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.

1.2 Renewable Natural Gas Feedstocks

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

Table 1. Renewable Natural Gas Feedstocks Types

Feedstock for RNG		Description
Anaerobic Digestion	Animal manure	Manure produced by livestock, including dairy cows, beef cattle, swine, sheep, goats, poultry, and horses.
	Food waste	Commercial 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.
	Landfill gas (LFG)	The anaerobic digestion of organic waste in landfills produces a mix of gases, including methane (40–60%).
	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.
Thermal Gasification	Agricultural residue	The material left in the field, orchard, vineyard, or other agricultural setting after a crop has been harvested. Inclusive of unusable portion of crop, stalks, stems, leaves, branches, and seed pods.
	Energy crops	Inclusive of perennial grasses, trees, and annual crops that can be grown to supply large volumes of uniform and consistent feedstocks for energy production.
	Forestry and forest product residue	Biomass generated from logging, forest and fire management activities, and milling. Inclusive of logging residues, forest thinnings, and mill residues. Also materials from public forestlands, but not specially designated forests (e.g., roadless areas, national parks, wilderness areas).
	Municipal solid waste (MSW)	Refers to the biogenic and non-biogenic fractions of waste that is generally landfilled after diversion of recyclable waste products (including food waste or other organics). MSW may include construction and demolition debris, plastics, etc.

ICF notes that biogas feedstocks are currently produced and utilized in different industrial applications, such as the paper and pulp milling industry. While at a high level there are no technical barriers for industrial processes and wastes to produce RNG, we do not consider these feedstock sources as part of the resource assessment for a number of reasons, including data availability, current productive use, such as in combined heat and power facilities, and the assumed limited potential as a source for pipeline injected RNG (as opposed to on-site consumption).

2 Renewable Natural Gas Resource Assessment

2.1 Assessment Methodology

The RNG resource assessment methodology is based on the objective to develop an inventory and economic supply curves of available organic waste feedstocks in NYS, including for animal manure, organic material in landfills, food waste (including from residential, commercial, and industrial applications), , and organic materials from WRRFs. In addition, thermal gasification of other biomass feedstocks, including agricultural residue, energy crops, forestry and forest product residue as well as gasification of the biogenic and non-biogenic fractions of MSW are examined.

ICF used a mix of existing studies, government data, and industry resources to estimate the current and future supply of the feedstocks. Table 2summarizes some of the resources that ICF used to complete this assessment, broken down by RNG feedstock:

Table 2. List of Data Sources for Renewable Natural Gas Feedstock Inventory

Feedstock for RNG	Potential Resources for Assessment
Animal manure	• U.S. Environmental Protection Agency (EPA) AgStar Project Database • U.S. Department of Agriculture (USDA) Census of Agriculture • NYS Department of Environmental Conservation (DEC)
Food waste	• U.S. Department of Energy (DOE) 2016 Billion Ton Report • Bioenergy Knowledge Discovery Framework (KDF) • NYS Pollution Prevention Institute
LFG	• U.S. EPA Landfill Methane Outreach Program • Environmental Research & Education Foundation (EREF)
WRRFs	• U.S. EPA Clean Watersheds Needs Survey (CWNS) • Water Environment Federation
Agricultural residue	• DOE 2016 Billion Ton Report • Bioenergy Knowledge Discovery Framework
Energy crops	• DOE 2016 Billion Ton Report • Bioenergy Knowledge Discovery Framework
Forestry and forest product residue	• DOE 2016 Billion Ton Report • Bioenergy Knowledge Discovery Framework
MSW	• DOE 2016 Billion Ton Report • Waste Business Journal

The RNG potentials included in the supply curves are 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).

For the RNG market more broadly, ICF assumed that the market would grow at a compound annual growth rate slightly higher than what has been observed in the U.S. from 2016 to 2020—a rate of about 30%.[6] 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.

2.1.1 Geography

Consistent across all feedstocks, we present the RNG resource assessment limited to in-state sources only. Where the location of individual facilities cannot be determined, ICF applied a breakdown of RNG feedstocks by ten recognized regions, as defined by the NYS Empire State Development agency's economic development regions. The regions and counties are outlined in Figure 2 and Table 3 below.

Figure 2. New York State Regions[7]

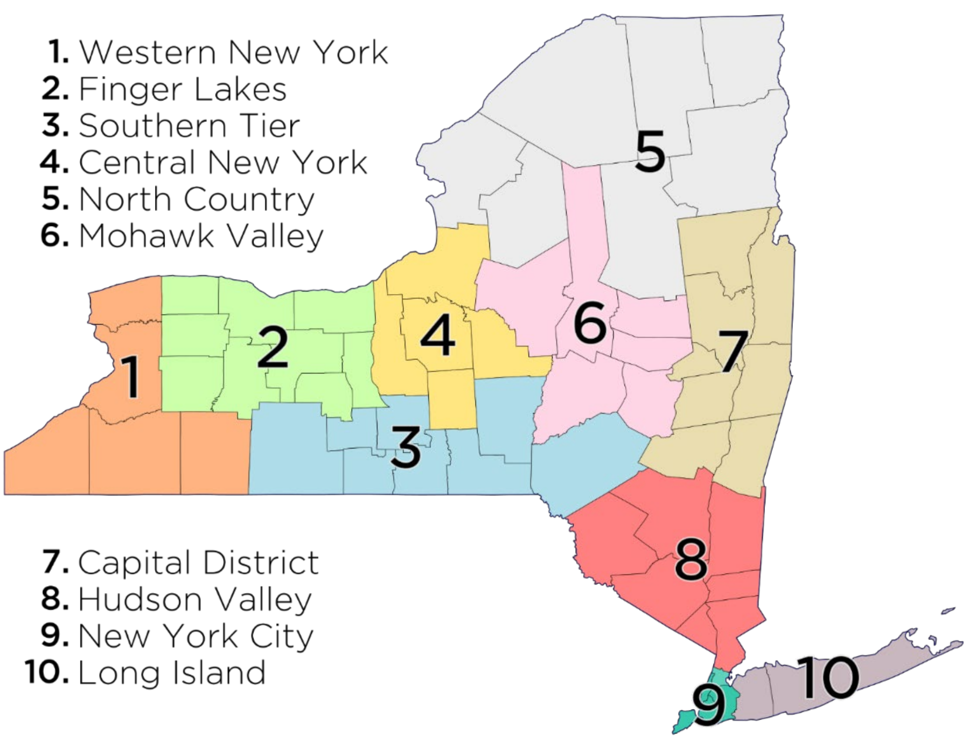


Table 3. New York State Counties by Region

Region	Counties
1 – WNY	Allegany, Cattaraugus, Chautauqua, Erie, Niagara
2 – FLX	Genesee, Livingston, Monroe, Ontario, Orleans, Seneca, Wayne, Wyoming, Yates
3 – SOT	Broome, Chemung, Chenango, Delaware, Schuyler, Steuben, Tioga, Tompkins
4 – CNY	Cayuga, Cortland, Madison, Onondaga, Oswego
5 – NOC	Clinton, Essex, Franklin, Hamilton, Jefferson, Lewis, St. Lawrence
6 – MHV	Fulton, Herkimer, Montgomery, Oneida, Otsego, Schoharie
7 – CAP	Albany, Columbia, Greene, Rensselaer, Saratoga, Schenectady, Warren, Washington
8 – HUD	Dutchess, Orange, Putnam, Rockland, Sullivan, Ulster, Westchester
9 – NYC	Bronx, Kings, New York, Queens, Richmond
10 – LNG	Nassau, Suffolk

2.1.2 Scenarios

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

- The **Limited Adoption Scenario** represents a low level of feedstock utilization, with utilization levels depending on feedstock, within a range of 15% to 40% for feedstocks that were converted to RNG using anaerobic digestion technologies. The utilization rates of feedstocks for thermal gasification in the Limited Adoption scenario ranges from 20% to 40%, at lower biomass prices. Overall, the Limited Adoption scenario captures 18% of the total RNG feedstock resource, based on the total RNG resource inventory developed for this analysis.
- The **Achievable Deployment Scenario** represents balanced assumptions regarding feedstock utilization, with a range from 25% to 55% for feedstocks converted to RNG using anaerobic digestion technologies. The utilization rates of feedstocks for thermal gasification in the Achievable Deployment scenario ranges from 40% to 50% at low- to medium-biomass prices. Overall, the Achievable Deployment scenario captures 33% of total RNG feedstock, based on the total RNG resource inventory.
- The **Optimistic Growth Scenario** represents higher levels of utilization and delivers 54% of the technical potential of RNG feedstock in NYS as outlined in the inventory. Utilization levels vary by feedstock, with a range from 30% to 75% for feedstocks that were converted to RNG using anaerobic digestion technologies. The utilization rates of feedstocks for thermal gasification in the Optimistic Growth scenario ranged from 50% to 60% at higher biomass prices. It is worth reiterating that this scenario does not represent a maximum achievable or technical potential scenario.
- For reference, the **Maximum Potential** is also included in Table 4 below and represents the total technical potential of RNG feedstocks in NYS. The only limitation is for animal manure, where ICF applied technical availability factors to each manure type to reflect that not all animal manure can be collected, due to practical considerations such as small farming operations and the inability to collect manure from grazing animals.

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 as the final year in the analysis. ICF presents the Limited Adoption, Achievable Deployment and Optimistic Growth 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.

2.2 Summary of Statewide Renewable Natural Gas Potential

The following subsection summarizes the statewide RNG potential for each feedstock and production technology by scenario. Table 4 compares the three scenarios and the maximum potential across feedstocks and production technologies in 2040, while Figure 3, Figure 4, and Figure 5 show each scenario over five-year intervals, broken out by feedstock.

Table 4. Estimated Annual Renewable Natural Gas Production in 2040 by Scenario (tBtu/yr.)

RNG Feedstock		Scenario			
		Limited Adoption	Achievable Deployment	Optimistic Growth	Maximum Potential
Anaerobic Digestion	Animal Manure	6.1	9.1	12.1	20.2
	Food Waste	2.4	3.4	4.3	6.1
	LFG	13.9	19.3	24.8	50.5
	WRRFs	1.8	2.4	3.2	7.1
	Subtotal	**24.2**	**34.2**	**44.4**	**83.9**
Thermal Gasification	Agricultural Residue	0.3	7.3	12.0	24.4
	Energy Crops	6.7	18.6	34.0	69.1
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	Subtotal	**23.2**	**55.5**	**102.2**	**188.4**
Total		**47.4**	**89.8**	**146.6**	**272.3**
Percentage of Total Feedstock		**17.6%**	**33.3%**	**54.4%**	**100%**

By way of comparison, NYS's natural gas consumption in the residential, commercial, industrial, transportation, and electrical generation sectors was 1,280 tBtu in 2017.[8]

Figure 3. Estimated Annual Renewable Natural Gas Production, Limited Adoption Scenario (tBtu/yr.)

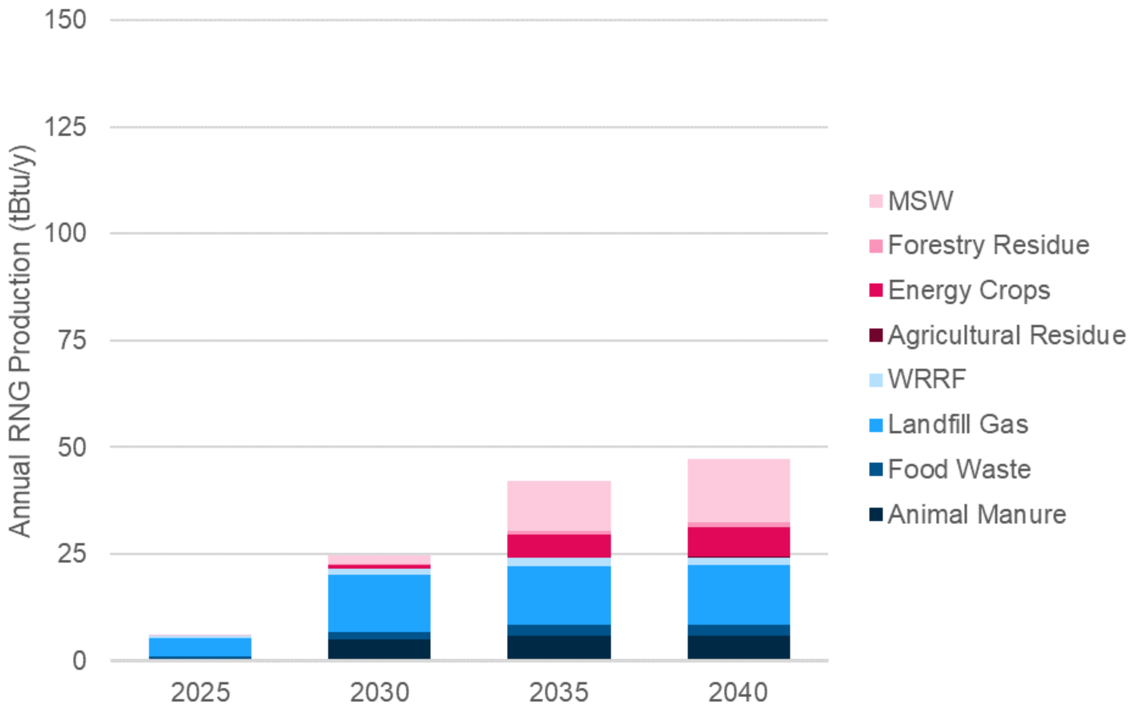


Figure 4. Estimated Annual Renewable Natural Gas Production, Achievable Deployment Scenario (tBtu/yr.)

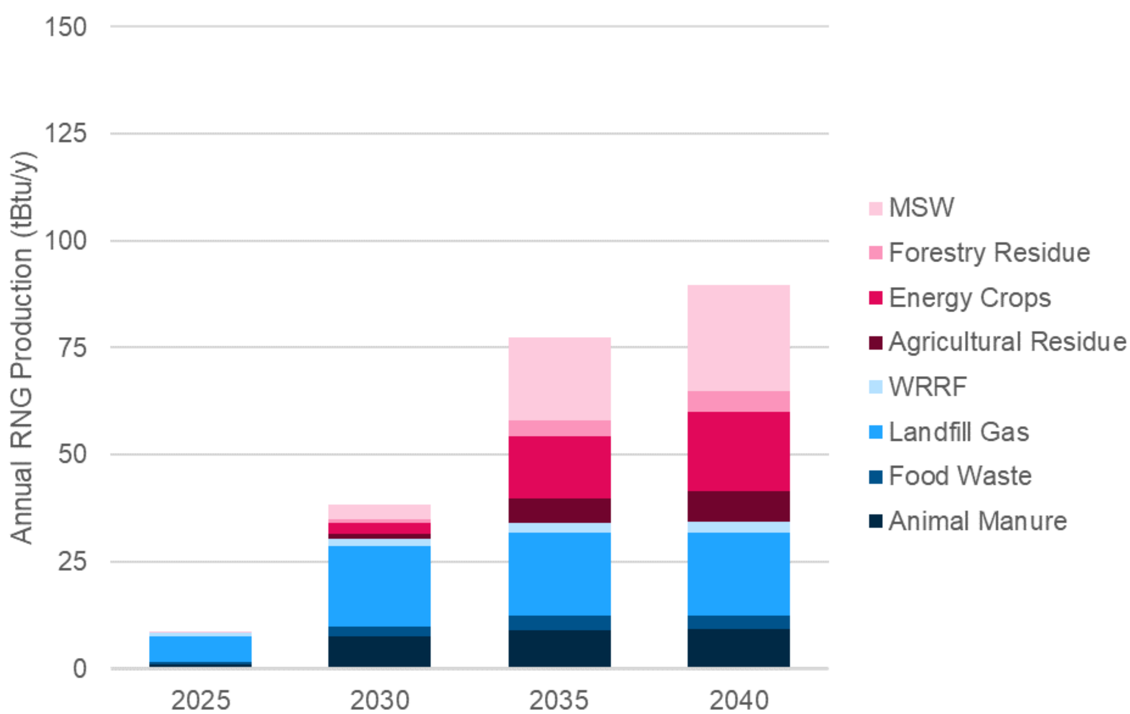
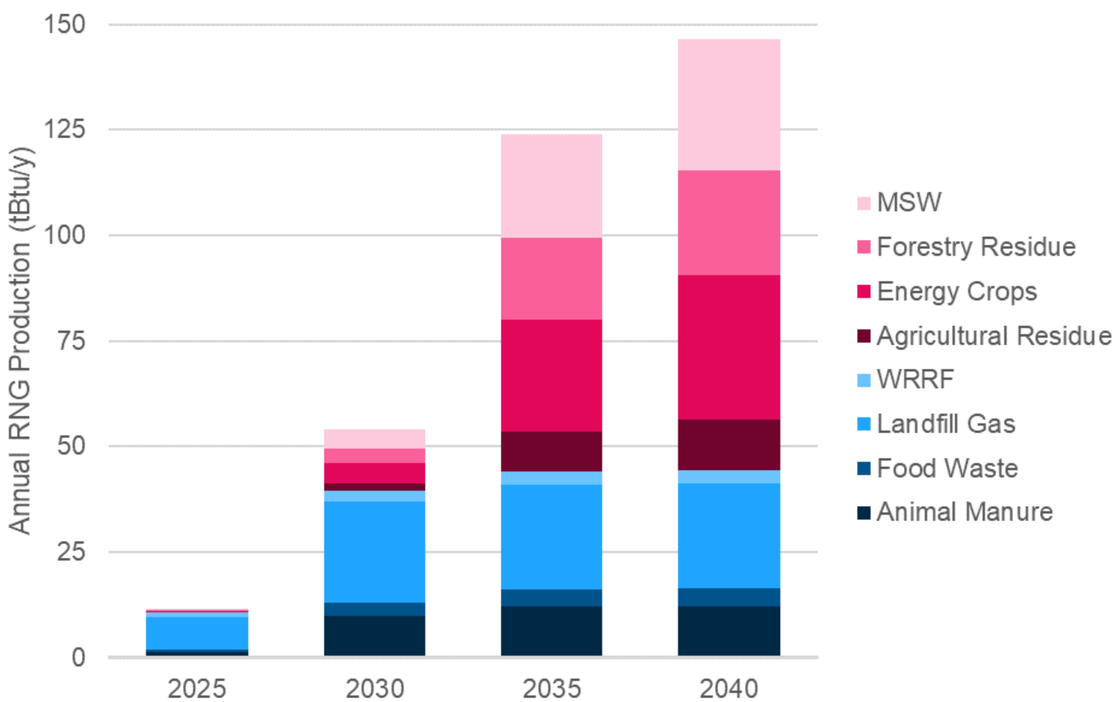


Figure 5. Estimated Annual Renewable Natural Gas Production, Optimistic Growth Scenario (tBtu/yr.)



2.3 Summary of Renewable Natural Gas Potential by Region

Figure 6 below shows the maximum annual RNG production for each scenario, broken out by region and RNG production technology. Figure 7 that follows shows the Achievable Deployment Scenario by region, broken out by feedstock. Detailed tables summarizing RNG potential by scenario, feedstock, and region are included in the appendix.

Figure 6. Estimated Maximum Annual Renewable Natural Gas Production by Region (tBtu/yr.)

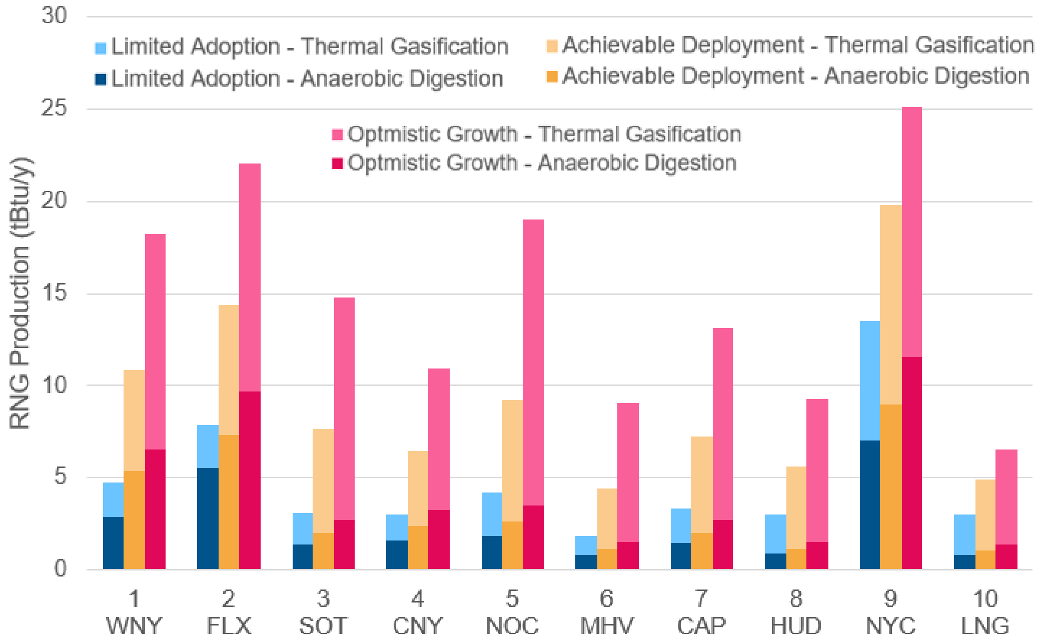
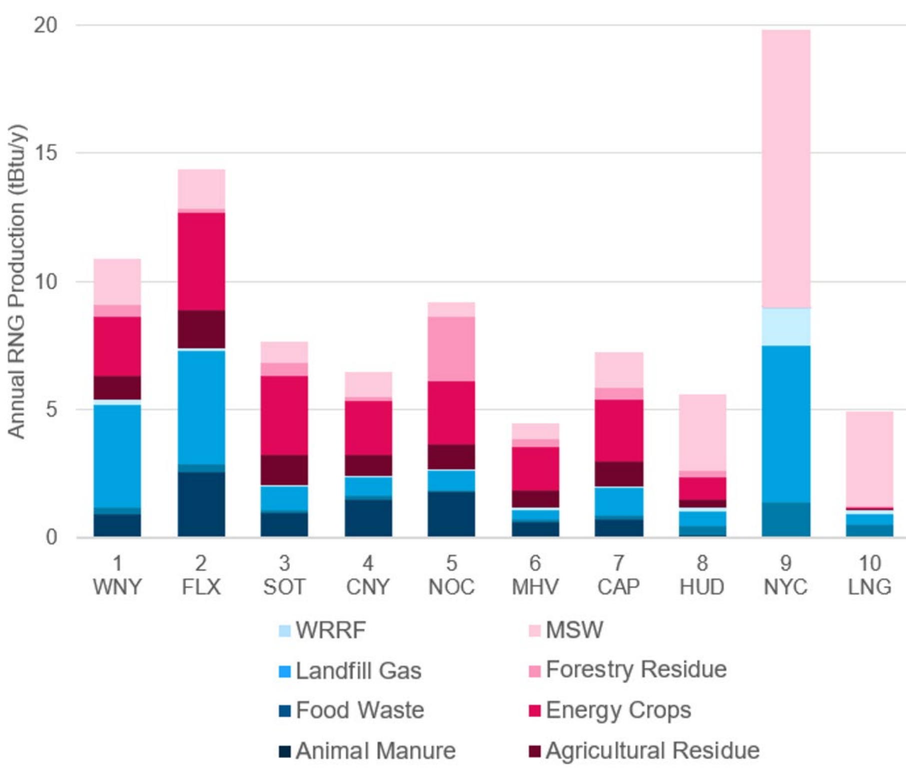


Figure 7. Annual Renewable Natural Gas Production by Region and Feedstock, Achievable Deployment Scenario (tBtu/yr.)



2.4 Renewable Natural Gas: Anaerobic Digestion of Biogenic Resources

2.4.1 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 United States Environmental Protection Agency (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 the following:[9]

- Diversifying farm revenue: The biogas produced from the digesters has the highest potential value. But digesters can also provide revenue streams via “tipping fees” from non-farm organic waste streams that are diverted to the digesters, organic nutrients from the digestion of animal manure, and displacement of animal bedding or peat moss by using digested solids.
- Conservation of agricultural land: Digesters can help to improve soil health by converting the nutrients in manure to a more accessible form for plants to use and help protect the local water resources by reducing nutrient run-off and destroying pathogens.
- Promoting energy independence: The RNG produced can reduce on-farm energy needs or provide energy via pipeline injection for use in other applications, thereby displacing fossil or geological natural gas.
- 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 manure storage pond), and gas handling equipment. There are a variety of livestock manure processing systems that are employed at farms today, including plug-flow or mixed plug-flow digesters, complete-mixed digesters, covered lagoons, fixed-film digesters, sequencing-batch reactors, and induced-blanketed digesters.

ICF considered animal manure from a variety of animal populations, including beef and dairy cows, broiler chickens, layer chickens, turkeys, and swine. Animal population and volatile solid estimates were provided by NYSERDA based on the 2018 State Inventory Tool (SIT) for 2016.[10] NYSERDA also provided ICF with a detailed list of concentrated animal feeding operations (CAFOs) with 487 in operation in NYS as of January 2020.

ICF developed the maximum RNG potential for NYS using animal manure production and animal population estimates provided by NYSERDA, and the energy content of dried manure taken from a California Energy Commission report prepared by the California Biomass Collaborative.[11] These inputs are summarized in Table 5.

Table 5. Key Parameters for Animal Manure Resource Renewable Natural Gas Potential

Animal Type	Volatile Solids (kg/head/year)	Higher Heating Value (HHV) (Btu/kg, dry basis)
Dairy:		
• Cows	2,804	16,111
• Replacement Heifers	1,251	16,111
Beef:		
• Cattle	1,308	16,345
• Calves	346	16,345
Swine	118	15,077
Poultry:		
• Layer Chickens	7	14,689
• Broiler Chickens	6	15,077
• Turkeys	22	14,830
Other:		
• Horses	1,002	9,362
• Sheep & Goats	210	9,362

A weighted average was applied to volatile solid production for more detailed livestock categories in the SIT relative to the higher-level head counts included in the CAFO database. For example, under beef cattle in the SIT there are eight different livestock type sub-categories for beef, with volatile solid production varying from 350 kg/head/yr. for calves, to 1,730 kg/head/yr. for bulls.

ICF used the animal head count and facility location information included in the CAFO database as a representation of the locational distribution of animal manure feedstock potential. While the potential for animal manure as an RNG feedstock does not directly relate to CAFOs, the existing accumulation of animal manure at CAFOs could conceivably indicate where animal manure could be used to produce RNG.

CAFOs accounted for approximately 40% of NYS's total livestock headcount, including dairy, beef cattle, poultry, swine, and other livestock. The remaining livestock, and resulting animal manure production and RNG potential, was distributed proportionally between the 10 regions based on the share of (1) livestock count for dairy and cattle manure, (2) poultry farm numbers for poultry manure, and (3) farmland for the remaining animal types (such as sheep and horses). Data on livestock numbers, poultry farms and farmland acreage by county was taken from the United States Department of Agriculture (USDA) 2017 Census of Agriculture.[12]

The EPA AgStar database indicates that there are 30 operational anaerobic digesters and biogas collections systems at farms in NYS including 5 covered manure storage systems which combust the collected biogas in a flare. Of these, 29 are also identified as CAFO facilities. The Cayuga Regional Digestor in Cayuga County is the only digester that is not also a CAFO, although the digester does receive dairy animal manure as well as food wastes. There is a lag between market developments and the AgStar database: In the past two years approximately 10 of the 25 digesters that were reported as producing electricity or using the biogas for cogeneration have since converted or are anticipated to convert to RNG production facilities.[13]

The livestock industry and animal manure production in NYS is concentrated in regions 1 through 7, with Hudson Valley, New York City and Long Island accounting for 1% of estimated animal manure production, 2% of NYS's CAFOs, and no anaerobic digesters (see Table 6). The western and central parts of the State (regions 1–4) dominate animal manure production and RNG potential, accounting for nearly two-thirds of in-state RNG production potential and number of CAFO facilities.

Table 6. Animal Manure Characteristics by Region

Region	CAFOs	Anaerobic Digesters	Animal Manure Production[14]
1 – WNY	58	2	9.9%
2 – FLX	139	12	28.3%
3 – SOT	48	1	10.4%
4 – CNY	72	8	16.3%
5 – NOC	84	3	19.6%
6 – MHV	35	1	6.7%
7 – CAP	41	2	7.6%
8 – HUD	9	0	1.0%
9 – NYC	1	0	0.0%
10 – LNG	0	0	0.0%
NYS	**487**	**30**	**100.0%**

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

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

- In the Limited Adoption Scenario, ICF assumed that, after accounting for the technical availability factor, 30% of the available manure remained and could be used to produce RNG.
- In the Achievable Deployment Scenario, ICF assumed that, after accounting for the technical availability factor, 45% of the available manure remained and could be used to produce RNG.
- In the Optimistic Growth Scenario, ICF assumed that, after accounting for the technical availability factor, 60% of the available manure remained and could be used to produce RNG.

Figure 8 shows the Limited Adoption, Achievable Deployment, and Optimistic Growth scenarios resource potential from animal manure between 2025 and 2040. Figure 9 includes the total annual RNG production potential (in units of tBtu/yr.) for 2040 in the scenarios by region.

Figure 8. Renewable Natural Gas Production Potential from Animal Manure (tBtu/yr.)

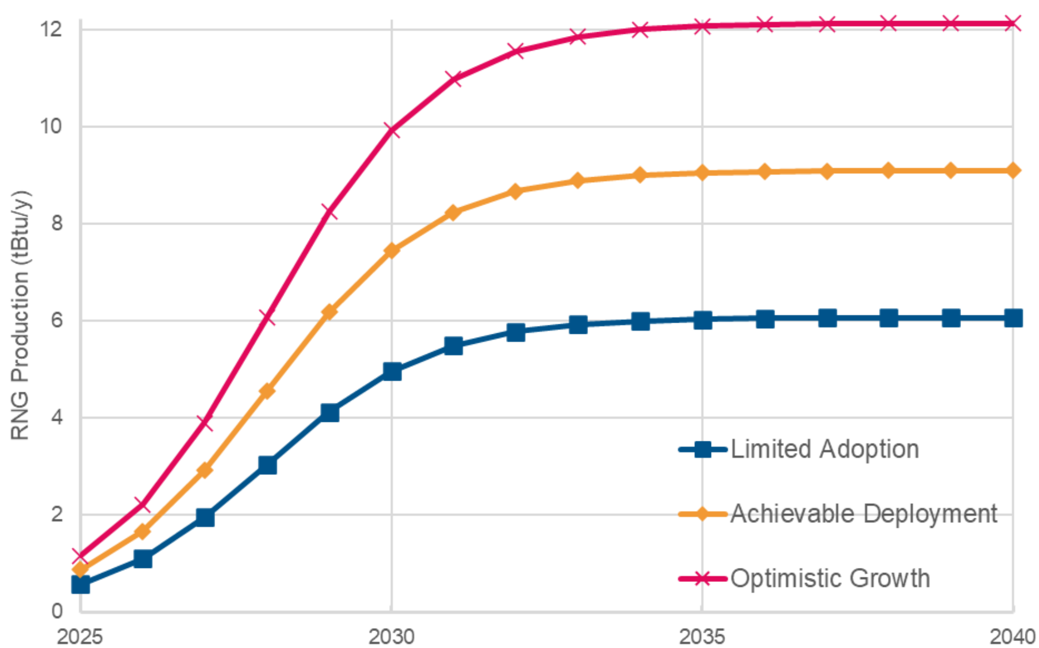
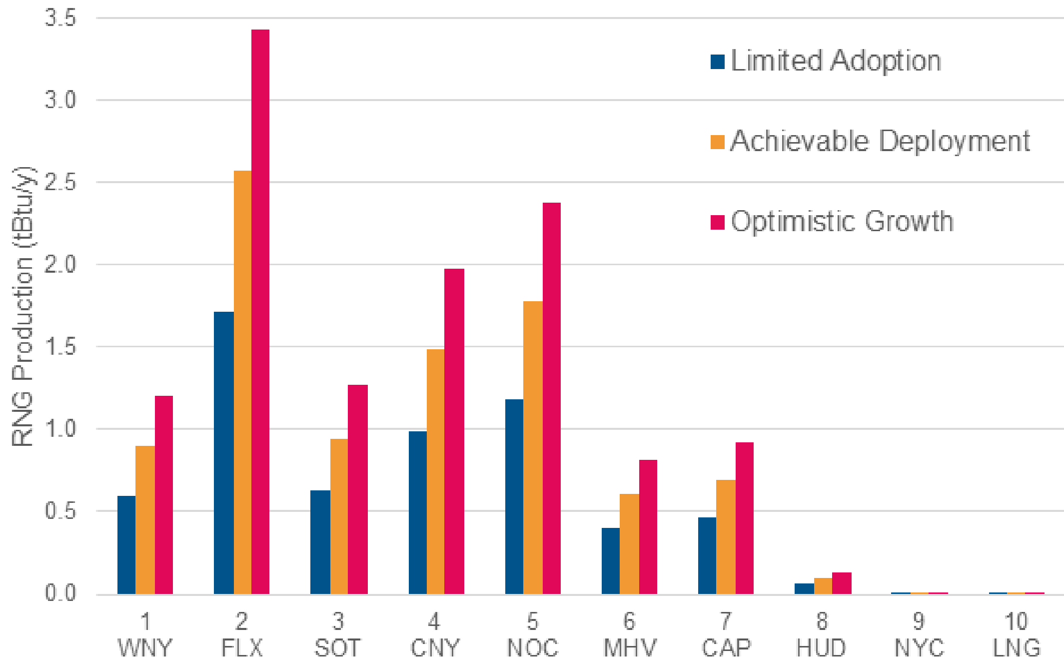


Figure 9. Annual Renewable Natural Gas Production Potential from Animal Manure in 2040 by Region (tBtu/yr.)



2.4.2 Food Waste

Food waste includes organic waste sources from commercial, industrial, and institutional facilities, such as food processors and manufacturers, grocery stores, cafeterias, and restaurants. Food waste from residential sources is generally not reflected in this analysis, except for data available for NYC but could be an additional resource for food waste feedstock with the implementation of effective waste diversion policies.

Food waste is a major component of municipal solid waste (MSW)—accounting for about 15% of MSW streams. More than 75% of food waste is landfilled. Food waste can be diverted from landfills to a composting or processing facility where it can be treated in an anaerobic digester. ICF limited our consideration to the potential for utilizing the food waste that is currently landfilled as a feedstock for RNG production via AD, thereby excluding the 25% of food waste that is already recycled or directed to waste-to-energy facilities. Furthermore, ICF has avoided any potential double counting of diverted food waste from landfills (as both a resource for producing additional RNG from landfill gas as well as potential feedstock for RNG production from AD) by only considering current waste-in-place at landfills in assessing the RNG potential from landfill gas.

ICF extracted information from the DOE's Bioenergy Knowledge Discovery Framework (DOE-BKDF), which includes information collected as part of DOE's Billion Ton Report (updated in 2016). The DOE-BKDF includes food waste at tipping fee price points ranging from $70/ton to $100/ton. NYS's food waste biomass potential is consistent across these price points. The food waste estimate includes food scraps and food processing wastes from industrial, institutional, and commercial sources. ICF assumed a high-heating value of 12.04 million British thermal units (MMBtu/ton) (dry). Note that the values from the DOE-BKDF are reported in dry tons, so the moisture content of the food waste has already been accounted for in the DOE's resource assessment.

ICF also extracted information from the NYS Pollution Prevention Institute's (PPI) database on food waste from commercial and industrial food processors.[15] Over 3,400 facilities are included in the PPI database, but the majority of the waste is generated at a relatively small number of facilities: 202 facilities that generate more than 10 tons of waste per week account for 68% of the total. The food waste volumes are reported in wet tons, with ICF applying a moisture content factor of 70%, consistent with the approach used in the DOE-BKDF, to arrive at dry ton estimates. ICF also determined that the PPI database reflects a subset of the DOE-BKDF food waste estimate, reflecting approximately 40% of the DOE-BKDF total.

ICF also included data from the New York City Department of Sanitation on residential food waste estimates.[16]

Food processor waste is provided at a facility level, with the remaining portion of the DOE- BKDF food waste estimate distributed proportionally to each of the 10 regions based on regional share of population, taken from the U.S. Census Bureau. The table below summarizes food waste production potential by region and reflects estimates from DOE-BKDF PPI, and the NYC Department of Sanitation (for Region 9, NYC).

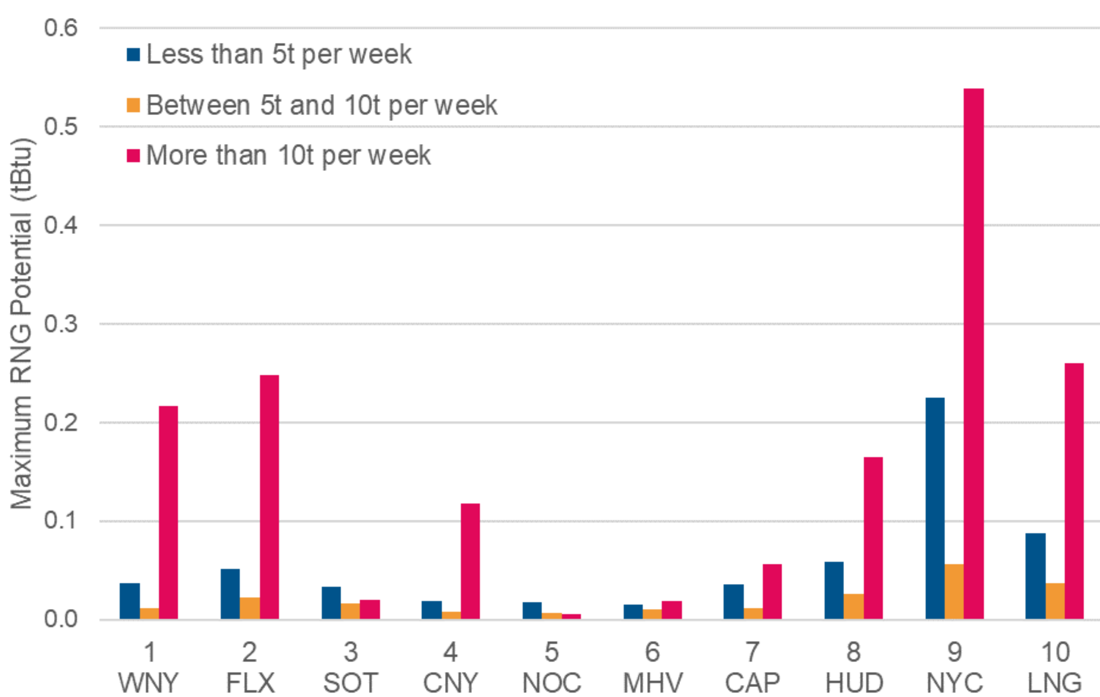
There are over 3,400 commercial and industrial food processors in NYS, with the majority of food waste generated at a relatively small number of facilities. Table 7 shows the number of food processors per region by facility size, measured in tons of waste produced per week.

Table 7. Number of Food Processing Facilities by Region (Wet Tons Per Week)

Region	Facility Size (tons per week)			
	<5	5 – 10	>10	Total
1 – WNY	167	10	32	209
2 – FLX	224	16	25	265
3 – SOT	134	12	3	149
4 – CNY	96	6	16	118
5 – NOC	86	6	1	93
6 – MHV	78	8	5	91
7 – CAP	151	9	13	173
8 – HUD	340	19	22	381
9 – NYC	1,329	43	56	1,428
10 – LNG	455	32	29	516
NYS	**3,060**	**161**	**202**	**3,423**

Figure 10 shows the maximum RNG production potential from food processor facilities in NYS, broken down by region and facility size. Over two-thirds of the food waste generated at food processors originates at just 202 large facilities that produce more than 10 wet tons per week. When expanded to include facilities that generate more than 5 wet tons per week, this proportion increases to over 75% from 363 facilities, out of a total of 3,423.

Figure 10. Renewable Natural Gas Production Potential from Food Waste by Facility Size (tBtu/yr.)



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

- In the Limited Adoption scenario, ICF assumed that 40% of available general food waste and food processor food waste would be diverted to AD systems.
- In the Achievable Deployment scenario, ICF assumed that 55% of available food waste and food processor food waste would be diverted to AD systems.
- In the Optimistic Growth scenario, ICF assumed that 70% of available food waste and food processor food waste would be diverted to AD systems.

Figure 11 shows the Limited Adoption, Achievable Deployment, and Optimistic Growth RNG resource potential scenarios from the anaerobic digestion of food waste between 2025 and 2040. Figure 12 includes the total annual RNG production potential (in units of tBtu/yr.) in 2040 for the three scenarios by region.

Figure 11. Renewable Natural Gas Production Potential from Food Waste (tBtu/y)

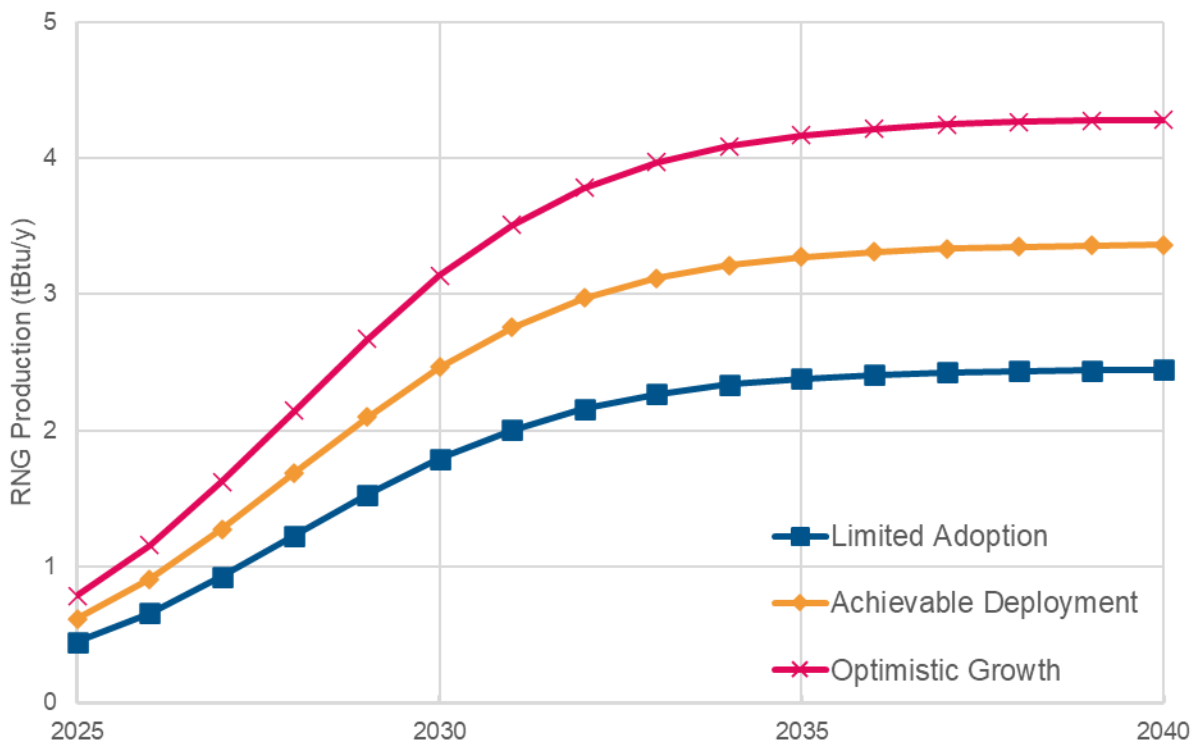
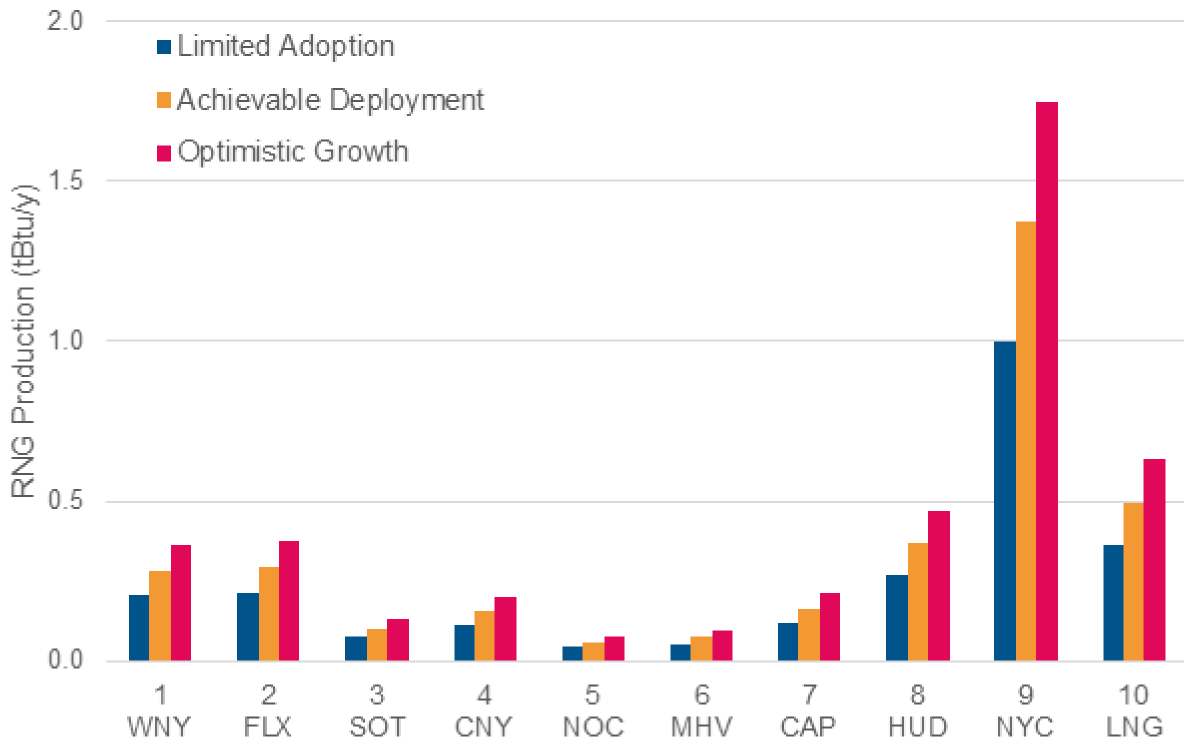


Figure 12. Annual Renewable Natural Gas Production Potential from Food Waste in 2040 by Region (tBtu/yr.)



2.4.3 Landfill Gas

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

The composition of the LFG is dependent on the materials in the landfill, and other factors, but is typically made up of methane (CH_4), carbon dioxide (CO_2), nitrogen (N_2), hydrogen (H_2), Carbon monoxide (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 8 summarizes landfill gas constituents, the typical concentration ranges in LFG, and commonly deployed upgrading technologies in use today.

Table 8. Landfill Gas Constituents and Corresponding Upgrading Technologies

LFG Constituent	Typical Concentration Range	Upgrading Technology for Removal
Carbon dioxide, CO2	40% – 60%	• High-selectivity membrane separation • Pressure swing adsorption (PSA) systems • Water scrubbing systems • Amine scrubbing systems
Hydrogen sulfide, H2S	0 – 1%	• Solid chemical scavenging • Liquid chemical scavenging • Solvent adsorption • Chemical oxidation-reduction
Siloxanes	< 0.1%	• Non-regenerative adsorption • Regenerative adsorption
Nitrogen, N2 Oxygen, O2	2% – 5% 0.1% – 1%	• PSA systems • Catalytic removal (O_2 only)

To estimate the feedstock potential of LFG in NYS, 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 waste-in-place (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 report methane content; for the facilities for which no data were reported, ICF assumed the median methane content of 49.6%.

To develop the RNG potential from LFG, ICF extracted data from the Landfill Methane Outreach Program (LMOP) administered by the EPA, which included more than 2,000 landfills nationally, with 86 in NYS and included in the inventory.

The EPA's LMOP database shows that there are 26 operational LFG-to-energy projects in NYS (see Table 9). Twenty-three of the projects capture LFG and combust it in reciprocating engines to make electricity, with two producing RNG and one landfill directly using the energy for on-site thermal needs.

The EPA currently estimates that there are four candidate landfills in NYS that could capture LFG for use as energy—the 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 WIP, and do not have operational, under construction, or planned projects. EPA candidate landfills can also be designated based on actual interest by the site.

Table 9. New York State Landfills by Region[17]

Region	Landfills	Landfill-to-Energy Projects	EPA Candidate Landfills
1 – WNY	9	4	-
2 – FLX	7	5	-
3 – SOT	8	3	1
4 – CNY	11	2	2
5 – NOC	6	3	-
6 – MHV	5	2	-
7 – CAP	12	4	1
8 – HUD	10	1	-
9 – NYC	6	1	-
10 – LNG	12	1	-
NYS	**86**	**26**	**4**

For including LFG in the RNG resource scenarios, ICF examined the RNG potential from other landfills in NYS beyond just the 4 identified by EPA. From a total of 86 landfills, ICF limited the scope to those facilities with WIP of greater than one million tons, decreasing the number of candidate landfills to 58. Also, due to the minimal and declining methane production of waste after 25 years in landfills, the team only considered landfills that are either currently open or were closed post-2000. This further reduced the number of candidate NYS landfills included in the analysis from 58 to 30.

ICF developed assumptions for the resource potentials for RNG production at these 30 landfills in the three scenarios, considering the potential at LFG facilities with collection systems in place, and at candidate landfills identified by the EPA. There is only one other LFG facility in NYS that does not fall into either of these categories and it was included among the potential LFG RNG production facilities in the Achievable Deployment and Optimistic Growth scenarios.

- In the Limited Adoption scenario, ICF assumed that RNG could be produced at 40% of the LFG facilities that have collection systems in place and at 25% of the candidate landfills.
- In the Achievable Deployment scenario, ICF assumed that RNG could be produced at 50% of the LFG facilities that have collection systems in place as well as 50% of the candidate landfills.
- In the Optimistic Growth scenario, ICF assumed that RNG could be produced at 65% of the LFG facilities that have collection systems in place and at 75% of the candidate landfills.

Figure 13 shows the Limited Adoption, Achievable Deployment, and Optimistic Growth RNG resource potential from LFG between 2025 and 2040. Figure 14 includes the total annual RNG production potential (in units of tBtu/yr.) for 2040 in the scenarios by region.

Figure 13. Renewable Natural Gas Production Potential from Landfill Gas (tBtu/yr.)

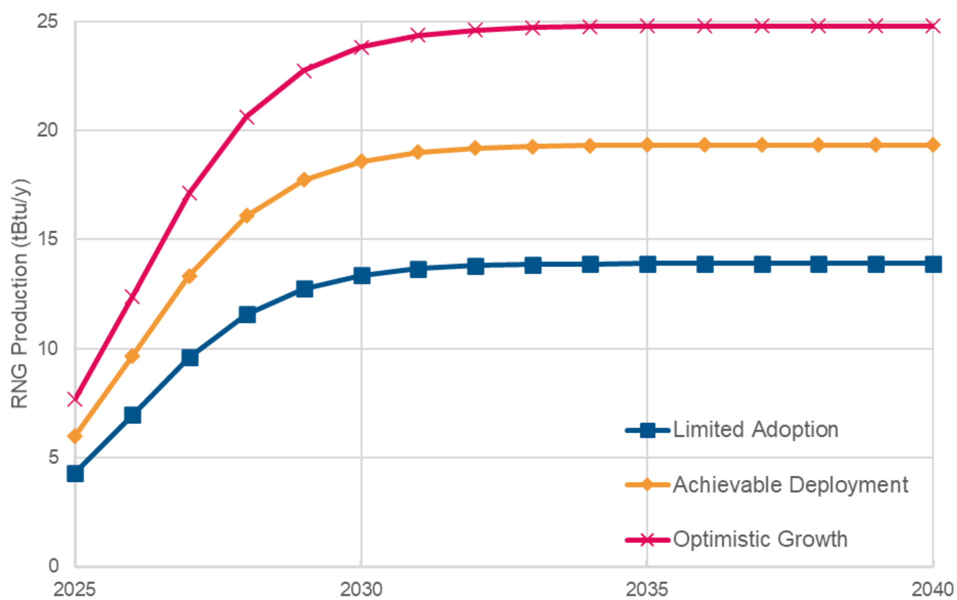
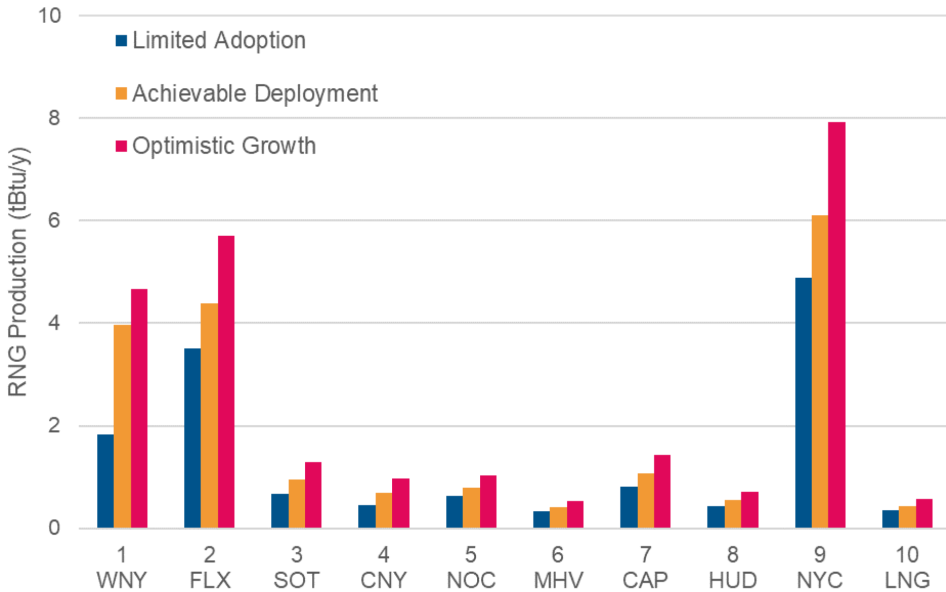


Figure 14. Annual Renewable Natural Gas Production Potential from Landfill Gas in 2040 by Region (tBtu/yr.)



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

Processing of this influent in a large WRRF is comprised typically of four stages: pre-treatment, primary, secondary, and tertiary treatments. These stages consist of mechanical, biological, and sometimes chemical processing.

- Pre-treatment removes materials that can be easily collected from the raw wastewater, which may otherwise damage or clog pumps or piping used in treatment processes (e.g., rags, trash, grit).
- In the primary treatment stage, the wastewater flows into large tanks or settling bins, thereby allowing settleable solids to sink (i.e., primary sludge) while fats, oils, or greases rise to the surface.

- The secondary treatment stage is designed to remove dissolved solids and typically uses microorganisms, such as bacteria and oxygen to convert the dissolved solids into microbial masses (i.e., activated sludge).
- Many facilities also employ a tertiary treatment stage, which is most often designed to remove nutrients (e.g., ammonia, nitrates, phosphates) and typically uses chemical or physical processes.

Primary sludge and waste activated sludge may be sent for further processing via anaerobic digestion, thereby producing digested sludge, methane, and other by-products. The methane is then either combusted in a flare or directed towards a productive use. The digested sludge is often sent to a landfill for ultimate disposal.

ICF used data reported by the EPA,[18] a study of WRRFs in New York State,[19] and previous work published by AGF[20] to estimate the amount of RNG that could be produced from wastewater treated by NYS WRRFs. Based on these data, ICF used an average energy yield of 7.003 MMBtu per million gallons of wastewater treated.

There are 587 WRRFs in NYS, which are designed to treat a total flow of over 2,700 million gallons per day (MGD) for the entire State. Figure 15 is a bar chart that shows the breakdown of NYS WRRFs by region, and within each region, by number of facilities in particular design flow ranges; less than 0.2 MGD, 0.2 to 1 MGD, 1 to 3.3 MGD, 3.3 to 7.25 MGD, 7.25 to 30 MGD, and greater than 30 MGD. In nine of the 10 regions, the majority of WRRFs have design flows less than 3.3 MGD; approximately 85% have flows less than 3.3 MGD, while nearly half have flows less than 0.2 MGD. These plants have very limited RNG production potential.

Figure 15. Number of Water Resource Recovery Facilities by Region and Facility Size (MGD)

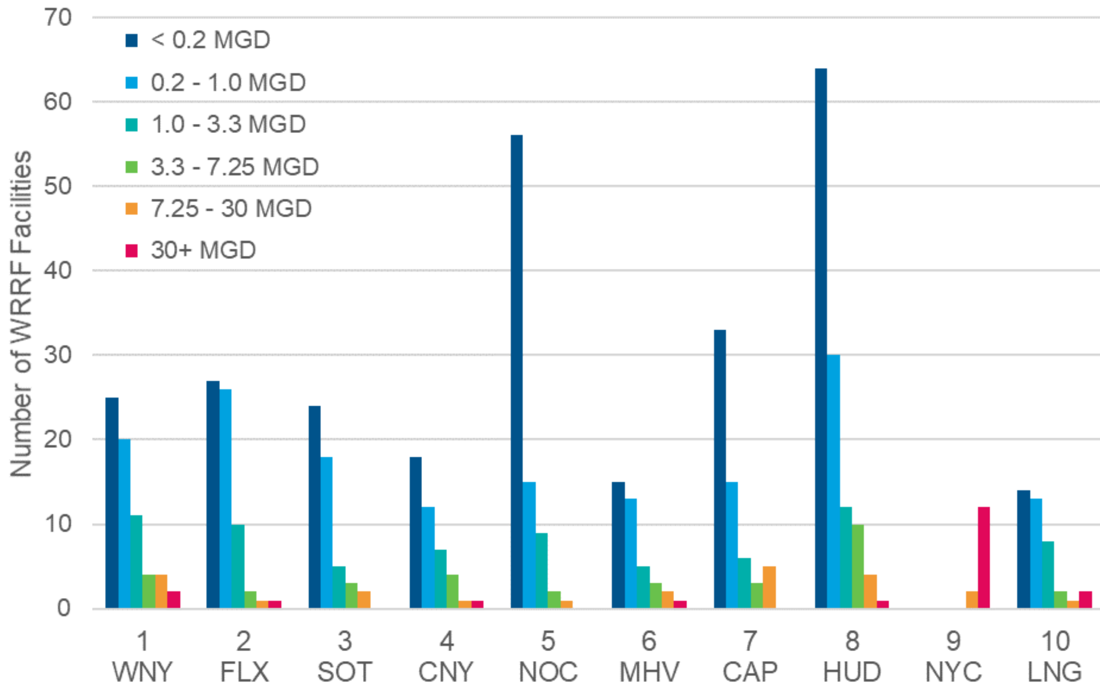


Table 10 presents NYS WRRFs by region and design flow range, with aggregated flow for each range. Over 70% of the State's design flow is treated by the State's 20 largest WRRFs. The 14 WRRFs in New York City (Region 9) treat over half the State's total design flow, and the largest WRRFs represent the State's greatest RNG resource potential.

Table 11 presents the total number of WRRFs in each region that have anaerobic digestion (AD) systems, broken out by design flow range. There are an estimated 115 WRRFs in NYS with AD systems with an aggregated design flow of 1,880 MGD, representing 68% of the State's total design flow.

Data from a NYSERDA study shows that many NYS facilities with AD systems flare some portion of the biogas they generate. Even in facilities where biogas is used for on-site electricity production, some portion of the biogas is flared due to limited gas storage or typical fluctuations in gas production. Most facilities reporting beneficial use of biogas said they used the gas for digester or facility heating. Approximately 20% of survey respondents reported using the biogas to generate on-site electricity.[21]

Table 10. Total Flow of Water Resource Recovery Facilities by Region (MGD)

Region	Facility Size (MGD)					
	<0.2	0.2 – 1.0	1.0 – 3.3	3.3 – 7.25	7.25 – 30	>30
1 – WNY	1.6	9.2	23.2	23.0	65.0	182.5
2 – FLX	2.3	11.7	16.5	10.6	15.6	86.7
3 – SOT	2.1	8.0	8.4	17.2	27.3	0.0
4 – CNY	1.4	5.1	15.8	20.2	8.1	71.2
5 – NOC	3.3	6.9	14.7	10.6	9.1	0.0
6 – MHV	1.2	6.6	6.8	16.2	14.9	48.0
7 – CAP	2.1	8.0	10.8	11.6	83.4	0.0
8 – HUD	4.5	14.8	23.0	49.8	58.6	79.4
9 – NYC	0.0	0.0	0.0	0.0	45.0	1,437.9
10 – LNG	1.2	6.3	15.2	8.5	21.2	110.1
NYS	**19.6**	**76.6**	**134.4**	**167.6**	**348.3**	**2,015.8**

Table 11. Water Resource Recovery Facilities with Anaerobic Digestion systems by Region

Region	Facility Size (MGD)					
	<0.2	0.2 – 1.0	1.0 – 3.3	3.3 – 7.25	7.25 – 30	>30
1 – WNY	1	5	6	2	0	1
2 – FLX	3	9	8	1	0	0
3 – SOT	2	4	4	3	2	0
4 – CNY	0	0	1	1	0	1
5 – NOC	0	1	4	1	1	0
6 – MHV	0	2	1	1	1	0
7 – CAP	1	2	2	0	1	0
8 – HUD	2	6	4	4	1	1
9 – NYC	0	0	0	0	2	11
10 – LNG	0	3	5	2	0	2
NYS	**9**	**32**	**35**	**15**	**8**	**16**
AD %	**3%**	**20%**	**48%**	**45%**	**35%**	**80%**

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

- In the Limited Adoption scenario, ICF assumed that RNG could be produced at 30% of the facilities with a capacity greater than 7.25 MGD.
- In the Achievable Deployment scenario, ICF assumed that RNG could be produced at 40% of the facilities with a capacity greater than 7.25 MGD.
- In the Optimistic Growth scenario, ICF assumed that RNG could be produced at 50% of the facilities with a capacity greater than 3.3 MGD.

Figure 16 shows the Limited Adoption, Achievable Deployment, and Optimistic Growth RNG resource potential from WRRFs between 2025 and 2040. Figure 17 includes the total annual RNG production potential (in units of tBtu/yr.) for 2040 in the three scenarios.

Figure 16. Renewable Natural Gas Production Potential from Water Resource Recovery Facilities (tBtu/yr.)

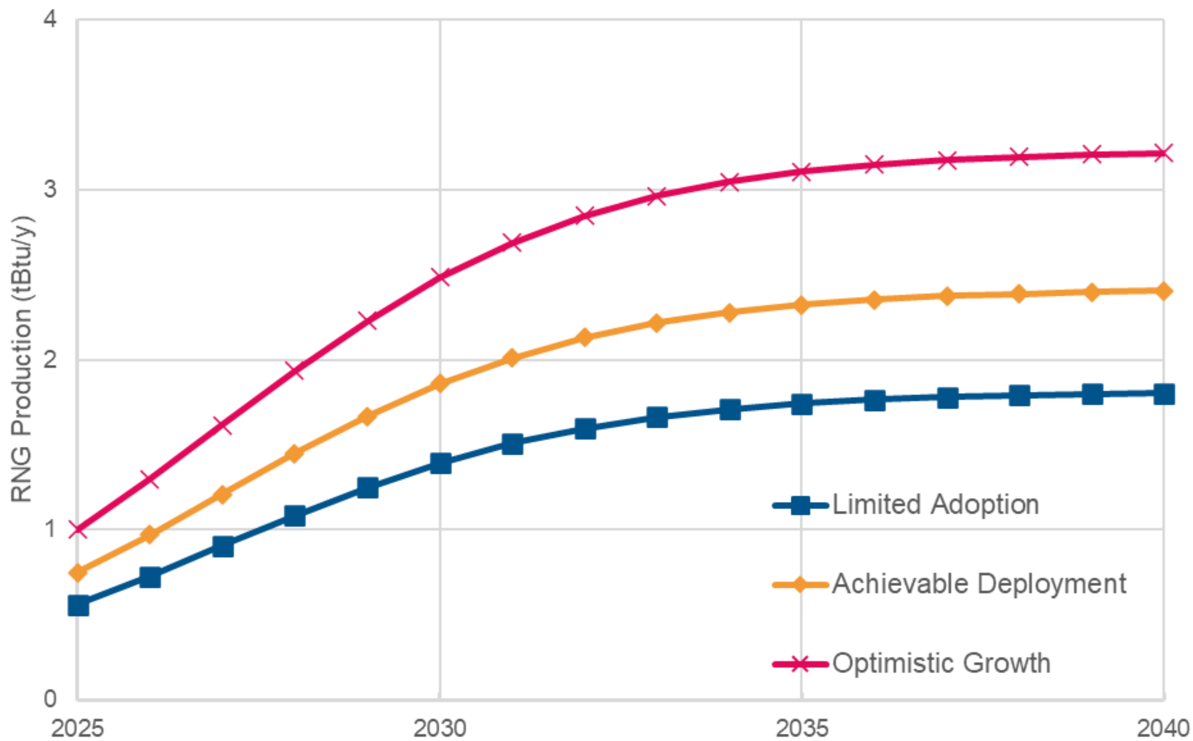
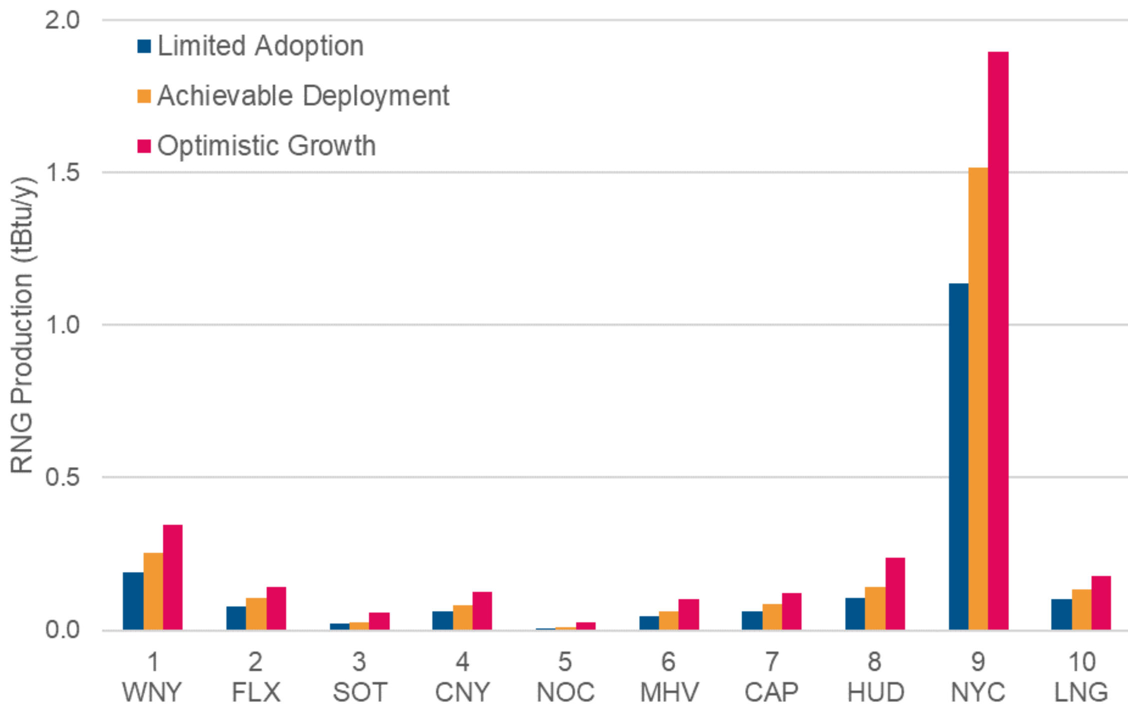


Figure 17. Annual Renewable Natural Gas Production Potential from Water Resource Recovery Facilities in 2040 by Region (tBtu/yr.)



2.5 Renewable Natural Gas: Thermal Gasification of Biogenic and Municipal Solid Waste Resources

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

To estimate the RNG production potential, ICF assumed a 65% efficiency for thermal gasification systems. This factor is based in part on the 2011 AGF Report on RNG, indicating a range of thermal gasification efficiencies in the range of 60% to 70%, depending upon the configuration and process conditions. The report authors also used a conversion efficiency of 65% in their assessment. More recently, GTI estimated the potential for RNG from the thermal gasification of wood waste in California and assumed a conversion efficiency of 60%.[22]

2.5.1 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. For the purposes of this analysis, ICF assumed that agricultural residues are converted to RNG via thermal gasification; however, note that agricultural residues (and sometimes crops) are sometimes added to anaerobic digesters.

ICF extracted information from the DOE Bioenergy KDF, including the following agricultural residues relevant to NYS: corn stover, wheat straw, non-citrus residues, and tree nut residues. ICF extracted data from the Bioenergy KDF at $10 price point increments, from $40/ton to $100/ton, that showed variation in production potential for agricultural residue biomass from 2025 out to 2040.

Table 12 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 12. Heating Values for Agricultural Residues

Agricultural Component	Btu/lb, dry	MMBtu/ton, dry
Corn stover	7,587	15.174
Wheat straw	7,527	15.054
Non-citrus residues	7,738	15.476
Tree nut residues	8,597	17.194

Agricultural residue was distributed proportionally between the 10 regions based on share of farmland, with total acreage of agricultural land by county in NYS taken from the USDA 2017 Census of Agriculture. Table 13 shows an annotated summary of the maximum agricultural residue potential at different biomass prices in 2040, broken down by region.

Table 13. Agricultural Residue Production Potential in 2040 by Region (Dry Tons)

Region	Biomass Price $40	Biomass Price $60	Biomass Price $80	s Price 00
1 – WNY	17,275	228,173	266,414	301,095
2 – FLX	28,771	380,017	443,707	501,467
3 – SOT	23,173	306,083	357,381	403,904
4 – CNY	15,672	207,006	241,699	273,163
5 – NOC	18,814	248,508	290,156	327,928
6 – MHV	12,822	169,358	197,742	223,483
7 – CAP	18,333	242,148	282,731	319,536
8 – HUD	6,560	86,642	101,163	114,332
9 – NYC	1	9	11	12
10 – LNG	640	8,456	9,873	11,158
NYS	**142,060**	**1,876,401**	**2,190,877**	**2,476,079**

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

- In the Limited Adoption scenario, ICF assumed that 20% of the agricultural residues available at $40/dry ton would be diverted to thermal gasification systems.
- In the Achievable Deployment scenario, ICF assumed that 40% of the agricultural residues available at $60/dry ton would be diverted to thermal gasification systems.
- In the Optimistic Growth scenario, ICF assumed that 50% of the agricultural residues available at $100/dry ton would be diverted to thermal gasification systems.

Figure 18 shows the Limited Adoption, Achievable Deployment, and Optimistic Growth RNG resource potential scenarios from the thermal gasification of agricultural residues between 2025 and 2040. Figure 19 shows the total annual RNG production potential (in units of tBtu/yr.) in 2040 for the three scenarios by region.

Figure 18. Annual Renewable Natural Gas Production Potential from Agricultural Residue (tBtu/yr.)

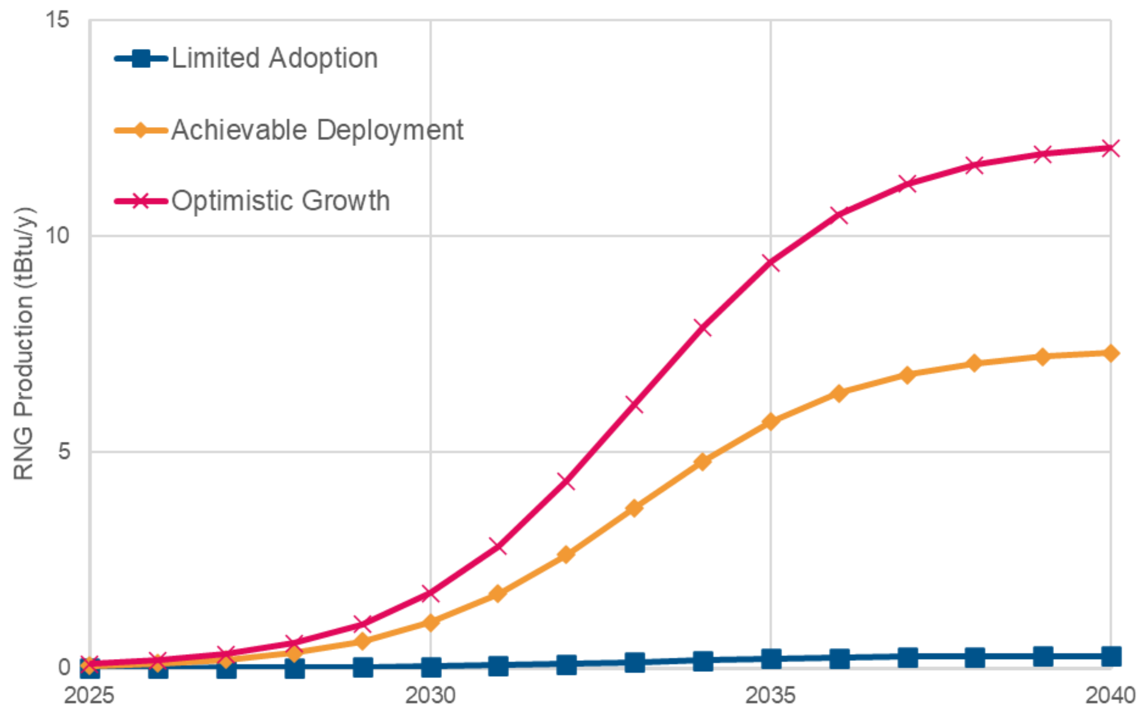
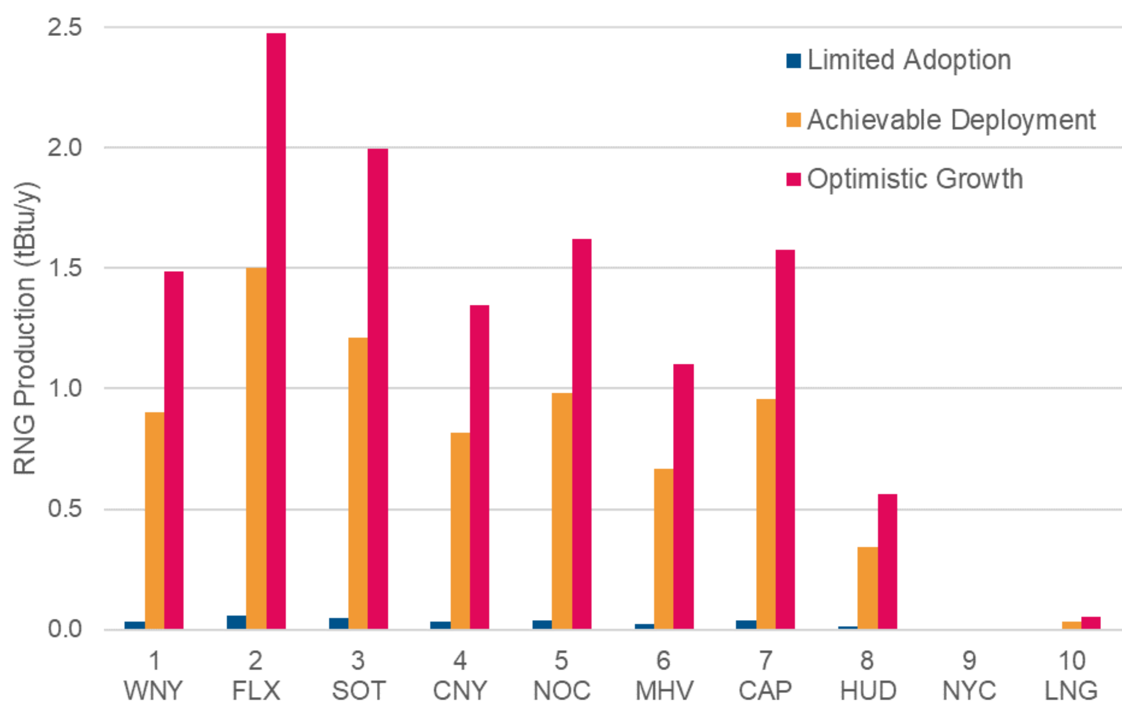


Figure 19. Renewable Natural Gas Production Potential from Agricultural Residue in 2040 by Region (tBtu/yr.)



2.5.2 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 DOE-BKDF at $10 price point increments, from $30/ton to $100/ton that showed variation in production potential for energy crops from 2025 out to 2040.

ICF's estimates of energy crop potential is based on DOE modeling in the Billion Ton Study. In this modeling, energy crops as an RNG feedstock are constrained by available and existing agricultural land. No land-use change is assumed to occur, except within the agricultural sector (i.e., forested land is not converted to agricultural land for energy crop purposes). In addition, rather than shifting existing agricultural production (e.g., corn and soy) to energy crop production, DOE's modeling also shows that energy crops are largely grown on idle or available pasture lands, particularly at lower farmgate prices.

Table 14 lists the energy content on an HHV basis for the various energy crops relevant to NYS.

Table 14. Heating Values for Energy Crops

Energy Crop	Btu/lb, dry	MMBtu/ton, dry
Biomass sorghum	7,240	14.48
Miscanthus	7,900	15.80
Poplar	7,775	15.55
Switchgrass	7,929	15.86
Willow	8,550	17.10

Table 15 shows the maximum energy crop production potential broken down by region. Regional proportions are based on the total acreage of agricultural land by county in NYS, consistent with the approach taken for the agricultural residue feedstock outlined above.

Table 15. Energy Crop Production Potential in 2040 by Region (Dry Tons)

Region	Biomass Price $40	Biomass Price $60	Biomass Price $80	Biomass Price $100
1 – WNY	516,095	630,241	687,357	810,099
2 – FLX	859,544	1,049,652	1,144,778	1,349,202
3 – SOT	692,315	845,437	922,055	1,086,708
4 – CNY	468,217	571,775	623,592	734,947
5 – NOC	562,088	686,407	748,613	882,294
6 – MHV	383,064	467,787	510,181	601,284
7 – CAP	547,704	668,842	729,456	859,715
8 – HUD	195,972	239,316	261,004	307,611
9 – NYC	21	26	28	33
10 – LNG	19,126	23,356	25,473	30,022
NYS	**4,244,147**	**5,182,839**	**5,652,537**	**6,661,915**

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

- In the Limited Adoption scenario, ICF assumed that 40% of the energy crops available at $30/dry ton would be diverted to thermal gasification systems.
- In the Achievable Deployment scenario, ICF assumed that 40% of the energy crops available at $40/dry ton would be diverted to thermal gasification systems.
- In the Optimistic Growth scenario, ICF assumed that 50% of the energy crops available at $100/dry ton would be diverted to thermal gasification systems.

Figure 20 shows the RNG resource potential from the thermal gasification of energy crops between 2025 and 2040 in the Limited Adoption, Achievable Deployment and Optimistic Growth scenarios. Figure 21 shows the annual RNG production potential (in units of tBtu/yr.) in 2040 for the three scenarios by region.

Figure 20. Annual Renewable Natural Gas Production Potential from Energy Crops (tBtu/yr.)

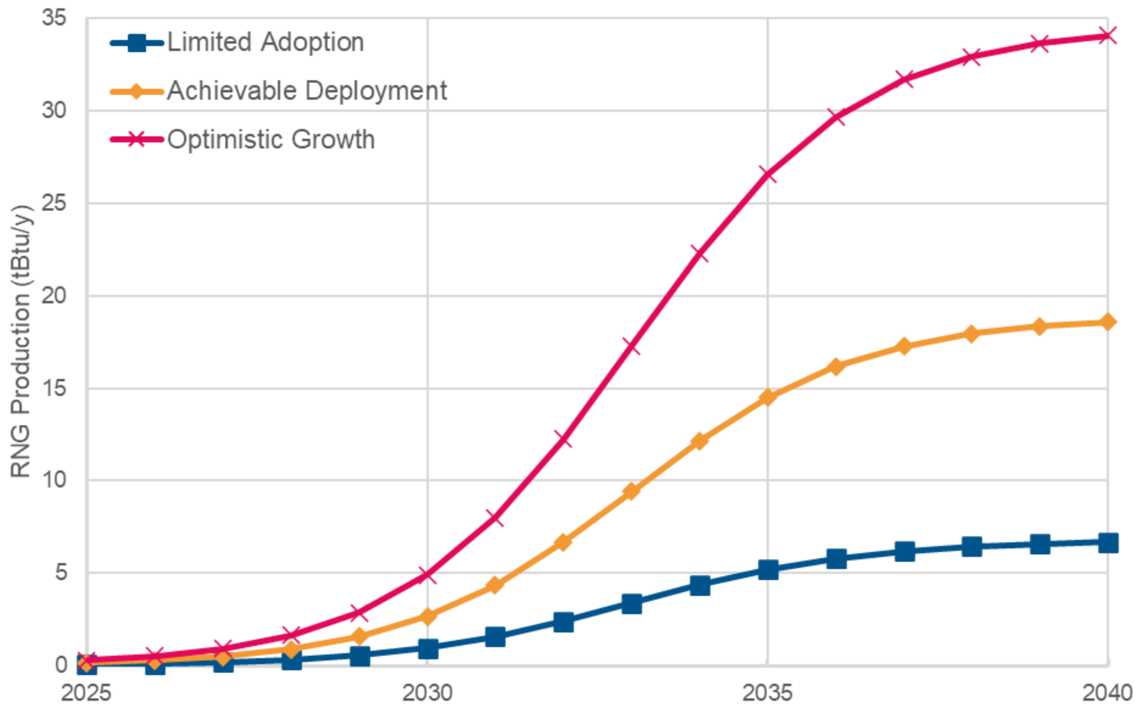
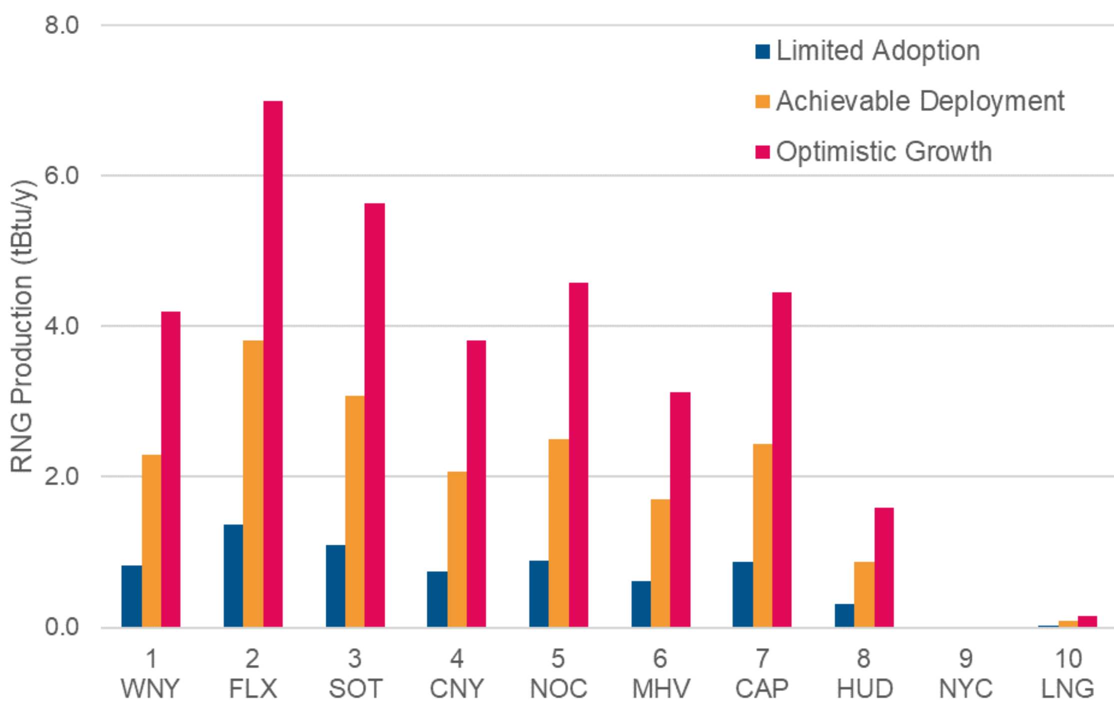


Figure 21. Renewable Natural Gas Production Potential from Energy Crops in 2040 by Region (tBtu/yr.)



2.5.3 Forestry and Forest Product Residues

Forestry and forest product residue includes 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: [23]

- Alterations to the biomass retention levels by slope class (e.g., slopes with between 40% and 80% grade included 40% biomass left on site, compared to the standard 30%).
- Removal of reserved (e.g., wild and scenic rivers, wilderness areas, USFS special interest areas, national parks) and roadless designated forestlands, forests on steep slopes and in wet land areas (e.g., stream management zones), and sites requiring cable systems.
- The assumptions only include thinnings for over stocked stands and does 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 county-level information on forest residues such as thinnings, mill residues, and different residues from woods (e.g., mixed wood, hardwood, and softwood). ICF extracted data at three price points, $30/ton, $60/ton, and $70/ton, that showed variation in production potential for forest and forest product residue biomass from 2025 out to 2040.

Table 16 lists the energy content on an higher heating value (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 16. Heating Values for Forestry and Forest Product Residues

Forestry and Forest Product	Btu/lb, dry	MMBtu/ton, dry
Mixed wood, whole trees	6,878	13.76
Hardwood, whole trees		
Softwood, whole trees		
Mixed wood, residue	6,500	13.00
Hardwood, residue		
Softwood, natural, residue		
Softwood, planted, residue		

Table 17 shows the maximum forestry and forest product residue potential broken down by region at different biomass price points.

Table 17. Forestry and Forest Product Production Potential in 2040 by Region (Dry Tons)

Region	Biomass Price $30	Biomass Price $60	Biomass Price $70
1 – WNY	6,866	109,978	702,036
2 – FLX	1,978	29,003	187,809
3 – SOT	26,851	116,808	628,765
4 – CNY	3,767	36,899	228,043
5 – NOC	411,738	588,420	1,630,477
6 – MHV	11,915	71,477	462,399
7 – CAP	42,461	101,643	501,339
8 – HUD	14,605	52,171	339,733
9 – NYC	0	0	0
10 – LNG	2,477	11,190	69,220
NYS	**522,658**	**1,117,586**	**4,749,813**

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

- In the Limited Adoption 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 Deployment scenario, ICF assumed that 50% of the forest and forestry product residues available at $60/dry ton would be diverted to thermal gasification systems.
- In the Optimistic Growth scenario, ICF assumed that 60% of the forest and forestry product residues available at $70/dry ton would be diverted to thermal gasification systems.

Figure 22 shows the RNG resource potential from the thermal gasification of forestry and forest product residues between 2025 and 2040 in the Limited Adoption, Achievable Deployment and Optimistic Growth scenarios. Figure 23 shows the annual RNG production potential (in units of tBtu/yr.) in 2040 for the three scenarios by region. The significant increase in RNG production potential in the Optimistic Growth scenario is linked to a much higher available resource base of forestry and forest product residues at the higher feedstock price of $70/dry ton.

Figure 22. Annual Renewable Natural Gas Production Potential from Forestry and Forest Product Residue (tBtu/yr.)

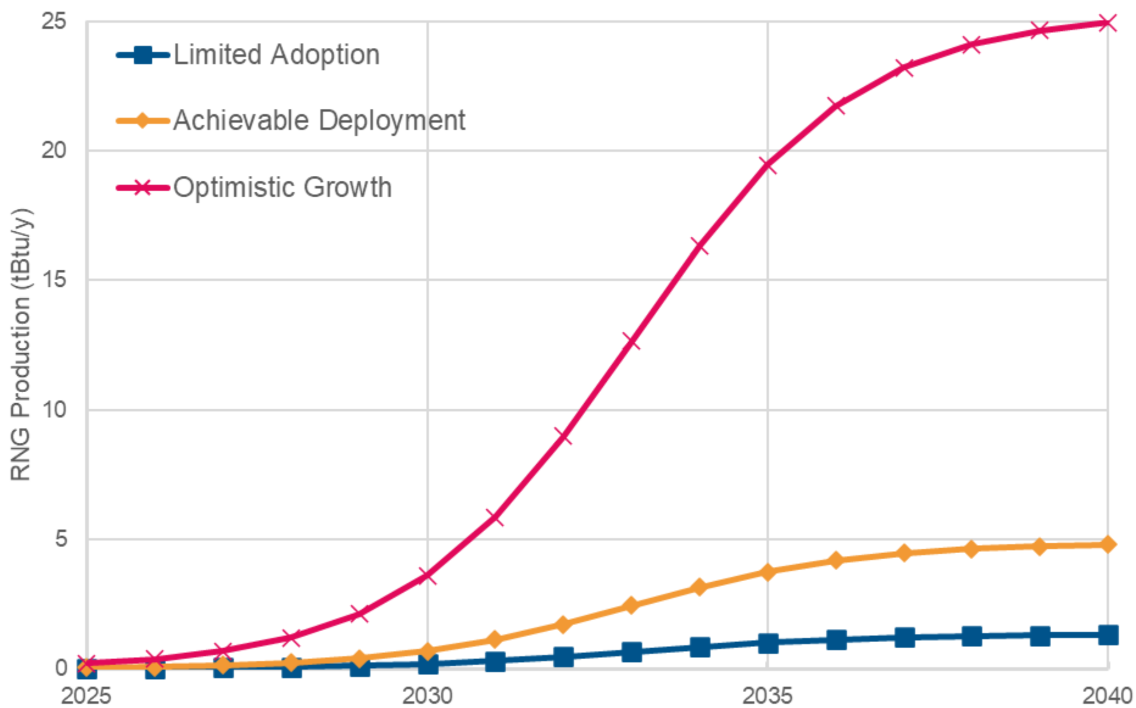


Figure 23. Renewable Natural Gas Production Potential from Forestry and Forest Product Residue in 2040 by Region (tBtu/yr.)

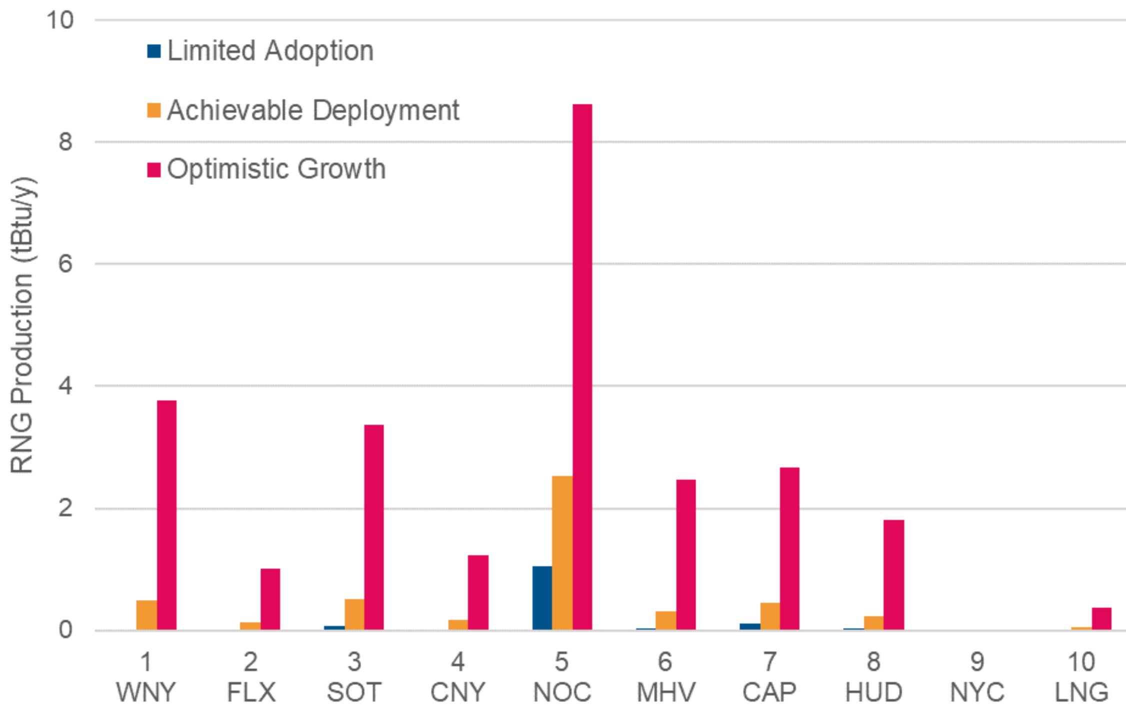
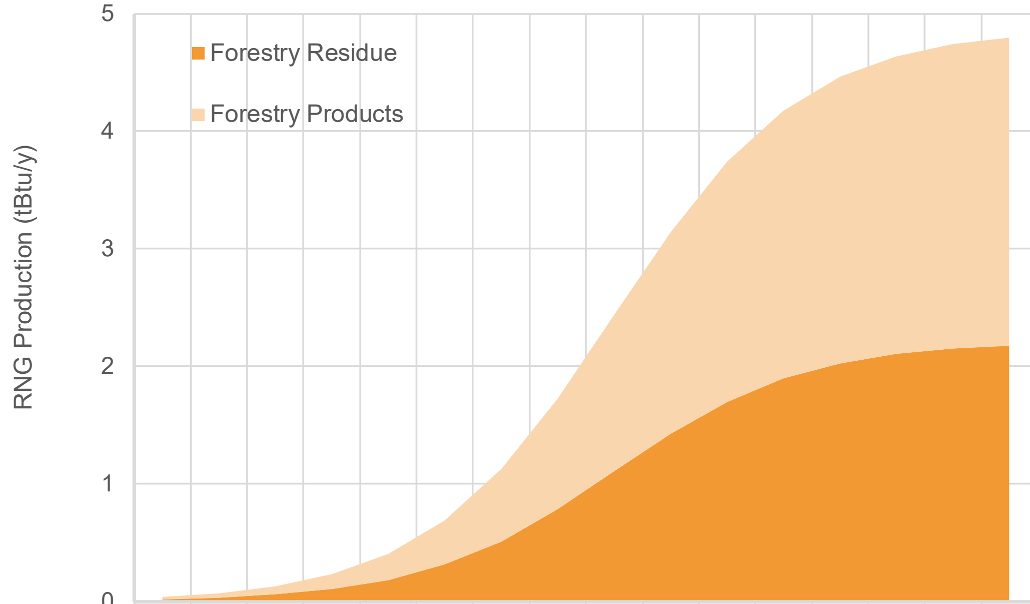


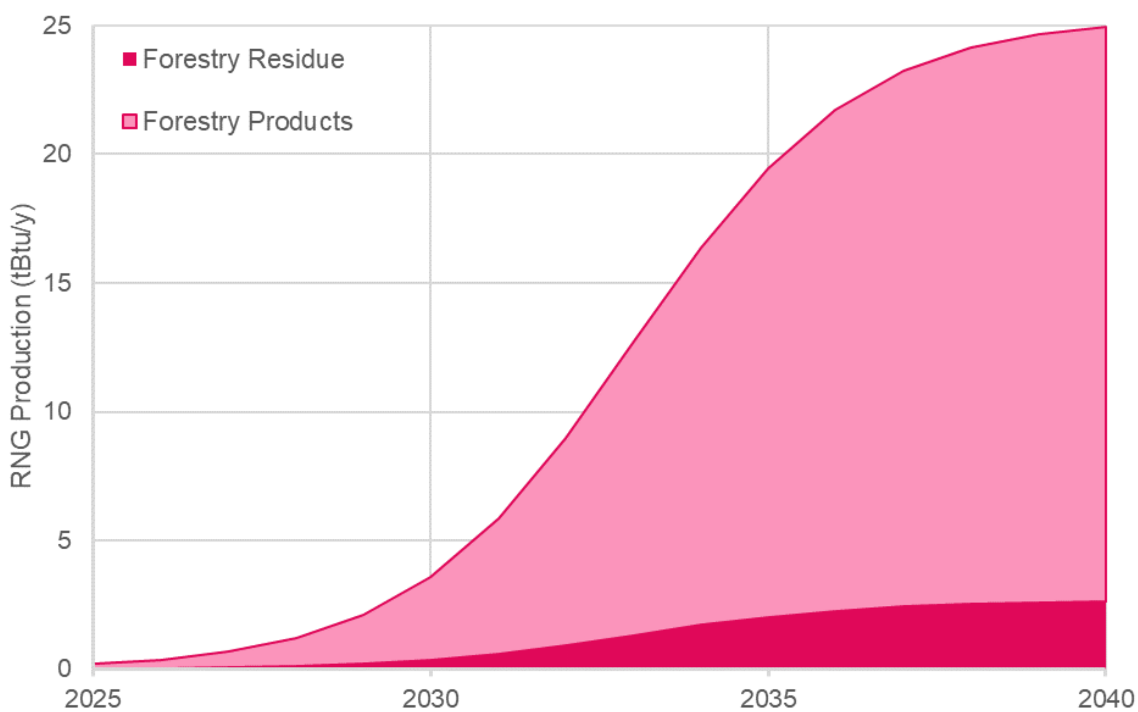
Figure 24 and Figure 25 show the RNG resource potential for the Achievable Deployment and Optimistic Growth scenarios, broken out by forestry residues and forestry products. The Limited Adoption scenario is not shown, as all of the RNG potential comes from forestry residues.

Figure 24. Renewable Natural Gas Production Potential by Forestry Type, Achievable Deployment Scenario (tBtu/yr.)



	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
Forestry Products	0.02	0.04	0.07	0.13	0.22	0.38	0.62	0.94	1.33	1.72	2.04	2.28	2.44	2.53	2.59	2.62
Forestry Residue	0.02	0.03	0.06	0.10	0.18	0.31	0.51	0.78	1.10	1.43	1.70	1.89	2.02	2.10	2.15	2.18

Figure 25. Renewable Natural Gas Production Potential by Forestry Type, Optimistic Growth Scenario (tBtu/yr.)



2.5.4 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 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.

For RNG potential from thermal gasification of MSW feedstock, ICF limited consideration to only MSW that is currently landfilled; this excludes MSW that is recycled or directed to waste-to-energy facilities. Furthermore, ICF notes that our landfill gas estimates are limited to waste in place at existing landfills, whereas the analysis for MSW in this section considers diverted components of the MSW stream. This constraint prevents the potential for double counting of other components of MSW that are considered in other parts of ICF's analysis, namely food waste.

ICF extracted information from the DOE's Bioenergy KDF, which includes information collected as part of DOE's Billion Ton Report. The DOE-BKDF includes the following waste residues: construction and demolition debris, paper and paperboard, plastics, rubber and leather, textiles, wood, yard trimmings, and other. ICF extracted data from the DOE-BKDF at two price points, $30/ton and $40/ton, that showed variation in the volume of MSW available in NYS. The $40/ton represents the highest production potential volume, with price points above this level remaining constant. The price points in the DOE-BKDF represent the assumed price at which it is economically feasible to divert MSW from landfills. In other words, the price point represents a feedstock cost and should not be confused with a tipping fee that landfills collect for waste disposal. Table 18 lists the energy content on an HHV basis for the various components of MSW relevant to NYS. To estimate the RNG production potential, ICF assumed a 65% efficiency for thermal gasification systems.

Table 18. Heating Values for Municipal Solid Waste Components

MSW Component	Btu/lb, dry	MMBtu/ton, dry
Paper and paperboard	7,642	15.28
Plastics	19,200	38.40
Rubber and leather	11,300	22.60
Textiles	8,000	16.00
Yard trimmings	6,448	12.90

Table 19 shows the maximum MSW potential broken down by region at a price of $40/ton. Regional proportions are based on population weighed by region in NYS, as MSW generation is typically tied to population levels.

Table 19. Municipal Solid Waste Production Potential at $40/ton in 2040 by Region (Dry Tons)

Region	Paper & Paperboard	Plastics	Rubber & Leather	Textiles	Yard Trimmings	Total
1 – WNY	71,162	88,322	19,461	36,288	17,964	233,197
2 – FLX	62,089	77,061	16,979	31,661	15,673	203,463
3 – SOT	32,516	40,356	8,892	16,581	8,208	106,553
4 – CNY	39,956	49,591	10,927	20,375	10,086	130,935
5 – NOC	21,493	26,676	5,878	10,960	5,426	70,432
6 – MHV	24,978	31,002	6,831	12,737	6,305	81,854
7 – CAP	55,904	69,384	15,288	28,507	14,112	183,195
8 – HUD	120,154	149,127	32,858	61,270	30,331	393,740
9 – NYC	431,064	535,010	117,883	219,814	108,815	1,412,588
10 – LNG	146,511	181,840	40,066	74,711	36,984	480,112
NYS	**1,005,826**	**1,248,368**	**275,064**	**512,905**	**253,905**	**3,296,068**

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

- In the Limited Adoption scenario, ICF assumed that 30% of the non-biogenic fraction of MSW available at $30/dry ton from the DOE-BKDF for paper and paperboard, plastics, rubber and leather, and textiles waste could be gasified.
- In the Achievable Deployment scenario, ICF assumed that 50% of the non-biogenic fraction of MSW available at $30/dry ton from the DOE-BKDF for paper and paperboard, plastics, rubber and leather, and textiles waste could be gasified.
- In the Optimistic Growth scenario, ICF assumed that 60% of the non-biogenic fraction of MSW available at $40/dry ton from the DOE-BKDF for paper and paperboard, plastics, rubber and leather, textiles, and yard trimmings could be gasified.

ICF notes that at the price of $30/ton, DOE reports no MSW wood or yard trimmings in NYS, meaning that without a higher price signal, the feedstock will not be economically feasible to obtain.

Figure 26 shows the RNG resource potential from the thermal gasification of MSW between 2025 and 2040 in the Limited Adoption, Achievable Deployment, and Optimistic Growth scenarios. Figure 27 shows the total annual RNG production potential (in units of tBtu/yr.) in 2040 for the three scenarios by region.

Figure 26. Annual Renewable Natural Gas Production Potential from Municipal Solid Waste (tBtu/yr.)

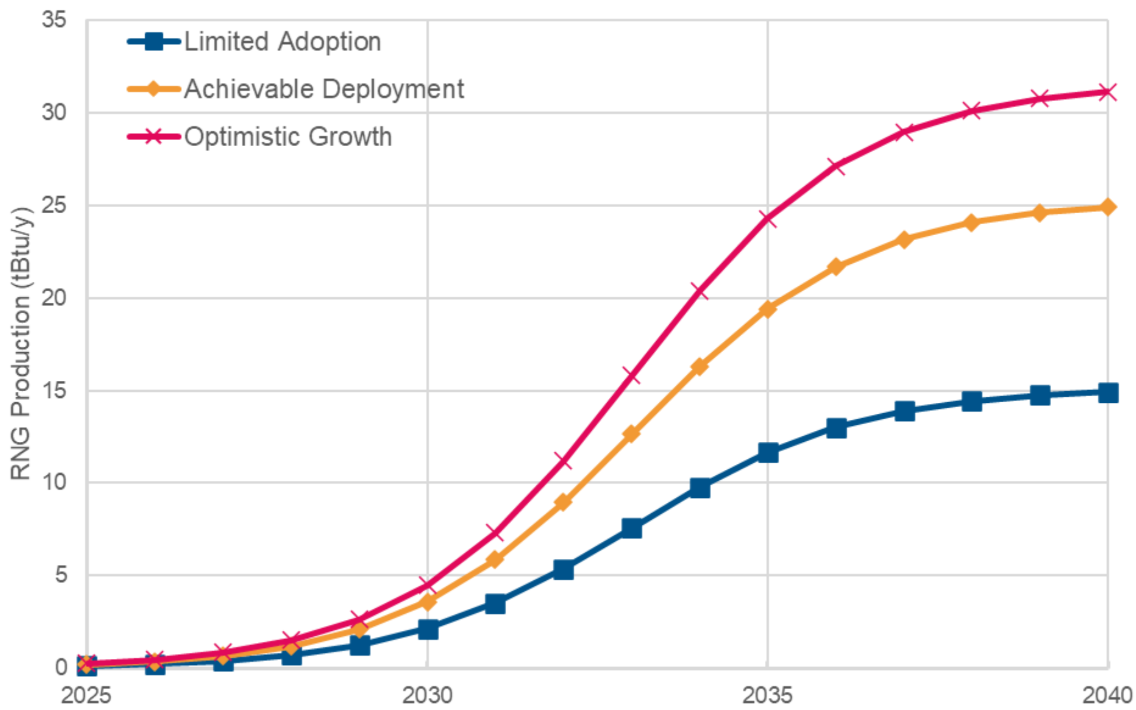
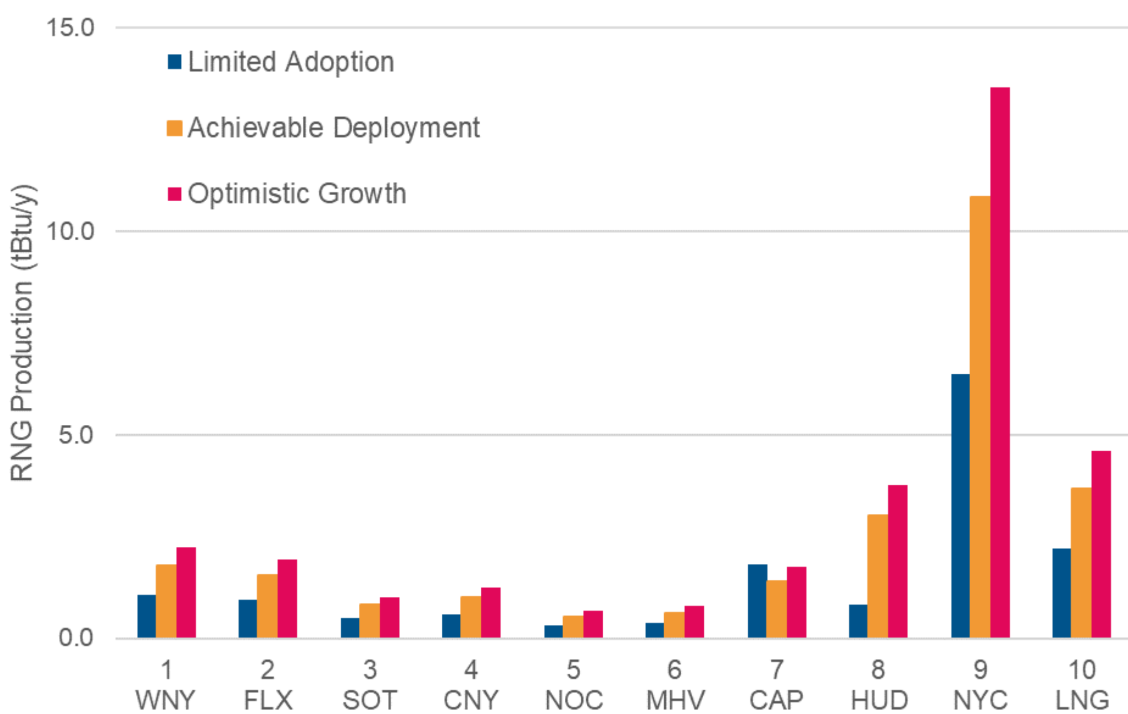


Figure 27. Renewable Natural Gas Production Potential from Municipal Solid Waste in 2040 by Region (tBtu/yr.)



3 Renewable Natural Gas Cost Assessment

3.1 Cost Assessment Summary

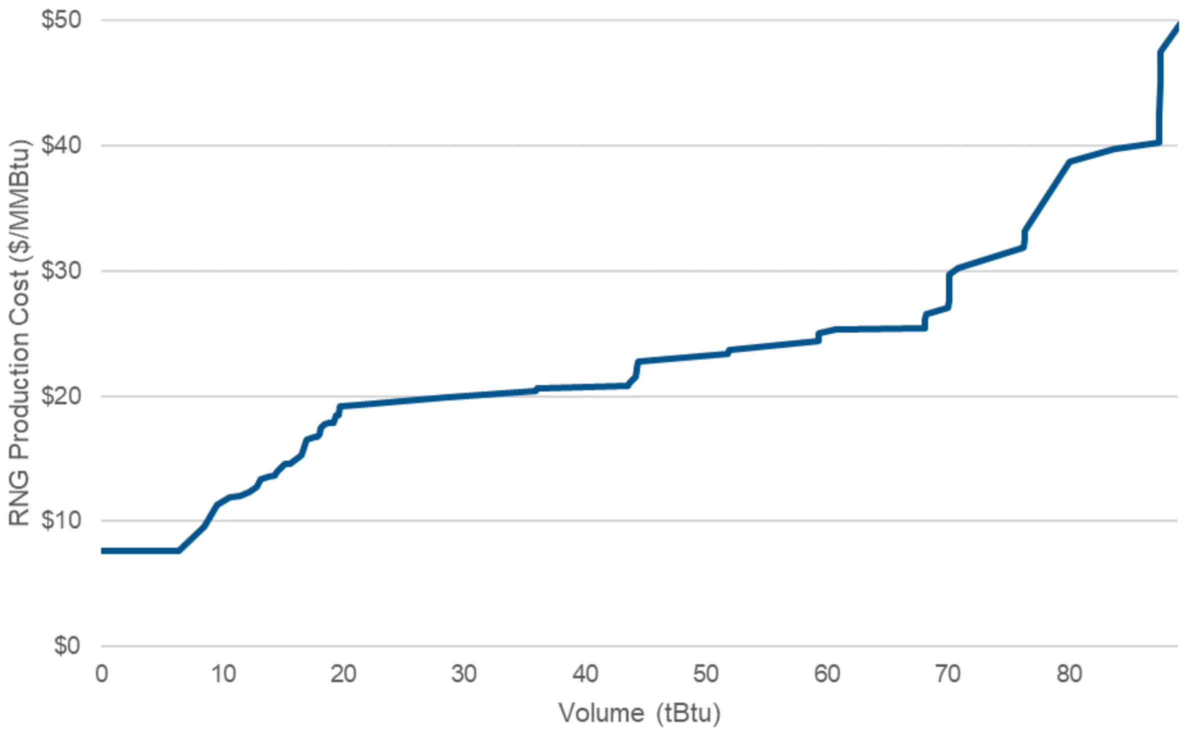
ICF reports that RNG will be available from various feedstocks in the range of less than $10/MMBtu to upwards of $40/MMBtu. Anaerobic digestion feedstocks, notably from LFG and WRRF, are more cost-effective in the near term. RNG via thermal gasification is more expensive, largely reflecting the immature state of commercial scale thermal gasification of feedstocks like those considered in our analysis, and the associated uncertainties around cost and feedstock availability.

Table 20 provides a summary of the different cost ranges and weighted average cost in New York State for each RNG feedstock and technology, while Figure 28 that follows shows the supply-cost curve for RNG production under the Achievable Deployment scenario in 2040.

Table 20. Summary of Cost Ranges by Feedstock Type

	Feedstock	Cost Range ($/MMBtu)	Weighted Average Cost ($/MMBtu)
Anaerobic Digestion	Animal Manure	$27.11 – $50.02	$34.56
	Food Waste	$19.24 – $30.24	$23.86
	Landfill Gas	$7.67 – $21.53	$11.29
	Water Resource Recovery Facilities	$13.36 – $68.69	$27.68
Thermal Gasification	Agricultural Residues	$19.87 – $39.78	$25.67
	Forestry and Forest Residues	$19.87 – $39.78	$25.67
	Energy Crops	$19.87 – $39.78	$25.67
	Municipal Solid Waste	$19.87 – $39.78	$25.67

Figure 28. Supply-Cost Curve for Renewable Natural Gas Potential in 2040, Achievable Deployment (tBtu v $/MMBtu)



ICF notes that the upper limit of the production cost range for some of the feedstocks, such as animal manure and WRRFs, is significant, and reflects the production of RNG from less economic facilities, such as WRRFs with low MGD flow and small farms with a limited number of livestock. These high-cost facilities represent the tail end of the RNG supply-cost curve. If the feedstock from these facilities is required for RNG production, there is the potential for alternative approaches to utilize this resource, rather than building a dedicated RNG production facility. For example, the raw feedstock could be collected and transported to a larger anaerobic digestion facility, avoiding much of the cost drivers that lead to the high costs shown in the Table 20.

3.2 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, conditioning, and other upgrading costs (depending on the type of technology used, the contaminant loadings, etc.); compression; and interconnection for pipeline injection. We also include operational costs for each technology type. Table 21 below outlines some of ICF's baseline assumptions that we employ in our RNG costing model.

Table 21. Illustrative ICF Renewable Natural Gas Cost Assumptions

Cost Parameter	ICF Cost Assumptions
Capital Costs	
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.
O&M Costs / Benefits	
Operational Costs	• Costs for each equipment type—digesters, conditioning equipment, collection equipment, and compressors—as well as utility charges for estimated electricity consumption.
Operational Revenues	• Some RNG projects generate revenue via tipping fees or selling digestate. Where appropriate this has been included.
Feedstock	• Feedstock costs (for thermal gasification), ranging from $30 to $100 per dry ton.
Delivery	• 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.
Levelized Cost of Gas	
Project Lifetimes	• Calculated based on the initial capital costs in Year 1, annual operational costs discounted, and RNG production discounted accordingly over a 20-year project lifetime.

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.

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 or thermal gasification technologies, and our supply-cost curves are meant to be illustrative, rather than deterministic. This is especially true of our outlook to 2040—the team has 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. For anaerobic digestion and thermal gasification systems the team has 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 (RFS) market and California's Low-Carbon Fuel Standard (LCFS) market. The project financing assumptions in ICF's cost modeling likely have a lower return than investors may be expecting in the market today; however, the cost assessment modeled seek 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.

3.3 Renewable Natural Gas from Anaerobic Digestion

3.3.1 Animal Manure

ICF developed assumptions for farming regions 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 22 includes the main assumptions used to estimate the cost of producing RNG from animal manure, while Table 23 that follows provides example cost inputs for low-cost and high-cost animal manure facilities, based on per unit of RNG production. For example, high-cost facilities are typically smaller and have lower overall capital and operating costs relative to larger facilities but have higher costs per unit of RNG produced. These cost estimates are illustrative and represent the upper and lower bounds of RNG production costs in New York State, with estimated weighted average costs shown in Table 20.

Table 22. Cost Consideration in Levelized Cost of Gas Analysis for Renewable Natural Gas from Animal Manure

Factor	Cost Elements Considered	Costs
Performance	• Capacity factor	• 95%
Installation Costs	• Construction / Engineering • Owner's cost	• 15-25% of installed costs of equipment • 10% of installed 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	• Commercial rate of 14.8 ¢/kWh for state • Average of \$7.58/MMBtu for state
Operations & Maintenance (O&M)	• 1 FTE for maintenance • Miscellany	• 15% of installed capital costs
For Injection	• Interconnect • Pipeline • Compressor	• \$1.5 million • \$2 million • \$0.1–\$0.325 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% • 8%

Table 23. Example Facility-Level Cost Inputs for Renewable Natural Gas from Animal Manure

Factor	High Per-Unit Production Cost	Low Per-Unit Production Cost
Facility size (cows)	1,300	4,000
Biogas production (SCFM)	90	265
Capital: collection and digester	\$2.15 million	\$4.78 million
Capital: conditioning (CO2/O2 removal)	\$1.06 million	\$2.285 million
Capital: sulfur treatment	\$0.1 million	\$0.2 million
Capital: compressor	\$0.1 million	\$0.15 million
Capital: pipeline (onsite)	\$2.0 million	\$2.0 million
Capital: utility interconnect	\$1.5 million	\$1.5 million
O&M: electricity and natural gas	\$0.18 million	\$0.54 million
Construction and engineering: installation	\$0.87 million	\$1.16 million
Construction and engineering: owner's cost	\$0.35 million	\$0.46 million

ICF reports a range of costs for RNG from animal manure at \$27.11/MMBtu to \$50.02/MMBtu, with a weighted average cost of \$34.56/MMBtu.

3.3.2 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, the team also included assumptions about the cost of collecting food waste and processing it accordingly (see Table 24). Table 25 that follows provides example cost inputs for low-cost and high food waste facilities. ICF notes that the costs below are illustrative and may not reflect real-world costs associated with RNG projects. For instance, in New York State, large-scale food waste digesters may face additional costs from having to treat effluent from the process—developers have approached this cost challenge in different ways, including treating the effluent on site or by sending it to municipal wastewater management systems. With a large population and high population density, large food waste digesters have been proposed to serve areas like New York City or Long Island—in these cases, the costs to build may be higher than those listed below, and those projects may face longer build times (thereby increasing developer risk and cost potentially).

Table 24. Cost Consideration in Levelized Cost of Gas Analysis for Renewable Natural Gas 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 installed costs of equipment • 10% of installed 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	• Commercial rate of 14.8 ¢/kWh for state • Average of $7.58/MMBtu for state
Operations & Maintenance	• 1.5 FTE for maintenance • Miscellany	• 15% of installed capital costs
Other	• Tipping fees	• Weighted statewide average of $66.17 (see Table 26)
For Injection	• Interconnect • Pipeline • Compressor	• $1.5 million • $2 million • $0.1–$0.325 million
Financial Parameters	• Rate of return • Discount rate	• 10% • 7%

Table 25. Example Facility-Level Cost Inputs for Renewable Natural Gas from Food Waste

Factor	High Per Unit Production Cost	Low Per Unit Production Cost
Food waste processed (ton/y)	30,000	120,000
Biogas production (SCFM)	250	1,000
Capital: organics processing	$7.0 million	$12.5 million
Capital: digester	$7.2 million	$19.2 million
Capital: collection	$0.17 million	$0.44 million
Capital: conditioning (CO2/O2 removal)	$1.36 million	$3.8 million
Capital: sulfur treatment	$0.1 million	$0.5 million
Capital: nitrogen rejection	$0.3 million	$2.5 million
Capital: compressor	$0.13 million	$0.33 million
Capital: pipeline (on-site)	$2.0 million	$2.0 million
Capital: utility interconnect	$1.5 million	$1.5 million
O&M: electricity and natural gas	$0.51 million	$2.3 million
Construction and engineering: installation	$0.97 million	$2.3 million
Construction and engineering: owner's cost	$0.39 million	$0.91 million

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). For reference, the tipping fees reported by EREF for 2020 are shown in Table 26.

Table 26. Average Tipping Fee by Region ($/ton)[24]

Region	
New York, statewide average	$71.71
Northeast: CT, DE, ME, MD, MA, NH, NJ, NY, PA, RI, VA, WV	$68.69
Midwest: IL, IN, IA, KS, MI, MN, MO, NE, OH, OH, WI	$47.85
Mountains / Plains: CO, MT, ND, SD, UT, WY	$47.83
Pacific: AK, AZ, CA, HI, ID, NV, OR, WA	$72.03
Southeast: AL, FL, GA, KY, MS, NC, SC, TN	$46.26
South Central: AR, LA, NM, OK, TX	$39.66
National Average	

ICF notes that the tipping fee for New York State is reported as about $72 with a standard deviation of nearly $30, which is the largest value reported for all the states in the Northeast, meaning that there is the largest range of tipping fees for states in the region. Higher tipping fees in areas like New York City, reporting in some instances of around $120 per ton, can help to offset the higher costs of food waste collection and digester systems. The values listed in Table 26 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. ICF developed cost estimates for New York State 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 $19.24/MMBtu to $30.24/MMBtu, with a weighted average cost of $23.86/MMBtu.

3.3.3 Landfill Gas

ICF developed assumptions for New York State by distinguishing between four types of landfills: (1) EPA candidate landfills[25] without collection systems in place, (2) EPA candidate landfills with collection systems in place, (3) other candidate landfills[26] without collection systems in place, and (4) other candidate landfills with collections systems in place.[27] 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 kilowatt-hours (kWh) per MMBtu of RNG injected and 6% of geological or fossil natural gas used in processing. Electricity costs and delivered natural gas costs are industrial rates reported at the State level by the EIA. Table 27 summarizes the key parameters that ICF employed in our cost analysis of LFG, while Table 28 provides example cost inputs for low- and high-cost LFG facilities.

Table 27. Cost Consideration in Levelized Cost of Gas Analysis for Renewable Natural Gas from Landfill Gas

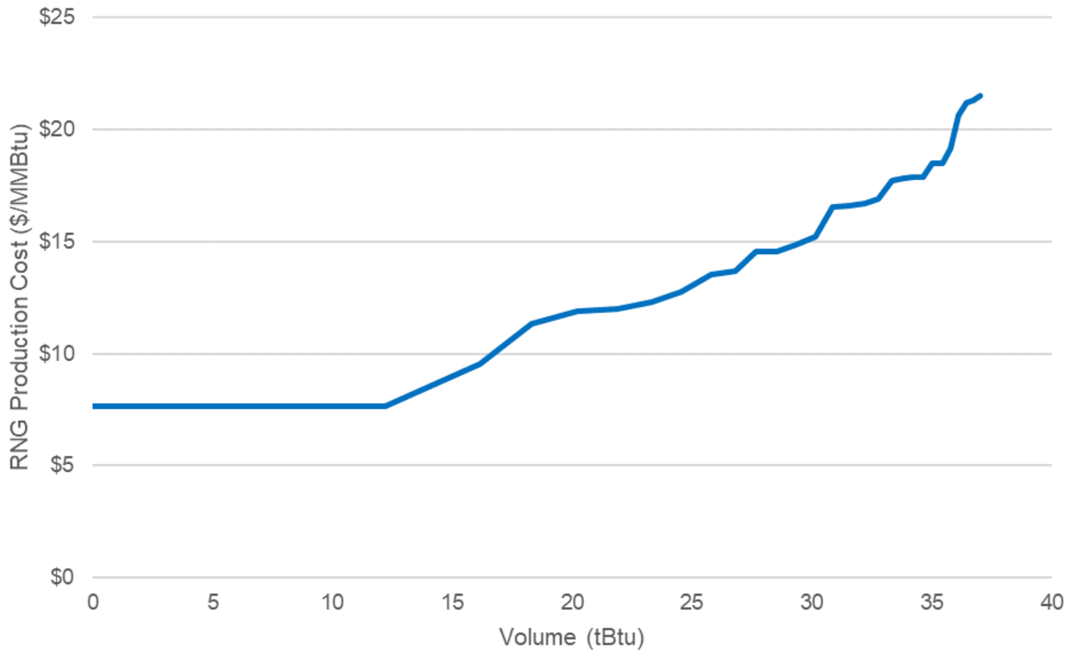
Factor	Cost Elements Considered	Costs
Performance	• Capacity factor	• 95%
Installation Costs	• Construction / Engineering • Owner's cost	• 25% of installed costs of equipment • 10% of installed costs of equipment
Gas Upgrading	• CO_2 separation • H_2S removal • N_2/O_2 removal • Siloxane removal	• $2.3 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	• Commercial rate of 14.8 ¢/kWh for state • Average of $7.58/MMBtu for state
Operations & Maintenance	• 1 FTE for maintenance • Miscellany	• 10% of installed capital costs
For Injection	• Interconnect • Pipeline • Compressor	• $1.5 million • $2 million • $0.13–$0.5 million
Financial Parameters	• Rate of return • Discount rate	• 10% • 7%

Table 28. Example Facility-Level Cost Inputs for Renewable Natural Gas from Landfill Gas

Factor	High Per Unit Production Cost	Low Per Unit Production Cost
Biogas production (SCFM)	240	4,800
Capital: collection	$0.17 million	$3.3 million
Capital: conditioning (CO2/O2 removal)	$0.85 million	$7.0 million
Capital: sulfur treatment	$0.1 million	$1.0 million
Capital: nitrogen rejection	$0.75 million	$2.5 million
Capital: compressor	$0.13 million	$0.45 million
Capital: pipeline (on-site)	$2.0 million	$2.0 million
Capital: utility interconnect	$1.5 million	$1.5 million
O&M: electricity and natural gas	$0.49 million	$9.7 million
Construction and engineering: installation	$0.96 million	$3.2 million
Construction and engineering: owner's cost	$0.38 million	$1.3 million

ICF reports an estimated cost of RNG from LFG of $7.67/MMBtu to $21.53/MMBtu, with a weighted average cost of $11.29/MMBtu. Figure 29 shows the supply-cost curve for RNG from landfill gas for New York State based on ICF's estimates.

Figure 29. Supply-Cost Curve for Renewable Natural Gas from Landfill Gas in New York State ($/MMBtu vs tBtu)



3.3.4 Water Resource Recovery Facilities

ICF developed assumptions for each region of NYS by distinguishing between WRRFs based on the throughput of the facilities. Table 29 includes the main assumptions used to estimate the cost of producing RNG at WRRFs, while the table that follows provides example cost inputs for low- and high-cost WRRF facilities.

Table 29. Cost Consideration in Levelized Cost of Gas Analysis for Renewable Natural Gas from Water Resource Recovery Facilities

Factor	Cost Elements Considered	Costs
Performance	• Capacity factor	• 95%
Installation Costs	• Construction / Engineering • Owner's cost	• 25% of installed costs of equipment • 10% of installed costs of equipment
Gas Upgrading	• CO_2 separation • H_2S removal • N_2/O_2 removal • Siloxane 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	• Industrial rate of 6.3 ¢/kWh for state • Average of \$7.58/MMBtu for state
Operations & Maintenance	• 1 FTE for maintenance • Miscellany	• 10% of installed capital costs
For Injection	• Interconnect • Pipeline • Compressor	• \$1.5 million • \$2 million • \$0.1–\$0.5 million
Financial Parameters	• Rate of return • Discount rate	• 10% • 7%

Table 30. Example Facility-Level Cost Inputs for Renewable Natural Gas from Water Resource Recovery Facilities

Factor	High Per Unit Production Cost	Low Per Unit Production Cost
Biogas production (SCFM)	60	1,270
Capital: collection	\$0.13 million	\$1.98 million
Capital: conditioning (CO2/O2 removal)	\$1.36 million	\$3.8 million
Capital: sulfur treatment	\$0.05 million	\$0.5 million
Capital: nitrogen rejection	\$0.20 million	\$2.5 million
Capital: compressor	\$0.10 million	\$0.33 million
Capital: pipeline (on-site)	\$2.0 million	\$2.0 million
Capital: utility interconnect	\$1.5 million	\$1.5 million
O&M: electricity and natural gas	\$0.12 million	\$2.58 million
Construction and engineering: installation	\$0.93 million	\$2.3 million
Construction and engineering: owner's cost	\$0.37 million	\$0.91 million

ICF notes that many wastewater treatment plants already have a digester in place as part of typical operations, and there are no additional costs assumed associated with building a digester. However, in the event that a new digester is required, or upgrades are required, the upfront capital expenditures will increase substantially compared to those listed in Table 30. While this additional cost might have a minor impact on the levelized costs of gas produced (because that cost is amortized over a 20-year lifetime of gas production), it may be a significant barrier to project execution by increasing the upfront costs to bring the project online. ICF reports an estimated cost of RNG from WRRFs of $13.36/MMBtu to $68.69/MMBtu, with a weighted average cost of $27.68/MMBtu. In the event that a new or refurbished digester is required, ICF estimates an additional cost of $1.45 to $3.20 per MMBtu depending on the system size and the specific site characteristics.

3.4 Renewable Natural Gas from Thermal Gasification

ICF used similar assumptions for RNG production from thermal gasification of feedstocks, including agricultural residue, forestry residue, energy crops, and MSW.[28] 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, with cost assumptions outlined in Table 31 and example cost inputs for low- and high-cost -thermal gasification facilities shown in Table 32.

Table 31. 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	• Commercial rate of 14.8¢/kWh for state • Average of \$7.58/MMBtu for state
Operations & Maintenance	• Feedstock • FTE for maintenance • Miscellany: water sourcing, treatment/disposal	• \$30/dry ton • 12% of installed capital costs
For Injection	• Interconnect • Pipeline	• \$2 million • \$1.5–\$7.2 million
Financial Parameters	• Rate of return • Discount rate	• 10% • 7%

Table 32. Example Facility-Level Cost Inputs for Renewable Natural Gas from Thermal Gasification

Factor	High Per Unit Production Cost	Low Per Unit Production Cost
Feedstock processed (tons/day)	200	2,000
Annual RNG production (MMBtu)	440,000	5,210,000
Capital: biomass handling and drying	\$6.3 million	\$27.3 million
Capital: gasification	\$18.0 million	\$86.9 million
Capital: syngas shifting	\$3.15 million	\$13.36 million
Capital: conditioning (CO2 removal)	\$7.39 million	\$34.17 million
Capital: cooling and water treatment	\$2.25 million	\$11.18 million
Capital: miscellaneous materials	\$7.48 million	\$32.01 million
Capital: methanation	\$6.17 million	\$27.26 million
Capital: electrical and controls	\$2.88 million	\$12.00 million
Capital: pipeline (on-site)	\$1.5 million	\$7.2 million
Capital: utility interconnect	\$2.0 million	\$2.0 million
O&M: electricity	\$2.93 million	\$29.34 million
Construction and engineering: installation	\$11.0 million	\$50.3 million
Construction and engineering: owner's cost	\$5.5 million	\$25.1 million

ICF reports estimated levelized costs of RNG from thermal gasification of \$19.87/MMBtu to \$39.78/MMBtu, with a weighted average cost of \$25.67/MMBtu.

Appendix A.

A.1 Renewable Natural Gas Potential by Region

A.1.1 Region 1—Western New York

Table A-1. Western New York Maximum Annual Renewable Natural Gas Production by Scenario (tBtu/yr.)

RNG Feedstock		Scenario: Limited Adoption	Scenario: Achievable Deployment	Scenario: Optimistic Growth
Anaerobic Digestion	Animal Manure	0.60	0.90	1.21
	Food Waste	0.21	0.28	0.36
	LFG	1.84	3.97	4.66
	WRRFs	0.19	0.25	0.35
	Subtotal	**2.84**	**5.41**	**6.57**
Thermal Gasification	Agricultural Residue	0.03	0.90	1.49
	Energy Crops	0.82	2.29	4.20
	Forestry and Forest Product Residue	0.02	0.49	3.76
	Municipal Solid Waste	1.07	1.79	2.24
	Subtotal	**1.95**	**5.47**	**11.69**
Total		**4.79**	**10.88**	**18.26**

A.1.2 Region 2—Finger Lakes

Table A-2. Finger Lakes Maximum Annual Renewable Natural Gas Production by Scenario (tBtu/yr.)

RNG Feedstock		Scenario: Limited Adoption	Scenario: Achievable Deployment	Scenario: Optimistic Growth
Anaerobic Digestion	Animal Manure	1.72	2.57	3.43
	Food Waste	0.22	0.30	0.38
	LFG	3.51	4.39	5.71
	WRRFs	0.08	0.10	0.14
	Subtotal	**5.52**	**7.37**	**9.66**
Thermal Gasification	Agricultural Residue	0.06	1.50	2.48
	Energy Crops	1.37	3.82	7.00
	Forestry and Forest Product Residue	0.01	0.13	1.01
	Municipal Solid Waste	0.94	1.56	1.95
	Subtotal	**2.37**	**7.00**	**12.43**
Total		**7.89**	**14.37**	**22.09**

A.1.3 Region 3—Southern Tier

Table A-3. Southern Tier Maximum Annual RNG Production by Scenario (tBtu/yr.)

RNG Feedstock				
		Limited Adoption	Achievable Deployment	c
Anaerobic Digestion	Animal Manure	0.63	0.95	1.27
	Food Waste	0.07	0.10	0.13
	LFG	0.67	0.95	1.29
	WRRFs	0.02	0.03	0.06
	Subtotal	**1.40**	**2.03**	**2.74**
Thermal Gasification	Agricultural Residue	0.05	1.21	1.99
	Energy Crops	1.10	3.07	5.64
	Forestry and Forest Product Residue	0.07	0.52	3.37
	Municipal Solid Waste	0.49	0.82	1.02
	Subtotal	**1.71**	**5.61**	**12.02**
Total		**3.11**	**7.64**	**14.76**

A.2 Region 4—Central New York

Table A-4. Central New York Maximum Annual Renewable Natural Gas Production by Scenario (tBtu/yr.)

RNG Feedstock		Scenario		
		Limited Adoption	Achievable Deployment	Optimistic Growth
Anaerobic Digestion	Animal Manure	0.99	1.49	1.98
	Food Waste	0.11	0.16	0.20
	LFG	0.46	0.70	0.97
	WRRFs	0.06	0.08	0.13
	Subtotal	**1.62**	**2.42**	**3.28**
Thermal Gasification	Agricultural Residue	0.03	0.82	1.35
	Energy Crops	0.75	2.08	3.81
	Forestry and Forest Product Residue	0.01	0.16	1.22
	Municipal Solid Waste	0.60	1.00	1.25
	Subtotal	**1.39**	**4.06**	**7.64**
Total		**3.01**	**6.49**	**10.92**

A.2.1 Region 5—North Country

Table A-5. North Country Maximum Annual Renewable Natural Gas Production by Scenario (tBtu/yr.)

RNG Feedstock		Scenario: Limited Adoption	Scenario: Achievable Deployment	Scenario: Optimistic Growth
Anaerobic Digestion	Animal Manure	1.19	1.78	2.37
	Food Waste	0.04	0.06	0.08
	LFG	0.63	0.79	1.02
	WRRFs	0.01	0.01	0.03
	Subtotal	**1.87**	**2.64**	**3.50**
Thermal Gasification	Agricultural Residue	0.04	0.98	1.62
	Energy Crops	0.90	2.49	4.58
	Forestry and Forest Product Residue	1.04	2.53	8.63
	Municipal Solid Waste	0.32	0.54	0.68
	Subtotal	**2.30**	**6.55**	**15.50**
Total		**4.17**	**9.18**	**18.99**

A.2.2 Region 6—Mohawk Valley

Table A-6. Mohawk Valley Maximum Annual Renewable Natural Gas Production by Scenario (tBtu/yr.)

RNG Feedstock		Scenario: Limited Adoption	Scenario: Achievable Deployment	Scenario: Optimistic Growth
Anaerobic Digestion	Animal Manure	0.41	0.61	0.81
	Food Waste	0.05	0.07	0.09
	LFG	0.33	0.41	0.53
	WRRFs	0.05	0.06	0.10
	Subtotal	**0.83**	**1.15**	**1.54**
Thermal Gasification	Agricultural Residue	0.03	0.67	1.10
	Energy Crops	0.61	1.70	3.12
	Forestry and Forest Product Residue	0.03	0.32	2.48
	Municipal Solid Waste	0.38	0.63	0.78
	Subtotal	**1.04**	**3.31**	**7.48**
Total		**1.88**	**4.47**	**9.02**

A.2.3 Region 7—Capital District

Table A-7. Capital District Maximum Annual Renewable Natural Gas Production by Scenario (tBtu/yr.)

RNG Feedstock		Scenario		
		Limited Adoption	Achievable Deployment	Optimistic Growth
Anaerobic Digestion	Animal Manure	0.46	0.69	0.93
	Food Waste	0.12	0.17	0.21
	LFG	0.81	1.07	1.42
	WRRFs	0.06	0.09	0.12
	Subtotal	**1.46**	**2.01**	**2.68**
Thermal Gasification	Agricultural Residue	0.04	0.96	1.58
	Energy Crops	0.87	2.43	4.46
	Forestry and Forest Product Residue	0.11	0.44	2.68
	Municipal Solid Waste	0.84	1.40	1.76
	Subtotal	**1.86**	**5.24**	**10.47**
Total		**3.32**	**7.25**	**13.15**

A.2.4 Region 8—Hudson Valley

Table A-8. Hudson Valley Maximum Annual Renewable Natural Gas Production by Scenario (tBtu/yr.)

RNG Feedstock		Scenario		
		Limited Adoption	Achievable Deployment	Optimistic Growth
Anaerobic Digestion	Animal Manure	0.06	0.09	0.13
	Food Waste	0.27	0.37	0.47
	LFG	0.44	0.55	0.71
	WRRFs	0.11	0.14	0.24
	Subtotal	**0.87**	**1.15**	**1.55**
Thermal Gasification	Agricultural Residue	0.01	0.34	0.56
	Energy Crops	0.31	0.87	1.60
	Forestry and Forest Product Residue	0.04	0.23	1.82
	Municipal Solid Waste	1.81	3.02	3.77
	Subtotal	**2.17**	**4.46**	**7.75**
Total		**3.05**	**5.61**	**9.30**

A.2.5 Region 9—New York City

Table A-9. New York City Maximum Annual Renewable Natural Gas Production by Scenario (tBtu/yr.)

RNG Feedstock		Scenario		
		Limited Adoption	Achievable Deployment	Optimistic Growth
Anaerobic Digestion	Animal Manure	-	-	-
	Food Waste	1.00	1.37	1.75
	LFG	4.88	6.10	7.93
	WRRFs	1.14	1.52	1.90
	Subtotal	**7.02**	**8.99**	**11.57**
Thermal Gasification	Agricultural Residue	-	-	-
	Energy Crops	-	-	-
	Forestry and Forest Product Residue	-	-	-
	Municipal Solid Waste	6.50	10.83	13.54
	Subtotal	**6.50**	**10.83**	**13.54**
Total		**13.51**	**19.82**	**25.11**

A.2.6 Region 10—Long Island

Table A-10. Long Island Maximum Annual Renewable Natural Gas Production by Scenario (tBtu/yr.)

RNG Feedstock		Scenario		
		Limited Adoption	Achievable Deployment	Optimistic Growth
Anaerobic Digestion	Animal Manure	0.00	0.00	0.01
	Food Waste	0.36	0.49	0.63
	LFG	0.35	0.43	0.57
	WRRFs	0.10	0.13	0.17
	Subtotal	**0.81**	**1.07**	**1.37**
Thermal Gasification	Agricultural Residue	0.00	0.03	0.06
	Energy Crops	0.03	0.08	0.16
	Forestry and Forest Product Residue	0.01	0.05	0.37
	Municipal Solid Waste	2.21	3.68	4.60
	Subtotal	**2.25**	**3.85**	**5.18**
Total		**3.06**	**4.92**	**6.56**

Endnotes

[1] NYSERDA, Patterns and Trends – New York State Energy Profile: 2003-2017, available online at https://www.nyserda.ny.gov/about/publications/ea-reports-and-studies/patterns-and-trends

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

[3] ICF notes that this is a useful definition but excludes RNG produced from the thermal gasification of the non-biogenic fraction of municipal solid waste (MSW). The thermal gasification of the non-biogenic fraction of MSW is projected to yield lower CO_2e emissions than geological natural gas and both the biogenic and non-biogenic portions of MSW are included in accessing the RNG resources in this study.

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

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[6] ICF estimates that there were about 17.5 trillion Btu (tBtu) of RNG produced in the United States for pipeline injection in 2016 and that there will be about 50 tBtu of RNG produced for pipeline injection by the end of 2020—this yields a compound annual growth rate of about 30%.

[7] NYS Empire State Development, 2020. https://esd.ny.gov/regions

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[10] NYSERDA, 2019. New York State GHG Inventory: 1990-2016, https://www.dec.ny.gov. file:///C:/Users/aidan.thompson/Downloads/greenhouse-gas-inventory%20(1).pdf

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[12] USDA, 2017. 2017 Census of Agriculture, https://www.nass.usda.gov/AgCensus/

[13] Per verbal feedback of NYSERDA staff.

[14] Percentages are rounded and may not sum to 100%.

[15] PPI, 2020. https://www.rit.edu/affiliate/nysp2i/organic-resource-locator

[16] NYC Department of Sanitation, 2017. 2017 Waste Characterization Study, https://dsny.cityofnewyork.us/wp-content/uploads/2018/04/2017-Waste-Characterization-Study.pdf

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[19] 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: https://wri.cals.cornell.edu/sites/wri.cals.cornell.edu/files/shared/documents/2013_Woodbury_Final.pdf.

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[23] DOE, 2011. 2011 Billion Ton Update – Assumptions and Implications Involving Forest Resources, https://www1.eere.energy.gov/bioenergy/pdfs/billion_ton_update.pdf

[24] Environmental Research & Education Foundation, Analysis of MSW Landfill Tipping Fees–2020. Retrieved from www.erefdn.org

[25] 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.

[26] Excluding those that are designated as EPA candidate landfills.

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

[28] Note that MSW here includes the non-organic, non-biogenic fraction of the MSW stream, and is therefore assumed to be a mix of biogenic and non-biogenic, including, but not limited to construction and demolition debris, paper and paperboard, plastics, rubber and leather, textiles, wood and yard trimmings.

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New York State Energy Research and Development Authority

17 Columbia Circle
Albany, NY 12203-6399

toll free: 866-NYSERDA
local: 518-862-1090
fax: 518-862-1091

info@nyserda.ny.gov
nyserda.ny.gov

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