Renewable Natural Gas Feasibility for the City of Austin

Final Report

July 2020

Submitted to:
ONE Gas
1301 S Mopac Expwy, Ste 400
Austin, TX 78746

Submitted by:
ICF Resources, L.L.C.
9300 Lee Highway
Fairfax, VA 22031

Contents

List of Figures

List of Tables

Executive Summary

The City of Austin has made long-term climate and clean energy commitments, including net-zero community-wide greenhouse gas (GHG) emissions by 2050, that will directly impact the natural gas system. As set out in the City of Austin resolution 202200220-047, [1] ONE Gas was directed by the City to conduct a Renewable Natural Gas (RNG) Feasibility Assessment that reviews the following:

- Opportunities for methane capture from and all sources in the Austin Area and in the surrounding region.
- The economic benefits of such opportunities for the City, gas providers, and ratepayers.
- Opportunities and benefits of the use of renewable credits and offsets to support sustainability goals.
- A target percentage of biomethane (and potentially, hydrogen) to be incorporated into the throughput of Texas Gas Service or other local distribution companies.
- A target date by which such percentage will be reached, to include interim goals for adoption.
- Options for a potential opt-in consumer renewable energy program modeled on the Austin Energy GreenChoice program.
- Local opportunities that retain revenue for the City.
- Options for Opportunities throughout the local economy, and how distribution companies can support local efforts.
- Options for offsets and renewable credits as another strategy for carbon emissions reductions.

Methodology

ICF was engaged by ONE Gas to conduct this feasibility assessment regarding the potential of RNG to contribute to meeting the City of Austin's clean energy objectives and address the issues raised in the resolution. To achieve the assessment objectives, ICF sought to address several questions, including:

- How much RNG can be produced in and around Austin, Texas and delivered to Austin, Texas from various feedstocks and via different production technologies?
- How much will it cost to produce RNG in and around Austin, Texas, with estimates out to 2050?
- What are the corresponding GHG emission reductions that might be achieved, and the associated costs, under different feedstock utilization scenarios?
- What are the potential economic and environmental impacts of deploying RNG to help meet the City of Austin's climate and clean energy objectives?

[1] City of Austin, 2020. Resolution no. 20200220-047, https://www.austintexas.gov/edims/document.cfm?id=336351

RNG is derived from biomass or other renewable resources and is a pipeline-quality gas that is fully interchangeable with conventional natural gas. As RNG is a “drop-in” replacement for natural gas, it can be safely employed in any end use typically fueled by natural gas, including electricity production, heating and cooling, industrial applications, and transportation. Today, about 50,000,000 million Btu per year (MMBtu/y) of RNG from landfills, dairy digesters, and water resource recovery facilities (WRRFs) is injected into pipelines, with production growing year-on-year.

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, WRRFs, agricultural residues, energy crops, forestry and forest product residues, and the nonbiogenic fraction of municipal solid waste (MSW). These feedstocks were assumed to be processed using one of two technologies to produce RNG: anaerobic digesters, and thermal gasification systems.

RNG 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 8,500,000 MMBtu/y and 33,400,000 MMBtu/y of RNG production by 2050, shown in the table below. For reference, total throughput in ONE Gas’s Central Texas natural gas system at roughly 23,300,000 MMBtu in 2019.

Summary of Estimated Annual RNG Production Potential by Scenario (MMBtu/y)

RNG Feedstock		Scenario		
		Limited Adoption	**Achievable Deployment**	**Optimistic Growth**
Anaerobic Digestion	Animal Manure	2,173,000	3,259,000	4,344,000
	Food Waste	156,000	453,000	577,000
	LFG	3,453,000	6,660,000	9,092,000
	WRRFs	159,000	320,000	441,000
Thermal Gasification	Agricultural Residue	578,000	1,283,000	1,633,000
	Energy Crops	811,000	8,107,000	11,653,000
	Forestry and Forest Product Residue	242,000	407,000	547,000
	Municipal Solid Waste	934,000	3,525,000	5,094,000
Total		**8,506,000**	**24,014,000**	**33,381,000**

In other words, using ICF's balanced assumptions regarding feedstock utilization and technology deployment in the three scenarios, there is enough RNG production potential to displace between 33% and 100% of ONE Gas's Central Texas natural gas system today. In addition, RNG resources in Travis County and the surrounding area could displace up to 75% of natural gas consumption in the Achievable Deployment scenario without accessing any potential RNG resources from outside the immediate region.

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

Summary of Estimated Cost Ranges by Feedstock Type

	Feedstock	Cost Range ($/MMBtu)
Anaerobic Digestion	Landfill Gas	$9.90 – $15.31
	Animal Manure	$22.00 – $45.16
	Water Resource Recovery Facilities	$10.87 – $33.26
	Food Waste	$20.40 – $29.60
Thermal Gasification	Agricultural Residues	$18.50 – $51.60
	Forestry and Forest Residues	$17.30 – $31.00
	Energy Crops	$18.30 – $56.10
	Municipal Solid Waste	$17.30 – $36.10

GHG Emission Reductions from RNG

RNG represents a valuable renewable energy source with a low or net negative carbon intensity depending on the feedstock. The GHG emission accounting methodology has a significant impact on how carbon intensities for RNG are estimated, with two methodologies used in this analysis to estimate GHG emission reductions relative to conventional natural gas consumption: a combustion accounting framework and a lifecycle accounting framework approach.

Using a combustion approach, ICF estimates that in the City of Austin region, 0.23 to 1.12 million metric tons (MMT) of GHG emissions could be reduced per year by 2050 through the deployment of RNG based on the Limited Adoption to Optimistic Growth scenarios. Expanding the geographic footprint to include RNG feedstocks from outside the immediate region, this increases to 0.45 to 1.78 MMT of GHG emissions that could be reduced per year by 2050. For comparison, the City of Austin's total direct GHG emissions in were 12.9 MMT in 2018.[2]

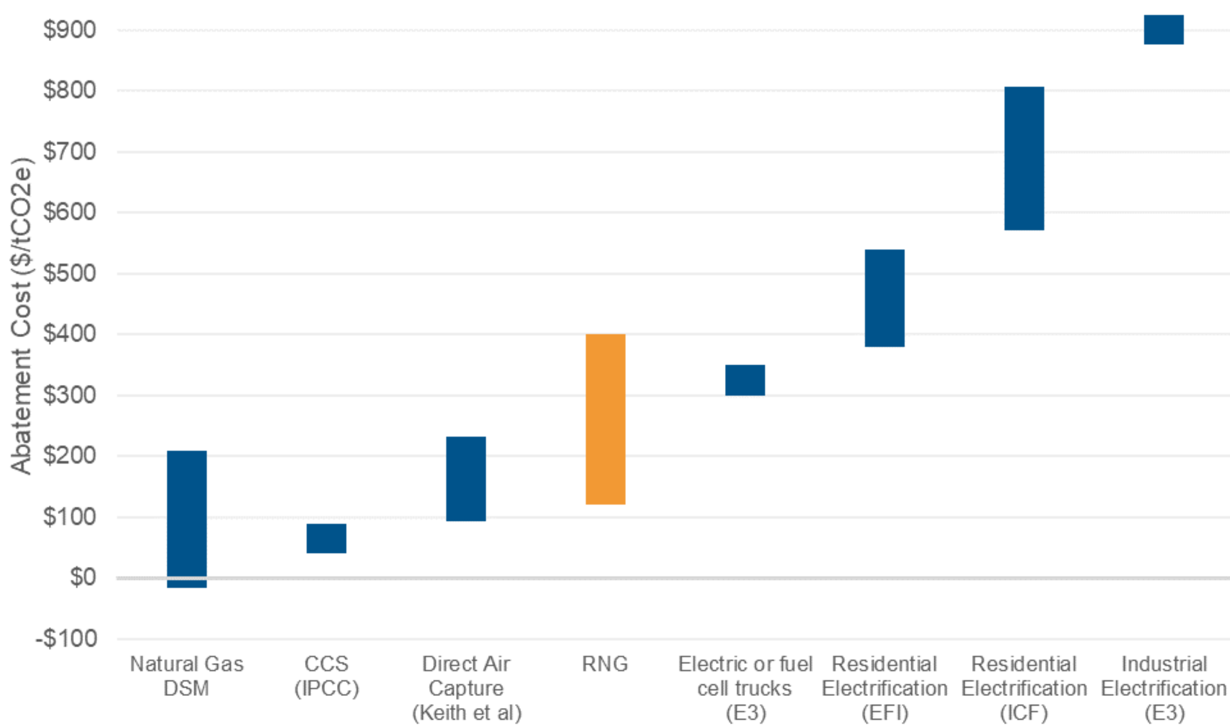
The GHG emission reduction estimates do not vary significantly with the use of a lifecycle accounting framework, with the total reductions ranging from 0.56 to 1.60 MMT of GHG emissions across the three scenarios in 2050.

[2] City of Austin, 2020. Austin Community Climate Plan, https://public.tableau.com/profile/cavan.merski#!/vizhome/CommunityInventoryMetricSprintDashboard/trend

RNG can play an important and cost-effective role to achieve aggressive decarbonization objectives over the long-term future, with ICF estimating GHG emission reductions at a cost of $120 to $400 per metric ton of carbon dioxide equivalent (tCO_2e). RNG is more expensive than its fossil counterpart, but in a decarbonization framework the proper comparison for RNG is to other abatement measures that are viewed as long-term strategies to reduce GHG emissions.

In this context, RNG is a cost-competitive option. The figure below shows a comparison of selected measures across various key studies for specific abatement measures that are likely to be required for economy-wide decarbonization by the 2050 timeframe, including natural gas demand side management (DSM), carbon capture and storage (CCS), RNG (from this study), direct air capture (whereby CO2 is captured directly from the air and a concentrated stream is sequestered or used for beneficial purposes), battery electric trucks (including fuel cell drivetrains), and electrification of certain end uses (including buildings and in the industrial sectors).

GHG Abatement Costs, Selected Measures ($/$tCO_2e$)



Economic Impacts

ICF employed IMPLAN, an input-output economic model, to quantify the economic impacts of producing RNG in Travis County, ONE Gas's Central Texas Service Area, and Texas. ICF accounted for multiple expenditures associated with RNG production from a variety of feedstocks relevant to Travis County and the surrounding region, including digester equipment, biogas conditioning equipment, miscellaneous support equipment, and construction/engineering costs; as well as pipeline for utility interconnection.

- Anaerobic digestion RNG production facilities on average will produce a total of 80—300 cumulative jobs per facility.

- These jobs have an expected average labor income of between $77,000 and $86,000 per job created, greater than the median household income in Travis County and Texas today. These jobs are created in sectors such as construction, engineering services, waste management, commercial and industrial machinery rental, and service industries (e.g., restaurants).
- For every job created through investment in anerobic digestion RNG production facilities, more than 2.2 jobs are created in supporting industries (indirect) and via spending by employees that are directly or indirectly supported by these industries (induced).
- Anerobic digestion RNG production facilities will also generate an average of $11-36 million of value-added economic output per facility, with an output multiplier of roughly 2, representing the total industry activity (including direct, indirect, and induced) divided by the direct industry activity.
- Thermal gasification facilities are likely to produce higher economic and employment impacts per facility relative to anaerobic digestion facilities, driven by larger-scale facilities and higher costs, although there remains uncertainty related to the development of the thermal gasification technology over time.

ICF's economic modeling results provide quantitative insights into the potential for renewable natural gas production in Travis County and the surrounding region, and presents a compelling economic opportunity for Travis County and the region.

Recommendations

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

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

Together, these three areas encompass the suite of actions that will help to realize the opportunities and overcome the challenges for RNG deployment in the City of Austin and surrounding region.

Strategic Direction

ICF recommends developing a strategic roadmap for regional policymakers and stakeholders based on a set of clear principles:

Principles:

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

RNG Deployment

The potential for RNG in the City of Austin and surrounding region's natural gas system is clear, with aggressive but attainable RNG throughput targets feasible over the medium-term and beyond. ICF's analysis of RNG potential at the local, regional, and national level supports the RNG volumes required to help decarbonize the region's natural gas system. However, ICF notes that for these broader RNG throughput targets to be cost-effective and successful, they would need to cover all natural gas distributors and suppliers in the region, and be supported by a broad and stable regulatory framework that provides a consistent RNG requirement across all suppliers and end users.

ONE Gas is well-positioned to take a leading role to facilitate the necessary development of RNG consumption in the natural gas system in the region, implemented through near-term voluntary throughput targets. Producing RNG from a local facility, such as from a landfill gas or wastewater facility in Travis County, could meet a near-term throughput target of 1–3%.

Market Approaches

- **Develop interconnection standards for RNG projects.** A consistent approach to evaluate RNG quality and constituent composition will facilitate the broader acceptance of different RNG feedstocks and encourage the development of RNG as a source for pipeline throughput and larger sources of demand (e.g., thermal use applications). ONE Gas has already developed these interconnection standards, and is ready to work with potential RNG project developers on interconnection.
- **Deploy RNG into the transportation market.** The transportation sector is a natural fit for the near-term focus of RNG deployment in the region: the combination of higher conventional energy costs and existing incentives makes for a clear opportunity. The market for RNG as a transportation fuel in the City of Austin and surrounding region should take advantage of other market forces, notably that California's market for natural gas as a transportation fuel is nearly saturated with RNG.
- **Establish common tracking across RNG markets**. A system to track and verify RNG in thermal use applications (i.e., outside of transportation and electricity sectors that currently have tracking systems in place) will become increasingly important as multiple sectors and regions seek to deploy RNG across various end uses.

Regulatory Approaches

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

- **Develop pilot or voluntary RNG procurement programs.** ICF recommends a near-term regulatory approach that supports voluntary purchase of RNG through gas utility service providers to help foster market growth, improve customer awareness, and satisfy nascent demand.
- **Expand RNG in the transportation sector through infrastructure investments.** ICF recommends an innovative regulatory structure whereby utilities are able to invest in NGV fueling infrastructure, offer beneficial and attractive tariffs to CNG users, and partner with key stakeholders to deploy CNG in key vehicle market segments.

- **Support the development of a broad and stable policy framework such as a Renewable Gas Standard.** ICF recommends that ONE Gas support a Renewable Gas Standard (RGS). This is the most robust policy structure, and it will help drive consistent demand in a diverse set of end uses, and assist the market to transition from a near-term focus on the transportation sector to a mid- to long-term focus on stationary uses in thermal applications. The RGS will act as a utility procurement mechanism, thereby providing supply and price certainty without disrupting the success and market participation in existing programs driving existing RNG deployment.

1. Introduction

ICF was engaged by ONE Gas to assess the potential of renewable natural gas (RNG) to contribute to meeting the City of Austin's clean energy objectives. The analysis is intended to help answer the following questions:

- How much RNG can be produced in and around Austin, Texas and delivered to Austin, Texas from various feedstocks?
- How much will it cost to produce RNG in and around Austin, Texas, with estimates out to 2050?
- What are the corresponding GHG emission reductions that might be achieved, and the associated costs, under different feedstock utilization scenarios?

The primary objective of the project is to characterize the technical and economic potential for RNG as a greenhouse gas (GHG) emission reduction strategy, with particular focus on local or regional resources in and around Austin, Texas. Further, the project will yield a series of deliverables that will support the City's and ONE Gas's efforts to improve the region's understanding and external stakeholders' understanding of the extent to which delivering RNG to all sectors of Austin's economy can contribute to broader GHG emission reduction initiatives.

The project is broken into eight tasks, outlined in the table below.

Table 1. Project Tasks

Task	Task Description
1	Develop Inventory of Potential RNG Sources
2	RNG Supply Assessment
3	Evaluate the Technical and Economic Potential of RNG for Austin, TX
4	Evaluation of GHG Reduction Potential of RNG in Austin, TX
5	Conduct RNG Policy Assessment
6	Assess Local and Regional Economic Impacts of RNG Deployment
7	Develop RNG Strategic Roadmap
8	Final Report

.

These tasks will cover the elements included in the City's Resolution No. 20200220-047, as outlined in the table below.[3]

Table 2. City of Austin Resolution Requirements

Task(s)	Feasibility Analysis Elements
Tasks 1 & 2	Opportunities for methane capture from and all sources in the Austin Area and in the surrounding region.
Tasks 3 & 6	The economic benefits of such opportunities for the City, gas providers, and ratepayers.
Tasks 4 & 5	Opportunities and benefits of the use of renewable credits and offsets to support sustainability goals.
Tasks 5 & 7	A target percentage of biomethane (and potentially, hydrogen) to be incorporated into the throughput of Texas Gas Service or other local distribution companies.
Tasks 5 & 6	A target date by which such percentage will be reached, to include interim goals for adoption.
Task 5	Options for a potential opt-in consumer renewable energy program modeled on the Austin Energy GreenChoice program.
Task 6	Local opportunities that retain revenue for the City.
Tasks 5-7	Options for Opportunities throughout the local economy, and how distribution companies can support local efforts.
Tasks 4-7	Options for offsets and renewable credits as another strategy for carbon emissions reductions.

Renewable Natural Gas

RNG is derived from biomass or other renewable resources, and is a pipeline-quality gas that is fully interchangeable with conventional natural gas. As a point of reference, the American Gas Association (AGA) uses the following definition for RNG:[4]

> *Pipeline-compatible gaseous fuel derived from biogenic or other renewable sources that has lower life cycle carbon dioxide equivalent (CO_2e) emissions than geological natural gas.* [5]

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

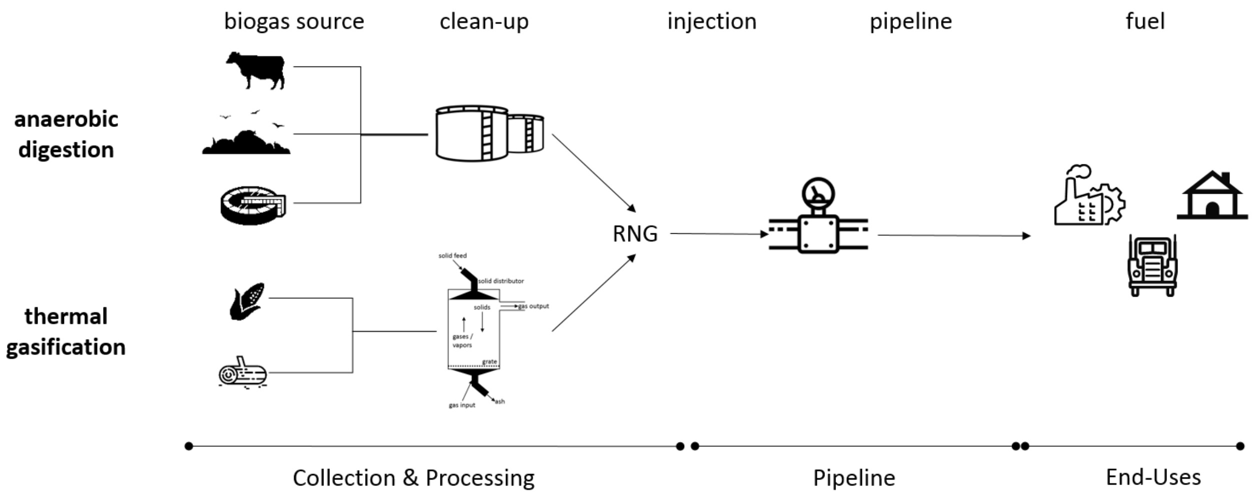
---

[3] City of Austin, 2020. Resolution No. 20200220-047, https://www.austintexas.gov/edims/document.cfm?id=336351

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

[5] 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). In most cases, however, the thermal gasification of the non-biogenic fraction of MSW yields lower CO_2e emissions than geological natural gas. As a result, MSW is included as an RNG resource in this study.

Figure 1. RNG Production Process via Anaerobic Digestion and Thermal Gasification



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. The four key processes in anaerobic digestion are:

- Hydrolysis
- Acidogenesis
- Acetogenesis
- Methanogenesis

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

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

Thermal Gasification

Biomass-like agricultural residues, forestry and forest produce residues, and energy crops have high energy content and are ideal candidates for thermal gasification. The thermal gasification of biomass to produce RNG occurs over a series of steps:

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

While biomass gasification technology is at an early stage of commercialization, the gasification and purification steps remain challenging. The gasification process typically yields a residual tar, which can foul downstream equipment. Furthermore, the presence of tar effectively precludes the use of a commercialized methanation unit. The high cost of conditioning the syngas in the presence of these tars has limited the potential for thermal gasification of biomass. For instance, in 1998, Tom Reed[6] 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 biomass, particularly agricultural residues, are often added to anaerobic digesters to increase gas production (by improving carbon-to-nitrogen ratios, especially in animal manure digesters). It is conceivable that some of the feedstocks considered here could be used in anaerobic digesters. For simplicity, ICF did not consider any multi-feedstock applications in our assessment; however, it is important to recognize that the RNG production market will continue to include mixed feedstock processing in a manner that is cost-effective.

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

2. RNG Feedstock Inventory

Summary

The following table summarizes the maximum RNG potential for each feedstock and production technology by geography of interest, in million Btu (MMBtu). The RNG potential includes different variables for each feedstock, but ultimately reflects the most aggressive options available, such as the highest biomass price and the utilization of all feedstocks at all facilities.

ICF emphasizes that the estimates included in the table below are based on the maximum RNG production potential from all feedstocks, and does not apply any economic or technical constraints on feedstock availability. An assessment of resource availability is presented in Section 3 of this report.

Table 3. RNG Production by Feedstock and Region (MMBtu/y)

RNG Feedstock	Travis County	ONE Gas Counties[7]	Rest of Texas	Texas
Animal Manure	452,000	14,239,000	251,967,000	266,659,000
Food Waste	334,000	234,000	7,378,000	7,946,000
Landfill Gas	5,803,000	892,000	98,461,000	105,156,000
Water Resource Recovery Facilities	257,000	80,000	4,395,000	4,731,000
Anaerobic Digestion Sub-Total	*6,846,000*	*15,445,000*	*362,201,000*	*384,492,000*
Agricultural Residue	83,000	941,000	43,282,000	44,307,000
Energy Crops	3,006,000	34,032,000	1,564,771,000	1,601,809,000
Forestry & Forest Product Residue	0	0	16,702,000	16,702,000
Municipal Solid Waste	3,079,000	2,360,000	64,635,000	70,074,000
Thermal Gasification Sub-Total	*6,168,000*	*37,334,000*	*1,689,391,000*	*1,732,892,000*
Total	**13,014,000**	**52,779,000**	**2,051,591,000**	**2,117,384,000**

[7] Discussed in further detail below, but includes other counties in ONE Gas's Central Texas Service Area: Caldwell, DeWitt, Gonzales, Hays, Lavaca, Williamson and Wilson.

RNG Feedstocks

RNG can be produced from a variety of renewable feedstocks, as described in the table below.

Table 4. RNG Feedstock Types

Feedstock for RNG		Description
Anaerobic Digestion	Animal manure	Manure produced by livestock, including dairy cows, beef cattle, swine, sheep, goats, poultry, and horses.
	Food waste	Commercial 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 non-biogenic fraction of waste that would be landfilled after diversion of other waste products (e.g., food waste or other organics), including construction and demolition debris, plastics, etc.

Inventory Methodology

The RNG feedstock inventory methodology is based on the objective of Task 1: identify the waste stream sources and feedstocks, and the corresponding technologies that can be used to produce RNG for a variety of end uses.

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

Table 5. List of Data Sources for RNG 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
Food waste	▪ U.S. Department of Energy (DOE) 2016 Billion Ton Report ▪ Bioenergy Knowledge Discovery Framework (KDF)
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	▪ U.S. DOE 2016 Billion Ton Report ▪ Bioenergy Knowledge Discovery Framework
Energy crops	▪ U.S. DOE 2016 Billion Ton Report ▪ Bioenergy Knowledge Discovery Framework
Forestry and forest product residue	▪ U.S. DOE 2016 Billion Ton Report ▪ Bioenergy Knowledge Discovery Framework
MSW	▪ U.S. DOE 2016 Billion Ton Report ▪ Waste Business Journal

This RNG feedstock inventory does not take into account resource availability—in a competitive market, resource availability is a function of factors, including but not limited to demand, feedstock costs, technological development, and the policies in place that might support RNG project development. ICF assessed the RNG resource potential of the different feedstocks that could be realized given the necessary market considerations (without explicitly defining what those are), outlined in Section 3.

Geography

Consistent across all feedstocks, we present RNG potential at the local, regional and state levels. The local level is defined as Travis County, and regional encompasses the surrounding counties that broadly reflect ONE Gas's Central Texas Service Area (CTX) – Caldwell, DeWitt, Gonzales, Hays, Lavaca, Williamson and Wilson. We also provide RNG feedstock information for the rest of Texas, and the Texas total.

RNG: Anaerobic Digestion of Biogenic or Renewable Resources

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 U.S. 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:[8]

- 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 lagoon), and gas handling equipment. There are a variety of livestock manure processing systems that are employed at farms today, including plug-flow or mixed plug-flow digesters, complete-mixed digesters, covered lagoons, fixed-film digesters, sequencing-batch reactors, and induced-blanked digesters. Most dairy manure projects today use the plug-flow or mixed plug-flow digesters.

ICF considered animal manure from a variety of animal populations, including beef and dairy cows, broiler chickens, layer chickens, turkeys, and swine. Animal populations were derived from the United States Department of Agriculture's (USDA) National Agricultural Statistics Service. ICF used information provided from the most recent census year (2017) and extracted total animal populations on a county and state level.[9] Based on this information, ICF identified animal populations at the local level by county, and for the rest of Texas.

ICF developed the maximum RNG potential using animal manure production and the energy content of dried manure taken from a California Energy Commission report prepared by the California Biomass Collaborative.[10] These inputs are summarized in the table below.

---

[8] More information available online at https://www.epa.gov/agstar/benefits-anaerobic-digestion.
[9] USDA, 2017. 2017 Census of Agriculture, https://www.nass.usda.gov/AgCensus/index.php
[10] Williams, R. B., B. M. Jenkins and S. Kaffka (California Biomass Collaborative). 2015. An Assessment of Biomass Resources in California, 2013 – DRAFT. Contractor Report to the California Energy Commission. PIER Contract 500-11-020. Available online here.

Table 6. Key Parameters for Animal Manure Resource RNG Potential

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

The U.S. EPA AgStar database indicates that there are 2 operational anaerobic digesters at farms in Texas, both in Dallam County. These two digesters use the biogas for on-site boiler or furnace fuel use.

The animal manure inventory does not identify specific facilities or locations where RNG will likely be produced. However, concentrated animal feeding operations (CAFOs) provide an indication of where RNG from animal manure could be produced. For example, of the 30 existing anaerobic digesters at farms in New York State, 29 are also licensed CAFOs.

The existing accumulation of animal manure at CAFOs located near pipeline infrastructure could conceivably increase the productive potential of animal manure as an RNG feedstock. The U.S. EPA reports that there are over 1,000 CAFOs in Texas, indicating that the infrastructure for the concentration of animal manure may not be a barrier to growth in RNG production from animal manure.

The table below shows the volume of animal feedstock available and maximum RNG potential in Travis County, surrounding CTX counties, and the rest of Texas. Note that the maximum RNG potential does not take into account the numerous limiting factors that would constrain the volume of RNG that could be produced from animal manure.

Table 7. Animal Manure Resource RNG Potential

Region	Animal Head Count (millions)	Maximum RNG Potential (MMBtu)
Travis County	0.25	452,000
Other CTX	21.26	14,239,000
Rest of Texas	137.56	251,967,000
Texas	159.07	266,659,000

Food Waste

Food waste is a major component of MSW—accounting for about 15% of MSW streams. More than 75% of food waste is landfilled. Food waste can be diverted from landfills to a composting or processing facility where it can be treated in an anaerobic digester. ICF limited our consideration to the potential for utilizing the food waste that is currently landfilled as a feedstock for RNG production via AD, thereby excluding the 25% of food waste that is recycled or directed to waste-to-energy facilities.

ICF extracted county and state level information from the U.S. DOE's Bioenergy Knowledge Discovery Framework (KDF), which includes information collected as part of U.S. DOE's Billion Ton Report (updated in 2016). The Bioenergy KDF includes food waste at tipping fee price points ranging from $70/ton to $100/ton. ICF assumed a high heating value of 12.04 MMBtu/ton (dry). Note that the values from the Bioenergy KDF are reported in dry tons, so the moisture content of the food waste has already been accounted for in the DOE's resource assessment.

As food waste is generated from population centers and typically diverted at waste transfer stations rather than delivered to landfills, it is challenging to identify specific facilities or projects that will generate RNG from food waste. However, food waste can potentially utilize existing or future AD systems at LFG and WRRF facilities. The table below shows the maximum volume of food waste available, and the maximum RNG potential in Travis County, surrounding CTX counties, and the rest of Texas, noting that no limiting factors were applied to the RNG potential.

Table 8. Maximum Food Waste Potential by Region in 2050

Region	Maximum Production (dry tons)	Maximum RNG Potential (MMBtu)
Travis County	27,756	334,000
Other CTX	19,442	234,000
Rest of Texas	612,985	7,378,000
Texas	660,183	7,946,000

Landfill Gas

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

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

Table 9. Landfill Gas Constituents and Corresponding Upgrading Technologies

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

To estimate the feedstock potential of LFG, ICF used outputs from the LandGEM model, which is an automated tool with a Microsoft Excel interface developed by the U.S. 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 U.S. EPA, which included more than 2,000 landfills, with 128 in Texas and included in the inventory.

The U.S. EPA's LMOP database shows that there are 30 operational, under construction or planned LFG-to-energy projects in Texas. 15 of the projects capture LFG and combust it in reciprocating engines to make electricity, 14 produce RNG, and one landfill has direct use for the energy (e.g., thermal use on-site).

The U.S. EPA currently estimates that there are 53 candidate landfills in Texas that could capture LFG for use as energy—the U.S. 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. Candidate landfills can also be designated based on actual interest by the site.

Table 10. Texas Landfills by Region[11]

Region	Landfills	Landfill-to-Energy Projects	EPA Candidate Landfills
Travis County	4	2	-
Other CTX	2	1	1
Rest of Texas	122	27	52
Texas	128	30	53

There are four large landfills in Travis County that have more than one million tons of WIP, as well as one in neighboring Williamson County, outlined in the table below. Due to the minimal and declining methane production of waste after 25 years in landfills, ICF typically only considers RNG potential from landfills that are either open or were closed post-2000.

Table 11. Landfills in CTX Service Area

Landfill	County	Status	Landfill-to-Energy	RNG Potential (MMBtu/year)
Austin Community RDF	Travis	Open	Electricity	2,115,000
Texas Disposal Systems LF	Travis	Open	Planned	1,549,000
Sunset Farms Landfill	Travis	Closed (2016)	Shutdown	2,138,000
FM 812 Landfill	Travis	Closed (1999)	Shutdown	N/A
Williamson County LF	Williamson	Open	Construction	892,000

The table below shows overall maximum RNG potential from LFG facilities in Travis County, surrounding CTX counties, and the rest of Texas.

Table 12. RNG Potential from Texas Landfills by Region

Region	Landfills	RNG Potential (MMBtu/y)
Travis County	3	5,803,000
Other CTX	1	892,000
Rest of Texas	94	98,461,000
Texas	98	105,156,000

Water Resource Recovery Facilities

Wastewater is created from residences and commercial or industrial facilities, and it consists primarily of waste liquids and solids from household water usage, from commercial water usage, or from industrial processes. Depending on the architecture of the sewer system and local regulation, it may also contain storm water from roofs, streets, or other runoff areas. The contents of the wastewater may include anything which is expelled (legally or not) from a

[11] Based on data from the LMOP at the U.S. EPA (updated December 2019).

household and enters the drains. If storm water is included in the wastewater sewer flow, it may also contain components collected during runoff: soil, metals, organic compounds, animal waste, oils, and solid debris such as leaves and branches.

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

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

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

To determine the WRRFs in Texas, ICF used the Clean Watersheds Needs Survey (CWNS) conducted in 2012 by the U.S. EPA, an assessment of capital investment needed for wastewater collection and treatment facilities to meet the water quality goals of the Clean Water Act, and includes more than 14,500 WRRFs. ICF distinguishes between facilities based on location and facility size as a measure of average flow (in units of million gallons per day, MGD). ICF also reviewed more than 1,200 facilities that are reported to have anaerobic digesters in place, as reported by the Water Environment Federation.

To estimate the amount of RNG produced from wastewater at WRRFs, ICF used data reported by the U.S. EPA,[12] a study of WRRFs in New York State,[13] and previous work published by AGF.[14] ICF used an average energy yield of 7.003 MMBtu/MG of wastewater.

There are 551 WRRFs in Texas, with a total flow of over 1,850 MGD. There are 13 WRRFs in Travis County, representing flow of 100 MGD, with a further 16 WRRFs in the surrounding CTX counties, but 15 of these are small WRRFs with a combined flow of 15 MGD.

---

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

[13] Wightman, J and Woodbury, P., Current and Potential Methane Production for Electricity and Heat from New York State Wastewater Treatment Plants, New York State Water Resources Institute at Cornell University. Available online here.

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

Of the 551 WRRFs, 35 have anaerobic digestion systems with a total flow of 680 MGD, or 38% of Texas's total flow. None of these WRRFs with anaerobic digestion systems are in Travis County or the surrounding CTX counties. The table summarizes WRRFs by flow and RNG potential.

Table 13. Texas WRRFs by Existing Flow [15]

Region	Large WRRFs (>7.25 MGD)	Small WRRFs (<7.25 MGD)	Total Flow (MGD)	RNG Potential (MMBtu/y)
Travis County	3	10	100.6	257,000
Other CTX	1	15	31.2	80,000
Rest of Texas	41	481	1,719.2	4,395,000
Texas	45	506	1,850.9	4,731,000

RNG: Thermal Gasification of Biogenic or Renewable 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 that biomass gasification technology is at an early stage of commercialization, RNG production potential for these feedstocks cannot be determined to a facility-specific level, in contrast to other feedstocks such as LFG and WRRFs. However, sources of thermal gasification feedstocks can be approximated at a regional level based on existing land use patterns and population levels. The specific approach for each feedstock is outlined below.

To estimate the RNG production potential, ICF assumed a 65% efficiency for thermal gasification systems. This factor is based in part on the 2011 AGF Report on RNG, indicating a range of thermal gasification efficiencies in the range of 60% to 70%, depending upon the configuration and process conditions. The report authors also used a conversion efficiency of 65% in their assessment. More recently, GTI estimated the potential for RNG from the thermal gasification of wood waste in California, and assumed a conversion efficiency of 60%.[16]

Agricultural Residues

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

ICF extracted information from the U.S. DOE Bioenergy KDF, including the following agricultural residues relevant to Texas: corn stover, sorghum stubble and wheat straw. These estimates are based on modeling undertaken as part of the 2016 Billion Ton Study, and utilizes the Policy

[15] Based on data from the LMOP at the U.S. EPA (updated December 2019).
[16] GTI, Low-Carbon Renewable Natural Gas from Wood Wastes, February 2019, available online at https://www.gti.energy/wp-content/uploads/2019/02/Low-Carbon-Renewable-Natural-Gas-RNG-from-Wood-Wastes-Final-Report-Feb2019.pdf

Analysis System (POLYSYS), a policy simulation model of the U.S. agricultural sector. The POLYSYS modeling framework simulates how commodity markets balance supply and demand via price adjustments based on known economic relationships, and is intended to reflect how agricultural producers respond to new and different agricultural market opportunities, such as for biomass. Available biomass is constrained to not exceed the tolerable soil loss limit of the USDA Natural Resources Conservation Service and to not allow long-term reduction of soil organic carbon

POLYSYS simulates exogenous price changes introduced as a farmgate price, which then solves for biomass supplies that may be brought to market in response to these prices. The farmgate price is held constant nationwide in all counties over all years of the simulation to allow farmers to respond by changing crops and practices gradually over time. [17]

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

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

ICF extracted data from the Bioenergy KDF at $10 price point increments, from $30/ton to $100/ton, that showed variation in production potential for agricultural residue biomass from 2025 out to 2040.

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

Table 14. Heating Values for Agricultural Residues

Agricultural Component	Btu/lb, dry	MMBtu/ton, dry
Corn stover	7,587	15.174
Sorghum stubble	6,620	13.240
Wheat straw	7,527	15.054

Agricultural residue is distributed proportionally by county based on state share of farmland, with total acreage of agricultural land in Texas taken from the USDA 2017 Census of Agriculture. Travis County accounts for 0.2% of farmland in Texas, while the surrounding CTX counties make up an another 2.1%. The table below shows an annotated summary of the maximum agricultural residue potential at different biomass prices in 2050, broken down by region.

[17] DOE, 2016. 2016 Billion Ton Report, https://www.energy.gov/eere/bioenergy/2016-billion-ton-report.

Table 15. Agricultural Residue Production Potential in 2050 by Region (dry tons)

Region	Biomass Price $30	Biomass Price $50	Biomass Price $100
Travis County	6,336	7,959	8,556
Other CTX	71,742	90,108	96,868
Rest of Texas	3,298,633	4,143,086	4,453,926
Texas	3,376,711	4,241,152	4,559,350

Using the heating values outlined above and assuming a 65% efficiency for thermal gasification systems, ICF estimated the RNG production potential from agricultural residue feedstocks at the different biomass prices in 2050, broken down by region.

Table 16. Agricultural Residue RNG Production Potential in 2050 by Region (MMBtu/y)

Region	Biomass Price $30	Biomass Price $50	Biomass Price $100
Travis County	61,446	77,395	83,142
Other CTX	695,696	876,273	941,343
Rest of Texas	31,987,531	40,290,312	43,282,144
Texas	32,744,674	41,243,981	44,306,629

Energy Crops

Energy crops are inclusive of perennial grasses, trees, and some annual crops that can be grown specifically to supply large volumes of uniform, consistent quality feedstocks for energy production. Energy crop estimates are based on the same modeling framework used to derive the agricultural residue estimates, outlined in the previous section. With respect to land use, 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. ICF extracted data from the Bioenergy KDF 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.

The table below lists the energy content on an HHV basis for the various energy crops relevant to Texas.

Table 17. 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

Similar to the approach taken above for agricultural residue, energy crop production is distributed proportionally by county based on state share of farmland, with total acreage of agricultural land in Texas taken from the USDA 2017 Census of Agriculture. Travis County accounts for 0.2% of farmland in Texas, while the surrounding CTX counties make up an another 2.1%. The table below shows the maximum energy crop production potential broken down by region.

Table 18. Energy Crop Production Potential in 2050 by Region (dry tons)

Region	Biomass Price $30	Biomass Price $40	Biomass Price $60	Biomass Price $100
Travis County	6,805	120,818	275,675	293,480
Other CTX	77,046	1,367,913	3,121,209	3,322,804
Rest of Texas	3,542,527	62,895,492	143,510,579	152,779,739
Texas	3,626,378	64,384,223	146,907,462	156,396,023

Using the heating values outlined above and assuming a 65% efficiency for thermal gasification systems, ICF estimated the RNG production potential from energy crop feedstocks at the different biomass prices in 2050, broken down by region.

Table 19. Energy Crop RNG Production Potential in 2050 by Region (MMBtu/y)

Region	Biomass Price $30	Biomass Price $40	Biomass Price $60	Biomass Price $100
Travis County	70,097	1,242,015	2,829,669	3,005,823
Other CTX	793,641	14,062,192	32,037,735	34,032,171
Rest of Texas	36,490,936	64,567,850	1,473,068,324	1,564,770,826
Texas	37,354,674	661,872,057	1,507,935,728	1,601,808,820

Forestry and Forest Product Residues

Forestry and forest product residues 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 U.S. DOE Billion Ton Update. The updated DOE Billion Ton study was altered to include additional sustainability criteria. Some of the changes included: [18]

- 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%).

[18] DOE, 2011. *2011 Billion Ton Update – Assumptions and Implications Involving Forest Resources*, http://web.ornl.gov/sci/ees/cbes/workshops/Stokes_B.pdf

- Removal of reserved (e.g., wild and scenic rivers, wilderness areas, USFS special interest areas, national parks) and roadless designated forestlands, forests on steep slopes and in wet land areas (e.g., stream management zones), and sites requiring cable systems.
- The assumptions only include thinnings for over-stocked stands and didn't include removals greater than the anticipated forest growth in a state.
- No road building greater than 0.5 miles.

These additional sustainability criteria provide a more realistic assessment of available forestland than other studies.

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

ICF extracted data from the Bioenergy KDF at three price points, $30/ton, $50/ton and $60/ton, that showed variation in production potential for forest and forest product residue biomass from 2025 out to 2040.

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

Table 20. Heating Values for Forestry and Forest Product Residues

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

The table below shows the maximum forestry and forest product residue potential broken down by region at different biomass price points. Based on data extracted from Bioenergy KDF, there are no forestry operations or forestry residues available for RNG production in Travis County, or surrounding CTX counties, although there are potential production volumes elsewhere in Texas.

Table 21. Forestry and Forest Product Residue Production Potential in 2050 by Region (dry tons)

Region	Biomass Price $30	Biomass Price $50	Biomass Price $60
Travis County	-	-	-
Other CTX	-	-	-
Rest of Texas	913,597	1,323,754	1,918,261
Texas	913,597	1,323,754	1,918,261

Using the heating values outlined above and assuming a 65% efficiency for thermal gasification systems, ICF estimated the RNG production potential from forestry and forest product residue feedstocks at the different biomass prices in 2050, broken down by region.

Table 22. Forestry and Forest Product Residue RNG Production Potential in 2050 by Region (MMBtu/y)

Region	Biomass Price $30	Biomass Price $50	Biomass Price $100
Travis County	-	-	-
Other CTX	-	-	-
Rest of Texas	7,719,895	11,387,059	16,702,475
Texas	7,719,895	11,387,059	16,702,475

Municipal Solid Waste

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

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

ICF extracted information from the U.S. DOE's Bioenergy KDF, which includes information collected as part of U.S. DOE's Billion Ton Report (updated in 2016). The Bioenergy KDF includes the following waste residues: construction and demolition (C&D) debris, paper and paperboard, plastics, rubber and leather, textiles, wood, yard trimmings, and other. ICF extracted data from the Bioenergy KDF at price points between $30/ton and $70/ton.

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

Table 23. Heating Values for MSW 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

The table below shows the maximum MSW potential broken down by region at a price of $70/ton. Regional proportions are based on population weighting by region in Texas, as MSW generation is typically tied to population levels. Travis County accounts for 4.4% of Texas's population, with the surrounding CTX counties making up another 3.4%.

Table 24. MSW Production Potential at $70 by Region (dry tons)

Region	Paper & Paperboard	Plastics	Rubber & Leather	Textiles	Yard Trimmings	Total
Travis County	58,813	72,995	16,084	29,991	14,846	192,729
Other CTX	42,728	53,031	11,685	21,789	10,786	140,019
Rest of Texas	1,237,076	1,535,380	338,304	630,827	312,281	4,053,868
Texas	1,338,617	1,661,407	366,073	682,606	337,913	4,386,616

Using the heating values outlined above and assuming a 65% efficiency for thermal gasification systems, ICF estimated the RNG production potential from MSW at a price of $70/ton, broken down by region.

Table 25. RNG Production Potential from MSW at $70 by Region (MMBtu/y)

Region	Paper & Paperboard	Plastics	Rubber & Leather	Textiles	Yard Trimmings	Total
Travis County	584,131	1,821,957	236,269	311,904	124,487	3,078,748
Other CTX	447,792	1,396,703	181,123	239,104	95,431	2,360,154
Rest of Texas	12,263,220	38,250,059	4,960,221	6,548,094	2,613,482	64,635,076
Texas	13,295,144	41,468,719	5,377,612	7,099,102	2,833,401	70,073,978

3. RNG Supply Curves

Supply Curve Methodology

ICF developed economic supply curves for three separate scenarios for each feedstock included in the RNG inventory in Section 2.

The RNG potential 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 we have seen over the last five years—a rate of about 35%.[19] ICF applied a logistic function to model the growth potential of the RNG production, whereby the initial stage of growth is approximated as an exponential, and thereafter growth slows to a linear rate and then approaches a plateau (or limited to no growth) at maturity.

Scenarios

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

- **Limited Adoption** represents a low level of feedstock utilization, with utilization levels depending on feedstock, with a range from 15% to 40% for feedstocks that were converted to RNG using anaerobic digestion technologies. The utilization rates of feedstocks for thermal gasification in this scenario ranges from 20% to 30%, at lower biomass prices. Overall, the Limited Adoption scenario captures 7% of the RNG feedstock resource in the CTX Service Area, based on the inventory developed in Section 2.
- **Achievable Deployment** represents balanced assumptions regarding feedstock utilization, with a range from 25% to 65% for feedstocks that were converted to RNG using anaerobic digestion technologies. The utilization rates of feedstocks for thermal gasification in this scenario ranges from 20% to 50% at low to medium biomass prices. Overall, the Achievable Deployment scenario captures 25% of the RNG feedstock resource available in the CTX Service Area.

[19] ICF estimates that there were about 17,500,000 MMBtu of RNG produced for pipeline injection in 2016 and that there will be about 50,000,000 MMBtu of RNG produced for pipeline injection be the end of 2020—this yields a compound annual growth rate of about 30%.

- **Optimistic Growth** represents higher levels of utilization, and delivers 31% of the technical potential of RNG feedstocks in the CTX Service Area. Utilization levels vary by feedstock, with a range from 30% to 80% for feedstocks that were converted to RNG using anaerobic digestion technologies. The utilization rates of feedstocks for thermal gasification in this scenario ranged from 20% to 70% at higher biomass prices. It is worth reiterating that the Optimistic Growth scenario does not represent a maximum achievable or technical potential scenario.

In the following sub-sections, ICF outlines the potential for RNG for pipeline injection, broken down by the feedstocks presented previously and considering the potential for RNG growth over time, with 2050 being 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.

Geography

Consistent with Section 2, we present RNG potential at the local, regional and state levels. The local level is defined as Travis County, and regional encompasses the surrounding counties that broadly reflect ONE Gas's Central Texas Service Area (CTX) – Caldwell, DeWitt, Gonzales, Hays, Lavaca, Williamson and Wilson.

ICF also includes separate estimates for the rest of Texas and nationally. These estimates are weighted by the share of natural gas consumption of ONE Gas's CTX Service Area (including Travis County) relative to the applicable geography. Natural gas consumption estimates are sourced from the EIA and include residential, commercial, industrial and transportation consumption.

Summary of RNG Potential by Geography

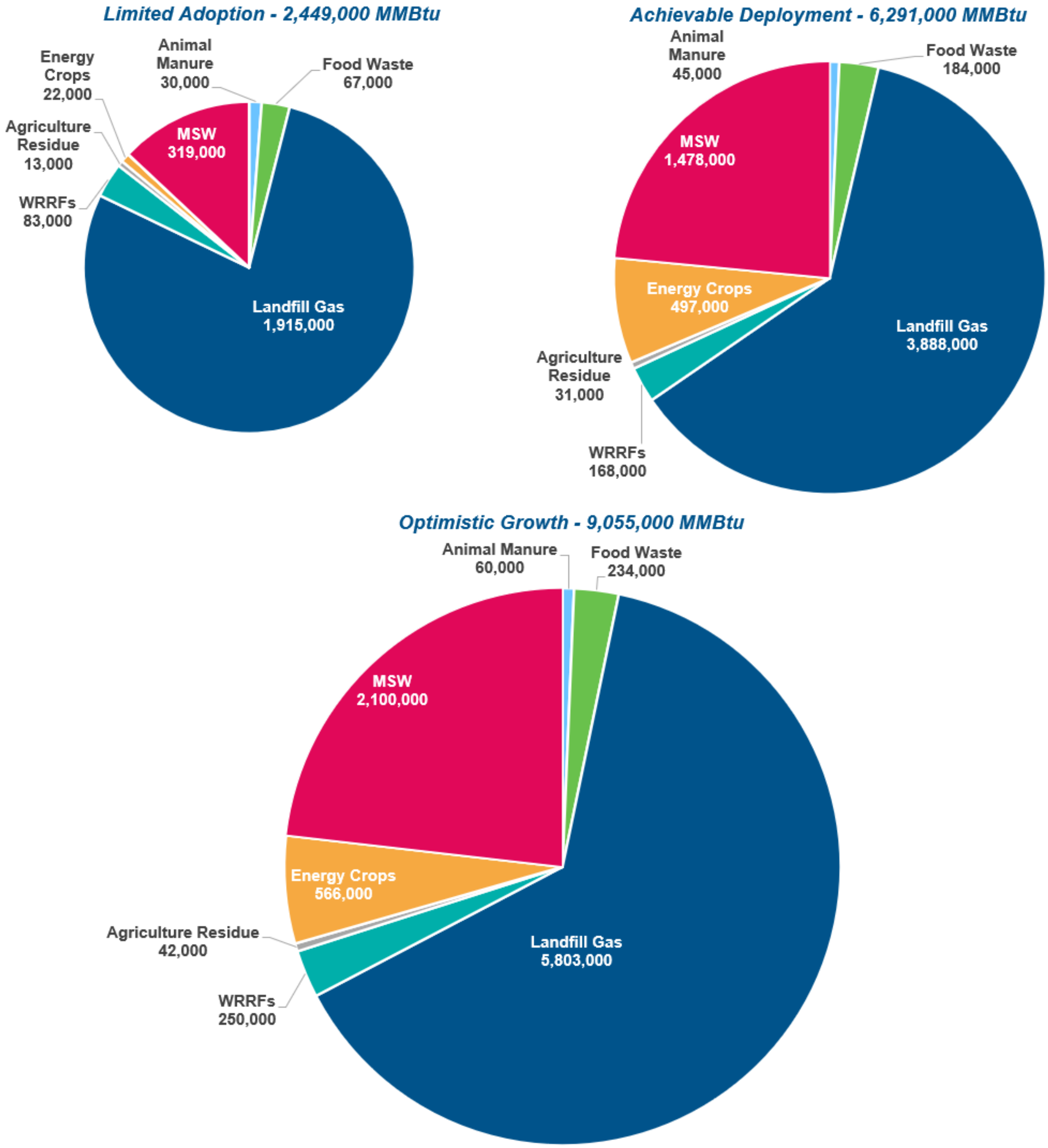
The following subsections summarize the RNG potential for each feedstock and production technology by scenario and geography of interest.

Travis County

The figure below includes estimates for Travis County for the Limited Adoption, Achievable Deployment and Optimistic Growth scenarios, and shows the development potential of each feedstock in 2050, reported in units of million Btu per year (MMBtu/y).

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

Figure 2. Estimated Annual RNG Production in Travis County by 2050 (MMBtu/y)



The Limited Adoption scenario captures less than 20% of the total resource available, as outlined in the inventory as part of Task 1. This proportions increases to nearly 50% in the Achievable Deployment scenario, and rising again to 70% in the Optimistic Growth scenario.

ONE Gas Central Texas Service Area

The table below includes estimates for ONE Gas's CTX Service Area, including Travis County, for the Limited Adoption, Achievable Deployment and Optimistic Growth scenarios. The table shows the development potential of each feedstock in 2050, reported in units of MMBtu/y. For reference, with total throughput in ONE Gas's Central Texas natural gas system at roughly 23,300,000 MMBtu in 2019, local RNG resources could displace up to 75% of natural gas consumption in the Achievable Deployment scenario without accessing any potential RNG resources from outside the immediate region.

Expanding the geography to the CTX Service Area delivers greater volumes of RNG feedstocks in all scenarios, with the Achievable Deployment and Optimistic Growth scenarios more than doubling the potential RNG available relative to the same scenarios limited to Travis County. With the inclusion of the surrounding less urbanized counties, animal manure and energy crops become important potential sources of RNG.

Table 26. Estimated Annual RNG Production in CTX Service Area by 2050 (MMBtu/y)

RNG Feedstock		Scenario		
		Limited Adoption	Achievable Deployment	Optimistic Growth
Anaerobic Digestion	Animal Manure	1,190,000	1,785,000	2,379,000
	Food Waste	95,000	312,000	398,000
	LFG	1,915,000	4,780,000	6,695,000
	WRRFs	82,000	209,000	307,000
Thermal Gasification	Agricultural Residue	151,000	381,000	512,000
	Energy Crops	259,000	6,122,000	6,973,000
	Forestry and Forest Product Residue	-	-	-
	Municipal Solid Waste	563,000	2,609,000	3,709,000
Total		**4,255,000**	**16,198,000**	**20,973,000**
Percentage of Total Available Feedstock[20]		**6.5%**	**24.6%**	**31.9%**

[20] Total feedstock reflects the maximum volume of RNG feedstocks available in the CTX Service Area, including all facilities and all biomass.

Rest of Texas

Table 27 below includes estimates for the rest of Texas for the Limited Adoption, Achievable Deployment and Optimistic Growth scenarios, and excludes the above RNG estimates for the CTX Service Area. The estimates are weighted by the share of natural gas consumption of ONE Gas's CTX Service Area (including Travis County) relative to Texas's total, a share of roughly 1% based on Texas's natural gas consumption of approximately 2,250 bcf in 2018.[21] Table 27 also shows the development potential of each feedstock in 2050, reported in units of MMBtu/y.

Table 27. Estimated Annual RNG Production in the Rest of Texas by 2050 (MMBtu/y)

RNG Feedstock		Scenario		
		Limited Adoption	Achievable Deployment	Optimistic Growth
Anaerobic Digestion	Animal Manure	188,000	282,000	376,000
	Food Waste	10,000	40,000	51,000
	LFG	244,000	488,000	650,000
	WRRFs	13,000	19,000	23,000
Thermal Gasification	Agricultural Residue	63,000	160,000	215,000
	Energy Crops	72,000	1,282,000	2,921,000
	Forestry and Forest Product Residue	23,000	56,000	99,000
	Municipal Solid Waste	66,000	307,000	437,000
Total		**680,000**	**2,635,000**	**4,772,000**
Percentage of Total Available Feedstock[22]		**0.03%**	**0.13%**	**0.23%**

[21] EIA, 2020. https://www.eia.gov/dnav/ng/ng_cons_sum_dcu_nus_a.htm
[22] Total feedstock reflects the maximum volume of RNG feedstocks available in Texas, including all facilities and all biomass.

National

Table 28 below includes estimates for the U.S., excluding Texas, for the Limited Adoption, Achievable Deployment and Optimistic Growth scenarios. The estimates are weighted by the share of natural gas consumption of ONE Gas's CTX Service Area relative to the U.S. total, equivalent to a share of roughly 0.1%. The table also shows the development potential of each feedstock in 2050, reported in units of MMBtu/y.

Table 28. Estimated Annual RNG Production in the U.S. (excl Texas) by 2050 (MMBtu/y)

RNG Feedstock		Scenario		
		Limited Adoption	Achievable Deployment	Optimistic Growth
Anaerobic Digestion	Animal Manure	795,000	1,192,000	1,589,000
	Food Waste	51,000	100,000	128,000
	LFG	1,294,000	1,392,000	1,746,000
	WRRFs	63,000	92,000	112,000
Thermal Gasification	Agricultural Residue	363,000	741,000	906,000
	Energy Crops	479,000	703,000	1,759,000
	Forestry and Forest Product Residue	219,000	350,000	447,000
	Municipal Solid Waste	306,000	608,000	949,000
Total		**3,571,000**	**5,180,000**	**7,635,000**
Percentage of Total Available Feedstock[23]		**0.03%**	**0.04%**	**0.06%**

[23] Total feedstock reflects the maximum volume of RNG feedstocks available in the U.S. excluding Texas, including all facilities and all biomass.

Summary of RNG Potential by Scenario

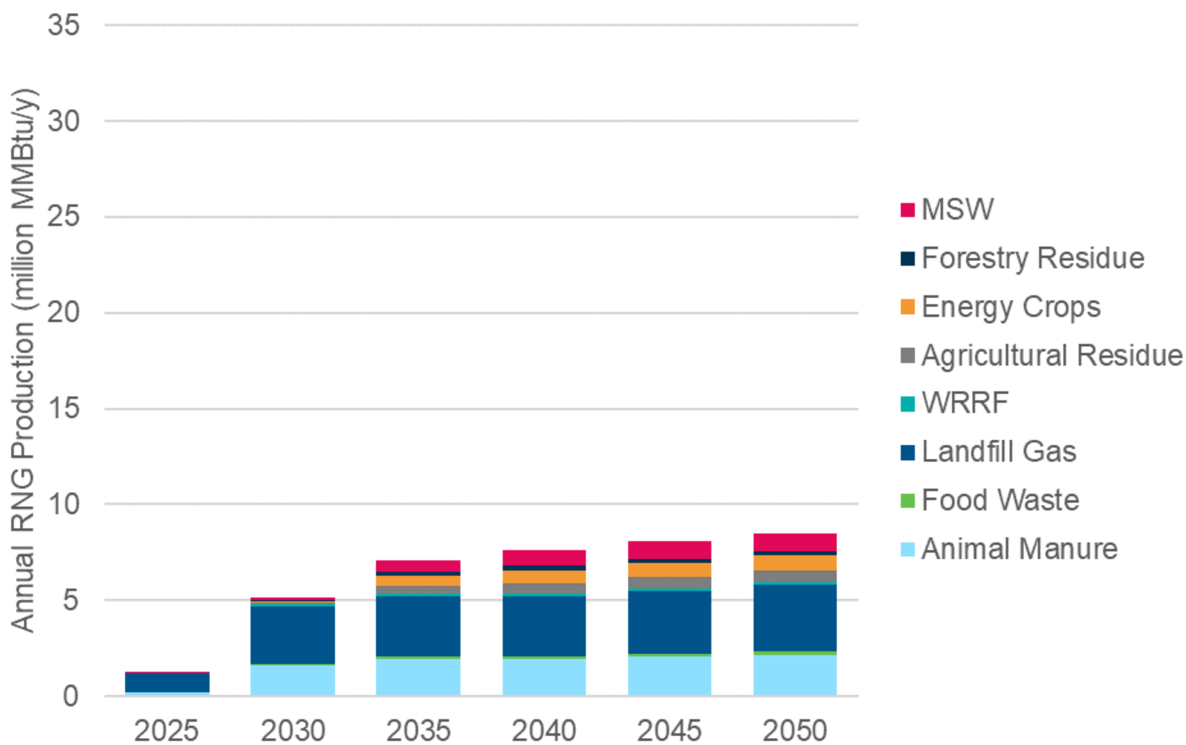
The following subsections show the total RNG potential for each feedstock and production technology by geography for each scenario.

Limited Adoption Scenario

Table 29. Limited Adoption Scenario Annual RNG Production (MMBtu/y)

RNG Feedstock		Geography				
		Travis County	Other CTX	Rest of Texas	Rest of US	Total
Anaerobic Digestion	Animal Manure	30,000	1,160,000	188,000	795,000	**2,173,000**
	Food Waste	67,000	28,000	10,000	51,000	**156,000**
	LFG	1,915,000	0	244,000	1,294,000	**3,453,000**
	WRRFs	82,000	0	13,000	63,000	**159,000**
Thermal Gasification	Agricultural Residue	12,000	139,000	63,000	363,000	**578,000**
	Energy Crops	21,000	238,000	72,000	479,000	**811,000**
	Forestry Residue	0	0	23,000	219,000	**242,000**
	MSW	318,000	244,000	66,000	306,000	**934,000**
Total		**2,446,000**	**1,809,000**	**680,000**	**3,571,000**	**8,506,000**

Figure 3. Estimated Annual RNG Production, Limited Adoption Scenario (million MMBtu/y)

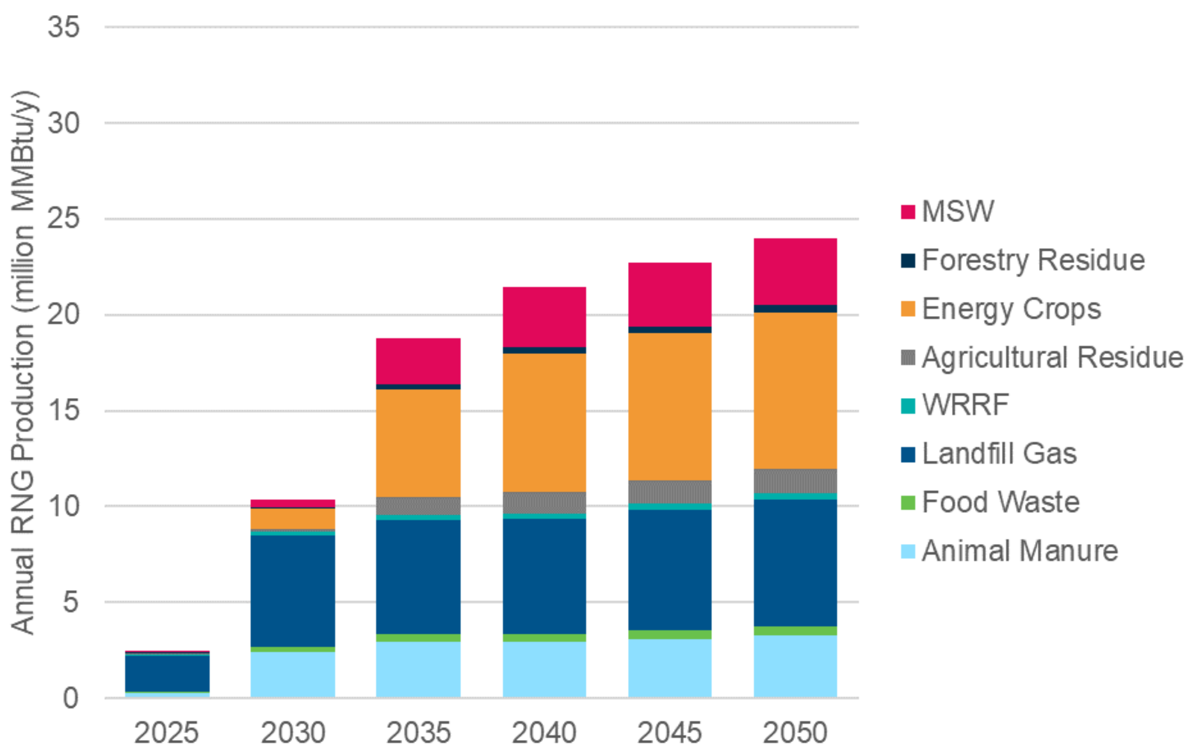


Achievable Deployment Scenario

Table 30. Achievable Deployment Scenario Annual RNG Production (MMBtu/y)

RNG Feedstock		Geography				
		Travis County	Other CTX	Rest of Texas	Rest of US	Total
Anaerobic Digestion	Animal Manure	45,000	1,740,000	282,000	1,192,000	**3,259,000**
	Food Waste	184,000	129,000	40,000	100,000	**453,000**
	LFG	3,888,000	892,000	488,000	1,392,000	**6,660,000**
	WRRFs	167,000	41,000	19,000	92,000	**320,000**
Thermal Gasification	Agricultural Residue	31,000	351,000	160,000	741,000	**1,283,000**
	Energy Crops	497,000	5,625,000	1,282,000	703,000	**8,107,000**
	Forestry Residue	0	0	56,000	350,000	**407,000**
	MSW	1,477,000	1,132,000	307,000	608,000	**3,525,000**
Total		**6,289,000**	**9,910,000**	**2,635,000**	**5,180,000**	**24,014,000**

Figure 4. Estimated Annual RNG Production, Achievable Deployment Scenario (million MMBtu/y)

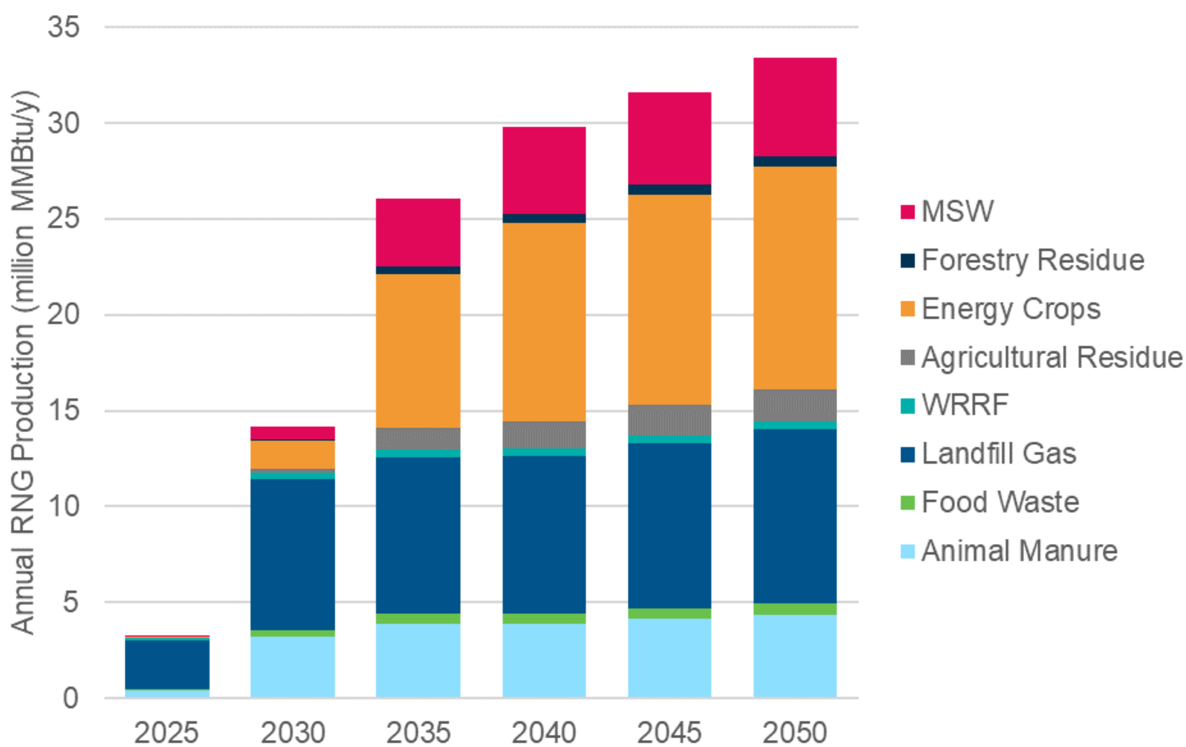


Optimistic Growth Scenario

Table 31. Optimistic Growth Scenario Annual RNG Production (MMBtu/y)

RNG Feedstock		Geography				
		Travis County	Other CTX	Rest of Texas	Rest of US	Total
Anaerobic Digestion	Animal Manure	60,000	2,320,000	376,000	1,589,000	**4,344,000**
	Food Waste	234,000	164,000	51,000	128,000	**577,000**
	LFG	5,803,000	892,000	650,000	1,746,000	**9,092,000**
	WRRFs	250,000	57,000	23,000	112,000	**441,000**
Thermal Gasification	Agricultural Residue	42,000	471,000	215,000	906,000	**1,633,000**
	Energy Crops	566,000	6,408,000	2,921,000	1,759,000	**11,653,000**
	Forestry Residue	0	0	99,000	447,000	**547,000**
	MSW	2,099,000	1,609,000	437,000	949,000	**5,094,000**
Total		**9,053,000**	**11,920,000**	**4,772,000**	**7,635,000**	**33,381,000**

Figure 5. Estimated Annual RNG Production, Optimistic Growth Scenario (million MMBtu/y)



RNG: Anaerobic Digestion of Biogenic or Renewable Resources

Animal Manure

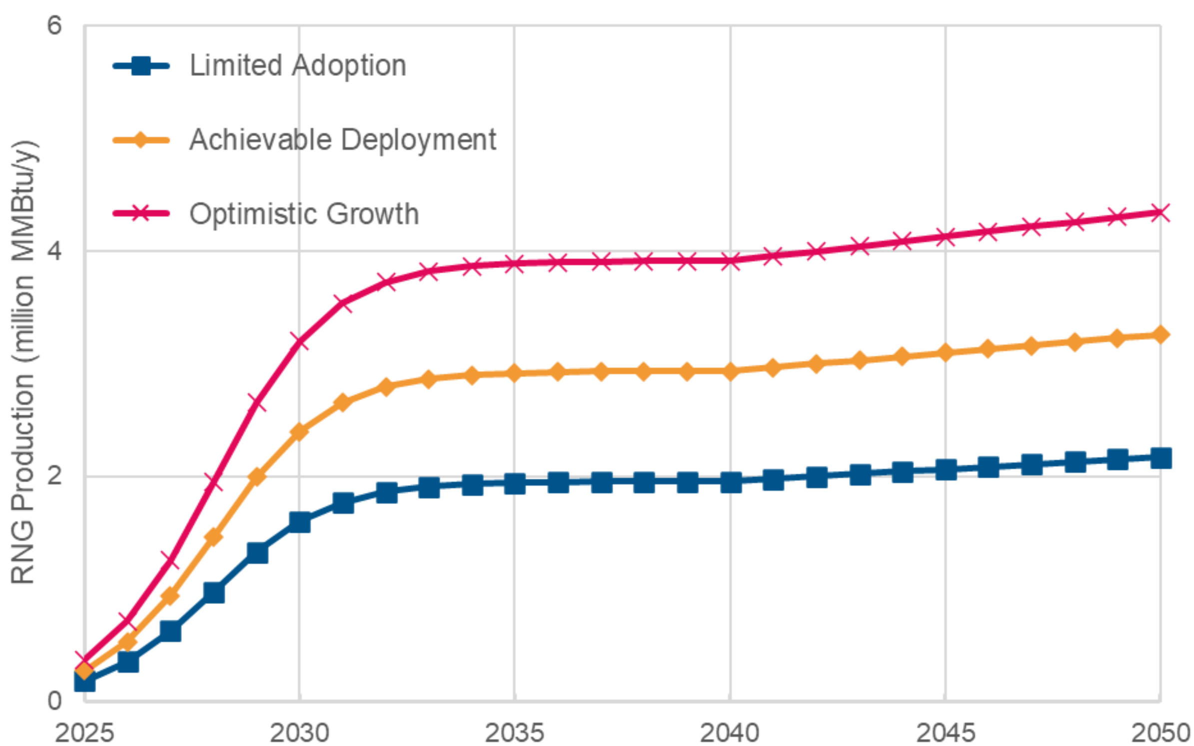
Prior to the application of economic and market constraints for animal manure as an RNG feedstock, ICF applied technical availability factors to each manure type to reflect that not all animal manure can be collected, due to practical considerations such as small farming operations and the inability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

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

- In the Limited Adoption scenario, ICF assumed that RNG could be produced from 30% of the animal manure, after accounting for the technical availability factor.
- In the Achievable Deployment scenario, ICF assumed that RNG could be produced from 45% of the animal manure, after accounting for the technical availability factor.
- In the Optimistic Growth scenario, ICF assumed that RNG could be produced from 60% of the animal manure, after accounting for the technical availability factor.

The figure below shows the Limited Adoption, Achievable Deployment and Optimistic Growth resource potential from animal manure between 2025 and 2050.

Figure 6. Annual RNG Production Potential from Animal Manure (million MMBtu/y)



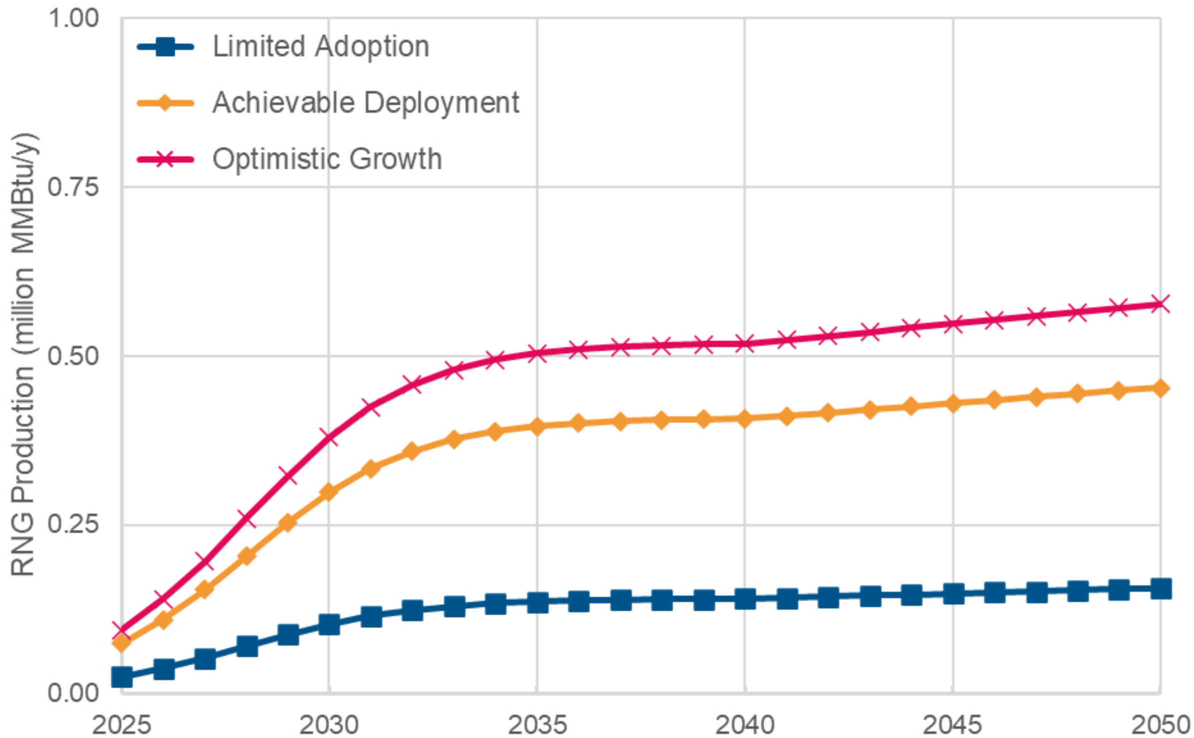
Food Waste

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

The figure below shows the Limited Adoption, Achievable Deployment and Optimistic Growth RNG resource potential scenarios from the anaerobic digestion of food waste between 2025 and 2050.

Figure 7. Annual RNG Production Potential from Food Waste (million MMBtu/y)



Landfill Gas

To develop the RNG potential from LFG, ICF extracted data from the Landfill Methane Outreach Program (LMOP) administered by the U.S. EPA, which included more than 2,000 landfills, with 128 in Texas and included in the inventory.

The U.S. EPA's LMOP database shows that there are 30 operational, under construction or planned LFG-to-energy projects in Texas. 15 of the projects capture LFG and combust it in reciprocating engines to make electricity, 14 produce RNG, and one landfill has direct use for the energy (e.g., thermal use on-site).

The U.S. EPA currently estimates that there are 53 candidate landfills in Texas that could capture LFG for use as energy—the U.S. 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. Candidate landfills can also be designated based on actual interest by the site.

Table 32. Texas Landfills by Region[24]

Region	Landfills	Landfill-to-Energy Projects	EPA Candidate Landfills
Travis County	4	2	-
Other CTX	2	1	1
Rest of Texas	122	27	52
Texas	128	30	53

There are four large landfills in Travis County that have more than one million tons of WIP, as well as one in neighboring Williamson County, outlined in the table below. Due to the minimal and declining methane production of waste after 25 years in landfills, ICF typically only considers RNG potential from landfills that are either open or were closed post-2000.

Table 33. Landfills in CTX Service Area

Landfill	County	Status	Landfill-to-Energy	RNG Potential (MMBtu/year)
Austin Community RDF	Travis	Open	Electricity	2,115,000
Texas Disposal Systems LF	Travis	Open	Planned	1,549,000
Sunset Farms Landfill	Travis	Closed (2016)	Shutdown	2,138,000
FM 812 Landfill	Travis	Closed (1999)	Shutdown	N/A
Williamson County LF	Williamson	Open	Construction	892,000

Due to the minimal and declining methane production of waste after 25 years in landfills, in building the scenarios ICF considered only landfills that are either open or were closed post-2000. This reduced the number of landfills included in our analysis to 30.

ICF developed assumptions for the resource potentials for RNG production at landfills in the three scenarios, considering the potential at LFG facilities with collection systems in place, LFG facilities that do not have collection systems in place, and candidate landfills identified by the U.S. EPA. As the number of eligible LFG facilities varies significantly by region, ICF applied different proportional limitations depending on the geography, as outlined below.

- In the Limited Adoption scenario, ICF assumed that one of the three LFG facilities in Travis County produce RNG, the candidate landfill in Williamson County does not produce RNG. In the rest of Texas a quarter of LFG facilities across the three categories are assumed to produce RNG. For the rest of the U.S., ICF assumed that RNG could be produced at 40% of

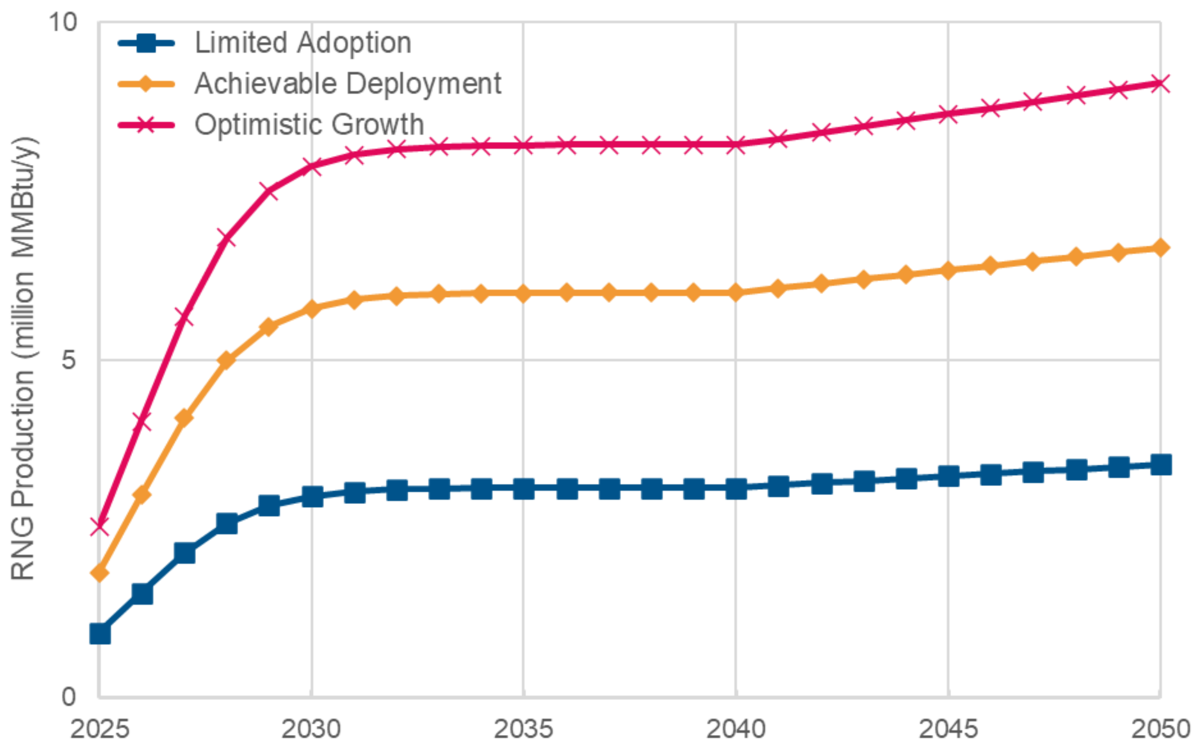
[24] Based on data from the LMOP at the U.S. EPA (updated December 2019).

the LFG facilities that have collection systems in place, 30% of the LFG facilities that do not have collection systems in place, and at 50% of the candidate landfills.

- In the Achievable Deployment scenario, ICF assumed that two of the three LFG facilities in Travis County and the candidate landfill in Williamson County produce RNG. In the rest of Texas one half of LFG facilities across the three categories are assumed to produce RNG. For the rest of the U.S., ICF assumed that RNG could be produced at 50% of the LFG facilities that have collection systems in place, 45% of the LFG facilities that do not have collection systems in place, and at 65% of the candidate landfills.
- In the Optimistic Growth scenario, ICF assumed that all three LFG facilities in Travis County and the candidate landfill in Williamson County produce RNG. In the rest of Texas and 75% of LFG facilities across the three categories are assumed to produce RNG. For the rest of the U.S., ICF assumed that RNG could be produced at 65% of the LFG facilities that have collection systems in place, 60% of the LFG facilities that do not have collection systems in place, and at 80% of the candidate landfills.

The figure below shows the Limited Adoption, Achievable Deployment and Optimistic Growth RNG resource potential from LFG between 2025 and 2050.

Figure 8. Annual RNG Production Potential from Landfill Gas (million MMBtu/y)



Water Resource Recovery Facilities

There are 551 WRRFs in Texas, with a total flow of over 1,850 MGD. There are 13 WRRFs in Travis County, representing flow of 100 MGD, with a further 16 WRRFs in the surrounding CTX counties, but 15 of these are small WRRFs with a combined flow of 15 MGD.

Of the 551 WRRFs, 35 have anaerobic digestion systems with a total flow of 680 MGD, or 38% of Texas's total flow. While none of these WRRFs with anaerobic digestion systems are in Travis County or the surrounding CTX counties, it is worth noting that there is an anaerobic digestion system at the Hornsby Bend biosolids management plant and takes in feedstock from the two largest WRRFs by flow in Travis County, the South Austin Regional and Walnut Creek facilities (see box below for more detail).

WRRFs and RNG Potential in Austin

Austin Water has two major wastewater treatment plants in Travis County: Walnut Creek and South Austin Regional. The water utility also manages a biosolids facility at Hornsby Bend, which has a well-established anaerobic digestion system, including eight digesters.

The treatment processes at the two WRRFs generate sludge that is pumped directly to the Hornsby Bend facility. These solids are then processed at the facility to produce compost for land application and public sales.

As part of this process the digesters also produce raw biogas. Over 600 standard cubic feet per minute (scfm) of biogas is produced, and this is forecast to grow to 800–1,000 scfm by 2040, largely driven by population growth. Currently, the facility utilizes less than half of the biogas for beneficial on-site use: a portion is used to fuel a combined heat and power (CHP) system for power and heat generation, and another portion fuels hot water boilers as needed for digester heating. The excess biogas not utilized in the CHP system or boilers is flared to the ambient atmosphere.

The Hornsby Bend facility provides an opportunity for more productive and enhanced uses of the waste feedstock from the two WRRFs, and avoid the flaring of excess biogas. Investment in the conditioning and upgrade of the biogas to produce pipeline-quality RNG would provide a near-term opportunity for the development, production and injection of locally-sourced RNG. In addition, the facility is located adjacent to ONE Gas's natural gas distribution infrastructure along State Route 973, avoiding more costly and challenging pipeline interconnection requirements.

RNG produced from Hornsby Bend could be directed towards use in the transportation sector, potentially providing environmental credits to offset the higher production costs associated with RNG. The role and benefits of RNG consumption in the transportation sector is discussed in more detail in Section 6.

The table below summarizes WRRFs by flow and RNG potential.

Table 34. Texas WRRFs by Existing Flow [25]

Region	Large WRRFs (>7.25 MGD)	Small WRRFs (<7.25 MGD)	Total Flow (MGD)	RNG Potential (MMBtu/y)
Travis County	3	10	100.6	257,000
Other CTX	1	15	31.2	80,000
Rest of Texas	41	481	1,719.2	4,395,000
Texas	45	506	1,850.9	4,731,000

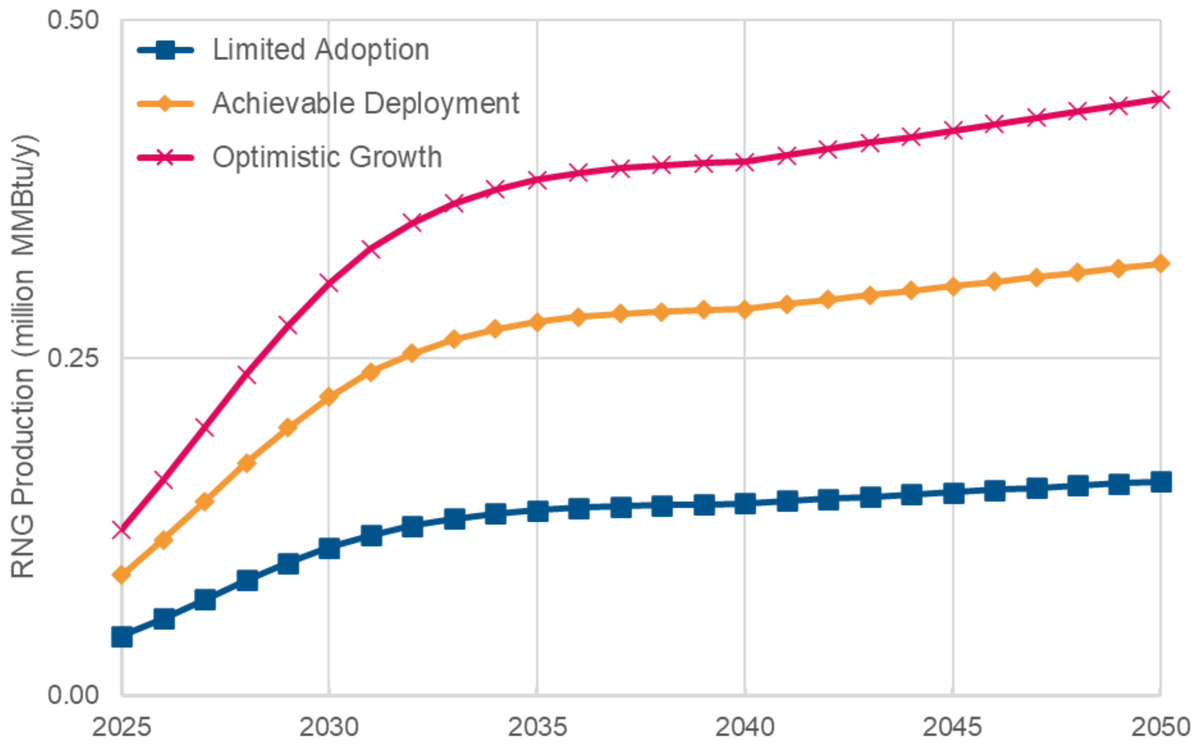
Similar to LFG facilities, as the number of WRRFs varies significantly by region, ICF applied different proportional limitations depending on the geography, as outlined below. ICF developed the following assumptions for the resource potentials for RNG production at WRRFs in the three scenarios:

- In the Limited Adoption scenario, ICF assumed that one of the three WRRFs in Travis County with a capacity greater than 7.25 MGD would produce RNG and the large WRRF in Williamson County would not produce RNG. In the rest of Texas and rest of the U.S., ICF assumed that 40% of the WRRFs with a capacity greater than 7.25 MGD would produce RNG.
- In the Achievable Deployment scenario, ICF assumed that two of the three WRRFs in Travis County with a capacity greater than 7.25 MGD and the large WRRF in Williamson County would produce RNG. In the rest of Texas and rest of the U.S., ICF assumed that 50% of the WRRFs with a capacity greater than 3.3 MGD would produce RNG.
- In the Optimistic Growth scenario, ICF assumed all three of the WRRFs in Travis County with a capacity greater than 7.25 MGD and the large WRRF in Williamson County would produce RNG, in addition to the medium-sized WRRF in Hays County. In the rest of Texas and rest of the U.S., ICF assumed that 60% of the WRRFs with a capacity greater than 3.3 MGD would produce RNG.

The figure below shows the Limited Adoption, Achievable Deployment, and Optimistic Growth RNG resource potential from WRRFs between 2025 and 2050.

[25] Based on data from the LMOP at the U.S. EPA (updated December 2019).

Figure 9. Annual RNG Production Potential from WRRFs (million MMBtu/y)



RNG: Thermal Gasification of Biogenic or Renewable Resources

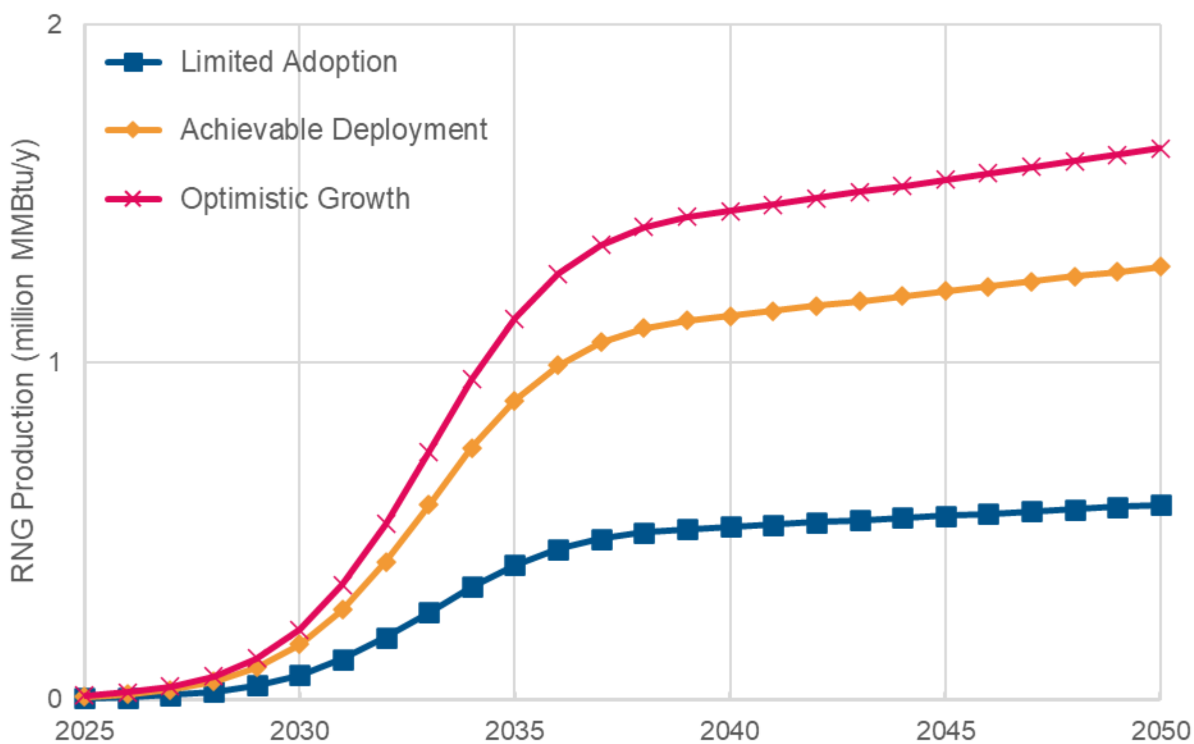
Agricultural Residues

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

The figure below shows the Limited Adoption, Achievable Deployment and Optimistic Growth RNG resource potential scenarios from the thermal gasification of agricultural residues between 2025 and 2050.

Figure 10. Annual RNG Production Potential from Agricultural Residue (million MMBtu/y)



Energy Crops

Energy crops are inclusive of perennial grasses, trees, and some annual crops that can be grown specifically to supply large volumes of uniform, consistent quality feedstocks for energy production. ICF extracted data from the Bioenergy KDF 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.

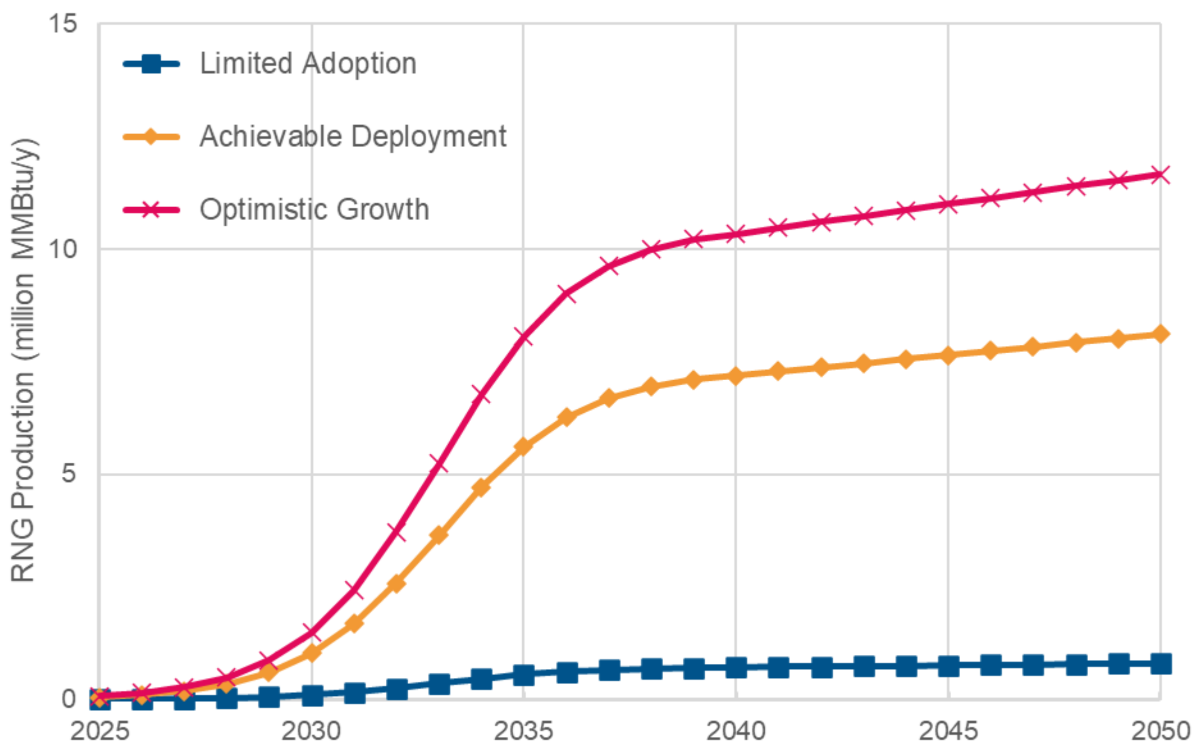
ICF developed assumptions for the RNG production potential from energy crops for the three scenarios:

- In the Limited Adoption scenario, ICF assumed that 20% of the energy crops available at $30/dry ton would be diverted to thermal gasification systems.
- In the Achievable Deployment scenario, ICF assumed that 20-40% of the energy crops available at $40/dry ton would be diverted to thermal gasification systems, depending on the geography.
- In the Optimistic Growth scenario, ICF assumed that 20% of the energy crops available at $50/dry ton would be diverted to thermal gasification systems.

ICF notes that there is significant RNG feedstock potential in Texas from energy crops, with the Achievable Deployment and Optimistic Growth scenarios seeing relatively large volumes of energy crops being used for RNG after 2035, as the thermal gasification technology develops.

Figure 11 below shows the RNG resource potential from the thermal gasification of energy crops between 2025 and 2050 in the Limited Adoption, Achievable Deployment and Optimistic Growth scenarios.

Figure 11. Annual RNG Production Potential from Energy Crops (million MMBtu/y)



Forestry and Forest Product Residues

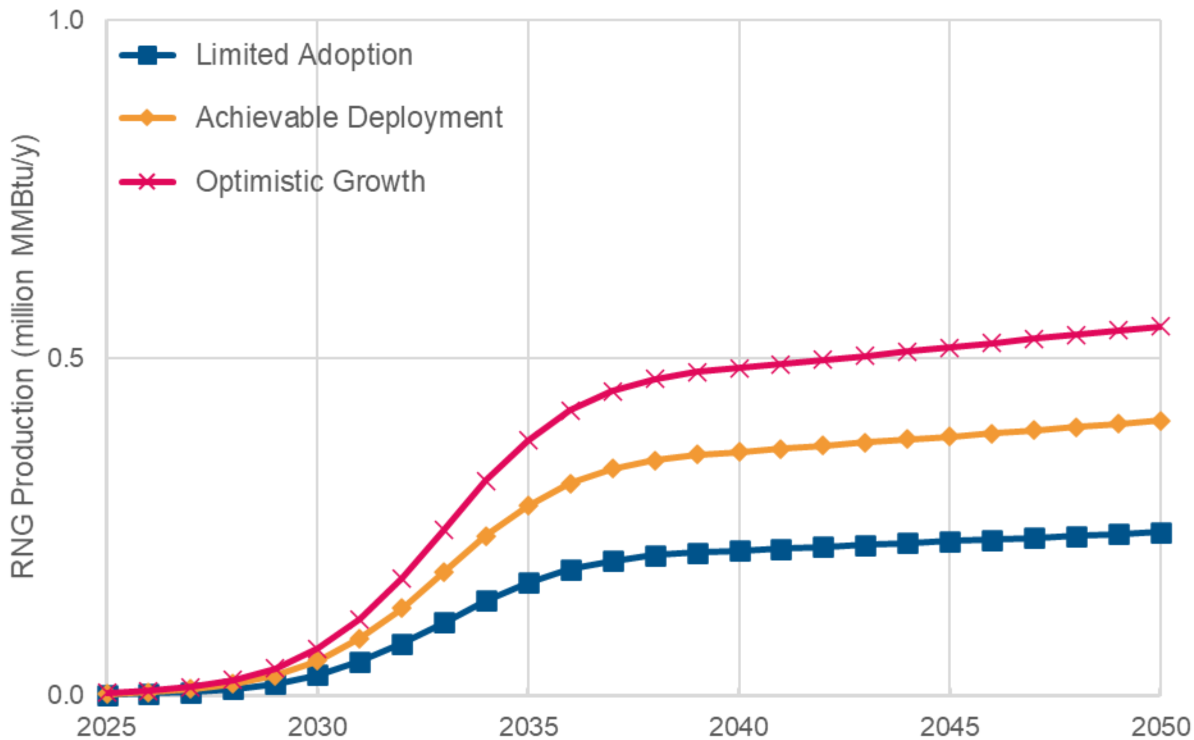
ICF extracted information from the U.S. DOE Bioenergy KDF, which includes information on forest residues such as thinnings, mill residues, and different residues from woods (e.g., mixedwood, hardwood, and softwood). ICF extracted data from the Bioenergy KDF at three price points, $30/ton, $50/ton and $60/ton, that showed variation in production potential for forest and forest product residue biomass from 2025 out to 2040.

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 $50/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 $100/dry ton would be diverted to thermal gasification systems.

Figure 12 below shows the RNG resource potential from the thermal gasification of forestry and forest product residues between 2025 and 2050 in the Limited Adoption, Achievable Deployment and Optimistic Growth scenarios.

Figure 12. Annual RNG Production Potential from Forestry & Forest Product Residue (million MMBtu/y)



Municipal Solid Waste

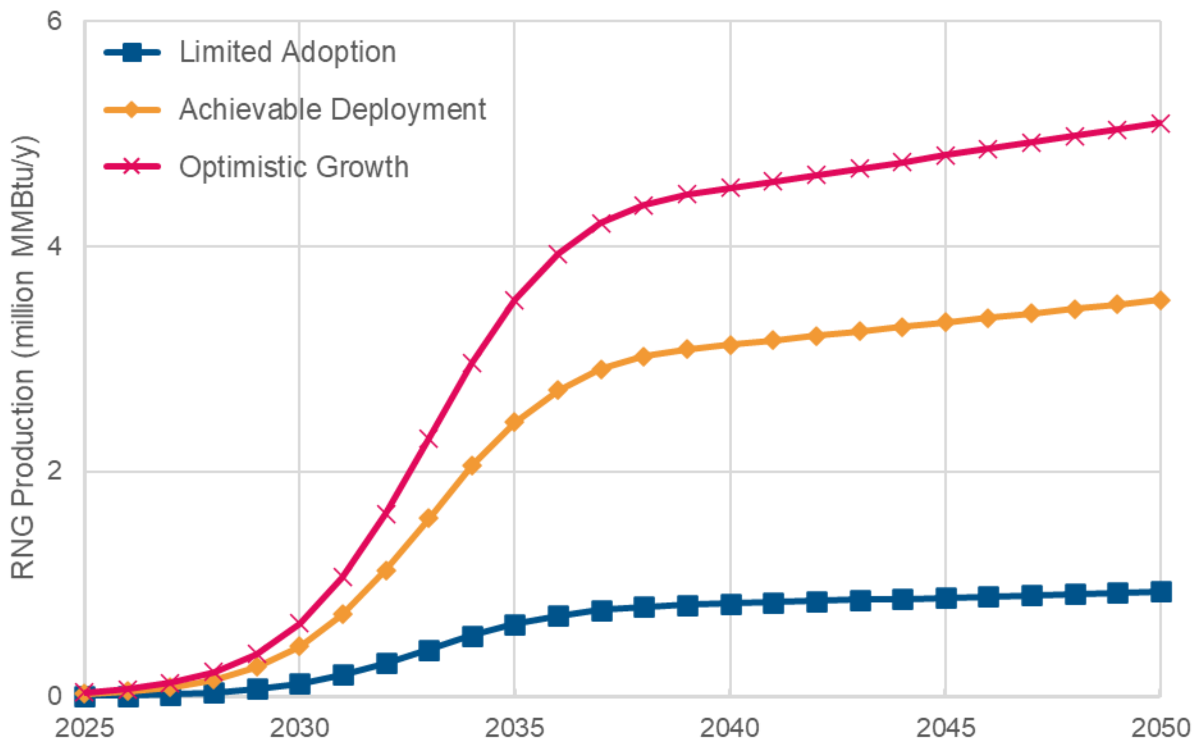
ICF extracted MSW information from the U.S. DOE's Bioenergy KDF, which includes information collected as part of U.S. DOE's Billion Ton Report. ICF limited our consideration to the potential for utilizing MSW that is currently landfilled as a feedstock for thermal gasification; this excludes MSW that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

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

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

The figure below shows the RNG resource potential from the thermal gasification of MSW between 2025 and 2050 in the Limited Adoption, Achievable Deployment and Optimistic Growth scenarios.

Figure 13. Annual RNG Production Potential from MSW (million MMBtu/y)



4. Cost Assessment

Cost Methodology

ICF developed assumptions for the capital expenditures and operational costs for RNG production from the various feedstock and technology pairings outlined previously. ICF characterizes costs based on a series of assumptions regarding the production facility sizes (as measured by gas throughput in units of standard cubic feet per minute [SCFM]), gas upgrading and conditioning and upgrading costs (depending on the type of technology used, the contaminant loadings, etc.), compression, and interconnect for pipeline injection. We also include operational costs for each technology type. Table 36Table 35 below outlines some of ICF's baseline assumptions that we employ in our RNG costing model.

Table 35. Illustrative ICF RNG Cost Assumptions

Cost Parameter	ICF Cost Assumptions
Facility Sizing	▪ Differentiate by feedstock and technology type: anaerobic digestion and thermal gasification. ▪ Prioritize larger facilities to the extent feasible, but driven by resource estimate.
Gas Conditioning and Upgrade	▪ Vary by feedstock type and technology required.
Compression	▪ Capital costs for compressing the conditioned/upgraded gas for pipeline injection.
Operational Costs	▪ Costs for each equipment type—digesters, conditioning equipment, collection equipment, and compressors—as well as utility charges for estimated electricity consumption.
Feedstock	▪ Feedstock costs (for thermal gasification), ranging from $30 to $100 per dry ton.
Financing	▪ Financing costs, including carrying costs of capital (assuming a 60/40 debt/equity ratio and an interest rate of 7%), an expected rate of return on investment (set at 10%), and a 15-year repayment period.
Delivery	▪ Cost of delivering the biogas at a price of $1.20/MMBtu. This cost is in line with financing, constructing, and maintaining a pipeline of about 1 mile in length. The costs of delivering the same volumes of biogas that require pipeline construction greater than 1 mile will increase, depending on feedstock/technology type, with a typical range of $1–$5/MMBtu.
Project Lifetimes	▪ 20 years. The levelized cost of gas was calculated based on the initial capital costs in Year 1, annual operational costs discounted at an annual rate of 5-8% over 20 years, and biogas production discounted at an annual rate of 5-8% for 20 years.

ICF notes that our cost estimates are not intended to replicate a developer's estimate when deploying a project. For instance, ICF recognizes that the cost category "conditioning and upgrading" actually represents an array of decisions that a project developer would have to make with respect to CO_2 removal, H_2S removal, siloxane removal, N_2/O_2 rejection, deployment of a thermal oxidizer, etc.

In addition, these cost estimates do not reflect the potential value of the environmental attributes associated with RNG, nor the current markets and policies that provide credit for these environmental attributes. While this section focuses purely on the costs associated with the production of RNG, Sections 5 and 6 discuss in more detail the market prices for RNG and the associated value of the environmental characteristics of RNG.

Furthermore, we understand that project developers have reported a wide range of interconnection costs, with numbers as low as $200,000 reported in some states, and as high as $9 million in other states. We appreciate the variance between projects, including those that use anaerobic digestion 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 2050—we have *not* included significant cost reductions that might occur as a result of a rapidly growing RNG market or sought to capture a technological breakthrough or breakthroughs. For anaerobic digestion and thermal gasification systems we have focused on projects that have reasonable scale, representative capital expenditures, and reasonable operations and maintenance estimates.

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

Table 36 provides a summary of the different cost ranges for each RNG feedstock and technology.

Table 36. Summary of Cost Ranges by Feedstock Type

	Feedstock	Cost Range ($/MMBtu)
Anaerobic Digestion	Landfill Gas	$9.90 – $15.31
	Animal Manure	$22.00 – $45.16
	Water Resource Recovery Facilities	$10.87 – $33.26
	Food Waste	$20.40 – $29.60
Thermal Gasification	Agricultural Residues	$18.50 – $51.60
	Forestry and Forest Residues	$17.30 – $31.00
	Energy Crops	$18.30 – $56.10
	Municipal Solid Waste	$17.30 – $36.10

RNG from Anaerobic Digestion

Animal Manure

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

Table 37 includes the main assumptions used to estimate the cost of producing RNG from animal manure.

Table 37. Cost Consideration in Levelized Cost of Gas Analysis for RNG from Animal Manure

Factor	Cost Elements Considered	Costs
Performance	▪ Capacity factor	▪ 95%
Installation Costs	▪ Construction / Engineering ▪ Owner's cost	▪ 15-25% of installed equipment costs ▪ 10% of installed equipment costs
Gas Upgrading	▪ CO_2 separation ▪ H_2S removal ▪ N_2/O_2 removal	▪ \$2.3 to \$7.0 million, depending on facility ▪ \$0.3 to \$1.0 million, depending on facility ▪ \$1.0 to \$2.5 million, depending on facility
Utility Costs	▪ Electricity: 30 kWh/MMBtu ▪ Natural Gas: 6% of product	▪ 4.6–13.7 ¢/kWh; average of 6.5 ¢/kWh for region ▪ \$3.00–\$8.25/MMBtu; average of \$4.75/MMBtu for region
Operations & Maintenance	▪ 1 FTE for maintenance ▪ Miscellany	▪ 15% of installed capital costs
For Injection	▪ Interconnect ▪ Pipeline ▪ Compressor	▪ \$0.5 million ▪ \$1 million ▪ \$0.2–\$0.5 million
Other	▪ Value of digestate ▪ Tipping fee	▪ Valued for dairy at about \$100/cow/y ▪ Excluded from analysis
Financial Parameters	▪ Rate of return ▪ Discount rate	▪ 10% ▪ 8%

ICF reports a range of costs for RNG from animal manure at \$22.0/MMBtu to \$45.2/MMBtu for ONE Gas's CTX Service Area. The low end of the RNG costs from animal manure are slightly higher in the study area than in other areas (as reported, for instance, in ICF's analysis for the American Gas Foundation) because of the average farm size for cows—dairy, beef, and heifers—is smaller than in other areas. For instance, ICF has developed cost estimates for farms that have upwards of 20,000 to 30,000 cows. By comparison, ICF analysis suggests that the larger operations in ONE Gas's CTX Service Area have upwards of 10,000 cows. Furthermore, the animal manure operations in ONE Gas's CTX Service Area tend to be non-dairy cow operations, including beef cows, heifers and calves, and chicken operations (e.g., Gonzales has about ten large poultry operations). These operations tend to face higher costs because the costs of manure management are higher (the operations in general are not as concentrated as dairy farms, thereby requiring more costly manure aggregation).

Food Waste

ICF made the simplifying assumption that food waste processing facilities would be purpose-built and be capable of processing 60,000 tons of waste per year. ICF estimates that these facilities would produce about 500 SCFM of biogas for conditioning and upgrading before pipeline injection. In addition to the other costs included in other anaerobic digestion systems, we also included assumptions about the cost of collecting food waste and processing it accordingly (see Table 38).

Table 38. Cost Consideration in Levelized Cost of Gas Analysis for RNG from Food Waste Digesters

Factor	Cost Elements Considered	Costs
Performance	▪ Capacity factor ▪ Processing capability	▪ 95% ▪ 60,000 tons per year
Dedicated Equipment	▪ Organics processing ▪ Digester	▪ $10.0 million ▪ $12.0 million
Installation Costs	▪ Construction / Engineering ▪ Owner's cost	▪ 25% of installed equipment costs ▪ 10% of installed equipment costs
Gas Upgrading	▪ CO_2 separation ▪ H_2S removal ▪ N_2/O_2 removal	▪ $2.3 to $7.0 million, depending on facility ▪ $0.3 million ▪ $1.0 million
Utility Costs	▪ Electricity: 28 kWh/MMBtu ▪ Natural Gas: 5% of product	▪ 4.6–13.7 ¢/kWh; average of 6.5 ¢/kWh for region ▪ $3.00–$8.25/MMBtu; average of $4.75/MMBtu for region
Operations & Maintenance	▪ 1.5 FTE for maintenance ▪ Miscellany	▪ 15% of installed capital costs
Other	▪ Tipping fees	▪ Varied by region; used weighted average of $49.07 (see Table 39)
For Injection	▪ Interconnect ▪ Pipeline ▪ Compressor	▪ $0.5 million ▪ $1 million ▪ $0.2–$0.5 million
Financial Parameters	▪ Rate of return ▪ Discount rate	▪ 10% ▪ 7%

ICF assumed that food waste facilities would be able to offset costs with tipping fees. ICF used values presented by an analysis of municipal solid waste landfills by Environmental Research & Education Foundation (EREF). The tipping fees reported by EREF for 2018 are shown in Table 39.

Table 39. Average Tipping Fee by Region ($/ton)[26]

Region	Tipping Fee
CTX Service Area	
Texas Disposal Systems LF[27]	$55.00
Regional	
Texas, statewide average	$37.78
South Central: AR, LA, NM, OK, TX	$34.80
Rest of U.S.	
Northeast: CT, DE, ME, MD, MA, NH, NJ, NY, PA, RI, VA, WV	$67.39
Pacific: AK, AZ, CA, HI, ID, NV, OR, WA	$68.46
Midwest: IL, IN, IA, KS, MI, MN, MO, NE, OH, OH, WI	$46.89
Mountains / Plains: CO, MT, ND, SD, UT, WY	$43.57
Southeast: AL, FL, GA, KY, MS, NC, SC, TN	$43.32
National Average	***$55.11***

The values listed in Table 39 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 our cost estimates assuming that anaerobic digesters discounted the tipping fee for food waste compared to MSW landfills by 20%.

ICF reports an estimated cost of RNG from food waste of $20.4/MMBtu to $29.6/MMBtu.

Landfill Gas

ICF developed assumptions for each region by distinguishing between four types of landfills: candidate landfills[28] without collection systems in place, candidate landfills with collection systems in place, landfills[29] without collection systems in place, and landfills with collections systems in place.[30] For each region, ICF further characterized the number of landfills across these four types of landfills, distinguishing facilities by estimated biogas throughput (reported in units of SCFM of biogas).

For utility costs, ICF assumed 25 kWh per MMBtu of RNG injected and 6% of geological or fossil natural gas used in processing. Electricity costs and delivered natural gas costs were reflective of industrial rates reported at the state level by the EIA.

---

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

[27] TDS, 2020. https://texasdisposal-https-texasdisposalsys.netdna-ssl.com/wp-content/uploads/2020/03/New-TDS-Gate-Rates-March-2020-Final.pdf

[28] 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.

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

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

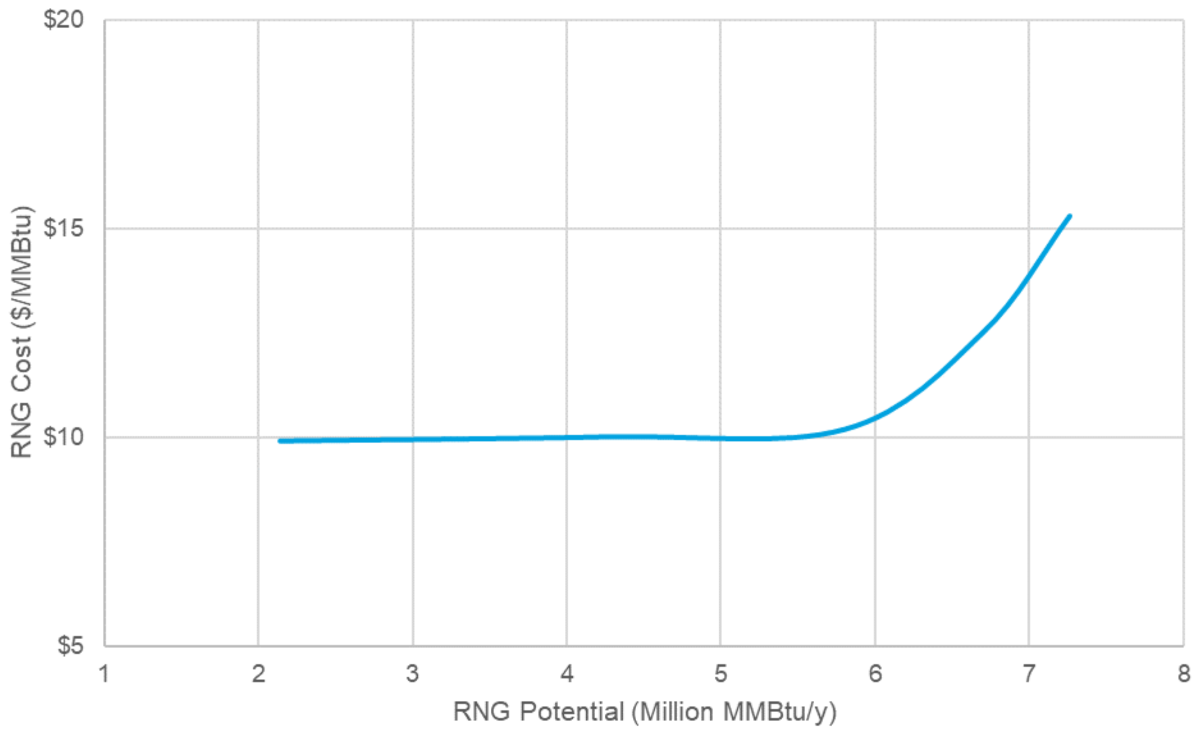
Table 40 summarizes the key parameters that ICF employed in our cost analysis of LFG.

Table 40. Cost Consideration in Levelized Cost of Gas Analysis for RNG from Landfill Gas

Factor	Cost Elements Considered	Costs
Performance	▪ Capacity factor	▪ 95%
Installation Costs	▪ Construction / Engineering ▪ Owner's cost	▪ 25% of installed equipment costs ▪ 10% of installed equipment costs
Gas Upgrading	▪ CO_2 separation ▪ H_2S removal ▪ N_2/O_2 removal	▪ $2.3 to $7.0 million, depending on facility ▪ $0.3 to $1.0 million, depending on facility ▪ $1.0 to $2.5 million, depending on facility
Utility Costs	▪ Electricity: 25 kWh/MMBtu ▪ Natural Gas: 6% of product	▪ 4.6–13.7 ¢/kWh; average of 6.5 ¢/kWh for region ▪ $3.00–$8.25/MMBtu; average of $4.75/MMBtu for region
Operations & Maintenance	▪ 1 FTE for maintenance ▪ Miscellany	▪ 10% of installed capital costs
For Injection	▪ Interconnect ▪ Pipeline ▪ Compressor	▪ $0.5 million ▪ $1 million ▪ $0.2–$0.5 million
Financial Parameters	▪ Rate of return ▪ Discount rate	▪ 10% ▪ 7%

Figure 14 includes ICF's estimates for the RNG from landfill gas supply curve for ONE Gas's CTX Service Area, ranging from about $10/MMBtu to around $15/MMBtu—this includes the five landfills, four of which are in Travis County and the fifth in Williamson County. The four facilities in Travis County are currently producing electricity, but could be converted to RNG production, and the facility in Williamson County (operated by Waste Management) is currently slated to start producing RNG for pipeline injection in 2020.

Figure 14. Supply-Cost Curve for RNG from Landfill Gas ($/MMBtu vs million MMBtu)



Water Resource Recovery Facilities

ICF developed assumptions for each region by distinguishing between WRRFs based on the throughput of the facilities. The table below includes the main assumptions used to estimate the cost of producing RNG at WRRFs.

Table 41. Cost Consideration in Levelized Cost of Gas Analysis for RNG from WRRFs

Factor	Cost Elements Considered	Costs
Performance	▪ Capacity factor	▪ 95%
Installation Costs	▪ Construction / Engineering ▪ Owner's cost	▪ 25% of installed equipment costs ▪ 10% of installed equipment costs
Gas Upgrading	▪ CO_2 separation ▪ H_2S removal ▪ N_2/O_2 removal	▪ $2.3 to $7.0 million, depending on facility ▪ $0.3 to $1.0 million, depending on facility ▪ $1.0 to $2.5 million, depending on facility
Utility Costs	▪ Electricity: 26 kWh/MMBtu ▪ Natural Gas: 6% of product	▪ 4.6–13.7 ¢/kWh; average of 6.5 ¢/kWh for region ▪ $3.00–$8.25/MMBtu; average of $4.75/MMBtu for region
Operations & Maintenance	▪ 1 FTE for maintenance ▪ Miscellany	▪ 10% of installed capital costs
For Injection	▪ Interconnect ▪ Pipeline ▪ Compressor	▪ $0.5 million ▪ $1 million ▪ $0.2–$0.5 million
Financial Parameters	▪ Rate of return ▪ Discount rate	▪ 10% ▪ 7%

ICF reports an estimated cost of RNG from WRRFs of $10.9/MMBtu to $33.3/MMBtu. The low end of the range represents the Hornsby Bend facility, a biosolids facility that receives the residual sludge from wastewater treatment at Walnut Creek and South Austin Regional; whereas the higher end of the range represents the smaller Brushy Creek Regional facility in Round Rock.

RNG from Thermal Gasification

ICF used similar assumptions across the thermal gasification of feedstocks, including agricultural residue, forestry residue, energy crops, and MSW.[31] There is considerable uncertainty around the costs for thermal gasification of feedstocks, as the technology has only been deployed at pilot scale to date or in the advanced stages of demonstration at pilot scale. This is in stark contrast to the anaerobic digestion technologies considered previously. ICF reports here on a range of facilities processing different volumes of feedstock (in units of tons per day, or tpd) that we employed for conducting the cost analysis.

Table 42. Thermal Gasification Cost Assumptions

Factor	Cost Elements Considered	Costs
Performance	▪ Capacity factor ▪ Processing capability	▪ 90% ▪ 1,000–2,000 tpd
Dedicated Equipment & Installation Costs	▪ Feedstock handling (drying, storage) ▪ Gasifier ▪ CO_2 removal ▪ Syngas reformer ▪ Methanation ▪ Other (cooling tower, water treatment) ▪ Miscellany (site work, etc.) ▪ Construction / Engineering	▪ $20–22 million ▪ $60 million ▪ $25 million ▪ $10 million ▪ $20 million ▪ $10 million ▪ All-in: $335 million for 1,000 tpd
Utility Costs	▪ Electricity: 30 kWh/MMBtu ▪ Natural Gas: 6% of product	▪ 4.6–13.7 ¢/kWh ▪ $3.00–$8.25/MMBtu
Operations & Maintenance	▪ Feedstock ▪ 3 FTE for maintenance ▪ Miscellany: water sourcing, treatment/disposal	▪ $30–$100/dry ton ▪ 12% of installed capital costs
For Injection	▪ Interconnect ▪ Pipeline ▪ Compressor	▪ $0.5 million ▪ $1 million ▪ $0.2–$0.5 million
Financial Parameters	▪ Rate of return ▪ Discount rate	▪ 10% ▪ 7%

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

ICF applied these estimates across each of the four feedstocks, their corresponding feedstock cost estimates, and assumed that the smaller facilities processing 1,000 tons per day would represent 50% of the processing capacity, and that the larger facilities processing 2,000 tons per day would represent the other 50% of the processing capacity. The number of facilities built in each region was constrained by the resource assessment.

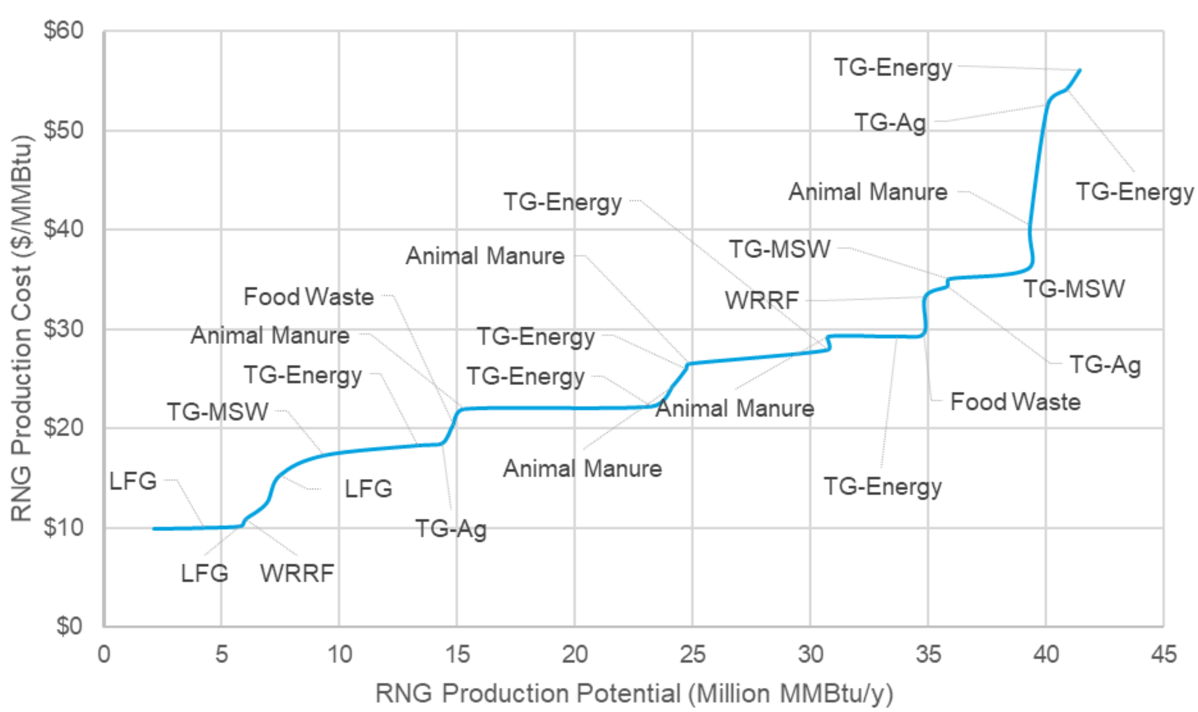
ICF reports an estimated levelized costs of RNG from thermal gasification as follows:

- Agricultural residues: \$18.5/MMBtu to \$51.6/MMBtu
- Forestry and forest residues: \$17.3/MMBtu to \$31.0/MMBtu
- Energy crops: \$18.3/MMBtu to \$56.1/MMBtu
- MSW: \$17.3/MMBtu to \$36.1/MMBtu

Combined Supply-Cost Curve for RNG

The figure below represents the supply-cost curve for RNG in ONE Gas's CTX Service Area, including resource potential (along the x-axis) and the estimated cost to deliver that RNG (along the y-axis). For the sake of reference, we have also included the contribution to each step in the supply curve—shown as landfill gas (LFG), animal manure, food waste, WRRFs, thermal gasification (with three feedstocks: energy crops (Energy), agricultural residues (Ag), and the non-biogenic fraction of municipal solid waste (MSW)). As highlighted previously, the front end of the supply curve is comprised of landfill gas and WRRFs, with the larger thermal gasification systems expected to be cost competitive in the 2040 timeline. The more immediately available opportunities from the anerobic digestion of animal manure and food waste are likely available in the range of \$20/MMBtu. The back-end of the supply curve is driven by higher costs of anaerobic digestion at smaller farms and smaller thermal gasification facilities.

Figure 15. Combined Supply-Cost Curve for RNG in CTX Service Area (\$/MMBtu vs million MMBtu)



5. GHG Accounting and Cost-Effectiveness

GHG Accounting Framework and Methodology

The GHG emissions of RNG, typically called a carbon intensity (e.g., grams of CO_2 equivalents per MJ of fuel), varies primarily based on the source of the fuel (i.e., feedstock), but can be impacted by other factors such as production efficiency and location as well as transmission distances. The assessment method and scope can also have a significant impact on how RNG carbon intensities and emissions are estimated and reported. This section provides a summary of commonly used GHG emission accounting methods and how they relate to the GHG emission profiles of RNG production and consumption.

Overview of Accounting Methods

GHG emission accounting for a given source of emissions relies on the application of an emission factor to activity data. In the example below, we use an emission factor for Texas's average electricity mix to determine the annual GHG emissions associated with an average Texas household's electricity consumption using data from the EPA[32] and EIA:[33]

$$446\ \frac{g\ CO_2e}{kWh} \times 14{,}300\ \frac{kWh}{house} = 6.4 \times 10^6\ \frac{g\ CO_2e}{house}$$

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

GHG emission profiles can be complex for specific products or resources, when a scope may consider elements outside of product use, such as emissions from supply chains, co-products, and disposal. For example, California's LCFS relies on a lifecycle assessment approach for estimating carbon intensities of transportation fuels. As a result, LCFS emissions for a specific transportation fuel pathway

Lifecycle Assessment

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

[32] US EPA, 2020. eGRID. Available at: https://www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid

[33] US EIA. 2018. Household Energy Use in Texas. Available at: https://www.eia.gov/consumption/residential/data/2015/

include all emission sources in the fuel lifecycle from resource extraction to final consumption in a vehicle.

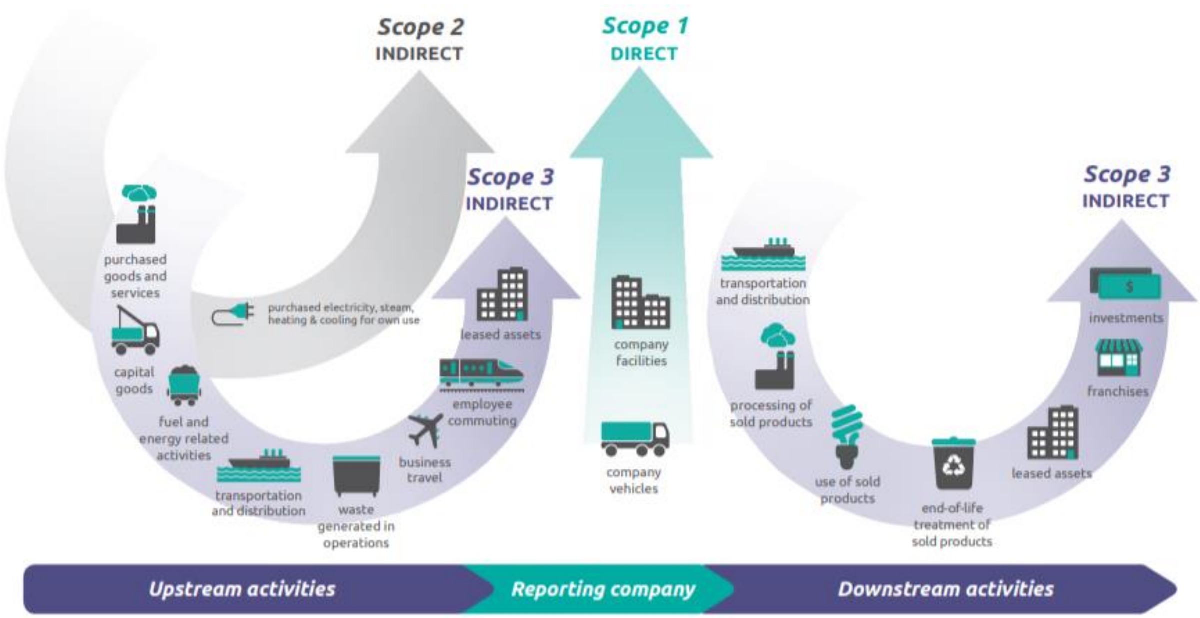
GHG emission accounting for inventories typically relies on guidance from the Intergovernmental Panel on Climate Change (IPCC) developed in 2006.[34] The IPCC provides guidance for different levels of detail depending on the availability of data and capacity of the inventory team for all sectors typically considered in a GHG inventory. GHG emission reporting programs that address a specific sector or subsector, like the LCFS, may have unique guidelines that diverge from IPCC and typical inventories in accounting methods.

Greenhouse Gas Protocol

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

The GHG Protocol uses "Scope" levels to define the different sources and activity data included within an assessment. Instead of thinking in terms of geographic or sector-based boundaries, the Protocol groups emissions in direct and indirect categories through these Scopes. Figure 16 shows how the Protocol groups these emission sources by Scopes, and how they relate to an organization's operations.

Figure 16. Scopes for Categorizing Emissions Under the 2019 GHG Protocol



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

---

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

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

RNG and GHG Accounting

There are two broad methodologies to account for the GHG emissions from RNG: a combustion accounting framework or a lifecycle accounting framework. A combustion GHG accounting framework is the standard approach for most volumetric GHG targets, inventories and mitigation measures (e.g. carbon taxes, cap-and-trade programs and RPS programs) as they are more closely tied to a particular jurisdiction—where the emissions physically occur.

Figure 17 details the differences between the two accounting frameworks relative to RNG production.

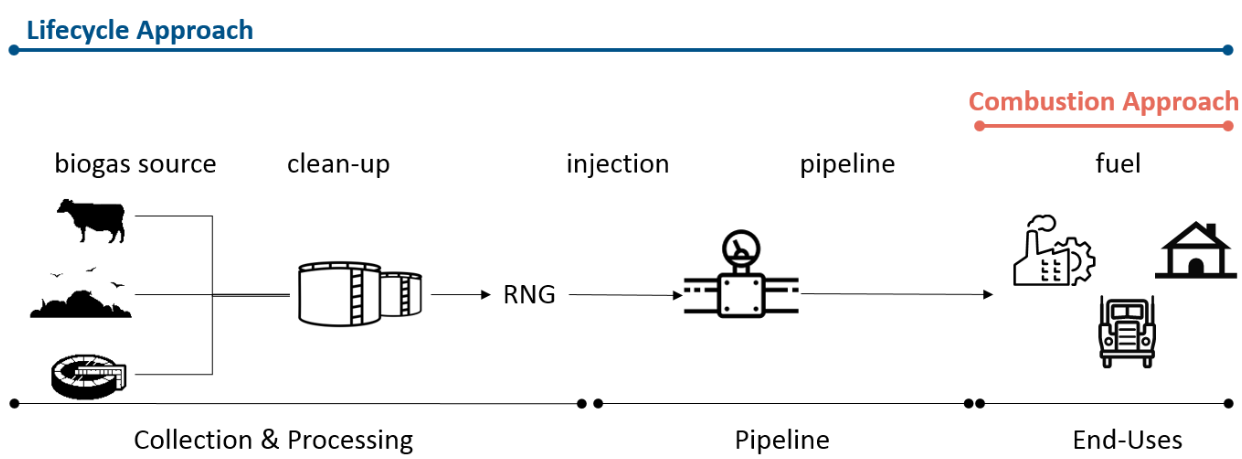
Accounting for Biogenic Emissions

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

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

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

Figure 17. GHG Accounting Frameworks for RNG Production



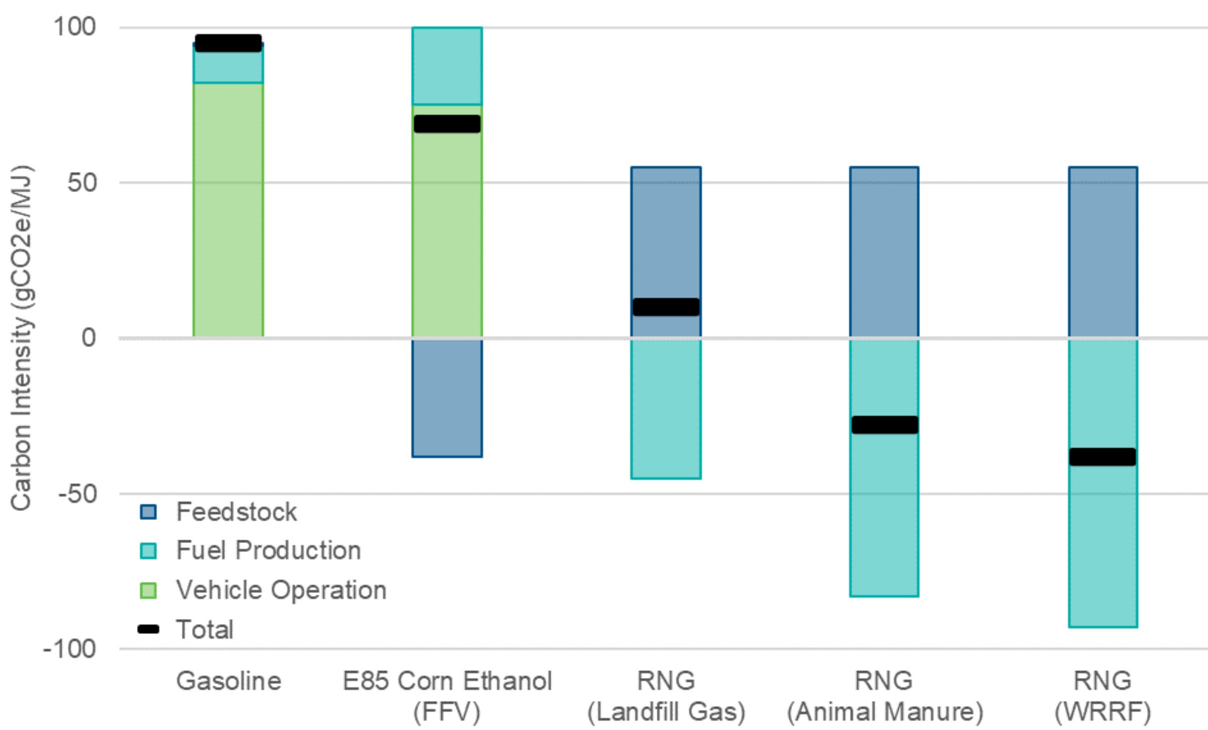
Using the combustion framework, the CO_2 emissions from the combustion of biogenic renewable fuels are considered zero, or carbon neutral. In other words, RNG has a carbon intensity of zero. This includes RNG from any biogenic feedstock, including landfill gas, animal manure, and food waste. Upstream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

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

Variations in Production

Figure 18 shows how these different lifecycle elements contribute to RNG's overall carbon intensity for a selection of RNG sources using Argonne's GREET model[35]: landfill gas, animal waste AD, wastewater sludge AD, and MSW AD. We have also included corn ethanol (E85 blend) and gasoline as reference points. Note that in the GREET model, the original sourcing of RNG is considered "fuel production" and not feedstock operations.

Figure 18. Summary of Carbon Intensities for Transportation Fuels Across Lifecycle Stages[36]



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

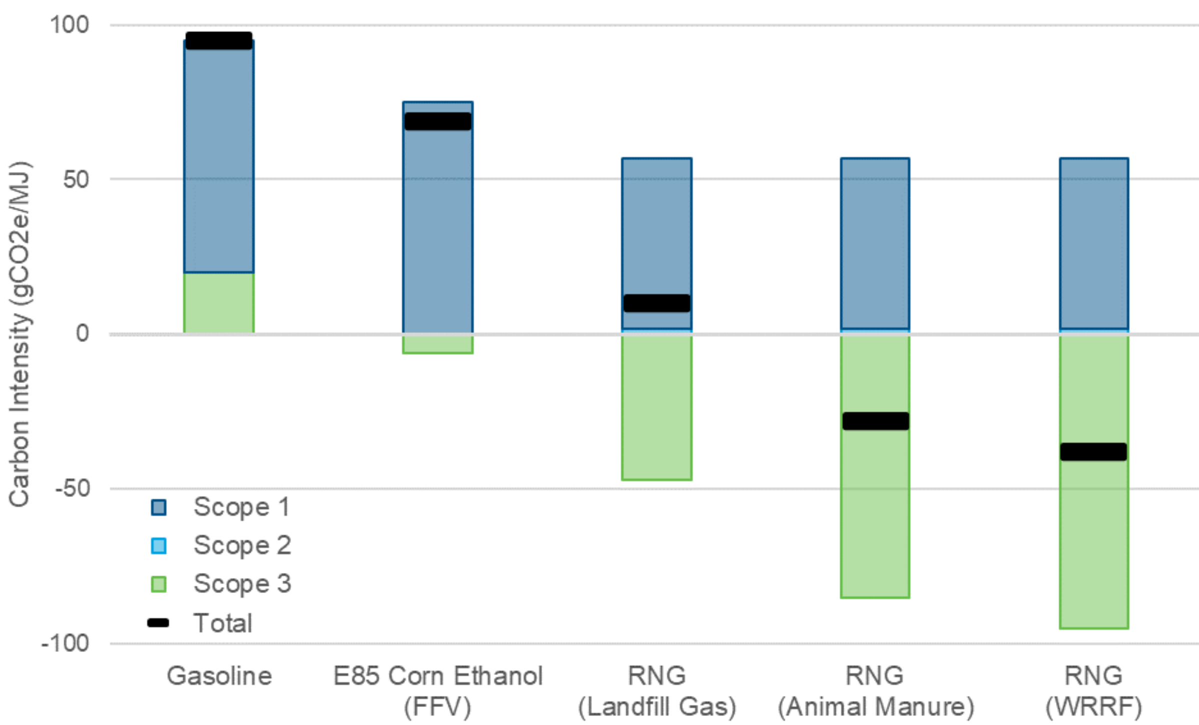
The biggest variations in RNG production come from the associated emissions credits from the different RNG sources. For landfill gas, animal waste, and wastewater sources, GREET assigns a significant credit for the reduction in vented and flared methane that would have occurred in absence of the production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

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

Variations Based on Accounting Method

Figure 19 shows the same GREET results from Figure 18 grouped into the GHG Protocol Scopes. Scope 1 is limited to the tailpipe emissions and Scope 3 includes all aspects of feedstock and fuel production activities. For RNG we have grouped the compression of gas before use into Scope 2, assuming electricity is used in compression.

Figure 19. RNG Lifecycle Carbon Intensity by Different GHG Protocol Scopes Using GREET Results[37]



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

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

Scope 3 emissions, would report a lower or negative carbon intensity for RNG, depending on the feedstock.

For example, the Los Angeles County Metropolitan Transportation Authority (LA Metro) is working to shift its entire directly operated bus fleet to RNG as soon as possible. Many of the potential RNG feedstocks that LA Metro may use have a negative carbon intensity under the emissions scope of the LCFS (e.g., animal waste, wastewater anaerobic digestion pathways). However, LA Metro's recent Climate Action and Adaptation Plan[38] included only Scope 1 and 2 emissions, which meant that RNG had net positive emissions from compression and combustion regardless of the feedstock.

Approach to RNG GHG Emission Factors

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

Figure 20 below presents the ranges of lifecycle CIs for different RNG feedstocks up to the point of pipeline injection for the EIA's West South Central Census Region, which includes Texas. These estimates are based on a combination of Argonne National Laboratory's GREET model, California Air Resources Board's modified California GREET model,[39] and ICF analysis. Table 43 that follows includes the lifecycle CIs for EIA's other census regions.

[38] LA Metro, 2019 https://media.metro.net/projects_studies/sustainability/images/Climate_Action_Plan.pdf
[39] ARB, 2019. https://ww3.arb.ca.gov/fuels/lcfs/ca-greet/ca-greet.htm

Figure 20. Lifecycle GHG Emission Factor Ranges for RNG Feedstocks, West South Central Region

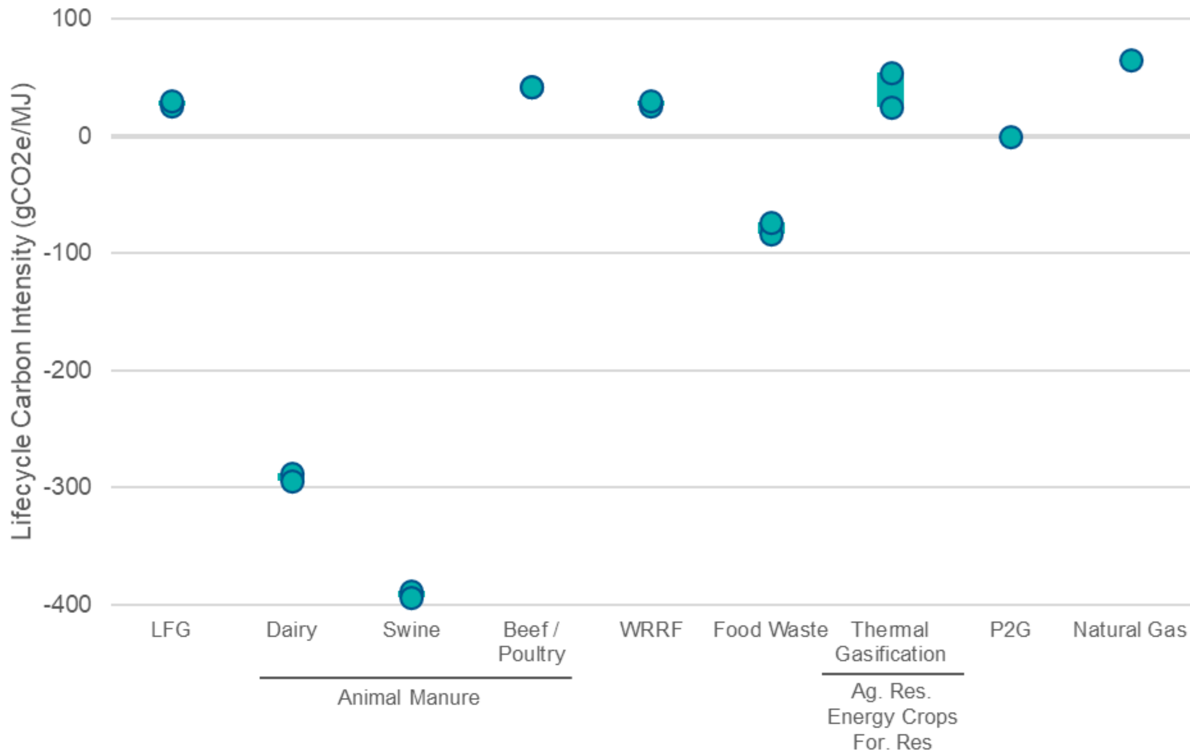


Table 43. Lifecycle GHG Emission Factor Ranges for RNG Feedstocks by Region, gCO_2e/MJ

Fuel	New England	Mid-Atlantic	South Atlantic	East North Central	West North Central	East South Central	Mountain	Pacific
LFG	18 – 26	15 – 21	22 – 26	28 – 34	28 – 32	26 – 28	21 – 32	13 – 29
Animal Manure								
Dairy	-304 – -294	-308 – -300	-299 – -294	-292 – -285	-292 – -286	-294 – -292	-300 – -286	-310 – -290
Swine	-404 – -394	-408 – -400	-399 – -394	-392 – -385	-392 – -386	-394 – -392	-400 – -386	-410 – -390
Beef/Poultry	36 – 36	31 – 31	36 – 36	46 – 46	44 – 44	38 – 38	44 – 44	41 – 41
WRRF	18 – 26	15 – 21	22 – 26	28 – 34	28 – 32	26 – 28	21 – 32	13 – 29
Food Waste	-97 – -82	-104 – -91	-90 – -82	-79 – -68	-79 – -70	-83 – -79	-91 – -70	-108 – -76
Agricultural Res.	25 – 55	25 – 55	25 – 55	25 – 55	25 – 55	25 – 55	25 – 55	25 – 55
Forestry Res.	25 – 55	25 – 55	25 – 55	25 – 55	25 – 55	25 – 55	25 – 55	25 – 55
Energy Crops	25 – 55	25 – 55	25 – 55	25 – 55	25 – 55	25 – 55	25 – 55	25 – 55
MSW	25 – 55	25 – 55	25 – 55	25 – 55	25 – 55	25 – 55	25 – 55	25 – 55
Natural Gas	65	65	65	65	65	65	65	65

ICF notes the following about these emission factors:

- The lowest carbon intensities are from feedstocks that prevent the release of fugitive methane, such as the collection and processing of dairy cow manure.
- RNG from WRRFs has the same CI range as landfill gas because both feedstocks start with raw biogas that is processed by the same type of gas upgrading equipment.

- Agricultural residue, energy crops, forestry products and forestry residues, as well as MSW all have the same CI range based on the thermal gasification process required to create biogas from woody biomass. This is an energy-intensive process, but inclusion of renewables and co-produced electricity on-site can reduce the emissions impact of gas production.

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

GHG Cost-Effectiveness

The GHG cost-effectiveness is reported on a dollar-per-ton basis and is calculated as the difference between the emissions attributable to RNG and fossil natural gas. For this report, ICF followed IPCC guidelines and does not include biogenic emissions of CO_2 from RNG. The cost-effectiveness calculation is simply as follows:

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

where the RNG_{cost} is simply the cost from the estimates reported previously. For the purposes of this report, we use a fossil natural gas price equal to the 3-year rolling average Henry Hub spot price reported by the EIA,[40] calculated as $2.96/MMBtu (in $2019).

In other words, the front end of the supply-cost curve is showing RNG of just under $10/MMBtu, which is equivalent to about $120 per metric ton of carbon dioxide equivalent (tCO_2e). As the estimated RNG cost increases to $25/MMBtu, we report an estimated cost-effectiveness of about $400/t$CO_2$e. This range in cost for RNG can be converted to provide an equivalent range for the cost-effectiveness of RNG for GHG emission reductions, in dollars per ton of carbon dioxide equivalent.

Estimating the cost-effectiveness of different GHG emission reduction measures is challenging and results can vary significantly across temporal and geographic considerations. Figure 21 shows a comparison of selected measures across various key studies for specific abatement measures that are likely to be required for economy-wide decarbonization in the 2050 timeframe, including natural gas demand side management (DSM),[41] carbon capture and storage (CCS),[42] RNG (from this study), direct air capture (whereby CO_2 is captured directly

---

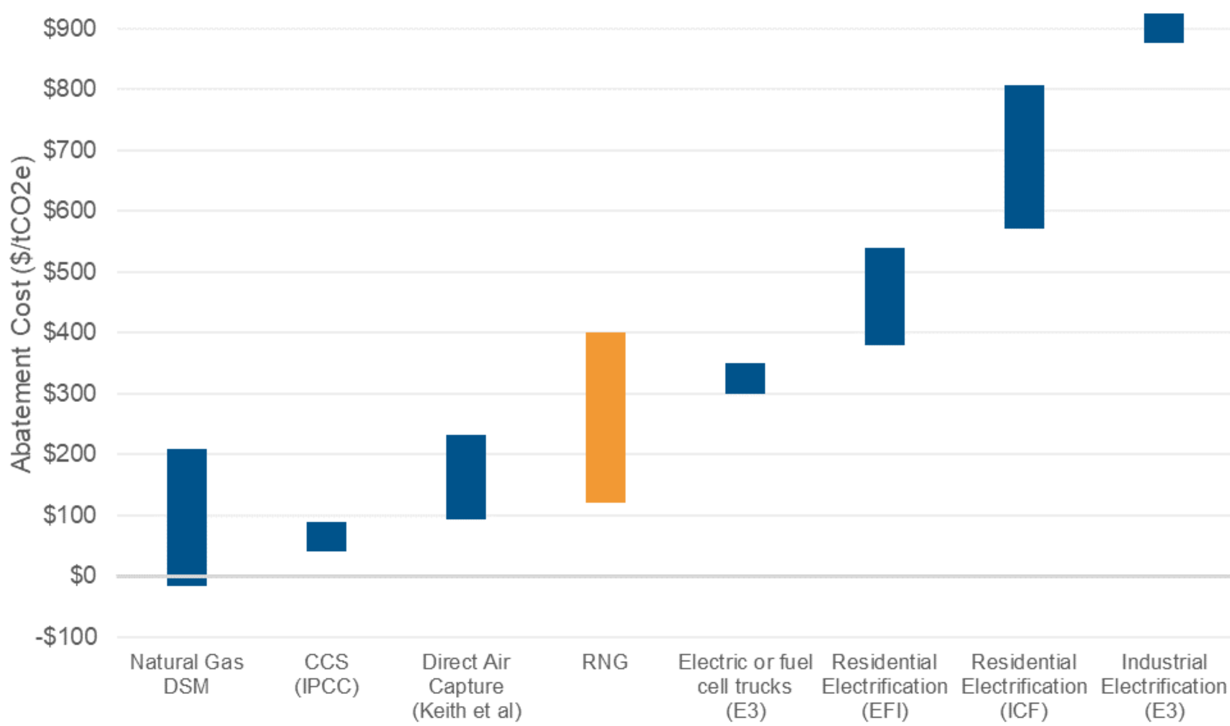
[40] EIA, Natural Gas Data, available online at https://www.eia.gov/dnav/ng/hist/rngwhhdA.htm

[41] See Con Edison's Smart Usage Rewards program (https://www.coned.com/en/save-money/rebates-incentives-tax-credits/rebates-incentives-tax-credits-for-commercial-industrial-buildings-customers/smart-usage-rewards/smart-usage-rewards-for-reducing-gas-demand) and National Grid's Demand Response Pilot program (https://www.nationalgridus.com/GDR).

[42] IPCC, 2005: IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck,

from the air and a concentrated stream is sequestered or used for beneficial purposes),[43] battery electric trucks (including fuel cell drivetrains),[44] and electrification of certain end uses (including buildings and in the industrial sectors).[45,46]

Figure 21. GHG Abatement Costs, Selected Measures, $/tCO_2e$



M. Loos, and L. A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp.

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

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

[45] Energy Futures Initiative (EFI), 2019. Optionality, Flexibility & Innovation: Pathways for Deep Decarbonization in California, https://static1.squarespace.com/static/58ec123cb3db2bd94e057628/t/5ced6fc515fcc0b190b60cd2/1559064542876/EFI_CA_Decarbonization_Full.pdf.

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

GHG Emissions from RNG Resource Assessment

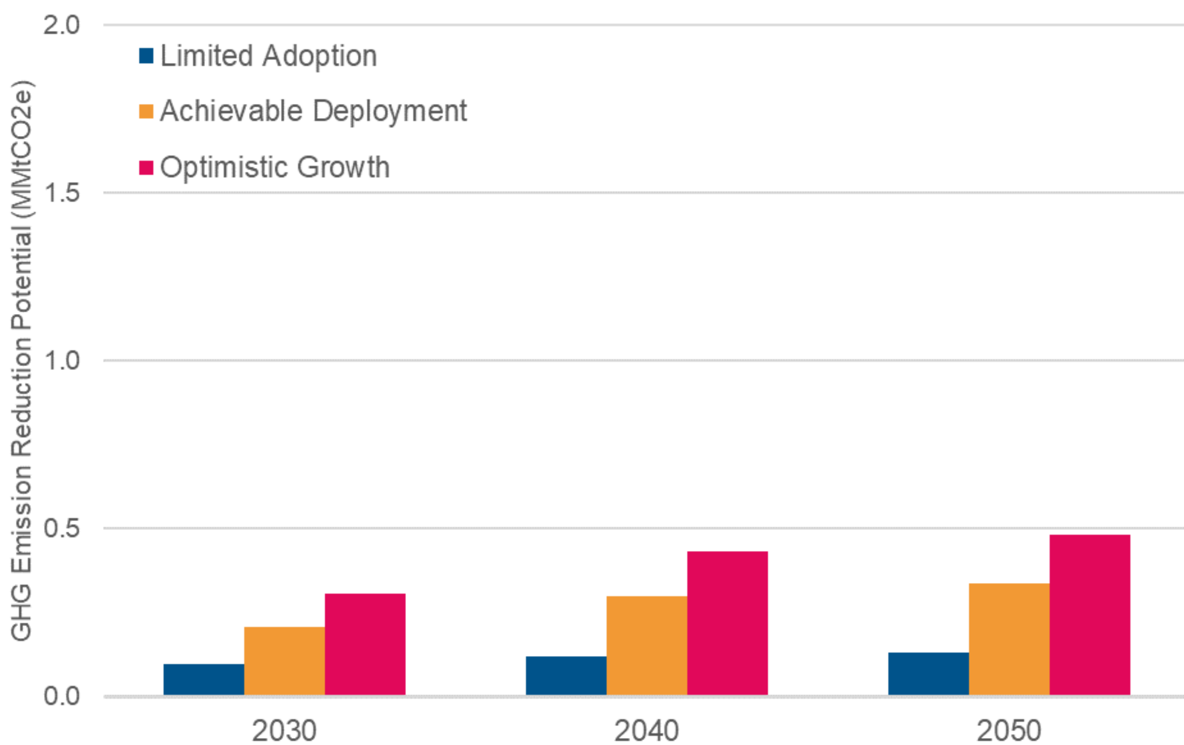
ICF applied the emission factors from the aforementioned combustion and lifecycle accounting approaches to estimate the GHG reduction potential across each of the RNG potential scenarios for Travis County, ONE Gas's CTX Service Area, and overall when including the rest of Texas and nationally, as reported previously in Section 3.

Combustion Accounting Framework

ICF reiterates that a combustion GHG accounting framework is the standard approach for most volumetric GHG targets, inventories and mitigation measures as they are more closely tied to where the emissions physically occur. When applying the combustion approach, the emission reduction estimates for the each scenario can be more easily compared to existing GHG inventories, such as the City of Austin's emissions by end use sector as shown in Figure 25. The lifecycle accounting GHG emission estimates included in the following section are not directly comparable to the City of Austin's GHG inventory.

The figures below show the range of GHG emission reductions using a combustion accounting framework, in units of million metric tons of CO_2e ($MMtCO_2e$). ICF estimates that 0.13 to 0.48 $MMtCO_2e$ of emissions could be reduced per year by 2050 through the deployment of RNG projects located in Travis County, shown in Figure 22.

Figure 22. Travis County RNG Emission Reduction Potential by Scenario, $MMtCO_2e$ (Combustion)



Expanding the geographic footprint to include RNG feedstocks from the surrounding CTX Service Area counties, this increases to between 0.23 and 1.12 $MMtCO_2e$ per year in 2050. ICF estimates that 0.45 to 1.78 $MMtCO_2e$ of emissions could be reduced per year by 2050 through the utilization of RNG feedstocks from outside the immediate City of Austin region, as reflected in the scenario totals.

Figure 23. CTX Service Area RNG Emission Reduction Potential by Scenario, MMtCO$_2$e (Combustion)

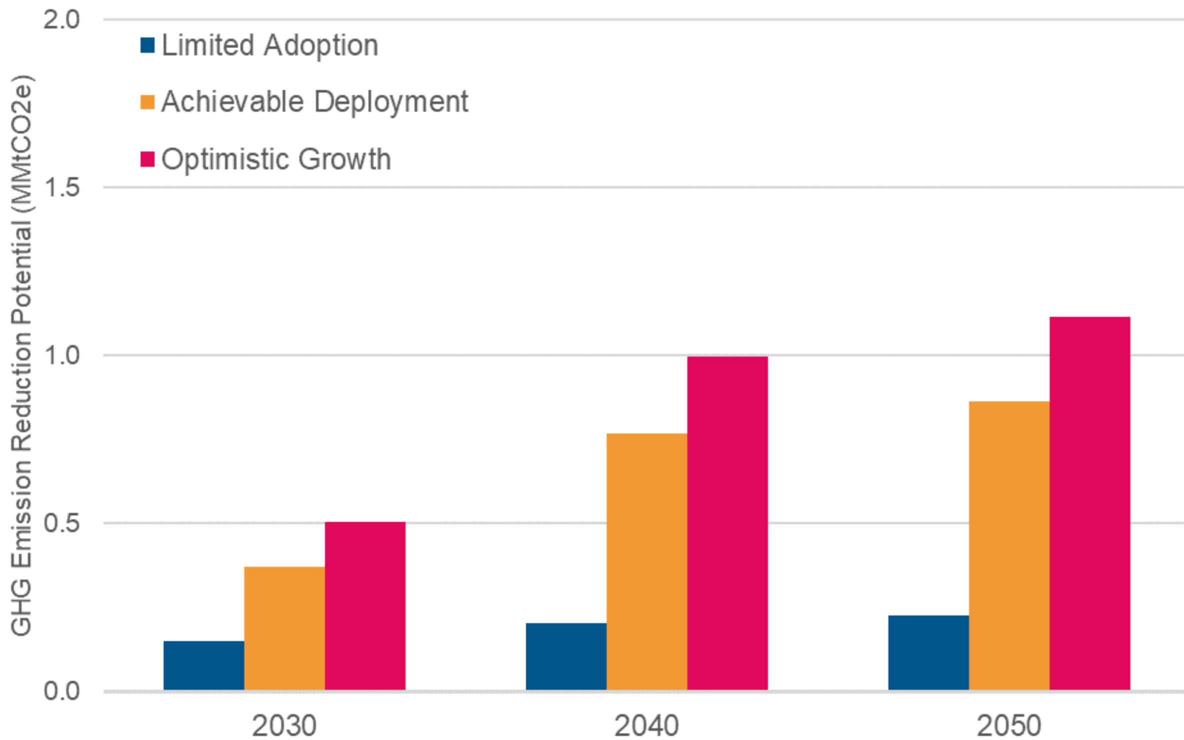
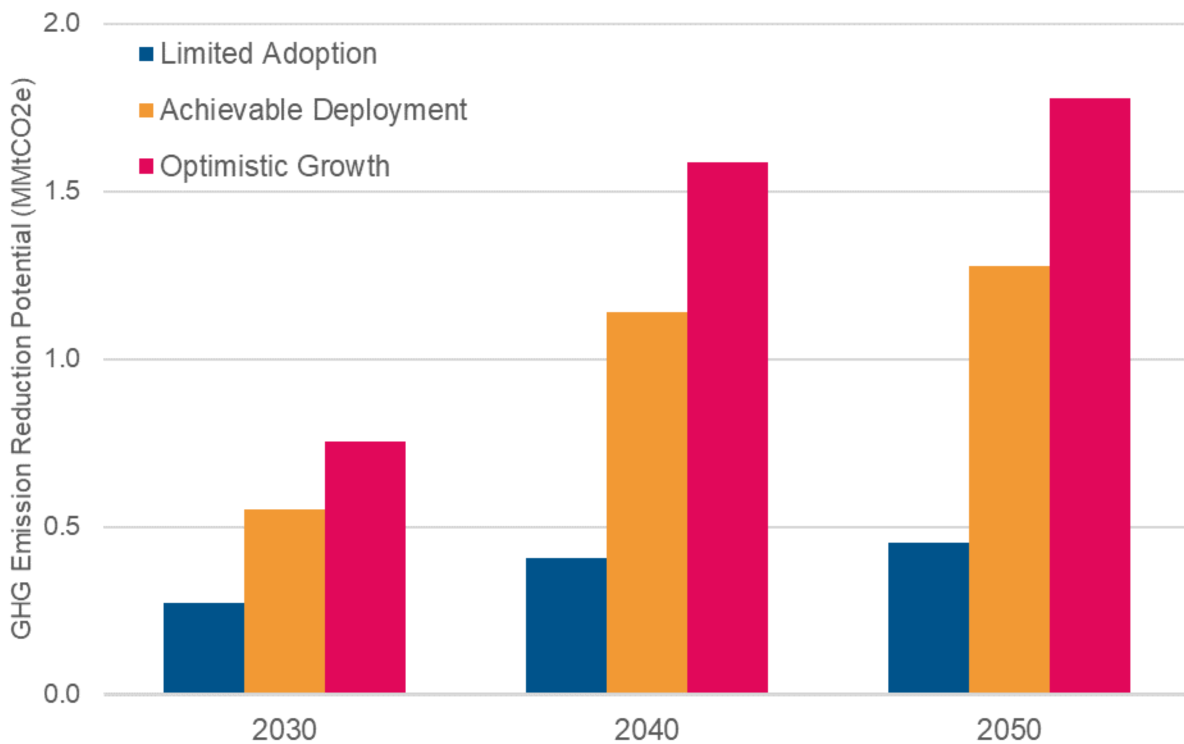
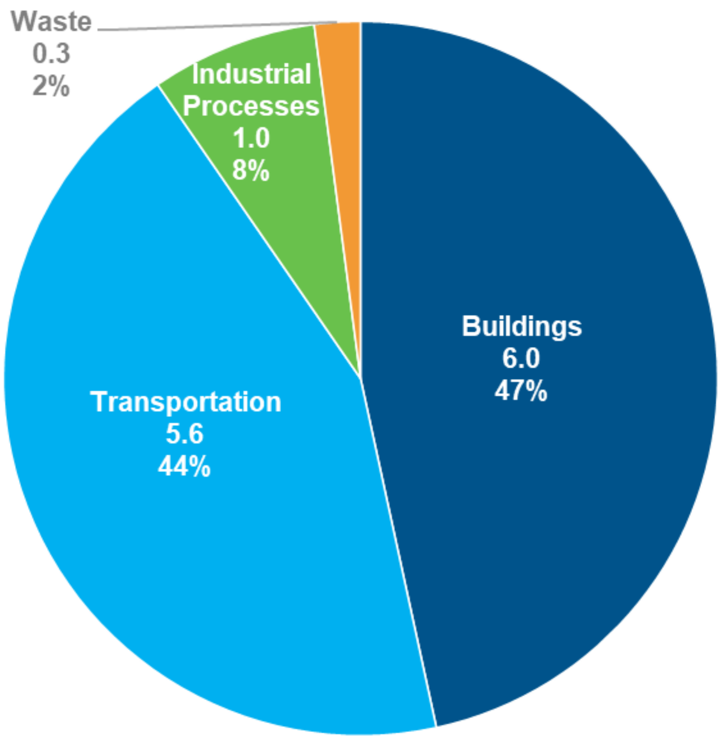


Figure 24. Total RNG Emission Reduction Potential by Scenario, MMtCO$_2$e (Combustion)



By way of comparison, the City of Austin's total GHG emissions were 12.9 $MMtCO_2e$ in 2018, shown in Figure 25 below.[47] The City of Austin GHG inventory does not disaggregate natural gas and electricity consumption in the buildings and industrial end use sectors.

Figure 25. City of Austin GHG Emissions by End Use Sector, $MMtCO_2e$

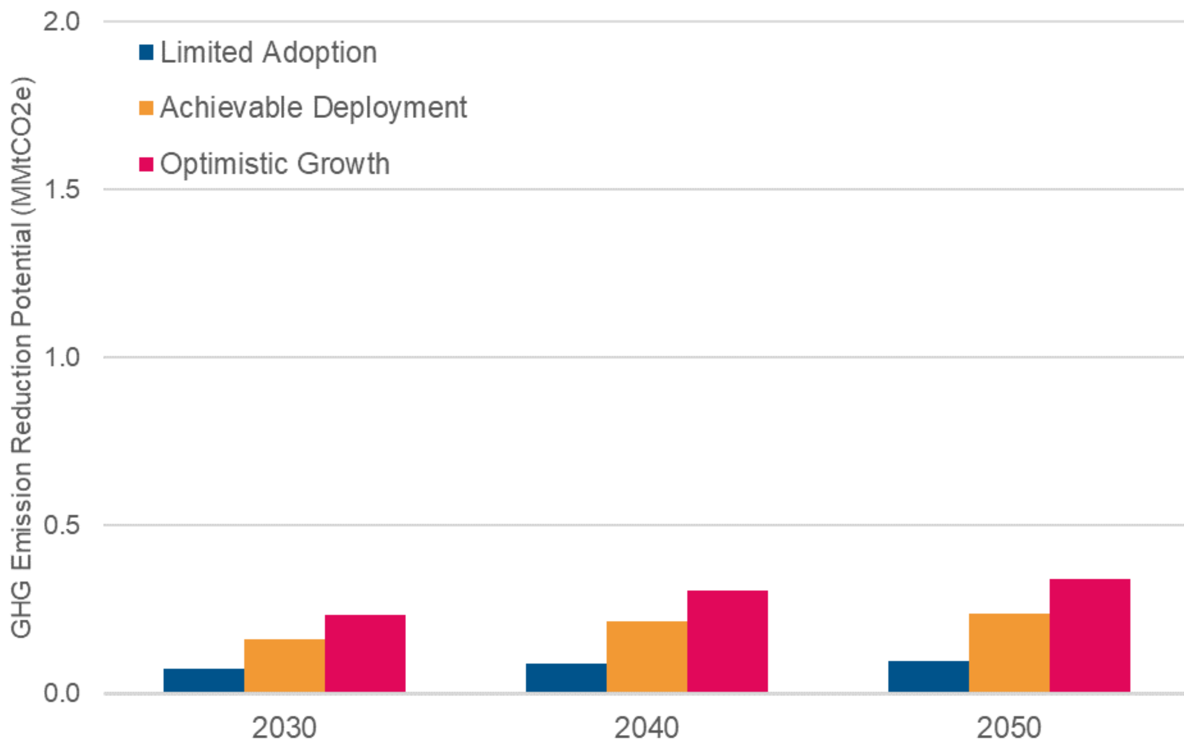


[47] City of Austin, 2020. Austin Community Climate Plan, https://public.tableau.com/profile/cavan.merski#!/vizhome/CommunityInventoryMetricSprintDashboard/trend

Lifecycle Accounting Framework

The figures below show the range of GHG emission reductions using a lifecycle accounting framework, in units of $MMtCO_2e$. ICF estimates that 0.10 to 0.34 $MMtCO_2e$ of emissions could be reduced per year by 2050 through the deployment of RNG projects located in Travis County, shown in Figure 26 below.

Figure 26. Travis County RNG Emission Reduction Potential by Scenario, $MMtCO_2e$ (Lifecycle)



As shown in the figure above and figures below, the emission reduction estimates using a lifecycle approach are largely lower relative to the estimates for the combustion approach. This is driven by the additional upstream emissions associated with the production of RNG from various feedstocks, counterbalanced by extra emission reductions primarily from avoided methane emissions, such as those from RNG produced from animal manure (see Figure 20 above).

Expanding the geographic footprint to include RNG feedstocks from the surrounding CTX Service Area counties, this increases to between 0.18 and 0.75 $MMtCO_2e$ per year in 2050. ICF estimates that 0.56 to 1.60 $MMtCO_2e$ of emissions could be reduced per year by 2050 through the utilization of RNG feedstocks from outside the immediate City of Austin region, as reflected in the scenario totals.

Figure 27. CTX Service Area RNG Emission Reduction Potential by Scenario, $MMtCO_2e$ (Lifecycle)

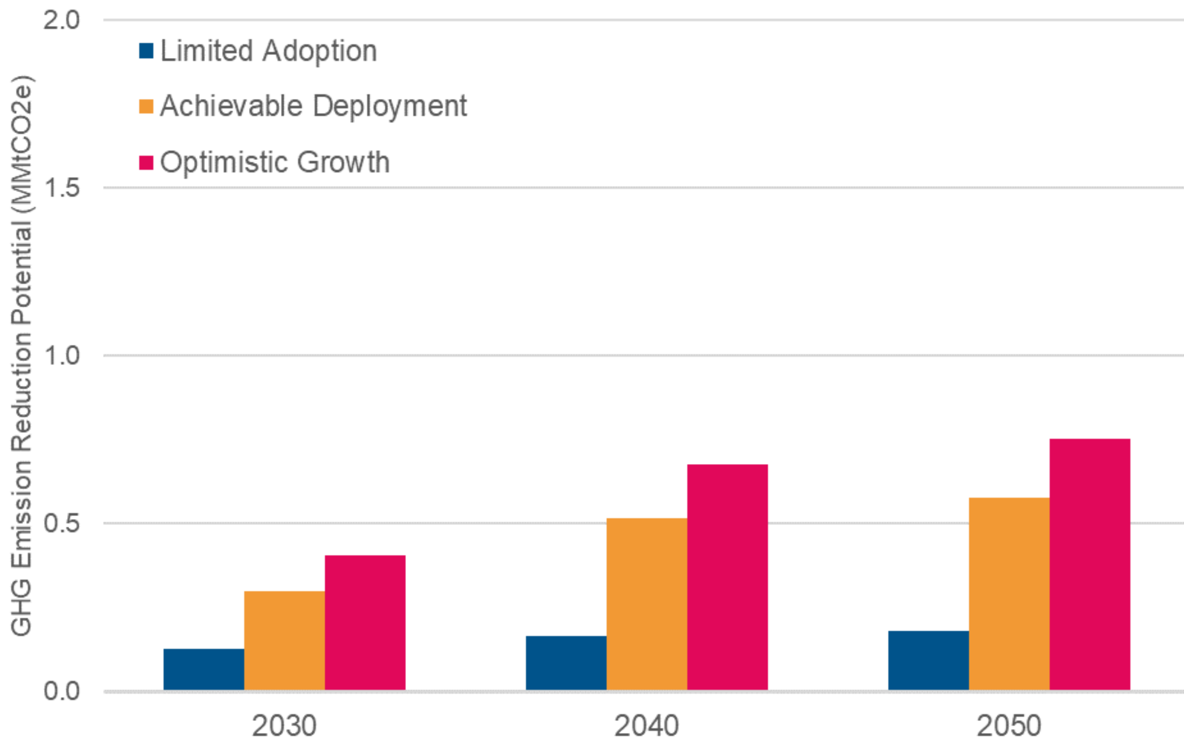
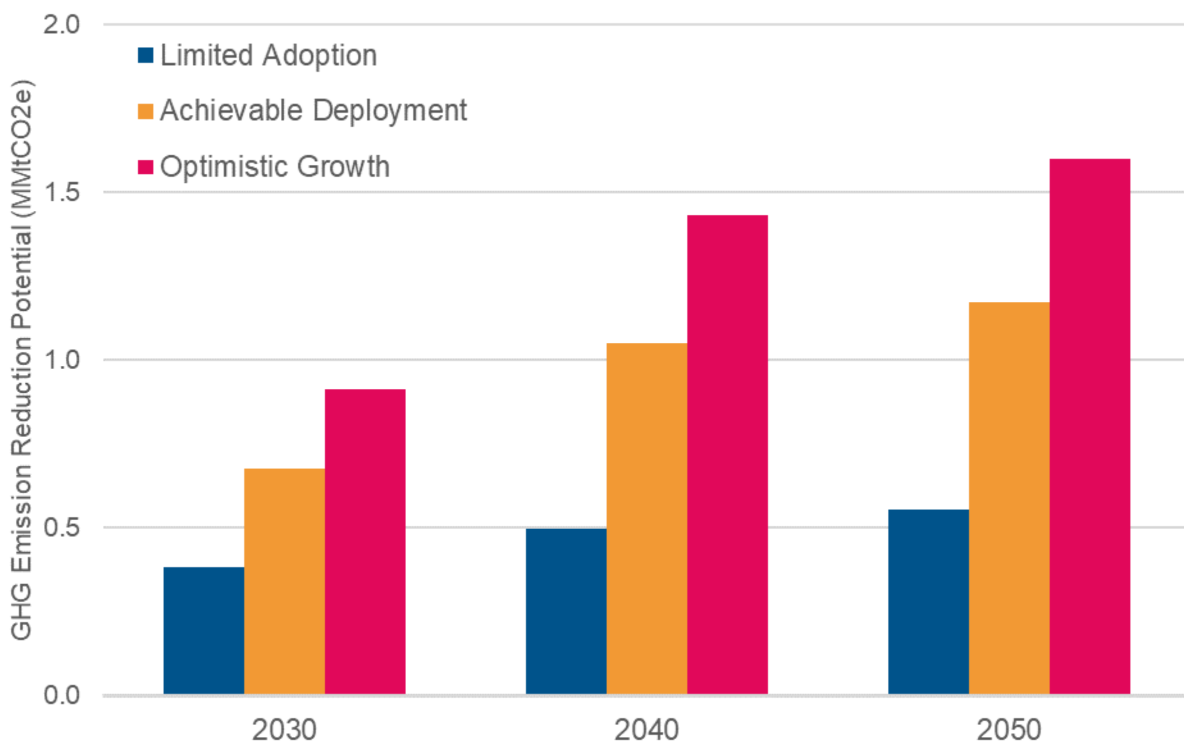


Figure 28. Total RNG Emission Reduction Potential by Scenario, $MMtCO_2e$ (Lifecycle)



6. RNG Policy Assessment

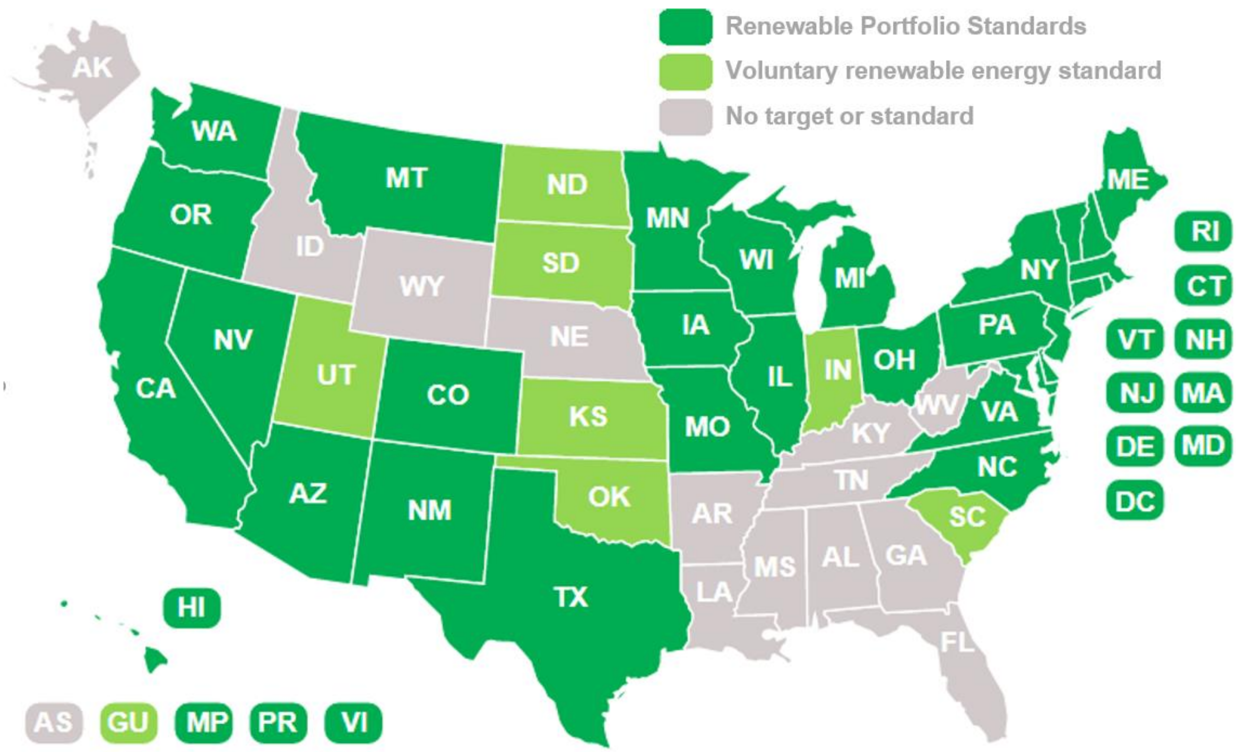
Review of End-Use Markets

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

Electricity Generation

Before the recent movement of RNG into the transportation sector, most biogas has been combusted on-site to generate electricity. The renewable electricity is typically used to comply with a Renewable Portfolio Standard (RPS), which requires a certain share of all final end user electricity consumption to come from eligible renewable generation technologies. 30 states and D.C. have passed mandatory renewable generation requirements or goals and seven more have passed voluntary standards or goals. Most of these programs include landfill gas as an eligible renewable resource, while some also include wastewater treatment plants and anaerobic digestion. Figure 29 shows the RPS requirements across the United States.

Figure 29. Renewable Portfolio Standards[48]



[48] National Conference of State Legislatures, 2020. https://www.ncsl.org/research/energy/renewable-portfolio-standards.aspx

Texas established a Renewable Generation Requirement in 1999, mandating 10,000 MW of installed renewable energy capacity by 2025, although Texas surpassed that target in 2009. Biomass-based waste products, including landfill gas, are eligible renewable energy technologies. There are nine landfill gas facilities currently participating in Texas's Renewable Energy Credit trading program, generating over 335 GWh of electricity in 2019.[49] Along with the statewide Renewable Generation Requirement, the City of Austin's community utility, Austin Energy, has set aggressive electric decarbonization objectives, with a goal of carbon-free electricity generation by 2035.[50]

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

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

The history of RECs in the renewable electricity market provides valuable lessons for RNG deployment. Stakeholders contemplated the concept of RECs as California considered an RPS in the mid-1990s, and this continued as multiple utilities and states advanced renewable electricity initiatives. The first retail REC product was sold in 1998.[51] REC markets helped to foster and stimulate growth of renewable power markets, as shown in Figure 30. By 2008, just five years after NREL started tracking renewable power markets in 2003, it was reported that REC markets accounted for nearly 65% of the annual renewable electricity consumed, which was three to four times greater than what was being consumed in utility green pricing programs or in competitive markets. Furthermore, this growth was occurring as the market continued to expand at a compound annual growth rate of 45%.[52,53]

---

[49] Public Utility Commission of Texas, 2020. 2019 Annual Report of the REC Program, https://www.texasrenewables.com/staticReports/Annual%20Report/2019%20ERCOT%20Annual%20REC%20Report.pdf

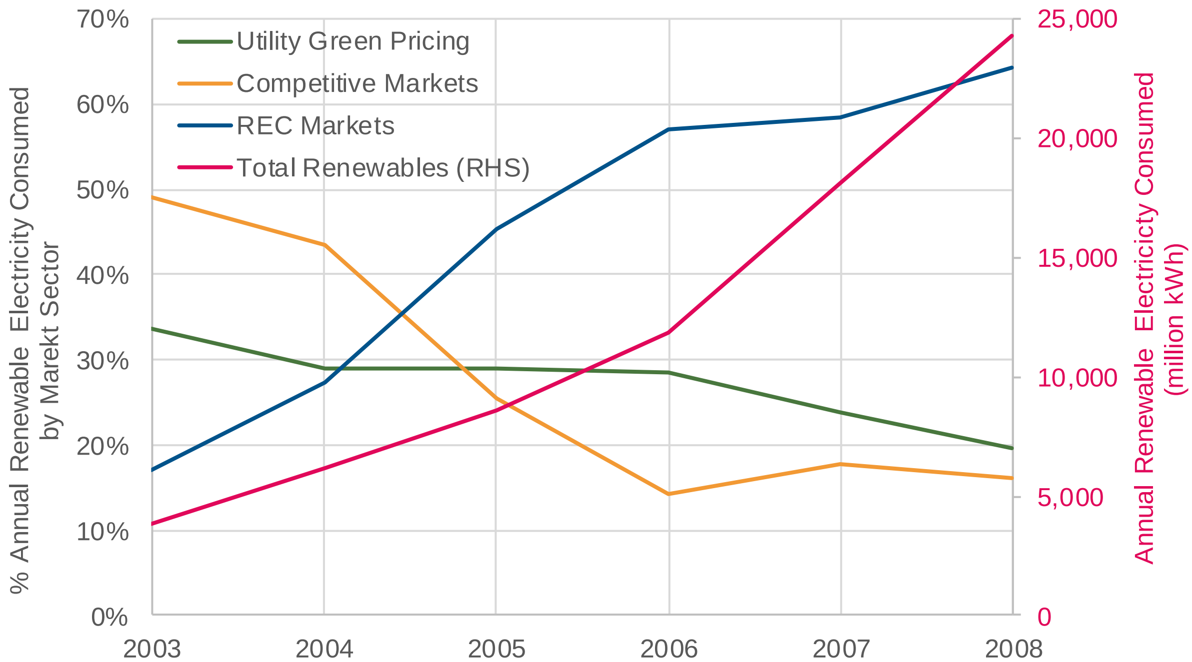
[50] Austin Energy, 2020. Austin Energy Resource, Generation and Climate Protection Plan to 2030, https://austinenergy.com/wcm/connect/6dd1c1c7-77e4-43e4-8789-838eb9f0790d/gen-res-climate-prot-plan-2030.pdf?MOD=AJPERES&CVID=n85G1po

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

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

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

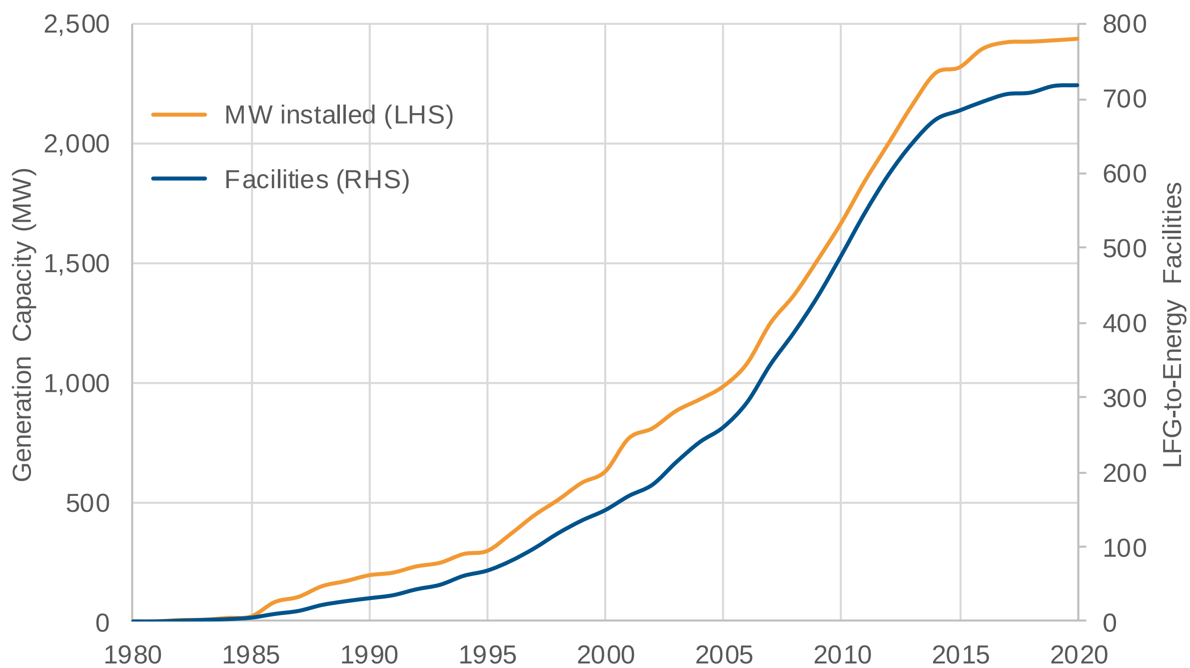
Figure 30. Percent and Total Renewable Electricity Consumption by Market Sector, 2003–2008



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

Landfill gas plays a substantive role in many RPS programs. The EPA database of Landfill Gas Energy Projects indicates that there are currently more than 450 operational LFG-to-electricity projects with a capacity exceeding 2,000 MW—see Figure 31. There has been a noticeable decrease in the rate of installed capacity and facilities since 2014. For instance, for the years 2005–2014, an average of 26 new facilities were brought online annually with installed capacity of 318 MW annually. This has decreased to just 4–5 facilities annually over the last four years, with an installed capacity of just 25 MW annually. This is likely due to the availability of RINs and, to a lesser extent, LCFS credits. ICF anticipates this trend to continue plateauing for LFG-to-electricity projects as investors seek out higher value in the LCFS and RIN markets.

Figure 31. Facilities and Installed Capacity of LFG-to-Electricity Facilities[54]



Transportation

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

NGVs are the most cost-effective vehicle technology to reduce local air pollutants and smog from heavy-duty trucks and buses. The latest commercially available natural gas engines are 90% cleaner than the EPA's current NOx emissions requirement, and 90% cleaner than the cleanest diesel engine.[55]

In addition, NGVs can be fueled with RNG with no changes to equipment or adverse impacts on performance. Over the last five years, RNG production for use as a transportation fuel has increased nearly six-fold, with over a third of all NGV fuel use relying on RNG in 2019.[56] This rise in RNG consumption in NGVs has been largely driven by the environmental crediting incentives provided by the federal RFS and carbon constraining policies like California's LCFS and Oregon's CFP, discussed in more detail below.

[54] ICF Analysis of LMOP Database.
[55] EPA and California Air Resources Board, 2018.
[56] NGV America, 2020. https://www.rngcoalition.com/infographic

RFS Program and RIN Prices

The RFS program sets volumetric targets for blending biofuels into transportation fuels across the entire United States—compliance is tracked through the production and retirement of Renewable Identification Numbers (RINs).[57] In most cases, a RIN is generally reported as an ethanol gallon equivalent. In 2013, the EPA determined that RNG qualified as an eligible fuel and could generate 'D3' RINs, with landfill RNG qualifying after meeting cellulosic content and GHG reduction thresholds. This led to a rapid expansion of RNG projects for pipeline injection and subsequent RNG use as a transportation fuel in NGVs.

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

In 2019, the D3 RIN price was at historically low levels, around $0.60 per RIN, equivalent to roughly $7/MMBtu. In early 2020, the D3 RIN market showed signs of returning to its previous structure, before trailing off with other components of the energy complex due to the Covid-19 pandemic. However, that market has recently started to rebound and D3 RIN prices have maintained steady pricing above $1.50 in May and June 2020. ICF expects the prices to increase in Q3 and Q4 of this year. Furthermore, ICF forecasts a D3 RIN price in the range of $2.10 to $2.40 for 2021 based on the current outlook for gasoline pricing.[58]

California LCFS Program and Credit Prices

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

---

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

[58] Small refiners (i.e., those with an average annual crude oil input less than 75,000 barrels per day) are allowed to petition the U.S. EPA for an economic hardship waiver from their obligations under the federal RFS—these are referred to as small refinery exemptions (SREs). The rate of SREs submitted and granted have more than quadrupled under the Trump Administration, undercutting the renewable volume obligations (RVO) annually by about 10%. As a result of these exemptions, up to 2019 the D3 RIN market had been significantly over-supplied, and prices collapsed.

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

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

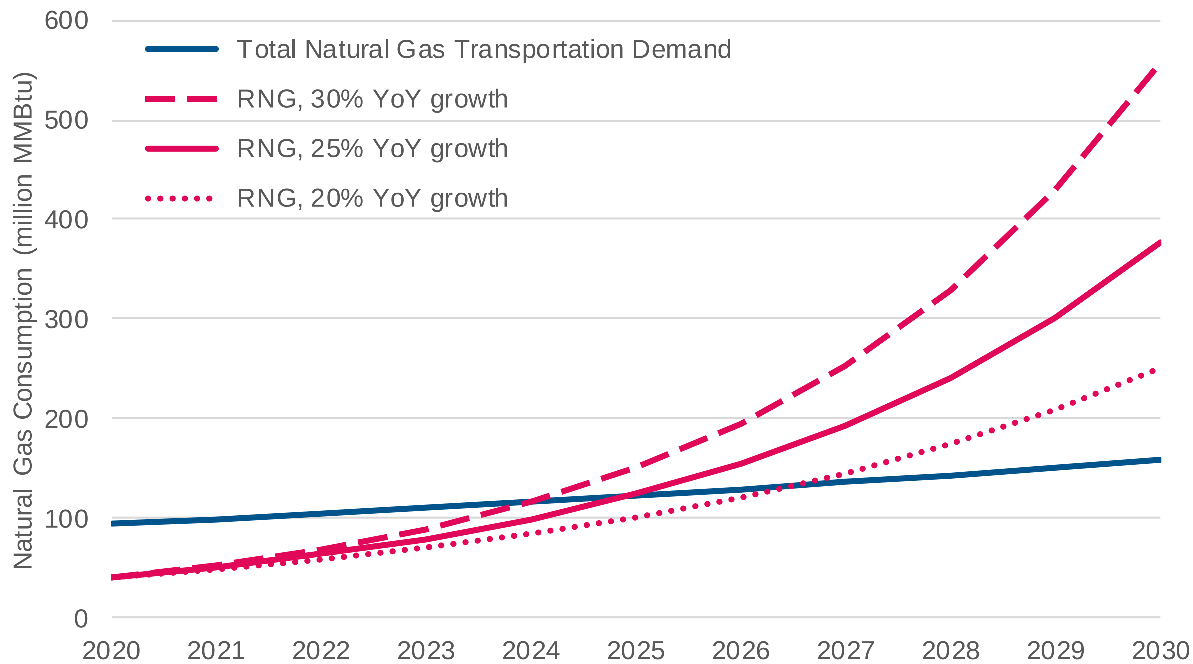
RNG Consumption in Transportation

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

Figure 32 helps demonstrate the potential for suturing the demand for natural gas as a transportation fuel with RNG production in the 2024–2027 timeline. This rising RNG consumption in the transportation sector is shown by the largest RNG procurement agreement between Clean Energy and logistics company UPS, where UPS will fuel its CNG vehicle fleet with RNG.[59]

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

Figure 32. Natural Gas as a Transportation Fuel



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

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

Transportation Demand in Austin and the CTX Service Area

The transportation sector remains an area of untapped demand for RNG in Austin and the surrounding region, and a viable near-term opportunity to direct relatively cost-effective RNG supply. The region is home to operators of large and small NGV fleets, including the City of

Austin, other local governments, and corporate fleets, which could provide feasible starting points to drive RNG demand.[60]

NGVs fueled by RNG would be eligible to generate RINs under the RFS program, presenting opportunities for participants in the NGV and RNG markets in the Austin region to capture the associated value of RINs. While contractual arrangements can vary substantially, fleet owners and operators, infrastructure owners, and natural gas distributors can all potentially facilitate and benefit from RNG deployment.

Pipeline (Stationary)

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

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

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

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

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

- Approved in 2017, Vermont Gas offers a voluntary RNG tariff program, providing retail gas customers the opportunity to purchase RNG in amounts proportionate to their monthly requirements.
- Consolidated Edison is very focused on RNG for pipeline injection as part of its consideration for the future of heating.

---

[60] Lone Star Clean Fuels Alliance, 2018. 2017 Transportation Technology Deployment Report, https://lonestarcfa.org/wp-content/uploads/2018/04/Clean-Cities-2017-Annual-Report-TX-Lone-Star-Clean-Fuels-Alliance-Central-Texas-Expanded-Edition.pdf

- National Grid's New York City Newtown Creek RNG demonstration project will be one of the first facilities in the U.S. that directly injects RNG into a local distribution system using biogas generated from a water and food waste facility.
- The joint venture between Dominion Energy and Smithfield Foods is set to become the largest RNG producer in the U.S., developing animal manure-based RNG in North Carolina, Virginia, and Utah, with plans to expand to California and Arizona.

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

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

Interconnection and Gas Quality

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

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

Table 44. Illustrative ONE Gas Quality Considerations for RNG Injection

Gas Quality Term	Generally Acceptable Limit
Hydrogen Sulfide	0.25 g/100 scf
Total Sulfur	5 g/100 scf
Carbon Dioxide (CO_2)	≤ 2.0%, by volume
Oxygen (O_2)	≤ 0.2%, by volume
Total Inerts (% by volume including O_2 and nitrogen)	≤ 5%, by volume
Heating Value	900 – 1,100 Btu
Temperature	40 – 140 °F
Water or Liquid Hydrocarbons	0
Water Vapor	< 7 lb/MMscf
Non-Hydrocarbon Gas	≤ 4%, by volume
Mercury	0.06 µg/m^3
Siloxanes	0.00 mg/m^3
Halocarbons	6.22 ppmv

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

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

For example, at the direction of the California Public Utilities Commission, the California Council on Science and Technology (CCST) assessed acceptable heating values and maximum siloxane specifications for RNG. CCST found that keeping the current minimum Wobbe Number requirement for RNG while relaxing the heating value specification to a level near 970 Btu/scf would not likely impact safety or equipment reliability. In relation to siloxanes, the CCST found that some RNG feedstocks are very unlikely to harbor siloxanes (e.g. dairy waste, agricultural residues or forestry residues), and less stringent monitoring requirements would be needed. The CCST also recommended a comprehensive research program to understand the operational, health, and safety consequences of various concentrations of siloxanes, due to inconclusive evidence for other RNG feedstocks.[61]

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

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

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

Regulatory and Policy Opportunities

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

Today, a handful of state-level policies are in place that are helping to shape the outlook for RNG beyond transportation, including the legislation summarized below.

- Oregon SB 98: allows natural gas utilities to make "qualified investments" and procure RNG from 3rd parties to meet portfolio targets for the percentage of gas purchased for distribution to retail customers. The RNG portfolio targets range from 5% between 2020 and 2024 to 30% between 2045 and 2050.
- California SB 1440: requires the California Public Utility Commission to establish RNG procurement goals or targets on natural gas investor-owned utilities. The legislation stipulates that the goals and targets need to be a cost-effective means of achieving reductions in short-lived climate pollutants and other GHG emission reductions.
- Nevada SB 154: authorizes natural gas utilities to engage in RNG activities and to recover the reasonable and prudent costs of such activities, including the purchase of and production of RNG. The legislation also includes voluntary procurement targets of not less

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

than 1% of the total amount of gas sold by 2025, not less than 2% by 2030, and not less than 3% by 2035.

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

Condition and Interconnection Tariffs

As outlined in Section 4, the costs of biogas conditioning and upgrading can be expensive; similarly, interconnection costs can be prohibitive for some project developers. These costs are the primary capital outlays at the outset of a project and have a material impact on the ability of projects to get financed. Under a tariff structure, the producer can avoid the significant upfront capital costs that can often impede project development.

Conditioning and interconnection tariffs allow utilities or LDCs to build and operate the upgrading and interconnection facilities, while recovering capital and operation and maintenance costs from the project developer at a pre-determined rate. Examples of where this has been done include:

- SoCalGas has a biogas conditioning and interconnection tariff; it “is an optional tariff service for customers that allows SoCalGas to plan, design, procure, construct, own, operate and maintain biogas conditioning and upgrading equipment on customer premises.”[62]
- TECO Peoples Gas in Florida had a tariff for biogas conditioning and upgrading approved in December 2017, and have since made modifications to the tariff to accommodate the receipt of RNG from biogas producers and an updated rate schedule for conditioning services.[63]
- Southwest Gas Company (SWGC) in Arizona has a biogas services tariff enabling them to enter into a service agreement with a biogas or RNG producer, and includes requirements for access to the production facilities, interconnection facilities, and gas quality testing facilities.[64]

Voluntary and Mandatory Programs

Utilities may offer opt-in voluntary programs to customers to help reduce the environmental impact of their energy supply. This is more common for electric utilities, such as Austin Energy’s GreenChoice program, which is a voluntary program that allows residential and commercial customers to opt-in and purchase electricity generated from Texas-based wind power projects.[65] Similar programs can be developed for gas utility customers, but for RNG consumption rather than renewable electricity.

---

[62] SoCalGas, information retrieved from https://www.socalgas.com/for-your-business/power-generation/biogas-conditioning-upgrading.

[63] TECO Peoples, tariff is available online at https://www.peoplesgas.com/files/tariff/tariffsection7.pdf.

[64] SWGC, Schedule No. G-65, Biogas and Renewable Natural Gas Services , available online at https://www.swgas.com/1409197529940/G-65-RNG-02262018.pdf.

[65] Austin Energy, 2020. https://austinenergy.com/ae/green-power/greenchoice/greenchoice-renewable-energy

Examples of voluntary programs include:

- Vermont Gas has had a voluntary program in place since 2018 for various blends of RNG. Vermont Gas customers consume about 6 BCF of RNG, which is sourced from Canada.[66]
- In April 2020 SoCalGas and San Diego Gas & Electric (SDG&E) requested settlement approval from the CPUC to offer a voluntary RNG Tariff program to their residential, small commercial, and industrial customers. SoCalGas and SDG&E have proposed to recoup program costs through rates charged to program participants.[67]
- National Grid proposed a Green Gas Tariff offering in April 2019 that will enable its customers to voluntarily purchase RNG to meet all or a portion of their energy needs. National Grid designed the tariff with four tiers, providing consumers with multiple options regarding the extent to which they want to green their gas.
- FortisBC, the main gas utility in the Canadian Province of British Columbia, has had a voluntary RNG tariff program since 2011, which has spurred RNG production in the region.[68]

Voluntary programs and opt-in green tariffs provide near-term opportunities for natural gas utilities, and regulators, to become accustomed to RNG and the RNG market, without requiring substantial and long-term commitments. An appropriate regulatory structure can support small-scale RNG deployment without imposing a large burden on customer bills and avoiding undue risk on the utility. For example, FortisBC's voluntary program provides an RNG cost cap of approximately $20/MMBtu, but the utility has been able to procure RNG at lower costs, with the current bill premium for RNG about $5.50/MMBtu.[69]

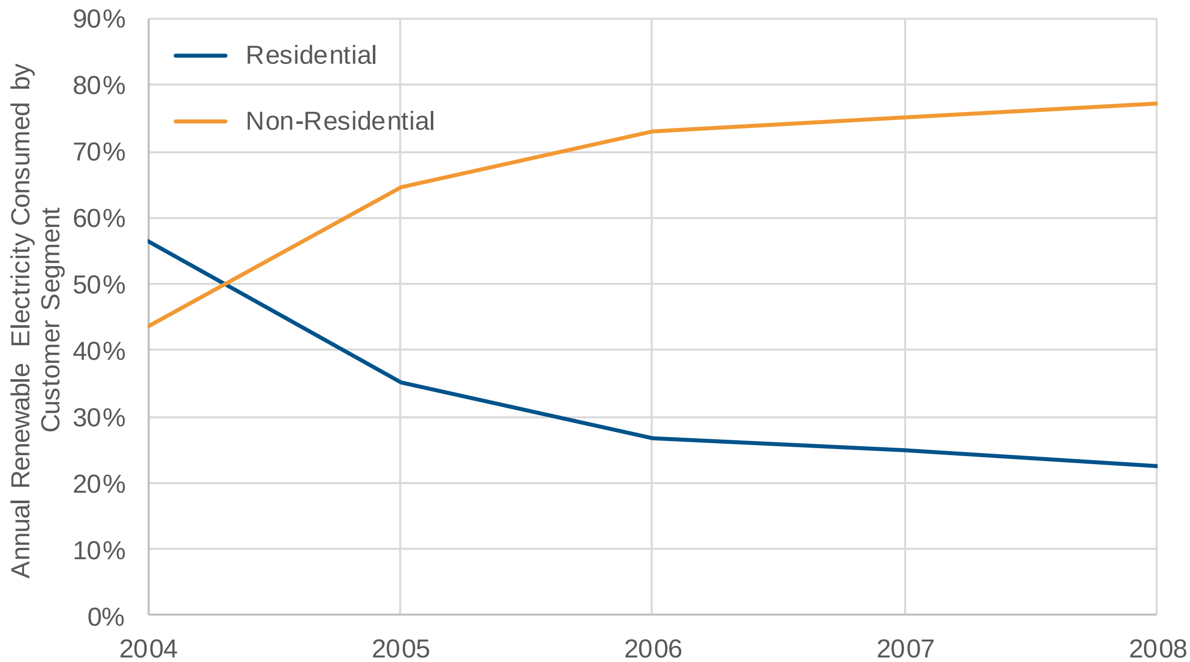
In addition, the recently approved voluntary tariff for SoCalGas and SDG&E includes provisions that allow for the true-up of any over or under collections related to the voluntary tariff, with future program charges adjusted to reflect these updates. At a high level these regulatory elements could be replicated to provide customers with choice, as well as minimizing risks for customers, RNG producers and natural gas utilities.

Voluntary markets were critical to the initial growth of renewable electricity, as residential and non-residential customers helped grow demand considerably in the early years of renewable electricity development (see Figure 33).[70,71]

---

[66] Vermont Gas, 2020. https://www.vermontgas.com/renewablenaturalgas/.
[67] SoCalGas, 2020. Application 19-02-015 https://www.socalgas.com/sites/default/files/Joint%20Motion%20for%20Approval%20of%20Settlement%20-%204-13-20%20Final.pdf
[68] FortisBC, 2020. https://www.fortisbc.com/services/sustainable-energy-options/renewable-natural-gas
[69] FortisBC, 2020. https://www.fortisbc.com/services/sustainable-energy-options/renewable-natural-gas/renewable-natural-gas-rates
[70] NREL, Green Power Marketing in the United States: A Status Report (Tenth Edition), December 2007, NREL/TLP-670-42502, https://www.nrel.gov/docs/fy08osti/42502.pdf.
[71] NREL, Green Power Marketing in the United States: A Status Report (2008 Data), September 2009, NREL/TLP-6A2-46851, https://www.nrel.gov/docs/fy08osti/42502.pdf.

Figure 33. Percent Annual Renewable Electricity Consumption by Customer Segment, 2004–2008



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

Renewable Gas Standard (RGS)

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

- A free-market approach whereby a procurement target is established and the market simply responds to the price signal according to the supply-cost curve for RNG production.
- A feed-in tariff, or standard offer contracts, would provide clear, reliable pricing for RNG producers. Although this approach provides a clear signal to help producers finance renewable gas projects, without distinguishing between feedstocks, a feed-in tariff has the potential to favor low-cost producers without recognizing the cost-effectiveness of GHG emission reductions.
- The RGS could take on a performance-based approach structure like the LCFS program in California, requiring a percent reduction in the carbon intensity of natural gas by some date. Similarly, the RGS could take on a structure that requires a percent volume target by some

date (different from an absolute volumetric target, as is prescribed in the federal RFS program).
- The coverage of an RGS would not necessarily be limited to just utilities and LDCs, but also encompass all suppliers of natural gas, including third-party suppliers such as natural gas marketers, similar to the broad coverage of RPS programs relative to electric load serving entities.

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

Tracking and Verification

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

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

Performance-based Approaches

In 2017 ICF researched and wrote about understanding the tradeoffs between different performance-based approach tradeoffs, focused on volumetric and carbon intensity targets. A performance-based approach should, in principle, provide clear signals to regulated parties and investors regarding the timeline required to achieve program targets, whether it be a carbon intensity target or volumetric target.

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

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

Complementary Measures

Energy Efficiency

Promoting energy efficiency measures is a cost-effective approach to reduce GHG emissions and help contribute to meeting both near- and long-term decarbonization objectives. Energy efficiency measures avoid the need for new energy infrastructure, promote resource conservation, and lower customer bills. Energy efficiency programs are also a large source employment and growth in the energy sector, including for construction, equipment production and manufacturing, installation, maintenance and repair.

Energy efficiency programs can focus on consumer behaviors, such as providing information on energy performance to induce changes in behaviors that lead to energy savings. Typical information includes practical energy conservation tips and recommendations, as well as cross promotions of other utility programs.

Equipment and building upgrades are another form of energy efficiency program. These programs typically include rebates or upfront cost reductions for the purchase and installation of high-efficiency equipment or infrastructure.

Carbon Offsets

Carbon offsets are a method for entities to meet GHG obligations through emission reductions that occur beyond their operations or facilities. A carbon offset represents a reduction of, or avoided, GHG emissions made in one place to compensate for GHG emissions generated at another location. Typically carbon offset credits represent one metric ton of CO_2e, and can be traded, purchased and retired to offset, or balance, GHG emissions elsewhere.

Offset credits are a mechanism to transfer a net GHG emission reduction from one entity to another. In contrast to localized pollutants, as greenhouse gases mix in the atmosphere and have a global climatic effect, it does not matter where GHG emission reductions occur. From a climate impact perspective, the effects are the same if an organization reduces emissions-intensive activities, or enables an equivalent emission-reducing activity somewhere else in the world. Carbon offsets are intended to make it more cost-effective for organizations to pursue GHG emission reductions, particularly if direct emissions abatement opportunities are expensive or not technically feasible.

Carbon offset credits can be generated from a variety of projects across multiple sectors, and can deliver additional economic and environmental benefits for project participants beyond GHG reductions. Costs for developing offset projects can vary significantly depending on the project type. Examples of project activities include:

- Land-use: sustainable forest management, urban forestry, afforestation and avoided deforestation.
- Agriculture: crop management, and avoided methane from livestock.

- Industrial: energy efficiency, ozone-depleting substance (refrigerant and foam) destruction, and fuel switching.
- Transportation: public transit, and traffic management.

A key component of carbon offset projects is 'additionality'. Additionality refers to the concept that the offset would not have occurred in a business-as-usual environment. Additionality tests attempt to ensure that the GHG emission reduction activities credited for an offset project would not have otherwise taken place without the value generated by the offset. Additionality tests include legal, regulatory, financial, barriers, common practice and performance tests. Depending on the complexity and uniqueness of an offset project, a combination of tests can be applied that bests demonstrates additionality.

In the case of natural gas consumption, carbon offsets would offset GHG emissions associated with the combustion of conventional natural gas by residential and commercial customers. Numerous natural gas utilities and suppliers offer customers the opportunity to reduce their carbon footprint through the use of offsets, such as National Gas and Electric, Washington Gas and NW Natural.

There are a number of offset trading platforms and markets where entities can purchase offset credits, including the Climate Action Reserve and American Carbon Registry. The costs to generate offsets, and the market prices for offsets, can vary based on the project as well as the monitoring and verification requirements for offset accreditation. For example, to generate eligible offsets for use in California's cap-and-trade (C&T) program requires project developers to comply with robust accreditation protocols.[72] Different voluntary offset protocols also offer robust accreditation frameworks, such as the global Gold Standard offset framework.[73]

The prices for offsets can also vary significantly, driven by the project itself, as well as the certification and accreditation framework, and other market factors. In general, offsets with accreditation from more robust and comprehensive certification schemes have higher prices. For example, as of June 2020 certified offsets in California's C&T are trading at approximately \$14/tCO_2e.[74] In contrast, Certified Emission Reductions (CER) accredited under the Clean Development Mechanism have traded at less than \$1/tCO_2e for the past five years.[75] Voluntary offset credit frameworks have shown a wide variance in prices, in part driven by the preferences of offset purchasers, including project types and accreditation schemes. In 2018 the transacted prices of various voluntary offset credits ranged from under \$1/tCO_2e to over \$70/tCO_2e.[76]

Offsets provide a relatively cost-effective and immediate opportunity to reduce GHG emissions, whether for an organization to meet climate objectives, or as a mechanism for customers to voluntary offset their carbon footprint. Offsets also offer the potential to reduce GHG emissions in the near-term, allowing time for the development and implementation of other decarbonization

[72] See CARB's Compliance Offset Program, https://ww3.arb.ca.gov/cc/capandtrade/offsets/offsets.htm.
[73] See the Gold Standard Guide, https://www.goldstandard.org/project-developers/standard-documents.
[74] ICE, 2020. California Carbon Offset Futures Report, https://www.theice.com/marketdata/reports/142
[75] ICE, 2020. CER Futures Report, https://www.theice.com/products/814666/CER-Futures/data?marketId=1240048&span=3
[76] World Bank, 2019. State and Trends of Carbon Pricing 2019, http://documents.worldbank.org/curated/en/191801559846379845/pdf/State-and-Trends-of-Carbon-Pricing-2019.pdf.

technologies and strategies. However, given the ambitious long-term climate objectives of various jurisdictions, including the City of Austin's net zero GHG by 2050 goal, carbon offsets will likely provide a complementary role relative to other decarbonization initiatives, rather than serving as a central strategy for current major sources of GHG emissions.

Waste Diversion

Waste diversion policies can help stimulate and capture RNG feedstock collection. The RNG industry could benefit considerably from complementary policies that help improve the accessibility of feedstocks while improving project development economics. This includes regulations or policies that encourage methane capture, encourage waste diversion and waste utilization, and forest management and thinning requirements.

The City of Austin's Zero Waste by 2040 goal, and accompanying Resource Recovery Master Plan, provides the overall framework for productive waste diversion activities. For example, the Master Plan identifies the enhanced role of the Hornsby Bend facility to process organic wastes such as yard trimmings and potentially food scraps.[77] The objective to capture organic waste streams for productive uses would work in tandem with, and encourage, the expansion of anaerobic digestion capacity, and RNG production and use in the region.

[77] City of Austin, 2011. Resource Recovery Master Plan, https://www.austintexas.gov/sites/default/files/files/Trash_and_Recycling/MasterPlan_Final_12.30.pdf

7. Economic Impact Assessment

IMPLAN Model Overview

In this analysis, the economic impacts were calculated analyzed using the IMPLAN (IMpact analysis for PLANning) online input-output model.[78] Input-output analysis is a form of economic analysis based on the interdependencies between economic sectors. Input-output is commonly used to estimate the impacts to an economy of specific actions, and to analyze the resulting ripple effects.

IMPLAN is developed and maintained by the Minnesota IMPLAN Group, and contains 546 sectors representing all private industries in the United States as defined by the North American Industry Classification System (NAICS) codes. Employment, employee compensation, industry expenditures, commodity demands, and relationships between industries form part of IMPLAN's database.

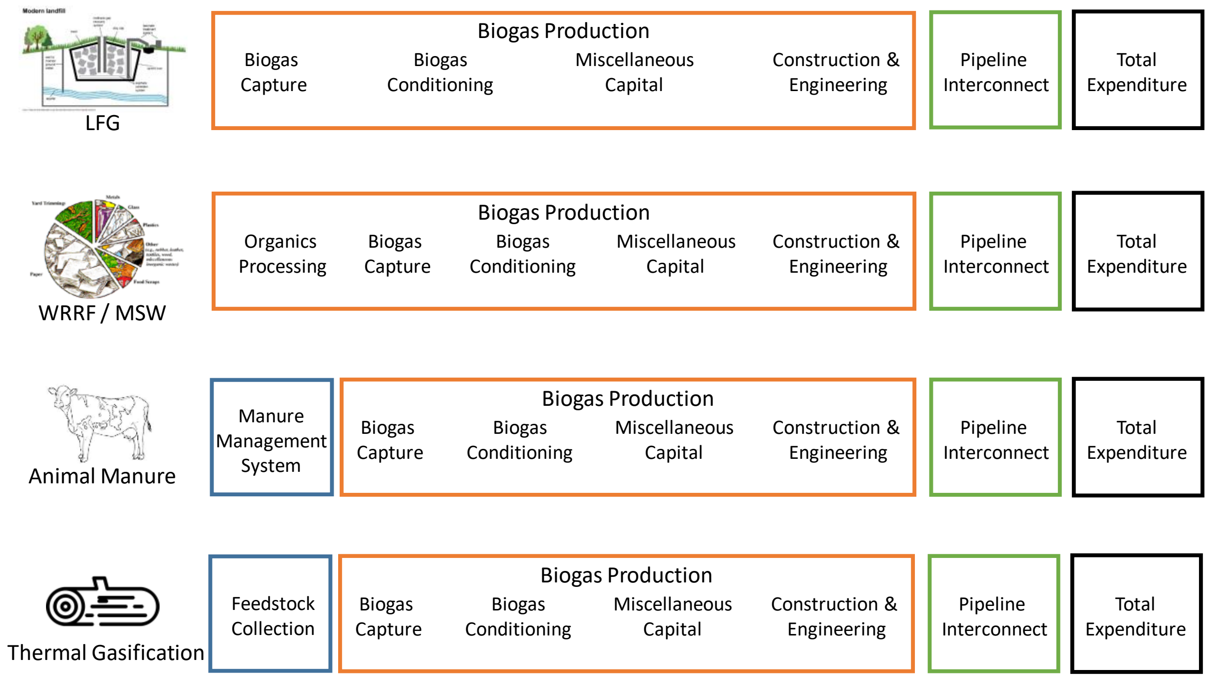
The IMPLAN model is a static input-output framework used to analyze the effects of an economic stimulus on a pre-specified economic region; in this case, on several scales including Travis County, ONE Gas's Central Texas Service Area, and Texas. IMPLAN is considered static because the impacts calculated by any scenario by the model estimate the indirect and induced impacts for one time period (typically on an annual basis).

Modeling Inputs

ICF accounted for multiple expenditures associated with RNG production, including digester equipment, biogas conditioning equipment, miscellaneous support equipment, and construction/engineering costs; as well as pipeline for utility interconnection. These are summarized in Figure 34 below.

[78] IMPLAN was developed by the Minnesota IMPLAN Group (MIG). There are over 1,500 active users of MIG databases and software in the United State as well as internationally. They have clients in federal and state government, universities, as well as private sector consultants. More information is available at www.implan.com

Figure 34. RNG Production Steps Considered in Analysis



In each case, we also included the annualized cost of operating and maintaining RNG production processes, including digester-related equipment, and pipelines. ICF estimated the costs for each RNG pathway by developing illustrative facilities for each feedstock type (as shown in Table 45 below). Table 45 includes the assumed biogas throughput for illustrative facilities by RNG production facility type, in units of standard cubic feet per minute (SCFM).

Table 45. Illustrative RNG Production Facilities Considered, by Feedstock Type

Feedstock Type	Illustrative Facility		
	Small	Medium	Large
Animal Manure			
Biogas output (SCFM)	90	180	300
Share of Facilities	65%	17.5%	17.5%
Landfill Gas			
Biogas output (SCFM)	1,680	2,880	4,800
Share of Facilities	20%	40%	40%
WRRFs			
Biogas output (SCFM)	50	110	530
Share of Facilities	30%	50%	20%
Thermal Gasification			
Feedstock processed (tpd)	200	1,000	2,000
Share of Facilities	60%	20%	20%

Results Overview

The economic impacts of RNG production are characterized by employment, labor income, and industry output.

- **Employment** is reported in terms of annualized job-years. The employment numbers are broken down by direct, indirect, and induced. We also present an employment metric referred to as a jobs multiplier (Table 46), which is the sum of job-years (included direct, indirect, and induced) divided by the direct job-years. This is an indicator of the type of employment activity statewide that is generated by investment in a technology. We also present labor income and labor income per worker. The latter is a coarse estimate of the value of jobs created by the corresponding investment.
- **Economy-wide Impacts**. We present several metrics measuring the impacts to the local economy, including value added and industry output.
  - Value Added measures the value of goods and services and is a measure comparable to net measurements of output such as gross state product (GSP).
  - Industry output multiplier mirrors the jobs multiplier and represents the total industry activity (including direct, indirect, and induced) divided by the direct industry activity. This is an indicator of the type of industry activity statewide that is generated by investment in a technology.

Table 46 below provides a summary of the employment impacts of RNG facilities. Table 46 that follows summarizes the economic impacts for RNG production facilities, including average capital expenditure, value added and output multiplier per facility.

Table 46. Summary of Average Employment Impacts per Facility by RNG Feedstock

Facility Type	Employment (FTE job years)				Income per Worker	Jobs Multiplier
	Direct	Indirect	Induced	Total		
Animal Manure	29	21	30	79	$85,671	2.2
Landfill Gas	73	40	54	167	$84,825	2.3
Thermal Gasification	630	535	546	1,711	$73,069	2.7
WWRFs	133	75	87	295	$77,180	2.7

The estimated income per worker (a proxy for salary) compares favorably with Travis County's and Texas's median household income, as reported by the Census Bureau's American Community Survey at $71,767 and $59,570, respectively.[79] For every job that is created via investment RNG production, our results indicate another two jobs will be created in supporting industries (indirect) and via spending by employees that are either directly or indirectly supported by these industries (induced).

Table 47. Summary of Average Economic Impacts per Facility by RNG Feedstock

Facility Type	Capital Expenditure ($millions)	Value Added ($millions)	Output Multiplier
Animal Manure	$4.2	$10.7	1.9
Landfill Gas	$14.8	$20.7	1.9
Thermal Gasification	$171.6	$165.3	1.9
WWRFs	$14.7	$35.6	1.8

The employment multipliers for the different RNG production facilities are estimated at between 2.2 and 2.7, while the economic output multipliers range from 1.8 to 1.9. These economic multipliers are consistent with other industries. For instance, in a previous study, ICF reviewed the economic potential of innovative crude production technologies, including solar steam generation and solar photovoltaics deployed at oil fields, and we reported output multipliers in the range of 1.5 to 1.7 and a jobs multiplier of 2.6 to 2.7.

The economic and employment impacts are larger for thermal gasification facilities, relative to the anaerobic digestion production facilities. These impacts are driven by higher upfront capital expenditures for thermal gasification facilities, as well as the larger capacity of the facilities. ICF notes that there remains uncertainty around the costs of the thermal gasification technology, with the potential for cost reductions over time that would reduce the economic and employment impacts as shown by the IMPLAN results.

[79] U.S. Census Bureau, 2014-2018 American Community Survey 5-Year Estimates.

The IMPLAN model includes more than 500 industry sectors; Table 48 below highlights the sectors that experienced the highest employment impacts. These sectors have been grouped broadly into two categories: RNG production facilities, and indirect and induced sectors. As noted previously, the indirect and induced sectors are those that are impacted by direct investments in the development of RNG production.

Table 48. Industry Sectors with Highest Increased Employment

Economic Grouping	IMPLAN Sectors
RNG Production Facilities	▪ Construction ▪ Waste management ▪ Commercial and industrial machinery equipment rental ▪ Architectural and engineering services ▪ Concrete product manufacturing ▪ Environmental and technical consulting services ▪ General and consumer goods ▪ Industrial gas manufacturing ▪ Oilseed farming
Indirect & Induced Sectors	▪ Wholesale trade ▪ Real estate ▪ Restaurants ▪ Employment services ▪ Building services and management services ▪ Insurance and brokerage

Table 49 below highlights the sectors that experienced the highest output impacts across the counties, grouped broadly into two categories: RNG production facilities, and indirect and induced sectors.

Table 49. Industry Sectors with Highest Output Impacts

Economic Grouping	IMPLAN Sectors
RNG Production Facilities	▪ Construction ▪ Commercial and industrial machinery equipment rental ▪ Petrochemical manufacturing ▪ Pipeline transportation ▪ General and consumer goods ▪ Natural gas distribution ▪ Architectural and engineering services ▪ Waste management ▪ Oilseed farming
Indirect & Induced Sectors	▪ Petroleum refineries ▪ Petrochemical manufacturing ▪ Wholesale trade ▪ Real estate ▪ Pipeline transportation ▪ Waste management ▪ Air transportation ▪ Truck transportation ▪ Employment services ▪ Oil and gas extraction ▪ Electric utilities

Household Impacts

This study did not directly assess the potential impact of RNG deployment on customer rates or the cost of service for the region's natural gas system. However, the incremental costs to household energy bills from the deployment of RNG can be estimated, although these estimates vary significantly, driven by the range in costs of RNG as outlined in Section 4.

Based on American Gas Association (AGA) estimates, the average residential customer in Texas consumed 49.9 MMBtu of natural gas in 2018.[80] Combined with average city gate and residential delivered prices for natural gas from the EIA, the table below provides a high level summary of the potential annual bill impacts for different blends of RNG at different costs.[81]

[80] AGA, 2019. Average Annual Residential Consumption per Customer by State, https://www.aga.org/contentassets/6894914d95e6467fae106015cbcb2abc/table6-14.pdf

[81] EIA, 2020. Natural Gas Price Data Series, https://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PG1_DMcf_a.htm and https://www.eia.gov/dnav/ng/NG_SUM_LSUM_A_EPG0_PRS_DMCF_A.htm

Table 50. Illustrative Texas Household Bill Impacts

Throughput Blend	RNG @ $10/MMBtu		RNG @ $15/MMBtu		RNG @ $20/MMBtu	
	Bill	%	Bill	%	Bill	%
Average Household Bill	*$550*	-	*$550*	-	*$550*	-
1% RNG	$553	0.5%	$555	0.9%	$558	1.4%
2% RNG	$555	0.9%	$560	1.8%	$565	2.7%
3% RNG	$558	1.4%	$565	2.8%	$573	4.1%

While these indicative estimates are helpful to show the near-term impacts of RNG deployment on household bills, ICF emphasizes that the cost-effectiveness of RNG should be measured relative to other emission reduction approaches, and the associated household impacts. As discussed in Section 5 and shown in Figure 21, the range of abatement costs for different long-term GHG mitigation strategies is substantial, and RNG has the potential to be a cost-effective option to decarbonize the energy system.

The above estimated household bill impacts also do not reflect the potential impact of voluntary RNG programs, as discussed in Section 6. Customers that opt-in to a voluntary RNG procurement program, and pay a premium for RNG, would have the potential to offset the bill impacts for other households.

Lastly, the above bill impacts do not reflect the potential use of RNG in the transportation sector, and accompanying environmental credit generation. Revenue from these environmental credits could be used to offset the higher relative costs of RNG, reducing the direct bill impact.

8. RNG Strategic Roadmap

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

Deploying RNG

ICF envisions a strategic roadmap to deploy RNG across the components outlined in Figure 35 below.

Figure 35. RNG Strategic Roadmap

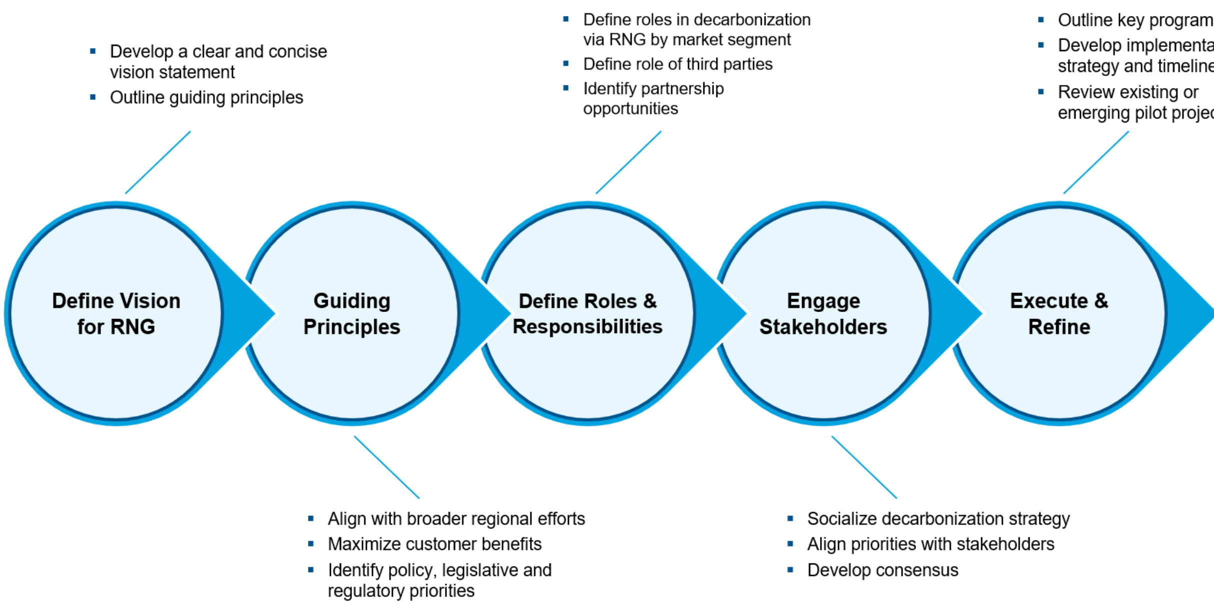


Figure 35 illustrates the Strategic Roadmap process that ICF recommends, including developing guiding principles, defining roles and responsibilities, engaging stakeholders, and executing the plan. ICF notes that the roadmap is portrayed in a linear fashion only for the sake of simplicity. There is nothing about the roadmap or the process that is inherently deterministic. Rather, the roadmap for the region will have to advance iteratively driven by the changing landscape.

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

ICF's overview of the Strategic Roadmap to deploy RNG in the City of Austin and the ONE Gas CTX Service Area is focused on the guiding principles outlined in Figure 35. In the sections that follow, ICF reviews market and regulatory actions that can be taken to deploy RNG. These actions largely (but not exclusively) address the other aspects of the roadmap, including the roles and responsibilities of different stakeholders, how to engage different stakeholders, and execution of various projects to deploy RNG.

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

RNG Deployment

The potential for RNG in the City of Austin and surrounding region's natural gas system is clear, with aggressive but attainable RNG throughput targets feasible over the medium-term and beyond. ICF's analysis of RNG potential at the local, regional, and national level supports the RNG volumes required to help decarbonize the region's natural gas system. However, ICF notes that for these broader RNG throughput targets to be cost-effective and successful, they would need to cover all natural gas distributors and suppliers in the region, and be supported by a broad and stable regulatory framework that provides a consistent RNG requirement across all suppliers and end users.

ONE Gas is well-positioned to take a leading role to facilitate the necessary development of RNG consumption in the natural gas system in the region, implemented through near-term voluntary throughput targets. Potential targets, and associated RNG volumes and GHG reductions, are outlined in Table 51 below.

Table 51. Illustrative ONE Gas RNG Throughput Targets and Volumes

Target	RNG Volume (MMBtu)	GHG Reductions (tCO_2e)
1% RNG	145,000	8,000
2% RNG	289,000	15,000
3% RNG	434,000	23,000
5% RNG	723,000	38,000
10% RNG	1,446,000	77,000

The RNG volumes and associated GHG emission reductions included in the table are illustrative only, and use ONE Gas's CTX Service Area total sales throughput of 14,460,000 MMBtu in 2019 as the reference level. Actual RNG volumes and emission reductions are dependent on the throughput levels in the specific target year, with forecasting throughput beyond the scope of this study.

The throughput targets are equivalent to proportional reductions in GHG emissions. For example, the deployment of 3% RNG is equal to a 3% reduction in GHG emissions from the direct combustion of total natural gas system throughput. The table also includes illustrative GHG emission reductions applying a combustion accounting approach. The GHG reductions shown in the table are equal to the volume of carbon offsets needed to deliver equivalent emission reductions – with 8,000 offsets required to provide the same emission reductions as 1%, or 145,000 MMBtu, of RNG.

As discussed in Section 3, there are sufficient feedstocks in the CTX Service Area to meet these proposed throughput targets, with potentially 682,000–2,305,000 MMBtu of RNG available for production in 2025, increasing to 3,614,000–16,507,000 MMBtu in 2035, based on ranges from the Limited Adoption and Optimistic Growth scenarios.

Specifically, the three landfills in Travis County have the combined potential to produce more than 5,000,000 MMBtu per year of RNG, while feedstocks from wastewater in Travis County could provide in excess of 250,000 MMBtu per year. These two feedstocks indicate that ONE Gas could meet near-term throughput targets of 1–3% using RNG from a local source, such as a landfill gas facility or the Hornsby Bend facility using wastewater as the RNG feedstock.

The resource scenarios discussed in Section 3 indicate that there are additional RNG resources in the region and beyond that could be accessed to meet broader and more ambitious throughput targets in the medium-term and beyond, including from animal manure, food waste and thermal gasification feedstocks. However, as noted above, a supportive and stable regulatory and policy framework encompassing all of the suppliers in the region's natural gas system would likely be needed to facilitate more aggressive targets. These market- and regulatory-focused efforts that are required to help achieve these targets are discussed in more detail below.

Guiding Principles

To achieve throughput targets outlined above, ONE Gas will need to be guided by a set of consistent and clear principles:

- ***Produce and deliver RNG safely and cost-effectively to participants and end-use customers.*** There is growing interest in RNG from consumers, especially in the commercial and industrial sectors. It is imperative that customers across the region know that market actors are delivering a safe product that helps to cost-effectively reduce the environmental footprint of natural gas operations.
- ***Contribute to broader regional GHG emission reduction objectives.*** The RNG strategy must align with the City of Austin's objectives with respect to GHG emission reductions.

- ***Pursue a flexible regulatory and legislative structure that values RNG deployment appropriately***. The region should seek to develop and support a regulatory and legislative structure that provides sufficient flexibility to achieve cost-effective GHG emission reductions while maintaining safety and reliability. This economy-wide structure should also be balanced and not focused on particular technologies or fuels, given the uncertainties and long timeframes needed to achieve deep decarbonization goals.
- ***Proactively engage with key stakeholders throughout the implementation of the RNG strategy.*** RNG deployment requires close coordination between regulators and stakeholders like gas utilities, LDCs, and investors. Similarly, an effective engagement strategy is needed with potential RNG suppliers (locally and regionally), potential end users in targeted segments (e.g., RNG in City of Austin refuse trucks), and key industry groups (e.g., American Gas Association, Coalition for Renewable Natural Gas).

Market-Based Approaches to RNG Deployment

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

Develop Interconnection Standards for RNG Projects

A uniform framework that includes the processes, requirements, and agreements that facilitate the pipeline connection of RNG projects would provide more certainty for stakeholders, particularly project developers, and enhance the efficiency and viability of different RNG projects. ONE Gas has already developed these interconnection standards, and is ready to work with potential RNG project developers on interconnection.

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

Deploy RNG into the Transportation Market

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

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

There are opportunities for expanding natural gas consumption in the medium- and heavy-duty vehicle market segments, thereby acting as a conduit for increased RNG deployment. The combination of the total cost of ownership for NGVs and the fueling infrastructure requirements remains a challenge to higher volumes. However, the appropriate combination of policy and market incentives can induce additional growth in NGVs. The regulatory considerations regarding NGV deployment are outlined in the following sub-section.

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

Establish Common Tracking Across RNG Markets

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

Although there is no analogous tracking system for RNG today, market actors are advancing the concept rapidly to help grow the market for RNG consumption outside of the transportation sector. As noted previously, the Midwest Renewable Energy Tracking System (M-RETS) has been trialing a thermal REC system since July 2019 with the intent of providing the same verification and price transparency to the RNG market as exists in the renewable electricity market. Similarly, the Center for Resource Solutions (CRS) has initiated a process to develop a Green-e® Renewable Fuels Standard with a stated goal "to accelerate the adoption of RNG, while ensuring that the gas is from sustainable renewable resources, meets the highest environmental standards, and that customers are protected in their purchase and ability to make verifiable usage claims."[82] The draft standard was released in an initial comment period in April 2020, with an anticipated second iteration to be released in Summer 2020 and a finalized standard to be published in Winter 2020.

Tracking will become increasingly important as numerous sectors and regions seek to deploy RNG, and RNG markets expand into multiple and broader end uses over the medium- and long-term. Tracking and verification through certification provides market certainty and can also help assure that markets and credits remain fungible.

---

[82] More information is available online via https://www.green-e.org/renewable-fuels.

Regulatory Approaches to RNG Deployment

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

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

ICF recommends a regulatory approach that stages potential RNG programs in the near-, mid-, and long-term horizons in an effort to reconcile conflicting requirements. In general, regulators tend to prefer piloting new customer programs when customer interest, cost assumptions, and the utility's execution capabilities are unconfirmed. This particularly applies to RNG programs because of the emerging aspects of the technology.

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

Pilot or Voluntary RNG Procurement Programs

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

Vermont has already approved a voluntary tariff and utilities in New York and California have filed proposals for approval of voluntary RNG tariffs. In the near-term ICF recommends ONE Gas work with regulators to file a voluntary tariff for RNG deployment, thereby sending a clear and immediate signal to the investor community that the region seeks to be at the forefront of RNG deployment. Voluntary procurement programs will also lay a foundation for establishing RNG demand in end uses beyond the transportation sector.

Expand RNG in Transportation through Infrastructure Investments

The transportation sector is a clear near-term opportunity for regional RNG deployment. However, the long-term opportunity for RNG in the transportation sector is limited because of low demand growth for natural gas as a transportation fuel.

The regulatory market for decarbonizing the transportation sector has favored liquid biofuels at the federal level (via the RFS) and transportation electrification (via the federal tax credit for electric vehicles), with less incentives for natural gas as a transportation fuel. ICF recommends an innovative regulatory structure to enable utilities to invest and recover costs in fueling infrastructure, offer beneficial and attractive tariffs to CNG users, and partner with key stakeholders to deploy CNG in key vehicle market segments. ICF envisions a regulatory structure analogous to the make-ready approach popularized by transportation electrification assessments whereby the utility helps to defray the costs of deploying fueling infrastructure, but site hosts retain ownership and are responsible for interfacing with the consumer.

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

Implementing a Renewable Gas Standard

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

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

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

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

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

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

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

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

  For instance, to incentivize higher-cost pathways, the feed-in tariff would need to be set at a level that would yield considerable windfall profits to lower-cost pathways (e.g., landfill gas). Some markets have included a degradation mechanism for feed-in tariffs to encourage technology cost reductions. However, it is unclear to what extent a simple degradation mechanism could be effective considering the cost disparities expected for different sources of RNG, which may also have varying levels of technology maturity and cost-reduction pathways.

- **Performance-based approach**. The RGS could take on a structure that requires a percent volume target by some date (different from an absolute volumetric target, as is prescribed in the federal RFS program). Similarly, an RGS could take on a structure like California's LCFS program, requiring a percent reduction in the carbon intensity of natural gas by some date.
  - Carbon intensity targets and percent volume targets should, in principle, provide clear signals to regulated parties and investors regarding the timeline required to achieve program targets.
  - The downside of a carbon intensity target is that it may introduce undue complexity to the RGS. For instance, consider the boundary conditions of the lifecycle GHG assessment of dairy digester gas. Without regulations in place to capture and burn the methane that is released, the gas receives a lower carbon intensity for being credited with the avoided emissions from *venting* methane. Landfill gas, on the other hand, being regulated and required to be captured and burned, receives a lower carbon intensity for being credited with the avoided emissions from *flaring* methane. The difference in the GHG benefit of avoided methane venting versus avoided methane flaring is significant: In the case of the former, avoided vented methane emissions have a global warming potential of 25, whereas in the latter, you are avoiding carbon dioxide emissions with a global warming potential of 1. In addition, new regulations can inadvertently change the boundary conditions of the analysis.
  - Another consideration related to a carbon intensity-based approach is the potential for the intent of the program to be expanded unexpectedly to include upstream emission reductions, such as methane leaks in the natural gas pipeline. This could provide additional compliance opportunities for utilities that produce additional GHG benefits, but may detract from the intent of stimulating RNG development. Additionally, and similar to the example above, other regulations and programs that address these system improvements could complicate the benefit calculation, creating moving targets and challenging utilities' assessments of investment value for different compliance pathways.

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

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

Appendix

U.S. DOE Billion Ton Study

The U.S. Department of Energy (DOE) has been quantifying the potential of U.S. biomass resources, under biophysical and economic constraints, for production of renewable energy and bioproducts since 2005. The 2016 *Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy* (BT16) is the third iteration of the DOE's efforts. BT16 reflects the most recent estimates of potential biomass in the U.S. that could be available for new industrial uses in the future.[83]

BT16 builds on previous research to address three broad questions:

- What is the potential economic availability of biomass resources using the latest-available yield and cost data?
- How does the addition of algae, miscanthus, eucalyptus, wastes, and other energy crops affect potential supply?
- With the addition of transportation and logistics costs, what is the economic availability of feedstocks delivered to the biorefinery?

At a high level, BT16 builds on DOE's previous analyses through:

- Updated farmgate/roadside analysis using the latest available data and specified enhancements,
- Additional feedstocks, including algae and specified energy crops, and
- Expanded analysis to include a scenario to illustrate the cost of transportation to biorefineries under specified logistical assumptions.

ICF utilized BT16, and the underlying data in the Bioenergy Knowledge Framework, to develop the RNG production inventory for specific feedstocks: food waste, agricultural residues, energy crops, forestry and forest product residues, and municipal solid waste. The assumptions and methodology used to estimate biomass volumes for each feedstock are outlined in the following sections.

Food Waste

Food waste as an RNG feedstock includes industrial, institutional and commercial food processing wastes, but does not include residential food waste. The National Renewable Energy Laboratory (NREL) has estimated that 20.6 million wet tons of food waste were generated in 2012. BT16 assumes that 65% of this food waste would be available at a biomass price of $40/dry ton, with a moisture content factor of 70% delivering a national total of 4.0 million dry tons. This food waste estimate adopts a conservative approach, and is lower than other regional or state-based estimates, such as from the California Biomass Collaborative.

[83] DOE, 2016. 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks, http://energy.gov/eere/bioenergy/2016-billion-ton-report.

Using the BT16 national food waste figure, ICF applies county-level population-weighted factors to estimate localized food waste estimates.

Agricultural Residues

Agricultural crop residues covered in BT16 and included in the U.S. DOE Bioenergy KDF include corn stover, cereal (wheat, oats, and barley) straws, and sorghum stubble. These crop residues require no additional cultivation or land and represent near-term opportunity feedstocks.

ICF extracted information from the Bioenergy KDF database on the following agricultural residues relevant to Texas: corn stover, sorghum stubble and wheat straw. These estimates are based on modeling undertaken as part of BT16, and utilizes the Policy Analysis System (POLYSYS), a policy simulation model of the U.S. agricultural sector.

The POLYSYS modeling framework simulates how commodity markets balance supply and demand via price adjustments based on known economic relationships, and is intended to reflect how agricultural producers respond to new and different agricultural market opportunities, such as for biomass. Available biomass is constrained to not exceed the tolerable soil loss limit of the USDA Natural Resources Conservation Service and to not allow long-term reduction of soil organic carbon

POLYSYS simulates exogenous price changes introduced as a farmgate price, which then solves for biomass supplies that may be brought to market in response to these prices. The farmgate price is held constant nationwide in all counties over all years of the simulation to allow farmers to respond by changing crops and practices gradually over time. [84]

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

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

Energy Crops

The assessment of energy crop potential utilizes the same modeling framework for agricultural residues, including POLYSYS, outlined above. The following are brief descriptions of energy crops included in BT16 and ICF's analysis.

[84] US DOE, 2016. 2016 Billion Ton Report, https://www.energy.gov/eere/bioenergy/2016-billion-ton-report.

- Biomass sorghum: annual herbaceous crop, currently grown in rotation throughout the Southeast and Great Plains for grains and forage. Biomass sorghum exhibits non-photoperiod sensitivity and drought tolerance.
- Energy cane: a perennial tropical grass with high yield potential across the Gulf South. Low-sugar, high-cellulose varieties (a hybrid of commercial and wild sugar cane species) can be established, managed, and harvested using existing sugar-cane industry equipment.
- Eucalyptus: short-rotation woody crop ideal for Gulf States as well as Georgia and South Carolina.
- Miscanthus: sterile triploid with low nutrient requirements and wide adaptability across cropland.
- Pine: tree representing the major commercial tree crop in the South, can be adapted to grow in high density on agricultural land assuming 8-year rotations.
- Poplar: short-rotation woody crop with great potential in the Lake States, the Northwest, the Mississippi Delta, and other regions.
- Switchgrass: model perennial native grass, with wide range and potential distribution.
- Willow: short-rotation woody crop assumed to be managed on a 20-year cycle and harvested at 4-year growth stages. It is being commercialized widely in the Northeast.

Specific input assumptions include yield improvements and land-use constraints, discussed in more detail below.

Yield improvements: field data indicates the potential for higher biomass yields in the future. BT16 applied yield improvement assumptions in this analysis by scenario, ranging from 1% to 4%, based on DOE research and stakeholder collaboration. Energy crop yields were derived from modeling of crop yields based on data from the Sun Grant Regional Feedstock Partnership in coordination with the Oregon State University PRISM (Parameter-elevation Relationships on Independent Slopes Model) modeling group. Modeled crop yield is generated with PRISM-EM based upon PRISM biweekly climate variables including precipitation, minimum temperature, maximum temperature, and Soil Survey Geographic Database soil pH, drainage, and salinity.

For the purposes of ICF’s RNG analysis, the yield assumptions did not provide significant variations in feedstock production over the long-term, with biomass price instead delivering greater variation. For this reason we focused on biomass prices as an assumption in the RNG production potential scenarios.

Land-use constraints: in addition to the constraint of available land, there are annual constraints (5% of permanent pasture, 20% of cropland pasture, 10% of cropland) and cumulative constraints (40% of permanent pasture, 40% of cropland pasture, 10% of cropland) applied to the model regarding land that can be converted to energy crops. These constraints are also bound by the management-intensive grazing (MiG) constraint of 1.5 acres of MiG required for one acre of pasture converted to energy crops. Eligible pasture is defined as having greater than or equal to 25 inches of annual precipitation, which excludes irrigated pasture acres amounting to 47.1 million acres of land nationally.

Rather than shifting existing agricultural production (e.g. corn and soy) to energy crop production, the BT16 modeling shows that energy crops are largely grown on idle or available pasture lands, particularly at lower farmgate prices.

Forestry and Forest Product Residues

ICF extracted information from the U.S. DOE Bioenergy KDF, which includes information on forest residues such as thinnings, mill residues, and different residues from woods (e.g., mixedwood, hardwood, and softwood).[85] The Bioenergy KDF estimates are used in BT16 and are based on ForSEAM, a linear programming model constructed to estimate forestland production over time, including for both traditional forest products but also products that meet biomass feedstock demands.

The ForSEAM model assumes that projected traditional timber demands will be met and estimates costs, land use, and competition between lands. The forestry and forest product residue estimates also reflect a cost minimization framework that minimizes the total costs (harvest costs and other costs) under a production target goal in addition to land, growth, and other constraints. The cost minimization framework includes the POLYSYS model as well as IMPLAN, an input-output model that estimates impacts to the economy.

ForSEAM estimates biomass potential from timber stand information across the conterminous United States. The model estimates the costs, the locations, and the kinds of biomass available to meet a prescribed demand. The demands are derived from the Forest Product Demand Component. This component is based on six USDA Forest Service scenarios with estimates developed by USFPM.

ForSEAM was constructed to estimate forestland production for traditional forest products and to meet biomass feedstock demands. The supply component includes general forest production activities for 305 production regions or agricultural statistic districts and is placed in a national linear programming model. Each region has a set of production activities defined by the scenario demands. These production activities include sawtimber, pulpwood, and biomass (fuelwood is defined as biomass for this report). Sawtimber and pulpwood harvest activities generate forest residues that can be harvested for energy and bioproducts, and whole trees can be removed for biomass under some specific assumptions of size. High-value sawtimber is never harvested for biomass.

ForSEAM and the underlying Forestry Inventory and Analysis (FIA) database provides the basis for determining how demand is met for conventional products such as sawtimber and pulpwood out to 2040. The demands are based on a set of projections for U.S. forests and forest products markets under varying market conditions. Scenarios evaluated in ForSEAM include combinations of housing demand, wood energy demand, and plantation management intensity.

The baseline scenario represents the lowest level of wood energy demands. In the moderate and high wood energy demand scenarios, feedstock prices rise sufficiently to reduce paper and paperboard production levels by 1% and 3%, respectively, below the baseline in 2040. In the high-demand scenario, impacts on prices are ameliorated somewhat by an assumed increase in investment in southern pine plantation management that would be expected as prices for softwood small roundwood increase. In addition, increases in timberland area (in USFPM/GFPM) are projected based on the assumption that increasing prices lead to increased

---

[85] Bioenergy Knowledge Discovery Framework, 2016. Billion Ton 2016 Data Explorer, https://bioenergykdf.net/map?model=bt16

land rents, and increasing land rents lead to increased conversion of marginal agricultural land to timberland.

Not all forestland in the United States is considered in the analysis, with only the conterminous United States is included. All protected, reserved, and non-roaded forestland is excluded. The analysis is restricted to only timberland instead of all forestlands. Although conventional products are removed from slopes greater than 40% using cable systems, no logging residues are recovered, leaving 100% on the site. Harvest in each state is also restricted to not exceed annual growth. There is no road construction, as only forest tracts located within a half mile of the roads are harvested. The current-year forest attributes reflect previous years' harvests and biomass removals, which means that dynamic stand tracking of forest growth is incorporated into the model and the analysis. Another underlying assumption is the retention of biomass to protect the site and maintain soil carbon. Also, there was no conversion of natural stands to plantations.

A final major assumption is that there are no forestland losses over the modeling time period and no land cover changes in the model. This means that fast-growing plantations specifically for biomass are not established after the harvest of a natural stand. All harvested stands are assumed to regenerate back to, and according to, the original cover. Natural stands regenerate to hardwood, softwoods, or mixed, as they were previously. Plantations are regenerated as plantations. An unfortunate downside to this approach is that insufficient amounts of biomass are generated in the out years of the modeling period to meet the high-demand scenarios. These scenarios were developed based on the establishment of millions of acres of plantations to be grown for biomass.

Shadow prices[86] are developed for the demand scenario biomass amounts. The shadow prices and the associated acres for the scenario demands (dry tons of biomass) are reported by product type (logging residues or whole-tree biomass), as well as other parameters of the study, across selected years. These shadow prices for the scenario demands are used to develop conventional supply curves to estimate biomass availability at roadside for a given cost. The out-year biomass availabilities are slightly reduced with the underlying assumption that no biomass plantations were established on forestland for the baseline example. In other scenarios, such as the supposedly highest biomass demand, there were even more significant reductions in out years, especially 2040, because biomass plantations were not established.

Municipal Solid Waste

In BT16 and the BKF, municipal solid waste (MSW) is defined as mixed commercial and residential wastes generally destined for landfill or incineration disposal, as well as yard trimmings. MSW categories available for bioenergy include paper and paperboard, plastics, rubber and leather, textiles, food wastes, and yard trimmings. Food wastes, such as those from industrial sources, are not included in the MSW data. Although MSW estimates represent gross supplies currently landfilled, not all of this supply is economically available due to preprocessing

[86] In this instance a shadow price is not market price, but an estimate of the economic value of the biomass in question.

cost considerations. MSW consists of a variety of items, ranging from organic food scraps to discarded furniture, packaging materials, textiles, batteries, appliances, and other materials.

MSW volumes are derived from U.S. EPA per-person MSW generation estimates of 2.36 lb per day (with moisture), after accounting for reduction, reuse, recycling and waste-to-energy.[87] This per-person figure is then applied to population data and category fractions to generate MSW estimates at a county level. The national MSW total is a conservative estimate relative to other national and regional analysis.

The prices of garbage supplies available after sorting are unknown. Price estimates for sorted organic fractions are generated using state-level average MSW tipping fees, with ICF applying regional- and facility-level tipping fee data if available. All supplies and prices are converted to dry tons and to a dollar per dry ton basis assuming the following moisture contents: food wastes 70%, yard trimmings 60%, paper and paperboard 15%, textiles 15%, rubber and leather 10%, and plastics 10%.

[87] US EPA, 2015. Advancing sustainable materials management: Facts and figures 2013 https://www.epa.gov/sites/production/files/2015-09/documents/2013_advncng_smm_rpt.pdf