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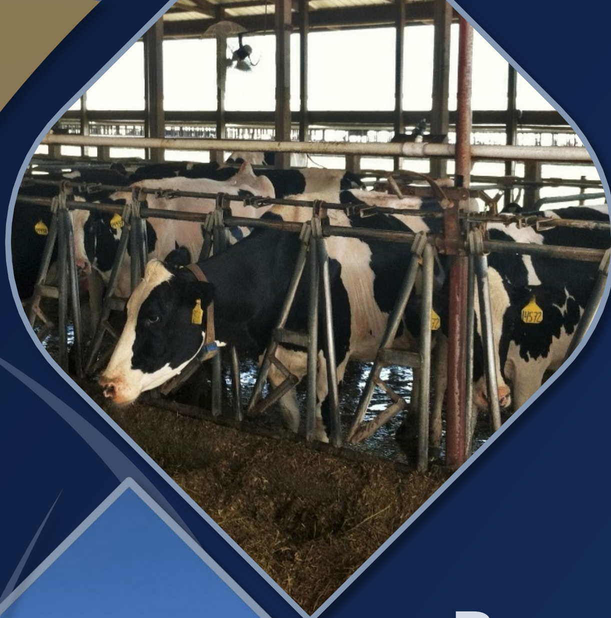

An Overview of Renewable Natural Gas from Biogas

January 2024

NaturalGas EPA POLLUTION PREVENTER

AgSTAR

LANDFILL METHANE OUTREACH PROGRAM

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This paper was revised and republished in January 2021 to make the following changes and updates:

- Updated text, content of Table 2, and references in Section 4.4, subsection Average CI Comparison for Vehicle Fuels
- Corrected Figure reference in Section 8.1, subsection Cost of Pipeline Interconnection
- Removed Big Run Landfill project example in Sections 8.7 and 9.0
- Added U.S. EPA's Biogas Toolkit to table in Section 10.0
- Corrected URLs in various locations in document, including Appendix A
- Added footnote for Main Sources of Data at end of Appendix A

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This paper was revised and republished in January 2024 to make the following updates:

- Updated content in Section 7.0, mainly related to nitrogen removal, including the addition of a new Figure 9 (renumbered existing Figure 9 in Section 8.0 to be Figure 10)

Table of Contents

List of Tables

List of Figures

1.0 INTRODUCTION

EPA encourages the recovery and beneficial use of biogas as a renewable energy resource, including the production of renewable natural gas (RNG) when feasible, as a means of reducing emissions and providing other environmental benefits. RNG is a term used to describe biogas that has been upgraded to use in place of fossil natural gas, either locally or remotely. EPA's partnership programs for the reduction of methane (CH_4) emissions—the Landfill Methane Outreach Program (LMOP), AgSTAR and Natural Gas STAR—offer data on potential sources of RNG feedstocks as well as technical and outreach resources and tools to support RNG project development.

EPA developed this document to provide biogas stakeholders and other interested parties with a resource to promote and potentially assist in the development of RNG projects. This document summarizes existing RNG operational projects in the United States and the potential for growth from the main sources of biogas feedstock. This document provides technical information on how raw biogas is upgraded into RNG and ultimately delivered and used by consumers. The document also addresses barriers, policies and incentives related to RNG project development.

2.0 WHAT IS RNG?

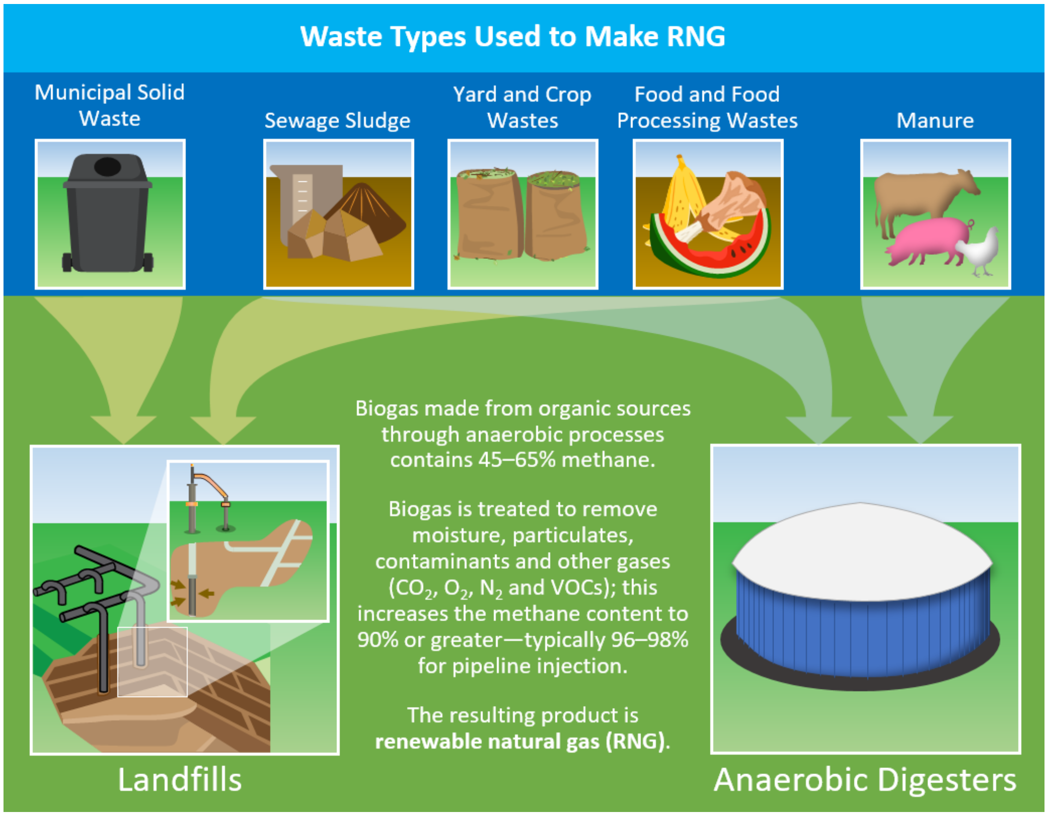
RNG is a term used to describe anaerobically-generated biogas that has been upgraded (or refined) for use in place of fossil natural gas. Raw biogas typically has a CH_4 content between 45 and 65 percent, depending on the source of the biogas, and must go through a series of steps to be converted into RNG. Treatment includes removing moisture, carbon dioxide (CO_2) and trace-level contaminants (including siloxanes, volatile organic compounds [VOCs] and hydrogen sulfide [H_2S]), as well as reducing the nitrogen (N_2) and oxygen (O_2) content. Once purified, the RNG has a CH_4 content of 90 percent or greater. RNG injected into a natural gas pipeline commonly has a CH_4 content between 96 and 98 percent.

As a substitute for fossil natural gas, RNG has many potential uses. RNG can be used as vehicle fuel, to generate electricity, in thermal applications, or as a bio-product feedstock. RNG can be injected into natural gas transmission or distribution pipelines, or it can be used locally (i.e., at or near the site where the gas is created). In this document, the term RNG does not encompass synthesis gas (syngas) produced through gasification of biomass or any other feedstocks.

2.1 Sources of RNG

Currently, there are four main sources of biogas used to produce RNG in the United States: municipal solid waste (MSW) landfills, anaerobic digestion (AD) at municipal water resource recovery facilities (WRRFs), AD at livestock farms and AD at stand-alone organic waste management operations. At each of these types of operations, biogas is produced as the organic materials are broken down by microorganisms in the absence of O_2 (i.e., anaerobic conditions). Figure 1 shows the main organic waste feedstocks that are placed into an MSW landfill or an AD facility. "Organic" in this context means the wastes come from, or were made of, plants or animals.

Figure 1. Organic Waste Types Used to Make RNG

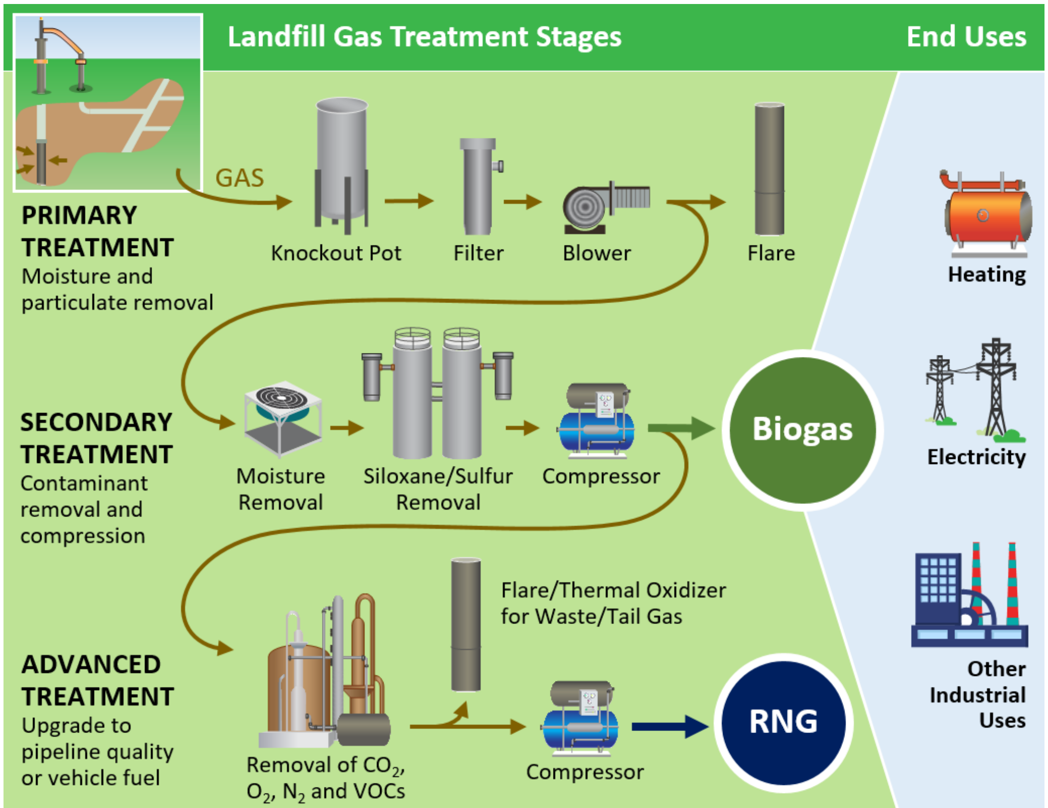


MSW Landfills

Landfill gas (LFG) is generated in MSW landfills[1] as the organic wastes decompose anaerobically. Instead of escaping into the air, LFG can be captured, converted and used as an energy resource. Applicable federal and state regulations require certain landfills to capture and destroy the LFG generated; for these sites an LFG collection infrastructure is already in place and potentially ready for an energy project. The diagram in Figure 2 provides an overview of the levels of treatment that LFG can undergo to be used as an energy resource.

[1] More information about MSW landfills is available at U.S. EPA. What Is a Municipal Solid Waste Landfill? https://www.epa.gov/landfills/municipal-solid-waste-landfills#whatis. Accessed November 18, 2019.

Figure 2. LFG Treatment Stages and Biogas End Uses



Municipal WRRFs

Many municipal WRRFs (also known as wastewater treatment facilities or publicly owned treatment works) use AD to treat sewage sludge on site, while some facilities send the sludge to other facilities for AD treatment. Biogas is one of the byproducts of sludge treatment through AD. WRRFs typically generate biogas with a high CH_4 content and extremely low N_2 and O_2 contents, which make them attractive candidates for RNG projects.

Approximately 133 to 177 WRRFs with AD were "co-digesting" other waste streams, such as source-separated food wastes, in 2017.[2] Co-digestion of food waste with WRRF sludge allows facilities to use existing assets and infrastructure to meet the growing interest in food waste management. With co-digestion, facilities can more efficiently use process equipment when they process multiple waste streams together. Facilities can also use co-digestion to adjust the proportions of solids being digested to improve digestion and increase biogas production.

Livestock Farms

Livestock farms can use AD to convert livestock (e.g., dairy, beef, swine, poultry) manure into biogas and digestate.[3] Some manure-based digesters co-digest other waste materials with the manure, including upstream (pre-consumer) food wastes such as beverage and distillery waste; fats, oils and greases;

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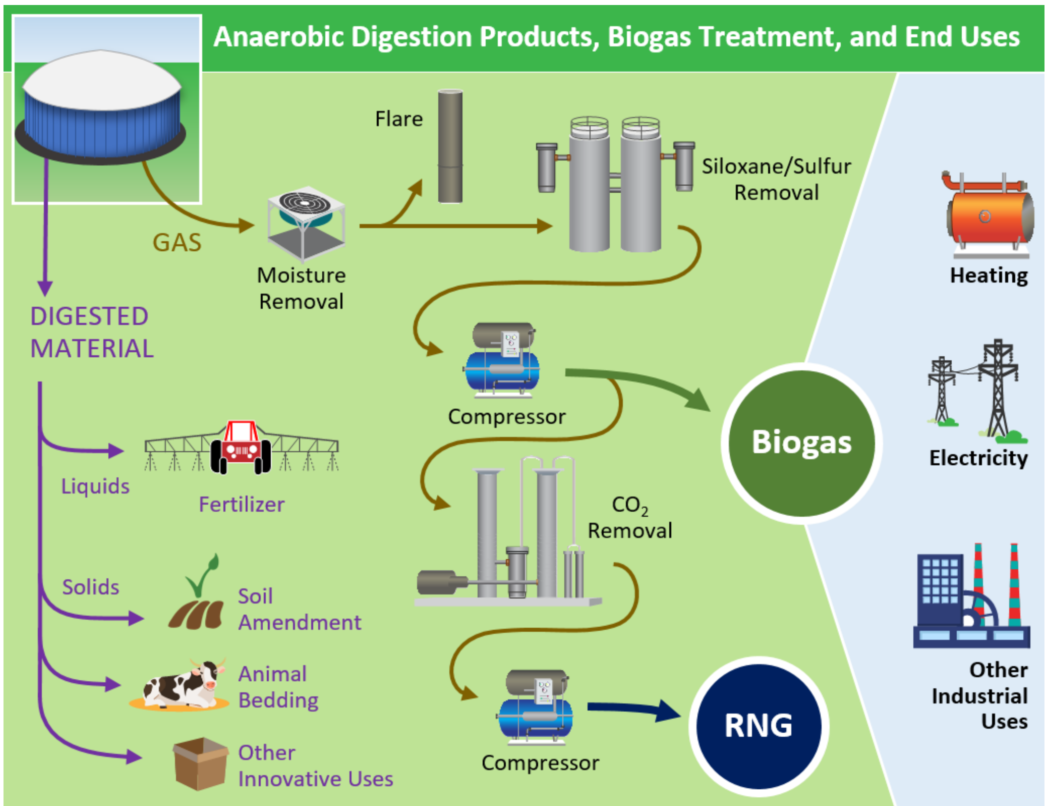
2 Goldstein, N. October 2017. The State of Organics Recycling in the U.S. BioCycle 58(9): 22. https://www.biocycle.net/2017/10/04/state-organics-recycling-u-s/. Accessed March 4, 2020. See Table 3 and additional discussion about data from the Water Environment & Reuse Foundation on page 6 of Goldstein's report.

3 Digestate is the nutrient-rich material left over after AD.

industrial food byproducts; or processing wastes from a dairy or slaughterhouse. Various sources estimate approximately 100 manure-based AD projects are co-digesting other organic waste materials.[4] The diagram in Figure 3 presents the biogas and typical digestate products from manure-based AD projects and the levels of treatment that AD biogas can undergo to be used as an energy resource.

Figure 3. AD Products, Biogas Treatment and End Uses



Stand-Alone Organic Waste Management Operations

Stand-alone digesters are the newest source of RNG in the United States. These AD projects break down source separated organic material—including food waste—to generate biogas, which can be converted to RNG. Digesters that primarily process food waste can also co-digest other organic materials including yard waste.[5] A 2018 EPA survey of U.S. AD facility operators showed that a total of 9.2 million tons of food waste was processed at 44 stand-alone digesters during 2016. The survey report indicates there were 62 stand-alone digesters operating in 2016, which suggests the actual amount of food waste processed in

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4 Goldstein, N. October 2017. The State of Organics Recycling in the U.S. BioCycle 58(9): 22. https://www.biocycle.net/2017/10/04/state-organics-recycling-u-s/. Accessed March 4, 2020. The article estimates that 94 manure-based AD projects were co-digesting. April 2017 research conducted using the AgSTAR database, case studies, articles and profiles showed 111 manure-based projects were co-digesting other materials. In March 2020, the AgSTAR database indicated 104 manure AD projects that co-digest other organic materials.

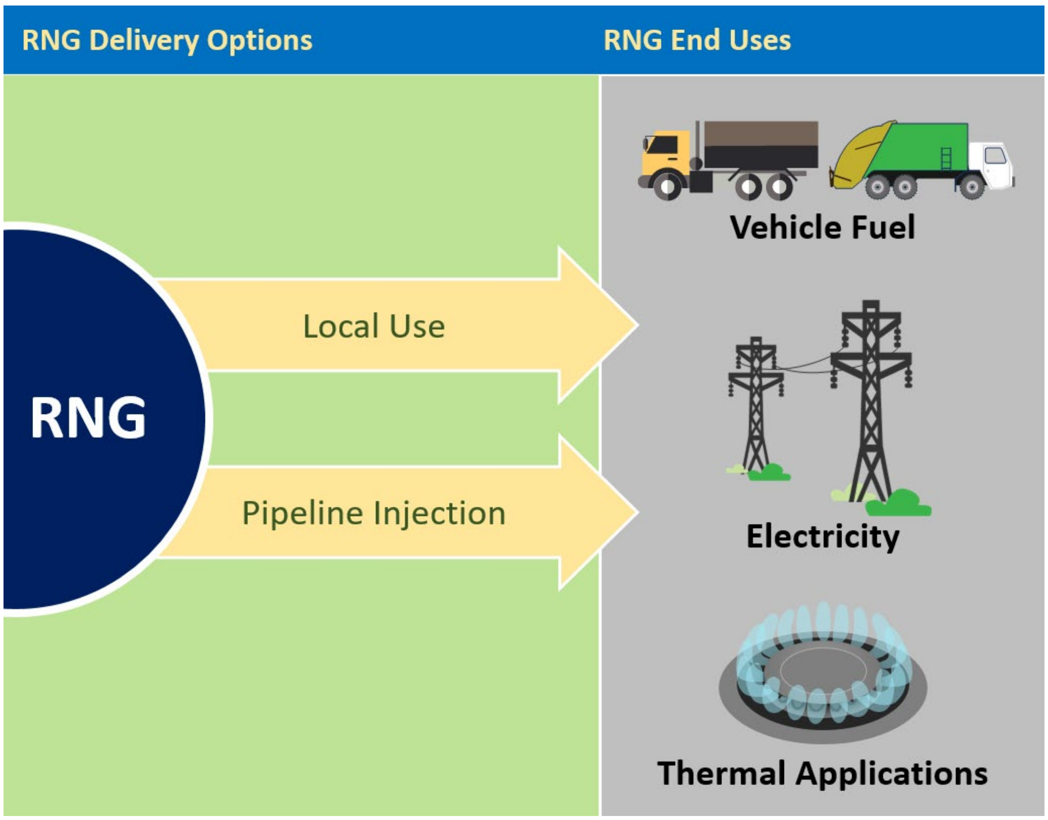
5 U.S. EPA. Types of Anaerobic Digesters. Stand-Alone Digesters. https://www.epa.gov/anaerobic-digestion/types-anaerobic-digesters#StandAloneAD. Accessed March 25, 2019.

this manner was higher. In addition, 20 of the stand-alone digesters surveyed processed more than 31 million gallons of liquid non-food waste and nearly 83,000 tons of solid non-food waste in 2016.[6]

3.0 OPTIONS FOR RNG DELIVERY AND USE

As shown in Figure 4, the two main methods for delivering RNG to end users are injection into a pipeline (fossil natural gas pipeline or dedicated RNG pipeline) or onsite/local applications (e.g., onsite vehicle fueling station, transport by truck). RNG is so chemically similar to fossil natural gas that it is a "drop-in" substitute, making it versatile. The methane in RNG is identical to methane in fossil natural gas, but the two gasses have constituents in very low concentrations that the other does not have. In addition to being used as vehicle fuel or for generating electricity, RNG can also be used to meet thermal energy demands (heat, steam, hot water, cooling or other processes) in the industrial, commercial, institutional or residential sectors.

Figure 4. RNG Delivery Options and Typical RNG End Uses



Over time, market drivers have shaped how RNG is used. In 2011, nearly all the RNG projects operating in the United States were providing RNG to generate electricity off site, as an effect of state-level Renewable Portfolio Standard (RPS) programs.[7] As the market for renewable transportation fuels emerged through federal and state rules and incentives, the overall number of RNG projects grew rapidly and the end use

6 U.S. EPA. September 2019. Anaerobic Digestion Facilities Processing Food Waste in the United States (2016). EPA/903/S-19/001. https://www.epa.gov/anaerobic-digestion/anaerobic-digestion-facilities-processing-food-waste-united-states-survey.

7 Escudero, J. May 2017. Powering Businesses, Homes & Vehicles with Waste: Growing the Economy & Jobs with Renewable Natural Gas. https://www.eesi.org/files/Johannes_Escudero_052317.pdf.

of the RNG shifted dramatically. In 2017, 76 percent of RNG projects were converting RNG into transportation fuels, while 24 percent generated electricity off site.[8]

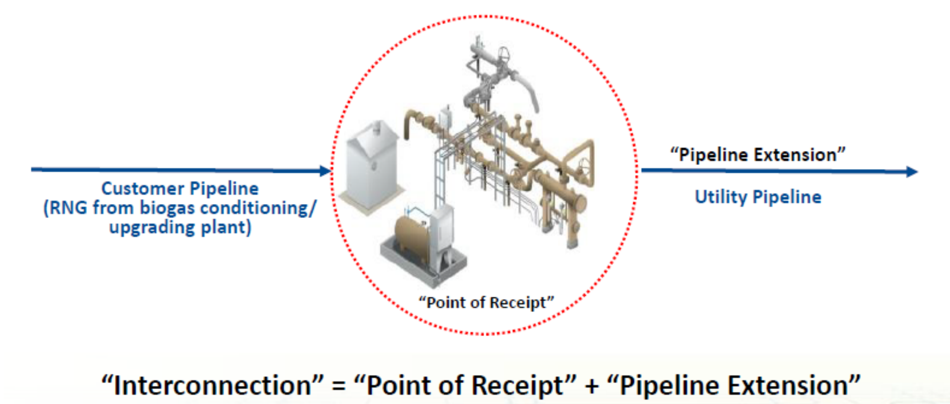
3.1 Pipeline Injection

Many RNG projects inject the product into a fossil natural gas pipeline. Appendix A lists known natural gas utilities who have received or plan to receive RNG into their networks. The RNG must meet the specification requirements of the receiving gas utility. This delivery method can be expensive due to extensive planning, land purchases, permitting, construction, and interconnection fees and equipment. However, pipeline injection can convey the RNG across a vast distribution network and provide flexibility on how and where the RNG is ultimately used.

Interconnection consists of two primary components, a "point of receipt" and a "pipeline extension," as shown in Figure 5. The point of receipt monitors the quality of the RNG to ensure that it meets specifications and includes equipment to prevent non-compliant gas from entering the pipeline. The point of receipt also meters and may odorize the RNG prior to injection. RNG can be delivered to the point of receipt from the production facility through piping built specifically for this purpose or by truck.

The pipeline extension is a dedicated pipeline to transfer the RNG from the point of receipt to the nearest fossil natural gas pipeline that has capacity to accept it. All projects have a pipeline extension to allow space for odorization, gas quality monitoring, and a shut off valve. Some distribution-level pipelines do not have the capacity to receive RNG injections (which are constant), due either to the cyclical nature of the pipeline users or to the size and volume of fossil natural gas flow. When the pipeline nearest to an RNG processing plant cannot accept the RNG, a longer pipeline extension is needed to reach a fossil natural gas pipeline with adequate capacity.[9]

Figure 5. Components of a Pipeline Interconnection[10]



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[8] Escudero, J. May 2017. Powering Businesses, Homes & Vehicles with Waste: Growing the Economy & Jobs with Renewable Natural Gas. https://www.eesi.org/files/Johannes_Escudero_052317.pdf.

[9] Lucas, J. October 2017. Interconnecting to the SoCalGas Pipeline. Presented at Power of Waste: RNG for California, Sacramento. https://www.socalgas.com/1443741248177/PowerofWaste_SoCalGas_Lucas.pdf.

[10] Lucas, J. September 2017. Renewable Natural Gas Projects. Presented at EPA Technology Transfer Workshop: Renewable Natural Gas—Driving Value for Natural Gas and Biogas Sectors. https://www.epa.gov/sites/production/files/2017-10/documents/lucas_rng_2017_panel1.pdf. Figure used with permission from Southern California Gas Company.

Alternatively, RNG can be injected into a dedicated pipeline instead of into a natural gas pipeline network.

Vehicle Fuel

RNG can be used as fuel, as compressed natural gas [CNG] or liquefied natural gas [LNG], in a variety of vehicle types. According to the U.S. Department of Energy's (DOE's) Alternative Fuels Data Center, in March 2019 there were 914 public and 678 private CNG stations and 66 public and 55 private LNG stations in the country.[11]

As of March 2020, the majority (91 percent) of LFG-sourced RNG pipeline injection projects were providing at least a portion of the RNG to a vehicle fuel market down the pipeline.[12] In these cases, fueling stations far removed from the biogas source were receiving the RNG at the other end of a pipeline network.

Electricity Production

While many biogas projects generate electricity from partially conditioned biogas, there are a number of projects (primarily landfill-based) where RNG is injected into a pipeline and used to generate electricity.

Thermal Applications

Numerous biogas energy projects use nearly raw biogas in direct thermal applications such as boilers, greenhouses and kilns. RNG projects for direct thermal applications are less common, as the bulk of incentives are for transportation and electricity end uses. However, as discussed in Section 8.7, some state policies have created a new interest in RNG for direct thermal uses.

3.2 Local Use

The predominant use of RNG on site or locally is for vehicle fuel.

Onsite Vehicle Fuel

Onsite RNG vehicle fuel projects avoid the need to meet natural gas pipeline specifications, and typically the vehicle fuel specifications are less stringent than the requirements from a pipeline operator. In addition, these projects avoid the costs to interconnect and transport the gas via pipeline. However, there must be an adequate and consistent demand for the RNG vehicle fuel. Matching the fleet demand to the RNG resource can be problematic in some rural areas with a source of biogas, as larger fleets are generally located in urban centers.

Often, the owner of the biogas source also has a vehicle fleet, for example a public works department that has a landfill and/or WRRF as well as a CNG-compatible fleet inventory. Some onsite fueling stations also allow corporate fleets operating in the area to use their stations. In either case, these types of projects, wherein the vehicles delivering a feedstock (e.g., garbage or food waste) are fueled by RNG from biogas produced by that feedstock, are considered "closed loop" or circular projects.

Generally, local-use vehicle fuel projects are smaller scale than pipeline injection vehicle fuel projects. Taking LFG-based RNG as an example, the average flow rate of local-use CNG projects is 145 cubic feet

[11] U.S. DOE. Alternative Fueling Station Locator. https://afdc.energy.gov/stations/#/analyze?country=US. Accessed March 27, 2019.

[12] U.S. EPA. March 2020. Landfill and Landfill Gas Energy Project Database. https://www.epa.gov/lmop/landfill-gas-energy-project-data.

per minute (cfm) of biogas inlet, while the average for pipeline injection projects with a vehicle fuel component is 2,940 cfm of biogas inlet, twenty times larger.[13]

Virtual Pipeline

If an RNG processing plant is not close to potential end users or an existing pipeline, a "virtual pipeline" can move compressed RNG from the point of generation to the point of injection or use. In a virtual pipeline scenario, the RNG is compressed to up to 4,000 pounds per square inch for injection into a natural gas tube trailer, and then transported off site by truck. Once it reaches the destination, the RNG is decompressed back down to the pressure required by the receiving facility. The decompression site must include a "decant" facility that heats the RNG as it decompresses to minimize the freezing of valves and regulators due to decompression. A virtual pipeline allows remote landfills, farms or other biogas sources to market their RNG in populated areas. Leasing companies that will contract for loading, transporting and off-loading the RNG are also available. The costs to transport RNG in a virtual pipeline are in addition to the costs associated with RNG processing equipment and infrastructure needed to compress and decompress the gas.

Some projects may employ more than one delivery mechanism to match the RNG supply with demand. For example, a project may have an onsite vehicle fueling station for a portion of the fuel and transport the remainder to an offsite fueling station via a virtual pipeline.

4.0 BENEFITS OF RNG

Developing RNG resources is one way to diversify fuel supplies and increase fuel security, provide economic benefits to communities and end users, improve local air quality and reduce greenhouse gas (GHG) emissions.

4.1 Fuel Diversity and Availability

Biogas feedstocks for RNG are generated continuously from a variety of sources (offering high availability rates), and the use of RNG increases and diversifies domestic energy production. For example, Atlantic City, New Jersey used CNG-fueled buses to provide critical services in 2012 after Hurricane Sandy when gasoline supplies were limited, showing the value of alternative fuel vehicles during natural disasters.[14]

4.2 Local Economic Impacts

Developing RNG projects can benefit local economies through the construction of infrastructure and sale of vehicles that can use this fuel source. Adding a renewable source of vehicle fuel to an area has the potential to draw outside vehicle fleets to a community, as the CNG produced from biogas can potentially be sold at a lower cost than fossil fuel-based vehicle fuel (due to incentives such as EPA's Renewable Fuel Standard [RFS]) or corporations may be looking for ways to green their fleets or increase corporate sustainability.

A 2017 study conducted for the California Natural Gas Vehicle Coalition analyzed the economic impacts of converting heavy-duty diesel-fueled trucks in California to RNG fuel, including the benefits of building

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13 See details and ranges of project sizes in Table 3 in Section 5.0 of this document. Data source is U.S. EPA. March 2020. Landfill and Landfill Gas Energy Project Database. https://www.epa.gov/lmop/landfill-gas-energy-project-data.

14 Bluestein, L. https://cleancities.energy.gov/files/u/news_events/document/document_url/49/emergency_preparedness_webinar.pdf.

RNG processing and fueling station infrastructure and the impact of purchasing CNG vehicles.[15] The study found that California RNG production facilities (based on a mix of landfill, WRRF and dairy feedstocks) would generate about 8.5 to 11.2 jobs per million diesel gallon equivalent of transportation fuel. By contrast, the petroleum refinery industry yields about 1.6 jobs per million diesel gallon equivalent of transportation fuel. Additionally, for every job created through investment in low nitrogen oxide (NO_X)-emitting natural gas trucks, natural gas fueling infrastructure and RNG production facilities, about 2.0 jobs are created in supporting industries (indirect) and via spending by employees that are directly or indirectly supported by these industries (induced).

For projects where there is common ownership between the RNG source and the fleet using RNG, vehicle fuel from RNG can also provide price stability (e.g., compared to diesel fuel purchases) through mid-term to long-term RNG supply contracts or through creating fuel for internal consumption.

4.3 Local Air Quality

Replacing traditional diesel or gasoline with RNG vehicle fuel can reduce pollutant emissions, resulting in local air quality benefits.

RNG combusts similarly to fossil natural gas, so pipeline operators make no distinctions between the two once the RNG meets the required specification and is injected into the pipeline network. Fossil natural gas typically contains several non-methane hydrocarbons, including ethane, propane, butane and pentane, as well as some trace organics, all in small concentrations. RNG does not generally contain non-methane hydrocarbons but does share some other low-concentration constituents with fossil natural gas, such as CO_2, N_2, O_2, H_2S and total sulfur. Fossil natural gas and RNG both contain trace organics (e.g., aromatic hydrocarbons, aldehydes and ketones), but samples of RNG show these in much lower concentrations than in fossil natural gas.[16,17]

Since 2017, most newly built vehicles are required to meet the same emission standards (including NO_X, particulate matter [PM] and carbon monoxide [CO]) regardless of fuel type,[18] so new natural gas vehicle emissions are comparable to those of new gasoline and diesel vehicles. However, when older model gasoline or diesel vehicle fleets are replaced with new natural gas vehicles, certain local air pollutant emissions are often reduced on an as-driven basis.

For example, replacement or aftermarket conversion of older gasoline vehicles with natural gas models can provide reductions across pollutants. The Argonne National Laboratory's Alternative Fuel Life-Cycle Environmental and Economic Transportation (AFLEET) tool[19] can be used to estimate emission reductions

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15 ICF. May 2017. Economic Impacts of Deploying Low NO_X Trucks Fueled by Renewable Natural Gas. https://www.masstransitmag.com/home/document/12330911/economic-impacts-of-deploying-low-nox-trucks-fueled-by-renewable-natural-gas.

16 Gas Technology Institute. May 2012. Guidance Document for the Introduction of Landfill-Derived Renewable Gas into Natural Gas Pipelines. https://www.gti.energy/wp-content/uploads/2018/09/120007_Landfill_Guidance_Document_FINALREPORT-05-9-2012.pdf.

17 Wiley, Kristine. October 2018. Renewable Natural Gas (RNG): Gas Quality Considerations. Presented at 2018 Natural Gas STAR and Methane Challenge Renewable Natural Gas Workshop. https://www.epa.gov/natural-gas-star-program/2018-natural-gas-star-and-methane-challenge-renewable-natural-gas-workshop.

18 U.S. EPA. Final Rule for Control of Air Pollution from Motor Vehicles: Tier 3 Motor Vehicle Emission and Fuel Standards. https://www.epa.gov/regulations-emissions-vehicles-and-engines/final-rule-control-air-pollution-motor-vehicles-tier-3.

19 Argonne National Laboratory. November 2018. AFLEET Tool. https://afleet-web.es.anl.gov/home/. Emission estimates based on a fleet replacement location in Washington, D.C.

for fleet replacement on an as-driven basis. A fleet location of Washington, D.C., was used for illustrative purposes along with the AFLEET tool's default input parameters, including annual mileage and fuel economy. Similar patterns in emission reduction percentages were derived for other fleet locations.

The AFLEET tool was used to analyze the emissions from gasoline pickups and refuse trucks in three older model years, with model year 2010 representing a median life age for the national pickup population and model year 2012 representing a median life age for the national refuse truck population.

The results in Table 1 indicate substantial percentage reductions in NO_X, VOC, PM_{10}, $PM_{2.5}$, CO and sulfur dioxide (SO_X) emissions for each of the older gasoline pickup models, as compared with a new (model year 2019) CNG pickup, with the most significant reductions achieved for the oldest model year. For refuse trucks, substantial emission reductions were shown for NO_X, exhaust VOC, PM_{10}, $PM_{2.5}$ and SO_X, again with the largest reductions from the oldest vehicle replacements.

Table 1. AFLEET Tool Emission Results for Replacement of Washington, D.C.-Based Older Model Year Gasoline Pickups or Diesel Refuse Trucks with New (Model Year 2019) Dedicated CNG Pickups or Refuse Trucks

Fuel/Vehicle Type	Model Year	Percentage Emission Reductions if Replaced by 2019 Model Year CNG Vehicle						
		NO_X	VOC (Exhaust)	VOC (Evaporative)	PM_{10}	$PM_{2.5}$	CO	SO_X
Gasoline Pickup	2005	87.4%	86.0%	87.5%	73.0%	68.9%	84.3%	38.1%
	2007	80.2%	78.8%	85.4%	73.0%	65.0%	81.9%	38.1%
	2010	66.7%	69.1%	75.6%	66.3%	60.0%	74.6%	38.1%
Diesel Refuse Truck	2006	99.4%	93.9%	7.14%	97.0%	96.9%	-571%	43.0%
	2009	99.2%	43.8%	7.14%	42.2%	41.5%	-2,180%	43.0%
	2012	96.8%	16.9%	7.14%	38.1%	38.5%	-3,025%	43.0%

However, CO emissions increased significantly for the CNG refuse trucks relative to the diesel baseline. This increase is due to the newest CNG refuse trucks being powered by spark-ignited cycle engines with three-way catalysts. Compared to the diesel refuse trucks, which are powered by compression ignition cycle engines, the CNG spark-ignited engines operate at tightly controlled stoichiometric fuel–air ratios that allow for three-way catalyst control[20] of NO_X, VOC and CO emissions but produce inherently higher CO emissions. However, new CNG refuse trucks do still comply with existing heavy-duty engine emission standards even with the higher CO emissions. When replacing older heavy-duty diesel vehicles with new dedicated CNG vehicles, local communities should consider this trade-off of lower NO_X and PM emissions

[20] Three-way catalysts are exhaust emission control devices for achieving simultaneous control of tailpipe NO_X, VOC and CO emissions. Three-way catalysts typically are deployed in conjunction with closed loop, stoichiometric fuel–air ratio fuel delivery to the engine for achieving the highest efficiency in catalytic reduction of NO_X, and oxidation of VOCs and CO in the engine exhaust emissions stream.

but higher CO emissions with respect to existing local air quality conditions and compliance with national standards.

Apart from combustion emissions, gasoline and diesel vehicles produce hydrocarbon emissions from the evaporation of fuel in onboard fuel tanks, but natural gas vehicle fuel systems emit minimal evaporative hydrocarbon emissions because they are sealed to the atmosphere.

4.4 GHG Emission Reductions

When fossil natural gas is replaced by RNG, the resulting GHG emission reductions provide a climate benefit. One way to characterize the climate benefit of a fuel is to determine its "carbon intensity" (CI) or "carbon footprint" based on a complete life cycle assessment that estimates the GHG emissions associated with producing and consuming the fuel. Argonne National Laboratory's AFLEET tool estimates that natural gas vehicles operating on fuel derived from RNG can yield GHG emission reductions of up to 75 percent, compared to gasoline or diesel vehicles.[21] The California Air Resources Board (CARB) uses similar life cycle assessment tools to estimate the GHG emissions associated with vehicle fuels for implementation of the state's Low Carbon Fuel Standard (LCFS).

Natural gas in any form (fossil or RNG) is less carbon-intensive than the other fossil fuels it typically replaces, including conventional transportation fuels (e.g., gasoline, diesel) in most cases and coal or petroleum for generating electricity.[22,23] RNG provides an additional benefit over fossil natural gas because it generally has a lower total carbon footprint, after accounting for emissions from fuel production, transport and use.[24,25,26] RNG's carbon footprint is even lower if a project can also take into account directly reducing CH_4 emissions from the organic waste used to produce the fuel.

Fuels from some RNG feedstocks can achieve negative carbon footprints by reducing CH_4 emissions through avoiding "business-as-usual" disposal pathways, such as projects that involve AD of manure and organic wastes.[27,28] In contrast, projects in which RNG is sourced from a landfill or WRRF where business-as-usual practices collect and destroy CH_4 cannot account for any climate benefit from that CH_4 destruction. These projects can account for the emissions avoided through recovering energy that would

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21 Argonne National Laboratory. AFLEET Tool. https://afleet-web.es.anl.gov/home/. Accessed March 4, 2020.

22 U.S. EIA. Frequently Asked Questions. How Much Carbon Dioxide Is Produced When Different Fuels Are Burned? https://www.eia.gov/tools/faqs/faq.php?id=73&t=11. Accessed March 4, 2020.

23 U.S. EPA. February 2018. Emissions & Generation Resource Integrated Database (eGRID). eGRID2016.

24 Kampman, B., C. Leguijt, T. Scholten, J. Tallat-Kelpsaite, R. Brückmann, G. Maroulis, J.P. Lesschen, K. Meesters, et al. December 2016. Optimal Use of Biogas from Waste Streams: An Assessment of the Potential of Biogas from Digestion in the EU Beyond 2020. European Commission. https://ec.europa.eu/energy/sites/ener/files/documents/ce_delft_3g84_biogas_beyond_2020_final_report.pdf.

25 Hass, H., H. Maas, R. Edwards, L. Lonza, J.F. Larivé, and D. Rickeard. January 2014. Well-to-wheels report version 4.a: JEC well-to-wheels analysis of future automotive fuels and powertrains in the European context. Report EUR 26236 EN. European Commission. https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/well-wheels-report-version-4a-jec-well-wheels-analysis.

26 Clark, C.E., J. Han, A. Burnham, J.B. Dunn, and M. Wang. December 2011. Life-Cycle Analysis of Shale Gas and Natural Gas. ANL/ESD/11-11. Argonne National Laboratory. https://greet.es.anl.gov/publication-shale_gas.

27 CARB and California Environmental Protection Agency. November 2014. Compliance Offset Protocol Livestock Projects: Capturing and Destroying Methane from Manure Management Systems. https://ww3.arb.ca.gov/cc/capandtrade/protocols/livestock/livestock.htm.

28 CARB and California Environmental Protection Agency. August 2018. Tier 1 Simplified CI Calculator Instruction Manual: Biomethane from Anaerobic Digestion of Organic Waste. https://ww3.arb.ca.gov/fuels/lcfs/ca-greet/ca-greet.htm.

otherwise be flared and wasted (as energy recovery is not required), however they have a positive carbon footprint overall.

Average CI Comparison for Vehicle Fuels

Using data from pathways that CARB has certified under the LCFS for 2021, Table 2 provides a comparison of average CIs for several renewable vehicle fuels to fossil-based fuels.

Table 2. CI Ranges of Fossil and Renewable Vehicle Fuels from CARB LCFS-Certified Pathways[29]

Fuel Category [a]	Feedstock	Average CI (g CO_2e/MJ) [b]	Range (g CO_2e/MJ)	Number of Pathways
Diesel	Fossil Crude	100	100	1
CNG, Fossil	Fossil Natural Gas	79	79	1
LNG, Fossil	Fossil Natural Gas	No data	--	--
CNG, Renewable	LFG	53	30 to 83	30
	Manure	-313	-533 to -151	24
	Wastewater	47	37 to 58	3
	Food and Green Waste	No data	--	--
LNG, Renewable	LFG	61	43 to 80	14
	Manure	-336	-360 to -312	3
	Wastewater	48	42 to 55	2
	Food and Green Waste	No data	--	--

a CARB accounts for relative energy efficiencies of different drive technologies relative to the baseline gasoline or diesel technologies by using energy economy ratios (EERs). EERs account for differences in fuel efficiency for a given vehicle type and alternative transportation fuel and compares it to a benchmark, conventional vehicle. Vehicle type- and fuel-specific EERs should be applied to average fuel CIs to facilitate comparison across fuel types. The average CI values provided in this table do not yet have EERs applied to them. [30]

b The exact CI of diesel is 100.45 grams of CO_2 equivalent per megajoule (g CO_2e/MJ), per CARB documentation.

The CIs of fuels from different RNG feedstocks and fossil natural gas are characterized by impacts occurring at distinct phases of the fuel life cycle. For example, tailpipe emissions of CO_2 from RNG fuels are considered carbon neutral because the carbon is biogenic, while tailpipe emissions of CO_2 from fossil natural gas fuels are not. As a result, CIs of fossil natural gas-based vehicle fuels are most impacted by tailpipe emissions, with lesser contributions from refining and resource extraction. As another example, RNG fuels derived from LFG receive no credits for CH_4 reduction under the LCFS because the baseline set by CARB for this pathway is flaring of the LFG. As a result, LFG-derived vehicle fuels have CIs that are most heavily influenced by the biogas upgrading plant and emissions during pipeline transport.[31] The exact CI

29 CARB. LCFS Pathway Certified Carbon Intensities. https://www.arb.ca.gov/fuels/lcfs/fuelpathways/pathwaytable.htm. File provided by CARB on December 3, 2020. CARB updates the pathway file regularly.

30 California Code of Regulations. 2020. Title 17. Public Health. Division 3. Air Resources. Chapter 1. Air Resources Board. Subchapter 10. Climate Change. Article 4. Regulations to Achieve Greenhouse Gas Emission Reductions. Subarticle 7. Low Carbon Fuel Standard. Section 95486. Generating and Calculating Credits and Deficits. May 27, 2020. https://govt.westlaw.com/calregs/Index?transitionType=Default&contextData=%28sc.Default%29. Accessed September 3, 2020.

31 CARB and California Environmental Protection Agency. 2018. Tier 1 Simplified CI Calculator for Biomethane from North American Landfills. https://ww3.arb.ca.gov/fuels/lcfs/ca-greet/ca-greet.htm. Accessed March 4, 2020.

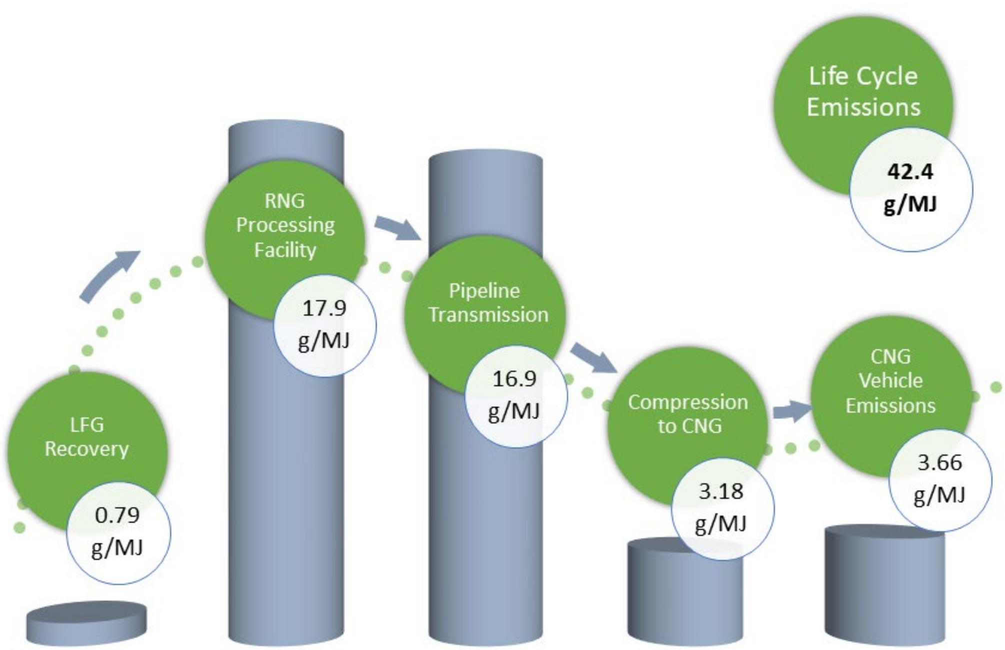
of a particular project depends on various factors and is particularly sensitive to the source of the energy used to power the gas upgrading equipment and compression in the pipeline, as well as the length of the transmission pipeline.

CIs for a Hypothetical LFG-to-CNG Project

Figure 6 illustrates example CIs associated with each major step in a hypothetical LFG-to-CNG project: LFG recovery at the landfill, treatment/processing of the raw LFG into RNG, transporting the RNG via pipeline networks to the CNG fueling stations, compression of the RNG at CNG fueling stations and emissions from the CNG vehicles. These example CIs were determined using CARB's Tier 1 Simplified CI Calculator for Biomethane from North American Landfills with the following inputs and assumptions:

- Input of 3,100 cfm raw LFG at 50 percent CH_4.
- RNG processing plant that:
    - Is powered by grid-purchased electricity.
    - Does not require any supplemental propane or fossil natural gas to achieve the target specifications for pipeline injection of the RNG.
    - Has an energy consumption of 0.009 kilowatt-hours per standard cubic foot (scf) of LFG and a 90 percent capture efficiency of CH_4, yielding 455 British thermal units (Btu) of RNG per scf (Btu/scf) of LFG.
- Three thousand miles of gas pipeline to transport the RNG from the landfill to the CNG fueling stations.
- U.S. average mix for the energy used to power the LFG recovery equipment, RNG upgrading/processing plant and transport of the LFG via pipeline.
- California grid mix for the energy used to compress RNG at the CNG fueling station.

Figure 6. Example CIs from LFG-RNG-CNG Life Cycle (g CO_2e/MJ)



4.5 Other Benefits of Natural Gas Vehicles

Natural gas vehicles, including those using RNG-derived fuel, offer other benefits to the community. Members of the public often view local green programs positively, which can present great marketing and publicity opportunities for a community. According to Clean Energy Fuels, dedicated natural gas-fueled refuse trucks produce less noise than comparable diesel-fueled refuse trucks, with a difference greater than 10 decibels at idle.[32] Reducing noise from trucks has positive and measurable health and economic benefits.[33]

5.0 OPERATIONAL RNG PROJECTS

Across all feedstocks, 34 states have more than 100 RNG projects operating and approximately 40 under construction as of February 2020.[34] EPA provides a national map showing the locations of projects producing RNG from either LFG or manure-based AD biogas.[35]

MSW Landfills

According to the EPA LMOP Landfill and LFG Energy Project Database, as of March 2020 there were 564 operational LFG energy projects, 65 of which produced RNG.[36] Table 3 provides a summary of the 65 LFG-to-RNG projects in the United States, including the number of projects and their sizes in terms of the amount of LFG used to create the RNG. The majority of these projects are producing RNG for use as transportation fuel, whether used locally (on site or near the landfill) or transported via pipeline to a location further away. The other projects use the RNG to generate electricity in thermal applications or to offset fossil natural gas usage in another manner.[37]

The first LFG-to-RNG project in the United States operated from 1975 to 1985 at the Palos Verdes Landfill in Los Angeles County, California.[38,39] The plant was designed to process 2 million standard cubic feet per day (mmscfd) of raw LFG into approximately 1 mmscfd of RNG for injection into a nearby pipeline.[40]

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32 Clean Energy Compression. July 2015. What Refuse Truck Fleets Are Doing to Make Our Air Cleaner. https://www.cleanenergyfuels.com/compression/blog/refuse-truck-fleets-switch-natural-gas-power-who-when-where-why/.

33 Pignier, N. May 2015. The Impact of Traffic Noise on Economy and Environment: A Short Literature Study. KTH Royal Institute of Technology. https://www.diva-portal.org/smash/get/diva2:812062/FULLTEXT01.pdf.

34 Coalition for Renewable Natural Gas. RNG Production Facilities Database. http://www.rngcoalition.com/rng-production-facilities. Accessed February 11, 2020.

35 U.S. EPA. RNG Project Map. https://www.epa.gov/lmop/renewable-natural-gas#rngmap. Accessed July 22, 2019.

36 U.S. EPA. March 2020. Landfill and Landfill Gas Energy Project Database. https://www.epa.gov/lmop/landfill-gas-energy-project-data.

37 U.S. EPA. March 2020. Landfill and Landfill Gas Energy Project Database. https://www.epa.gov/lmop/landfill-gas-energy-project-data.

38 Cosulich, J., S.-L. Ahmed, and J.F. Stahl. 1992. Palos Verdes Landfill Gas to Energy Facility. http://gwcouncil.org/publications/nawtec/proceedings-of-15th-biennial-conference/.

39 Bowerman, F., N. Rohatgi, K. Chen, and R. Lockwood. July 1977. A Case Study of the Los Angeles County Palos Verdes Landfill Gas Development Project. EPA/600/3-77/047. https://cfpub.epa.gov/si/si_public_record_Report.cfm?Lab=ORD&dirEntryID=49543.

40 U.S. DOE. March 1978. Proceedings of a Symposium on the Utilization of Methane Generated in Landfills. https://www.osti.gov/biblio/6652887.

Table 3. Breakdown of LFG-to-RNG Project Types and Sizes in the United States from the LMOP Landfill and LFG Energy Project Database

RNG Delivery Method / Project Type	Number of Projects	Project Size—LFG Flow (cfm)
Local / CNG	6	49 to 201 (average 145)
Local / LNG	1	2,410
Pipeline Injection / Vehicle Fuel	53	413 to 10,417 (average 2,753)
Pipeline Injection / Industrial, Electricity or Other	5	757 to 5,833 (average 2,940)

Municipal WRRFs

In 2013, about 48 percent of the total wastewater flow in the United States was treated through AD.[41] According to the U.S. GHG Inventory, in 2017 approximately 18,260 million gallons per day (MGD) of wastewater effluent were sent to WRRFs with AD.[42] In 2019, 13 WRRF biogas projects (listed in Table 4) were creating RNG.[43,44]

Table 4. WRRF Digester Gas-to-RNG Projects Operating in the United States in 2019

WRRF Project Location	Start Year	WRRF Average Flow Rate in MGD
91st Avenue, Phoenix, AZ	2019	138
City of San Mateo, CA	2016	15.7
Las Gallinas Valley Sanitary District, CA	2017	2.67
Point Loma, CA	2012	175
Persigo (Grand Junction), CO	2015	8.5
South Platte Water Renewal Partners, CO	2019	~24
Honouliuli, HI	2016	26.1
Dubuque, IA	2017	7
Warrior Biogas Reuse Project, KS	2018	5.5
Newark, OH	2011	8
San Antonio Water Systems, TX	2010	94.7
South Treatment Plant, WA	1987	70
Janesville, WI	2012	13

Livestock Farms

According to the EPA AgSTAR project database, as of March 2020 there are 255 operational digester projects that accept livestock manure. The majority (79 percent) of the manure-based digester projects

41 U.S. DOE. July 2016. 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy. https://www.energy.gov/sites/prod/files/2016/12/f34/2016_billion_ton_report_12.2.16_0.pdf.

42 Working spreadsheet for 2017 U.S. GHG Inventory for Wastewater Treatment.

43 Mintz, M., P. Vos, M. Tomich, and A. Blumenthal. October 2019. Database of Renewable Natural Gas (RNG) Projects: 2019 Update. Argonne National Laboratory. https://www.anl.gov/es/reference/renewable-natural-gas-database.

44 Gilbert, D. November 2019. "Biogas" Project Up and Running at Wastewater Plant. https://littletonindependent.net/stories/biogas-project-up-and-running-at-wastewater-plant,288922.

are at dairy farms, and 14 percent are at swine farms. The remainder process a mix of animal manure effluents, including those from poultry and beef cattle.[45]

The earliest U.S. manure-based digester project to create RNG began in 2004 at Whitesides Dairy in Idaho. The Whitesides project was the first biogas production facility at a large commercial dairy in the state and provided approximately 10 million cubic feet of RNG annually to Intermountain Gas until 2009, when the project ended.[46]

The majority (84 percent) of manure-based digester projects are generating electricity, and many of them are also recovering waste heat in combined heat and power[47] (or cogeneration) projects. More than 20 manure-based digester projects are currently producing RNG from their biogas with a variety of RNG end uses including electricity, vehicle fuel and pipeline gas. [48]

Organic Waste Management Operations

EPA's 2018 AD survey results show that of the 43 stand-alone facilities that reported on their biogas end use, five produce CNG for either company vehicles or for sale to other customers, while none provide RNG for pipeline injection.[49]

6.0 CONSIDERATIONS FOR PROJECT FEASIBILITY AND POTENTIAL FOR GROWTH

In addition to the sites discussed in Section 5.0 that are recovering biogas as a renewable energy resource, there are many other biogas-producing sites in the United States that could potentially capture their biogas for energy. Based on market conditions and incentives, several of the sites already recovering biogas for electricity generation or other applications could switch to producing RNG instead; several LFG energy projects have already made this change. In addition, more organic waste in this country could be digested for energy recovery instead of being landfilled. A subset of the sources in these categories could produce RNG.

Considerations for the feasibility of an RNG project include:

- The quantity and quality of biogas available for conversion (e.g., LFG and WRRF biogas tend to require more constituent removal than manure-based or organic waste AD projects);
- Economic considerations (e.g., financing options, available incentives);
- End user availability for the RNG (e.g., proximity to a fossil natural gas pipeline without physical connection barriers, a local distribution company's interest in taking RNG, a local vehicle fuel demand, a natural gas-consuming business with sustainability goals); and
- A reliable power source for the compression and cleanup processes.

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45 U.S. EPA. March 2020. Livestock Anaerobic Digester Database. https://www.epa.gov/agstar/livestock-anaerobic-digester-database.

46 U.S. EPA. March 2020. Livestock Anaerobic Digester Database. https://www.epa.gov/agstar/livestock-anaerobic-digester-database.

47 Combined heat and power or cogeneration projects recover and beneficially use the waste heat from the combustion unit that is generating electricity, thus providing a greater overall efficiency.

48 U.S. EPA. March 2020. Livestock Anaerobic Digester Database. https://www.epa.gov/agstar/livestock-anaerobic-digester-database.

49 U.S. EPA. September 2019. Anaerobic Digestion Facilities Processing Food Waste in the United States (2016). EPA/903/S-19/001. https://www.epa.gov/anaerobic-digestion/anaerobic-digestion-facilities-processing-food-waste-united-states-survey.

Higher flows of biogas (e.g., greater than 1,000 cfm for LFG-sourced projects) are needed for pipeline injection projects to be financially feasible, but local-use RNG-to-vehicle fuel projects are feasible at lower flows (e.g., as low as 50 cfm for LFG-sourced projects). Gas conditioning technology improvements have allowed smaller biogas volumes to be economically treated when used directly in onsite vehicle fueling stations or aggregated with output from other sites to make use of one fossil natural gas pipeline interconnect.

Prior to implementing any type of biogas energy project, an end user (or buyer of environmental attributes) must be identified and appropriate agreements must be in place. For RNG projects, if onsite vehicle fueling, direct pipeline injection or virtual pipeline transport is not feasible, an otherwise attractive project may not be viable.

MSW Landfills

There is a significant opportunity for growth in RNG from LFG. LMOP defines a "candidate" landfill as a landfill that is currently accepting waste or has been closed five years or less, has at least one million tons of waste, and does not have an operational, under-construction or planned LFG energy project. A landfill can also be designated as a candidate landfill based on actual interest for a project at the site. As of March 2020, there were approximately 480 candidate landfills with the potential to collect a combined 500 mmscfd of LFG. Out of these 480 landfills, approximately 375 have between 100 and 1,000 cfm of LFG available, and approximately 90 have greater than 1,000 cfm of LFG. There are also landfills with operational energy projects that are flaring excess LFG—approximately 85 of these landfills have 100 to 1,000 cfm of excess gas, and approximately 30 have more than 1,000 cfm of excess gas.[50]

Municipal WRRFs

A 2014 National Renewable Energy Laboratory report analyzed flow rate data from approximately 18,000 WRRFs to estimate their CH_4 potential. After subtracting out the biogas used for combined heat and power projects at WRRFs, the National Renewable Energy Laboratory estimated 1.9 million metric tons of CH_4 available for recovery from these facilities.[51]

The Water Environment Federation (WEF) maintains a "phase 1" database that lists information for approximately 1,250 WRRFs that have AD on site or send sludge to another facility to be treated by AD.[52] The economic viability of a WRRF biogas project primarily depends on the amount of organic feedstock (e.g., wastewater sludge, commercial or industrial waste) that is available for AD. Typically, a larger WRRF (in terms of influent flow) has a greater opportunity for biogas capture and use. In March 2015, Argonne National Laboratory analyzed data in the WEF database, which included a summary of the counts of biogas utilization projects for varying WRRF capacities, as shown in Table 5.

50 U.S. EPA. March 2020. Landfill and Landfill Gas Energy Project Database. https://www.epa.gov/lmop/landfill-gas-energy-project-data.

51 Saur, G., and A. Milbrandt. July 2014. Renewable Hydrogen Potential from Biogas in the United States. NREL/TP-5400-60283. https://www.nrel.gov/docs/fy14osti/60283.pdf.

52 WEF. 2015. Biogas Data. http://www.resourcerecoverydata.org/biogasdata.php. Accessed March 27, 2019.

Table 5. Number of Biogas Utilization Projects for Varying WRRF Capacities[53]

WRRF Average Flow Rate in MGD	Number of WRRFs with AD	Number Using Biogas / Number Not Using Biogas
<1	96	55 / 41
1 to 10	690	505 / 185
10 to 100	276	238 / 38
100 to 1,000	29	26 / 3

The WEF database contains approximately 5,100 WRRFs in total, so it does not represent the entire list of operating WRRFs nationwide, which is between 15,000 and 18,000 WRRFs.[54] Of the WRRFs in the WEF database, 3,200 have an average flow rate greater than 1 MGD; more than 60 percent of these facilities do not send solids to AD, and therefore do not produce biogas. There are 12,000 facilities with average flow rates less than 1 MGD, and only a small number of these facilities have AD;[55] WRRFs of this size are not expected to support an RNG project.

The project information in Table 4 of this document shows that of the 13 WRRF biogas-to-RNG projects operating in 2019, about half are at WRRFs greater than 15 MGD in average flow rate. Table 5 notes 185 WRRFs with average flow rates between 1 and 10 MGD that have AD but are not beneficially using the biogas; these WRRFs could potentially use their biogas for a local-use RNG project if demand is present. For the 41 WRRFs with average flow rates greater than 10 MGD that have AD but are not using the biogas for energy, they likely could produce RNG from their biogas for either local or pipeline delivery if other project considerations are favorable. There is likely additional RNG generation potential at WRRFs not represented in the WEF database.

Livestock Farms

Candidate sites are generally considered to be dairies with at least 500 cows or swine facilities with at least 2,000 sows or feeder pigs. This is a rough estimate that accounts for the general manure production rates and composition of these animals and should only be used for general screening, since smaller operations have been successfully developed into beneficial use applications. According to estimates from

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53 U.S. DOE. July 2016. 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy. https://www.energy.gov/sites/prod/files/2016/12/f34/2016_billion_ton_report_12.2.16_0.pdf. Citing Shen, Y., J.L. Linville, M. Urgun-Demirtas, M.M. Mintz, and S.W. Snyder. 2015. An Overview of Biogas Production and Utilization at Full-Scale Wastewater Treatment Plants (WWTPs) in the United States: Challenges and Opportunities Towards Energy-Neutral WWTPs. Renewable & Sustainable Energy Reviews 50: 346–62. The WRRF counts in Table 5 sum to fewer than the count of 1,250 WRRFs noted in the text; the remaining ~150 WRRFs in the WEF database that were not noted in the 2015 Argonne study are presumed to have not had sufficient average flow rate data to be categorized by size.

54 Lono-Batura, M., Y. Qi, and N. Beecher. December 2012. Biogas Production and Potential from U.S. Wastewater Treatment. BioCycle 53(12): 46. https://www.biocycle.net/2012/12/18/biogas-production-and-potential-from-u-s-wastewater-treatment/. Citing U.S. EPA 2008 Clean Watershed Needs Survey.

55 Lono-Batura, M., Y. Qi, and N. Beecher. December 2012. Biogas Production and Potential from U.S. Wastewater Treatment. BioCycle 53(12): 46. https://www.biocycle.net/2012/12/18/biogas-production-and-potential-from-u-s-wastewater-treatment/.

DOE, nearly 1.5 billion cubic feet of digester gas from farms that could be recovered for energy are flared each year.[56]

AgSTAR estimates that more than 8,000 large swine or dairy farms could create RNG from manure-based digesters, including nearly 800 dairies in California alone (the largest dairy-producing state).[57] As of March 2020, there were approximately 10 dairy digester projects under construction in California and another 31 under development.[58] If all 8,000 of the candidate farms produced and captured biogas to produce RNG, AgSTAR estimates they could create the equivalent of 1.3 billion diesel gallons, enough to fuel nearly 150,000 refuse trucks.[59]

Organic Waste Management Operations

EPA reports that about 94 percent of the food that is thrown away in this country is either landfilled or combusted for energy. Of the 40.7 million tons of food waste generated in 2017, 30.6 million tons were landfilled and 7.5 million tons were combusted with energy recovery. The remaining approximately 2.6 million tons were composted.[60] In 2015, EPA and the U.S. Department of Agriculture created the U.S. 2030 Food Loss and Waste Reduction Goal, which includes a goal to reduce food waste going to landfills or combustion with energy recovery by 50 percent over a 2010 baseline.[61]

AD facilities can process food waste that would otherwise be landfilled or combusted. In 2015, it was estimated that the number of stand-alone AD facilities could double in the next five to ten years, while processing capacity could quadruple in the next five years.[62] It is also estimated that AD of 100 tons of organic waste per day can generate enough biogas to create between 900 and 1,400 gasoline gallon equivalents (GGE) of CNG per day, depending on the type of organic waste, AD technology used and CH_4 capture efficiency of the RNG technology used.[63,64,65]

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56 U.S. DOE. July 2016. 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy. https://www.energy.gov/sites/prod/files/2016/12/f34/2016_billion_ton_report_12.2.16_0.pdf.

57 U.S. EPA. June 2018. Market Opportunities for Biogas Recovery Systems at U.S. Livestock Facilities. https://www.epa.gov/sites/production/files/2018-06/documents/epa430r18006agstarmarketreport2018.pdf.

58 U.S. EPA. March 2020. Livestock Anaerobic Digester Database. https://www.epa.gov/agstar/livestock-anaerobic-digester-database.

59 U.S. EPA. June 2018. Market Opportunities for Biogas Recovery Systems at U.S. Livestock Facilities. https://www.epa.gov/sites/production/files/2018-06/documents/epa430r18006agstarmarketreport2018.pdf.

60 U.S. EPA. November 2019. Advancing Sustainable Materials Management: 2017 Fact Sheet. EPA/530/F-19/007. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/advancing-sustainable-materials-management.

61 U.S. EPA. United States 2030 Food Loss and Waste Reduction Goal. https://www.epa.gov/sustainable-management-food/united-states-2030-food-loss-and-waste-reduction-goal. Accessed March 5, 2020.

62 EREF. August 2015. Anaerobic Digestion of Municipal Solid Waste: Report on the State of Practice.

63 U.S. EPA. March 2008. Anaerobic Digestion of Food Waste. Final Report. Table ES-1. https://nerc.org/documents/anaerobic_digestion_report_march_2008.pdf.

64 U.S. EPA. May 2017. LFGcost-Web. Version 3.2. https://www.epa.gov/lmop/lfgcost-web-landfill-gas-energy-cost-model.

65 U.S. EPA. May 2019. Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARM). Organic Materials Chapters. https://www.epa.gov/sites/production/files/2019-06/documents/warm_v15_organics.pdf.

7.0 PURIFICATION PROCESSES AND GENERAL TECHNOLOGIES

Raw biogas, which is typically between 45 and 65 percent CH_4 depending on the feedstock, must go through a series of steps to be converted into RNG (at 90 percent CH_4 or greater, depending on the specification for the pipeline or other end use). Constituents of RNG that most often have specifications or limits to meet are CO_2, O_2, inert gases (including N_2), total sulfur, H_2S, siloxanes and VOCs. Other properties that are prescribed by pipelines or end users include heating value, temperature, pressure and moisture content.

Typical steps to convert raw biogas to RNG are reviewed below. As shown in Figure 2 and Figure 3, the treatment can be divided into:

- Primary: basic moisture and particulate removal.
- Secondary: additional moisture removal, contaminant removal and compression.
- Advanced: CO_2, O_2, N_2 and VOC removal and further compression.

The primary and secondary treatment stages produce a medium-Btu gas, which means the heating value of this treated biogas is less than that of fossil natural gas (typically about half). The advanced treatment stage produces RNG, with a heating value similar to fossil natural gas.

As part of advanced treatment, some CH_4 is stripped out along with the CO_2 and other residual constituents—especially H_2S—and routed to a flare or thermal oxidizer for destruction. The amount of CH_4 stripped out as this "tail gas" depends on the technology used to upgrade the biogas, the CH_4 specification for the RNG and the cost–benefit ratio of additional CH_4 capture versus the additional capital expense to achieve it.

Primary Treatment

Primary treatment consists of basic moisture and particulate removal from the raw biogas. The raw biogas passes through a knockout pot, filter and blower to remove moisture. This treatment is all that is required for destroying the LFG in a combustion flare; in addition, some LFG energy projects have used only primary treatment when combusting LFG in medium-Btu applications such as leachate evaporators, boilers and kilns.

Secondary Treatment

Secondary treatment consists of additional moisture removal, contaminant removal and compression. The process first uses an after cooler to condense and remove additional moisture, then removes contaminants such as siloxanes and sulfur. The type of contaminants removed depends on the end use and which constituents are present in the biogas and at what levels. The treated gas can also be compressed further as needed. These secondary treatments are used to produce medium-Btu gas for direct thermal applications such as boilers or for electricity generation applications such as engines and turbines.

Advanced Treatment

Advanced treatment is critical to transform biogas into RNG. Advanced treatment must remove CO_2, O_2, N_2, VOCs and siloxanes (as needed), although some projects may remove these types of contaminants in an earlier stage. The selection of the advanced treatment technology type is site-specific and project-specific, and there are advantages and disadvantages to each type. Sections 7.1 through 7.4 describe advanced treatment technologies in detail, along with their benefits and drawbacks.

Fuel Specifications

For pipeline injection projects, regardless of the eventual end use at the other end of a pipeline network, there is typically a higher CH_4 content specification to meet than for onsite vehicle fuel projects. As a result, these projects usually recover a higher fraction of the CH_4, typically in the 96 to 98 percent range. Pipeline specifications also put low limits on the levels of O_2 and inert gases that are allowed in the RNG.[66] Tail gas from these projects must be destroyed in a flare or thermal oxidizer, using supplemental fuel since tail gas does not have a sufficient heating value to sustain combustion.

In the United States, CNG vehicle fuel project developers generally design projects to meet the technical requirements set by the Society of Automotive Engineers *Surface Vehicle Recommended Practice J1616™ for Compressed Natural Gas Vehicle Fuel* (SAE J1616). SAE J1616 sets minimum requirements for CNG fuel composition and properties to ensure vehicle, engine and component durability, safety and performance. It provides technical requirements for several fuel properties and potential constituents including CH_4, sulfur compounds, O_2 and particulate material. SAE J1616 references CARB's CNG commercial fuel composition for several specifications, including 88 percent CH_4 (minimum) and 1 percent O_2 (maximum).[67]

7.1 CO_2 Removal Technologies

There are four common ways to remove CO_2 during the advanced treatment stage: membranes, pressure swing adsorption (PSA), solvent scrubbing and water scrubbing. Each technology has strengths and weaknesses that are evaluated and balanced on a case-by-case basis for each potential RNG facility to select the technology best suited for that particular site. Each technology can achieve RNG quality standards necessary for pipeline injection or onsite vehicle use, but it is often a matter of upfront capital expense versus ongoing operating expense.

Based on 2018 data in Argonne National Laboratory's database of RNG projects, the CO_2 removal technology distribution for RNG projects at landfills in the United States was 27 percent using solvent scrubbing, 24 percent using membrane systems, 10 percent using PSA and 8 percent using both membranes and PSA, with the balance using water scrubbing or an unknown technology. For manure-based AD biogas-to-RNG projects in the United States in 2018, 64 percent were using membrane systems, 12 percent were using PSA and 6 percent were using water scrubbing, with the balance using another technology.[68] Figure 7 and Figure 8 show these breakdowns in chart form.

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66 Smyth, P., and J. Pierce. January 2011. Quantification of the Incremental Cost of Nitrogen and Oxygen Removal at High-Btu Plants. Presented at 14th Annual EPA LMOP Conference and Project Expo. p. 33. https://www.epa.gov/sites/production/files/2016-06/documents/smyth.pdf.

67 Society of Automotive Engineers International. March 2017. Recommended Practice for Compressed Natural Gas Vehicle Fuel. Surface Vehicle Recommended Practice J1616™. Section 4, Technical Requirements, and Appendix D, Table D.2, CARB Commercial Fuel Composition. https://www.sae.org/standards/content/j1616_201703/.

68 Mintz, M., P. Vos, M. Tomich, and A. Blumenthal. October 2019. Database of Renewable Natural Gas (RNG) Projects: 2019 Update. Argonne National Laboratory. https://www.anl.gov/es/reference/renewable-natural-gas-database.

Figure 7. CO_2 Removal Technologies for U.S. LFG-to-RNG Projects in 2018

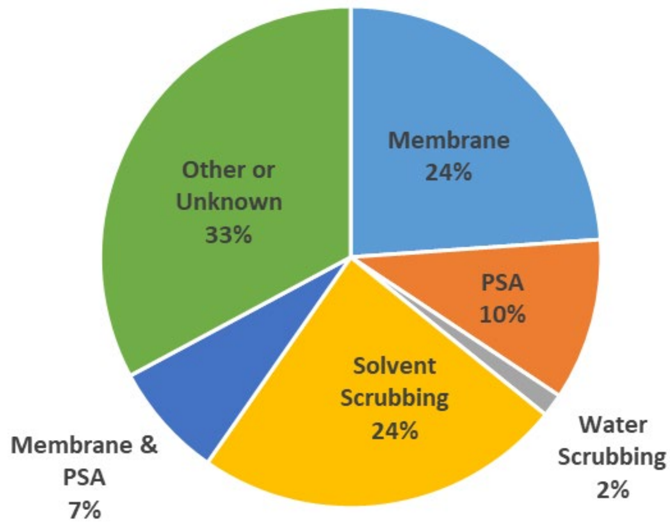
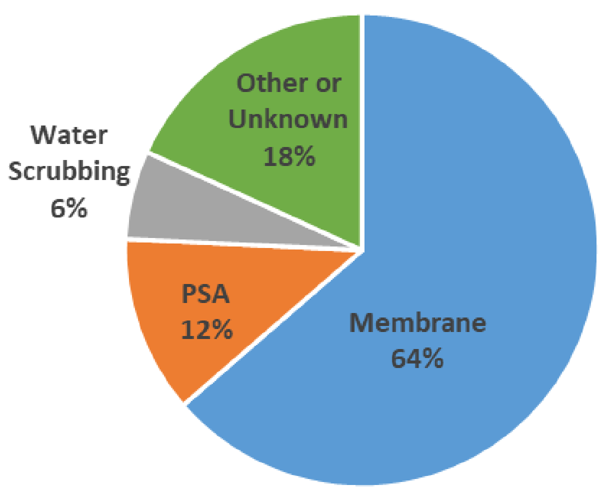


Figure 8. CO_2 Removal Technologies for U.S. Manure-Based Biogas-to-RNG Projects in 2018



By comparison, Europe had more than 80 RNG projects in 2014, with approximately 65 percent of the projects using water or solvent scrubbing, 23 percent using PSA and 11 percent using membranes.[69]

[69] U.S. EPA. September 2016. Evaluating the Air Quality, Climate & Economic Impacts of Biogas Management Technologies. EPA/600/R-16/099. https://nepis.epa.gov/Exe/ZyPDF.cgi/P100QCXZ.PDF?Dockey=P100QCXZ.PDF.

Membrane Systems

A membrane is a type of filter that has a specific pore size rating and operates similarly to a screen or sieve, retaining particles larger than the membrane's pore size. The material that the membrane is constructed from and the method by which the large particles are captured is technology specific. Membranes are often used to remove CO_2 and other unwanted constituents when upgrading raw biogas to RNG.

Single-Pass Membrane System

Onsite CNG vehicle fuel use typically does not require a heating value as high as that required by pipeline injection projects, and it also allows some minor levels of O_2 and inert gases. Therefore, onsite vehicle fuel applications with lower biogas volumes often use a single-pass membrane system that captures approximately 65 to 80 percent of the CH_4. These systems either send the remaining 20 to 35 percent of the CH_4 out as tail gas for economical destruction in an onsite flare or blend it with the remaining biogas for use in turbine or reciprocating engine electrical generating equipment. More efficient gas conditioning technology that would produce a product gas with a higher heating value is available for lower biogas flows, but historically it has not been economically feasible due to the added capital expense.

Multiple-Pass Membrane System

Larger-scale onsite vehicle fuel applications can use membrane technology similar to that of smaller-scale applications, but with more efficient processes that capture additional CH_4 via multiple passes through the membranes. Many of these sites use gas conditioning technology that captures approximately 96 to 99 percent of the CH_4. Tail gas from these projects must be destroyed in a flare or thermal oxidizer using supplemental fuel, since the tail gas does not have a sufficient heating value to sustain combustion.[70] The increased volume of RNG produced from conditioning larger biogas volumes can typically justify the added capital and operational expenses and the addition of a thermal oxidizer.

PSA

In PSA systems, adsorbent media are pressurized with the incoming biogas. A difference in molecular size allows CH_4 to pass through into the product gas, while the media capture CO_2 and, to a lesser extent, N_2. Once the media have been saturated, they are depressurized, and the CO_2 and N_2 are released into the tail gas stream. A typical PSA system employs multiple vessels operating in different stages of pressurization, depressurization and regeneration. PSA can capture between 95 and 98 percent of the CH_4; the exact percentage will vary depending on the design of the PSA, which is optimized to balance system performance and system economics.

Solvent Scrubbing

Solvent scrubbing processes use a chemical solvent such as amine or a physical solvent like Selexol to strip CO_2 and H_2S from the biogas stream. CO_2 is adsorbed into the solvent, allowing CH_4 to pass through into the RNG product stream. In an amine system, the solution is heated in a separate vessel to release the CO_2 into the tail gas stream; in a Selexol process, the solvent is depressurized, which releases the CO_2. CH_4 capture efficiency varies between 97 and 99 percent for physical solvents but is often greater than 99 percent for amine solvents given that amine solutions are particularly selective for CO_2.

70 U.S. EPA. September 2016. Evaluating the Air Quality, Climate & Economic Impacts of Biogas Management Technologies. EPA/600/R-16/099. p. 29. https://nepis.epa.gov/Exe/ZyPDF.cgi/P100QCXZ.PDF?Dockey=P100QCXZ.PDF.

Water Scrubbing

Water scrubbing (sometimes called water wash) is a simple process in which the biogas is pressurized into water. CO_2 is adsorbed into the water while the CH_4 passes through into the RNG product stream. The water is then depressurized, and the CO_2 is allowed to pass through in the tail gas. CH_4 capture efficiency of water scrubbing systems is typically greater than 99 percent.

Biogas Flow Rates for CO_2 Removal Technologies

Each CO_2 removal technology allows for a different range of biogas flow rates. Typical flow rates for the four main technologies are summarized in Table 6. Process flow diagrams of the four main types of advanced CO_2 removal technologies (membrane, solvent, PSA, water scrubbing) were presented in a webinar by LMOP Industry Partner DTE Biomass Energy.[71]

Table 6. Typical Flow Rates for Advanced CO_2 Removal Technologies

Technology	Inlet Biogas Flow Range (standard cfm [scfm])
Single-Pass Membrane	50 to 400
Multiple-Pass Membrane	200 to 10,000+
PSA	50 to 5,000+
Solvent Scrubbing	1,000 to 10,000+
Water Scrubbing	50 to 3,000

Additional discussion of primary, secondary and advanced treatment is available in Chapter 3 of the LMOP *LFG Energy Project Development Handbook*.[72]

7.2 VOC/Siloxane Removal Technologies

For any vehicle fuel or pipeline injection project, a critical part of the LFG conditioning process is the removal of VOCs and siloxanes. Even trace amounts of siloxanes can damage engines, turbines and compressors and so must be removed. VOCs are an environmental pollutant that would be sufficiently destroyed in an engine or turbine, but they are similar in molecular structure to siloxanes. This means any medium that is designed to remove siloxanes will also capture VOCs—usually one cannot be removed without capturing the other.

The concentration of siloxanes within biogas can vary widely by source type and the specific site. A 2017 report prepared by the California Biogas Collaborative noted the following ranges by source type for siloxane concentrations in raw biogas: 0 to 400 milligrams per cubic meter (mg/m^3) for WRRFs, 0 to 50 mg/m^3 for landfills and 0 to 0.2 mg/m^3 for livestock farms (no results available for stand-alone MSW digesters).[73] These results indicate that siloxane contamination is a potential issue mainly with WRRF biogas and LFG, primarily because siloxanes are found in many cosmetic, health and beauty products.

71 Hill, M.R. November 2017. Upgrading Landfill Gas to Pipeline Quality Natural Gas. https://www.epa.gov/sites/production/files/2017-11/documents/lmop_webinar_november_16_2017.pdf.

72 U.S. EPA. June 2017. LFG Energy Project Development Handbook. https://www.epa.gov/lmop/landfill-gas-energy-project-development-handbook.

73 California Biomass Collaborative. January 2017. Renewable Energy Resource, Technology, and Economic Assessments. Appendix H—Task 8: Comparative Assessment of Technology Options for Biogas Clean-Up. CEC-500-2017-007-APH. https://cwec.ucdavis.edu/wp-content/uploads/03-16-2017-CEC-500-2017-007.pdf.

For projects with lower gas flows or projects with higher gas flows but relatively low concentrations of VOCs and siloxanes, a non-regenerative carbon medium is typically used to remove the contaminants. Companies that specialize in the removal of these compounds will analyze gas samples and prepare a site-specific carbon medium 'recipe' best suited for removing them. Under normal operation, gas quality is periodically monitored to determine when the medium is saturated and replacement is necessary. These types of media can be disposed of in a landfill, and no other special handling is required.

For higher gas flows or projects with high concentrations of VOCs or siloxanes, a regenerative process is required. As with the non-regenerative systems, a medium is used to capture the contaminants, but instead of disposing of media once saturated, the media are regenerated through a temperature swing adsorption (TSA) or PSA process. VOCs and siloxanes de-adsorb with a change in pressure or temperature and are directed to a flare or thermal oxidizer for combustion. These flares require pilot gas to fuel the flare, which can be either biogas, propane or fossil natural gas.

7.3 N_2 Removal Technologies

N_2 removal (or rejection) may be required as a part of the biogas conditioning system, depending on the biogas inlet N_2 levels and the required RNG specifications. N_2 can be difficult and expensive to remove from biogas given the similar diameters of N_2 and CH_4 molecules, which are approximately 3.6 angstroms and 3.8 angstroms, respectively.

The typical biogas conditioning process to create RNG initially removes trace-level contaminants and most CO_2, while allowing N_2 to pass through the system with the CH_4. However, some biogas conditioning systems remove N_2 concurrently with CO_2 using adsorbents that have a high kinetic selectivity toward N_2 and O_2. Either way, a secondary N_2-specific rejection system may be required at the end of the gas conditioning system to reduce N_2 to acceptable end use levels. N_2 removal processing can potentially reduce a facility's overall CH_4 recovery rate—the impact on CH_4 recovery varies depending on the inlet N_2, outlet N_2 specifications and the technology used to remove the N_2.

Commercially available N_2 rejection systems for biogas streams include PSA, membranes and cryogenic distillation. The following sections provide a basic overview of these technologies including an estimated CH_4 capture efficiency for each, which represents the percentage of CH_4 in the N_2 removal system's inlet stream that is captured in the outlet flow (i.e., not an overall CH_4 capture efficiency for the full advanced treatment process).

PSA

As noted in Section 7.1, PSA systems use the molecular size differences of gas particles to separate them. One type of PSA system for N_2 removal uses an activated carbon adsorbent which also captures O_2. The CH_4 capture efficiency of this type of system is about 96 percent. However, the product gas is then at low pressure and must be recompressed to pipeline requirements. Another option is a kinetic PSA system in which the pore size of the adsorbent is controlled to be 3.7 angstroms so that N_2 is adsorbed but CH_4 is not. This system's CH_4 capture efficiency is about 90 percent and the product gas is left at high pressure so may not need recompression. In both types, the inlet N_2 feed can be relatively high (e.g., 15 percent), but the adsorption capacity can be impacted by impurities in the gas stream.

Membrane

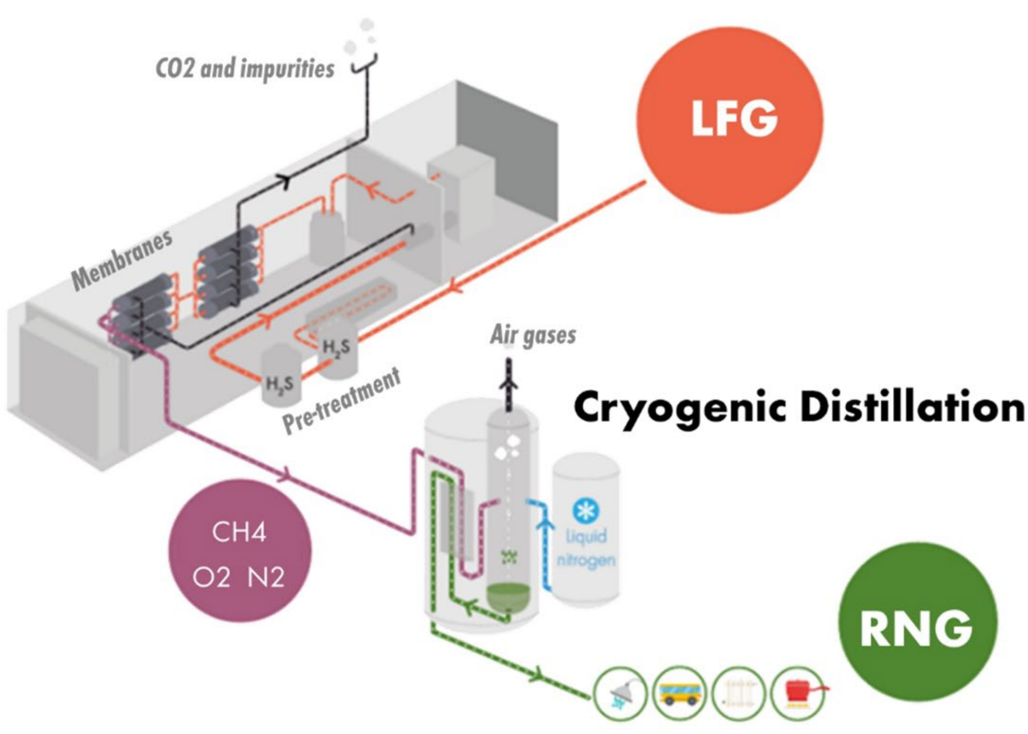
One type of membrane used specifically for N_2 removal is made of a polyether ether ketone (PEEK) material that has been widely used in the natural gas industry given its resistance to chemicals and solvents. A multi-stage N_2 rejection system using PEEK membranes can differentiate between CH_4 and N_2

molecules easier than a conventional membrane system that is focused on CO_2 removal. The N_2 inlet to this type of system can be as high as 10 percent (in the intermediate gas stream following CO_2 removal) and the CH_4 capture efficiency is 96 percent or higher. Membranes can be added or removed as flow increases or decreases so the system is scalable, but a high inlet pressure (500 psi) is required. The product gas is at a low pressure and must be recompressed to pipeline requirements.

Cryogenic Distillation

Low-pressure cryogenic distillation separates CH_4 from air gases by lowering the temperature of the intermediate gas stream (following CO_2 removal) to a point where the CH_4 liquefies but N_2 and O_2 do not. The process uses liquid N_2 to cool the gas to such a low temperature (approximately -250 degrees Fahrenheit). This technology can accommodate projects with large air intake in the raw biogas as it can process up to 30 percent N_2 content. Its CH_4 capture efficiency is between 92 and 99 percent depending on the O_2 inlet rate and the O_2 gas grid specification. Figure 9 provides an example process diagram for a system that removes CO_2 via membranes and then N_2 by cryogenic distillation—liquid N_2 is introduced into the distillation tower in the center, cooling the intermediate gas stream and causing the liquid CH_4 (product gas) to collect at the bottom.

Figure 9. Example Cryogenic Distillation Process Diagram



Used with permission from Waga Energy.

N_2 Prevention

Because of the potential intrusion of ambient air (which contains N_2) when biogas is collected from landfills, N_2 is typically more of an issue in LFG as compared to biogas from anaerobic digesters. An exception to this can be biogas collected from agricultural waste lagoons with membrane covers, as these systems can also allow air leaks into the raw biogas stream.

Many system designers and project developers advocate for reducing the N_2 content at the source, prior to biogas conditioning, as a more cost-effective method of achieving the outlet N_2 specification. There are hardware and software options available to help LFG system operators improve wellfield efficiencies and mitigate cleanup costs. An LMOP 2017 webinar provides information on landfill wellfield design, construction and operational considerations for RNG projects.[74]

LMOP's RNG Flow Rate Estimation Tool[75] can serve as a screening guide to help stakeholders quickly estimate normalized gas flows for LFG-to-RNG projects.

LMOP's RNG Flow Rate Tool calculates the adjusted flow rate and corresponding heat content (Btu) value of LFG after adjusting a wellfield to meet the inlet specifications for RNG treatment/processing technology.

Treatment technologies often specify that the inlet gas must contain N_2 levels lower than what may be typically measured in LFG; adjusting the collection system to achieve N_2 levels may impact the LFG flow rate.

7.4 O_2 Removal Technologies

Many natural gas utilities have strict limits on O_2 for RNG that is injected into a pipeline network. Excessive amounts of O_2 can accelerate pipeline infrastructure corrosion, resulting in many utilities setting the upper limit of allowable O_2 from 0.2 percent to as low as 2 parts per million. For RNG used directly in vehicles, SAE J1616 has no limit for O_2 due to the low water vapor content requirements. CARB's specifications for commercial CNG chemical composition set a 1 percent O_2 upper limit. While it is usually feasible to reduce O_2 in LFG to less than 1 percent through wellfield tuning and improvements, O_2 removal systems are often required for pipeline injection projects on landfills.

Stand-alone O_2 removal systems remove O_2 through a catalytic reactor and typically are the last step in the LFG conditioning process. Biogas is heated and passed over a catalyst bed, where the O_2 reacts with some of the CH_4 to create CO_2 and water. The biogas exiting the reactor is saturated with moisture and must be dehydrated, typically by using a desiccant dryer or temperature swing adsorption process. Other processes involved in the conditioning of LFG, such as membrane separators and PSA, do remove some O_2, which must be considered when designing and sizing a project. Some PSA systems are also effective in removing nearly all O_2.

Due to the added capital and operating costs of incorporating an O_2 removal system, these systems are often found to be cost-prohibitive for projects with an LFG flow rate less than 1,000 scfm. Costs to heat the biogas and remove moisture must also be considered when developing project financials. These systems may negatively impact CH_4 capture efficiency and add CO_2 to the product gas stream as well. The CH_4 loss and CO_2 addition are small, but not negligible.

7.5 The Future of RNG Processing Technologies

There are continuing advancements in RNG processing technologies to improve CH_4 recovery rates, reduce the impacts of elevated N_2 and reduce the energy intensity of each process. Increased selectivity

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[74] U.S. EPA. November 2017. Wellfield Operations and Technologies for Upgrading Landfill Gas. https://www.epa.gov/lmop/wellfield-operations-and-technologies-upgrading-landfill-gas. Accessed April 3, 2019.

[75] U.S. EPA. January 2020. Renewable Natural Gas Flow Rate Estimation Tool. https://www.epa.gov/lmop/renewable-natural-gas-flow-rate-estimation-tool.

in membrane and PSA systems, along with solvent technology, continue to be developed. These improvements will likely continue as long as there is a strong market for RNG.

7.6 Reliable Power Sources for Advanced Treatment

Advanced treatment to upgrade biogas into RNG requires a reliable power source. The power can be purchased from the grid or generated on site.

If the electricity market pricing is favorable and enough power service is available at the location of the project, the local electric utility can power the processing plant. Even with reliable power purchased from the grid, some RNG projects have backup emergency generators to power the processing in the case of a power outage.

Some RNG projects also generate power for the production facility on site. If the process is powered with renewable energy such as solar, wind, excess biogas not sent to the RNG processing plant or even residual tail gas from the RNG processing plant, the overall CI of the LFG-to-fuel pathway can be reduced, which could result in additional credits from RNG used for transportation fuel.

The tail gas left over from the upgrading process has a diluted CH_4 content that can typically vary from less than 1 percent to as much as 30 percent. For example, at the Cedar Hills Regional Landfill in Washington, the tail gas from the RNG processing plant is mixed with unconditioned LFG and routed to a series of 300-kilowatt Detroit Diesel engines modified for biogas operation, which generate 4 to 5 megawatts of electricity or approximately 80 percent of the electricity needed to run the plant.[76]

7.7 Compressing RNG

Final compression of the RNG depends on how the gas will be used. For vehicles, final CNG storage compression is around 3,500 pound-force per square inch gauge (psig). If the gas is transported via tube/tank trailer, the compression can be as high as 4,000 psig, while for pipeline injection, the compression varies between 50 to 1,000 psig depending on the interconnect location and the pipeline.[77]

8.0 BARRIERS, POLICY DRIVERS AND INCENTIVES RELATED TO RNG PROJECT DEVELOPMENT

RNG project development faces two main types of barriers: economic and technical. The economics of project development can be challenging to overcome, primarily due to the abundance and prolonged low cost of fossil natural gas. Under current market conditions, it is more expensive to produce RNG from any feedstock than it is to purchase fossil natural gas. This price disparity is often amplified by the challenges and costs associated with pipeline interconnection to move the RNG to end use customers.

On the technical side, upgrading raw biogas to RNG requires meeting numerous gas quality specifications, which can vary by state or pipeline system and can be difficult to achieve cost-effectively depending on the biogas source. Additionally, utilities may have the misconception that RNG is not as clean as, or is somehow lower in quality than, fossil natural gas. The following sections describe the nature of each barrier in detail, with solutions to overcome them.

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76 U.S. EPA. March 2020. Landfill and LFG Energy Project Database (LMOP Project IDs 1685-0 and 1685-1). https://www.epa.gov/lmop/landfill-gas-energy-project-data. See also http://www.bioenergy-wa.com/faq/.

77 American Biogas Council. How to Make RNG/Biomethane. https://americanbiogascouncil.org/resources/how-to-make-rng-biomethane/. Accessed March 28, 2019.

8.1 Economic Barriers

The two main economic barriers to producing RNG are the capital and operating costs associated with capturing and cleaning biogas into RNG, relative to the current low price of fossil natural gas, and the cost of delivering RNG to customers, often by building a pipeline interconnection or investing in equipment to deliver the RNG another way. Because fossil natural gas has been less expensive to produce in recent years, it is difficult for RNG to be cost-effective on a straight economic basis. The cost disparity between RNG and conventional fossil natural gas production can be mitigated by policy or legislation that creates demand for and premium pricing for RNG. In addition, in some cases the cost to capture the biogas can be considered a "sunk" cost because the facility has already put in biogas collection infrastructure apart from the RNG (biogas upgrading) project.

Without a pipeline interconnection, it is often difficult to link an RNG supply to customer demand, which could be local or remote. However, the costs associated with gas cleanup and/or interconnection can be reduced through scale economies from partnerships and shared infrastructure, such as digester clusters that share a single upgrading skid and injection point.

Cost of Processing to RNG Quality

The 2019 average Henry Hub spot price of fossil natural gas was $2.57 per million Btu ($3.17 in 2018 and $2.99 in 2017).[78] At this price, it is impossible for RNG to directly compete with the market price of fossil natural gas (i.e., without environmental attribute value), given the costs associated with capturing biogas and processing it into RNG. A collaborative study published in 2016 determined a cost range of $7 per million Btu (very large-scale) to $25 per million Btu (small-scale) for projects upgrading biogas to RNG for pipeline injection.[79] While state and federal environmental attribute market incentives (i.e., credits) exist, particularly for use as an on-road transportation fuel, the pricing and stability of environmental attributes created under these programs can be volatile. For example, between March 2015 and March 2020, the price of D3 Renewable Identification Numbers (RINs) under the EPA RFS was as low as $0.48 and as high as $2.95.[80] Given this volatility, some financial institutions may be hesitant to accept these credits, or apply a steep discount to the credit value when calculating the potential revenue these environmental attributes may provide to a project.[81] It takes a certain type of investor with a particular risk profile to be comfortable with financing an RNG project. Additional policy mechanisms and voluntary or mandatory markets to create longer-term stability and additional value for RNG's environmental attributes, regardless of how the RNG is ultimately used, would help encourage investment or allow for longer-term purchase agreements, similar to how RPS programs for electricity helped generate longer-term power purchase agreements (PPAs) with premium pricing for electricity projects.

Cost of Pipeline Interconnection

Pipeline interconnection can be a significant barrier to RNG project implementation, particularly when working with local distribution companies. The interconnection equipment, pipeline extensions and an often-lengthy planning process can add costs to the point of making a project uneconomical. In California,

78 U.S. EIA. Natural Gas. April 2020. Henry Hub Natural Gas Spot Price. https://www.eia.gov/dnav/ng/hist/rngwhhdm.htm. Accessed April 30, 2020.

79 U.S. EPA. September 2016. Evaluating the Air Quality, Climate & Economic Impacts of Biogas Management Technologies. EPA/600/R-16/099. https://nepis.epa.gov/Exe/ZyPDF.cgi/P100QCXZ.PDF?Dockey=P100QCXZ.PDF.

80 U.S. EPA. RIN Trades and Price Information. https://www.epa.gov/fuels-registration-reporting-and-compliance-help/rin-trades-and-price-information. Accessed April 29, 2020.

81 M.J. Bradley & Associates. July 2019. Renewable Natural Gas Project Economics. https://www.mjbradley.com/sites/default/files/RNGEconomics07152019.pdf.

for example, interconnection costs average between $1.5 and $3 million per site, depending on facility size and location (see Figure 9).[82] These high costs and long lead times can be challenging for RNG project developers and make projects difficult to finance. In addition, utilities that are required to provide least-cost services to their customers are restricted from taking on these added costs without regulatory approval(s), adding to the complexity.

An impediment to many manure-based and small stand-alone and wastewater digester projects pursuing RNG pipeline injection is the high cost of natural gas utility interconnects as compared to the relatively small quantity of RNG produced per project. However, in recent years, the cost and scale at which biogas cleanup technology can work has been reduced considerably.

Moreover, multiple projects have successfully enabled development and use of a single interconnect (injection point) for aggregating biogas from more than one manure-based digester project. Under this "hub and spoke" model, partially conditioned biogas can be transported to one RNG conditioning and utility interconnect location or multiple RNG gas conditioning facilities can transport RNG fuel via a virtual pipeline with compressed gas tube trailers to a common interconnect location. Each method has been demonstrated in the past few years.

8.2 Technical Barriers

Varying Specifications for RNG Injection

In the United States, hundreds of independent gas systems make up the natural gas pipeline network, and each system has its own requirements. Some of these requirements, such as elevated heating (Btu) values, may effectively prohibit RNG interconnection. For example, a project may not be able to get financing out of concern that the RNG will not consistently meet strict specifications, leading to lost revenue. If pipeline specifications were more standardized, there would be more clarity and certainty for RNG project developers as well as equipment and technology providers.

In California, Southern California Gas Company (SoCalGas) Rule 30 included a minimum heating value of 990 Btu/scf as one of its pipeline requirements. Given the technical and economic challenges of consistently meeting that specification (equivalent to 98 percent CH_4), very few RNG projects were built in California. In fact, more than 95 percent of the RNG earning LCFS credits in 2017 was sourced from out-of-state facilities.[83] SoCalGas undertook extensive testing to evaluate whether any RNG with a lower heating value could be accepted into the pipeline without introducing risk to the pipeline network. Because of the tests, Rule 30 was amended in 2017 to allow the interconnection parties to request a gas quality deviation for lower heating values. However, the California Public Utilities Commission (CPUC) must approve any waiver before the RNG is injected into the pipeline, which adds time and cost to a project.[84]

Treatment Processes

Another potential challenge in developing an RNG project is the quality of the source biogas. While it is technically possible to condition biogas of almost any quality into RNG, systems that can process large flows of biogas at extremely low CH_4 concentrations or with high levels of undesirable constituents (such

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82 CPUC. June 2015. Decision Regarding the Costs of Compliance with Decision 14-01-034 and Adoption of Biomethane Promotion Policies and Program. Decision 15-06-029. http://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M152/K572/152572023.PDF.

83 Notes from attending US Biogas 2017 conference.

84 Lucas, J. October 2017. SoCalGas' Interconnection Process, Tools and Improvements. Presented at US Biogas 2017.

as H_2S, VOCs, siloxanes, N_2, or O_2) are difficult to scale down to smaller flow ranges. This can eliminate projects from consideration until the inlet biogas quality can be increased. Non-landfill sources of biogas typically generate lower biogas flows than landfills do, but the biogas is cleaner than LFG (e.g., greater than 60 percent CH_4 and less costly to purify).

For landfills, one of the largest impediments to additional RNG project development is the presence of N_2 in the LFG. N_2 is an inert gas that reduces the heating value of the RNG, and with most gas conditioning technologies it is difficult to remove. Gas conditioning technology or LFG wellfield operational changes that can address these elevated N_2 levels are discussed in Section 7.0.

8.3 Perception of RNG Quality

One common misconception about RNG is that it is of sub-par quality (e.g., has higher contaminant levels) compared to fossil natural gas. Comparisons of constituent concentrations for fossil natural gas and RNG from three types of feedstocks by the Gas Technology Institute show that RNG typically has lower or similar concentrations for pollutants such as CO_2, O_2, H_2S, total sulfur, aromatic hydrocarbons and other VOCs, while RNG typically has higher concentrations of pollutants such as metals, siloxanes and halocarbons.[85] Education can help to inform project stakeholders and the public about RNG and its development while emphasizing the benefits that can be realized from these projects. Several groups have created outreach materials to educate different audiences and to provide technical assistance to stakeholders evaluating RNG projects. For example:

- SoCalGas developed an RNG tool kit that includes the basics of RNG, information on upgrading technologies, gas specifications, interconnection questions, incentives, and other tools and resources. Other than the broad overview materials, most of these resources are specific to California.
- The Coalition for Renewable Natural Gas provides state and federal policy tracking, data for RNG projects, a model pipeline specification and reports.
- The U.S. DOE Alternative Fuels Data Center provides data and tools related to RNG, with an emphasis on vehicle fuel applications.
- Energy Vision has profiled many RNG projects and compiled several reports and fact sheets detailing the environmental, economic and air quality benefits this strategy achieves.

8.4 Policies and Incentives Related to Pipeline Injection

A policy change that can help overcome RNG project development barriers is the establishment of interconnection incentives and flexible, transparent biogas quality guidelines for pipeline injection. Interconnection incentive programs help developers offset the upfront costs of establishing a project. Established yet flexible quality guidelines or standards make it easier for developers to design the proper biogas treatment system for the appropriate amount of upgrading to meet the specifications. Examples of incentive programs and biogas quality standards for pipeline injection are discussed below.

Example: Policies and Incentives in California

California Senate Bill (SB) 1383 directed CARB to implement regulations to reduce CH_4 emissions by 40 percent by 2030 as compared to 2013 levels. Further, given dairy farming's prominent contribution to

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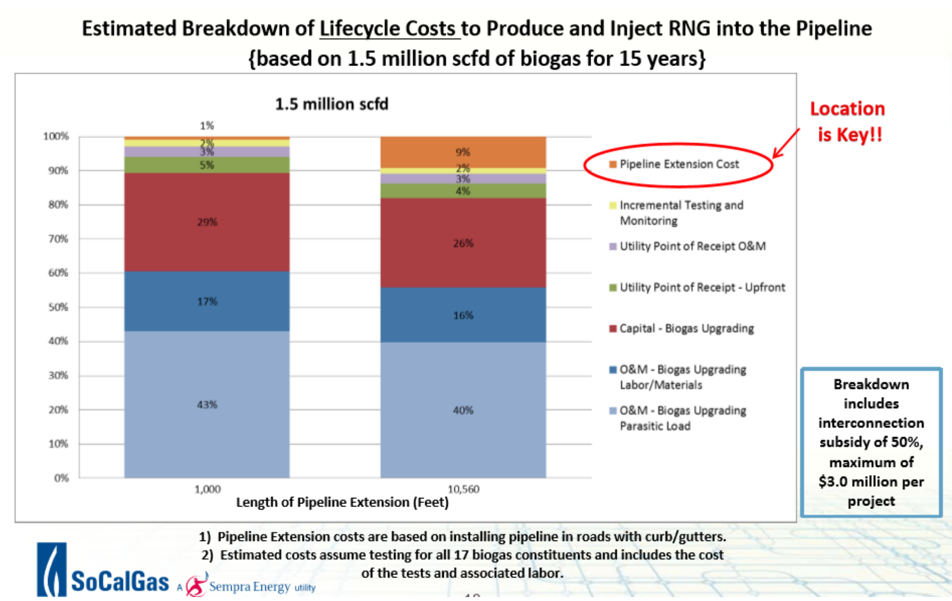
85 Wiley, Kristine. October 2018. Renewable Natural Gas (RNG): Gas Quality Considerations. Presented at 2018 Natural Gas STAR and Methane Challenge Renewable Natural Gas Workshop. https://www.epa.gov/natural-gas-star-program/2018-natural-gas-star-and-methane-challenge-renewable-natural-gas-workshop.

CH_4 emissions in the state, SB 1383 included provisions directing gas corporations to implement at least five (combined total in the state, not per corporation) dairy-based RNG pipeline injection projects. The bill allows for "reasonable pipeline infrastructure costs" to be recoverable in the rates.[86]

The California biomethane interconnection incentive program has $40 million available to offset interconnection costs through December 31, 2021. The program provides 50 percent of eligible biogas collection and interconnection costs (up to $5 million per project) for cluster (three or more) dairy projects and 50 percent of eligible interconnection costs (up to $3 million per project) for other RNG sources including landfills, WRRFs, stand-alone organic waste digesters and non-cluster (one or two) dairy projects.[87,88]

SoCalGas has estimated the life cycle costs to upgrade biogas into RNG and inject it into the pipeline and analyzed the relative cost of each component to help prospective projects evaluate the major cost drivers in their projects. The cost breakdown in Figure 10 incorporates a $3 million subsidy from the biomethane interconnection incentive program for eligible interconnection costs.[89]

Figure 10. Breakdown of RNG Processing and Interconnection Costs[90]



86 Lucas, J. September 2017. Renewable Natural Gas Projects. Presented at EPA Technology Transfer Workshop: Renewable Natural Gas—Driving Value for Natural Gas and Biogas Sectors. https://www.epa.gov/sites/production/files/2017-10/documents/lucas_rng_2017_panel1.pdf.

87 Lucas, J. September 2017. Renewable Natural Gas Projects. Presented at EPA Technology Transfer Workshop: Renewable Natural Gas—Driving Value for Natural Gas and Biogas Sectors. https://www.epa.gov/sites/production/files/2017-10/documents/lucas_rng_2017_panel1.pdf.

88 California State Assembly. September 2016. AB 2313: Renewable Natural Gas: Monetary Incentive Program for Biomethane Projects: Pipeline Infrastructure. https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201520160AB2313. Accessed April 3, 2019.

89 Lucas, J. September 2017. Renewable Natural Gas Projects. Presented at EPA Technology Transfer Workshop: Renewable Natural Gas—Driving Value for Natural Gas and Biogas Sectors. https://www.epa.gov/sites/production/files/2017-10/documents/lucas_rng_2017_panel1.pdf.

90 Lucas, J. September 2017. Renewable Natural Gas Projects. Presented at EPA Technology Transfer Workshop: Renewable Natural Gas—Driving Value for Natural Gas and Biogas Sectors. https://www.epa.gov/sites/production/files/2017-10/documents/lucas_rng_2017_panel1.pdf. Figure used with permission from Southern California Gas Company.

Example: Policies and Incentives in Washington

On March 22, 2018, the Governor of Washington signed House Bill 2580, "Promoting Renewable Natural Gas."[91] This established a voluntary program that encourages increased production of RNG through tax incentives and tools, including an inventory of potential RNG supply and associated costs. The legislation also directed relevant state agencies and regulatory bodies to establish voluntary gas quality standards for injection of RNG into the natural gas system, and policy recommendations to promote RNG development. The Washington State Department of Commerce and Washington State University's Energy Program, an LMOP State Partner, jointly provided a study to the legislature in December 2018, with an inventory of RNG opportunities and information on economics and policies related to RNG project development within the state.[92]

Example: Gas Quality Standards at a State Level

Illinois set standards in the mid-1980s for transportation of natural gas, including CH_4 from landfills. The gas must meet the standards implemented by the Illinois Commerce Commission before it may be placed into the public utility gas system.[93]

Missouri has historical quality standards for natural gas that are applicable to all gases being furnished by a utility that falls under the jurisdiction of the Missouri Public Service Commission.[94] This standard was established before "RNG" was a common term, but RNG is included because the standard is applicable to all gas distributed in the state.

Example: Gas Quality Standards at the Utility Level

The Coalition for Renewable Natural Gas tracks gas quality specifications for more than 40 major transmission gas pipeline operators in the United States, with links to their tariffs.[95]

Example: Interconnect Guide for RNG in Northeastern States

In September 2019, the Northeast Gas Association and the Gas Technology Institute published a guide to provide a technical framework for introducing RNG into the natural gas distribution pipeline network in parts of the northeastern United States. Although basic criteria had been established for alternative gases including RNG, inconsistent approaches to evaluating acceptance criteria and trace constituent composition had proven to be a barrier to wide-scale acceptance of RNG directly into distribution networks. The guide was written to maximize acceptance of this valuable energy resource, by minimizing technical uncertainty and better quantifying potential risks, without compromising public safety and

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91 Washington State Legislature. Bill Information: HB 2580—2017-18. https://app.leg.wa.gov/billsummary?BillNumber=2580&Year=2017. Accessed March 27, 2019.

92 Washington State Department of Commerce and Washington State University Energy Program. December 2018. Promoting Renewable Natural Gas in Washington State. http://www.commerce.wa.gov/wp-content/uploads/2019/01/Energy-Promoting-RNG-in-Washington-State.pdf.

93 Illinois Public Utility Commission. 1987. Safety and Quality Standards for Gas Transportation for a Private Energy Entity by Gas Utilities. Section 530.10: Standards. http://www.ilga.gov/commission/jcar/admincode/083/08300530sections.html. Accessed March 27, 2019.

94 Missouri Public Service Commission. 2019. Rules of Department of Economic Development: Division 240—Public Service Commission. Chapter 10—Utilities. Standards of Quality. 4 CSR 240-10.30. https://www.sos.mo.gov/cmsimages/adrules/csr/current/4csr/4c240-10.pdf.

95 Coalition for Renewable Natural Gas. Major Transmission Pipeline Tariffs. http://www.rngcoalition.com/pipeline-database. Accessed April 3, 2019.

facility integrity. The guideline also addresses current challenges to RNG injection through the following objectives:[96]

- Provide a consistent approach for assessing project viability.
- Define requirements to avoid interruption of service.
- Provide a standardized framework to reduce uncertainty and optimize design.
- Outline structure for the RNG development process.
- List roles and responsibilities for each party.

The guideline includes helpful elements such as a process flow diagram, checklists, proposed biogas constituent sampling plans, a list of technical references and a sample interconnect agreement.

8.5 Policies and Incentives Related to Use of RNG as Transportation Fuel

Federal

The federal RFS requires obligated parties to meet a Renewable Volume Obligation based on the amount of petroleum-based fuels they produce or import annually; one way to meet the Renewable Volume Obligation is by obtaining tradeable credits known as RINs, which are issued to producers of renewable fuels. To generate RINs, a fuel must meet one of the EPA-approved pathways. RNG can fall under two different RIN categories based on the biogas source:

- D3, the category for biogas from landfills, municipal wastewater treatment facility digesters, agricultural digesters, and separated MSW digesters; and biogas from the cellulosic components of biomass processed in other waste digesters.

- D5, the category for biogas from waste digesters (e.g., organic fraction of municipal solid waste or food waste).

State-Specific LCFSs

California's LCFS was designed to encourage the use and production of cleaner low-carbon fuels in the state. The LCFS sets CI targets that transportation fuel providers in the state must meet each year. The CI targets decrease over time, which results in a higher percentage of lower CI fuels (e.g., natural gas, RNG, hydrogen, electricity) in the fuel mix. The LCFS parameters are expressed in terms of the CI of gasoline and diesel and the fuels that replace them. A fuel's CI is the measure of GHG emissions associated with producing and consuming it and is based on a complete life cycle analysis. Fuels with CIs lower than the annual standard set by the LCFS generate credits, while fuels with higher CIs generate deficits. The LCFS includes various fuel pathways, including for RNG made from the various feedstocks of anaerobic digester biogas or LFG.[97]

Oregon's Clean Fuels Program seeks to reduce the CI of transportation fuels in Oregon. It functions very similarly to California's LCFS and also includes approved pathways for RNG made from AD biogas or LFG

96 Northeast Gas Association and Gas Technology Institute. August 2019. Interconnect Guide for Renewable Natural Gas (RNG) in New York State. https://www.northeastgas.org/pdf/nga_gti_interconnect_0919.pdf.

97 California Low Carbon Fuel Standard, California Code of Regulations, Title 17, Sections 95480–95489; 95491–95497. https://www.arb.ca.gov/regact/2015/lcfs2015/lcfsfinalregorder.pdf.

as the feedstock.[98] The CFP includes standards for gasoline and its fuel substitutes and diesel and its fuel substitutes.

National Ambient Air Quality Standards

Local jurisdictions that are unable to meet EPA-established National Ambient Air Quality Standards must develop strategies to attain the standards, including a timeline to achieve compliance. In urban areas of non-attainment for ozone and PM, transportation-related emission reduction strategies must be part of the solution. Replacing heavy-duty diesel vehicles with natural gas vehicles running on RNG provides near-zero emissions of NO_X and serves as a low-carbon alternative. This can be an important part of the implementation plan for these urban centers to achieve attainment.

Municipal Natural Gas Fleet Conversion

Municipal vehicle fleets—especially transit buses and refuse trucks—are often among the largest fuel consumers in a city. Many U.S. cities have committed to reducing the petroleum dependency of their fleets by replacing their existing fleets with vehicles that run on alternative fuel, including RNG. In 2016, eight major cities (Atlanta, Charlotte, Indianapolis, Orlando, Rochester, Sacramento, San Diego and West Palm Beach) formed the Energy Secure Cities Coalition, with a combined goal of replacing 50,000 petroleum-fueled vehicles with alternative-fueled vehicles by 2025.[99]

In addition to city-owned fleet upgrades, other municipalities have built CNG fleet requirements into their franchise agreements with third-party waste haulers that operate within their jurisdiction to achieve greener fleets. For example, in Seminole County, Florida, two waste haulers that cover approximately 65,000 homes are required to replace their diesel trucks with CNG vehicles by the end of 2020.[100] The EPA Managing and Transforming Waste Streams Tool has sample franchise agreement language for requiring CNG or other alternative fuel vehicles.[101]

8.6 State Regulatory Policies and Incentives Related to Electricity

While power prices have been relatively low and are forecasted to remain low for the foreseeable future, some state RPS programs have renewable energy certificates (RECs) that are favorable to RNG derived from biogas.

In 2018 legislation, California adopted an updated and aggressive RPS under SB 100. The RPS now requires 60 percent renewables-sourced electricity by 2030 and 100 percent carbon-free electricity by 2045. RNG is eligible to generate RECs if certified by the California Energy Commission (CEC) but Assembly Bill 2196

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98 Oregon Department of Environmental Quality. Fuel Pathways—Carbon Intensity Values. https://www.oregon.gov/deq/ghgp/cfp/Pages/Clean-Fuel-Pathways.aspx. Accessed December 23, 2020.

99 Securing America's Future Energy. March 2016. Eight Major Cities Unite to Form Energy Secure Cities Coalition—Fleets Embracing Alternative Fuels to Improve America's National and Economic Security. https://archive.secureenergy.org/press/eight-major-cities-unite-to-form-energy-secure-cities-coalition-fleets-embracing-alternative-fuels-to-improve-americas-national-and-economic-security/.

100 Comas, M.E. July 2017. Seminole Switching to Natural-Gas Garbage Trucks. Orlando Sentinel. http://www.orlandosentinel.com/news/seminole/os-seminole-county-waste-natural-gas-20170727-story.html.

101 U.S. EPA. Managing and Transforming Waste Streams—A Tool for Communities. https://www.epa.gov/transforming-waste-tool/local-government-clauses-transforming-waste-streams-communities#purchasing. Accessed July 22, 2019.

in 2012 reduced reliance on non-California RNG for the purposes of RPS compliance; this provides additional incentive for potential RNG producers located in California.[102]

California's SB 1122 created the Bioenergy Market Adjusting Tariff, which offers eligible small bioenergy renewable generators the opportunity to export electricity to the state's three large investor-owned utilities through a fixed-price standard contract. Category 1 covers biogas from WRRFs, municipal organic waste diversion, food processing and co-digestion, while category 2 covers dairy and other agricultural bioenergy. This has created an opportunity for smaller biogas projects (less than 3 megawatts) to receive long-term PPAs.[103]

The North Carolina RPS, whose targets are not as aggressive as California's, has an animal waste carve-out that is driving investment in manure-based RNG-to-electricity projects. As a result, these RNG projects can negotiate for long-term PPAs to help utilities achieve the mandated RPS targets. Swine waste carve-outs constituted 0.07 percent of prior year retail sales in 2017, constituted 0.14 percent of prior year retail sales in 2019 and will constitute 0.20 percent of prior year retail sales by 2022.[104] See Section 9.0 for a cluster project example in Missouri that is being used to satisfy North Carolina RPS requirements.

As of April 2020, 30 states, Washington, D.C., and three territories had an RPS for electricity; seven states and one territory had a Renewable Portfolio Goal for electricity; three states had a Clean Energy Standard; and two states had a Clean Energy Goal.[105,106]

8.7 Policies and Incentives Related to Sustainability and Environmental Goals

Limited incentives and policy drivers are currently available to direct thermal end uses of RNG, but some state and local voluntary programs are emerging. Additionally, corporate sustainability goals create demand for RNG, including goals that involve carbon footprint reductions or other types of emission reductions.

More than 20 states are initiating economy-wide GHG targets, setting long-term goals and implementing policies to achieve GHG reductions.[107] As these policies are implemented, they can affect all industries operating in the state, including local distribution companies. As a result, these companies are searching for lower-carbon feedstocks to reduce their carbon footprint.

Much like a consumer would pay to participate in a voluntary green power program at their local electric utility, consumers in Pennsylvania now have an option to purchase a credit for RNG sourced from LFG. The Energy Co-op in Pennsylvania has offered voluntary Renewable Natural Gas Credits in partnership

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[102] Ingram, W. October 2017. Reducing Methane Emissions from California's Wastes. Presented at US Biogas 2017.

[103] CPUC. Bioenergy Feed-in Tariff Program (SB 1122). http://www.cpuc.ca.gov/SB_1122/. Accessed March 25, 2019.

[104] Payne, T., and B. Gale. September 2017. Roeslein Alternative Energy & Duke Energy—Missouri Swine Waste Green Gas Project. https://www.epa.gov/natural-gas-star-program/duke-energy-rng-green-electricity-livestock-waste-missouri-and-north. Accessed April 3, 2019.

[105] NC Clean Energy Technology Center. Database of State Incentives for Renewables & Efficiency. Renewable & Clean Energy Standards (map). http://www.dsireusa.org/resources/detailed-summary-maps/. Accessed March 9, 2020.

[106] National Conference of State Legislatures. April 2020. State Renewable Portfolio Standards and Goals. https://www.ncsl.org/research/energy/renewable-portfolio-standards.aspx. Accessed June 25, 2020.

[107] M.J. Bradley & Associates. April 2017. Renewable Natural Gas. The RNG Opportunity for Natural Gas Utilities. https://mjbradley.com/reports/renewable-natural-gas-rng-opportunity-natural-gas-utilities.

with PECO, the local gas utility, since 2016.[108] Vermont Gas launched a similar program in 2017,[109] and as of 2019, efforts were underway in California, New York and Minnesota. Similarly, FortisBC in Canada has offered a voluntary RNG program since 2011 that allows customers to pay a premium to increase the blend of RNG into their natural gas supply.[110] There are a variety of brokers to help certify that the RNG volume sold through a voluntary utility program matches the quantity of RNG injected into its system. Customers pay a higher gas supply rate depending on their selected RNG percentage.

In March 2019, SoCalGas in California announced a plan to replace 5 percent of its fossil natural gas supply with RNG by 2022 and 20 percent by 2030, as part of the company's vision to be the "cleanest natural gas utility in North America." Toward this goal, SoCalGas filed a request with the CPUC to allow its residential and small commercial/industrial customers the option to purchase RNG. Customers who choose to participate would select from a range of dollar amounts or a percentage of total gas usage (for commercial customers), and their monthly gas bill would have a line item showing the extra cost. A settlement agreement was filed with CPUC in April 2020 which provided some updated functions of this RNG tariff program, and CPUC was expected to make a decision on the program later in 2020.[111,112,113,114]

The Midwest Renewable Energy Tracking System (M-RETS) is a web-based system used by power generators, utilities, marketers and qualified reporting entities to track and retire RECs generated under RPSs and other environmental credit systems. In 2019, M-RETS began adapting its software to meet the needs of emerging voluntary programs for thermal energy credits, which were anticipated based on corporate sustainability goals and commitments. M-RETS launched its platform to track renewable thermal certificates in January 2020.[115]

Many corporations and local governments are developing their own GHG emission inventories and incorporating the results into sustainability plans for reducing their carbon footprints and potentially even becoming carbon neutral. Carbon neutrality is when an emitter reduces its carbon footprint to zero through various measures, including emission reduction projects.[116] One standard that corporations use

108 The Energy Co-op. Renewable Natural Gas. https://www.theenergy.coop/services-we-offer/natural-gas/. Accessed March 25, 2019.

109 Vermont Gas. VGS Renewable Natural Gas. https://www.vermontgas.com/renewablenaturalgas/. Accessed July 23, 2019.

110 FortisBC. Renewable Natural Gas. https://www.fortisbc.com/services/sustainable-energy-options/renewable-natural-gas. Accessed March 25, 2019.

111 Sempra Energy. February 2019. SoCalGas Seeks to Offer Renewable Natural Gas to Customers. https://www.sempra.com/socalgas-seeks-offer-renewable-natural-gas-customers. Accessed October 4, 2019.

112 Sempra Energy. March 2019. SoCalGas Announces Vision to Be Cleanest Natural Gas Utility. https://www.sempra.com/newsroom/spotlight-articles/socalgas-announces-vision-be-cleanest-natural-gas-utility. Accessed October 4, 2019.

113 Paulson, L. California Energy Markets. April 2020. SoCal Gas RNG Tariff Filed With CPUC. https://www.newsdata.com/california_energy_markets/regulation_status/socal-gas-rng-tariff-filed-with-cpuc/article_b130e2dc-8664-11ea-8c42-33938bdf0f9b.html. Accessed June 24, 2020.

114 SoCalGas. June 12, 2020. RNG Tariff Overview. https://docs.cpuc.ca.gov/PublishedDocs/Efile/G000/M340/K738/340738713.PDF.

115 U.S. Gain. January 2020. US Gain to provide RNG through new M-RETS RTC platform. Biomass Magazine. http://biomassmagazine.com/articles/16783/us-gain-to-provide-rng-through-new-m-rets-rtc-platform. Accessed February 20, 2020.

116 Natural Capital Partners. CarbonNeutral Protocol. https://www.carbonneutral.com/the-carbonneutral-protocol. Accessed April 15, 2019.

to help determine their carbon footprint is *The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard*[117] which categorizes emissions into three areas:

- Scope 1 emissions are direct GHG emissions from sources that are owned or controlled by the company.
- Scope 2 emissions are GHG emissions from the generation of purchased electricity that the company consumes.
- Scope 3 emissions are all other indirect GHG emissions that are a result of the company's activities where the company neither owns nor controls the source (reduction of Scope 3 emissions is considered optional for reaching carbon neutrality).

One avenue to reduce Scope 1 emissions is a "directed biogas" wherein the end user extracts an amount of natural gas from the pipeline that is equivalent to the amount of RNG injected into the pipeline from the project. The exact RNG molecules are not necessarily delivered to the end user, but the same amount of fuel is used.[118]

117 World Resources Institute and World Business Council for Sustainable Development. The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard. https://ghgprotocol.org/corporate-standard. Accessed April 15, 2019.

118 Harf, J. June 2018. L'Oréal USA on Why Thermal Energy Is Key to Their Sustainability Goals. https://www.renewablethermal.org/loreal-usa-on-why-thermal-energy-is-key-to-their-sustainability-goals/. Accessed April 15, 2019.

9.0 EXAMPLES

9.1 RNG Projects with Feedstock, Delivery Method and End Use

MSW Landfills

Altamont Landfill—MSW to Vehicle Fuel (LNG)	
Location:	Alameda County, California
RNG Start Year:	2009
Description:	There is only one known currently operating onsite LFG-to-LNG project in the United States, which is at the Altamont Landfill.[119] Since the LNG plant started up in 2009, Waste Management and Linde have displaced 2.5 million gallons of diesel fuel per year by producing up to 13,000 gallons of LNG per day, enough to fuel 300 garbage trucks. The landfill also produces enough electricity from LFG to power the LNG plant and about 8,000 homes per year.[120]

Greentree Landfill—MSW to Pipeline-Injected RNG for Electricity	
Location:	Kersey, Pennsylvania
RNG Start Year:	2007
Description:	The project developed at Greentree Landfill employs membrane, PSA and activated carbon technologies to upgrade approximately 8.4 mmscfd of LFG into RNG (plant capacity is about 15 mmscfd of raw LFG). A dedicated 7-mile pipeline delivers the RNG to the National Fuel Gas interstate pipeline network; the project is expected to produce more than 2 billion cubic feet of RNG per year. Ultimately, through a series of gas sales contracts, the RNG is being used in combined cycle equipment to generate renewable electricity and RECs.[121]

119 U.S. EPA. 2010. Altamont Landfill Gas to Liquefied Natural Gas Project. https://www.epa.gov/lmop/landfill-gas-energy-project-data#altamont. Accessed April 1, 2019.

120 Waste Management, "Case Study: Altamont Landfill and Resource Recovery Facility". https://www.wm.com/documents/pdfs-for-services-section/Case-studies-municipal/PSS_CsStdyAltamLndfllREVISE_rFjjg.pdf.

121 2007 EPA LMOP Project of the Year Award Application. Greentree High Btu Landfill Gas Project. November 2007.

Rodefeld Landfill—MSW and Manure to Pipeline-Injected RNG to Vehicle Fuel	
Location:	Madison, Wisconsin
RNG Start Year:	2011/2019
Description:	Dane County, Wisconsin, has been creating vehicle fuel from LFG on site since 2011 (and generating electricity before that), but completed a new project in 2019 to inject RNG into ANR-TransCanada's natural gas interstate transmission pipeline for use at regional CNG fueling stations. As part of this effort, the County built an off-loading station to allow other biogas plants (including manure-based AD facilities) in the area that convert their gas into RNG to truck their RNG to this station (for a small fee) to tap into the pipeline connection. The project is expected to displace at least 3 million gallons of fossil fuels during the first 12 months of operation.[122]

St. Landry Parish Landfill—MSW to Vehicle Fuel (CNG)	
Location:	St. Landry Parish, Louisiana
RNG Start Year:	2012
Description:	St. Landry Parish, in conjunction with BioCNG, developed a multiphase onsite LFG conditioning and CNG fueling system and an offsite virtual pipeline RNG station. The initial project phase started in 2012, processing 50 scfm of LFG to produce up to 210 GGE of CNG per day for the Parish's use. About three years later, the Parish entered into an agreement with a private waste hauler to fuel its fleet of refuse hauling trucks and constructed a 100-cfm gas conditioning system that produced an additional 420 GGE of vehicle fuel. The Parish added a tube trailer filling system at the landfill, and constructed an offsite RNG trailer off-loading decant panel and a CNG fueling station with natural gas back-up.[123,124]

122 Voegele, E. May 2019. Dane County, Wisconsin, celebrates the opening of RNG project. http://biomassmagazine.com/articles/16126/dane-county-wisconsin-celebrates-the-opening-of-rng-project. Accessed July 22, 2019.

123 Tetra Tech. St. Landry Parish Landfill Biogas Expansion Project, Louisiana. http://www.tetratech.com/en/projects/st-landry-parish-landfill-biogas-expansion-project-louisiana. Accessed March 28, 2019.

124 Wittmann, S. May 2016. Not Stopping at First. Renewable Energy From Waste (May/June). http://www.unisonsolutions.com/wp-content/uploads/2016/07/St-Landry_REWmag-May-June-2016.pdf.

Municipal WRRFs

Janesville WRRF—Sewage Sludge to Vehicle Fuel (CNG)	
Location:	Janesville, Wisconsin
RNG Start Year:	2012
Description:	Janesville has the first community-scale WRRF in the country to fuel public fleet vehicles with CNG produced from biogas on site. [125] The city has digested biosolids since 1970 and generated electricity from biogas since 1985.[126] In 2010, the WRRF began implementing upgrades to further treat a portion of the biogas and also start co-digesting industrial organic wastes. In June 2012, the city began fueling about 10 CNG municipal vehicles with plans to increase that number to 40 vehicles in the future.[127] The WRRF processes about 18 MGD of wastewater, generates 140 cfm of biogas (of which 50 cfm is used to create CNG) at 62 percent CH_4, and has a maximum fuel production capacity of 275 GGE per day.[128]

Newtown Creek WRRF—Sewage Sludge to Pipeline-Injected RNG	
Location:	New York City, New York
RNG Start Year:	2020 (expected)
Description:	The Newtown Creek WRRF is the largest WRRF in New York City, treating up to 310 million gallons of wastewater on an average day and producing more than 500 million cubic feet of biogas per year from eight digesters that together can hold a total of 24 million gallons of sludge.[129] About 40 percent of the biogas is used in boilers to provide heat for the digesters and other buildings, with the remaining 60 percent being flared. Since at least 2014, the city has been exploring the use of excess biogas to create RNG,[130] and as of March 2019, plans were underway to inject RNG into the National Grid pipeline distribution system for residential and commercial consumption.[131] The facility is anticipated to provide enough RNG to heat 2,500 homes and may co-digest an organic slurry from food waste to boost biogas production.[132]

125 Energy Vision. 2013. Turning Waste into Vehicle Fuel: Renewable Natural Gas (RNG). A Step-by-Step Guide for Communities. https://energy-vision.org/ev-publications/EV-RNG-Community-Guide.pdf.

126 U.S. DOE Midwest CHP Technical Assistance Partnership. Janesville Wastewater Treatment Plant. https://chptap.lbl.gov/profile/109/JanesvilleWWT-Project_Profile.pdf.

127 Energy Vision. 2013. Turning Waste into Vehicle Fuel: Renewable Natural Gas (RNG). A Step-by-Step Guide for Communities. https://energy-vision.org/ev-publications/EV-RNG-Community-Guide.pdf.

128 BioCNG. Fact Sheet: City of Janesville Wastewater Treatment Plant. http://biocng.us/wp-content/uploads/2015/06/Janesville-Fact-Sheet-2015.pdf.

129 Siegel, N. January 2018. October Tour Recap: Newtown Creek Wastewater Treatment Plant. GreenHomeNYC. https://greenhomenyc.org/blog/october-tour-recap-newtown-creek-wastewater-treatment-plant/. Accessed April 1, 2019.

130 NYC Environmental Protection. December 2013. City Announces Innovative New Partnerships That Will Reduce the Amount of Organic Waste Sent to Landfills, Produce a Reliable Source of Clean Energy and Improve Air Quality. https://www1.nyc.gov/html/dep/html/press_releases/13-121pr.shtml#.XKJaTqR7lEZ. Accessed April 1, 2019.

131 Neighbour, D., and G. Zwicker. March 2019. What China Can Learn from New York City about Wastewater Management. Scientific American. https://blogs.scientificamerican.com/observations/what-china-can-learn-from-new-york-city-about-wastewater-management/. Accessed April 1, 2019.

132 Chahbazpour, D. September 2017. National Grid—Newtown Creek Renewable Gas Demonstration. Presented at EPA Technology Transfer Workshop: Renewable Natural Gas—Driving Value for Natural Gas and Biogas Sectors. https://www.epa.gov/natural-gas-star-program/renewable-natural-gas-driving-value-natural-gas-and-biogas-sectors-workshop.

Point Loma WRRF—Sewage Sludge to Pipeline-Injected RNG for Electricity	
Location:	San Diego, California
RNG Start Year:	2012
Description:	BioFuels Energy, LLC, financed, built and operates the RNG production facility at the Point Loma Wastewater Treatment Facility. The facility can process up to 1.6 mmscfd of biogas generated from eight digesters. [133] BioFuels Energy cleans the biogas to San Diego Gas & Electric's pipeline gas specifications, and after injection into the pipeline system, the RNG is "directed" to fuel cells at two customers: University of California–San Diego (2.8 megawatts) and City of San Diego South Bay Water Reclamation Plant (1.4 megawatts).[134] This process uses existing pipelines and increases the options for biogas usage. This project was the first in California to inject RNG into a natural gas pipeline.[135]

San Antonio Water System (SAWS)—Sewage Sludge to Pipeline-Injected RNG	
Location:	Bexar County, Texas
RNG Start Year:	2010
Description:	SAWS partnered with Ameresco to produce biogas by adding a new biosolids AD process to its facility. In 2010, Ameresco began processing more than 1.5 mmscfd of biogas at 60 percent CH_4 to deliver at least 900,000 cubic feet of RNG per day to a nearby fossil natural gas pipeline for sale on the open market. In addition to offsetting the use of fossil natural gas, SAWS receives approximately $200,000 in royalties annually from the sale of the biogas, which helps keep its rates reasonable.[136,137]

133 BioFuels Energy, LLC. Projects. Biogas Projects. https://biofuelsenergyllc.com/projects. Accessed March 13, 2020.

134 Mazanec, F.. BioFuels Energy, LLC. October 2016. Turning Waste Into Renewable Natural Gas: Point Loma Wastewater Treatment Plant Case Study—Five Years After Commercial Operation. https://www.socalgas.com/1443740098116/Biogas-to-RNG-at-Point-Loma-Wastewater-Treatment-Facility.pdf.

135 Argonne National Laboratory. August 2017. Waste-to-Fuel: A Case Study of Converting Food Waste to Renewable Natural Gas as a Transportation Fuel. ANL/ESD-17/9. https://afdc.energy.gov/files/u/publication/waste_to_fuel.pdf.

136 San Antonio Water System. Biogas. https://www.saws.org/your-water/water-recycling/biogas/. Accessed March 13, 2020.

137 Ameresco. 2017. Case Study: San Antonio Water System, TX. http://www.ameresco.com/wp-content/uploads/2017/11/san-antonio-water-system-tx.pdf.

Livestock Farms

Hilarides Dairy—Manure to Vehicle Fuel (CNG)	
Location:	Tulare County, California
RNG Start Year:	2009
Description:	Hilarides Dairy is a family-run dairy that has been digesting manure from more than 9,000 cows in a covered lagoon digester since December 2004.[138] Part of the 226,000 cubic feet of biogas produced per day in 2017 produced CNG to fuel two heavy-duty milk trucks and six on-farm pickup trucks, displacing 230,000 gallons of diesel annually.[139] When Hilarides began cleaning and compressing its biogas for vehicle fuel in early 2009, it became the first dairy in the United States to do so. The dairy also continues to generate electricity from about two-thirds of the generated biogas.[140,141]

Roeslein Cluster Project—Manure to Pipeline-Injected RNG to Electricity and Vehicle Fuel	
Location:	Missouri
RNG Start Year:	2016
Description:	The North Carolina RPS includes a carve-out for renewable energy from animal waste (poultry and swine), and a utility can meet a portion of the targets through out-of-state purchases. Duke Energy opted to incorporate RNG from manure-based digesters in Missouri to meet its North Carolina RPS obligations, agreeing to purchase one-third of the RNG from a cluster project of nine farms through a 10-year PPA. Roeslein Alternative Energy's RNG production will be built out in phases through 2020; three of the farms were producing RNG as of 2018. The Ruckman Farm began processing 1,350 cfm of biogas using a PSA system in June 2016, injecting the RNG into the American Natural Resources gas pipeline. Locust Ridge Farm and Valley View Farm use membrane systems to process about 400 scfm of biogas each and truck their RNG via a virtual pipeline to the interconnection point at Ruckman Farm. One of Duke's combined cycle power plants in the Southeast pulls the appropriate amount of gas from the local pipeline to generate electricity. Beyond its obligations to Duke, this project also sells excess RNG into the vehicle fuel market.[142,143,144]

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Stand-Alone Organic Waste Management Operations

Blue Line Biogenic CNG Facility—Organic Waste to Vehicle Fuel (CNG)	
Location:	South San Francisco, California
RNG Start Year:	2014
Description:	South San Francisco Scavenger Company (SSFSC) and Blue Line Transfer developed this dry AD system with eight modular AD tunnels and a total processing capacity of 11,200 tons per year. The green waste and food waste feedstocks are collected from commercial and residential (approximately 20,000 households) customers. The project is producing between 380 and 500 diesel gallon equivalents of RNG per day, which fuel 34 CNG vehicles owned by SSFSC. The trucks are filled every weeknight using a slow fill system that provides a mix of CNG from RNG and fossil natural gas, but on weekends the trucks receive renewable CNG only. SSFSC is selling D5 RINs and carbon credits under California's LCFS.[145,146]

CR&R AD Facility—Organic Waste to Pipeline-Injected RNG for Vehicle Fuel (CNG)	
Location:	Perris, California
RNG Start Year:	2016
Description:	CR&R Environmental Services' AD project uses residential and commercial green (yard) and food waste feedstocks, with an initial maximum capacity of 83,600 tons per year (three more phases will follow at a capacity of 83,600 tons each). The system was designed to also accept other types of organic waste including solid and liquid food waste.[147] At full build-out, the facility will be able to convert about 334,000 tons of waste per year into 4 million diesel gallon equivalents of RNG and 250,000 tons of fertilizer.[148] In 2017, the biogas produced was cleaned and compressed into CNG for use by 75 CR&R refuse trucks, but in 2018 CR&R began injecting all the RNG into the SoCalGas fossil natural gas system via a newly built 1.4-mile pipeline, becoming the first RNG project in California to do so. CR&R now pulls the RNG back out of the pipeline to compress it for its vehicles. [149,150] In late 2018, the facility's LCFS application was approved with its requested CI.[151]

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9.2 Corporate Alternative Fuel Fleets

Corporate sustainability goals are also driving a shift from diesel-based fleets to natural gas-based fleets.

Waste Management, Inc.—CNG and LNG

Waste Management has set a goal to reduce fleet emissions by 45 percent by 2038, as compared to a 2010 baseline, by transitioning 90 percent of its fleet from diesel to alternative fuel vehicles. At the end of 2017, Waste Management had more than 32,000 fleet vehicles overall, including more than 6,500 running on some form of natural gas and 33 percent of those natural gas vehicles fueled by an RNG source. All of the company's fleet operating in California, Oregon and Washington runs on RNG-sourced fuel.[152] Two examples of Waste Management-owned landfills that produce RNG vehicle fuel are the Altamont Landfill (California), with a renewable LNG facility that fueled 170 of the company's waste trucks in 2017, and the Outer Loop Landfill (Kentucky), which produces enough CNG to fuel approximately 800 vehicles.[153]

United Parcel Service (UPS)—CNG and LNG

UPS has 51 natural gas fueling stations across the country (including six new CNG stations in 2017) and a fleet of more than 5,200 natural gas vehicles (including 450 purchased during 2017). During 2017, UPS used more than 15 million gallons of vehicle fuel from RNG in its fleet, an increase from 4.6 million gallons in 2016. In the same year, UPS signed two new agreements to purchase 1.5 million gallons of RNG per year from Fair Oaks Dairy in Indiana and 10 million gallons of RNG per year from Big Ox Energy, based in Wisconsin.[154,155] In 2019, UPS announced the company will purchase a total of 170 million gallon equivalents of RNG from Clean Energy Fuels Corp. through 2026 for use at 18 of its stations in 12 states. This decision is part of UPS' goal to have alternative fuel make up 40 percent of its total ground fuel purchases by 2025 and reduce its ground fleet's GHG emissions by 12 percent by 2025.[156]

152 Waste Management. 2018. Driving Change. 2018 Sustainability Report. http://www.wm.com/sustainability/pdfs/WasteManagement_SustainabilityReport_2018.pdf.

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10.0 RESOURCES

Hyperlinked Resource	Organization
Alternative Fuels Data Center	U.S. DOE
AD webpage	U.S. EPA
AD Facilities Processing Food Waste in the United States: Survey Results	U.S. EPA
Biogas Toolkit	U.S. EPA
Gas Quality Database (information from major transmission pipeline tariffs)	The Coalition for Renewable Natural Gas
Interconnect Guide for RNG in New York State	Northeast Gas Association; Gas Technology Institute
Landfill and LFG Energy Project Database	U.S. EPA LMOP
LFG Energy Project Development Handbook	U.S. EPA LMOP
Livestock Anaerobic Digester Database	U.S. EPA AgSTAR
Managing and Transforming Waste Streams: A Tool for Communities	U.S. EPA
Renewable thermal credit tracking system	M-RETS
RIN Calculator	American Biogas Council
RNG Database	Argonne National Laboratory
RNG Flow Rate Estimation Tool	U.S. EPA LMOP
RNG Project Map	U.S. EPA LMOP / AgSTAR
RNG Tool Kit	SoCalGas
RNG webpage	U.S. EPA LMOP
WRRF “phase 1” database	Water Environment Federation

11.0 ABBREVIATIONS, ACRONYMS AND UNITS OF MEASURE

AD	anaerobic digestion
AFLEET	Alternative Fuel Life-Cycle Environmental and Economic Transportation
Btu	British thermal unit
CARB	California Air Resources Board
CEC	California Energy Commission
cfm	cubic feet per minute
CH_4	methane
CI	carbon intensity
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
CPUC	California Public Utilities Commission
DOE	U.S. Department of Energy
g CO_2e/MJ	grams of CO_2 equivalent per megajoule
GGE	gasoline gallon equivalents
GHG	greenhouse gas
H_2S	hydrogen sulfide
LCFS	Low Carbon Fuel Standard
LFG	landfill gas
LMOP	U.S. EPA Landfill Methane Outreach Program
LNG	liquefied natural gas
M-RETS	Midwest Renewable Energy Tracking System
mg/m^3	milligrams per cubic meter
MGD	million gallons per day
mmscfd	million standard cubic feet per day
MSW	municipal solid waste
N_2	nitrogen
NO_X	nitrogen oxide

O_2	oxygen
PM	particulate matter
PPA	power purchase agreement
PSA	pressure swing adsorption
psig	pound-force per square inch gauge
REC	renewable energy certificate
RIN	Renewable Identification Number
RFS	Renewable Fuel Standard
RNG	renewable natural gas
RPS	Renewable Portfolio Standard
SAE J1616	Society of Automotive Engineers *Surface Vehicle Recommended Practice J1616™ for Compressed Natural Gas Vehicle Fuel*
SAWS	San Antonio Water System
SB	Senate bill
scf	standard cubic foot
scfm	standard cubic feet per minute
SoCalGas	Southern California Gas Company
SO_X	sulfur dioxide
SSFSC	South San Francisco Scavenger Company
UPS	United Parcel Service
VOC	volatile organic compound
WEF	Water Environment Federation
WRRF	water resource recovery facility

Appendix A: Natural Gas Companies Accepting RNG into Pipelines

Company Name and Website	State(s) where RNG is Injected	Feedstock(s)[1]	Company Information about RNG	Company's Pipeline Interconnection Standard / Tariff / Similar
Enterprise Pipeline	Texas	LF		
Equitrans Midstream	Pennsylvania	LF		Equitrans, L.P. FERC Gas Tariff
Four-S Oil Company	Texas	LF		
Fremont Department of Utilities Gas Distribution	Nebraska	WW		
General Gas Pipeline, LLC	Tennessee	LF		
Great Lakes Gas Transmission Company	Michigan	LF		Great Lakes Gas Transmission Tariff
Gulf South Pipeline	Louisiana, Texas	LF		Gulf South Pipeline Company Tariff
Hawaii Gas Transmission and Distribution	Hawaii	WW	Hawaii Gas RNG page	
Houston Pipe Line Company	Texas	LF		Houston Pipe Line Company Gas Quality Specifications
Kinder Morgan	Arizona, Mississippi, Oklahoma, Texas	LF, WW		Kinder Morgan Tariffs page
Memphis Light, Gas and Water (MLGW)	Tennessee	LF		
Metropolitan Utilities District of Omaha	Nebraska	LF		
Montana-Dakota Utilities Co.	Montana	LF		Montana-Dakota Utilities - Rates and Tariffs
Mountaineer Gas Company	West Virginia	LF		Mountaineer Gas Company - Rates and Tariffs
National Fuel Gas	Pennsylvania	LF	National Fuel Gas Distribution Corporation Gas Transportation Operating Procedures Manual	National Fuel PA Regulatory, Tariff and GTOP

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Company Name and Website	State(s) where RNG is Injected	Feedstock(s)[1]	Company Information about RNG	Company's Pipeline Interconnection Standard / Tariff / Similar
National Gas & Oil Cooperative	Ohio	WW		
National Grid	New York	LF, WW	Renewable Gas - Vision for a Sustainable Gas Network	National Grid - Service Rates
Northern Indiana Public Service Company (NIPSCO)	Indiana	Ag		NIPSCO Rate for Gas Service Renewable Gas Balancing Service
Northern Natural Gas	Kansas, Nebraska, Wisconsin	Ag, WW		Northern Natural Gas Tariff page
NW Natural	Oregon	WW	NW Natural RNG page	NW Natural Oregon Tariff Book
Pacific Gas and Electric Company (PG&E)	California	Ag	PG&E Interconnecting biomethane suppply page	PG&E Tariffs page
Panhandle Eastern Pipe Line Company	Kansas	LF		Panhandle Eastern Pipe Line Company FERC NGA Gas Tariff page
Peoples Natural Gas	Pennsylvania	LF	Peoples Producers, Suppliers & Gas Supply page	Peoples Gas Quality Quick Reference Guide
Philadelphia Gas Works	National	LF		
Piedmont Natural Gas Company, Inc.	North Carolina	Ag		Piedmont Natural Gas Index of Tariff & Service Regulations
Puget Sound Energy	Washington	LF, WW		Puget Sound Energy Natural gas tariffs & rules page
Southern California Gas Company (SoCalGas)	California	Ag, OW, WW	SoCalGas Renewable Gas page	SoCalGas Rule No. 30 Transportation of Customer-Owned Gas
Southern Company Gas	Georgia	LF		
Southern Company Gas (Atlanta Gas Light Company)	Georgia	LF		Atlanta Gas Light Company Tariff
Southern Star Central Gas Pipeline	Kansas, Oklahoma	LF		FERC Gas Tariff of Southern Star Central Gas Pipeline, Inc.

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Company Name and Website	State(s) where RNG is Injected	Feedstock(s)[1]	Company Information about RNG	Company's Pipeline Interconnection Standard / Tariff / Similar
Summit Utilities, Inc.	Maine	Ag	Summit Announces RNG Initiative - May 2019	
Texas Gas Transmission LLC	Kentucky	LF		Texas Gas Transmission, LLC Tariff
UGI Utilities	Pennsylvania	LF		UGI Tariffs
Utica Gas Services (subsidiary of Williams Gas Pipeline)	Ohio	LF		
Vectren Energy Delivery	Ohio	LF		Vectren Rates & tariffs page
Vermont Gas	Iowa, Quebec, Vermont	Ag, LF, WW	VGS Renewable Natural Gas page	
Williams Gas Pipeline	Washington	LF		Transcontinental Gas Pipe Line Company, LLC FERC Gas Tariff
Wisconsin Public Service Corporation	Wisconsin	OW		
Xcel Energy	Colorado	WW		
XTO Energy	Oklahoma	LF		

Main Sources of Data for Inclusion of Utilities in this List

- U.S. EPA. March 2020. Landfill and LFG Energy Project Database. https://www.epa.gov/lmop/landfill-gas-energy-project-data.
- U.S. EPA. March 2020. Livestock Anaerobic Digester Database. https://www.epa.gov/agstar/livestock-anaerobic-digester-database.
- Mintz, M., P. Vos, M. Tomich, and A. Blumenthal. October 2019. Database of Renewable Natural Gas (RNG) Projects: 2019 Update. Argonne National Laboratory. https://www.anl.gov/es/reference/renewable-natural-gas-database.

[1.] **Feedstock(s) of the RNG Injected**

Ag	biogas from agricultural digester (may co-digest organic waste)
LF	landfill gas
WW	biogas from wastewater digester (may co-digest organic waste)
OW	biogas from organic waste digester (food waste and/or other organic waste types)