

# Upgrading Biogas to RNG

**Paul Greene** ▪ Montrose Environmental

Favorable policies and environmental benefits are earning renewable natural gas (RNG) market acceptance. Upgrading technologies are critical to producing RNG that is ready to serve this market.

Renewable natural gas (RNG) is primarily composed of methane, as well as trace gases, such as hydrogen sulfide, carbon dioxide, and other volatile organic compounds (VOCs). RNG feedstocks can be sourced from municipal wastewater treatment plants, large agricultural farms, solid waste landfills, and organic food waste generators. These feedstocks are processed and sealed in an anaerobic digester, where a host of bacteria convert the organic material into a biogas that is predominantly methane. The biogas is processed to remove impurities, thus upgrading the raw gas to RNG.

This article focuses on the technologies used to upgrade biogas to RNG. It also highlights the environmental benefits of RNG and the policies that are helping it to earn market acceptance.

## RNG feedstocks

*Wastewater biosolids.* Municipal wastewater treatment plants generate RNG via anaerobic digestion of biosolids from both the primary and secondary treatment processes. The digesters generate biogas that is roughly 55–60% methane and 40–45% $CO_2$, and contains hydrogen sulfide ($H_2S$), trace amounts of siloxanes, and water vapor.

*Solid landfill waste.* Landfills are a common source of biogas for RNG production. Similar to biogas from a digester, landfill gas is primarily methane, $CO_2$, $H_2S$, and water vapor. However, unlike digester gas, landfill gas often has significant quantities of oxygen and nitrogen from air drawn in via extraction wells that are used to pull the gas out of the landfill.

*Manure and farm waste.* Dairy farms and hog farms are increasingly common host sites for RNG projects. Manure from the farm is added to the digester, and the resulting biogas is upgraded to RNG. The major benefit of these applications is their potential to dramatically reduce emissions.

*Food waste.* Food waste is an attractive RNG feedstock because it can produce a high yield of gas. Manure and biosolids are highly stabilized materials, meaning that the bulk of the energy from the feedstock has already been extracted. Food waste, on the other hand, has largely yet to degrade and can yield much more biogas per pound of digester feed.

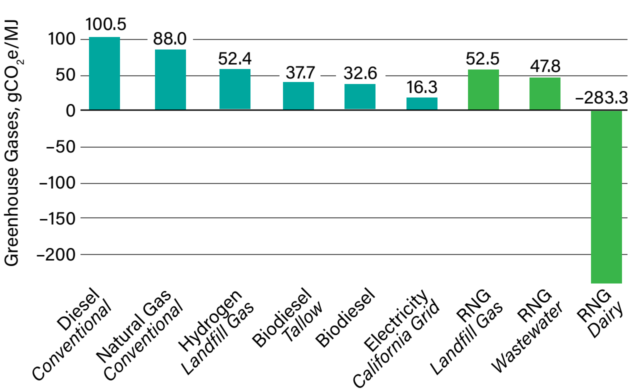
## Carbon intensity

RNG is almost identical in composition to conventional natural gas from fossil sources, but unlike fossil natural gas, it has a low carbon intensity (CI) — a measure of the grams of carbon dioxide equivalent ($CO_2e$) emitted for every megajoule (MJ) of energy produced (Figure 1) *(1)*. The value of RNG is directly connected to its CI score. CI accounts for the entire lifecycle of the fuel, so it varies depending on how the RNG was produced.

The CI score compares the greenhouse gas emissions of a site before and after the implementation of the RNG project. And, the CI takes into account all of the carbon emitted along the supply chain for that fuel, including the carbon used to explore, mine, collect, produce, transport, distribute, dispense, and burn the fuel. The value in $gCO_2e/MJ$ of energy is then adjusted for energy economy rate (EER) to produce a final EER-adjusted CI score. This EER-adjusted CI score quantifies the emissions from the use of alternative fuel per MJ of conventional fuel displaced. For comparison, a CI of 100 is assigned to liquid gasoline used as a vehicle fuel. Fuels with a CI score lower than 100 are considered environmentally friendly.

To illustrate the impact of an RNG project on CI score, consider a dairy farm that stores its cow manure in open impoundments, which are large methane emissions point sources. The operating conditions of the impoundment are anaerobic. Living organisms in the manure naturally convert volatile solids into methane-rich biogas, and the biogas is then released from the impoundment as fugitive emissions.

Should an anaerobic digester be installed at this farm, all volatile solids would instead be contained within the digester. The resulting methane gas would be captured and sent for upgrading, rather than being released as emissions. Because of the dramatic reduction in emissions, RNG produced from dairy manure can have CI values as low as –283.3 *(1)*.




▲ **Figure 1.** RNG produced from landfill gas, wastewater biosolids, and manure has much lower carbon intensity (CI) scores than conventional fossil natural gas *(1)*.

## RNG upgrading

Table 1 compares the four main technologies used to upgrade biogas to RNG: membrane separation, pressure-swing adsorption (PSA), amine scrubbing, and water wash (*i.e.,* water scrubbing). These technologies are typically deployed individually, but they are occasionally installed in series to satisfy certain purity requirements.

PSA and membrane systems are both dry upgrading systems that physically separate $CO_2$ from $CH_4$ based on molecular size, driving pressure, and ionic charge. On the other hand, water wash and amine scrubbing systems are both wet upgrading systems that separate $CO_2$ from $CH_4$ by solubilizing the $CO_2$ in a liquid solution while allowing methane to pass through.

The pole charge and size of $CO_2$ and methane molecules are key to separating them in a mixed gas stream. Carbon dioxide is composed of a central carbon with oxygen atoms bonded to each side in a somewhat linear shape. Oxygen atoms have a higher electronegativity than carbon, which causes them to hold electrons more tightly, resulting in negative charges at the oxygen ends of the molecule. Methane is composed of a central carbon with four hydrogens spaced uniformly around the center. Carbon dioxide is smaller and more polar than methane — properties that are key to both its physical and chemical separation.

## Membrane separation

Membrane separation systems use polymeric membranes to separate $CO_2$ from methane under high pressure. Membranes are long, thin fibers with a hollow center core, typically about 0.5–1 mm in diameter. As compressed biogas travels down the length of the fiber, the small, ionic $CO_2$ molecules permeate through the porous membrane, while the methane stays in the central core (Figure 2).

Thousands of membrane fibers are bundled together into 4-, 6-, or 12-in.-diameter tubes that are commonly 1.2-m long

Table 1. Comparison of methods used to upgrade biogas to renewable natural gas (RNG).

| | Membrane Separation | Pressure-Swing Adsorption | Amine Scrubbing | Water Wash |
|---|---|---|---|---|
| Description | Pressure-driven filtration | Pressure-driven media adsorption | Chemical adsorption and thermal desorption of $CO_2$ | Pressurized water scrubbing and desorption of $CO_2$ |
| Temperature | Stage 1: 20°C<br>Stage 2: 40°C | 15–25°C | Stage 1: 30°C<br>Stage 2: 100°C | Ambient |
| Feed Pressure | 200–250 psig | 120 psig | 1–3 psig | 150 psig |
| Considerations | ▪ Requires extensive drying of feedstock<br>▪ Pretreatment to remove $H_2S$ is advisable | ▪ Requires drying of feedstock<br>▪ Commonly requires tail gas treatment | ▪ Best where low-cost waste heat is available<br>▪ Can achieve 99.9% $CH_4$ | ▪ Drying of feedstock is not mandatory<br>▪ Pretreatment to remove $H_2S$ is advisable |
| Wet or Dry Process | Dry | Dry | Wet | Wet |

(Figure 3). Dozens of tubes are configured in parallel into banks based on the quantity of gas to be processed, and each bank comprises a stage. Two to three stages of filtration are required to achieve greater than 98% methane purity. A common configuration includes discharging the permeate from Stage 1, and recirculating the permeate from Stage 2 back to Stage 1 to maximize methane capture (Figure 4). To enhance performance, the biogas feed is compressed to about 200 psi and the retentate is drawn out by a vacuum pump.

Prior to entering the membrane bundle, biogas is often treated in an activated carbon filter to remove $H_2S$ and volatile organic compounds (VOCs). To be conservative, the raw gas is also aggressively dried to ensure VOCs have been removed to the extent possible. VOCs can irreversibly foul or compromise some types of membranes. Drying can be done economically by refrigerating the gas to 40–60°F and capturing the resulting condensate.

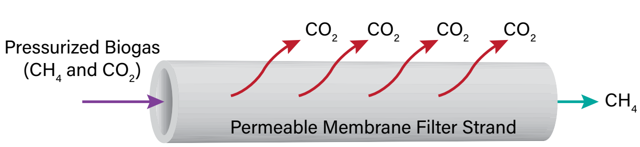
The permeability of membranes can be manipulated by controlling the operating temperature. Cooler membranes have tighter pores and thus higher selectivity for smaller molecules like $CO_2$. Warmer temperatures loosen the pores to accommodate higher flowrates but reduce selectivity. System suppliers must balance flowrate and temperature to optimize performance and operating cost. Membrane manufacturers have recently improved membrane selectivity and overall methane recovery, enhancing performance and the economics of RNG production.

Two entities are involved in the supply of membrane RNG upgrading systems. Membrane manufacturers spin polymers into membrane fibers and bundle the membranes into modules. Engineered system suppliers place the membrane bundles into skidded systems that include rack configurations, gas recirculation strategies, pumps, valves, instruments, and controls (Figure 5). A typical lead time for installation of a complete membrane upgrading system is 12 months from order to startup.

The composition of the biogas dictates the design considerations of the separation system. For example, it can be difficult to separate nitrogen from methane using membranes. Additional gas polishing is required when there is a significant amount of nitrogen in the raw biogas, such as landfill gas or gas from covered lagoons. These streams also typically have high oxygen levels that can cause performance issues, as membranes are not selective for oxygen.

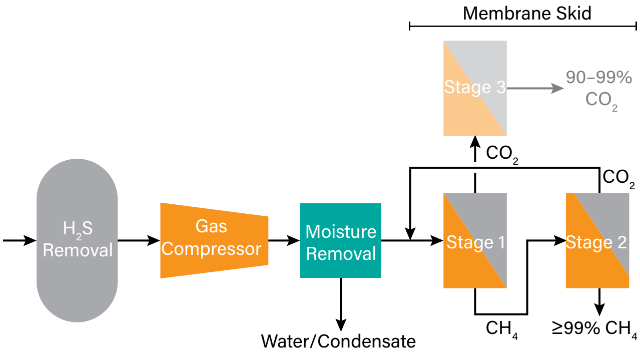
Systems can be configured to produce recoverable $CO_2$ liquid byproduct that can be sold to the food industry as an ingredient (*e.g.,* carbonated drinks). Pursuing this option eliminates nearly all emissions. Alternatively, gaseous $CO_2$ emissions can be sent to greenhouses for plant farming or to other recovery systems.

The key benefits of membrane systems include low overall operating expenses and ease of installation, opera-




▲ **Figure 2.** Pressurized biogas flows through the hollow core of a selectively permeable membrane that allows carbon dioxide to permeate but retains methane, producing a concentrated methane stream.

▲ **Figure 3.** Thousands of membrane fiber strands are bundled into each tube, and dozens of tubes are configured in parallel for a single stage of separation. Photo courtesy of Evonik.




▲ **Figure 4.** A common membrane separation configuration includes two stages with a recycle stream to maximize methane recovery. The permeate from Stage 1 can be fed to an optional Stage 3 to produce a purified $CO_2$ stream for reuse.

◀ **Figure 5.** This membrane system upgrades landfill gas to renewable natural gas (RNG).

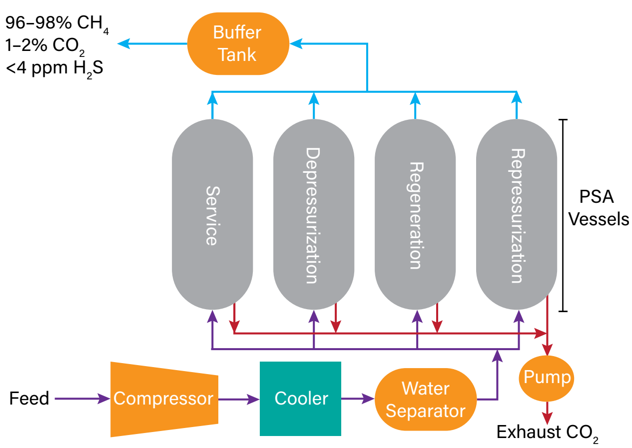
tion, and maintenance. They are able to produce high yields of very pure gas, with a methane loss of less than 0.5% and a possible purity of greater than 99%. Manufacturers claim a ten-year membrane life, but since the technology is relatively new, it is unclear if this is an accurate estimate.

## Pressure-swing adsorption

PSA is a batch process of several vessels running in parallel under pressure (Figure 6). Central to the process is an adsorptive media, similar to activated carbon, that separates gas molecules based on their molecular weight and size. Cooling the gas to about 5°C prior to entering the adsorptive vessels removes water from the gas to maintain a dry atmosphere and maximizes performance. The media preferentially adsorbs carbon dioxide because it is smaller than methane, which enables it to permeate more easily and deeper into the tiny pores of the carbon bed. Almost all of the methane passes through the process columns, while the media traps the $CO_2$.

The adsorption process is reversible. After a vessel has been saturated with contaminant gas, it can be regenerated by reducing the pressure. At lower pressures, trapped $CO_2$, $H_2S$, and trace methane desorb from the media in a separate gas stream called tail gas. Each of the four to ten adsorber vessels in a system cycles between service, depressurization, regeneration, and repressurization. Common cycle times are two to four minutes.

PSA systems can achieve methane purities of 96–98%. They are suitable for biogas streams that contain oxygen and nitrogen, such as those from landfill gas or covered lagoons (Figure 7). For this reason, they are often installed as a polishing system in series with another separations technology to remove oxygen and nitrogen. They are also economical at a wide range of flowrates.

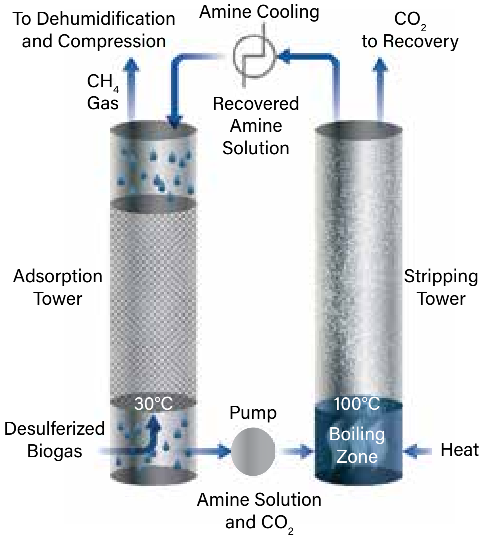



▲ **Figure 6.** A pressure-swing adsorption (PSA) system consists of up to ten vessels in series that contain an adsorptive media. The media adsorbs contaminants but allows methane to pass through. The process can be reversed by lowering the pressure, allowing the $CO_2$, $H_2S$, and trace methane to desorb from the media. Each vessel cycles through a process of service, depressurization, regeneration, and repressurization.

▲ **Figure 7.** This pressure-swing adsorption (PSA) system at a pig farm consists of four adsorptive vessels in series.

## Amine scrubbing

Amine scrubbing systems use a two-step approach of adsorption and desorption (or stripping) to upgrade biogas (Figure 8). In the first vessel, the amine scrubbing solvent — *e.g.*, mono diethanol amine (MDEA) — reacts with the $CO_2$ in the biogas, retaining it in solution. The methane passes through the packed tower untouched by the scrubbing chemical. The solvent, saturated with $CO_2$, is then pumped to a packed stripping tower, where it is heated to its boiling point to reverse the chemical reaction. The $CO_2$ disassociates from the scrubbing solution and is discharged. The regenerated solution is then cooled and reused in a closed-loop system. The recovered methane is dehumidified in a desiccant dryer and then pressurized to supply the natural gas grid.




◀ **Figure 8.** In the first phase of amine scrubbing, contaminants react with an amine scrubbing solution. Once the amine solution is saturated with $CO_2$, it is pumped to the stripping tower, where it is heated to reverse the chemical reaction. The amine solution is then reused in the first tower.

Biogas with $H_2S$ levels greater than 300 ppm typically needs to be pretreated. Amine scrubbing systems run at relatively low operating pressure of about 0.5–3 psig, which decreases equipment and operational costs. The operating temperature of the adsorption and stripping columns are 70°F and 212°F, respectively. While the relatively low operating pressure decreases costs, the heat requirement for the regeneration tower is an important consideration. Applications that have a steady supply of waste heat are ideal for amine scrubbing, such as when a combined heat and power (CHP) engine is paired with an RNG system.

High methane purities (>99.9%) can be achieved in the recovered natural gas (Figure 9). High $CO_2$ purities in the offgas can be achieved to accommodate reuse. Amine technology, however, does not appreciably remove $O_2$ or $N_2$.

## Water wash

Similar to amine scrubbing, water wash systems are a two-step process (Figure 10). In the first step, biogas enters a high-pressure (150 psig) reactor column, where it flows upward as chilled water flows downward. Soluble gases such as $CO_2$ dissolve in the water. In the second step, the water, saturated with contaminants, is depressurized in a separate tower, releasing the $CO_2$ from solution. The process is akin to producing a carbonated beverage by dissolving $CO_2$ in the liquid under pressure; the $CO_2$ is then released when the bottle is opened for consumption.

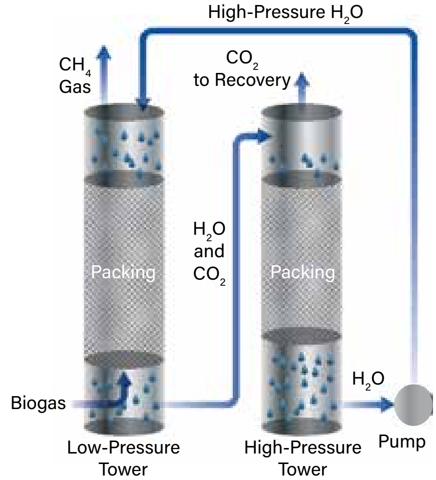
Makeup water is added to the system and blowdown water is purged to maintain a desired pH and water quality. Any $H_2S$ in the biogas is absorbed in the process and purged from the system into the wastewater blowdown. However, some system suppliers suggest removing $H_2S$ prior to water wash.

Water wash systems can achieve high RNG purity of more than 98% (Figure 11). The offgas can be vented or polished for reuse. As $O_2$ and $N_2$ are only partially removed during water wash, polishing may be necessary to meet aggressive specifications. Proper component selection is paramount to meet the rigors of a high-pressure environment.

## Policy perspective

As of today, California has the most robust program that rewards projects with good CI scores, called the Low Carbon Fuel Standard (LCFS). Several other states, such

◀ **Figure 9.** This amine scrubber unit is installed at a digester site.




◀ **Figure 10.** Water wash systems use a two-step process. In the high-pressure column, $CO_2$ dissolves in water, and in the low-pressure column, $CO_2$ degasses. The water is pumped back to the high-pressure column in a closed-loop system.

◀ **Figure 11.** This water wash system installed at a digester site can achieve high methane purities.

*Article continues on p. 39*


## Literature Cited

1. **Navigant Consulting, Inc.,** "Analysis of the Role of Gas for a Low-Carbon California Future," Southern California Gas Co., Monterey Park, CA, www.socalgas.com/1443741887279/SoCal-Gas_Renewable_Gas_Final-Report.pdf (July 24, 2018).
2. **International Energy Agency,** "Net Zero by 2050: A Roadmap for the Global Energy Sector," IEA, Paris, France, https://iea.blob.core.windows.net/assets/ad0d4830-bd7e-47b6-838c-40d115733c13/NetZeroby2050-ARoadmapfortheGlobalEnergySector.pdf (May 2021).
3. **Hanselman, J.,** "The Role of Renewable Natural Gas in the Decarbonization of Our Economy," Vanguard Renewables, Wellesley, MA, https://vanguardrenewables.com/the-role-of-renewable-natural-gas-in-the-decarbonization-of-our-economy (Apr. 2021).
4. **ICF International,** "Renewable Sources of Natural Gas," American Gas Foundation, Washington, DC, https://gasfoundation.org/2019/12/18/renewable-sources-of-natural-gas (Dec. 19, 2019).
5. **Jackson, R. B., *et al.,*** "Methane Removal and Atmospheric Restoration," *Nature Sustainability,* **2,** pp. 436–438, https://par.nsf.gov/servlets/purl/10142837 (June 2019).
6. **ICF International,** "Greenhouse Gas Mitigation Options and Costs for Agricultural Land and Animal Production within the United States," U.S. Dept. of Agriculture, Washington, DC, www.usda.gov/sites/default/files/documents/GHG_Mitigation_Options.pdf (Feb. 2013).
7. **U.S. Environmental Protection Agency,** "Basic Information about Landfill Gas," EPA, Washington, DC, www.epa.gov/lmop/basic-information-about-landfill-gas (accessed May 24, 2021).
8. **Ward, M., *et al.,*** "Aerial Methane Survey Finds a Fraction of Point Sources Responsible for More than a Third of California's Methane Emissions," California Energy Commission, Sacramento, CA, www.energy.ca.gov/news/2019-11/aerial-methane-survey-finds-fraction-point-sources-responsible-more-third (Nov. 2019).
9. **Ross, M.,** "What Every Operator Should Know About Biological Phosphorus Removal," Water Environment Federation, Alexandria, VA, www.wef.org/globalassets/assets-wef/direct-download-library/public/operator-essentials/wet-operator-essentials---biological-phosphorus-removal---july13.pdf (July 2013).
10. **Vanguard Renewables,** "Goodrich Farm, Salisbury, VT," https://vanguardrenewables.com/portfolio-items/goodrich-farm-salisbury-vt (accessed Aug. 2021).
11. **Ingram, W.,** "Staff Report: Calculating Life Cycle Carbon Intensity Values of Transportation Fuels in California," California Air Resources Board, Sacramento, CA, ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/peerreview/050515staffreport_ca-greet.pdf (Mar. 2015).
12. **Haines, D.,** "Getting the Facts on Renewable Natural Gas," 2nd Annual AGA-EPA Natural Gas STAR/Methane Challenge Renewable Natural Gas Workshop & Exhibit, www.epa.gov/sites/default/files/2018-11/documents/7._deanna_haines-508.pdf (Oct. 23, 2018).


*Article continues from p. 33*

as Oregon and Washington, have similar LCFS programs that aim to reduce the CI of their state's vehicle fleets. The programs allow for sale and use of RNG that is generated out-of-state. Consequently, projects around the country can capitalize on this opportunity to sell RNG to the west coast.

Another policy favorable to RNG is the Federal Renewable Fuel Standard (RFS), which aims to reduce the CI of the nation's vehicle fleet. This is the same policy that currently mandates 10% ethanol in gasoline at the pumps. Under the RFS, all low-CI fuels are registered and tracked using a unique identifier number for every gallon of liquid fuel or cubic foot of a gaseous fuel. These renewable identification numbers (RINs) provide a means to enforce compliance with the standard.

RNG produced from cellulosic feedstocks, such as manures, biosolids, and landfill gas, have the most lucrative RIN, the D3 RIN. RNG from non-cellulosic sources, such as food waste feedstock, have the less-lucrative D5 RIN. RINs are generated by the RNG project, and they are purchased by petroleum refiners. The U.S. Environmental Protection Agency (EPA) manages the RFS, and each year, the EPA sets the production size of the biofuel industry by issuing a target number of RINs that the obligated parties must purchase, called the renewable volume obligation (RVO).

Controversy surrounds the electric RIN (E-RIN), which was intended for RNG used to power a generator or cell that then fuels an electric vehicle. This RIN was intended to help drive sales of electric cars and trucks. The EPA, however, has not issued an annual RVO for E-RINs as required by the RFS statute.

Favorable policy is increasing the availability and market share of RNG. Market acceptance, technology advancements, and environmental benefits have positioned RNG to help reduce overall GHG emissions. CEP


## Literature Cited

1. **California Air Resources Board,** "Carbon Intensity of Key Transportation Fuels," CARB, Sacramento, CA (2019).



**PAUL GREENE** is a technology specialist in anaerobic digestion, biogas upgrading, and waste-to-energy with more than 30 years of experience in the water, wastewater, energy, and environmental services industries. He is a founding member of the U.S. biogas industry, helping to establish the American Biogas Council (ABC), an organization dedicated to advancing anaerobic digestion technology and organics diversion; he served as the first chairman of ABC. Greene holds a BS in chemical engineering from Lafayette College.