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WORKING PAPER

THE PRODUCTION AND USE OF RENEWABLE NATURAL GAS AS A CLIMATE STRATEGY IN THE UNITED STATES

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EXECUTIVE SUMMARY

Highlights

- The production of renewable natural gas (RNG, also known as biomethane or upgraded biogas) is an emerging strategy to turn organic waste into a low-carbon fuel for use in vehicles.
- This working paper explores RNG's potential as a climate-change strategy in the United States, including the conditions under which it can achieve large greenhouse gas (GHG) emissions reductions compared to fossil fuels used to power vehicles.
- We find that RNG has the potential to be an effective GHG reduction strategy when it meets two conditions: It is produced from waste, and its use reduces methane emissions to the atmosphere.
- The most promising RNG projects include food and yard waste diverted from landfills and livestock manure projects on farms that aren't already capturing methane. Analyses have shown that using RNG from these projects in heavy-duty vehicles can result in net GHG reductions on a life-cycle basis.
- Municipalities, states, and companies considering RNG as a climate strategy will need to determine the net GHG impacts, costs, and benefits of new projects and policies on a case-by-case basis.

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Suggested Citation: Gasper, R., and T. Searchinger. 2018. "The Production and Use of Renewable Natural Gas as a Climate Strategy in the United States." Working Paper. Washington, DC: World Resources Institute. Available online at http://www.wri.org/publication/renewable-natural-gas.

Renewable Natural Gas as a Vehicle Fuel in the United States

The production of RNG from organic waste for use as a vehicle fuel is an emerging strategy that businesses, states, and municipalities are pursuing to make use of waste-derived methane and lower the carbon footprint of vehicle fleets. RNG is primarily made from wet organic wastes, which include livestock manure; sludge from wastewater treatment; inedible fats, oils, and greases (FOG) from commercial and industrial food processing operations; and food and yard waste disposed of in landfills or diverted from landfills and processed separately to make RNG. When wet wastes decompose under typical management practices—for instance, when food waste is disposed of in a landfill—they produce biogas, a mix of carbon dioxide, methane, and other trace elements that can escape to the atmosphere and contribute to climate change (U.S. Environmental Protection Agency 2017a). Biogas can be captured and processed into RNG, which is essentially pure methane and is interchangeable with conventional, fossil-fuel derived natural gas in any of its uses, including power generation, heating, and vehicle fuel. The resulting fuel, which is recognized as a low-carbon fuel under the federal Renewable Fuel Standard and similar state policies, can be distributed in the same pipelines and fueling pumps as conventional natural gas and used in any vehicle with a natural gas engine (Hamberg et al. 2012). This working paper focuses on RNG use as a vehicle fuel because this is where most RNG is used today, driven in large part by the federal Renewable Fuel Standard and low-carbon fuel standards in California and Oregon. (See page 27 for a glossary of terms used in this paper.)

RNG production is relatively limited in the United States, but growing rapidly. Driven in large part by the economic incentives provided by renewable and low-carbon fuel policies, RNG production grew from 1.4 million ethanol-equivalent gallons in 2011 to nearly 190 million in 2016 (U.S. Environmental Protection Agency 2017b). Cities and towns are increasingly using RNG to more efficiently manage local waste and power municipal vehicle fleets like garbage trucks and buses. Private companies—particularly waste disposal services and companies that use heavy-duty vehicles for freight—are beginning to add RNG as a domestic, renewable, low-carbon fuel option in their efforts to reduce GHG emissions. California has acknowledged RNG as part of its comprehensive plans to address climate change (California Air Resources Board 2017a). Municipalities and businesses undertaking RNG projects have pointed to benefits beyond potential GHG reductions, including improved local air quality and associated public health benefits, reduction in waste management costs, and avoided price volatility of fossil fuels (Underwood and Tomich 2012; U.S. Department of Agriculture et al. 2014).

How Can RNG Production and Use Reduce GHG Emissions?

RNG produced from organic wastes can lead to GHG emission reductions by avoiding GHG emissions from waste management and displacing the use of fossil fuels in vehicles. Figure ES-1 provides a generic illustration of typical sources of emissions and avoided emissions across RNG supply chains produced from anaerobic digestion of wet organic waste sources. Three main sources of GHG emissions across RNG's life cycle as a vehicle fuel are

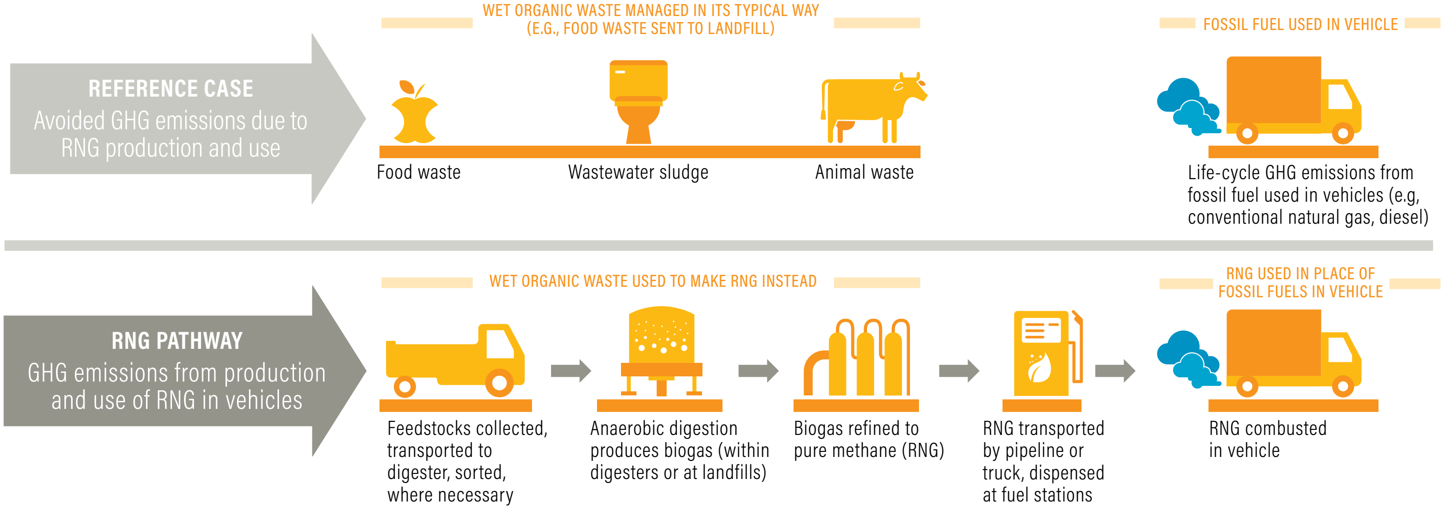
- energy use required to produce, process, and distribute the fuel for use in vehicles;
- combustion of RNG in the vehicle; and
- leaks of methane that can occur at all stages in the life cycle from production through use.

These emissions sources are represented by the RNG Pathway in Figure ES-1.[1]

Sources of GHG emissions that are avoided because of the production and use of RNG from organic waste are represented by the Reference Case in Figure ES-1. These primarily include the following:

- GHG emissions that would have occurred under typical waste management but are prevented because the wastes are used to make RNG instead. For example, food waste used to produce RNG might otherwise be sent to a landfill where some methane would escape to the atmosphere and some would be captured and burned to convert most of the methane to carbon dioxide before it enters the atmosphere (that is, flared). Animal waste on a farm might otherwise be placed in an open lagoon that would emit methane.
- GHG emissions displaced from use of RNG intermediary products and coproducts. For example, some of the biogas produced could be used for power generation, displacing electricity from the grid.

Figure ES-1 | **Life-Cycle GHG Impacts of RNG Produced from Organic Waste for Vehicle Fuel (assumes no land-use change impacts)**



Avoided GHG emissions can be larger than emissions from the RNG pathway when RNG is made from wet wastes that would otherwise cause methane emissions.

Note: This figure provides a generic illustration of typical sources of GHG emissions and avoided emissions across RNG supply chains produced from wet organic wastes (food and yard waste, wastewater sludge, and livestock manure). Feedstock collection and transportation is only relevant where resources aren't processed into RNG on site, which will mainly be the case for fats, oils, and greases (FOG), as well as food and/or yard waste diverted from landfill disposal. At landfills, anaerobic digestion naturally occurs, producing a form of biogas known as landfill gas that can be collected and processed into RNG. In life-cycle GHG analyses of RNG pathways, including the displacement of fossil fuel in the vehicle, emissions from sources illustrated in the RNG pathway would be added. Avoided emissions from sources illustrated in the RNG pathway, as well as any avoided emissions from use of RNG intermediary or coproducts, would be subtracted. This illustration is not intended to provide a complete picture of all sources in any given pathway, which will need to be assessed on a case-by-case basis, and does not apply to RNG feedstocks that require dedicated use of land.
Source: WRI.

- Displacement of life-cycle GHG emissions from fossil fuel use in vehicles. RNG will typically replace conventional natural gas in existing natural gas trucks or displace diesel fuel when a fleet owner replaces a diesel truck with a natural gas vehicle that runs on RNG.

The net life-cycle GHG emissions associated with RNG would be determined by adding together all GHG emissions associated with the RNG pathway (bottom panel in Figure ES-1) and subtracting the avoided emissions from the reference case and any use of RNG coproducts that result in further avoided emissions (top panel in Figure ES-1).

While the potential benefits of RNG from wet and gaseous waste sources are promising, its production and use may not always lead to large GHG emissions reductions. RNG's net impact on GHG emissions will depend on several factors, including what feedstocks are used to produce RNG and how they would otherwise have been managed, how much methane escapes to the atmosphere between RNG production and when it is combusted in vehicles, and what fuel is replaced in the vehicle.

Much recent research has focused on RNG's potential benefits, but a detailed analysis of the conditions under which RNG can generate climate benefits and its potential risks is missing from the discussion. This working paper begins to address that gap by providing an analysis of RNG's potential as an effective and economically viable GHG reduction tool, drawing on and synthesizing relevant literature. Municipalities, companies, and states considering RNG as part of a climate strategy can use this paper as a resource to understand the basics of RNG production from organic waste, the conditions under which it can lead to large net GHG reductions, its costs and incentives, and critical gaps in data and analysis of the issue.

Key Findings

Generally speaking, RNG has potential as an effective GHG reduction strategy when it meets two conditions: It is produced from organic waste, and its production and use results in net methane emissions reductions. Use of waste avoids competition with food production, timber, other human needs, and ecosystem carbon storage that is vital to mitigating climate change (Searchinger and Heimlich 2015). Methane is a powerful GHG that remains in the atmosphere for a shorter time than carbon dioxide but has 25 to 34 times the global warming potential over 100 years (Myhre et al. 2013).[2] Reducing emissions of methane and other short-lived climate pollutants in addition to carbon dioxide is critical to avoiding the worst impacts of climate change (Haines et al. 2017).

RNG produced from wet wastes that are leading to methane emissions under current management practices can potentially meet both conditions. These sources—which include food and yard waste, sludge from wastewater treatment, and livestock manure—are the main feedstocks used to make RNG in the United States today and are abundant across the country (Table ES-1). Together, management of these wastes comprises nearly one-third of all methane emissions in the United States (U.S. Environmental Protection Agency 2017a). RNG made from food and yard waste diverted from landfills and from livestock manure projects where methane emissions aren't currently controlled is particularly promising and can actually lead to net GHG emissions reductions when used as a vehicle fuel (California Air Resources Board 2018).

Table ES-1 | RNG as a Climate Strategy

RNG IS MOST LIKELY TO ACHIEVE LARGE NET GHG REDUCTIONS COMPARED TO FOSSIL FUELS USED IN VEHICLES WHEN IT MEETS TWO CONDITIONS:

1. It is made from waste rather than dedicated uses of land.
2. Its production and use reduces methane emissions.

THE FOLLOWING RNG PROJECT TYPES ARE MOST LIKELY TO MEET BOTH CONDITIONS:

- food and yard waste diverted from landfill disposal
- livestock manure where methane is currently uncontrolled
- sludge at wastewater treatment facilities that aren't already capturing methane
- landfill gas from landfills that aren't capturing methane or that significantly increase the amount of methane they capture when producing RNG

Source: WRI.

Early market research and experiences on the ground suggest that wet waste-derived RNG projects can be economically viable at sites around the country, although high up-front costs and other challenges exist. While it costs more to produce RNG than conventional natural gas, low-carbon fuel markets and other sources of revenue and incentives are allowing producers to offer RNG at competitive prices and make returns on their investments relatively quickly in some cases. Some existing projects have payback periods ranging from immediate to about 10 years (Energy Vision 2017).

RNG production from wet wastes that meets the criteria described in this working paper could be an effective GHG reduction strategy for both private and public entities, particularly in the near to medium term. Public and private fleet owners can achieve immediate GHG reductions by using methane that would otherwise be emitted as RNG for vehicle fuel. States and municipalities can use RNG as a component of a comprehensive climate action plan to address methane emissions.

In some contexts, RNG could lead to a net increase in methane emissions when used as a vehicle fuel. This could occur when RNG production does not result from capture of methane that would otherwise be released and, instead, comprises new methane, which we define as methane that would not otherwise have entered the atmosphere. New methane will generally be produced when feedstocks used to produce RNG would otherwise have resulted in carbon dioxide emissions; for example, at landfills that already capture and burn methane, converting most of it to carbon dioxide before it's released to the atmosphere. RNG projects involving new methane production can lead to a net increase in methane emissions due to leaks and venting that occurs from its production through use in the vehicle. Leaks can erode or outweigh the climate benefit of RNG comprising new methane compared to diesel fuel, which is petroleum-based and therefore is not associated with methane leakage. If RNG comprising new methane replaces conventional natural gas, the net impact on methane emissions will only depend on differences in methane leaks due to gas production and processing because all other components of the supply chain and associated leakage rates are the same.

More data, analysis, and on-the-ground experience are needed to fully evaluate the climate and economic benefits of RNG and its role in near-through long-term climate change strategies. Key topics for future research include

- improved data and analysis on methane leakage specific to RNG, particularly from production and processing;
- sensitivity analysis of life-cycle carbon intensities of RNG from various pathways under a range of methane leakage rate assumptions and choice of global warming potential values for methane;
- estimation of break-even methane leakage rates at which RNG comprising new methane will have climate benefits over petroleum-based fuels or other low-carbon fuels or technologies (for example, electric vehicles);
- estimates of RNG market potential from wet waste incorporating the effects of low-carbon fuel markets and other incentives; and
- a comparison of RNG's climate benefits, costs, and feasibility compared to other low-carbon fuels and/or technologies and other methane reduction strategies.

INTRODUCTION

The production of renewable natural gas (RNG, also known as biomethane or upgraded biogas) from organic waste for use as a vehicle fuel is an emerging strategy that federal governments, states and provinces, municipalities and universities, and businesses are pursuing to make use of waste-derived methane and lower the carbon footprint of their vehicle fleets. In the United States, RNG is primarily made from organic wastes, including food and yard waste; livestock manure; fats, oils, and grease (FOG); and sludge left over from wastewater treatment. When these wastes decompose under typical management practices—for instance, when food waste is disposed of in a landfill—they produce biogas, a mix of carbon dioxide, methane, and other trace elements that can escape into the atmosphere. RNG is biogas that has been captured and processed into essentially pure methane like conventional, fossil-fuel derived natural gas and can be used for the same applications, including for power generation, heating, and vehicles (Hamberg et al. 2012). This working paper focuses on RNG use as a vehicle fuel—whether for direct use in vehicles or through injection into the natural gas pipeline network—because this is where most RNG is being used today, driven by policy incentives provided by federal and state renewable and low-carbon fuel standard programs.

As a vehicle fuel, RNG can be compressed or liquefied, distributed in the same pipelines and fuel pumps as conventional natural gas, and used in any vehicle equipped with a natural gas engine. RNG emits the same amount of carbon dioxide as conventional natural gas when it is combusted during vehicle operation. But RNG is not a fossil fuel, and its production can prevent and reduce the methane emissions that would otherwise have occurred if the waste had been managed the usual way. Methane is a much more potent greenhouse gas (GHG) than carbon dioxide. Thus, on a life-cycle basis, RNG made from methane that would otherwise have escaped to the atmosphere can lead to much lower GHG emissions than conventional natural gas and other fossil fuels. Because of the avoided emissions associated with its production, RNG made from organic waste is recognized as both a renewable fuel under the Renewable Fuel Standard (RFS) and as a low-carbon fuel under California's Low Carbon Fuel Standard (LCFS) and Oregon's Clean Fuels Program (CFP).

While RNG production is still relatively limited in the United States, it has grown rapidly in large part due to the economic incentives created by these renewable and low-carbon fuel policies, from 1.4 million ethanol-equivalent gallons in 2011 to nearly 190 million gallons in 2016 (U.S. Environmental Protection Agency 2017b). As a vehicle fuel, RNG is primarily used in medium- and heavy-duty vehicles. Cities and towns are increasingly using RNG as a way to more efficiently manage local waste and power municipal vehicle fleets like garbage trucks and buses. Private companies—particularly waste disposal services and companies that use heavy-duty vehicles for freight—are beginning to add RNG as a low-carbon fuel option in their efforts to reduce GHG emissions. California has recognized RNG as part of its comprehensive plans to address climate change (California Air Resources Board 2017a). Recent studies have described other benefits of RNG production and use, including improved local air quality and associated public health benefits when it displaces the use of diesel fuel (Underwood and Tomich 2012; ICF 2017).

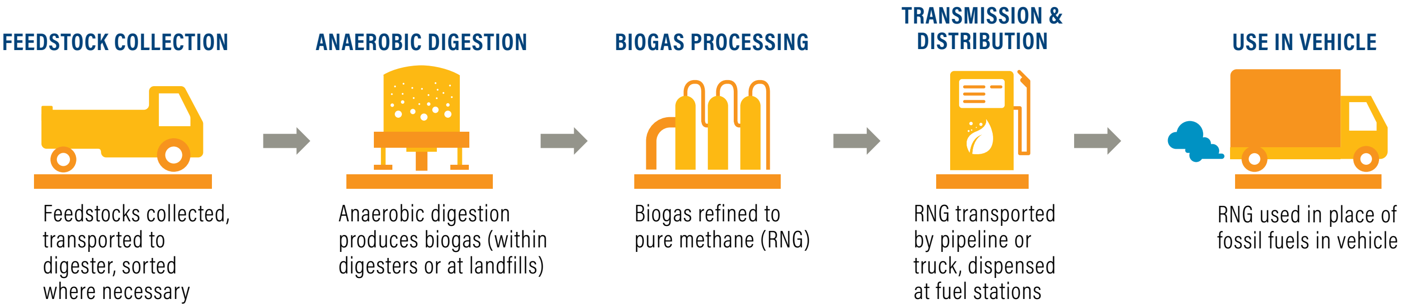
However, while RNG's potential benefits are promising, its production and use may not always lead to certain, large GHG reductions. The existence and magnitude of the climate benefits realized due to increased RNG development, deployment, and utilization will depend on several factors, including what feedstocks are used to produce the fuel and how they would have been managed if not used to produce RNG, how much methane escapes to the atmosphere between RNG production and its ultimate use in a vehicle, and which fuel RNG replaces in the vehicle. Much recent research has focused on the potential benefits of RNG from waste sources, but a detailed analysis of the conditions under which RNG can generate climate benefits is missing from the discussion.

We conducted an analysis to begin filling this gap with an initial exploration of RNG's potential to cut GHG emissions and serve as an economically viable component of a climate-change strategy. Companies, states, and municipalities interested in RNG as a mitigation tool can use this paper as a starting point to understand the basics of waste-derived RNG production and use as a vehicle fuel, the conditions under which it will lead to GHG benefits, and its costs and incentives. We also identify data gaps that need to be addressed for a more complete understanding of RNG's potential role in private or public strategies to address climate change.

The paper is organized as follows:

- Section 1, RNG Production and Trends in the United States, describes the basics of RNG production, its current use as a low-carbon strategy, and economic and policy drivers in the United States.
- Section 2, Achieving Climate Benefits from RNG Production and Use, explores the conditions under which RNG will lead to GHG emission reductions and describes which RNG projects are likely to meet these conditions and lead to climate benefits.
- Section 3, Economic Feasibility of RNG from Wet Wastes, synthesizes existing research on the economic viability of RNG production from sources that can achieve large net GHG reductions by meeting the conditions in section two, including costs, incentives, and market opportunities.
- Section 4 contains conclusions and suggestions for further research.
- The glossary defines terms related to RNG production and use as they are used in this working paper.

Figure 1 | **Renewable Natural Gas Production via Anaerobic Digestion**



Notes: Feedstock collection and transportation is only relevant where resources aren't processed into RNG on site, which will mainly be the case for FOG, as well as food and/or yard waste diverted from landfill disposal. At landfills, anaerobic digestion naturally occurs, forming a biogas known as landfill gas that can be collected and processed into RNG.
Source: WRI.

RNG PRODUCTION AND TRENDS IN THE UNITED STATES

RNG production for vehicle fuel is relatively limited in the United States but is growing rapidly due in part to shifting waste management practices and the recognition of RNG as a renewable and low-carbon fuel under federal and state policies (Linville et al. 2015; U.S. Department of Energy 2017a; Warner et al. 2017). In this section, we describe the RNG supply chain (as produced through anaerobic digestion of waste), the basis for its production and use as a renewable or low-carbon strategy, and its current production and trends in the United States.

The RNG Supply Chain

Figure 1 illustrates the production of RNG from anaerobic digestion of waste and its use as a vehicle fuel. The supply chain includes feedstock collection (in some cases), conversion of feedstocks to biogas, conditioning or cleaning and upgrading of biogas to produce RNG, distribution of RNG, and use of RNG in vehicles.

Most RNG in the United States is produced through anaerobic digestion, a process that converts organic materials into biogas through decomposition in the absence of oxygen. Anaerobic digestion technologies are mature and commercially available today and are generally best suited for relatively high-moisture feedstocks. At landfills, anaerobic digestion of organic waste naturally occurs, producing landfill gas, a form of biogas that can be collected and processed into RNG. The following feedstocks are most commonly used for RNG today (U.S. Department of Energy 2017a):

- **food waste and yard trimmings:** food, food processing by-products, and yard trimmings sent for disposal
- **sludge derived from wastewater treatment:** untreated solids remaining after wastewater processing
- **livestock manure:** Livestock manure is often used as a soil fertilizer, but farms with a high concentration of livestock often produce more manure than they can use. Excess manure, particularly high-moisture manure from swine, dairy cows, and beef cattle, is suitable for anaerobic digestion.
- **fats, oils, and greases (FOG):** inedible by-products of meat processing and industrial- and commercial-scale cooking operations.

These feedstocks are processed at landfills or in anaerobic digesters installed on farms, at wastewater treatment facilities, or in separate locations that collect organic fractions of municipal solid waste diverted from landfill disposal. Multiple feedstocks are often digested together, either at separate biogas facilities that collect waste from multiple sources or at livestock operations or wastewater treatment plants that supplement their primary waste feedstocks with food or other wastes (for example, FOG) brought in from other locations (U.S. Department of Agriculture et al. 2014).

In this paper, we use the term *wet waste* to refer to the feedstocks listed above, a classification used by the U.S. Department of Energy (DOE) (2017a).[3] RNG can also be produced from relatively drier plant-based feedstocks, which we'll refer to as *dry feedstocks*, including

- **agricultural crop residues**: plant portions of crops that aren't removed during harvesting (e.g., corn stover, wheat straw);
- **forestry residue and other wood waste**: woody material not removed in forest harvesting operations; woody material resulting from precommercial wood thinnings or thinning conducted to improve forest health; unused mill processing materials; urban wood waste (for example, discarded furniture, landscaping residue); and
- **energy crops**: a crop grown for use as a fuel (for example, switchgrass).

In some cases, dry, herbaceous feedstocks (for example, crop residues) can be mixed in anaerobic digesters with manure, sludge, or food waste to boost methane production (U.S. Department of Agriculture et al. 2014). As primary feedstock, woody biomass is better suited for conversion to gas using technologies that gasify feedstocks through a thermochemical process.[4] Thermal gasification technologies for biomass have been piloted in Europe but are not yet commercialized, so dry, woody biomass feedstock may be part of the future production of RNG, but is less relevant in the United States today (Murrayet al. 2014).

The biogas produced from anaerobic digestion is typically composed of about 50–70 percent methane, 30–40 percent carbon dioxide, and trace quantities of other components (U.S. Department of Agriculture et al. 2014). Biogas can be used for electricity generation, on-site heating, or combined heat and power generation with minimal processing. However, for use in vehicles or injection into the natural gas pipeline network, the biogas must be processed further to meet engine manufacturer or natural gas utility pipeline specifications. This includes cleaning to remove harmful constituents (for example, siloxanes, hydrogen sulfide, ammonia, volatile organic compounds) and upgrading to increase the energy content of the fuel similar to that of conventional natural gas, which is around 1,000 British thermal units per cubic foot of gas at standard temperature and pressure (Miller et al. 2015).

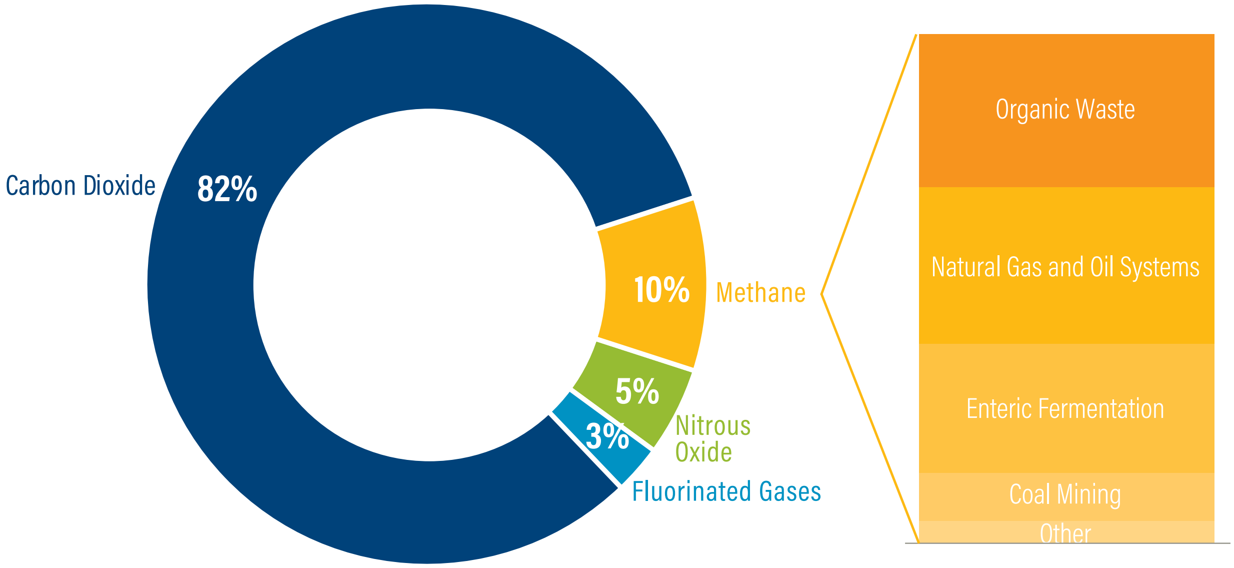
After cleaning or conditioning and upgrading, the resulting biogas is essentially pure methane and can be used interchangeably with conventional natural gas in any of its end uses. The resulting product is commonly referred to as renewable natural gas, biomethane, or upgraded biogas. The RNG can then be compressed or liquefied and used as a replacement for conventional compressed natural gas (CNG) or liquefied natural gas (LNG) in existing natural gas vehicles and infrastructure. The gas can be dispensed from an on-site fueling station or transported to an off-site fueling station by truck, rail, or pipeline. Companies, states, or municipalities that already have natural gas vehicles as part of their fleets can shift these vehicles to run on RNG rather than conventional natural gas, or they can shift portions of their fleets that run on petroleum-based fuels to natural gas and RNG. According to estimates from the Department of Energy, around 150,000 natural gas vehicles are on the road in the United States, constituting about 1 percent of all heavy-duty on-highway vehicles, and 1,800 fueling stations offer CNG and LNG, about 1,000 of which are available for public use (U.S. Department of Energy 2017b).

RNG's Use as a Low-Carbon Strategy

RNG is used as a low-carbon strategy primarily because its production and use can capture or otherwise prevent methane emissions from the management of wet wastes at landfills, farms, and wastewater treatment plants. Together, these three sources constituted 30 percent of methane emissions and 3 percent of total U.S. GHG emissions in 2015 (Figure 2).

Methane is much more effective at trapping heat than carbon dioxide with 25 to 34 times the warming potential over 100 years (Myhre et al. 2013).[5] When biogas is captured and upgraded to RNG, methane that would otherwise enter the atmosphere is converted to less potent carbon dioxide when combusted in the vehicle. In this way, RNG production and use as a vehicle fuel can lead to much lower GHG emissions on a life-cycle basis than wet waste feedstocks managed in the usual way. (However, large net GHG savings will only occur when RNG meets certain conditions described in detail in Section 2.) Because of its GHG reduction potential, RNG from organic waste is recognized as a low-carbon fuel under the

Figure 2 | **U.S. Greenhouse Gas Emissions, 2015**



Note: Organic waste category includes landfills, manure management, and wastewater treatment.
Source: U.S. Environmental Protection Agency 2017a.

federal renewable fuel standard and state low-carbon fuel standards and is used as a tool to reduce waste methane emissions, described below.

Renewable and low-carbon fuel standards

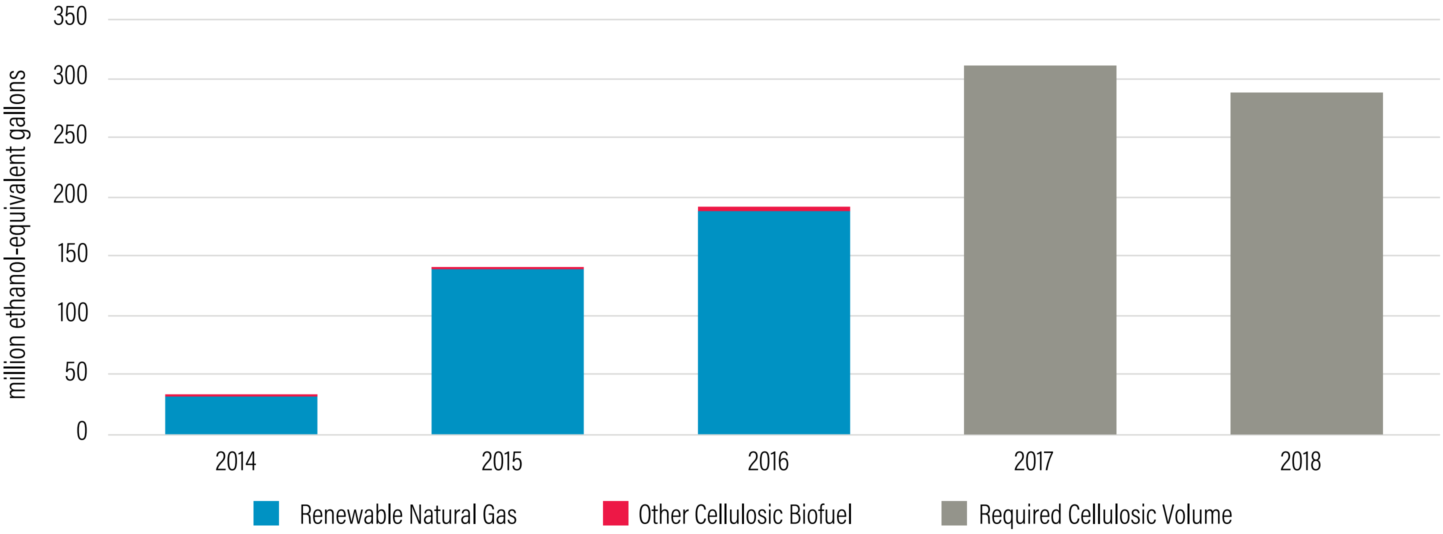
The federal Renewable Fuel Standard (RFS) requires a certain volume of renewable fuels to replace or reduce petroleum-based transportation fuel sold in the United States (Energy Policy Act 2005; Energy Independence and Security Act 2007). The U.S. Environmental Protection Agency (EPA) sets required volumes each year for four renewable fuel categories, which require the following minimum life-cycle GHG emissions improvement thresholds compared to the petroleum-based fuel they replace:

- Conventional biofuel (ethanol derived from corn starch) requires a minimum 20 percent reduction in life-cycle GHG emissions.
- Advanced biofuel (any renewable fuel besides corn starch ethanol that meets the required GHG reduction threshold) requires a minimum 50 percent reduction in life-cycle GHG emissions.
  - Cellulosic biofuel (renewable fuel derived from cellulose, hemi-cellulose, or lignin) requires a minimum 60 percent reduction in life-cycle GHG emissions.
  - Biomass-based diesel (biodiesel that meets the required GHG reduction threshold) requires a minimum 50 percent reduction in life-cycle GHG emissions.

Each gallon of renewable fuel produced generates a renewable identification number (RIN), which can be purchased by obligated parties to meet the required biofuel volumes.

In July 2014, the EPA changed the way RNG is treated under the RFS. Under the updated classification, RNG produced from landfill gas, wastewater treatment sludge, animal waste, municipal solid waste comprising material similar to landfills, and anaerobic digesters containing predominantly cellulosic feedstocks can receive credit as cellulosic biofuel under the program, generating the highest value RINs (Federal Register 2014).[6] Since the change in classification, RNG production increased nearly sixfold, from 33 million ethanol equivalent gallons in 2014 to 189 million ethanol equivalent gallons in 2016, and constituted 98 percent of all cellulosic RINs generated for compliance with the policy (U.S. Environmental Protection Agency 2017b). (See Figure 3.) In December 2016, final required cellulosic volumes for 2017 were set at 311 million ethanol equivalent gallons (Federal Register 2016).

Figure 3 | **Renewable Natural Gas Produced for Compliance with the Renewable Fuel Standard**



Note: Data represent the quantity of liquid and compressed RNG produced under EPA's Renewable Fuel Standard on an ethanol-equivalent basis. Prior to 2014, EPA used the term *biogas* to refer to RNG from landfill gas, manure digesters, and wastewater treatment plants. In 2014, EPA changed its fuel definitions to refer to biogas as a feedstock rather than a fuel type, and began using the term *renewable natural gas* for fuel derived from biogas from landfills, manure digesters, municipal wastewater treatment facility digesters, agricultural digesters, and separated MSW digesters. For more details, see https://www.gpo.gov/fdsys/pkg/FR-2014-07-18/pdf/2014-16413.pdf.
Source: U.S. Environmental Protection Agency 2017b.

In November 2017, the EPA finalized required cellulosic volumes for 2018 that are 7 percent lower than 2017 levels at 288 million ethanol equivalent gallons (Federal Register 2017) based on its projections of how much cellulosic fuel will be available. This is the first time in the program's history that required renewable fuel volumes have been lower than the previous year's requirements. It remains to be seen how this change will affect RIN prices and RNG markets, but this shift highlights the regulatory uncertainty associated with the RFS that has contributed to RIN price volatility in the past and caused challenges for investment in RNG and other low-carbon fuels.

California and Oregon have market-based low-carbon fuel standards in place, which are helping to drive RNG production. California's Low Carbon Fuel Standard, which took effect in 2011, requires a reduction in the average carbon-intensity of transportation fuels sold in the state to 10 percent below 2010 levels by 2020 (California Air Resources Board 2017b). Oregon began fully implementing a similar program in 2016 that will reduce the average carbon intensity of the state's transportation fuels 10 percent below 2015 levels by 2025 (Oregon Department of Environmental Quality 2017). Credits under these programs are generated according to the life-cycle carbon intensities of fuels certified by the California Air Resources Board (CARB) that are sold, supplied, or offered for sale in the state. CARB has certified RNG derived from landfill gas, wastewater sludge, animal manure, and source-separated food and green waste. The certified carbon intensities of RNG from these sources range from around 50 percent to well over 100 percent less carbon-intensive than fossil fuels (California Air Resources Board 2018). RNG from dairy manure and food and green waste have the lowest carbon intensity values of any low-carbon fuel under the policy and therefore can generate the highest credit values. RNG can simultaneously generate credits under the state programs and RINs under the RFS. Together, these incentives can be worth much more than the gas itself, which we discuss in more detail in Section 3, providing price support that is expected to continue to incentivize RNG production in the coming years (Jaffe et al. 2016).

Policies to address methane from organic waste sources

Federal and state policies to reduce methane emissions directly and indirectly encourage collection and use of biogas, including for use as RNG in vehicles. Federal regulations require new and existing landfills that meet certain size and pollutant emissions thresholds to collect landfill gas and control landfill gas emissions. These rules allow the landfill gas to be burned without putting it to use (that is, flared), but landfill operators can put the gas to use for electricity generation, heat, or as RNG to recoup the costs of the collection system (Russell et al. 2017). In 2016, EPA finalized rules reducing the threshold emission levels over which landfills must implement gas collection and control systems (U.S. Environmental Protection Agency 2017c).[7]

At the state level, California is encouraging use of RNG as part of a comprehensive approach to methane reduction in support of its broader climate goals. RNG is part of Senate Bill 1383, signed in 2016, which required the development of a comprehensive strategy to reduce emissions of short-lived climate pollutants in the state. One component of the legislation directed CARB to implement near- and long-term policies to encourage RNG production and pipeline injection and to divert organic waste from landfills, among other strategies to cut total state methane emissions 40–45 percent below 2013 levels by 2030 (State of California 2016; California Air Resources Board 2017c). California's Department of Food and Agriculture provides financial assistance for dairy manure digester projects. In 2017, the department awarded $35 million in grants for 18 new projects, 12 of which will upgrade the biogas to RNG and 6 of which will use the biogas for direct combustion with the possibility of upgrading to RNG in the future (California Department of Food and Agriculture 2018). RNG is also part of California's scoping plan to meet its 2030 climate goals and put its emissions on a pathway to deep decarbonization by mid-century by providing a low-carbon fuel source for end uses that can't feasibly be electrified in the near to medium term (Miller et al. 2015; Jaffe et al. 2016; California Air Resources Board 2017a). Although California has the most comprehensive current approach to methane, several other U.S. states and communities have established policies to reduce the amount of organic wastes, including food and yard waste, disposed in landfills (Linville et al. 2015).

RNG Projects in the United States

Although thousands of sites produce biogas, few currently upgrade biogas to RNG. A publicly available database of RNG projects does not currently exist, but preliminary work by the DOE identified about 60 operational RNG projects, 10 projects under construction, and 20 planned projects as of July 2015 (Mintz 2015b). Most of the operational projects identified and 90 percent of reported RNG production occurred at landfills, while diverted food waste from landfills constituted the single largest source category for projects planned and under construction. More recent numbers from the Coalition for Renewable Natural Gas, which represents companies including producers of more than 90 percent of all RNG in North America and 98 percent of the cellulosic biofuel produced under the Renewable Fuel Standard, identified about 60 operational projects in 2017, with at least 22 new projects on track for 2018. According to the coalition's data, nearly 76 percent of RNG produced in 2017 was dedicated for vehicle fuel with the remaining 24 percent of production dedicated for off-site electricity generation. RNG production for transportation fuel in 2018 is projected to exceed 254 million ethanol-equivalent gallons (161 million diesel gallon equivalent [dge]) (Escuder 2017). Still, RNG currently constitutes just a small fraction of fuel demand for heavy-duty trucks and buses, which was 40 billion gallons of diesel in 2017 (U.S. Energy Information Administration 2017a).[8]

Fuel from existing RNG projects is largely used to power commercial and municipal medium- and heavy-duty vehicles, including garbage trucks, freight trucks, and buses (Box 1). For example, the city of Perris, California, partnered with its waste management company, CR&R Waste and Recycling Services, to produce RNG from food and yard waste collected from the region. CR&R will fuel its entire fleet of 900 waste management vehicles with RNG from the project once it's fully scaled, and the remaining fuel will be sold throughout the state. Fair Oaks Dairy in Indiana produces RNG from livestock manure on the farm and uses it to power long-haul trucks that transport milk to surrounding states.

In addition to GHG reductions, other benefits have been associated with RNG projects, including

- securing a long-term, fixed-price fuel source to avoid fossil fuel price volatility;
- enhancing the local economy through development of new revenue streams, job creation, and energy savings for businesses and local governments operating vehicle fleets (U.S. Department of Agriculture et al. 2014, 2015);
- reducing waste management costs (for example, landfill tipping fees, hauling costs) U.S. Department of Agriculture et al. 2015);
- reducing air pollutants that harm public health, including nitrogen oxides and particulate matter (ICF 2017); and
- selling and using by-products of anaerobic digestion, including fiber that can be used for animal bedding and nutrients that can be preserved and used as soil amendments.

Plentiful RNG feedstocks exist where biogas is already being produced or could potentially be produced and collected. Biogas is already being captured and used to produce energy at 682 landfill gas projects, 64 of which are upgrading the landfill gas for direct fuel use or pipeline injection (U.S. Environmental Protection Agency 2017f). The EPA estimates that an additional 400 candidate landfills could cost-effectively produce electricity or fuel with biogas, about half of which already have a gas collection system in place. The U.S. Department of Agriculture (USDA) identified 250 operational digesters at livestock farms as of May 2016, and the EPA estimates that biogas recovery systems are technically feasible at about 8,000 additional dairy and hog farms (U.S. Environmental Protection Agency 2016, 2017e). Wastewater treatment plants are an emerging source of biogas production for energy use as well. Anaerobic digestion is currently used to manage waste at more than 1,200 wastewater treatment facilities out of more than 3,100 facilities that process more than 1 million gallons of wastewater per day, but only about 10 percent of facilities put collected biogas to use (U.S. Department of Agriculture et al. 2014; Langholtzet al. 2016). The EPA estimates that more than 2,400 additional digesters could be added at wastewater treatment plants that treat more than 1 million gallons of water per day. Where biogas is used for energy, it is typically used for electricity or combined heat and power generation rather than upgraded for use as RNG (Langholtz et al. 2016).

A DOE assessment of wet feedstocks for biofuel production found that these resources are currently underutilized. The department estimates that 77 million dry tons of food waste, animal manure, wastewater sludge, and FOG are produced every year. About 27 million dry tons per year are already beneficially used, leaving 50 million dry tons of feedstocks potentially available for use, an inherent energy content equivalent to 6 billion gallons of diesel (U.S. Department of Energy 2017a).

Box 1 | RNG Projects on the Ground in the United States

The three examples below provide an illustration of the variety of RNG projects that can be economically viable. A database of RNG projects does not currently exist, but more examples and case studies can be found at Energy Vision (2017), U.S. Department of Energy (2017b), and U.S. Environmental Protection Agency (2017d, 2017e).

The **St. Landry Parish, Louisiana, landfill gas project** opened in 2012 to upgrade landfill biogas into RNG to fuel local municipal vehicles. In 2015, the facility was expanded, and additional fuel is now being sold to Progressive Waste, a private waste management company, in a long-term offtake agreement. The project produces 175,000 gallons of gasoline equivalent per year, which powers 20 municipal vehicles and 10 to 15 waste trucks. The project is entirely off-grid (that is, not injected into the natural gas pipeline). The fuel for municipal vehicles is distributed at an on-site fueling station, and the gas sold to Progressive Fueling is transmitted to a private fueling station by truck. Public and private partners in the project includes St. Landry Parish Solid Waste Commission, BioCNG (a biogas upgrading company), Progressive Waste, and other contractors and consultants. Capital investments for the first two phases of the project were estimated at about $3.5 million and were funded in part through state grants and tax incentives, with an estimated payback period of 7 to 10 years (Energy Vision 2017).

CR&R Waste and Recycling Services developed a large-scale source-separated anaerobic digester in Perris, California, which produces RNG from food and yard waste from the City of Perris and the surrounding region. The project's first phase was fully operational in April 2017. Once operations are fully scaled up (four phases total), the project will be able to produce 4 million gallons of diesel equivalent fuel per year and 260,000 tons of fertilizer. CR&R will fuel its entire fleet of 900 waste management vehicles with RNG from the project. The CR&R project is the first project in California to inject renewable natural gas into the pipeline for vehicle fuel use, in partnership with the Southern California Gas Company, allowing for distribution of the fuel throughout the state. Total capital costs for the first phase of the project were $55 million, partially funded by state grants. CR&R will also generate revenue to contribute to future funding by charging residents to collect the food and yard waste it uses as feedstock (Energy Vision 2017).

Fair Oaks Dairy in Indiana produces RNG from livestock manure on the farm and uses it to power long-haul trucks that transport milk to surrounding states. The project produces a maximum of 1.5 million diesel gallon equivalent fuel per year, enough to fuel 42 milk trucks. The biogas is produced and upgraded to RNG on-site and sent to two off-site fueling stations by pipeline. The digestate is used to produce fertilizer that is then used on the farm. The total plant cost was estimated at $18.5 million, largely privately financed by Fair Oaks Dairy and Amp Americas, a private RNG producer and distributor, with a small amount covered by federal funds. A state grant was used to cover some of the costs associated with the natural gas trucks. The project has an estimated payback period of about 10 years. Amp recently announced a second dairy digester RNG project at an adjacent farm in Fair Oaks, Indiana. Once operational, later this year, it will be the largest project of its kind in the United States (Energy Vision 2017; Zimmerman 2017).

However, these sources would not necessarily generate net GHG reductions in every case, as we discuss in Section 2. In addition, more work is needed to estimate the technical or market potential of RNG that could be produced from these resources given shifting market dynamics over time, competition among various feedstocks and end uses, energy prices, incentives and other revenue streams, and other factors. Only a few studies have gone beyond an assessment of feedstock availability to estimate the technical or market potential of RNG that can be produced from these sources at the national level:[9]

- Hamberg et al. (2012) estimated that 4 billion dge could be economically practical from landfill gas (or food and yard waste), wastewater sludge, and livestock manure.
- The American Gas Foundation (2011) estimated the market potential of RNG at 335–871 trillion British thermal units of energy per year from landfill gas, wastewater sludge, and animal manure.
- The U.S. Department of Agriculture et al. (2014) estimated that 2 billion dge could be technically feasible to produce from wastewater sludge, landfills, and livestock manure.
- Saur and Milbrandt (2014) estimated that 6 million tons of biogas is technically available for upgrading to RNG (not counting biogas already being used for other purposes) from landfills, wastewater treatment, manure, and industrial, institutional, and commercial food waste.

Most market estimates are calculated by assuming that some proportion of the total feedstock availability can feasibly be captured and not based on a dynamic approach that incorporates production costs, energy prices, and other factors over time. Because these studies take a variety of different approaches—including feedstocks considered, methods and assumptions, and outputs—their results aren't readily comparable.

ACHIEVING CLIMATE BENEFITS FROM RNG PRODUCTION AND USE

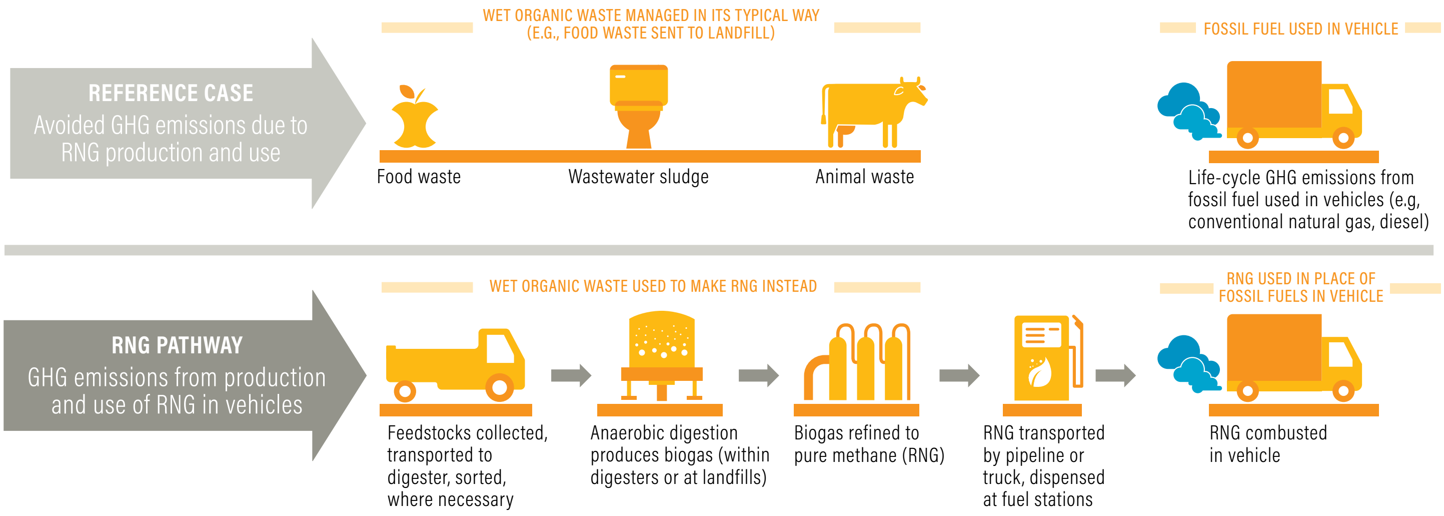
Municipalities, states, companies, or other entities considering RNG as part of a climate strategy will need to ensure that RNG projects and policies result in deep GHG emission reductions.

Under What Conditions Can RNG Production and Use Achieve Large Net GHG Benefits?

Determining RNG's carbon intensity as a vehicle fuel requires a life-cycle accounting of energy use and GHG emissions from all stages of the RNG supply chain, from production through end use (also known as "well-to-wheels"), as well as the GHG emissions avoided as a result of RNG production and use of its coproducts.

Figure 4 provides a generic illustration of typical sources of emissions and avoided emissions across RNG supply chains produced from anaerobic digestion of wet waste sources. The counterfactual reference case pathway represents an assessment of how the waste materials would otherwise be managed if not digested and made into RNG. Food waste destined for a landfill, for example, may result in some methane leakage and some carbon dioxide emissions from landfill gas that is collected and flared. Animal waste on a farm may otherwise be placed in an open lagoon that would emit methane. The RNG pathway represents the new use of wastes as RNG feedstocks. The RNG pathway results in GHG emissions from all stages of the supply chain, including biogas production and processing, RNG distribution, and use of the fuel in the vehicle. This typically includes carbon dioxide, methane, and nitrous oxide emissions associated with heat and electricity used to produce and transport RNG and its intermediary products, management of leftover materials, combustion of RNG in the vehicle, and methane leaks that occur along the entire supply chain.[10] In some cases, use of intermediary or coproducts of RNG production can lead to avoided GHG emissions, including displacement of synthetic fertilizer with soil amendments produced during anaerobic digestion or displacement of grid electricity due to use of biogas to meet energy demands on site. The net life-cycle GHG emissions associated with RNG would be determined by calculating total well-to-wheels emissions

Figure 4 | **GHG Emissions and Avoided Emissions in Waste-Derived Renewable Natural Gas Pathways (assuming no land-use change impacts)**



Avoided GHG emissions can be larger than emissions from the RNG pathway when RNG is made from wet wastes that would otherwise cause methane emissions.

Note: This figure provides a generic illustration of typical sources of GHG emissions and avoided emissions across RNG supply chains produced from anaerobic digestion of landfill gas, food waste, sludge, and animal waste. In life-cycle GHG analyses of RNG pathways, emissions indicated by red arrows would be added, and avoided emissions depicted by blue arrows would be subtracted or added as a negative GHG credit. This illustration is not intended to provide a complete picture of all emission sources in any given pathway, which will need to be assessed on a case-by-case basis, and it does not apply to RNG pathways that require dedicated uses of land.
Source: WRI.

associated with the RNG pathway (shown in the bottom panel of Figure 4) and subtracting the avoided emissions from the reference case and use of RNG coproducts (top panel). RNG's net GHG emissions will be negative when reference case emissions are greater than emissions under the RNG pathway.

The GHG impact of an RNG project or policy can be determined by comparing its net life-cycle emissions to that of the fossil fuel it replaces, which will typically be either diesel fuel or conventional natural gas in the case of heavy-duty vehicles. The net life-cycle emissions or life-cycle carbon intensity of RNG can also be useful for comparing against other low-carbon technology and fuel options available to policymakers and fleet owners, including electric vehicles, hydrogen fuel cell vehicles, and other biofuels (for example, biodiesel). A comparison of alternative fuel options based on GHG emissions, cost, feasibility, and other environmental impacts (for example, emissions of local air pollutants, water use) is beyond the scope of this working paper but would be a useful topic for further research.

RNG production and use will generate significant net GHG reductions compared to fossil fuels used in vehicles when its well-to-wheels emissions, including all sources noted in Figure 4, are much lower than the emissions that would otherwise occur under the reference case. This will generally occur if RNG meets two conditions, described in detail below:

1. *RNG must be produced from waste rather than dedicated uses of land or biomass diverted from other uses that would likely be replaced at significant cost*

The use of waste feedstocks for RNG holds the potential for GHG emission reductions while avoiding competition with food, timber, and other human needs, as well as ecosystems and their carbon storage.

Use of dedicated crops for bioenergy, including RNG production, generally cannot provide a sustainable long-term solution to climate change. As WRI has discussed in previous work, given its high and growing demands for food production, natural carbon storage, and to support biodiversity, the world lacks spare land to produce bioenergy. The world's population is on a course to demand roughly 70–100 percent more food over the next 40 years, including not only crops but also milk and meat from animals fed by grasses. Even without additional competition from bioenergy, it will be a great challenge to preserve the world's natural carbon sinks—a vital strategy to avoid the worst impacts of climate change—while meeting rising food demands and other human needs (Searchinger and Heimlich 2015).

In addition to the lack of true surplus lands, land always has an opportunity cost, not just in economic terms but in carbon terms as well. In general, any land productive enough to produce some kind of crop for bioenergy economically is also productive enough at a minimum to grow trees and sequester carbon or to produce food. The former directly stores carbon and therefore holds down climate change and the latter frees other land to store carbon by meeting human needs. Even lands sometimes characterized as marginal have important opportunity costs in this way. Many lands treated as marginal are simply poor croplands but not poor for other uses. In general, analyses that have found benefits from dedicating land to bioenergy have ignored these carbon opportunity costs.

Examples of exceptions where crops for bioenergy would not compete with land use might include new production of cover crops where cover crops for food production are implausible or intercropped grasses or shrubs for bioenergy in tree plantations (Searchinger and Heimlich 2015).

In addition, determining what feedstocks constitute waste could be complex in some cases. The simplest definition of waste is a product that has no alternative use; but alternative uses typically depend on economics, and the economics often change over time. A waste at one time becomes a valuable product at another. As an extreme example, gasoline was once the thrown-away waste product of kerosene production. Some potential feedstocks may have alternative uses that are sufficiently marginal to ignore. Inevitably, alternative use will often be a question of degree.[11]

One potential criterion could be to determine whether diversion of a potential feedstock for energy production is likely to result in replacement by other materials whose production involves significant GHG emissions or other social and environmental costs. If not, the material can be considered a waste. Typical wet feedstocks are generally likely to meet this criterion, although in some cases they are currently used for other bioenergy purposes (see

Box 2 | Shifting Feedstocks from Other Bioenergy Uses to RNG for Vehicle Fuel

Most biogas that is currently collected and used for energy at landfills, livestock operations, and wastewater treatment plants is used for power or heat applications, driven in part by renewable electricity markets and other renewable policies (Murray et al. 2014; Russell et al. 2017). However, the economics are shifting with increasing incentives provided by renewable vehicle fuel markets, greater availability of lower-cost renewable electricity resources (that is, wind and solar), and increasingly stringent air quality regulations that power generators must meet (Miller et al. 2015). Operators of some existing biogas projects are finding that they are offered much lower rates from utilities when their power purchase agreements expire (U.S. Department of Agriculture et al. 2015). As a result, sites currently using biogas for power and/or heat may choose to shift resources to RNG production for vehicle fuel after or even before current power purchase agreements expire.

While these decisions will largely be driven by economics, policymakers using RNG as part of a climate portfolio will need to consider the GHG impacts of shifting resources already being used for other bioenergy applications to RNG for vehicle fuel. In general, the greatest GHG benefits of RNG can be achieved by using waste that is not currently being used to produce bioenergy. The issue is one of additionality: GHG reductions only result from additional efforts. Because biogas is likely to replace fossil fuels, whether used for heat and power or for use in vehicles, shifting resources that are already being used for electricity production is unlikely to result in very large additional GHG emissions reductions.

However, exceptions may exist. For example, RNG could lead to additional reductions if producers would otherwise begin flaring their biogas if they were unable to renew their current power purchase agreements. It could also potentially be more beneficial from a climate and economic perspective to upgrade biogas to RNG for applications that can't be easily or cheaply electrified, like heavy-duty vehicles, rather than electricity generation where other low-cost, zero-carbon resources like wind and solar already exist. However, innovations in electric battery and hydrogen fuel cell electric trucks and buses by Tesla, Nikola, and others may open up opportunities for electrification of heavy-duty transportation more quickly than once expected. The Union of Concerned Scientists (2017) argues that RNG could be used most efficiently and achieve the greatest potential GHG reductions when used to power electric vehicles rather than as a vehicle fuel in itself.

The net impact of shifting existing feedstocks to RNG will depend on the relative efficiency of use, the electricity mix currently being replaced with electricity from biogas, and other factors that would need to be determined on a context-specific basis using a life-cycle GHG assessment, as described in more detail in the main text. Further analysis of the relative benefits of RNG in competing applications or the best use of feedstocks in various potential bioenergy applications could help inform further evaluation of RNG as part of a climate change strategy (for example, full life-cycle analyses of various end uses for feedstocks as described in Miller et al. [2015]). We do not conduct such an evaluation in this paper.

Box 2). Some forms of agricultural, forestry, and green residues that are composted, landfilled, or burned could also meet this criterion (Miller et al. 2015; Jaffe et al. 2016). Deeper analysis of the social and environmental implications of using various feedstocks for RNG would be appropriate.

2. *RNG production and use must reduce methane emissions.*

Because methane, the main component of natural gas, is a much more potent GHG than carbon dioxide, its capture or avoided release from existing sources provides one of the greatest potential advantages of RNG. However, in some contexts, RNG production does not result from methane capture and, instead, comprises *new methane*, which we define as methane that would not otherwise have entered the atmosphere. New methane will generally be produced when management of feedstocks used for RNG would otherwise have resulted in carbon dioxide emissions, as indicated in the following examples:

1. The feedstocks used to produce RNG would have decomposed largely as carbon dioxide in typical management practices. This is generally the case for dry feedstocks, which would decompose in the presence of oxygen or be burned, primarily producing carbon dioxide rather than methane. If these feedstocks are converted to RNG instead, most of the methane produced would be new methane (U.S. Environmental Protection Agency 2015).

2. The feedstocks used to produce RNG would have produced methane during decomposition, but that methane would be captured and combusted as part of typical waste management practices, therefore entering the atmosphere largely as carbon dioxide. This is the case at many landfills and wastewater treatment plants where biogas is captured and either burned as an air pollution management strategy (that is, flared) or for energy use. Flaring at these sites typically converts 98–99 percent of the methane burned to carbon dioxide (U.S. Environmental Protection Agency 2011).

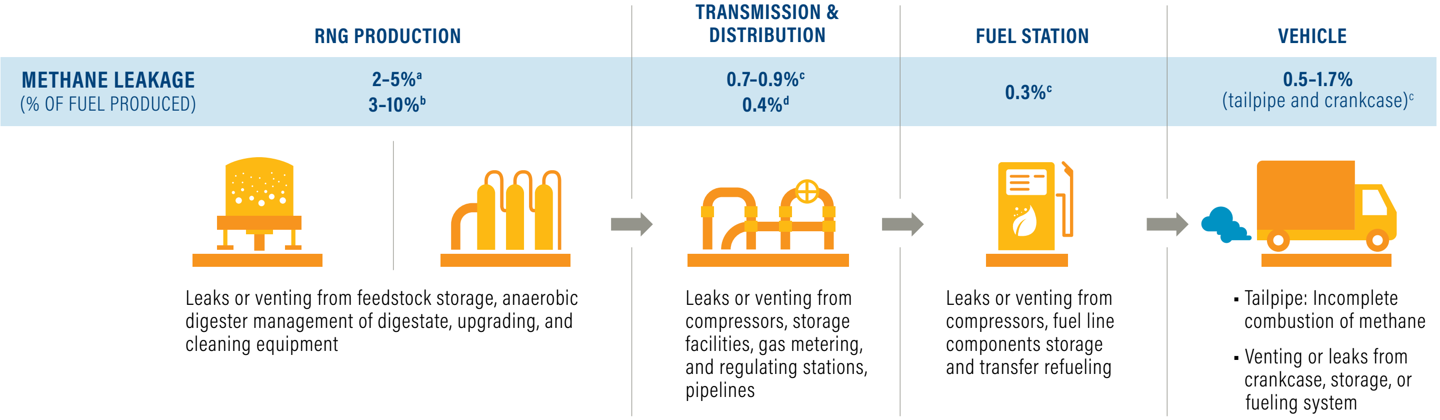
3. Anaerobic digestion techniques lead to more methane production than would have occurred under typical management practices. This may occur when a primary feedstock is supplemented with other wastes, including FOG, food scraps, or agricultural waste, as a means to increase total methane production, a practice commonly used with animal manure and wastewater sludge (Linville et al. 2015).

The circumstances under which new methane is produced may change as the reference case changes over time due to shifts in management practices and technologies.

RNG projects that lead to new methane production can lead to a net increase in methane emissions due to methane leaks and venting that occurs throughout the RNG supply chain, which includes components specific to RNG, namely biogas production and upgrading, as well as those shared with conventional natural gas; namely, distribution in natural gas pipelines and fueling stations and combustion in natural gas vehicle engines. Common sources of methane emissions include leaks from the seals of anaerobic digesters during biogas production, venting and off-gassing during upgrading, leaks from compression equipment and pipelines during transmission and distribution, leaks in valves or other fueling system components at the pump, and incomplete combustion of methane, as well as other leakage and venting when RNG is used in vehicles (Figure 5).

Similar to conventional natural gas, such leaks can erode or outweigh RNG's climate benefit relative to petroleum-based fossil fuels and other alternative fuels (Bradbury et al. 2013). By a back-of-an-envelope calculation, loss of more than 3.3 to 4.5 percent of any new methane via leaks and venting before the gas is actually burned could cancel out the climate benefits of RNG that comprises new methane, compared to petroleum-based fuels.[12] In practice, this leakage threshold could be lower when accounting for fossil fuel use along the supply chain, inefficiencies of RNG use compared to use of petroleum-based fuels, and the warming potential of methane within shorter time periods than 100 years. For example, studies on conventional natural gas have shown that system-wide leakage rates would need to be below 0.8 percent of total natural gas production for heavy-duty vehicles running on compressed natural gas to have immediate climate benefits over petroleum-based fuels (Alvarez et al. 2012; Camuzeaux et al. 2015).

Figure 5 | **Estimates of Methane Leakage across the Renewable Natural Gas Supply Chain**



	RNG PRODUCTION	TRANSMISSION & DISTRIBUTION	FUEL STATION	VEHICLE
METHANE LEAKAGE (% OF FUEL PRODUCED)	2-5%[a] 3-10%[b]	0.7-0.9%[c] 0.4%[d]	0.3%[c]	0.5-1.7% (tailpipe and crankcase)[c]
	Leaks or venting from feedstock storage, anaerobic digester management of digestate, upgrading, and cleaning equipment	Leaks or venting from compressors, storage facilities, gas metering, and regulating stations, pipelines	Leaks or venting from compressors, fuel line components storage and transfer refueling	▪ Tailpipe: Incomplete combustion of methane ▪ Venting or leaks from crankcase, storage, or fueling system

Note that RNG projects only have the potential to increase net methane emissions to the atmosphere in certain contexts, described in more detail in the text.

Notes:

[a] Commonly used in life-cycle GHG analyses of RNG by Argonne National Laboratory and the California Air Resources Board; based on Börjesson and Berglund (2006).

[b] UNFCCC 2012.

[c] Delgado and Muncrief 2015.

[d] Littlefield et al. 2017.

The transmission and distribution, fuel station, and vehicle aspects of the supply chain are common to renewable natural gas and conventional natural gas. Methane leakage rates from transmission and distribution, the fuel station, and the vehicle are from recent syntheses of data or literature reviews. Because we are unaware of any syntheses of methane leakage rates from RNG production (including anaerobic digestion, cleaning, and upgrading), we present leakage rates that are commonly used in life-cycle analyses of RNG or used for reporting purposes in GHG inventories. Leakage rates in some studies are expressed in terms of percentage of fuel delivered, but converting to percentage of fuel produced does not change the estimates shown here.

Source: WRI.

Significant research has been conducted to improve estimates of methane leakage rates from conventional natural gas systems (Environmental Defense Fund 2017). This work provides useful insights into leakage rates from parts of the supply chain shared with RNG. Recent literature has estimated methane leakage rates of 0.4–0.9 percent of fuel produced from transmission and distribution, 0.3 percent from the fueling station, and 0.5–1.7 percent from the vehicle tailpipe and crankcase. Pipeline compressor stations and use in the vehicle were the largest downstream sources of methane emissions noted in these studies (Delgado and Muncrief 2015; Littlefield et al. 2017). A recent study by Clark et al. (2017) also identified vehicles as significant sources of methane leakage, with rates ranging from 0.5 to 3 percent of fuel consumed, depending on the type of vehicle.

Less work has focused on leakage from RNG production, including anaerobic digestion, upgrading, cleaning, and/or storage of biogas. While several studies have assessed leakage in specific contexts, we are not aware of any work that has synthesized data on leakage from various RNG feedstocks or production processes in the United States. Leakage rates of 2–5 percent of biogas produced from anaerobic digestion and 2 percent of biogas processed for upgrading are commonly used in life-cycle analysis of RNG produced from wet wastes (Han, Mintz, and Wang 2011; California Air Resources Board 2014a). Default leakage rates for biogas production systems for international inventories and reporting standards range from about 3 to 10 percent, depending on digester type (UNFCCC 2012; IPCC 2006).[13] (In the context of new methane from wet wastes, leakage from biogas production wouldn't increase net methane emissions in cases where anaerobic digestion would have happened as part of typical management practices.)

Given the importance of methane leakage, companies, municipalities, and states considering RNG as a climate strategy will need to evaluate whether new projects or policies will lead to new methane production and estimate leakage rates along the supply chain using the most robust data available. Because methane is a short-lived climate pollutant, these entities may want to assess life-cycle GHG impacts over multiple time horizons, including shorter time frames in addition to the commonly used 100-year time frame. The 20-year global warming potential for methane, which is 84–86 times that of carbon dioxide, is sometimes used. Alvarez et al. (2012) developed a methodology that enables comparison of fuels over a continuum rather than a single specified time horizon, which can be used to determine to what extent and over what time frame fuel switching would yield a climate benefit.

Many strategies are available to reduce methane leakage, although they may not always be under the control of the producer or end user of RNG. RNG producers can use efficient technologies and operational practices to limit leakage from anaerobic digestion, where relevant, as well as biogas upgrading (for example, see Jonerholm and Lundborg 2012; Sun et al. 2015) New project developers can choose project locations or types that reduce leakage compared to others. For example, locating RNG production or processing closer to end users can reduce pipeline leakage, or using RNG for on-site fueling can eliminate pipeline leakage. Fleet owners and operators can choose technologies to limit leakage from vehicle use, such as closed crankcase technologies, which are now commercially available (Clark et al. 2017). Leakage that occurs throughout the transmission and distribution network generally is beyond the control of RNG producers and end users and will require concerted action to reduce. However, state and local policymakers can put policies in place to address leakage from these sources as part of their overall climate change strategies. Companies can reduce these emissions with cost-effective technologies that are currently available to cut emissions from transmission and distribution of natural gas from compressor stations to storage tanks to pipelines (Bradbury et al. 2013; Warner et al. 2015).

Further data and analysis on methane leakage specific to RNG is needed. It would be useful, for example, to understand the maximum leakage rates at which RNG has climate benefits over diesel fuel over various time horizons, similar to the studies that Alvarez et al. (2012) and Camuzeaux et al. (2015) conducted around conventional natural gas.

Which RNG Projects Can Meet These Conditions?

RNG produced from wet wastes that are presently already leading to methane emissions in typical management practices is most likely to meet both conditions described previously. These projects generally include food and yard waste in landfills or diverted from landfills, wastewater sludge, FOG, and manure from livestock operations (Table 1). Avoided methane emissions account for the very low and negative carbon intensities estimated for RNG from some types of wet waste estimated by other organizations, including the California Air Resources Board for implementation of its low-carbon fuel standard (for example, dairy manure and food and green waste).

While WRI doesn't endorse any specific RNG life-cycle GHG analysis, CARB's certified RNG pathways provide a reasonable starting point for estimating the GHG reduction potential of RNG from wet sources (Figure 6). Certified life-cycle carbon intensities of RNG range from about 50 percent to well over 100 percent less carbon-intensive than fossil fuels. The landfill gas pathways are 53 percent less carbon-intensive than diesel fuel and 44 percent less carbon-intensive than natural gas on average; and the wastewater sludge pathways are 81 percent less carbon-intensive than diesel and 77 percent less intensive than conventional natural gas, respectively (California Air Resources Board 2018). The carbon intensities of RNG from anaerobic digestion of food and green waste and from dairy manure are negative because of credits given for avoided methane emissions, an average of -264 grams carbon dioxide equivalent per megajoule (gCO_2e/MJ) for RNG derived from dairy manure and -23 gCO_2e/MJ for the single approved pathway for RNG from source-separated food and green waste. RNG from these sources is the least carbon-intensive fuel option of any alternative under California's low-carbon fuel standard. However, these estimated carbon intensities are sensitive to assumptions used to conduct the analysis (see Box 3).

Table 1 | **Achieving Large GHG Reductions with RNG**

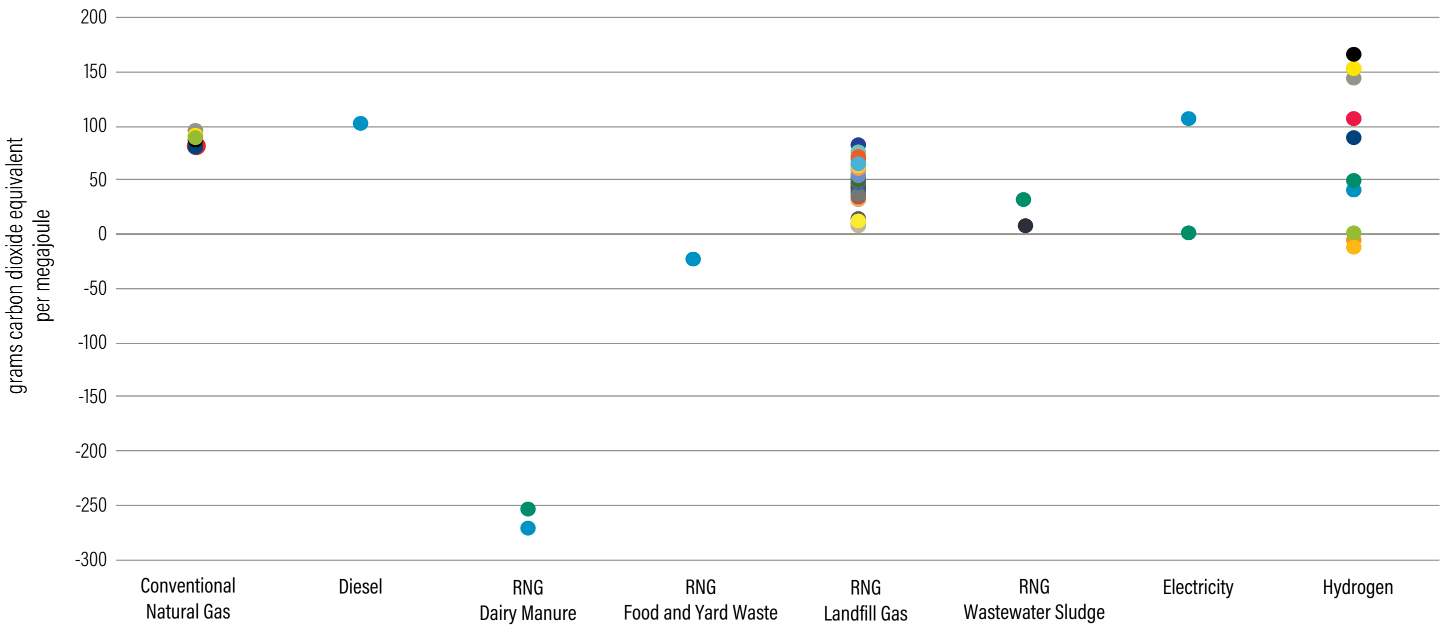
RNG IS MOST LIKELY TO ACHIEVE LARGE NET GHG REDUCTIONS COMPARED TO FOSSIL FUELS USED IN VEHICLES WHEN IT MEETS TWO CONDITIONS:

1. It is made from waste rather than dedicated uses of land.
2. Its production and use reduces methane emissions.

RNG PROJECT TYPES MOST LIKELY TO MEET BOTH CONDITIONS:

- food and yard waste diverted from landfill disposal
- livestock manure where methane is currently uncontrolled
- sludge at wastewater treatment facilities that aren't already capturing methane
- landfill gas from landfills that aren't capturing methane or that significantly increase the amount of methane they capture when producing RNG

Figure 6 | **Life-Cycle Carbon Intensities of RNG and Other Transport Fuels Certified under California's Low-Carbon Fuel Standard**



Source: California Air Resources Board 2017d.

Box 3 | Assumptions Used in the California Air Resources Board Certified RNG Pathways

The California Air Resources Board assumes a 100-year global warming potential of 25 for methane and provides the default methane leakage assumptions listed in Table 2 in the model underlying certified carbon intensities of RNG fuel pathways (CA-GREET 2.0). These assumptions, among others, will significantly affect the life-cycle carbon intensities of RNG calculated using this tool. As we discuss in the text, methane leakage rates from biogas production and processing have not been well studied. If life-cycle analyses underestimate these or other methane leakage rates along the supply chain, the actual carbon intensities of RNG would be higher. Recent work by Clark et al. (2017), for example, found higher leakage rates from some types of vehicles than currently used as default assumptions in the GREET tool. Likewise, if policymakers or other potential RNG project developers are concerned about the warming potential of methane along a shorter time period than 100 years, a higher global warming potential for methane would be appropriate, which would decrease the calculated carbon intensities for RNG pathways that lead to a net reduction in methane produced (for example, animal manure and food and green waste) and increase the calculated carbon intensities for pathways that lead to a net increase in methane produced (for example, wastewater sludge). Sensitivity analysis of RNG carbon intensities based on a range of assumed leakage rates, global warming potential, and other key assumptions would be helpful to get a better sense of the range of potential GHG reductions possible with waste-derived RNG.

Table 2 | Default Methane Leakage Rates from Waste RNG Pathways Certified by the California Air Resources Board

RNG PATHWAY	METHANE LEAKAGE RATE	SOURCE
ANAEROBIC DIGESTION		
Livestock Manure	2–5% of initial methane produced[a]	California-modified Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation tool (CA-GREET 2.0), Dairy CNG Template, Offset Credit Tab, April 17, 2017, https://www.arb.ca.gov/fuels/lcfs/ca-greet/ca-greet2-dairycng.xlsma
Wastewater Sludge	1% of initial methane produced	CA-GREET 2.0, RNG Tab, September 29, 2015, https://www.arb.ca.gov/fuels/lcfs/ca-greet/ca-greet.htm
BIOGAS CONDITIONING		
Landfill Gas	1% of methane at inlet to upgrading	CA-GREET 2.0, RNG Tab, September 29, 2015, https://www.arb.ca.gov/fuels/lcfs/ca-greet/ca-greet.htm
Livestock Manure	2% of RNG at inlet to upgrading	CA-GREET 2.0, Dairy CNG Template, Offset Credit Tab, April 17, 2017, https://www.arb.ca.gov/fuels/lcfs/ca-greet/ca-greet2-dairycng.xlsm
Food and Green Waste	1% of initial methane produced plus 2% of purified methane[b]	CARB Certified High-Solids Anaerobic Digestion Pathway, (California Air Resources Board 2012)
Wastewater Sludge	1% of methane at inlet to upgrading	CA-GREET 2.0, RNG Tab, September 29, 2015, https://www.arb.ca.gov/fuels/lcfs/ca-greet/ca-greet.htm
TRANSMISSION AND DISTRIBUTION	0.4% OF NATURAL GAS THROUGHPUT	CA-GREET 2.0, INPUTS TAB, SEPTEMBER 29, 2015, HTTPS://WWW.ARB.CA.GOV/FUELS/LCFS/CA-GREET/CA-GREET.HTM
USE IN VEHICLE	0.0375 GRAMS OF METHANE EMISSIONS PER MILE	CARB CERTIFIED HIGH-SOLIDS ANAEROBIC DIGESTION PATHWAY (CALIFORNIA AIR RESOURCES BOARD 2012)

Notes:

[a] Methane leaks from the digester are based on CARB's Livestock Offset Protocol under California's cap-and-trade program (https://www.arb.ca.gov/regact/2014/capandtrade14/ctlivestockprotocol.pdf). Biogas collection efficiencies in the Protocol are 98 percent for complete mix, plug flow, or fixed film digesters, 95 percent for bank-to-bank impermeable covered anaerobic lagoons, and (95 percent * percent area covered) for partial area, impermeable anaerobic covered lagoons.

[b] Methane leaks from this pathway are from feed and product gas compressors.

Further analysis of life-cycle carbon intensities of various RNG pathways, including sensitivity analyses under a range of potential leakage rates and other assumptions, would improve our understanding of waste-derived RNG's GHG reduction potential.

In cases where biogas produced by wet wastes is collected and flared as part of typical management practices—which is the case at many landfills and wastewater treatment plants—production of RNG may lead to a net increase in methane produced. For example, The California Air Resources Board's certified wastewater sludge-to-RNG pathway indicates that RNG production at medium-to-large wastewater treatment plants can increase methane emissions by at least 34 percent, from 704,000 grams of methane per day to 940,000 grams per day, because biogas at these facilities would otherwise be flared (California Air Resources Board 2014a).[14] In these cases, the calculated life-cycle carbon intensities may still be lower than fossil fuels due to the avoided carbon dioxide emissions from flaring. RNG from medium-to-large wastewater treatment plants had a calculated life-cycle carbon intensity around 8 gCO_2e/MJ, despite the increase in methane emissions, which is 11 times lower than the carbon intensity of conventional natural gas. However, if methane leakage rates are higher in reality than what is assumed in the analysis, RNG may be less beneficial from a climate perspective or may actually lead to a net increase in GHG emissions.

Given what we know about leakage today, and the uncertainty around leakage rates from RNG production, it could be risky to include these resources as part of a climate strategy, unless new RNG projects can achieve significant improvements in the efficiency of existing biogas collection systems. Landfill gas collection systems are highly inefficient, with uncontrolled emissions in the range of 15 to 25 percent of biogas produced (California Air Resources Board 2012). Opportunities may exist to increase the efficiency of gas capture at landfills, even those in compliance with new source performance standards; for example, by increasing the frequency with which gas collection wells are monitored and adjusted. Operators of landfill gas-to-RNG projects have an incentive to invest time and money in technological or operational improvements and repairs to maximize the amount of gas that can be captured and upgraded. If infrastructure improvements associated with a new RNG project increased collection efficiencies beyond current levels (and beyond levels required by any applicable existing regulations), not all of the RNG would comprise new methane.

We aren't aware of research that broadly investigates how much collection efficiencies have been or could be improved due to implementation of RNG projects at landfills with existing collection systems in place. However, case studies from the automated landfill gas collection company Loci Controls demonstrate the increases in gas capture and reduction in frequency of gas diversions to flare that have been documented from one technological approach on the ground at landfill gas-to-RNG projects, among other project types (Loci Controls 2018a). Implementation of the company's automated collection system increased gas collection by 17 percent at a southwestern landfill gas-to-RNG project, for example (Loci Controls 2018b). The company indicates that its experience with the technology has shown increases in gas collection in the range of 10 to 30 percent across existing projects and demonstrations, with higher levels of improvement noted in some exceptional cases.[15] Research into the potential for RNG projects to reduce methane emissions at landfills with existing gas collection systems and documentation of improvements made on the ground would be helpful, given how financially attractive these sites are for new projects, as discussed in more detail in Section 3.

Similar risks would arise with RNG production from dry feedstocks, which would otherwise mostly produce carbon dioxide when they decompose. This means that RNG from agricultural, forestry, and other woody residues that may be considered waste may not meet the second condition. Likewise, even if energy crops could meet the first condition, they may not meet the second condition. Although dry feedstocks are not currently used as primary sources of RNG, the commercialization of thermal gasification technologies could enable their use in the future, and many resource assessments of RNG potential include them (for example, Hamberg et al. 2012; Murray et al. 2014). Research on the life-cycle GHG emissions and other environmental and economic implications of these feedstocks is therefore needed.

In any case, RNG project and policy developers will need to determine the net GHG impacts of RNG on a case-by-case basis, since emissions will vary not only on the basis of feedstocks, but on project location, technology and processes used for collection, production and end-use, and other factors (Mintz 2015a; Jaffe et al. 2016). Life-cycle analysis of vehicle fuels provides a systematic method to account for energy use and GHG emissions at all stages in the life cycle of fuel, and different organizations have developed a variety of models to calculate life-cycle emissions of fuels. They include the publicly accessible GREET model developed by Argonne National Laboratory and modifications of that model used by the California Air Resources Board (CA-GREET. Because the GREET model does not factor in indirect land-use change, it could not be used to evaluate biomass from dedicated uses of land, which would generally not meet our first condition.) In addition, some models are targeted specifically toward corporate fleets, such as Business for Social Responsibility's Fuel Sustainability Tool (Business for Social Responsibility 2016). WRI does not endorse any particular model or the assumptions used in existing life-cycle analyses conducted with these models, but they can serve as useful tools and foundations for further analysis.

Although well-to-wheels must always be the ultimate focus, different actors may approach the calculations differently. For example, a fleet owner with its own pumps that buys RNG from a generic source will need to rely on broad calculations of average well-to-pump RNG emissions. But that fleet owner can do its own calculations of emissions at the pump and in its vehicles in generating a final GHG balance. By contrast, a producer of RNG will need to rely on generic calculations of emissions from RNG distribution and use but can use its own calculations of the production emissions that it can control directly.

One of the conventions in many life-cycle analyses of bioenergy that we do not recommend is to ignore the carbon dioxide released by burning the bioenergy fuel, which in this case would be RNG. Life-cycle assessments for various RNG feedstocks conducted by Argonne National Laboratory and California's Air Resources Board using GREET do include emissions from combustion of RNG in the vehicle. However, many life-cycle analyses of bioenergy more broadly ignore the carbon dioxide from burning the fuel due to the assumption that the carbon released by burning the biomass is offset by the carbon absorbed by the original plant growth that produced the biomass.[16] Failing to fully count both the emissions produced by the fuel itself and the carbon dioxide removals during photosynthesis can lead to errors or failure to fully appreciate the implications of bioenergy use, described in more detail in Searchinger et al. (2015).

Another critical issue in life-cycle GHG analyses is appropriate assessment of the reference case. It is critical that the reference case accurately reflect current waste management practices. For example, Argonne National Laboratory's assessment of RNG from dairy manure showed that a 10 percent change in the amount of methane assumed to be controlled and flared in the reference case led to a 130 percent change in the estimated net life-cycle GHG emissions of RNG (Han et al. 2011). And typical waste management practices may change over time. For example, anaerobic digestion of manure otherwise destined for an open lagoon reduces methane emissions and therefore generates GHG benefits. This methane reduction can be an important benefit of RNG today, but over time, due to new policies or voluntary shifts in manure management, the realistic alternative to RNG might be some kind of capture of this methane regardless—although its end usage may vary. The reference case would then involve not a simple release of the methane into the atmosphere, but a flaring of captured methane gas, for example. Realistically analyzing the current reference case and reanalyzing it over time, in light of new technologies and policies, is necessary for an accurate understanding of life-cycle GHG benefits.

Similarly, accurate assessment of the fuel RNG replaces will also be necessary. In the near term, RNG may largely be used to replace conventional natural gas in existing natural gas vehicles. But in specific projects and contexts and over the longer term, RNG may displace the use of diesel as fleets transition directly to natural gas vehicles that run on RNG. When RNG displaces diesel, it can lead to additional carbon dioxide reductions since diesel emits more carbon dioxide per unit of energy than natural gas. However, the relative impact of methane leakage could be greater than in cases where RNG replaces conventional natural gas.

ECONOMIC FEASIBILITY OF RNG FROM WET WASTES

In addition to GHG and other environmental implications, entities considering RNG as a climate strategy also need to assess its economic feasibility. Of course, determining whether a project is economically feasible or attractive is largely in the eye of the beholder. Depending on their motivations and resources, different entities can accept longer payback periods or higher up-front capital requirements than others. But early experiences on the ground indicate that a variety of different types of waste-derived RNG projects—including various feedstock types, production scales, and fuel buyers—can be economically feasible and cost-effective, in some cases with expected payback periods of 5 to 10 years or less. And resource assessments suggest that significant untapped potential remains to produce RNG from wet waste sources, which have the greatest potential to meet the criteria described in Section 2 and achieve large net GHG reductions.

In this section, we synthesize research on the economic feasibility of RNG production from wet waste sources, including production costs, sources of revenue, cost savings and incentives, and market potential.

Costs to Produce RNG from Wet Waste

The costs to produce RNG from wet wastes typically include

- collection, storage, sorting, and cleaning of feedstocks at projects that bring in waste from off site (for example, livestock manure or wastewater sludge projects that supplement with food waste and FOG);
- installation, operation, and maintenance of anaerobic digesters to produce biogas or a biogas collection system at landfills, where needed;
- installation, operation, and maintenance of conditioning equipment to clean and upgrade biogas into RNG; and
- equipment and infrastructure to distribute the finished RNG.

Total production costs vary widely by project due to many factors, including required capital investment, volume of production, transportation costs, and whether the gas is distributed through the natural gas pipeline network (Underwood and Tomich 2012; Murray et al. 2014; Miller et al. 2015; Jaffe et al. 2016; Russell et al. 2017), described below.

Capital investment required

Capital costs for RNG projects can be high, ranging from hundreds of thousands to tens of millions of dollars depending on the technologies used and the scale of production (Murray et al. 2014; Jaffe et al. 2016; Energy Vision 2017). Project developers can limit the capital investments required by locating projects at sites that require relatively less buildout than others. For example, landfill projects only require installation of a collection system to gather biogas that is already being produced from the organic waste disposed of on-site, rather than installation of a digester. Many landfills already have these collection systems in place (Miller et al. 2015). Likewise, projects at wastewater treatment plants and livestock farms that already have anaerobic digesters installed can avoid what would otherwise constitute a large proportion of total up-front costs (Jaffe et al. 2016). However, all RNG projects will require capital for conditioning equipment, which can be prohibitive for smaller-scale producers (Jaffe et al. 2016; Russell et al. 2017).

The magnitude of capital costs will also depend on the equipment and infrastructure needed to deliver and, in some cases, use the gas. If some of the RNG is used to refuel trucks on-site, project developers may need to construct a new fueling station with adequate storage capacity. If some or all of the gas will be used off-site, construction of pipelines may be necessary to reach an off-site fueling station or to connect with the natural gas distribution network. Fleets transitioning from diesel to RNG will need to purchase new natural gas vehicles or convert existing diesel engines to run on natural gas.

Volume of production

Production and conditioning of biogas show significant economies of scale. Upgrading and cleaning costs, for example, range from tens to hundreds of dollars per million British thermal units (MMBtu), depending on the volumes processed (Jaffe et al. 2016). Due to the distributed nature of waste feedstocks, it will not be practical to transport and convert them to gas in mass quantities (U.S. Department of Energy 2017a). However, some studies have suggested that aggregating feedstocks or biogas from multiple local sources into a single site for anaerobic digestion or biogas processing can help cut costs (Miller et al. 2015). For example, Jaffe et al. (2016) estimated that RNG project costs at California dairies could be cut by 60 percent through centralized conditioning and pipeline injection. Murray et al. (2014) estimated that centralized processing of biogas derived from manure would be 74 to 85 percent less costly than processing on individual farms. The potential to cut costs through use of different production models warrants additional research.

Transportation costs

The distances that feedstocks, biogas, and finished RNG must be transported along the supply chain significantly affect project costs and feasibility (Hamberg et al. 2012; Miller et al. 2015). Waste streams from wastewater treatment plants, landfills, and homes and businesses offer promising market potential in part because these sites are widely geographically distributed and typically located close to potential end users (U.S. Department of Energy 2017a). But costs to collect feedstocks and deliver the finished fuel can pose a challenge for sites like livestock operations, which have a large resource base but are located in rural areas or far from existing fueling stations or the pipeline network.

Pipeline distribution

RNG project developers will need to ensure that all the RNG continuously produced from a project can be sold to end users, and it can be a challenge to deliver all the gas to end users (Underwood and Tomich 2012). In most current projects on the ground, the RNG producer and/or project investor also use at least a portion of the gas produced—for example, in the case of municipalities that invest in landfill gas or wastewater projects and use the RNG to fuel their waste trucks and other municipal vehicles. This model allows states, municipalities, or private fleet owners to secure a long-term, fixed-cost gas supply. But local fuel demand may not be high enough to offtake all of the gas produced. When larger volumes are required for economies of scale or to satisfy local climate or waste-management objectives, pipeline distribution may be required to connect the supply with distant markets (Mintz 2015b; Miller et al. 2015).

Several studies have noted that pipeline injection carries high costs as well as logistical challenges of negotiating with utilities or pipeline operators that can be prohibitive for some projects (Miller et al. 2015; Jaffe et al. 2016; Russell et al. 2017; U.S. Department of Energy 2017a). Pipeline specifications vary by state and owner, and upgrading biogas to meet these requirements tends to be more expensive than direct use in vehicles because engine manufacturers guarantee performance at a lower energy content, although the on-site storage required for direct use can be costly as well. In addition to the costs of upgrading and cleaning the gas to meet pipeline standards, interconnection requires costs of pipeline construction to get the gas to the network, compression stations, and real-time or intermittent monitoring to ensure that the gas continues to meet injection standards. Total upgrading, cleaning, and interconnection costs are estimated in the tens to hundreds of thousands of dollars per site outside of California, and $1.5–3.5 million per site within California, where pipeline injection requirements are the most stringent in the United States (Russell et al. 2017). Although some utilities are interested in injecting RNG into their networks—not only for transportation use, but to offer to their residential, commercial, and industrial customers as well—they cannot invest in RNG infrastructure without regulatory approval (Russell et al. 2017).

California's Public Utility Commission is pioneering an approach to address this issue with a recently established incentive program to offset the costs of pipeline interconnection for RNG projects, up to $5 million per project for clustered dairy projects and up to $3 million for other individual projects, with total funding for the program capped at $40 million (Public Utility Commission of the State of California 2015; State of California 2016).

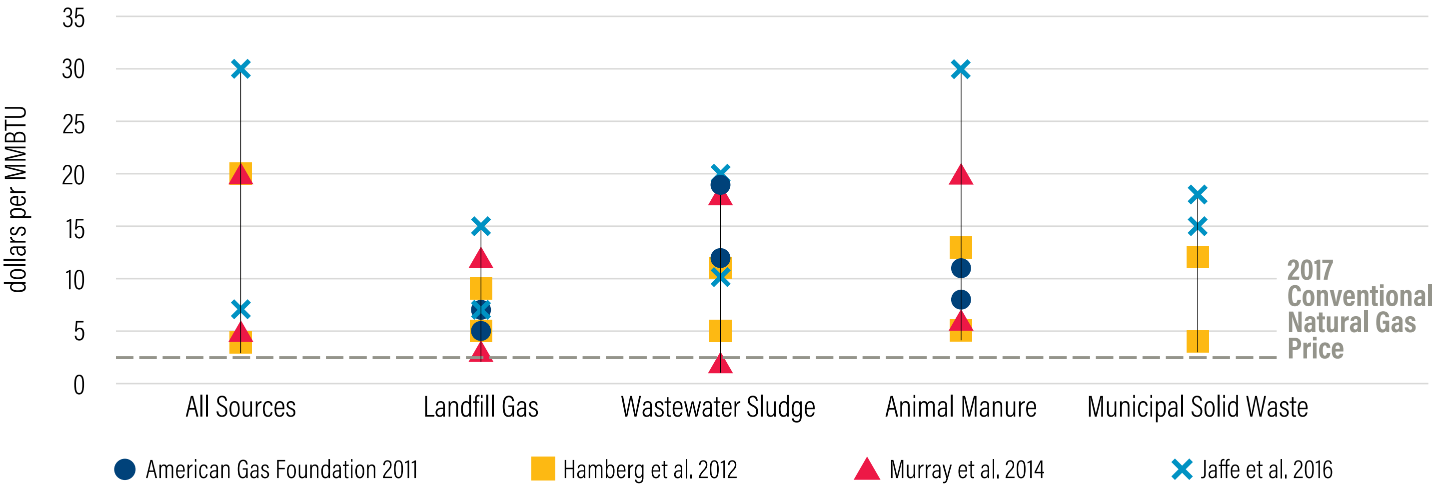
Cost Data

While data on the ground is limited, available estimates show that waste-derived RNG production tends to be relatively expensive, compared to conventional natural gas. Four recent studies provide synthesized cost estimates: The American Gas Foundation (2011) models average RNG production costs in the United States for two RNG market penetration scenarios based on cost data from available literature and its own previous estimates. Hamberg et al. (2012) provide a synthesis of estimates from the literature. Murray et al. (2014) calculate national supply curves using project data and technology estimates provided by equipment vendors. And Jaffe et al. (2016) calculate supply curves for resources in California using project data, estimates in the literature, and comments to the California Public Utility Commission. Cost estimates from these sources range from about $3–30/MMBtu for RNG derived from landfill gas, wastewater sludge, animal waste, and diverted food and yard waste combined (Figure 7), and the supply curves show that a significant amount of RNG could be supplied from these sources at $10/MMBtu or less. The wide range is in part due to differences among the studies in terms of data, methodology, and assumptions. However, costs also vary widely, project to project, on the basis of feedstock type, volume of production, infrastructure requirements, and location with respect to the pipeline, among other factors.

Meanwhile, conventional natural gas has averaged about $3.50/MMBtu since 2010, with average annual prices ranging from $2.52–4.37/MMBtu (U.S. Energy Information Administration 2017b) and prices are projected to remain below an average $5.00/MMBtu (2016) per year through 2030 in the absence of any policy changes (U.S. Energy Information Administration 2017c).

With conventional natural gas prices so low, fleet managers are increasingly finding investment in natural gas vehicles to be cost-effective, particularly in long-distance hauling, waste management, and transit (Jaffe et al. 2015; Boersma 2016). Natural gas vehicles are more expensive than diesel, with costs to consumers on the order of $25,000–30,000 more, but they can pay for themselves in three years or fewer when they travel more than 120,000 miles per year (Jaffe et al. 2015).[17] Although oil prices have fallen in recent years, the U.S. Energy Information Administration projects natural gas to continue to have a substantial price advantage over diesel

Figure 7 | **Estimated RNG Production Costs from Anaerobic Digestion of Wet Waste Sources**



Notes: Data are from four studies synthesizing costs from literature, economic models, and project data. RNG production costs reflect anaerobic digestion of waste sources to produce RNG for pipeline injection. The natural gas price provided for reference represents the 2017 average Henry Hub spot price for natural gas from the U.S. Energy Information Administration.
Source: WRI.

through 2030 (Brown 2017). Greater availability of natural gas vehicles presents an opportunity to replace relatively high carbon-intensity conventional natural gas with low and negative carbon-intensity RNG. But with production costs upwards of $3/MMBtu, it will be difficult for producers to offer RNG at or below parity with conventional natural gas (Miller et al. 2015) without the presence of incentives and other sources of revenue, discussed below.

Sources of Revenue, Financing, and Other Incentives

In addition to sale of the RNG itself, RNG projects can generate multiple sources of revenue and/or cost savings:

- **Sale of credits for compliance with renewable and low-carbon fuel markets**
  Recent prices under renewable and low-carbon fuel markets provide significant price support for RNG production for vehicle fuel (U.S. Department of Energy 2017a). At 2016 prices, for example, Jaffe et al. (2016) found that RINs under the Renewable Fuel Standard provided an effective incentive of $23.32/MMBtu,[18] and credits under California's low-carbon fuel standard provided an additional incentive of $4.00-$4.25/MMBtu for RNG produced from landfill gas, $45/MMBtu from dairy manure, and $12.75/MMBtu from municipal solid waste sources for fuel sold, supplied, or offered for sale in California.[19] Together, these markets provide more than enough of a price premium, compared to conventional natural gas, to allow profitable RNG production. The modeling of Jaffe et al. (2016) found that these policies could drive RNG production equal to levels five times greater than California's 2015 natural gas use in vehicles, assuming credit prices remain at 2016 levels through the 2020s and with conventional natural gas priced at $3.00/MMBtu.

  Although renewable and low-carbon fuel markets can provide substantial economic incentive for RNG production, they carry risk since their future prices can't be predicted with certainty. RIN prices have historically been volatile due to regulatory uncertainty around the policy and the volumes that EPA will set each year, as well as past problems with fraudulent RINs. And the potential value of these markets typically cannot be used to secure a loan for up-front capital (Mintz 2015b; U.S. Department of Agriculture et al. 2015).

- **Avoided waste disposal costs or waste collection fees**
  Most sources of waste that can be used for RNG feedstock would have to pay for disposal of that waste, through landfill tipping fees or wastewater remediation fees, for example. The opportunity to use waste that has little or even negative value as a commodity can itself be economically attractive (U.S. Department of Energy 2017a). Feedstock collection costs can be small or even negative when use of waste for RNG production leads to avoided disposal costs

(Jaffe et al. 2016; Langholtz et al. 2016). Projects that divert waste from landfills can allow waste managers to avoid tipping fees, significantly affecting project economics in some cases (Underwood and Tomich 2012; Hamberg et al. 2012; Jaffe et al. 2016). In 2014, landfill tipping fees averaged $49.78/ton nationwide, and are expected to increase as landfills approach capacity and populations increase (U.S. Department of Energy 2017a). Tipping fees vary widely from state to state, ranging from $25 to $35 in the Midwest and Southeast, up to $75 or more per ton in the Northeast (U.S. Department of Energy 2017a). Jaffe et al. (2016) found that the market potential of RNG in California is highly sensitive to tipping fee rates. For example, if tipping fees in the state were 20 percent higher than current levels, the market potential of RNG produced from separated organic municipal solid waste projects would increase sevenfold. Source-separated projects that collect yard and food waste (for example, the CR&R Digester in Perris, California, discussed in Box 1) can also charge homes and businesses for collection of the waste that is then used for RNG feedstock.

- **Sale or use of intermediary or coproducts from the RNG production process**
  Multiple intermediary products or coproducts can be sold off-site to generate an additional revenue stream or used on-site, leading to cost savings. Some of the biogas produced can be used for heat and power, which can be sold or used to meet other on-site energy needs. The nutrient-rich digestate left over from biogas production can be used to produce fertilizer, which can be sold or used to displace and offset the costs of fertilizer at livestock operations, and the solid digestate can be used for animal bedding.

- **Sale of offset credits under carbon markets**
  California's cap-and-trade program and the Regional Greenhouse Gas Initiative both allow avoided methane emissions from livestock manure projects to generate offsets that can be sold for compliance (California Air Resources Board 2014b; RGGI, Inc. 2013).

Other state and federal policies support RNG production and use through financing and other incentives. In recent years, federal programs have offered funding for anaerobic digesters and other biogas system components through USDA's Rural Energy for America Program, Environmental Quality Incentives Program, Bioenergy Program for Advanced Biofuel, Biorefinery Assistance Program, and Conservation Innovation Grants, and the DOE's Clean Cities Program (U.S. Department of Agriculture et al. 2015). Some states and municipalities also offer assistance with financing through cost-sharing, grants, loans, and loan guarantees. Many states also offer grants, loans, rebates, vouchers, and tax incentives for purchase of natural gas vehicles and development of natural gas fueling infrastructure, which can assist with RNG project development (U.S. Department of Energy 2017b).

Together, these revenue streams and incentives can greatly shift project economics, allowing producers to offset and recoup relatively high up-front costs. Early experiences show that a diverse range of RNG project types can be economically viable and potentially cost-effective, with payback periods ranging from immediate to about 10 years in some cases (U.S. Environmental Protection Agency 2014; Linville et al. 2015; Energy Vision 2017).[20]

Market Opportunities

As previously described, additional research is needed to estimate the market potential of RNG from wet wastes. But experience on the ground shows that projects across multiple wet waste sources can be economically feasible. Assessments of the available resource base and market opportunities across wet waste sources conducted by the DOE, EPA, and USDA find that untapped potential remains, with an excess of 50 million dry tons of food waste, animal manure, wastewater sludge, and FOG available for use each year (U.S. Department of Energy 2017a).

Generally speaking, landfills offer the greatest current economic potential, compared to other sources, because they require relatively little buildout and have a customer base readily available in the form of heavy-duty waste management vehicles. However, many landfills are already collecting landfill gas and either flaring the gas or using it for power or heat. RNG from these sources would be risky from a climate perspective unless investments made as part of the RNG project could significantly improve landfill gas collection efficiencies, as described in Section 2. RNG projects at landfills not already collecting gas would offer more certainty in achieving climate benefits. The EPA estimates that an additional 400 candidate landfills could effectively collect and produce energy with biogas; of these, 184 are not currently collecting landfill gas according to data from EPA's Landfill Methane Outreach Program (U.S. Department of Agriculture et al. 2014; U.S. Environmental Protection Agency 2016, 2017f). Over the longer term, however, as landfills reach capacity and states and municipalities put policies in place to prevent organic waste from landfill disposal, the resource base will likely decline.

In any case, diverting organic waste before it reaches the landfill provides an opportunity to achieve much deeper GHG reductions than landfill gas projects. Anaerobic digestion of source-separated food and yard waste can lead to GHG benefits even if the landfill that would otherwise accept the waste has a gas collection system in place because these systems are not 100 percent efficient. By avoiding the uncontrolled methane emissions altogether, diverted waste projects can earn some of the highest credit values in California's and Oregon's low-carbon fuel markets (California Air Resources Board 2012). These projects require high up-front costs because all infrastructure to produce RNG will need to be constructed from scratch. But the revenue that can be generated from waste collection costs or through avoided tipping fees, combined with revenue from low-carbon fuel markets, can make these projects economically attractive. And because these projects aggregate waste from multiple sources, they can benefit from economies of scale and be strategically located near pipelines, fueling stations, and existing waste transfer stations where waste is already sorted (U.S. Department of Energy 2017a). These projects also may be an increasingly attractive option as states and municipalities across the country take steps to divert organic waste from landfills for other environmental and economic reasons.

Similar to landfills, many wastewater treatment plants already collect biogas generated during waste treatment and flare or, to a more limited extent, use it for heat or power (Seiple et al. 2017). The EPA estimates that more than 2,400 additional digesters could be added at existing wastewater treatment facilities, but the economic feasibility at these sites has not been evaluated as market potential studies focus on sites that already have anaerobic digesters in place (U.S. Environmental Protection Agency 2014). However, regulatory approaches to wastewater treatment are shifting away from narrow, prescriptive approaches that have stifled innovation in the past toward a performance-based approach that may open the door for more wastewater facilities to explore new bioenergy projects while maintaining their commitment to public health and environmental protection. Many existing facilities are nearing the end of their useful lives, presenting an opportunity to add new digesters and conditioning equipment as existing facilities are replaced or upgraded (U.S. Department of Energy 2017a). Additionally, many wastewater treatment plants are already equipped to handle more waste than they currently process and could potentially accept food and yard waste diverted from landfills.

Livestock operations offer significant resource potential, with biogas recovery systems technically feasible at 8,000 additional dairy and hog farms across the country (U.S. Department of Agriculture et al. 2014). Costs can be prohibitive for these projects, especially for smaller farms located far from the pipeline or potential end users. But some farms may be promising candidates for off-grid projects that make use of RNG produced locally and experience its benefits locally, rather than connecting to the pipeline (Parker et al. 2017). Similar to diverted food and yard waste projects, livestock projects can fetch high credit prices under California's LCFS because of its negative certified carbon intensity.

CONCLUSION

Early research and experience suggest that opportunities exist for states, municipalities, and companies to cut GHG emissions by using RNG produced from wet wastes as a vehicle fuel. RNG can lead to life-cycle GHG reductions of at least 50 percent and in some cases well over 100 percent, compared with fossil fuels, when it is produced from wastes that would lead to methane emissions in typical management practices—including food and yard waste, landfill gas, manure at livestock operations, FOG, and sludge at wastewater treatment plants. Source-separated food and yard waste and manure projects will generally offer the greatest potential for large net GHG reductions and involve little, if any, risk of increasing GHG emissions even if methane leakage rates are underestimated in life-cycle analyses. Although RNG from wet waste sources is more expensive to produce than conventional natural gas, experiences on the ground are finding that RNG projects can be economically viable at sites around the country, with estimated payback periods under 10 years in some cases.

RNG's GHG reduction potential suggests that it could be an attractive low-carbon strategy, particularly in the near to medium term, provided it meets the two criteria we described in this working paper. RNG projects can lead to immediate reductions in methane emissions from organic waste sources. When sourced from diverted food and yard waste or livestock manure, RNG can provide the least carbon-intensive source of low-carbon fuel currently available for heavy-duty vehicles. Both of these emissions sources must be addressed to avoid the most dangerous impacts of climate change (Hausker et al. 2015). Entities considering use of RNG as a climate strategy will need to assess the GHG impacts, costs, and benefits on a case-by-case basis as they will vary from project to project.

This working paper has provided a starting point to understand RNG's potential as GHG reduction strategy, but more research and on-the-ground experience are needed to fully evaluate RNG's climate and economic benefits and its role in near- to long-term climate plans. We have highlighted the following topics as ripe for future exploration:

- Better data on methane leakage from all aspects of the RNG supply chain, especially from production and processing
- Sensitivity analysis of RNG carbon intensities under a range of methane leakage, methane global warming potential, and other key assumptions
- Analysis of the potential to estimate break-even methane leakage rates across the supply chain for waste-derived RNG pathways below which RNG will have immediate climate benefits over conventional natural gas and petroleum-based fossil fuels
- Life-cycle GHG estimates for RNG production from dry wastes (for example, forest, yard, and agricultural residues) and analyses of other social and economic implications of potential use of these feedstocks for RNG
- Estimates of RNG market potential from wet waste sources that incorporate the effects of low-carbon fuel markets and other incentives
- Development of a database of RNG projects on the ground that includes costs, incentives, life-cycle GHG emission benefits, and other data, if possible
- Scenario modeling of RNG's GHG mitigation potential and its contributions to state and/or national GHG emission reduction goals under a range of market conditions
- Comparison of RNG's climate benefits, costs, and feasibility to other low-carbon fuels and other methane reduction strategies

Better understanding of these topics, together with more experience on the ground, will enable continued evaluation of waste-derived RNG production and use as an economically feasible, potentially cost-effective tool to address climate change.

GLOSSARY

BIOGAS: A gaseous mix of carbon dioxide and methane that is produced from the decomposition of organic materials in the absence of oxygen.

CONVENTIONAL NATURAL GAS: A composed of comprising primarily methane.

FEEDSTOCK: A material used as fuel or converted to fuel for energy purposes. RNG feedstocks are organic materials that generally fall into two categories according to moisture content:

> **WET FEEDSTOCKS:** Food waste, yard waste, fats, oils, and greases (FOG), manure, sludge from wastewater treatment. These are the main feedstocks used to produce RNG today, and they are typically converted to RNG through anaerobic digestion, either in separated anaerobic digesters or at landfills.
>
> **DRY FEEDSTOCKS:** Agricultural crop residue, forestry residue and other wood waste, and energy crops. Woody feedstocks are not generally used for RNG production today because the gasification technologies best suited to convert them to gas are not commercially available, but they may be used in the future as these technologies mature.

LANDFILL GAS: Biogas that is produced from the decomposition of organic materials within landfills.

METHANE LEAKAGE: Methane gas escaping from infrastructure into the atmosphere.

RENEWABLE NATURAL GAS: Biogas that has been processed into essentially pure methane, which can be used interchangeably with conventional natural gas in all its end uses.

WASTE: A material with no alternative use.

ENDNOTES

1. If dedicated crops, such as switchgrass, were used to produce RNG, additional GHG emissions would result from land-use change and decreased carbon sequestration from the opportunity cost of using land that could otherwise store carbon. Dedicated crops are not used to produce RNG today because the technologies used to convert them to gas are not yet commercially available, but they are sometimes included in assessments of RNG's technical or market potential.
2. According to the 2006 methodologies for national GHG reporting recommended by the IPCC guidelines, methane has 25 times the overall global warming potential over 100 years of carbon dioxide, and the most recent IPCC comprehensive assessment raised this figure to 28–34. Because the production of methane from biomass means modestly fewer emissions of carbon dioxide, the net additional warming multiple is roughly 22 or 30. Because methane is a short-lived climate pollutant, use of a higher global warming potential to estimate RNG's net GHG impacts may be appropriate, as discussed in more detail in Section 2.
3. While yard waste is not generally considered a wet feedstock, we include it in our discussion because it is suitable for high-solids anaerobic digestion with food waste (California Air Resources Board 2012).
4. The gas produced from thermochemical technologies, typically referred to as syngas, largely comprises carbon monoxide and hydrogen. The syngas can then be methanated, cleaned, and upgraded into RNG.
5. According to the 2006 methodologies for national GHG reporting recommended by the IPCC guidelines, methane has 25 times the overall global warming potential over 100 years of carbon dioxide, and the most recent IPCC comprehensive assessment raised this figure to 28–34. Because the production of methane from biomass means modestly fewer emissions of carbon dioxide, the net additional warming multiple is roughly 22 or 30. Because methane is a short-lived climate pollutant, use of a higher global warming potential to estimate RNG's net GHG impacts may be appropriate, as discussed in more detail in Section 2.
6. The EPA treats biogas produced in separated municipal solid waste digesters containing cellulosic materials that would otherwise end up in landfills as cellulosic biofuel under the rule in the same manner as landfill biogas. This is also true for digester gas from agricultural digesters that process predominantly cellulosic materials such as manure, crop residue, and yard waste. However, wastes that are not predominantly cellulosic may be processed in waste digesters, for example non-manure animal waste and separated food waste high in starch and sugars. The predominantly non-cellulosic portion of the digester biogas would qualify as an advanced biofuel rather than a cellulosic biofuel, satisfying EPA's required GHG reduction threshold of 50 percent. For more information, see: <https://www.gpo.gov/fdsys/pkg/FR-2014-07-18/pdf/2014-16413.pdf>.
7. On May 31, 2017, the EPA issued a 90-day stay of these rules. Since the stay expired on August 29, 2017, the existing rules are currently in effect, although EPA intends to complete reconsidering portions of the rules. For more information, see https://www.epa.gov/stationary-sources-air-pollution/municipal-solid-waste-landfills-new-source-performance-standards.
8. Data in this paragraph was converted to common units using conversion factors from the U.S. Department of Energy: https://epact.energy.gov/fuel-conversion-factors.
9. This list only includes market potential studies that present RNG potential from waste feedstocks separately from RNG potential from dedicated energy crops.
10. If RNG were produced from energy-dedicated crops, calculation of life-cycle GHG emissions would also have to account for the GHG opportunity costs of using land, such as the carbon storage that its use for bioenergy would ultimately sacrifice. Many life-cycle calculations of bioenergy have been flawed because they do not fully account for these emissions. For more details, see Searchinger, and Heimlich (2015). Avoiding Bioenergy Competition for Food Crops and Land. Accessible at: http://www.wri.org/publication/avoiding-bioenergy-competition-foodcrops-and-land.
11. For one effort to differentiate the costs of alternative uses of waste sources, see Brander et al. (2009).
12. Methane has a global warming potential in the range of 25–34, and when biomass is converted to methane instead of carbon dioxide, the net additional warming multiple is roughly 22 or 30. By simple arithmetic, if converting a gram of carbon in biomass into methane instead of carbon dioxide increases the 100-year global warming impact 30 times, then a 3.3 percent leakage rate of the additional methane produced for RNG production would generate 100 percent of the warming effect over 100 years as allowing the biomass to be decomposed or burned into carbon dioxide. In that case, even if each gram of carbon in waste biomass replaced one gram of carbon in fossil fuels, the leakage rate would entirely eliminate the GHG reductions. With a net warming impact of 22, a leakage rate of 4.54 percent would eliminate all global warming benefits.
13. The UNFCCC Clean Development Mechanism methodology for calculating project and leakage emissions from digesters provides default assumptions of 2.8–10 percent depending on the digester type (UNFCCC 2012). The values are 2.8 percent for digesters with steel or lined concrete or fiberglass digesters and a gas holding system (egg shaped digesters) and monolithic construction; 5 percent for floating gas holders with no external water seal; and 10 percent for digesters with unlined concrete/ferro cement/brick masonry arched type gas holding section, monolithic fixed dome digesters, and covered anaerobic lagoons. The IPCC recommends a default assumption of 5 percent absent additional information in its guidelines on national GHG inventory development (IPCC 2006). Other estimates from projects in Sweden indicate that average methane leakage rates from biogas production at wastewater treatment plants, digesters of separated household waste, and digesters of industrial waste are 3 percent, 1.7 percent, and 0.2 percent of biogas produced, respectively (Jonerholm and Lundborg 2012).
14. Estimated using data from Table VI-6 from California Air Resources Board (2014a). We assumed methane emissions from anaerobic digestion and management of the supernatant and digestate would have occurred if RNG were not produced as part of wastewater treatment practices, so the only additional methane emissions were due to biogas refining stages 1 and 2 and combustion in the vehicle. The estimate accounts for avoided methane emissions from off-site power generation that is displaced under the RNG pathway.
15. Personal communication with Sarah Rizk, Director of Business and Sales at Loci Controls.

16. For example, when crops are diverted to ethanol, the convention is to ignore the emissions from burning the biofuel in the vehicle, as well as the carbon emitted from fermentation of starches into ethanol. These emissions are known as biogenic emissions because they come from the carbon in the plants themselves. They are also offset by the combination of carbon absorbed by additional crop production and reductions in carbon emitted by people and livestock if not all food is replaced and there are therefore reductions in food consumption. This reduced food consumption can be significant, but it is unlikely that many policymakers would wish to pursue strategies designed to reduce GHG emissions by reducing food. Laying out where emissions actually occur is therefore important for properly understanding the life-cycle analysis. In addition, the portion of new crops produced by clearing new land will also lead to emissions from deforestation and other land-use changes, which must also be counted along with the carbon absorbed by additional crops. The net result may be increases in emissions. These emissions can be counted as land use change and are so counted in some models. If they are counted, the overall life-cycle calculation can become potentially accurate even if it ignores the carbon emitted from burning the fuel (as well as the carbon in new crop production and carbon in reduced food consumption). Yet, to assure mathematically correct calculations in a transparent way, the analysis should explicitly count both the emissions and offsets of all biogenic carbon. For more details, see Searchinger et al. (2015).
17. The calculation in this study was made on the basis of a diesel price of $4 per gallon, LNG price of $2.45 per diesel gallon equivalent (dge), and CNG price of $2.34 per dge.
18. Estimates are based on 2016 cellulosic RIN prices of $1.78/gallon of ethanol equivalent.
19. Estimates are based on a credit price of $120 per credit, the average monthly price at the end of the first quarter of 2016. Credits under California's low-carbon fuel standard traded at an average of around $100/credit in 2016 and $90/credit in 2017. For more information see https://www.arb.ca.gov/fuels/lcfs/credit/20180109_deccreditreport.pdf/.
20. While a database of RNG projects with costs, incentives, and other data does not exist, Energy Vision profiles provide some of this information for 14 RNG vehicle fuel projects in the United States (Energy Vision 2017). Of the 14, 10 provided plant costs, which range from $350,000 to $55 million, and 7 provided estimated payback periods, which range from immediate to about 10 years.

REFERENCES

Alvarez, Ramón A., Stephen W. Pacala, James J. Winebrake, William L. Chameides, and Steven P. Hamburg. 2012. "Greater Focus Needed on Methane Leakage from Natural Gas Infrastructure." *Proceedings of the National Academy of Sciences* 109 (17): 6435–40. doi:10.1073/pnas.1202407109.

American Gas Foundation. 2011. *The Potential for Renewable Gas: Biogas Derived from Biomass Feedstocks and Upgraded to Pipeline Quality.* Prepared by the Gas Technology Institute, Washington, DC.

Boersma, Tim. 2016. *Natural Gas in the United States in 2016.* Washington, DC: Brookings Institution.

Börjesson, Pål, and Maria Berglund. 2006. "Environmental Systems Analysis of Biogas systems—Part I: Fuel-Cycle Emissions." *Biomass and Bioenergy* 30 (5): 469–85. doi:10.1016/j.biombioe.2005.11.014.

Bradbury, James, Michael Obeiter, Laura Draucker, and Amanda Stevens. 2013. *Clearing the Air: Reducing Upstream Greenhouse Gas Emissions from U.S. Natural Gas Systems.* Washington, DC: World Resources Institute.

Brander, Matthew, Charlotte Hutchison, Chris Sherrington, Ann Ballinger, Catherine Beswick, Adam Baddeley, Mairi Black, Jeremy Woods, and Richard Murphy. 2009. *Methodology and Evidence Base on the Indirect Greenhouse Gas Effects of Using Wastes, Residues, and By-Products for Biofuels and Bioenergy.* Report to the Renewable Fuels Agency and the Department for Energy and Climate Change. Ecometrica, Eunomia, Imperial College London.

Brown, Stephen P. A. 2017. "Natural Gas vs. Oil in U.S. Transportation: Will Prices Confer an Advantage to Natural Gas?" *Energy Policy* 110 (Supplement C): 210–21. doi:10.1016/j.enpol.2017.08.018.

Business for Social Responsibility. 2016. *Fuel Sustainability Tool.* https://www.bsr.org/collaboration/groups/future-of-fuels.

California Air Resources Board. 2012. *Proposed Low Carbon Fuel Standard (LCFS) Pathway for the Production of Biomethane from High Solids Anaerobic Digestion (HSAD) of Organic (Food and Green) Wastes.* Sacramento, CA.

California Air Resources Board. 2014a. *Low Carbon Fuel Standard (LCFS) Pathway for the Production of Biomethane from the Mesophilic Anaerobic Digestion of Wastewater Sludge at a Publicly-Owned Treatment Works (POTW).* Sacramento, CA.

California Air Resources Board. 2014b. *Compliance Offset Protocol Livestock Projects.* Sacramento, CA.

California Air Resources Board. 2017a. *The 2017 Climate Change Scoping Plan Update: The Proposed Strategy for Achieving California's 2030 Greenhouse Gas Target.* Sacramento, CA.

California Air Resources Board. 2017b. "Low Carbon Fuel Standard." https://www.arb.ca.gov/fuels/lcfs/lcfs.htm.

California Air Resources Board. 2017c. *Short-Lived Climate Pollutant Reduction Strategy.* Sacramento, CA.

California Air Resources Board. 2017d. "LCFS Pathway Certified Carbon Intensities." https://www.arb.ca.gov/fuels/lcfs/fuelpathways/pathwaytable.htm.

California Department of Food and Agriculture. 2018. *Report of Funded Projects (2015-2017).* Sacramento, CA.

Camuzeaux, Jonathan R., Ramón A. Alvarez, Susanne A. Brooks, Joshua B. Browne, and Thomas Sterner. 2015. "Influence of Methane Emissions and Vehicle Efficiency on the Climate Implications of Heavy-Duty Natural Gas Trucks." *Environmental Science & Technology* 49 (11): 6402–10. doi:10.1021/acs.est.5b00412.

Clark, Nigel N., David L. McKain, Derek R. Johnson, W. Scott Wayne, Hailin Li, Vyacheslav Akkerman, Cesar Sandoval et al. 2017. "Pump-to-Wheels Methane Emissions from the Heavy-Duty Transportation Sector." *Environmental Science & Technology* 51 (2): 968–76. doi:10.1021/acs.est.5b06059.

Delgado, Oscar, and Rachel Muncrief. 2015. *Assessment of Heavy-Duty Natural Gas Vehicle Emissions: Implications and Policy Recommendations.* The International Council on Clean Transportation.

Energy Independence and Security Act 2007. 2007. 42 USC 17001.

Energy Vision. 2017. "Case Studies: RNG Project Profiles." http://energy-vision.org/resources/project-profiles/.

Energy Policy Act of 2005. 2005. 42 USC 15801.

Environmental Defense Fund. *Methane Research: The 16 Study Series.* 2017. https://www.edf.org/sites/default/files/methane_studies_fact_sheet.pdf?_ga=1.191285231.474833959.1456855095.

Escuder, Johannes. 2017. "Powering Businesses, Homes and Vehicles with Waste: How to Grow the Economy & Jobs with Biogas & Renewable Natural Gas." Washington, DC, May 23.

Federal Register, 40 CFR Part 80. 2014. *Regulation of Fuels and Fuel Additives: RFS Pathways II, and Technical Amendments to the RFS Standards and E15 Misfueling Mitigation Requirements; Final Rule.*

Federal Register, 40 CFR Part 80. 2016. *Renewable Fuel Standard Program: Standards for 2017 and BiomassBased Diesel Volume for 2018.*

Federal Register, 40 CFR Part 80. 2017. *Renewable Fuel Standard Program: Standards for 2018 and BiomassBased Diesel Volume for 2019; Proposed Rule.*

Haines, Andy, Markus Amann, Nathan Borgford-Parnell, Sunday Leonard, Johan Kuylenstierna, and Drew Shindell. 2017. "Short-Lived Climate Pollutant Mitigation and the Sustainable Development Goals." *Nature Climate Change* 7 (12): 863–69. doi:10.1038/s41558-017-0012-x.

Hamberg, Karen, Don Furseth, Jim Wegrzyn, Anthony LaRusso, Donald Chahbazpour, Gail Richardson, Barry Carr et al. 2012. *Renewable Natural Gas for Transportation: An Overview of the Feedstock Capacity, Economics, and GHG Emission Reduction Benefits of RNG as a Low-Carbon Fuel.* A White Paper for the National Petroleum Council–Future Transportation Fuels Study.

Han, Jeongwoo, Marianne Mintz, and Michael Wang. 2011. *Argonne GREET Publication: Waste-to-Wheel Analysis of Anaerobic-Digestion-Based Renewable Natural Gas Pathways with the GREET Model.* Argonne, IL: Argonne National Laboratory. https://greet.es.anl.gov/publication-waste-to-wheel-analysis.

Hausker, Karl, Kristin Igusky, Rebecca Gasper, Nate Aden, and Michael Obeiter. 2015. *Delivering on the U.S. Climate Commitment: A 10-Point Plan toward a Low-Carbon Future.* Washington, DC: World Resources Institute.

ICF International, Inc. 2017. *Economic Impacts of Deploying Low NOx Trucks Fueled by Renewable Natural Gas.*

IPCC (Intergovernmental Panel on Climate Change). 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories.* Prepared by the National Greenhouse Gas Inventories Programme. IGES, Japan.

Jaffe, Amy, R. Dominguez-Faus, N. Parker, D. Scheitrum, J. Wilcock, and M. Miller. 2016. *The Feasibility of Renewable Natural Gas as a Large-Scale, Low Carbon Substitute.* Prepared for the California Air Resources Board and the California Environmental Protection Agency. Davis, CA: STEPS Program, Institute of Transportation Studies, University of California, Davis.

Jaffe, Amy, Rosa Dominguez-Faus, Allen Lee, Kenneth B. Medlock, Nathan C. Parker, Rosa Dominguez-Faus, Kenneth B. Medlock III et al. 2015. *STEPS White Paper: Exploring the Role of Natural Gas in U.S. Trucking.* Davis, CA: Institute of Transportation Studies, University of California, Davis.

Jonerholm, Katarina, and Hans Lundborg. 2012. *Methane Losses in the Biogas System.* Baltic Biogas Bus.

Langholtz, Matthew, Bryce J. Stokes, and Laurence Eaton. 2016. *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy.* ORNL/TM-2016/160. Oak Ridge, TN: Oak Ridge National Laboratory, U.S. Department of Energy.

Linville, Jessica L., Yanwen Shen, May M. Wu, and Meltem Urgun-Demirtas. 2015. "Current State of Anaerobic Digestion of Organic Wastes in North America." *Current Sustainable/Renewable Energy Reports* 2 (4): 136–44. doi:10.1007/s40518-015-0039-4.

Littlefield, James A., Joe Marriott, Greg A. Schivley, and Timothy J. Skone. 2017. "Synthesis of Recent Ground-Level Methane Emission Measurements from the U.S. Natural Gas Supply Chain." *Journal of Cleaner Production* 148 (Supplement C): 118–26. doi:10.1016/j.jclepro.2017.01.101.

Loci Controls. 2018a. "Publications." Accessed March 22. https://locicontrols.com/publications.php.

Loci Controls. 2018b. "Case Study 4." Accessed March 22. https://locicontrols.com/perch/resources/case-study-4b-loci-controls-increases-ch4-collection-by-17-at-high-btu-013118.pdf.

Miller, Marshall, Michael Ippoliti, Nathan Parker, Rosa Dominguez-Faus, and Lewis Fulton. 2015. *Renewable Natural Gas as a Transportation Fuel Research Roadmap.* Prepared for the California Energy Commission.

Mintz, Marianne. 2015a. "Renewable Natural Gas: New Rules, New Opportunities." June 29.

Mintz, Marianne. 2015b. "Renewable Natural Gas for Vehicle Fuel: Projects, Prospects, and D3 RINS." presented at the REFOR 15, Boston, MA, October 21.

Murray, Brian, Christopher Galik, and Tibor Veigh. 2014. *Biogas in the United States: An Assessment of Market Potential in a Carbon-Constrained Future.* Durham, NC: Nicholas Institute for Environmental Policy Solutions, Duke University.

Myhre, Gunnar, Drew Shindell, Francois-Marie Breon, William Collins, Jan Fuglestvedt, Jianping Huang, Dorothy Koch et al. 2013. "Anthropogenic and Natural Radiative Forcing." In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge and New York: Cambridge University Press.

Oregon Department of Environmental Quality. 2017. "Oregon Clean Fuels Program." http://www.oregon.gov/deq/aq/programs/Pages/Clean-Fuels-Regulations.aspx.

Parker, Nathan, Robert Williams, Rosa Dominguez-Faus, and Daniel Scheitrum. 2017. "Renewable Natural Gas in California: An Assessment of the Technical and Economic Potential." *Energy Policy* 111 (Supplement C): 235–45. doi:10.1016/j.enpol.2017.09.034.

Public Utility Commission of the State of California. 2015. *Decision Regarding the Costs of Compliance with Decision 14-01-034 and Adoption of Biomethane Promotion Policies and Program.* Vol. Decision 15-06-029.

RGGI, Inc. 2013. "Regional Greenhouse Gas Initiative Model Rule."

Russell, Pye, Dana Lowell, and Brian Jones. 2017. *Renewable Natural Gas: The RNG Opportunity for Natural Gas Utilities.* M.J. Bradley & Associates. http://www.mjbradley.com/reports/renewable-natural-gas-rng-opportunity-natural-gas-utilities.

Saur, Genevieve, and Anelia Milbrandt. 2014. *Renewable Hydrogen Potential from Biogas in the United States.* Golden, CO: National Renewable Energy Laboratory.

Searchinger, Tim, Robert Edwards, Declan Mulligan, Ralph Heimlich, and Richard Plevin. 2015. "Do Biofuel Policies Seek to Cut Emissions by Cutting Food?", *Science* 347 (6229): 1420–22.

Searchinger, Tim, and Ralph Heimlich. 2015. *Avoiding Bioenergy Competition for Food Crops and Land.* Working Paper, Installment 9 of Creating a Sustainable Food Future. Washington, DC: World Resources Institute. http://www.wri.org/publication/avoiding-bioenergy-competition-foodcrops-and-land.

Seiple, Timothy E., André M. Coleman, and Richard L. Skaggs. 2017. "Municipal Wastewater Sludge as a Sustainable Bioresource in the United States." *Journal of Environmental Management* 197 (Supplement C): 673–80. doi:10.1016/j.jenvman.2017.04.032.

State of California, Assembly Bill No. 2313. 2016. "Renewable Natural Gas: Monetary Incentive Program for Biomethane Projects: Pipeline Infrastructure."

State of California, Senate Bill No. 1383. 2016. "Short-Lived Climate Pollutants: Methane Emissions: Dairy and Livestock: Organic Waste: Landfills."

Sun, Qie, Hailong Li, Jinying Yan, Longcheng Liu, Zhixin Yu, and Xinhai Yu. 2015. "Selection of Appropriate Biogas Upgrading Technology—a Review of Biogas Cleaning, Upgrading and Utilisation." *Renewable and Sustainable Energy Reviews* 51 (November): 521–32. doi:10.1016/j.rser.2015.06.029.

Underwood, J., and M. Tomich. 2012. Turning Waste Into Vehicle Fuel: A Step-by-Step Guide for Communities. Energy Vision. http://energy-vision.org/ev-publications/EV-RNG-Community-Guide.pdf.

UNFCCC (United Nations Framework Convention on Climate Change). 2012. *Methodological Tool: Project and Leakage Emissions from Anaerobic Digesters, Version 01.0.0.*

Union of Concerned Scientists. 2017. *The Promises and Limits of Biomethane as a Transportation Fuel.* Washington, DC.

U.S. Department of Agriculture, U.S. Environmental Protection Agency, and U.S. Department of Energy. 2014. *Biogas Opportunities Roadmap: Voluntary Actions to Reduce Methane Emissions and Increase Energy Independence.* Washington, DC.

U.S. Department of Agriculture, U.S. Environmental Protection Agency, U.S. Department of Energy. 2015. *Biogas Opportunities Roadmap: Progress Report.* Washington, DC.

U.S. Department of Energy. 2017a. *Biofuels and Bioproducts from Wet and Gaseous Waste Streams: Challenges and Opportunities.* Developed by Allegheny Science & Technology (AS&T) for Department of Energy's Bioenergy Technologies Office.

U.S. Department of Energy. 2017b. "Alternative Fuels Data Center." https://www.afdc.energy.gov/.

U.S. Energy Information Administration. 2017a. "Sales of Distillate Fuel Oil by End Use." https://www.eia.gov/opendata/qb.php?category=711246&sdid=TOTAL.TRFCRUS.A.

U.S. Energy Information Administration. 2017b. "Henry Hub Natural Gas Spot Price." https://www.eia.gov/dnav/ng/hist/rngwhhda.htm.

U.S. Energy Information Administration. 2017c. *Annual Energy Outlook 2017.* https://www.eia.gov/outlooks/aeo/.

U.S. Environmental Protection Agency. 2011. *Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from Municipal Solid Waste Landfills.* Washington, DC.

U.S. Environmental Protection Agency. 2014. *Food Waste to Energy: How Six Water Resource Recovery Facilities Are Boosting Biogas Production and the Bottom Line.* Region 9 San Francisco, CA and National Risk Management Research Lab Office of Research and Development, Cincinnati, OH.

U.S. Environmental Protection Agency. 2015. *Framework for Assessing Biogenic CO_2 Emissions from Stationary Sources.* Washington, DC.

U.S. Environmental Protection Agency. 2016. *AgSTAR Data and Trends.* https://www.epa.gov/agstar/agstar-data-and-trends.

U.S. Environmental Protection Agency. 2017a. *Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990–2015.* Washington, DC.

U.S. Environmental Protection Agency. 2017b. "Spreadsheet of RIN Generation and Renewable Fuel Volume Production by Fuel Type for the Renewable Fuel Standard." https://www.epa.gov/fuels-registration-reporting-and-compliance-help/spreadsheet-rin-generation-and-renewable-fuel-0.

U.S. Environmental Protection Agency. 2017c. "Landfill Methane Outreach Program (LMOP)." https://www.epa.gov/lmop.

U.S. Environmental Protection Agency. 2017d. "AgSTAR: Biogas Recovery in the Agriculture Sector." https://www.epa.gov/agstar.

U.S. Environmental Protection Agency. 2017e. "Municipal Solid Waste Landfills: New Source Performance Standards (NSPS), Emission Guidelines (EG) and Compliance Times: Reconsideration and Stay of Effective Date." https://www.epa.gov/stationary-sources-air-pollution/municipal-solid-waste-landfills-new-source-performance-standards-0.

U.S. Environmental Protection Agency. 2017f. "Landfill Gas Energy Project Data and Landfill Technical Data." https://www.epa.gov/lmop/landfill-gas-energy-project-data-and-landfill-technical-data.

Warner, Ethan, Kristi Moriarty, John Lewis, Anelia Milbrand, and Amy Schwab. 2017. *2015 Bioenergy Market Report.* Golden, CO: National Renewable Energy Laboratory.

Warner, Ethan, Daniel Steinberg, Elke Hodson, and Garvin Heath. 2015. *Potential Cost-Effective Opportunities for Methane Emission Abatement.* Joint Institute for Strategic Energy Analysis and U.S. Department of Energy, Office of Energy Policy and Systems Analysis.

Zimmerman, Grant. 2017. "Powering Businesses, Homes and Vehicles with Waste: How to Grow the Economy & Jobs with Biogas & Renewable Natural Gas." Washington, DC, May 23.

ACKNOWLEDGMENTS

The authors would like to thank Leah Schleifer for her contributions to earlier versions of this work. Thank you also to our peer reviewers and others who provided valuable inputs or feedback: Nate Aden, Anthy Alexiades, Anil Baral, Celina Bonugli, James Bradbury, Jonathan Camuzeaux, Tyler Clevenger, Bill Edmonds, Xiaotian Fu, Christopher Galik, Delfina Grinspan, Jeongwoo Han, Karl Hausker, Kristin Igusky, Brian Jones, Brendan Jordan, Kevin Kennedy, Brian Lipinski, Dana Lowell, Eliot Metzger, Anelia Milbrandt, Marshall Miller, Mark Philbrick, Anil Prahbu, David Rich, Joe Rudek, Richard Skaggs, and Nate Springer. While our colleagues were very generous with their time and input, this working paper reflects the views of the authors alone. We also wish to thank Emily Matthews, Julie Moretti, Caroline Taylor, and Romain Warnault for editing and design, Andrew Pickens for communications support, and WRI's science and research team, especially Daryl Ditz and Maria Hart.

This publication was made possible due to financial support from the UPS Foundation.

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ABOUT WRI

World Resources Institute is a global research organization that turns big ideas into action at the nexus of environment, economic opportunity, and human well-being.

Our Challenge

Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

Our Vision

We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

Our Approach

COUNT IT

We start with data. We conduct independent research and draw on the latest technology to develop new insights and recommendations. Our rigorous analysis identifies risks, unveils opportunities, and informs smart strategies. We focus our efforts on influential and emerging economies where the future of sustainability will be determined.

CHANGE IT

We use our research to influence government policies, business strategies, and civil society action. We test projects with communities, companies, and government agencies to build a strong evidence base. Then, we work with partners to deliver change on the ground that alleviates poverty and strengthens society. We hold ourselves accountable to ensure our outcomes will be bold and enduring.

SCALE IT

We don't think small. Once tested, we work with partners to adopt and expand our efforts regionally and globally. We engage with decision-makers to carry out our ideas and elevate our impact. We measure success through government and business actions that improve people's lives and sustain a healthy environment.